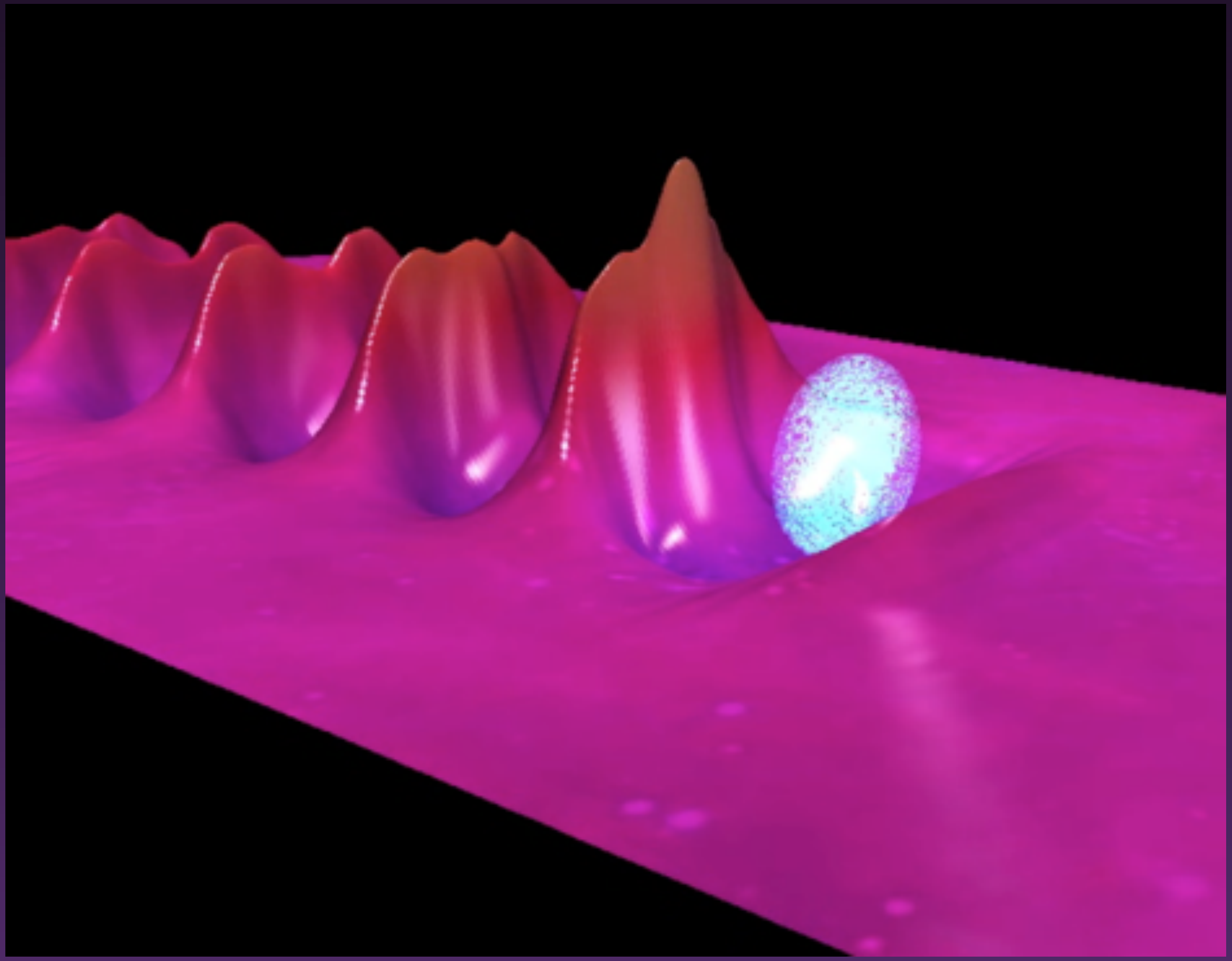
Compact Light Sources from Laser Plasma Accelerators



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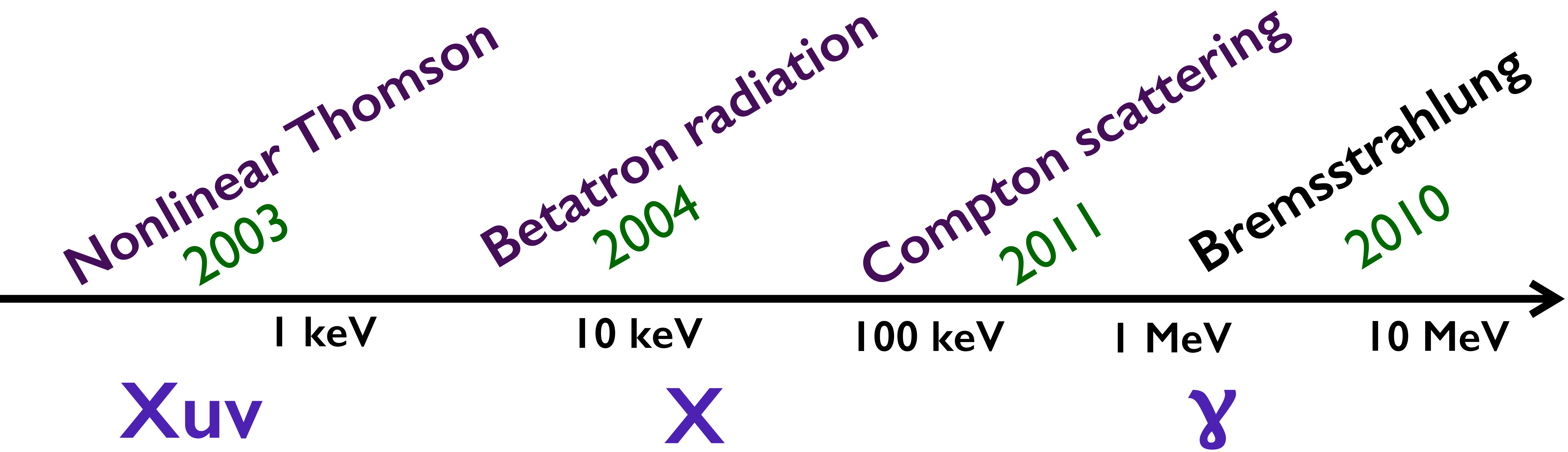
The 6th International Conference "Charged & Neutral Particles Channeling Phenomena - **Channeling 2014**, Capri, Italia, October 5-10 (2014)

X rays source with Laser Plasma accelerators

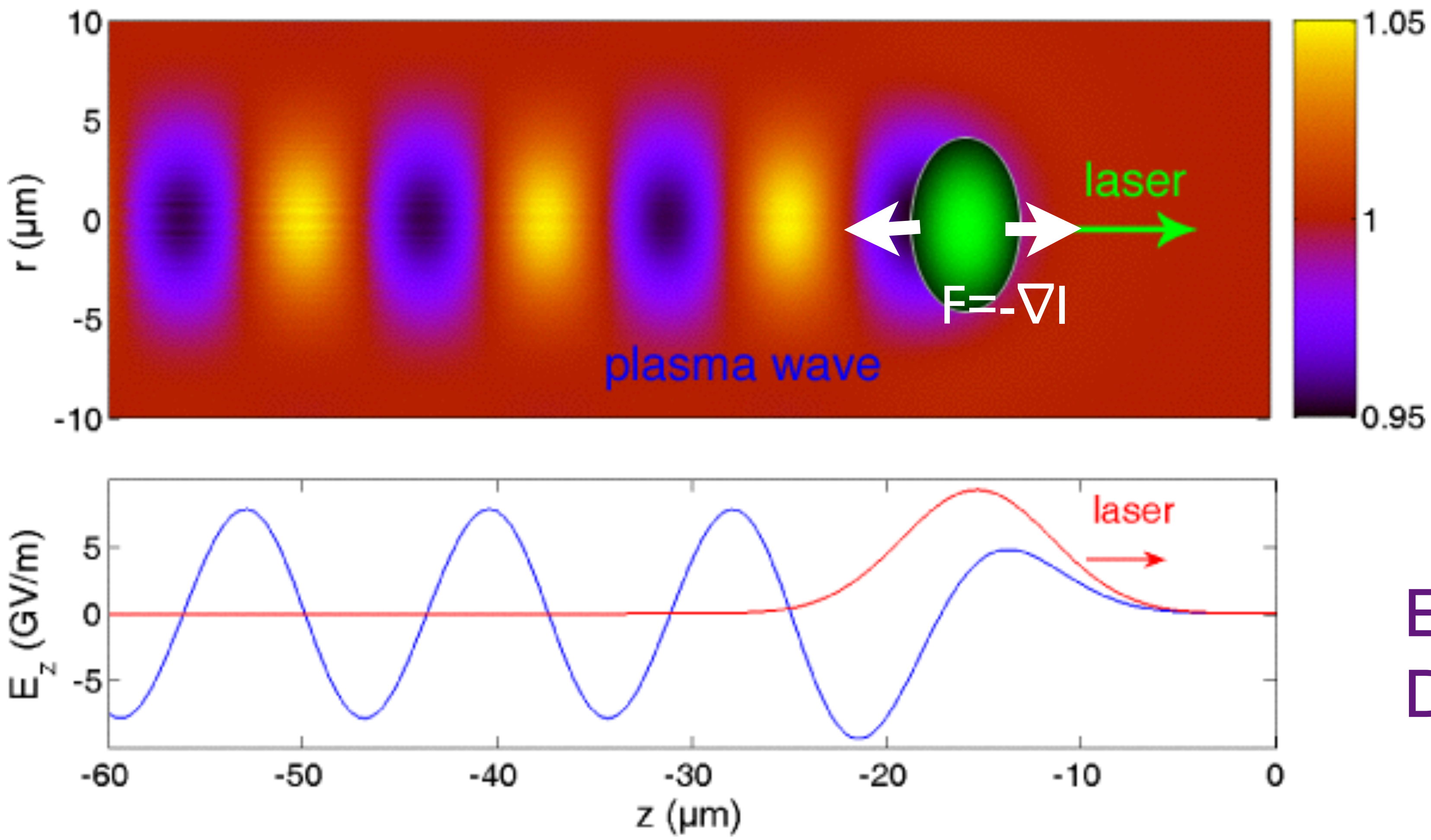


Common features: Collimated beams (mrad)
Femtosecond duration (few fs)
Micron source size
High peak brightness (>10^{20} ph/s/mm^2/mrad^2)

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

Laser Plasma Accelerator: Principle

electron density perturbation and longitudinal wakefield



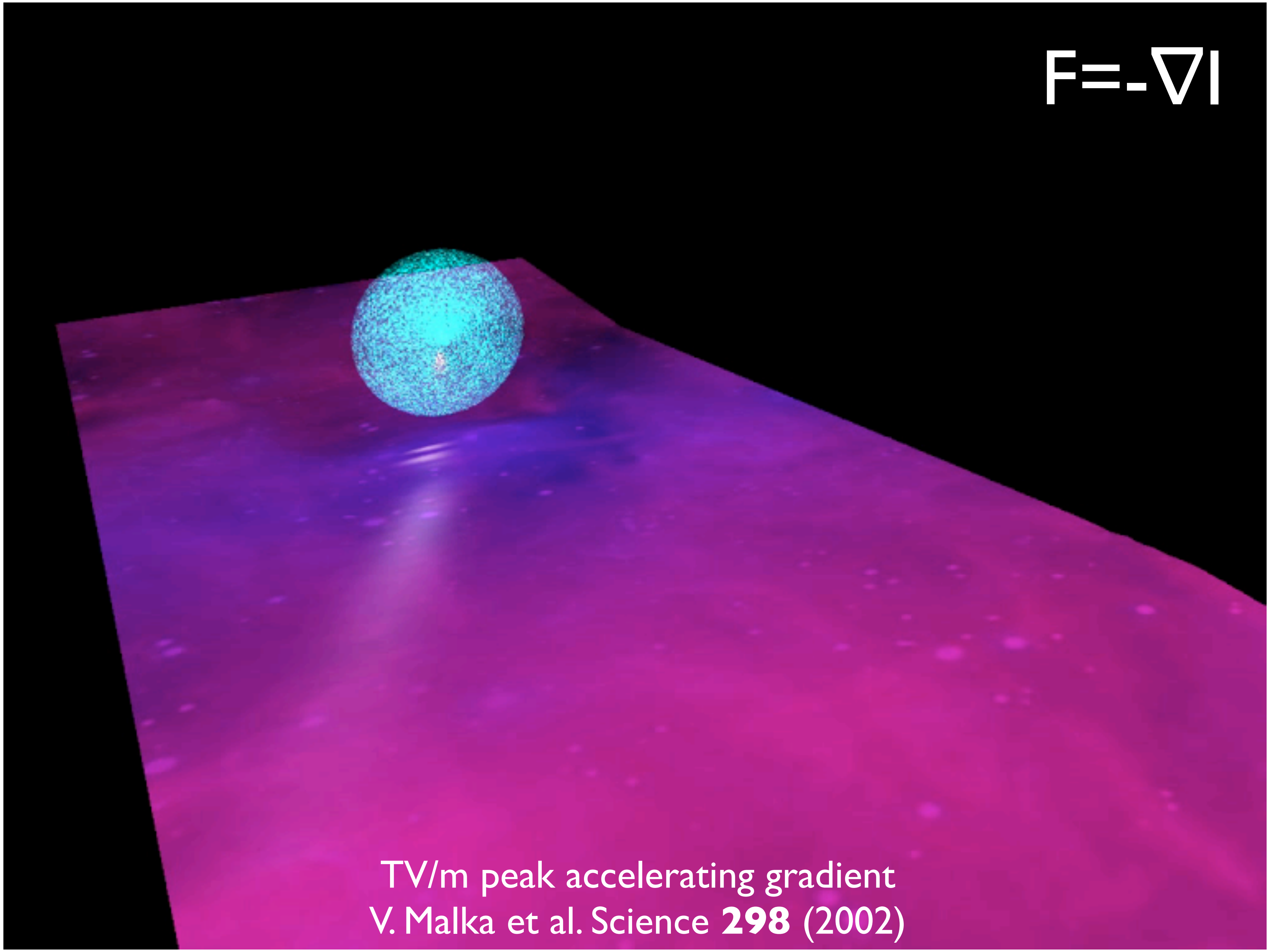
wave in the wake of a boat

E_z = 300 GV/m for 100 %
Density Perturbation at 10^{19} cc^{-1}

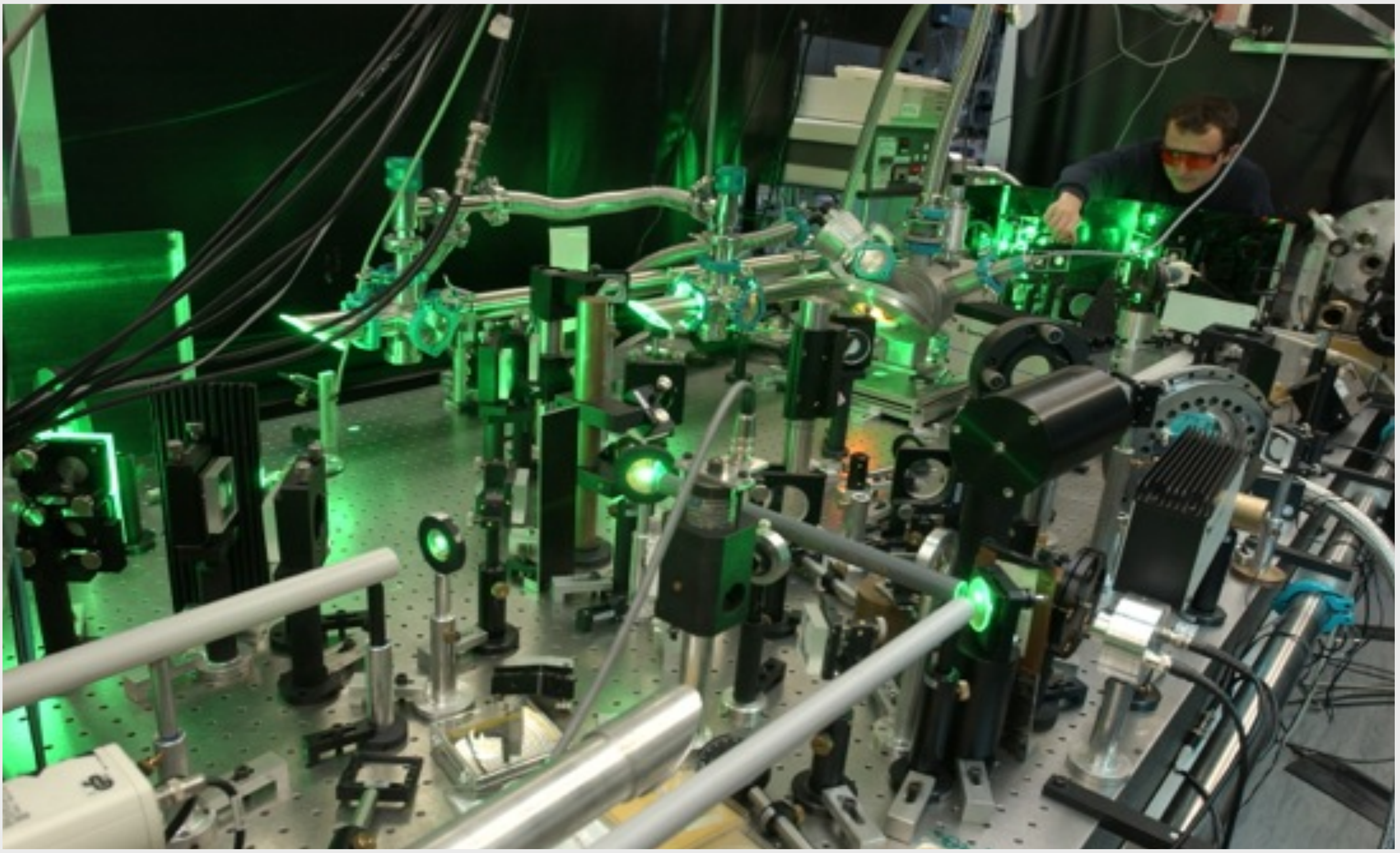
$$v_{phase}^{epw} = v_g^{laser} \sim c$$

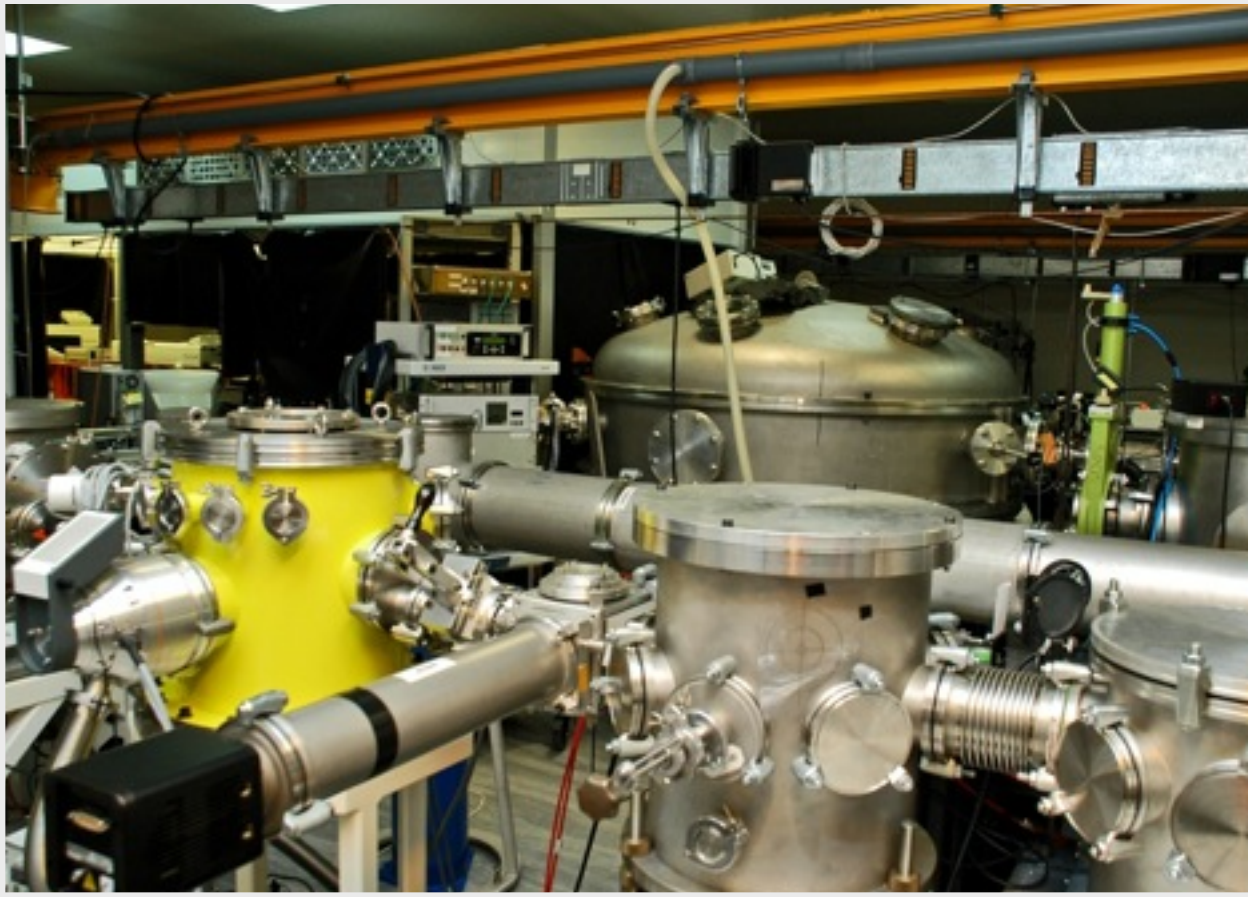
T. Tajima and J. Dawson, PRL **43**, 267 (1979)

The laser wakefield



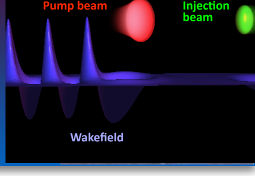
Laser "Salle Jaune"



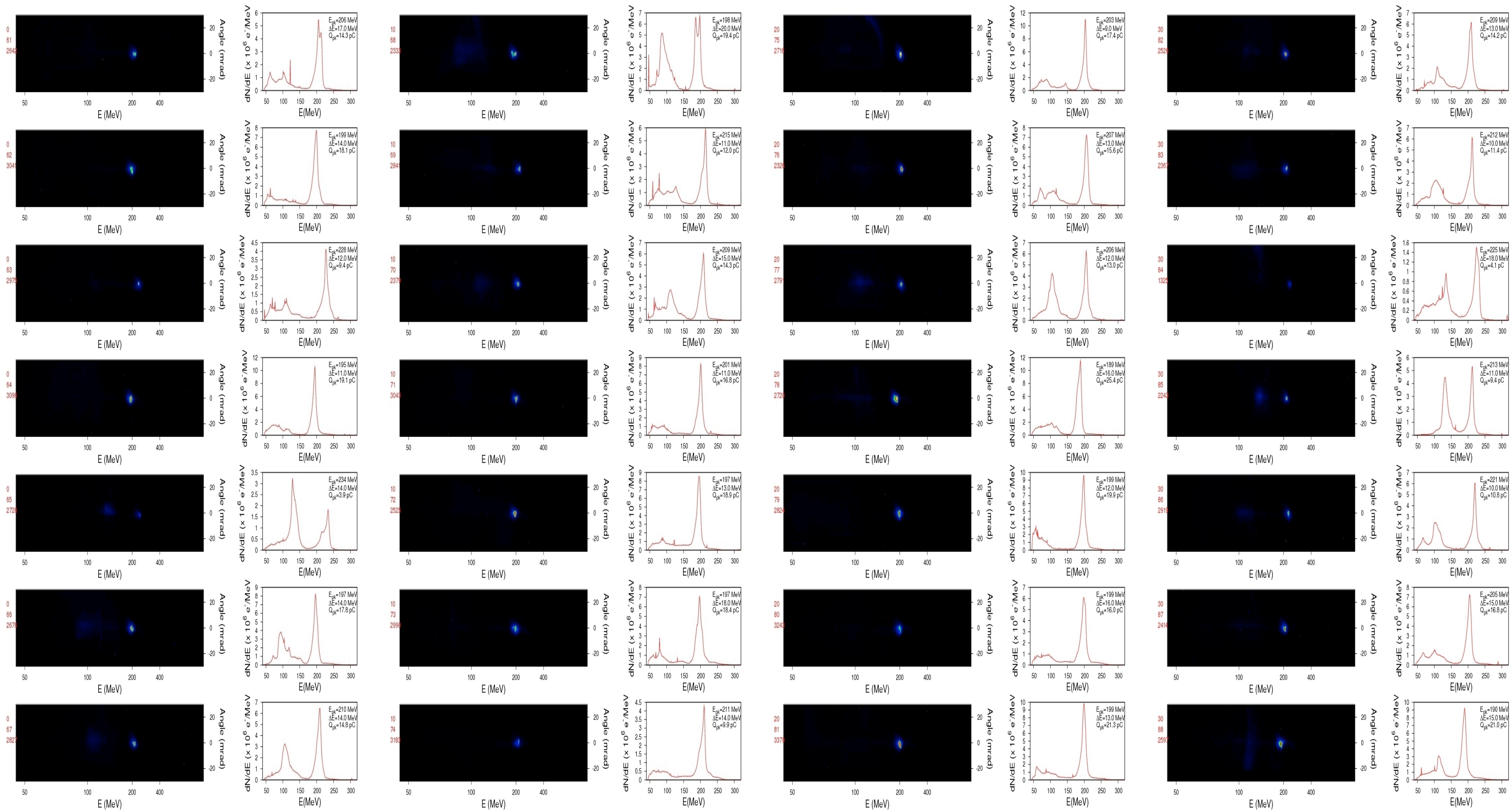


Ti:sapphire CPA laser
1.5 J / 30 fs - 10 Hz

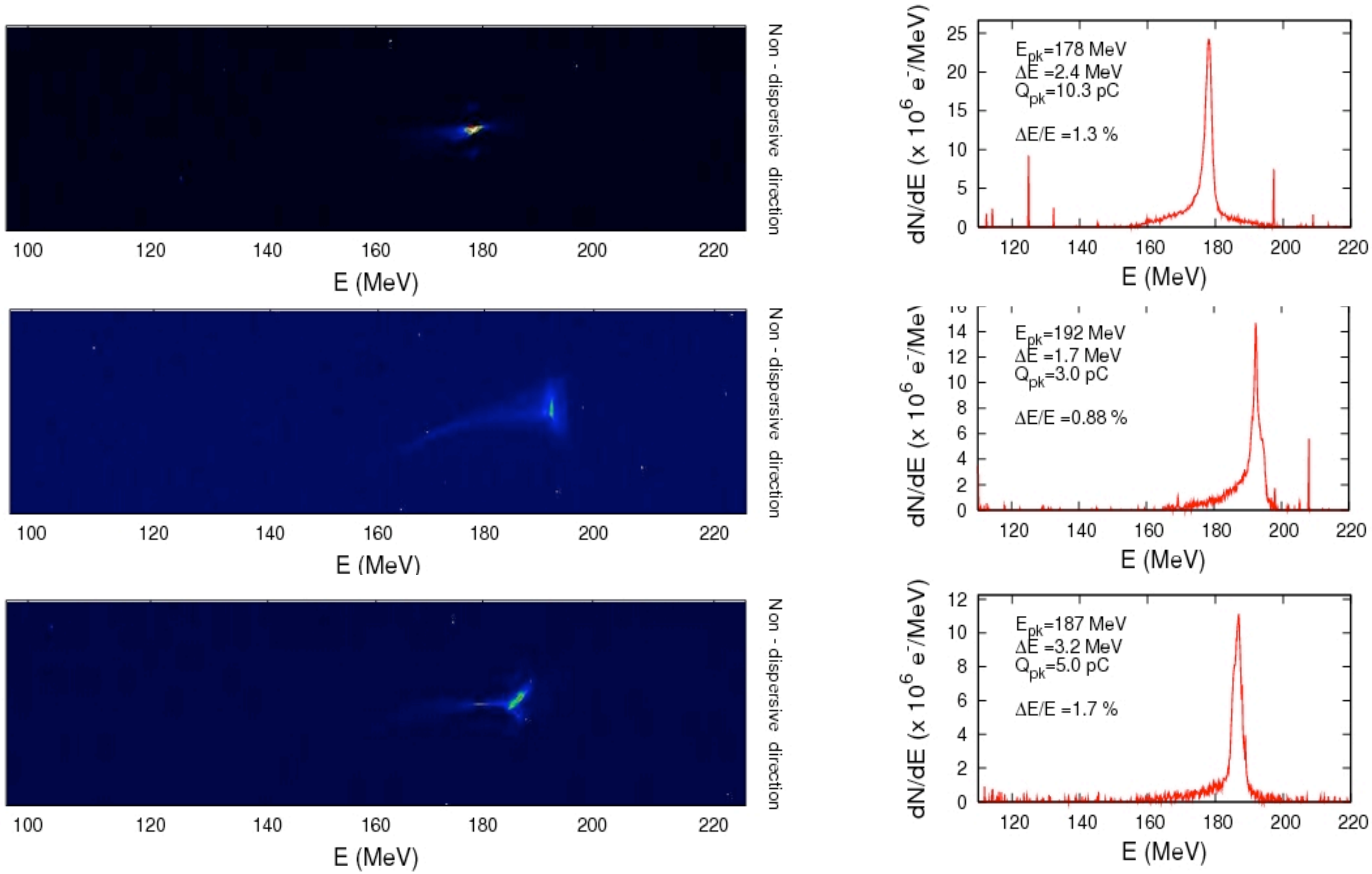
Towards a Stable Laser Plasma Accelerators



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

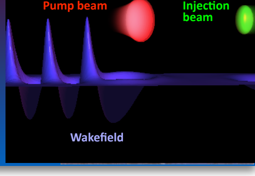


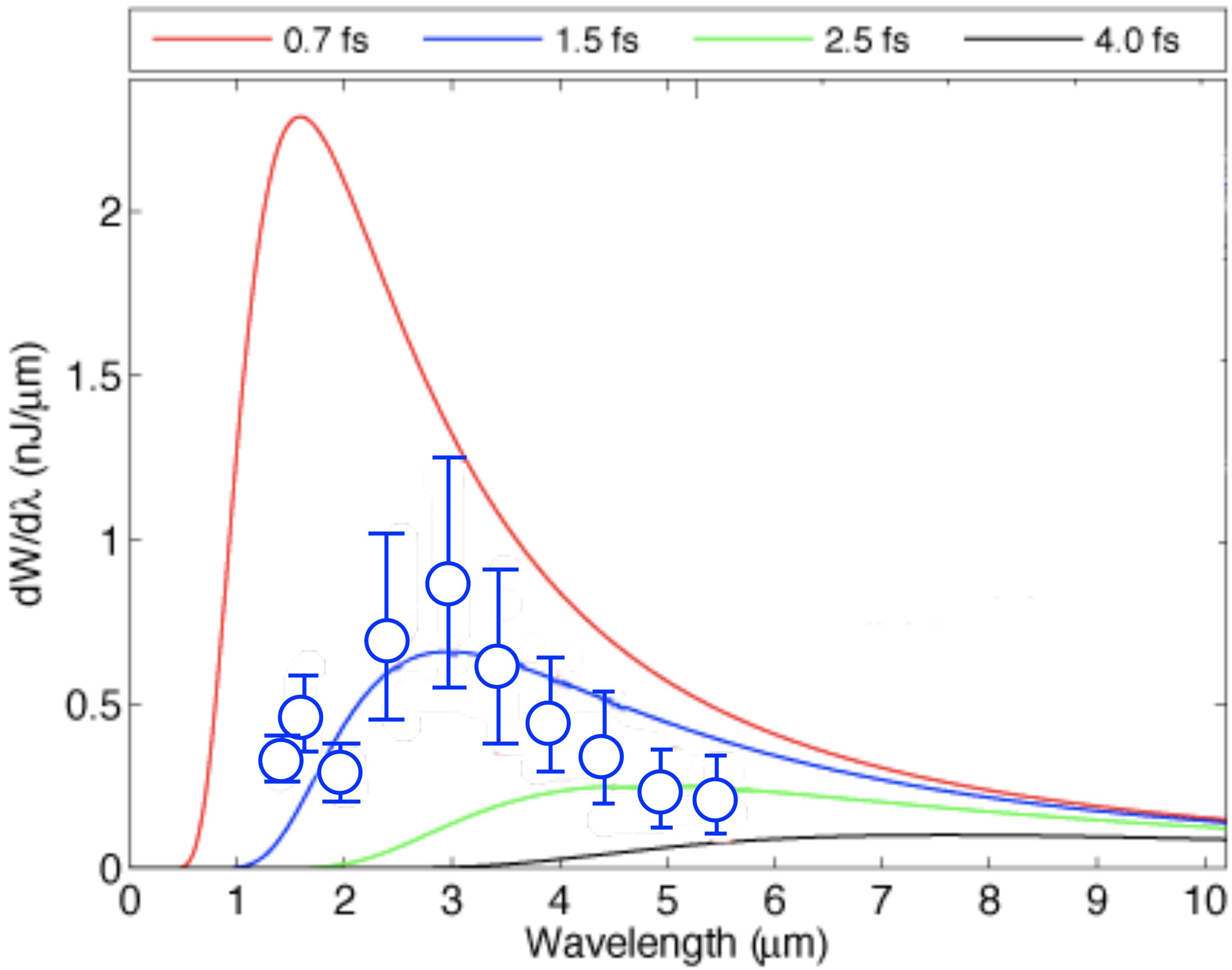
1% relative energy spread



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

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

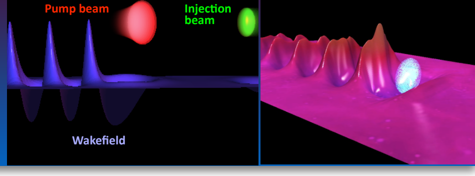
Peak at 3 µm

Coherent

1.5 fs RMS duration : Peak current of 4 kA

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

LPA achievements



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 %	√
Peak energy at 4 GeV with PW laser	√
Ultra short e-bunch : 1,5 fs rms	√
Low divergence : 2 mrad	√
Low emittance : π.mm.mrad	√

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

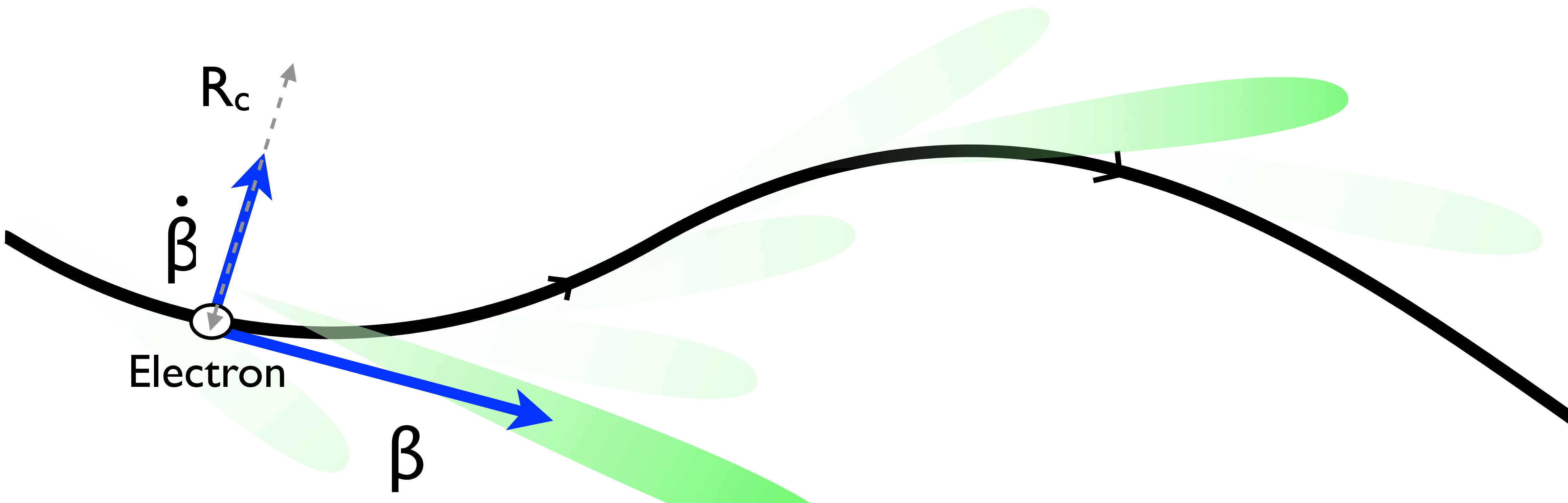
Moving charge radiation

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)

X rays Source with Laser Plasma Accelerators : Outline

- Betatron radiation produced in LPA
  - Principle & Experimental results
- All optical Compton gamma rays source
  - Principle & Experimental results
- Compact nano undulators
  - Principle & Simulations
- Conclusion

- **Betatron radiation produced in LPA**
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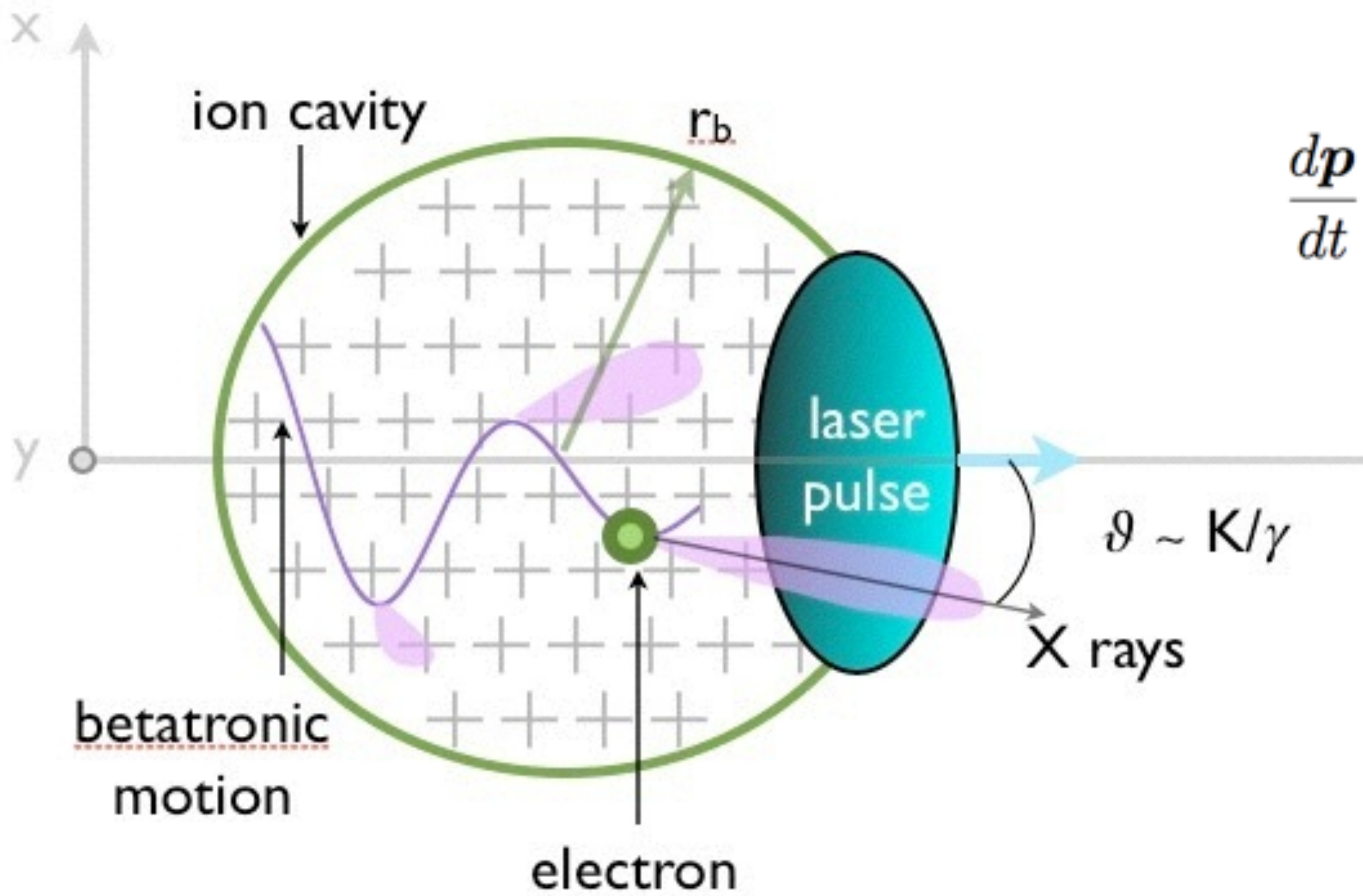
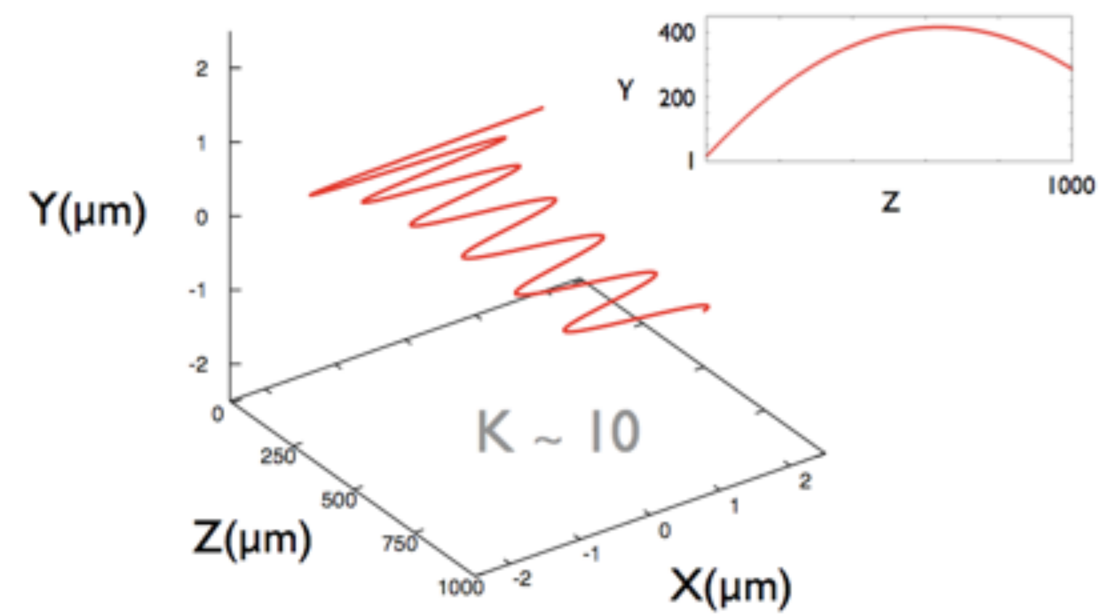
Betatron radiation properties



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



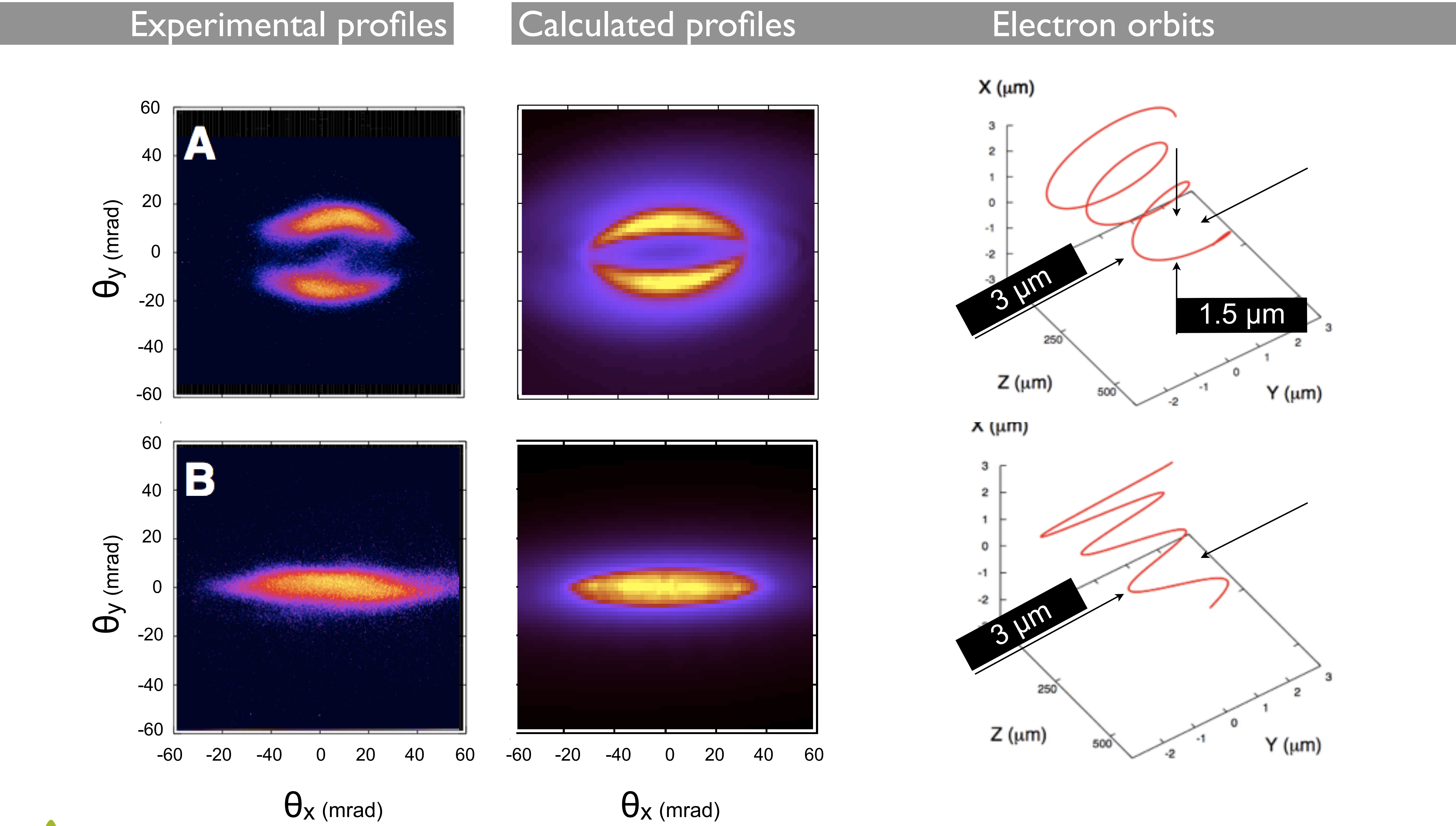
Betatron oscillation properties:

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

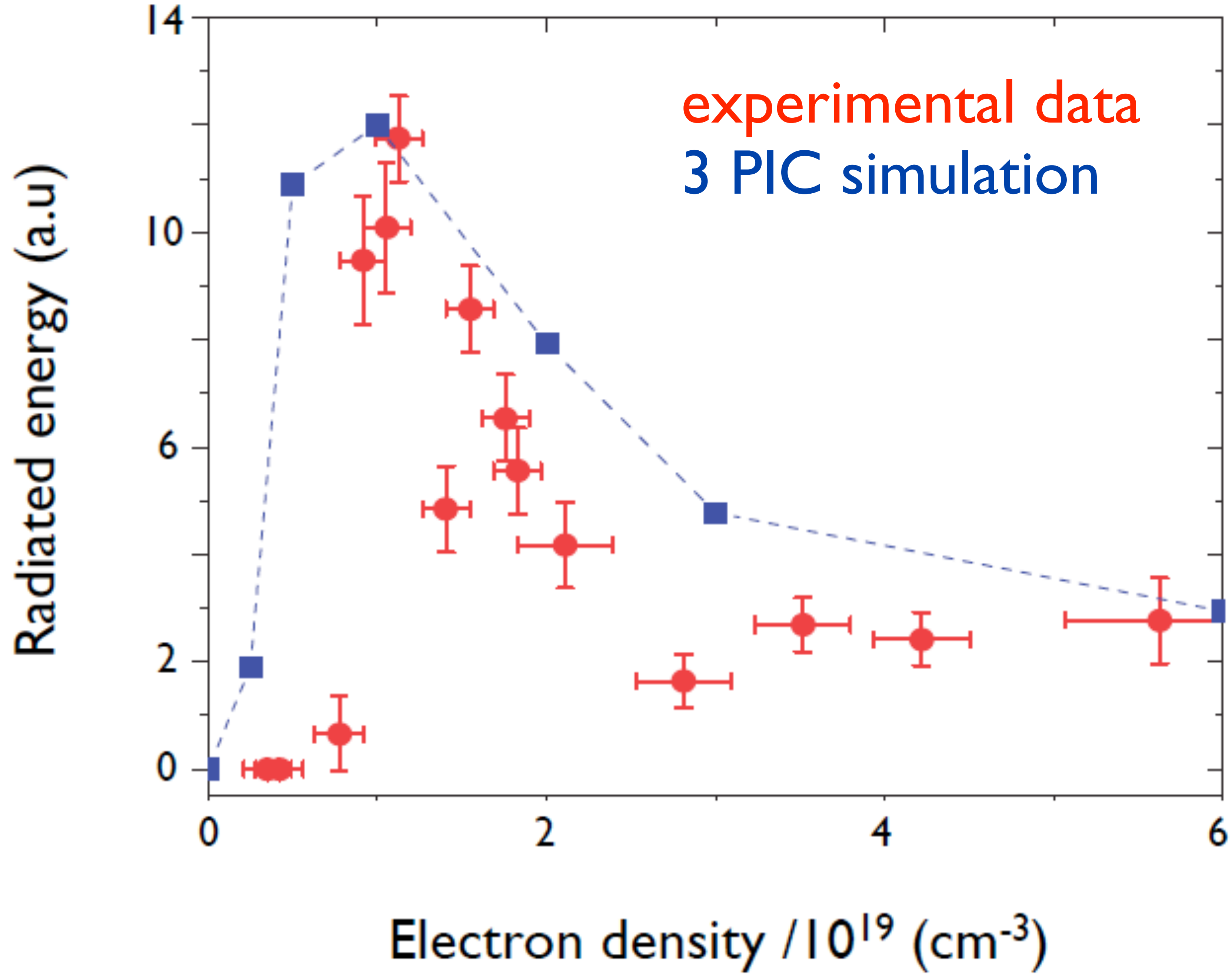
~ 100 MeV → $r_\beta \sim 1\ \mu m$, $n_e \sim 10^{19}\ cm^{-3}$

$$\lambda_u \sim 200\ \mu m$$
$$K \sim 5$$

A more precise source size estimation

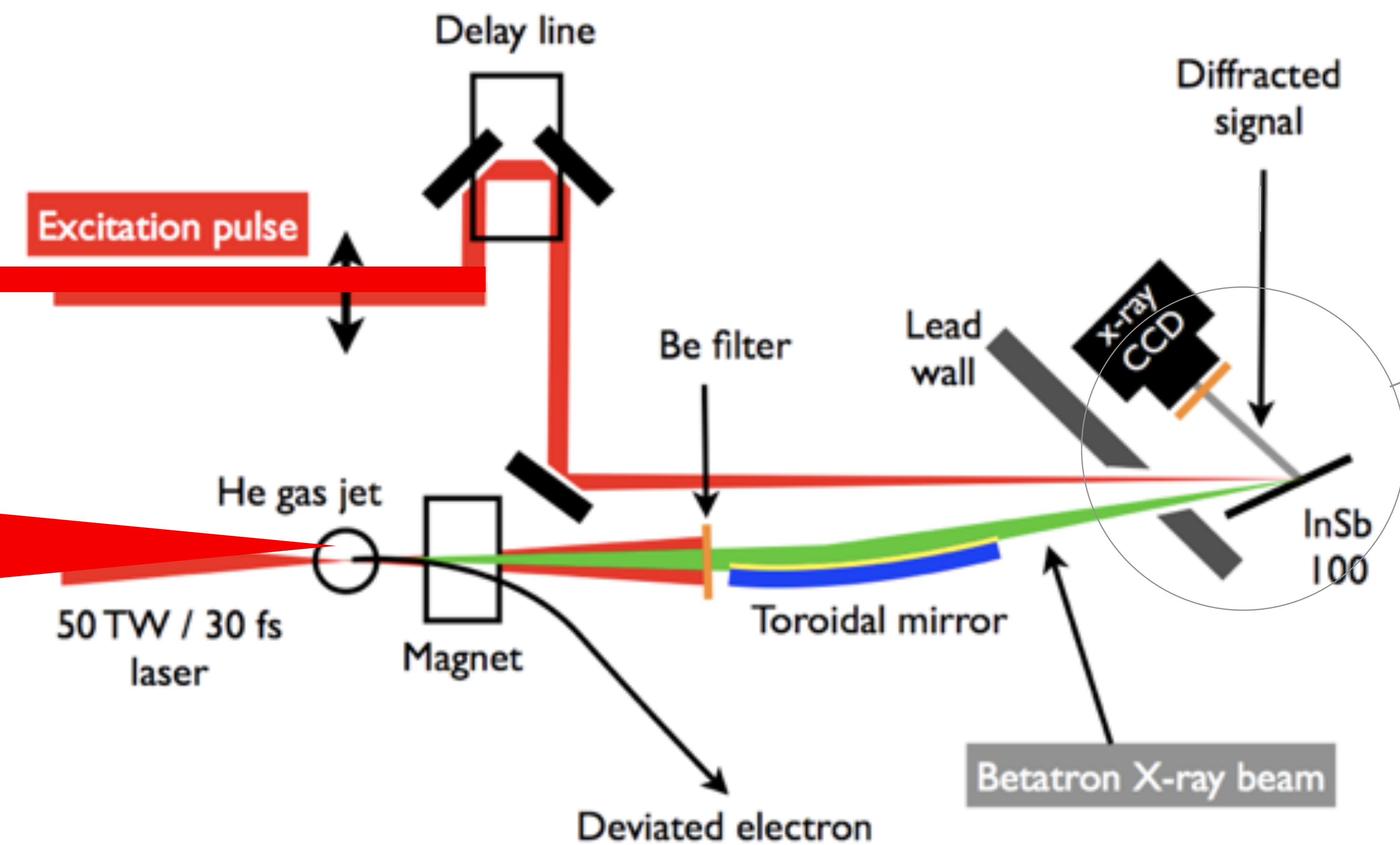


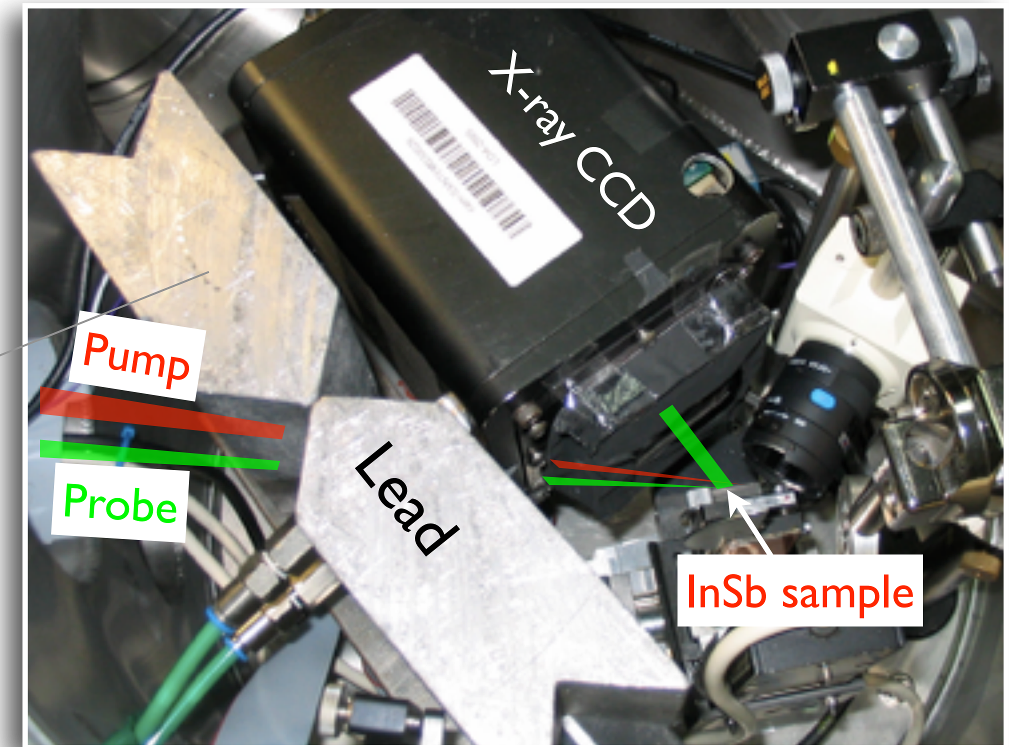
Betatron signal variation with density

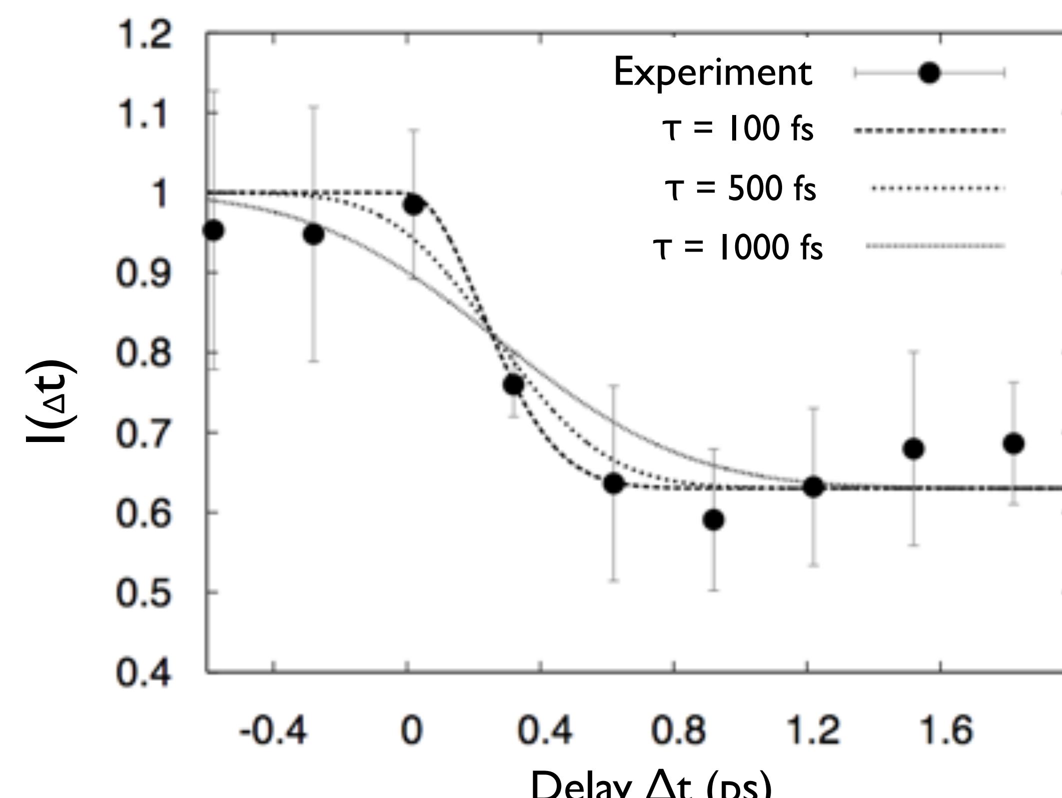


A. Rousse *et al.*, Phys. Rev. Lett., 93, 135005 (2004)

Femtosecond x-ray diffraction: Non thermal melting (InSb)

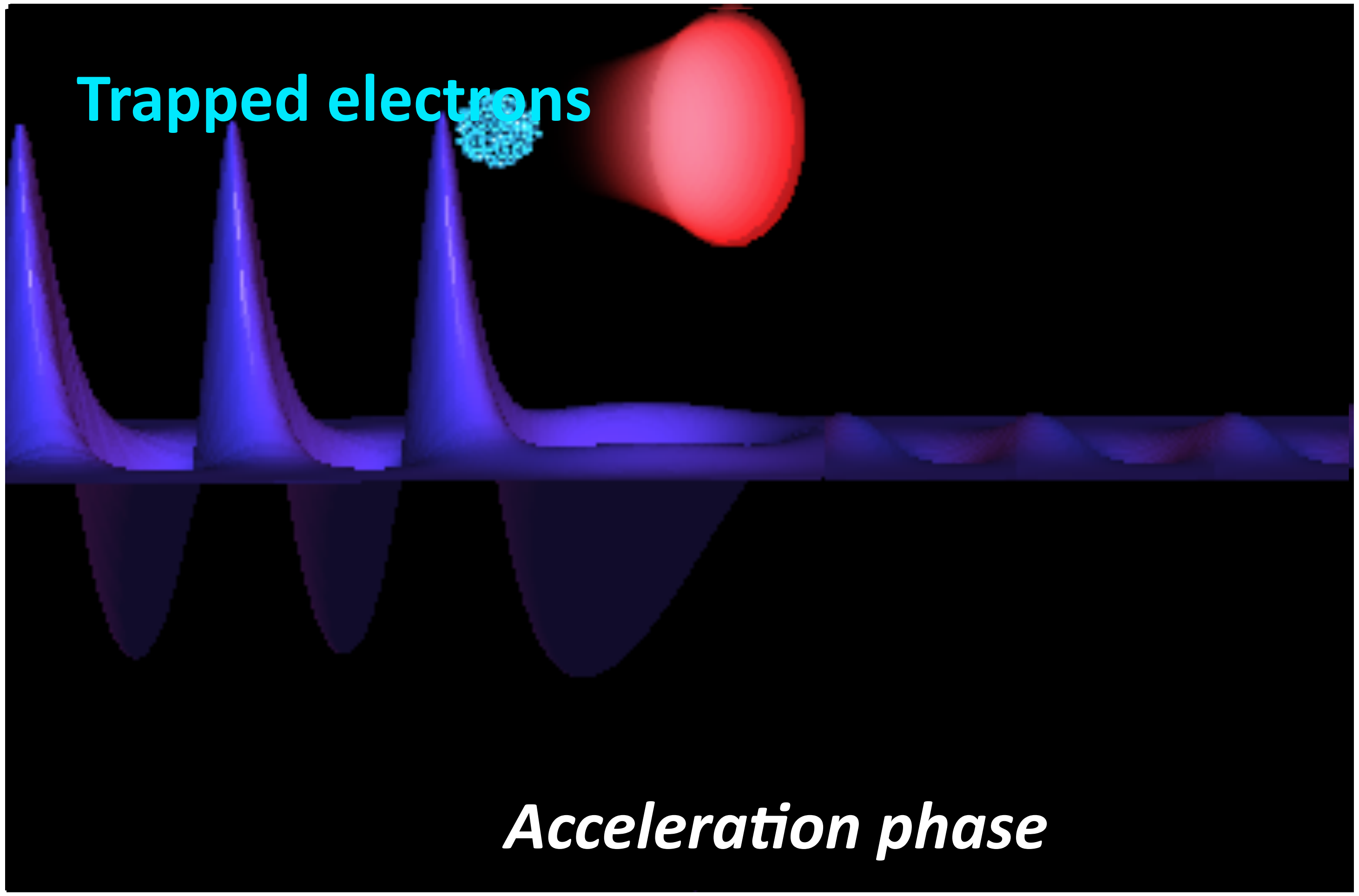






Ultrafast phase transition can be measured with tens fs resolution - limited by shot to shot fluctuations of the source

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.

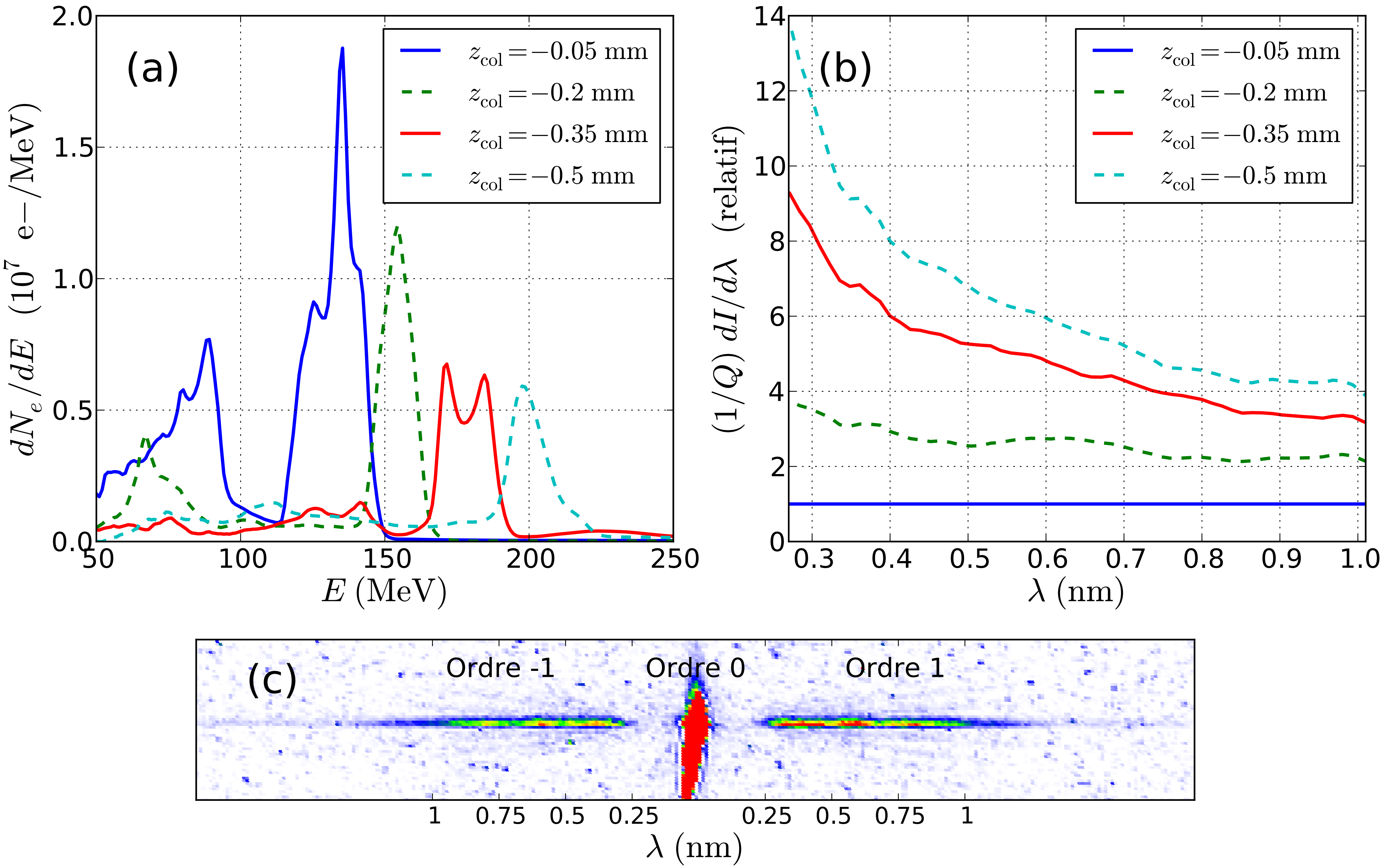
- The ponderomotive force $-\vec{\nabla} a_0^2$ excites the plasma wave.

- 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)



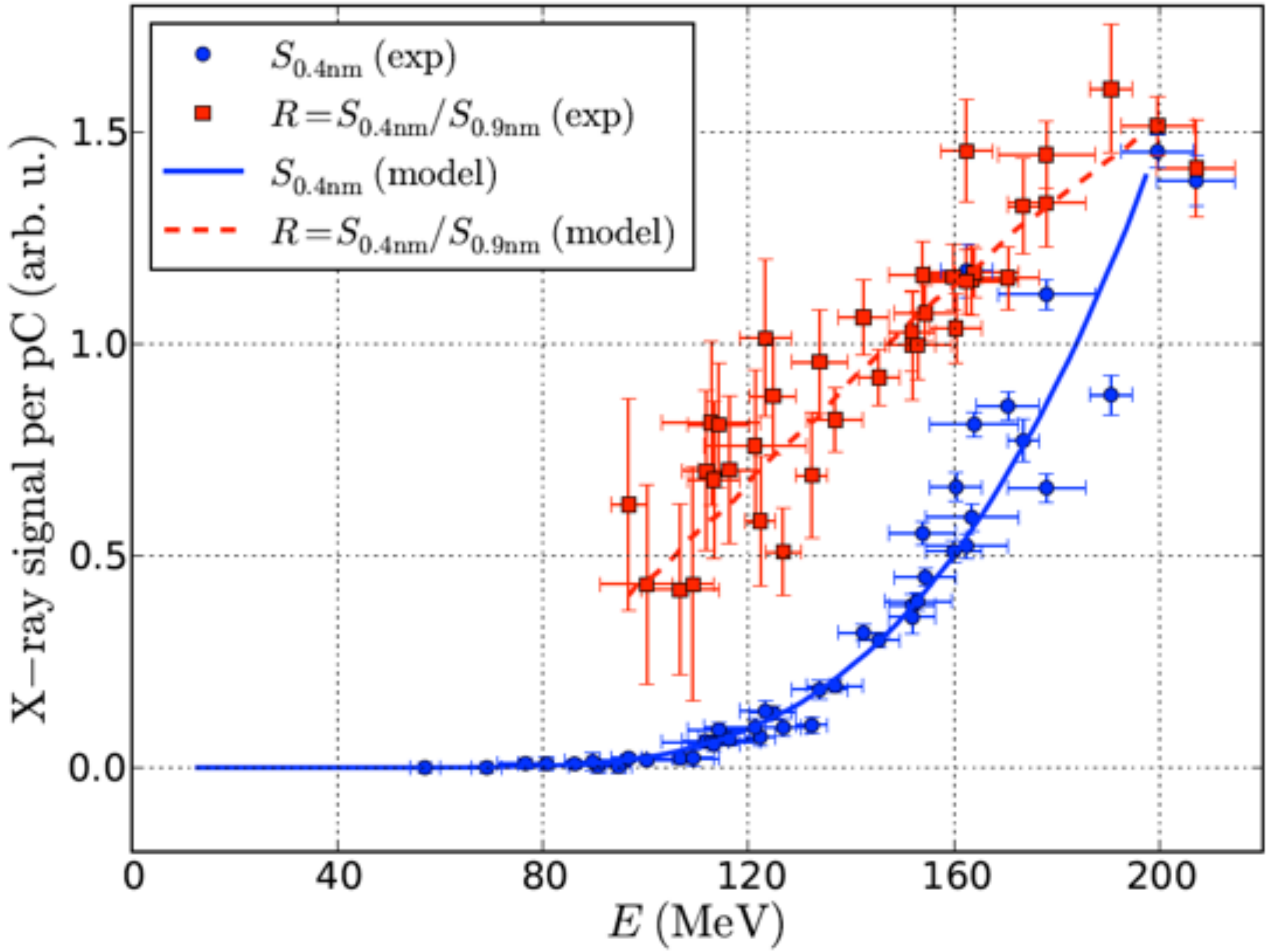
Thanks to the colliding laser pulses scheme, clear correlations between electron beam energy and betatron X ray distribution are observed

Electron and X ray correlation : comparison

The best agreement is obtained for :

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

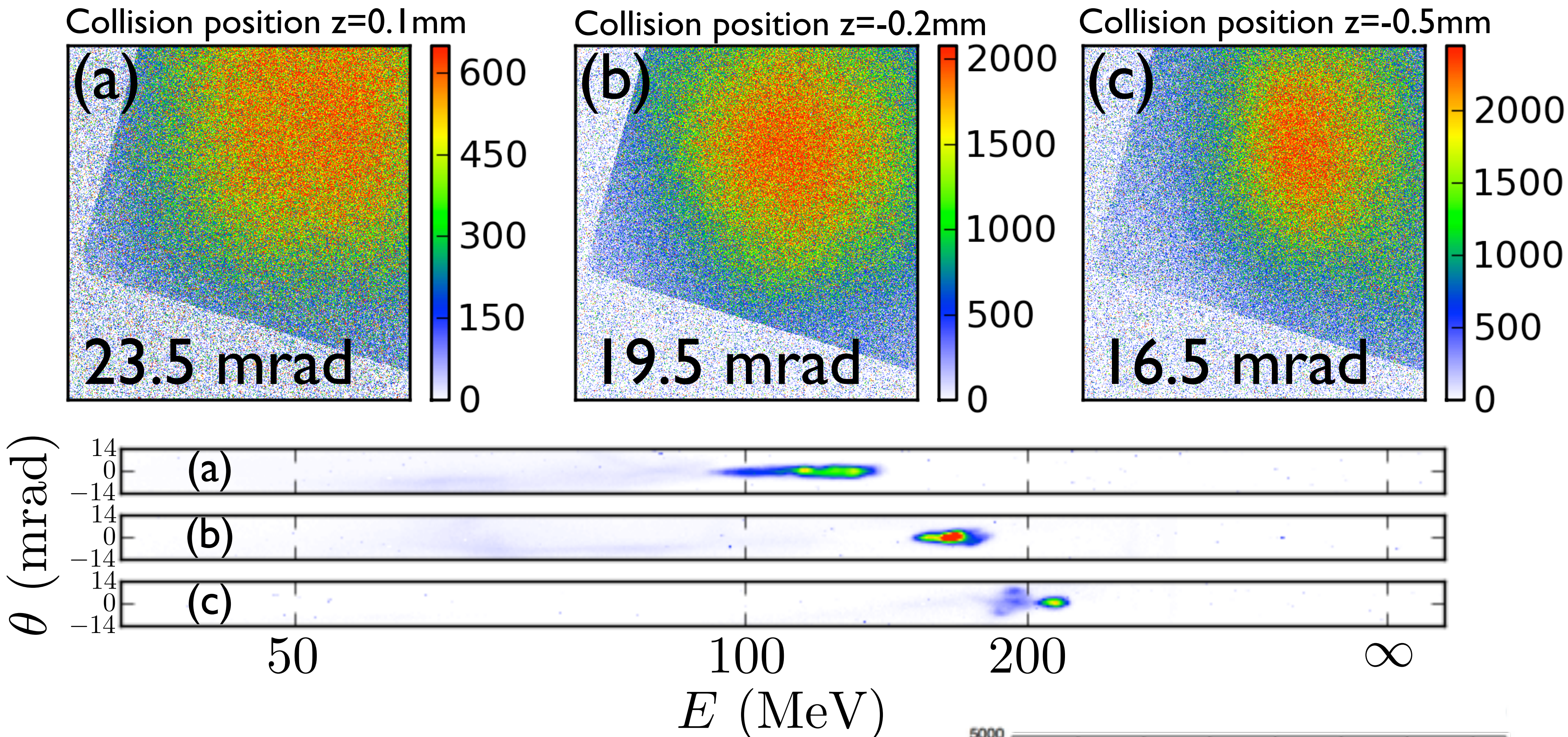
$$(\text{ or } \alpha\sigma = 0.23\ \mu\text{m})$$



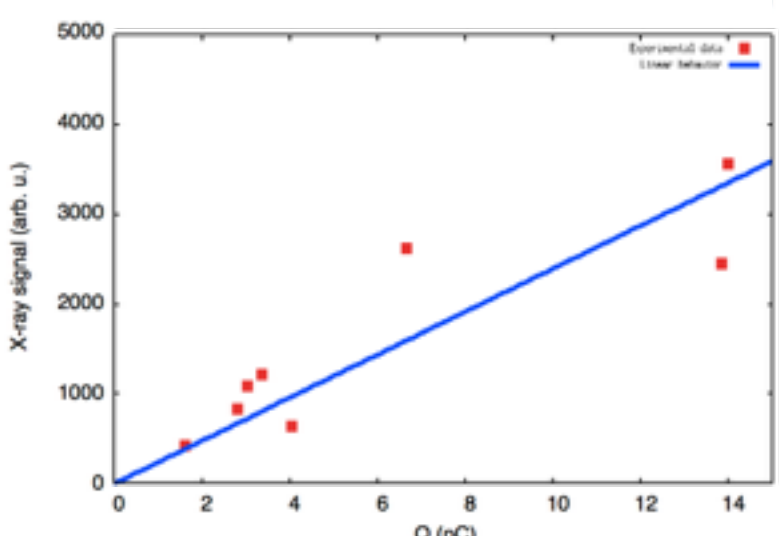
S. Corde *et al.*, Phys. Rev. Lett. **107**, 225003 (2011)

Electron and X ray correlation : divergence and charge

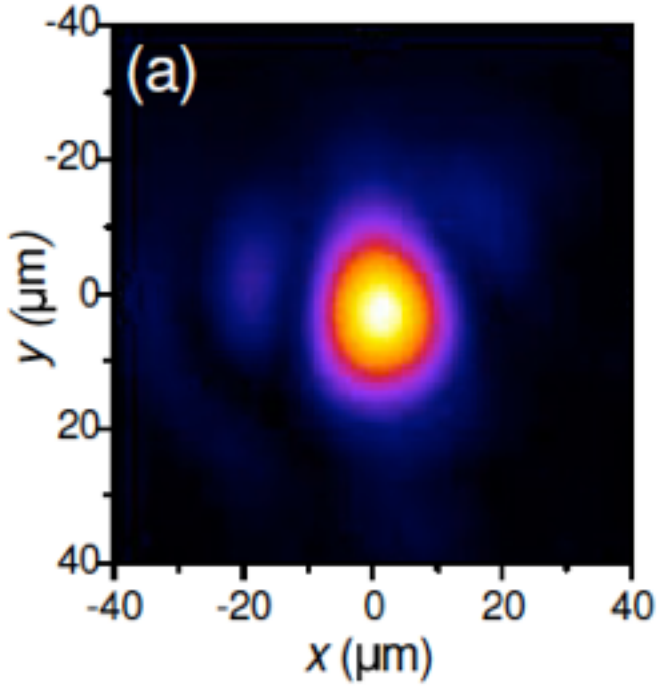
Divergence (FWHM) the X betatron signal with the electron beam energy:



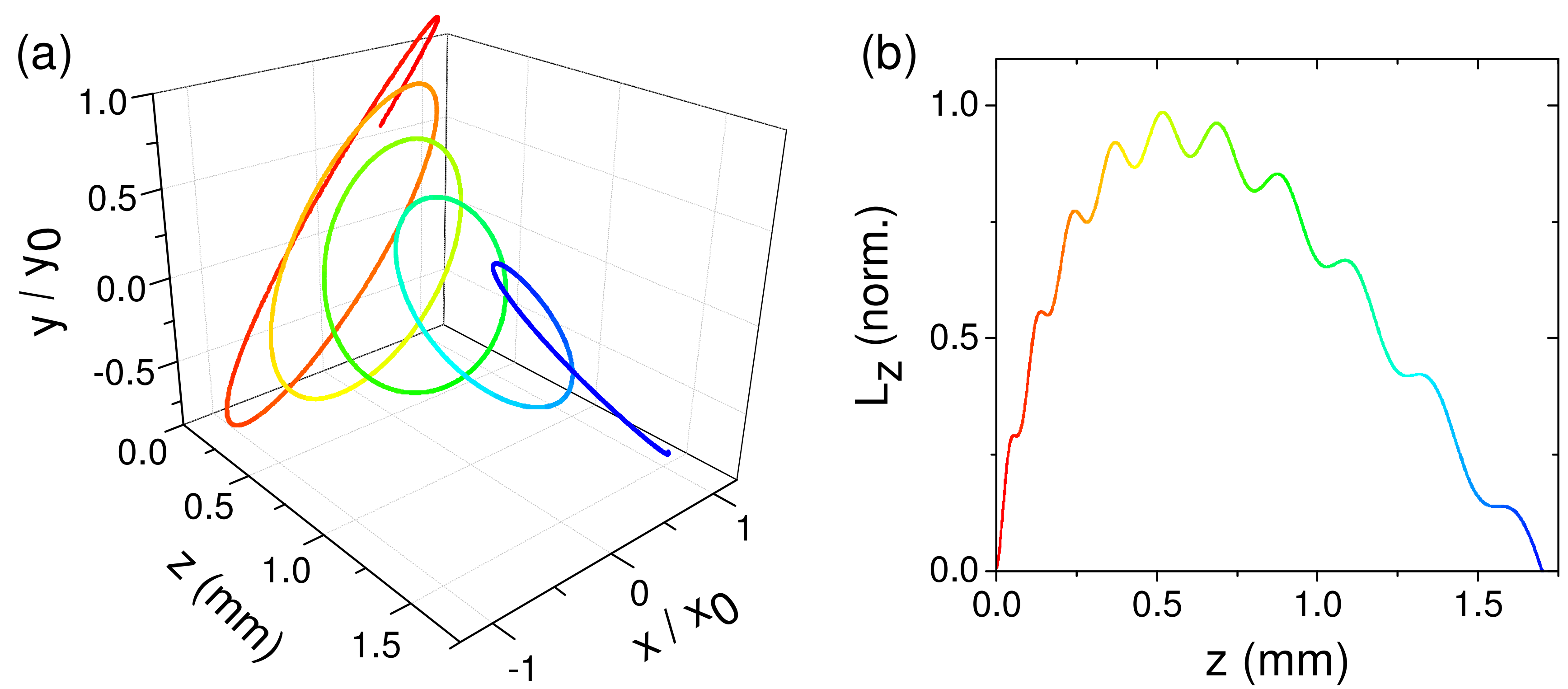
Linear dependency of the X betatron signal with the electron beam charge (for a fixed electron beam energy at ~220 MeV)



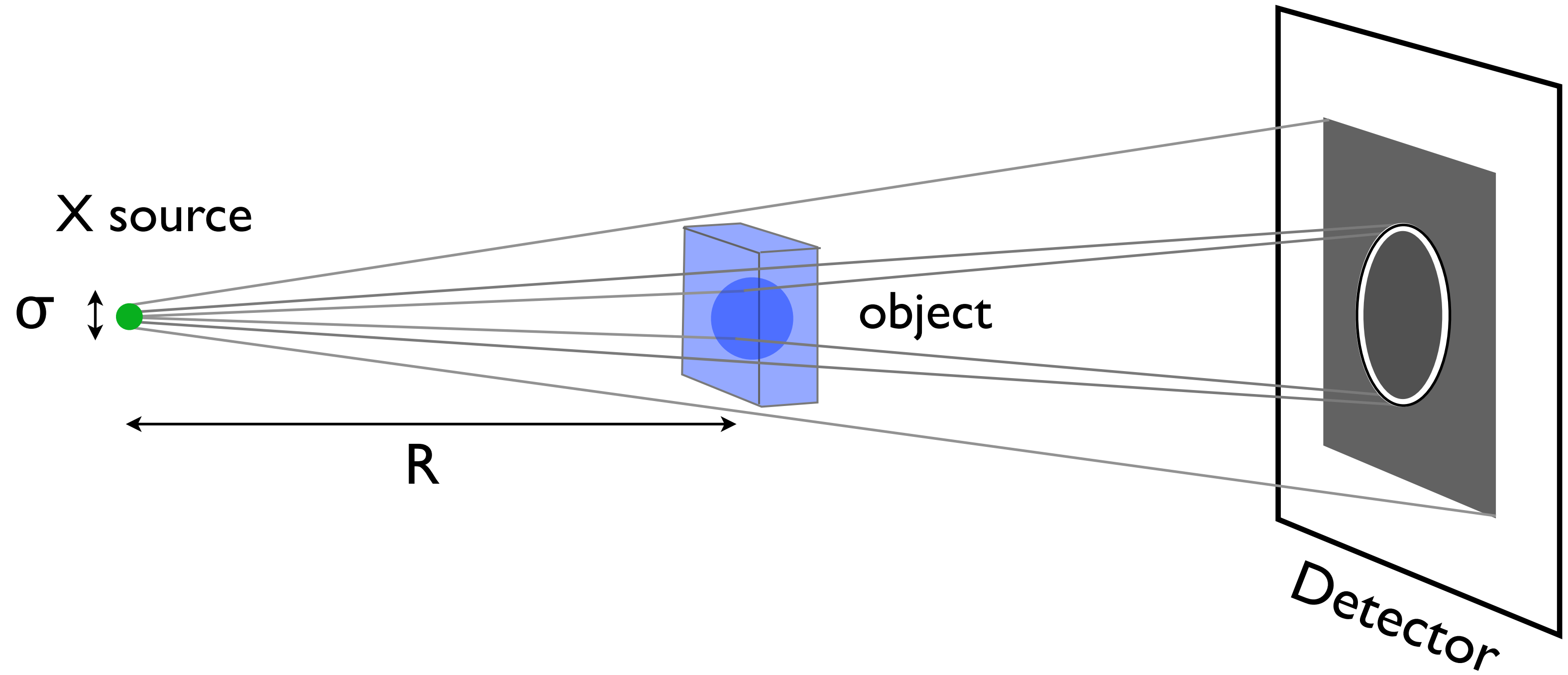
Angular momentum growth in a LPWA



Asymmetric laser pulse
- ➡ asymmetric plasma cavity
- ➡ angular momentum grows



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

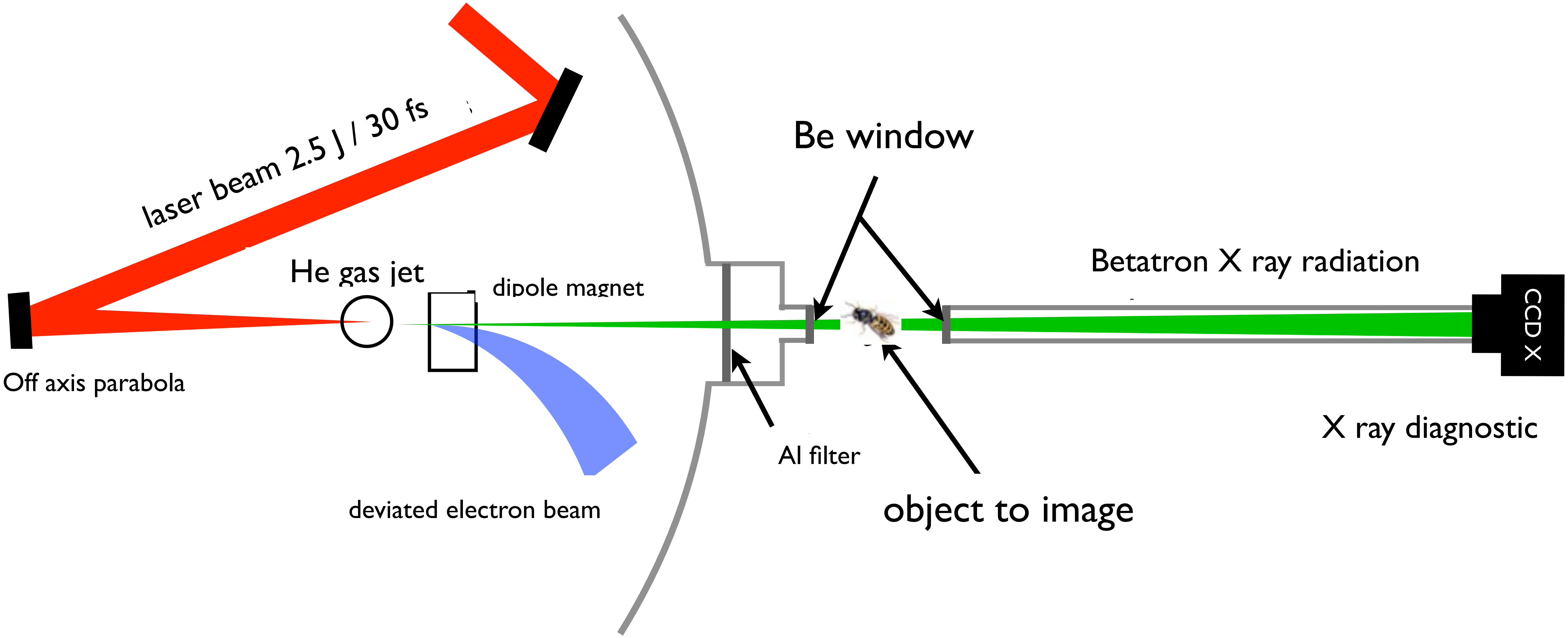
- **Phase contrast**

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 :

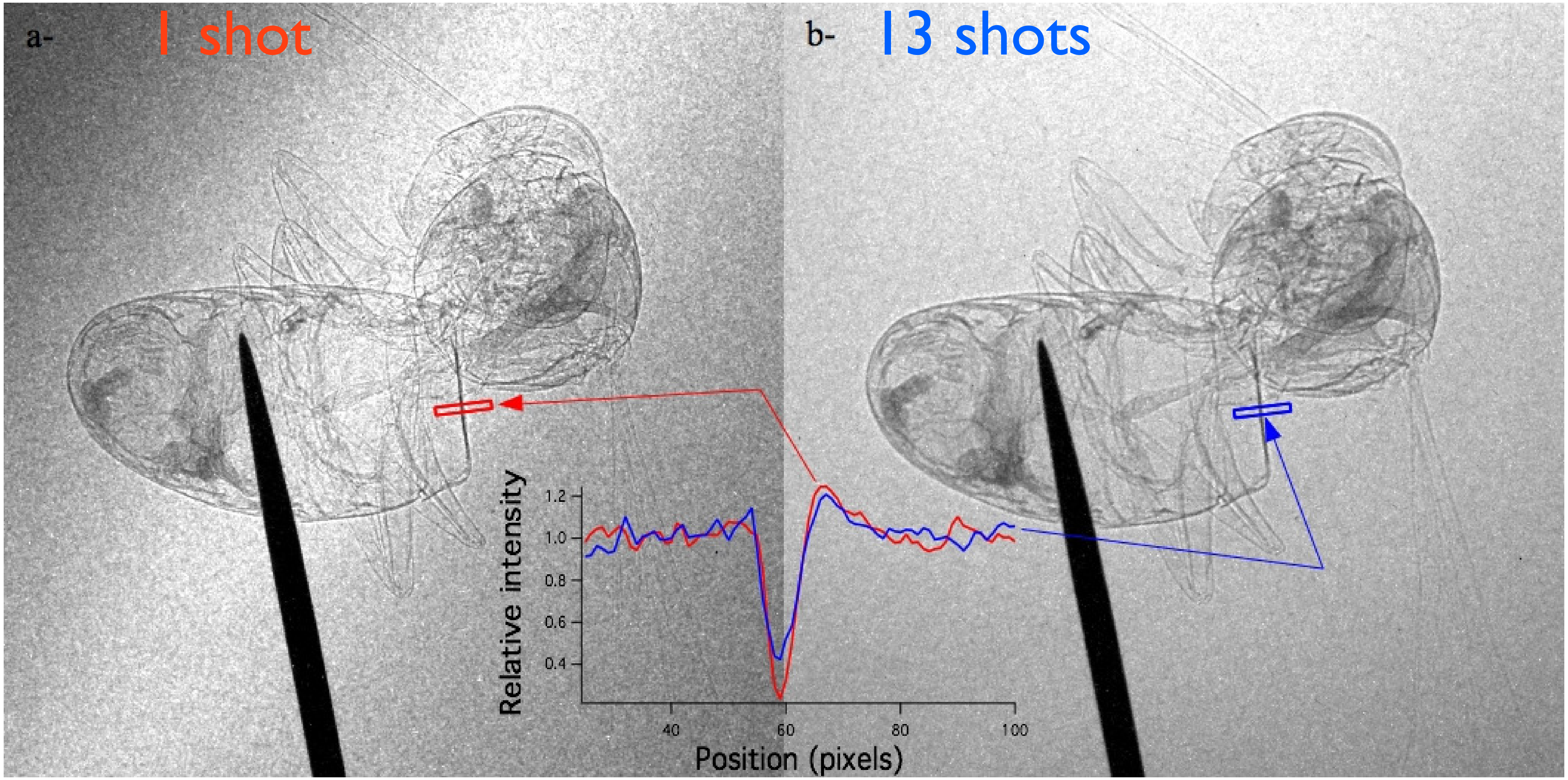
- E_c = 12.3 keV
- 2.2×10^8 photons/0.1%BW/sr/shot at 10 keV
- N = 10^9 photons in 28 mrad (FWHM) divergence beam

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

X ray Phase Contrast Radiography: 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.



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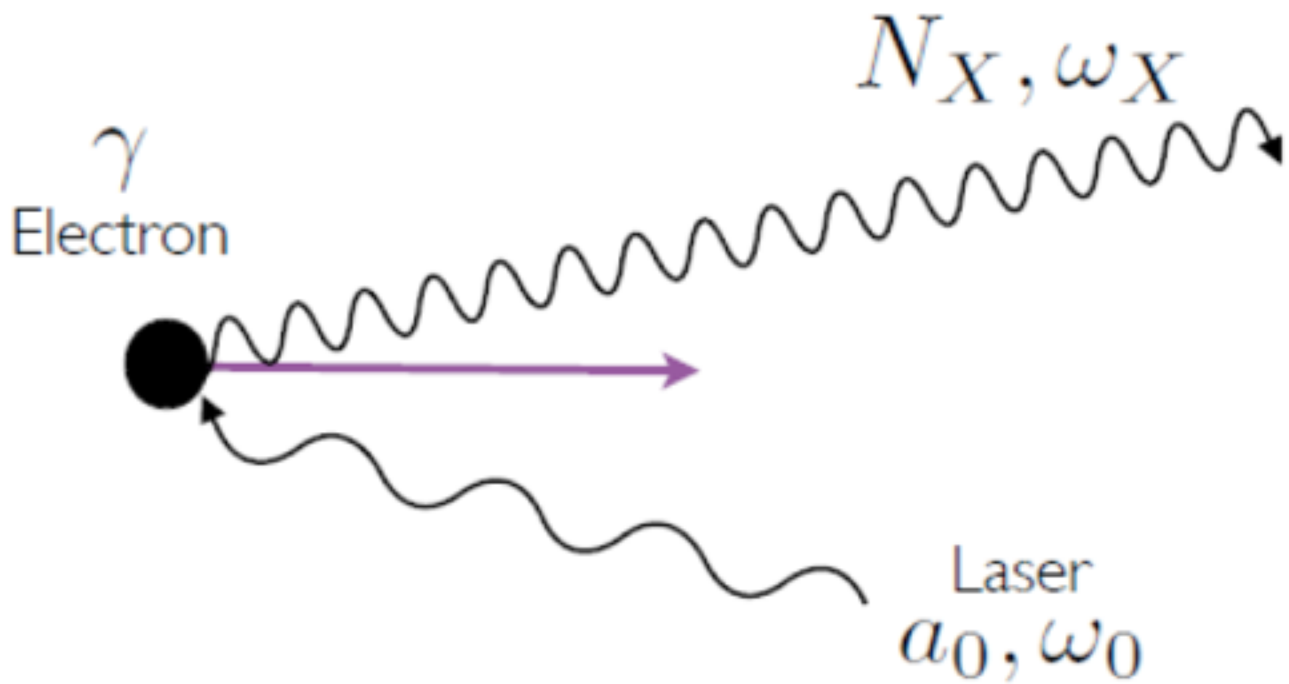
◉ Conclusion

Inverse Compton Scattering



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

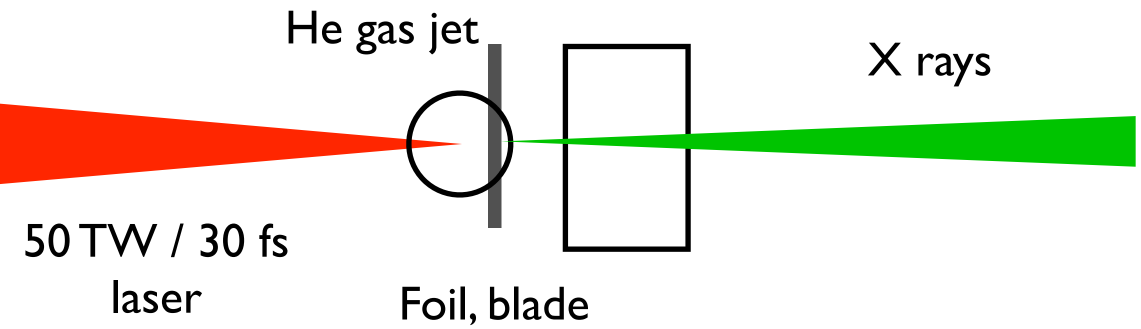
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

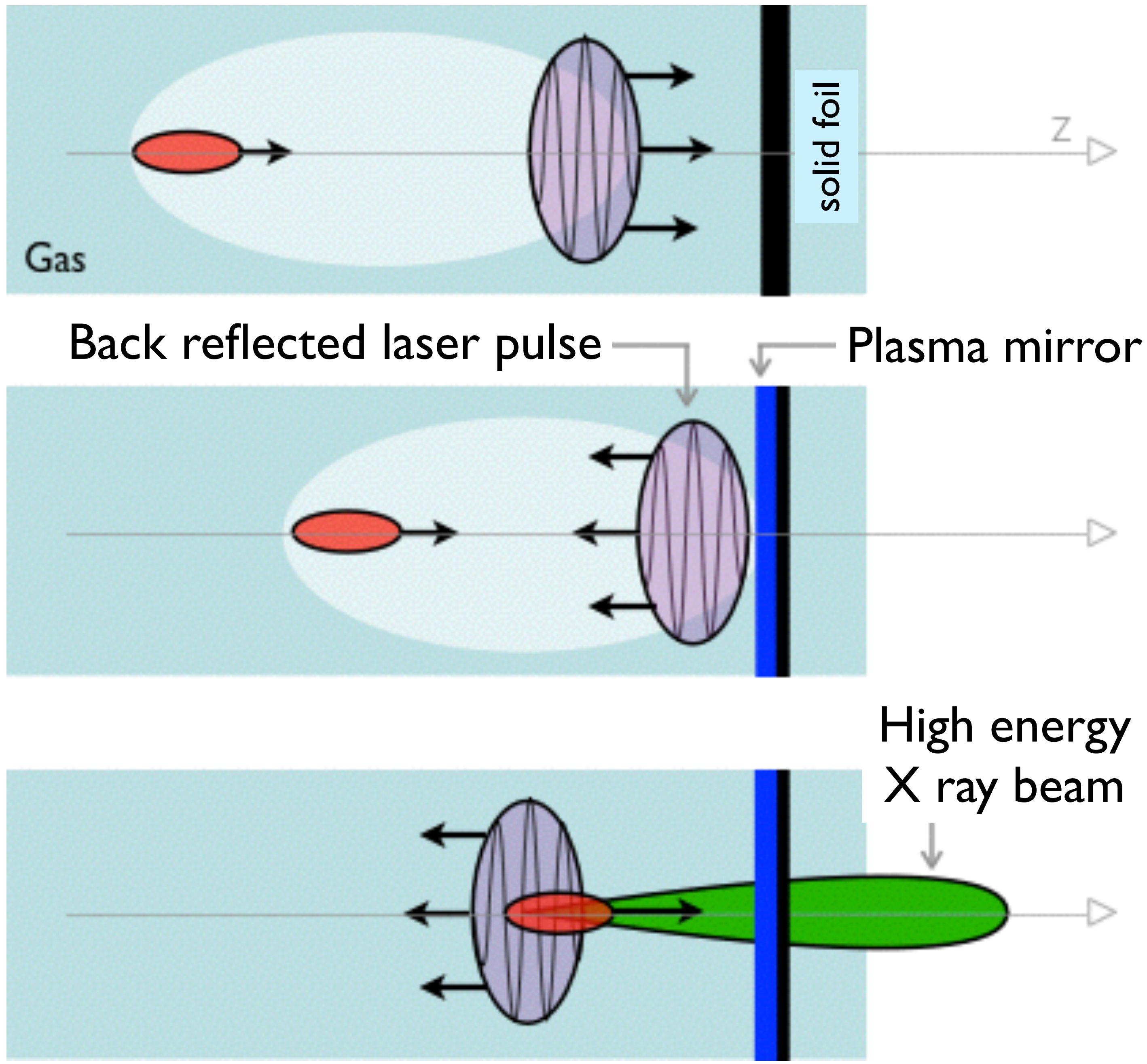
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

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

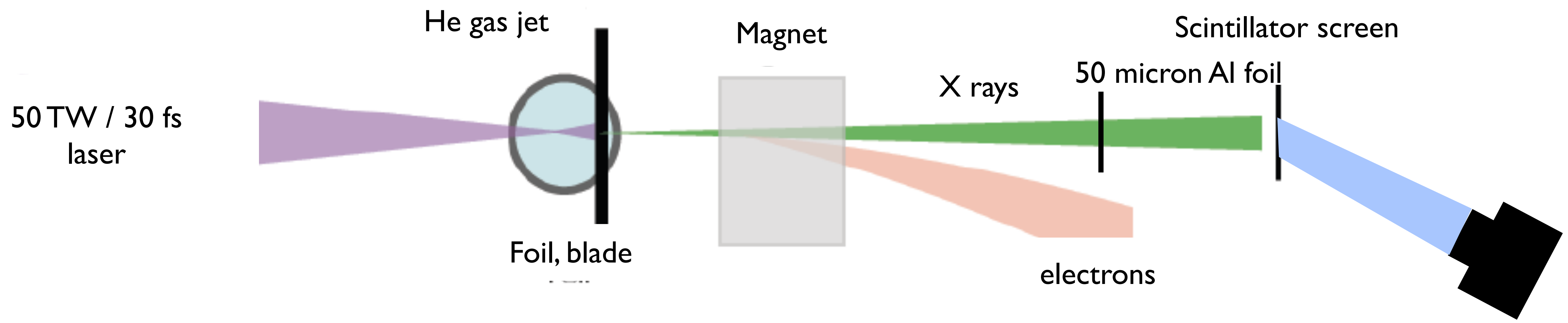
A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

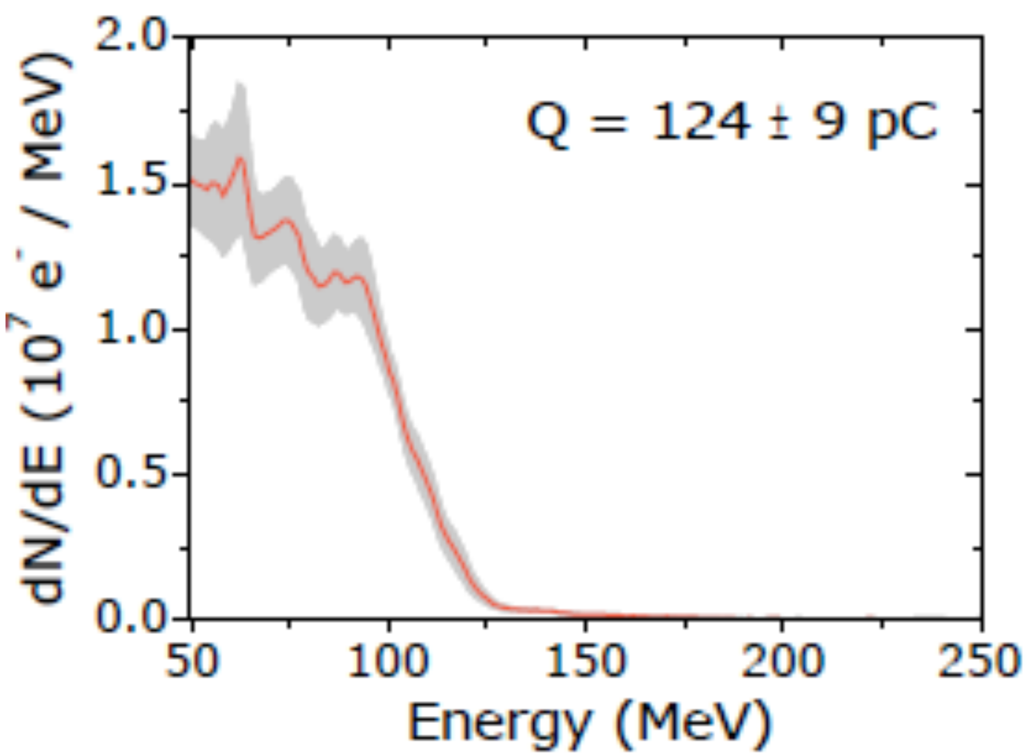
No alignement : the laser and the electron beams naturally overlap

Save the laser energy !

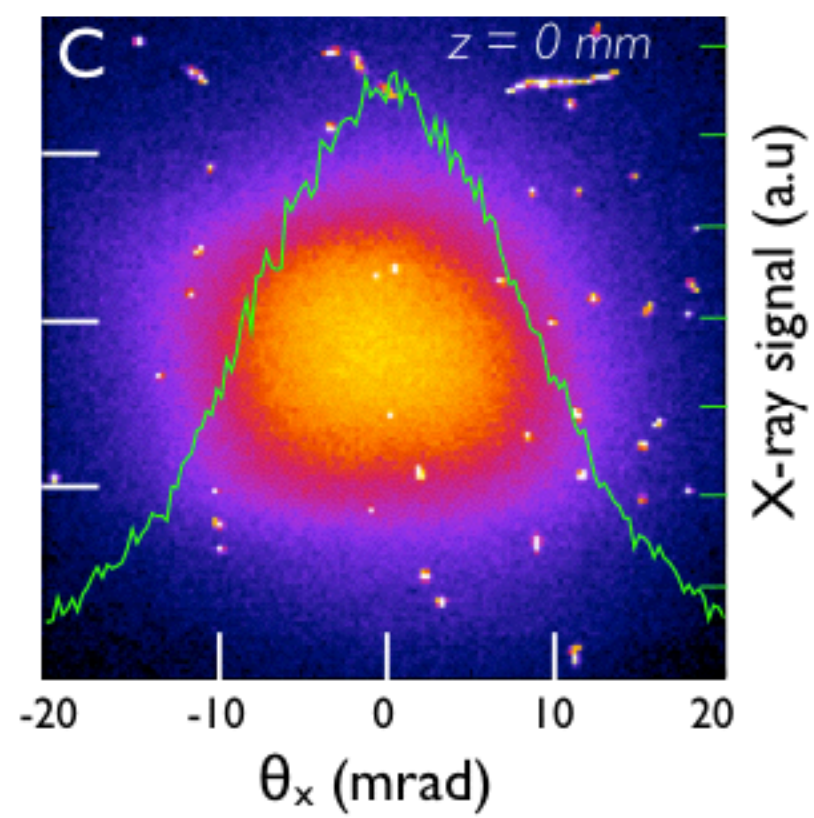
Inverse Compton Scattering : Experimental set-up



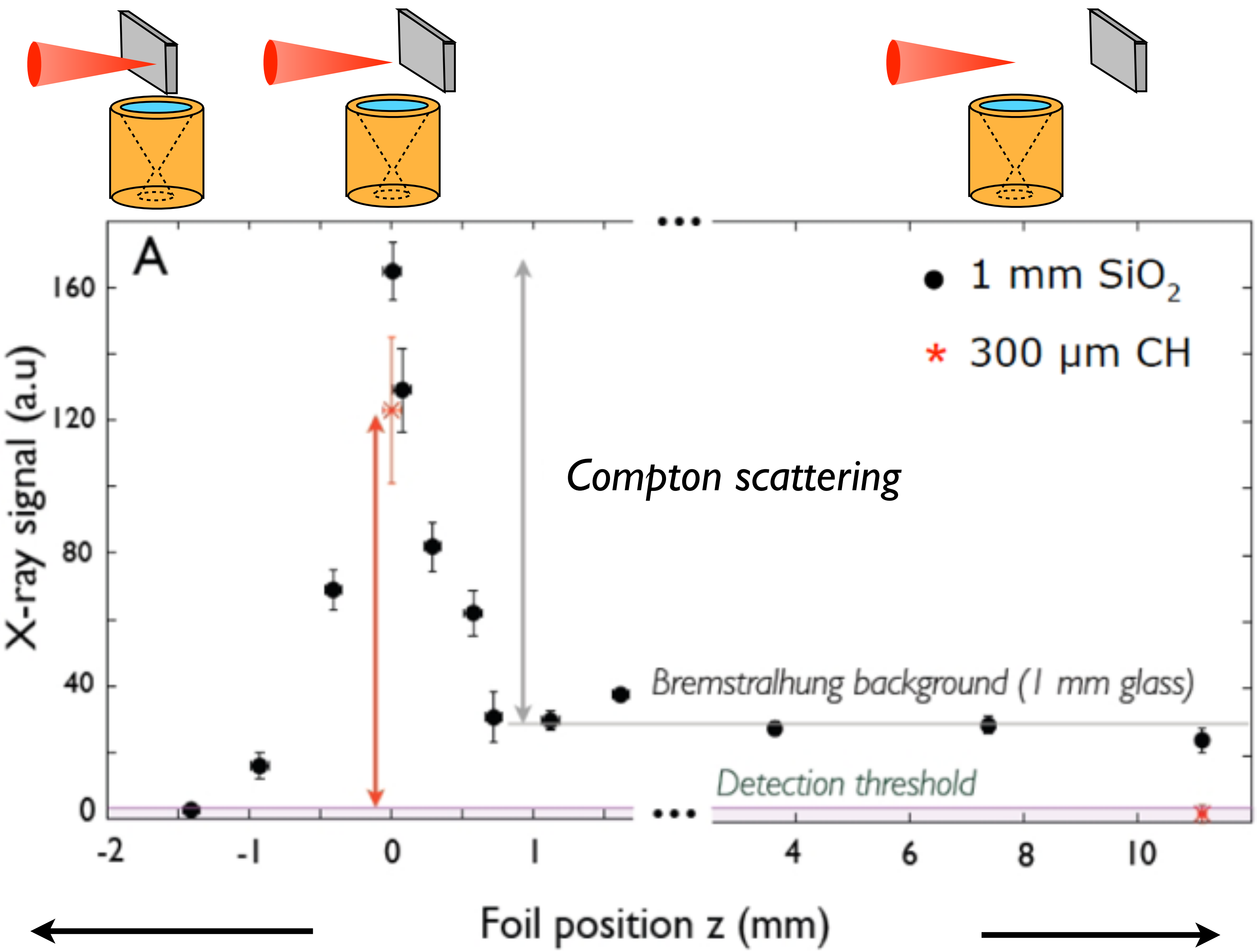
Electron spectra



X ray beam profile

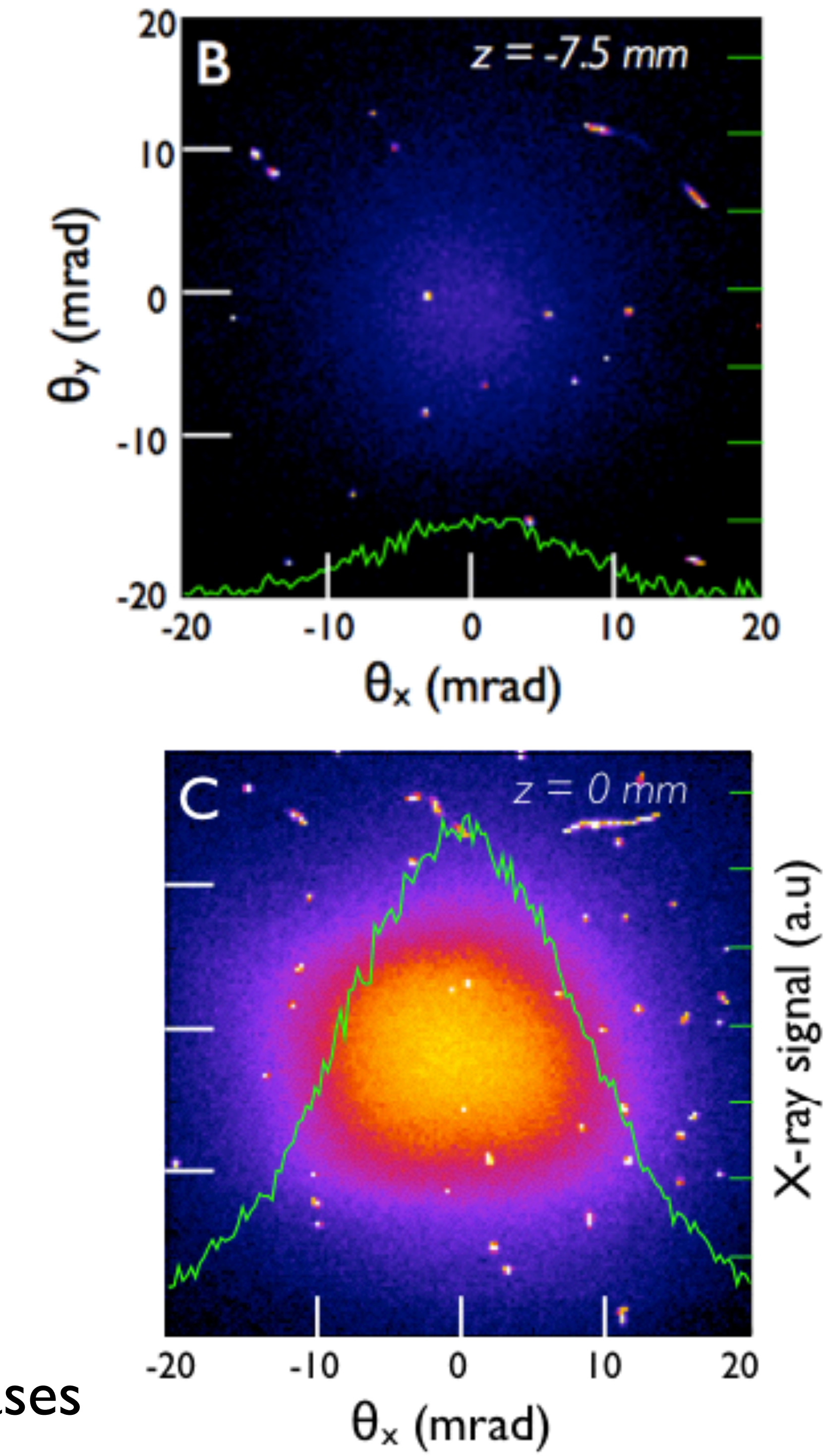


Inverse Compton Scattering : Experimental results



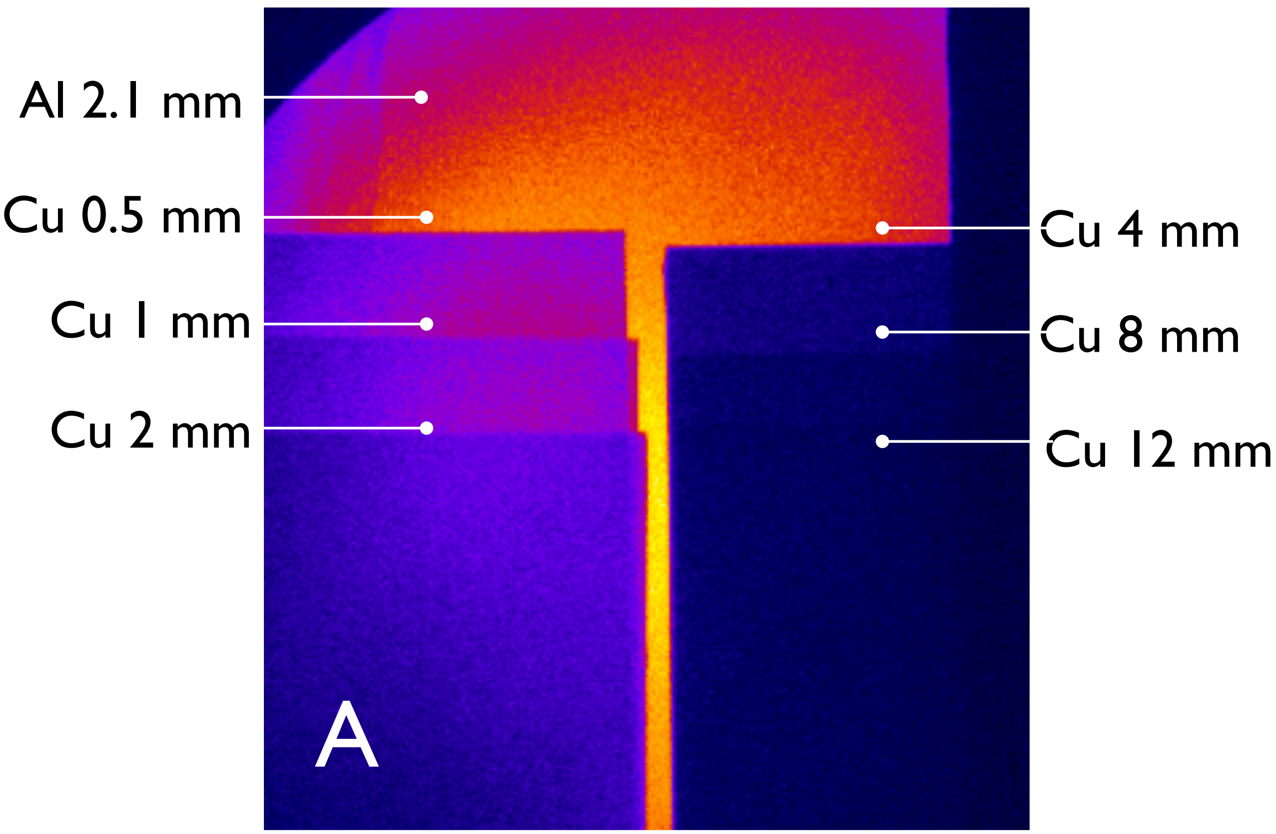
electron energy decreases

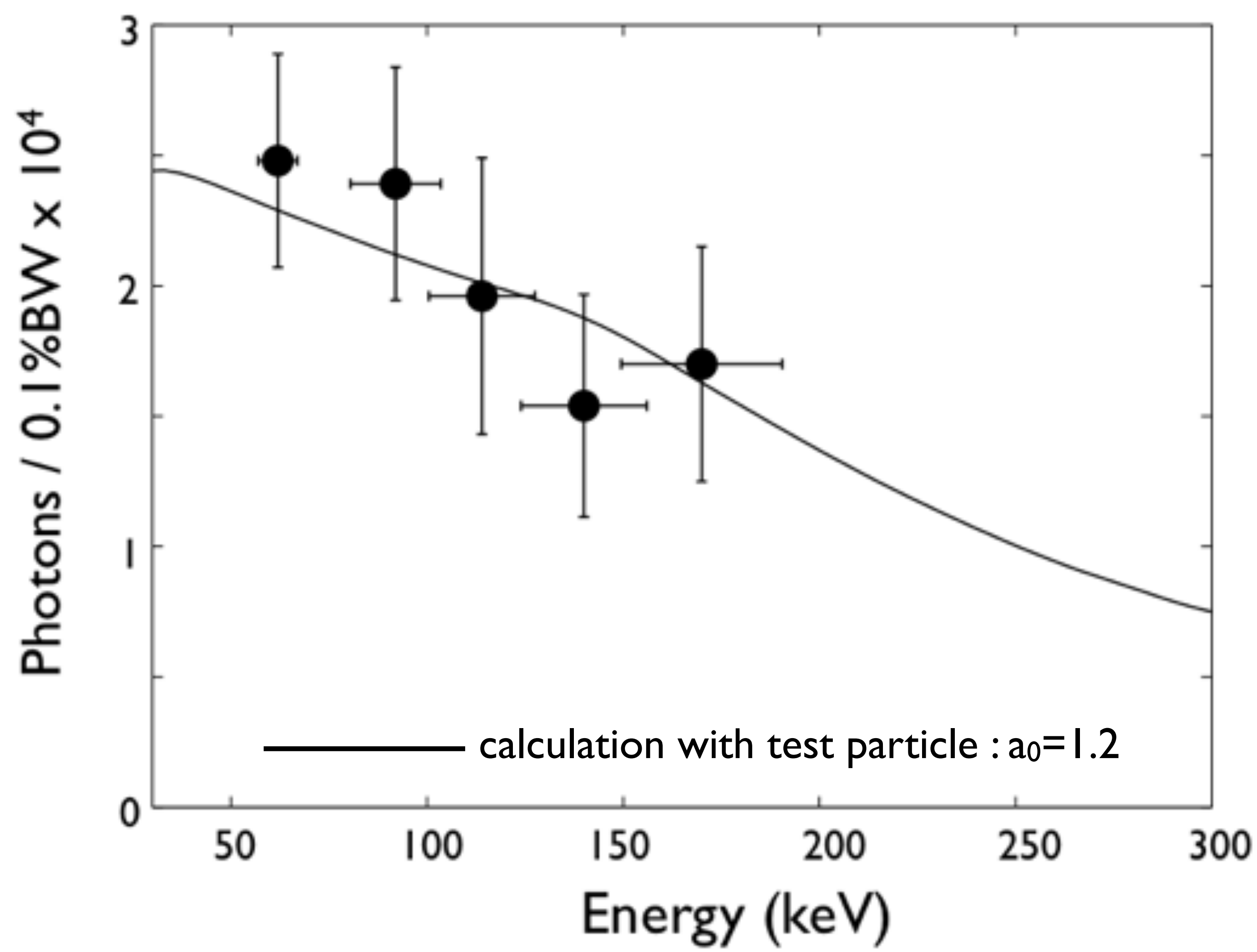
laser intensity decreases



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

Inverse Compton Scattering : Compton Spectra

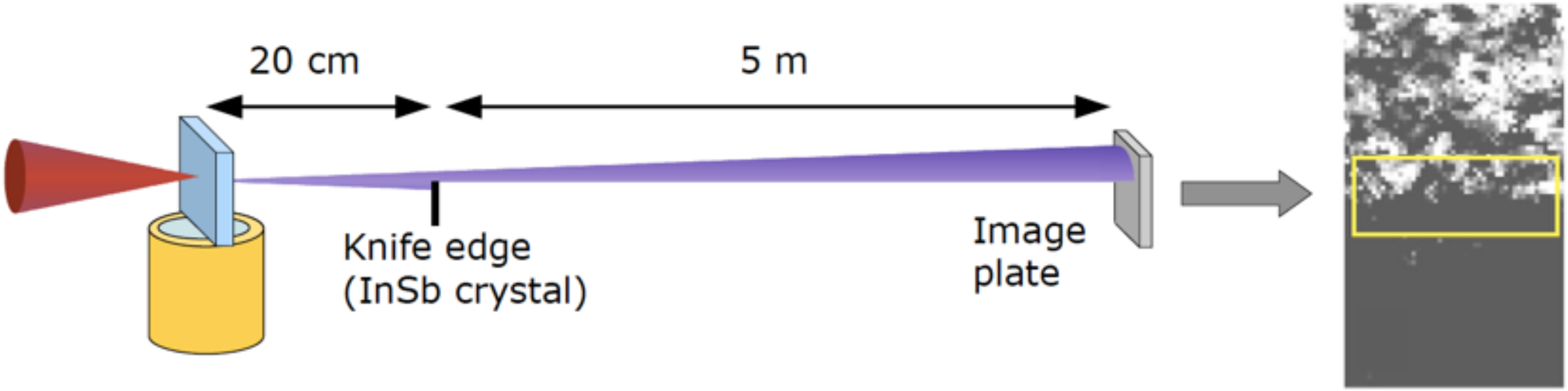


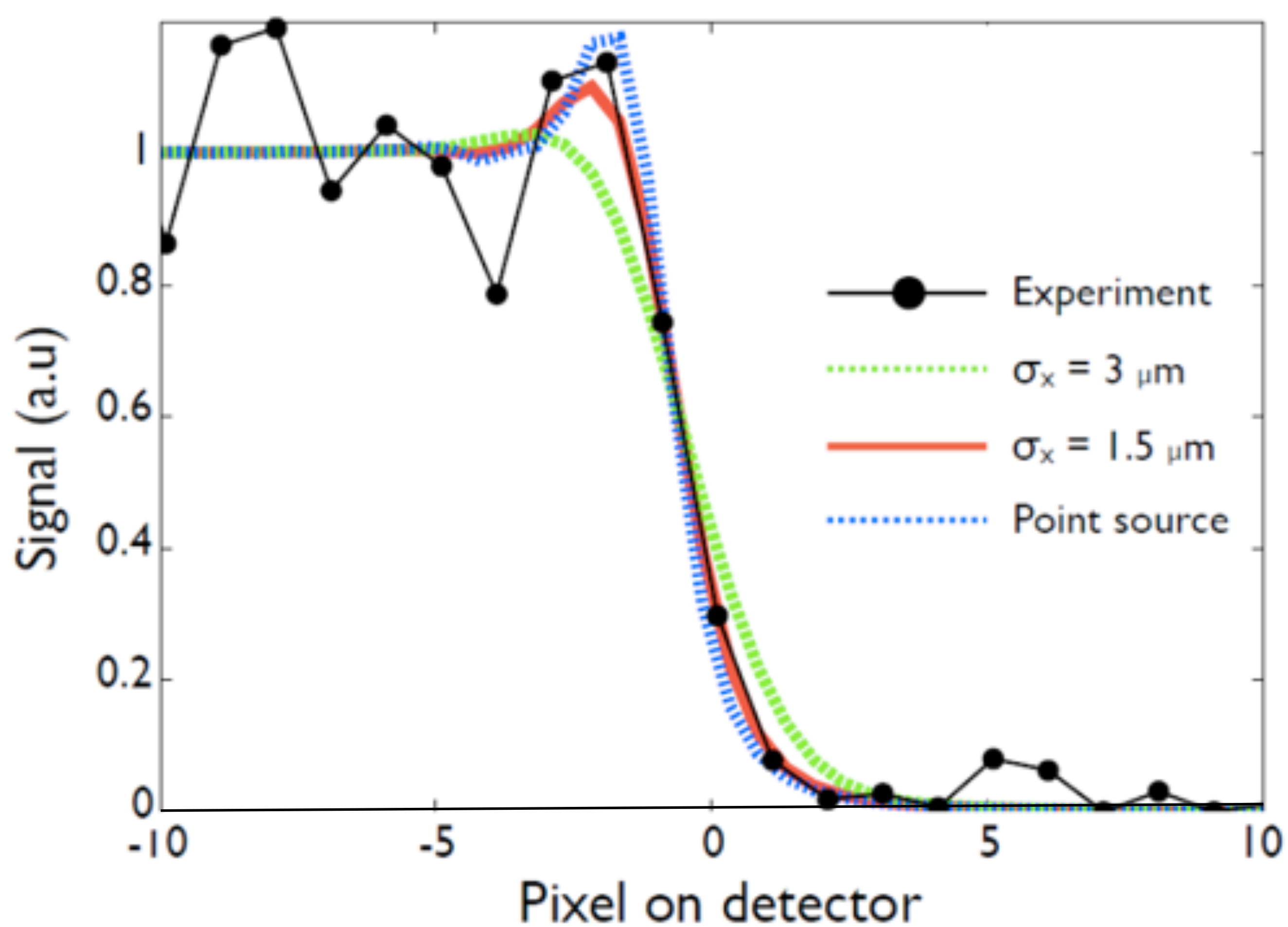


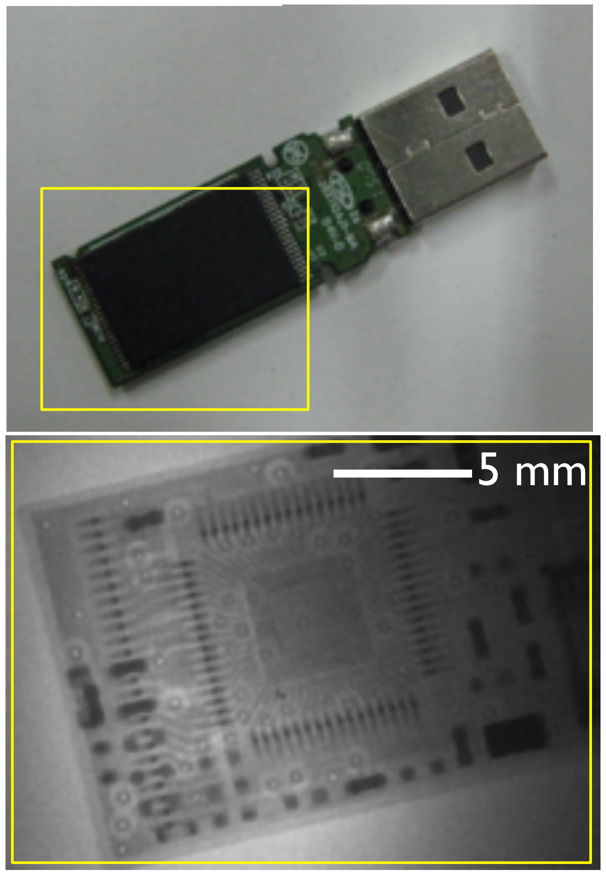
- About 10^8 ph/shot, a few 10^4 ph/shot/0.1%BW@100 keV
- Broad electron spectrum => broad X ray spectra
- Brightness: 10^{21} ph/s/mm^2/mrad^2/0.1%BW @100 keV

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

Inverse Compton Scattering : Source size







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

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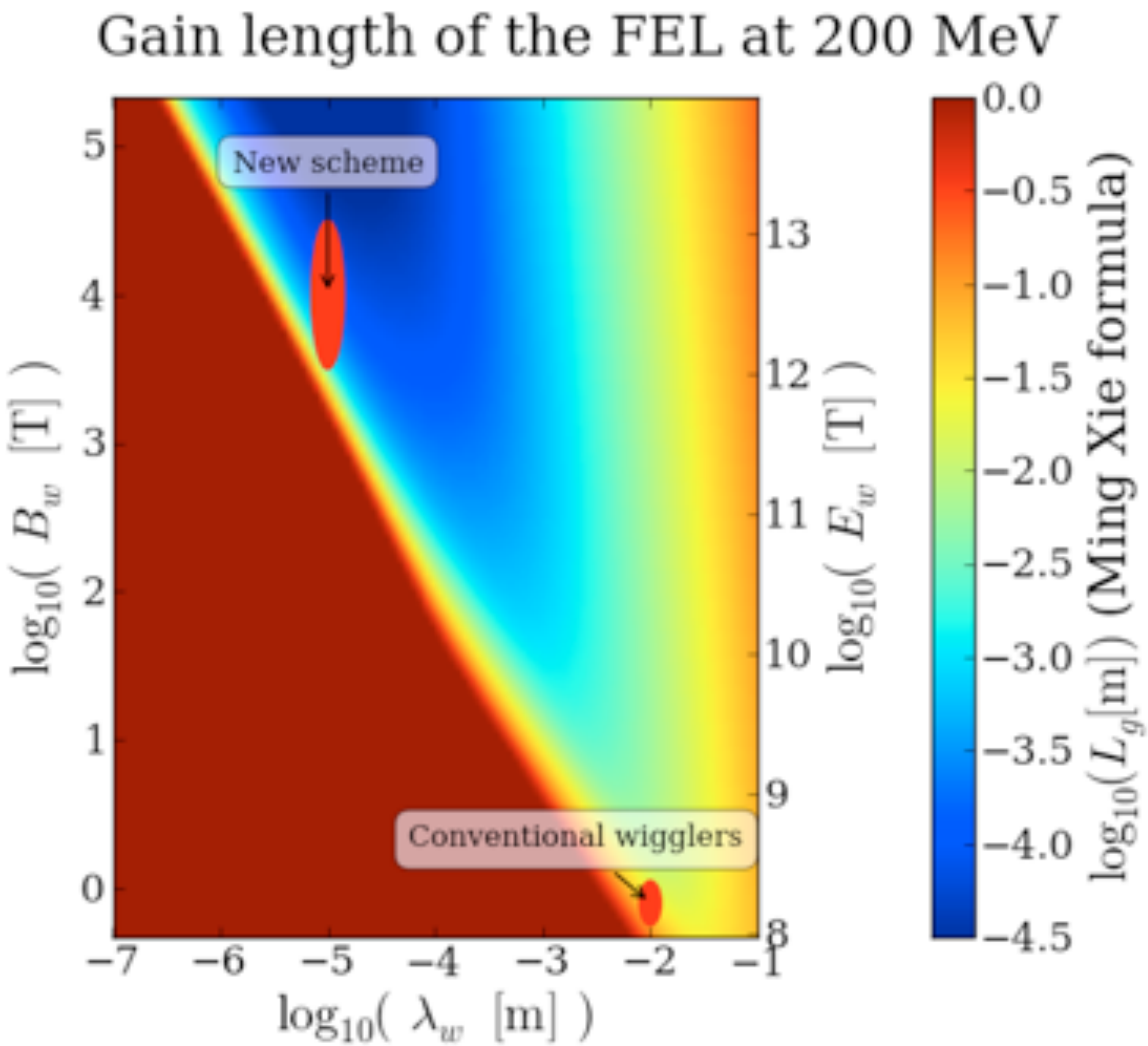
Innovative compact radiation sources based on LPA



Undulating with plasma fields

Laser-induced charge separation in nano-elements

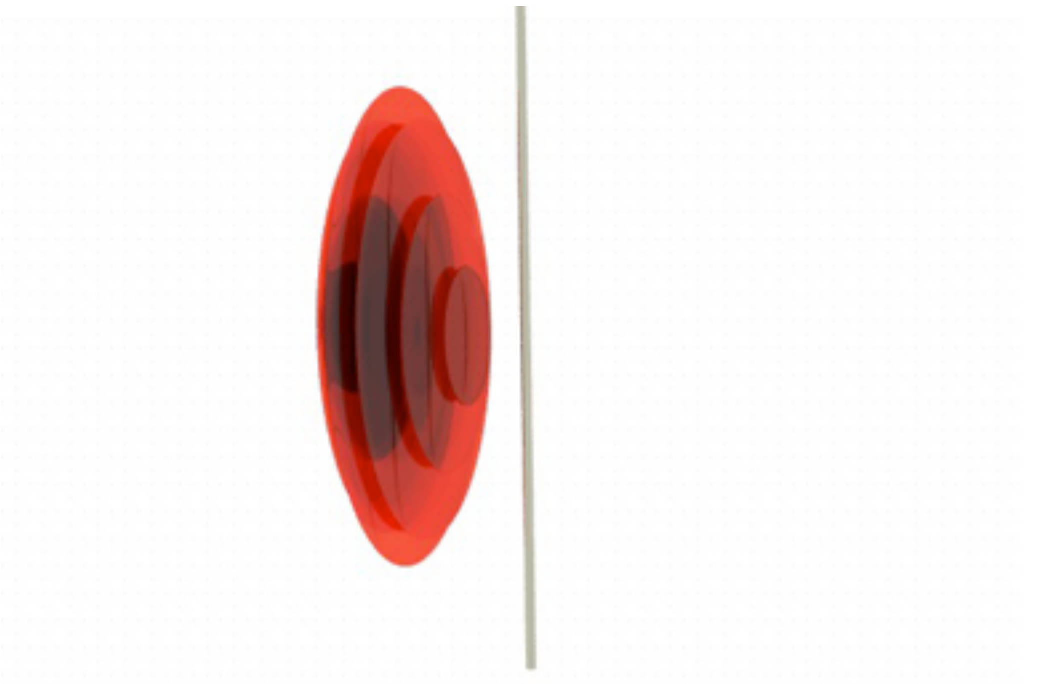
Laser absorption similar to Brunel heating

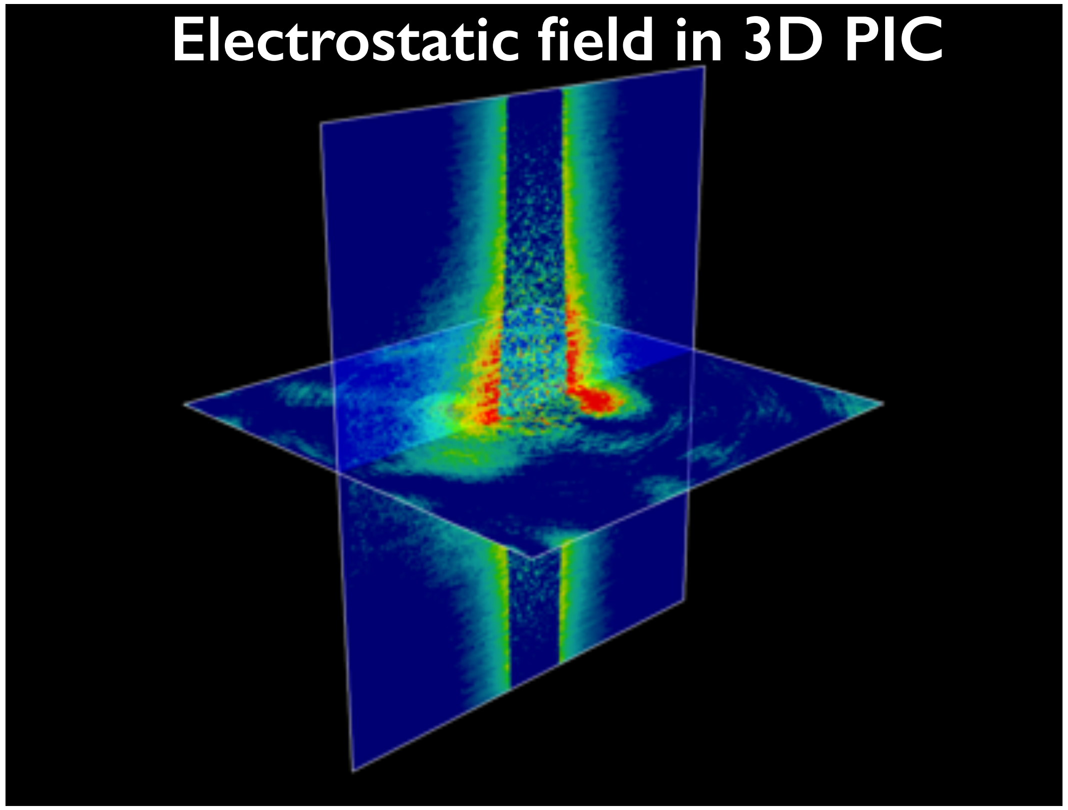
Resulting e-static field: $E \simeq E_{las}(R_{wire}/r)^{1/2}$

Periodically arranged wires:

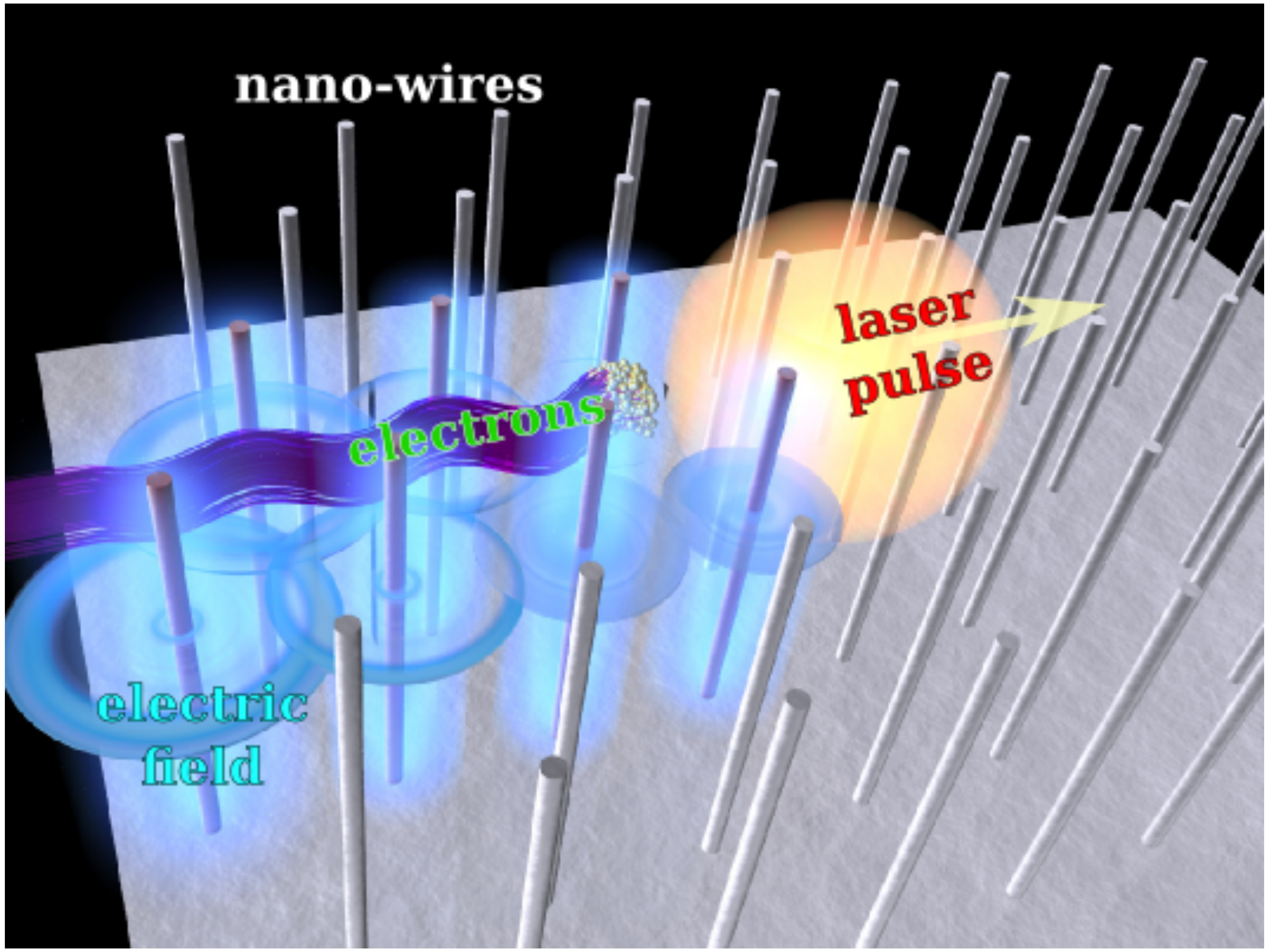
=> imposed period λ_u

=> transverse spacings control strength





Advanced concept for ultra compact X rays beam



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

Undulating with plasma fields

2D/3D/CIRC PIC

Laser system

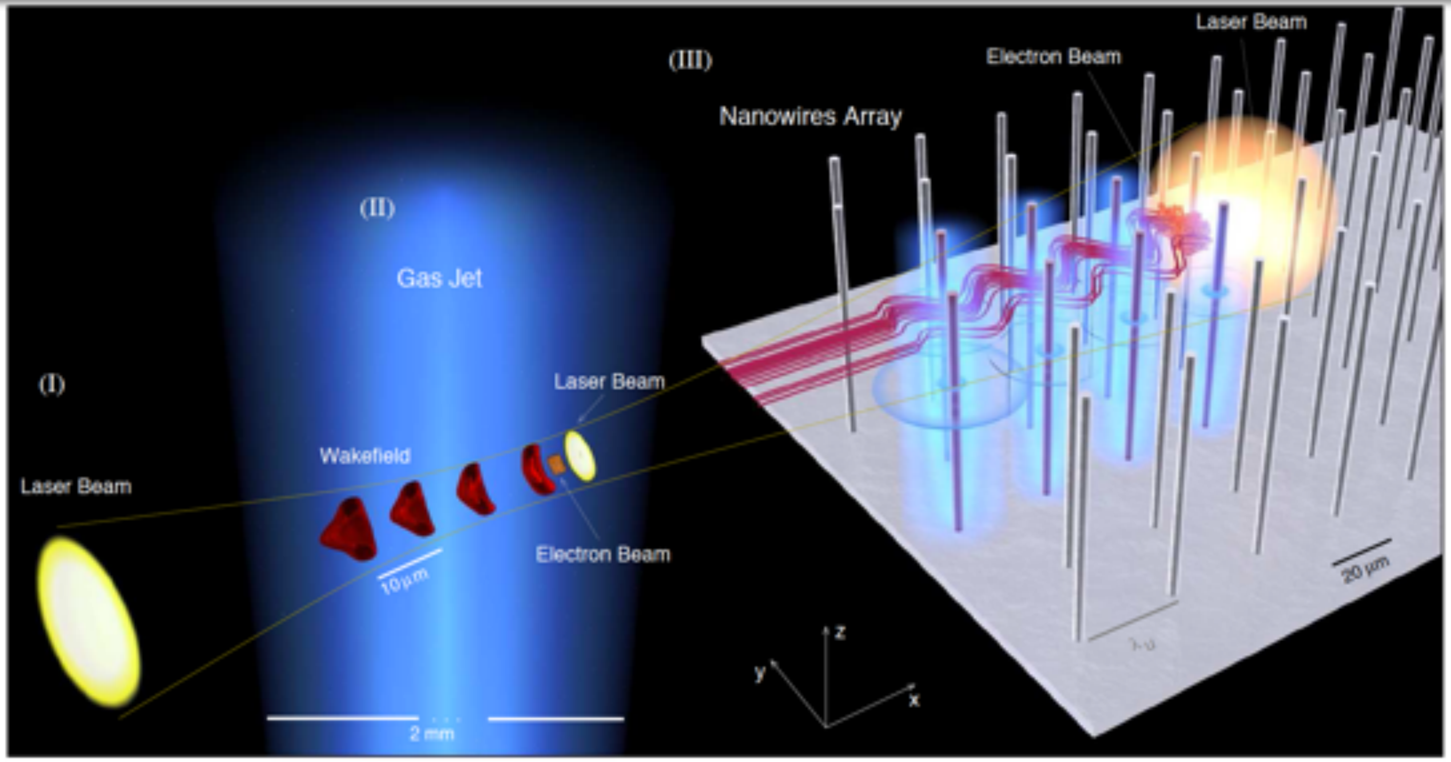
Pulse duration	30 fs
Pulse energy	0.7 J

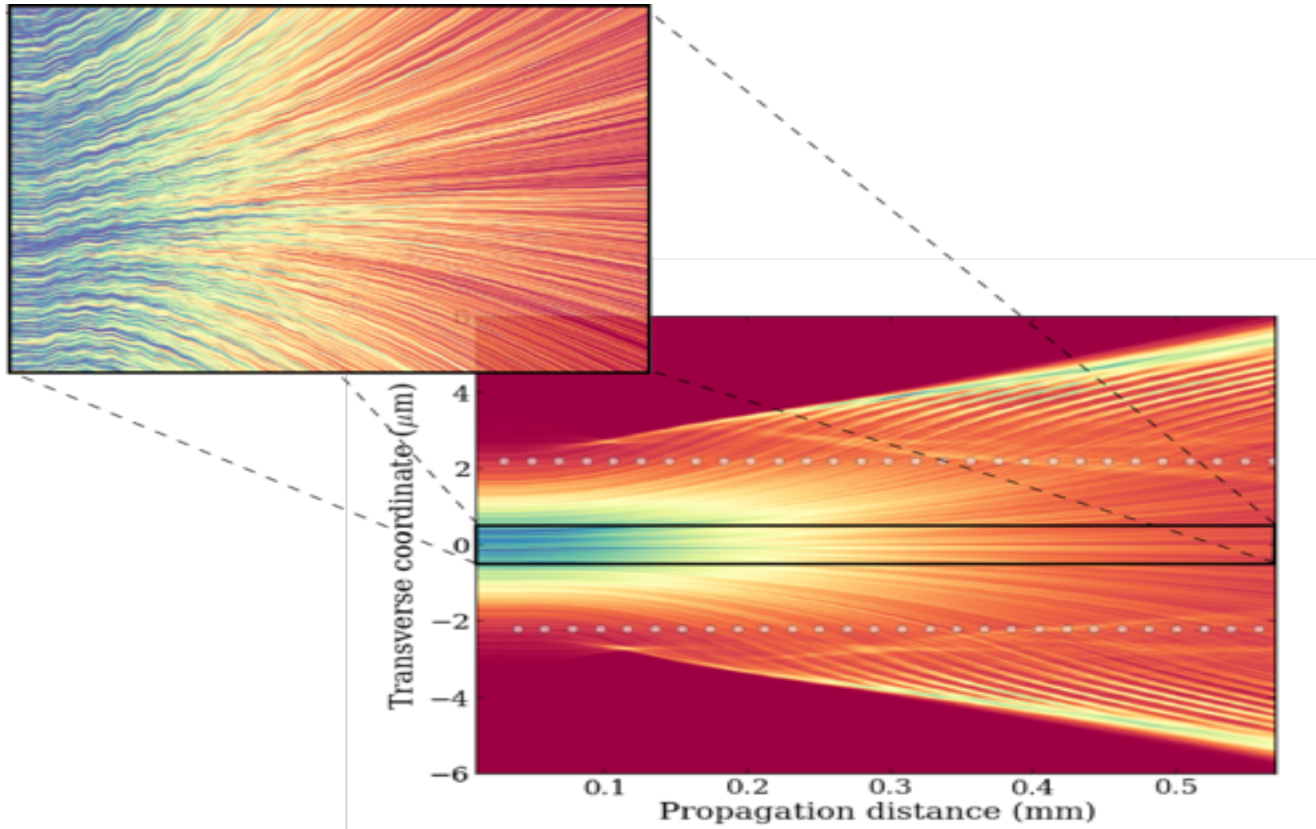
Wires configuration

Diameter	0.4 μm
Period	24 μm
Transverse spacings	11 μm

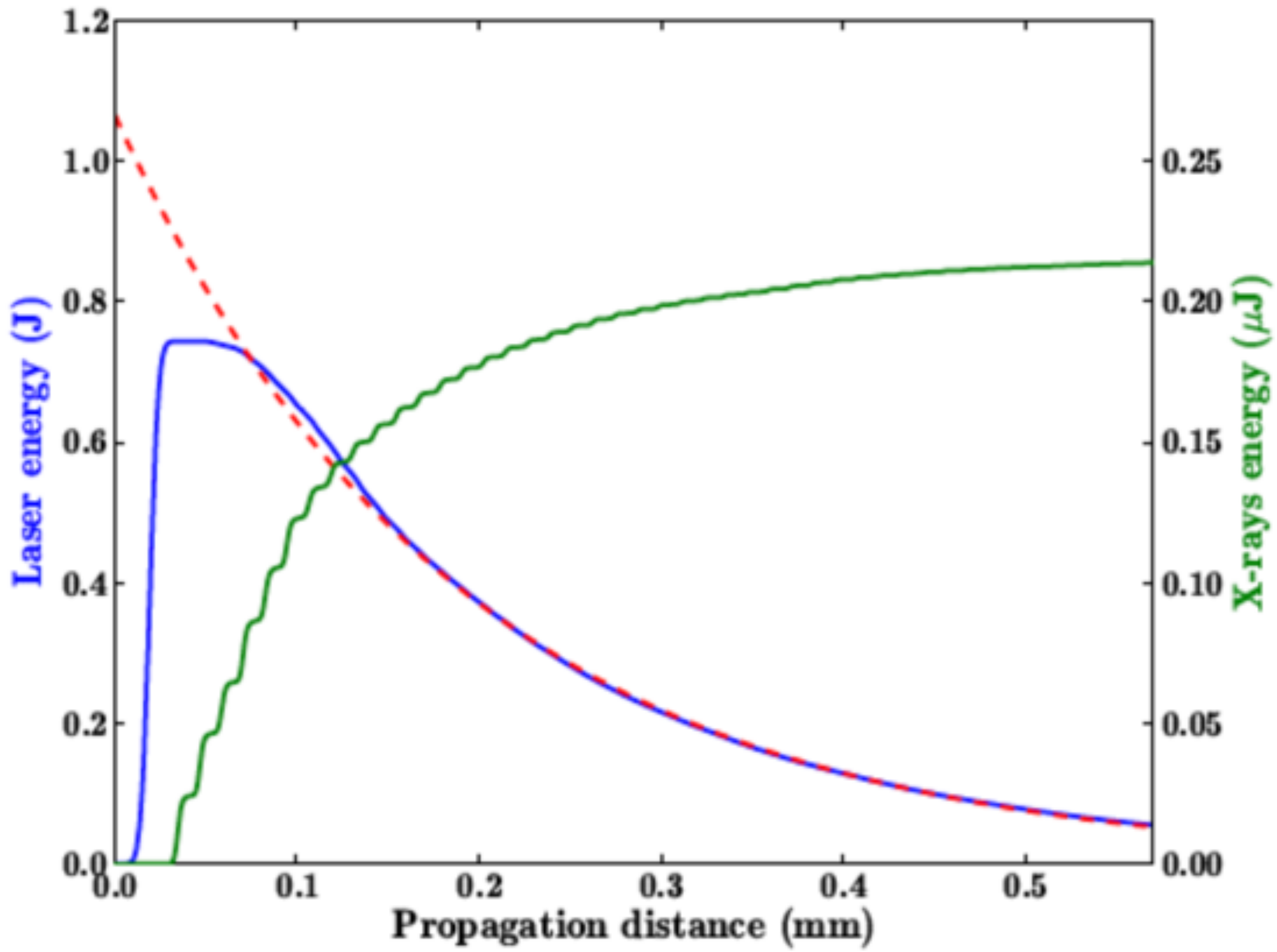
LPA electron beam

Emittance	0.2 mm.mrad
Energy	200-600 MeV
Energy spread	1 %





Undulating with plasma fields



Diffractive losses $I_{las}(x) \sim \exp(-x/l_{loss})$:

$l_{loss} = \lambda_u \sigma_\perp (2\pi R_{wire})^{-1/2} \simeq 0.2$ mm

Laser losses dominate electron divergence

Undulator parameter $K_{0loss} \simeq 0.7$

Undulating with plasma fields

Varying electron energy

Energy 200 / 400 / 600 MeV

Undulator emission

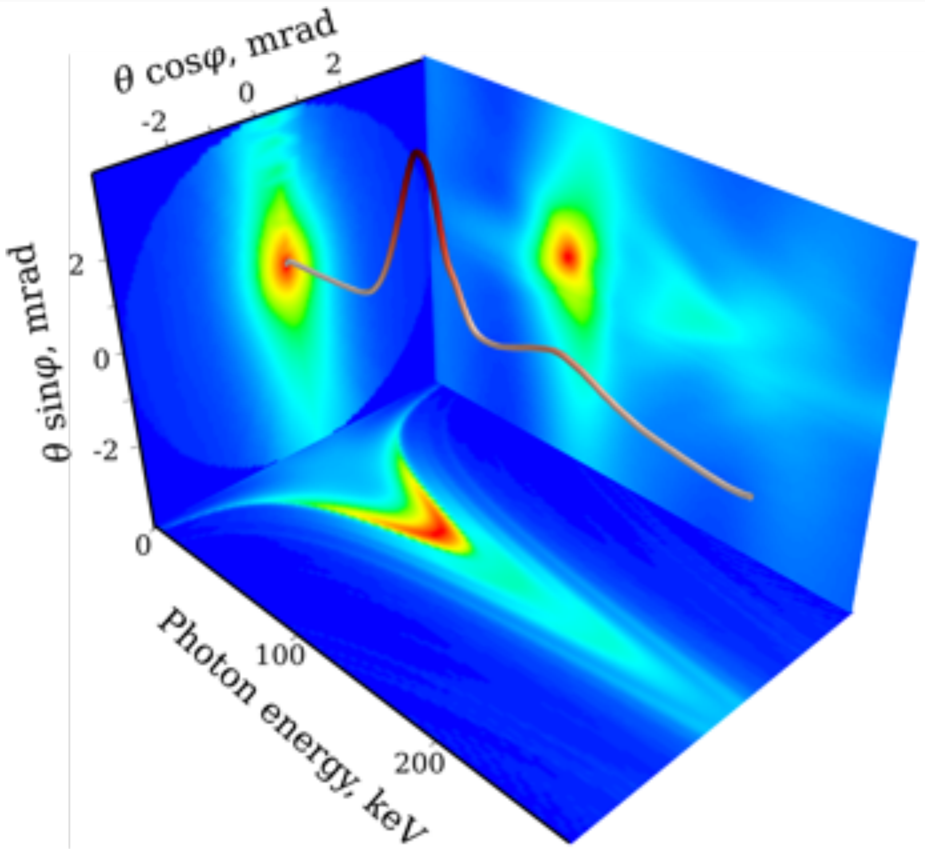
Photon energy 12 / 47 / 106 keV

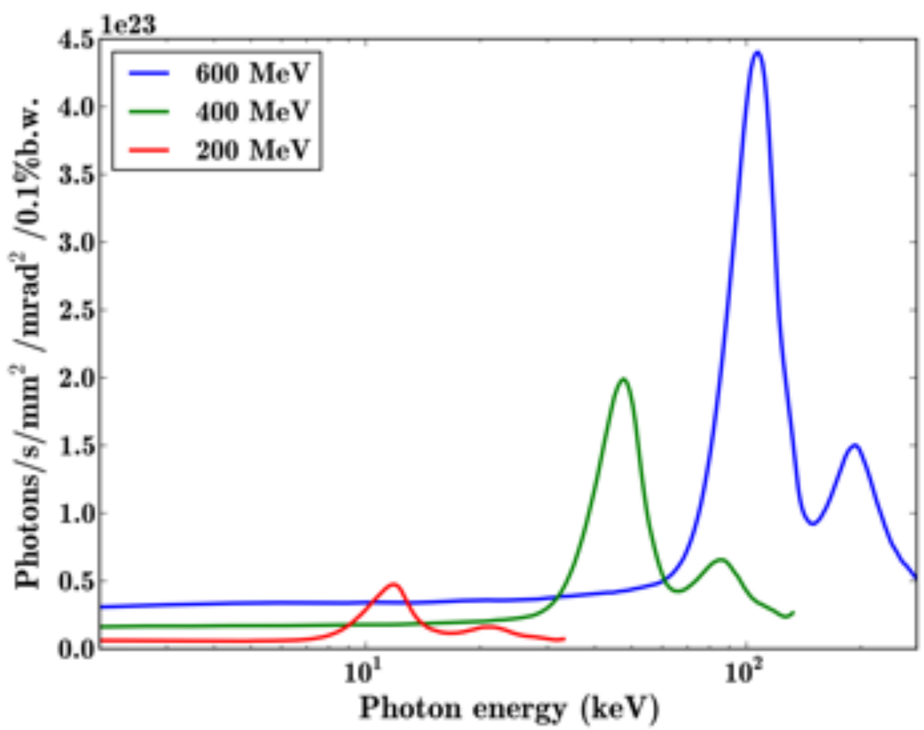
Brightness 0.5 / 2 / 4.5×10^{23}s.u.

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

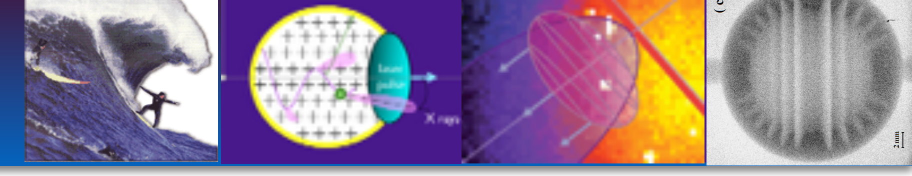




X rays Source with Laser Plasma Accelerators : Outline

- Betatron radiation produced in LPA
  - Principle & Experimental results
- All optical Compton gamma rays source
  - Principle & Experimental results
- Compact nano undulators
  - Principle & Simulations
- **Conclusion**

Conclusion



Laser plasma accelerators can deliver high quality e and X ray beams

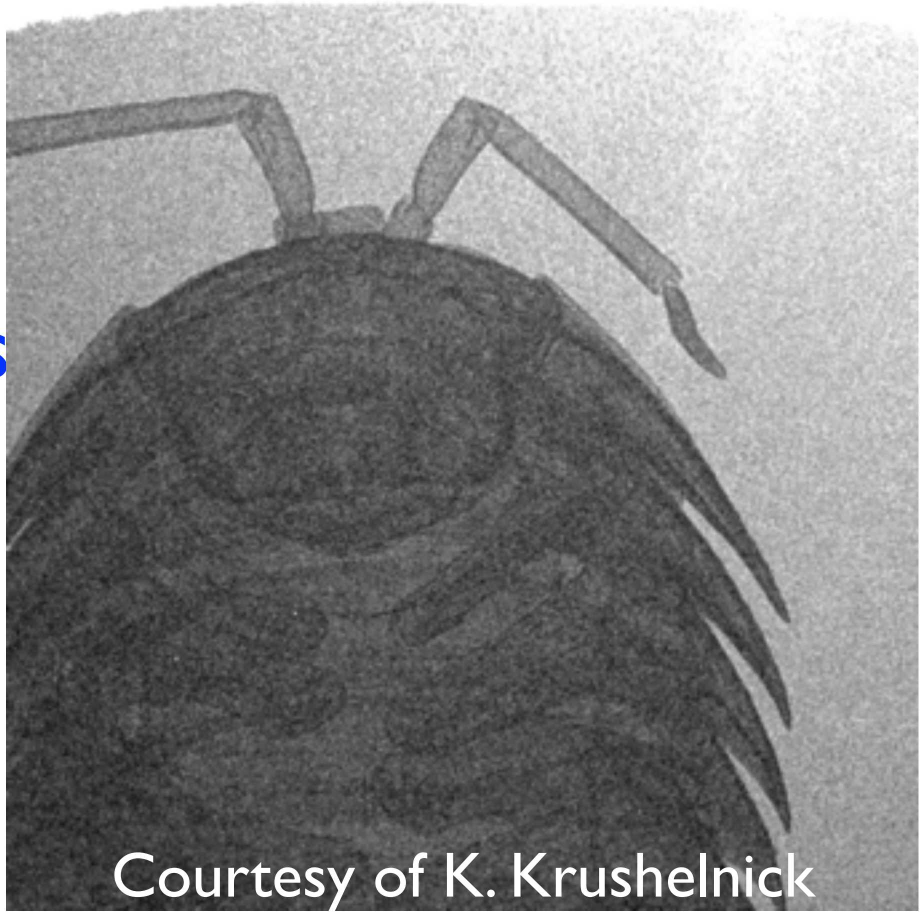
(i) Betatron : 10^8-10^9 ph/shot - fs - micron - 10's keV - 10's mrad

(ii) Compton : 10^8-10^9 ph/shot - fs - micron - 100's keV-10^4 photons/shot/0.1% BW @ 100 keV(10 000 brighter than existing sources

(iii) Bremsstrahlung:10^5-10^6 ph/shot - ps - 10's micron - 10's MeV

(iv) Promising for compact FEL

(v) Open new perspective with plasma undulators


Courtesy of K. Krushelnick

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