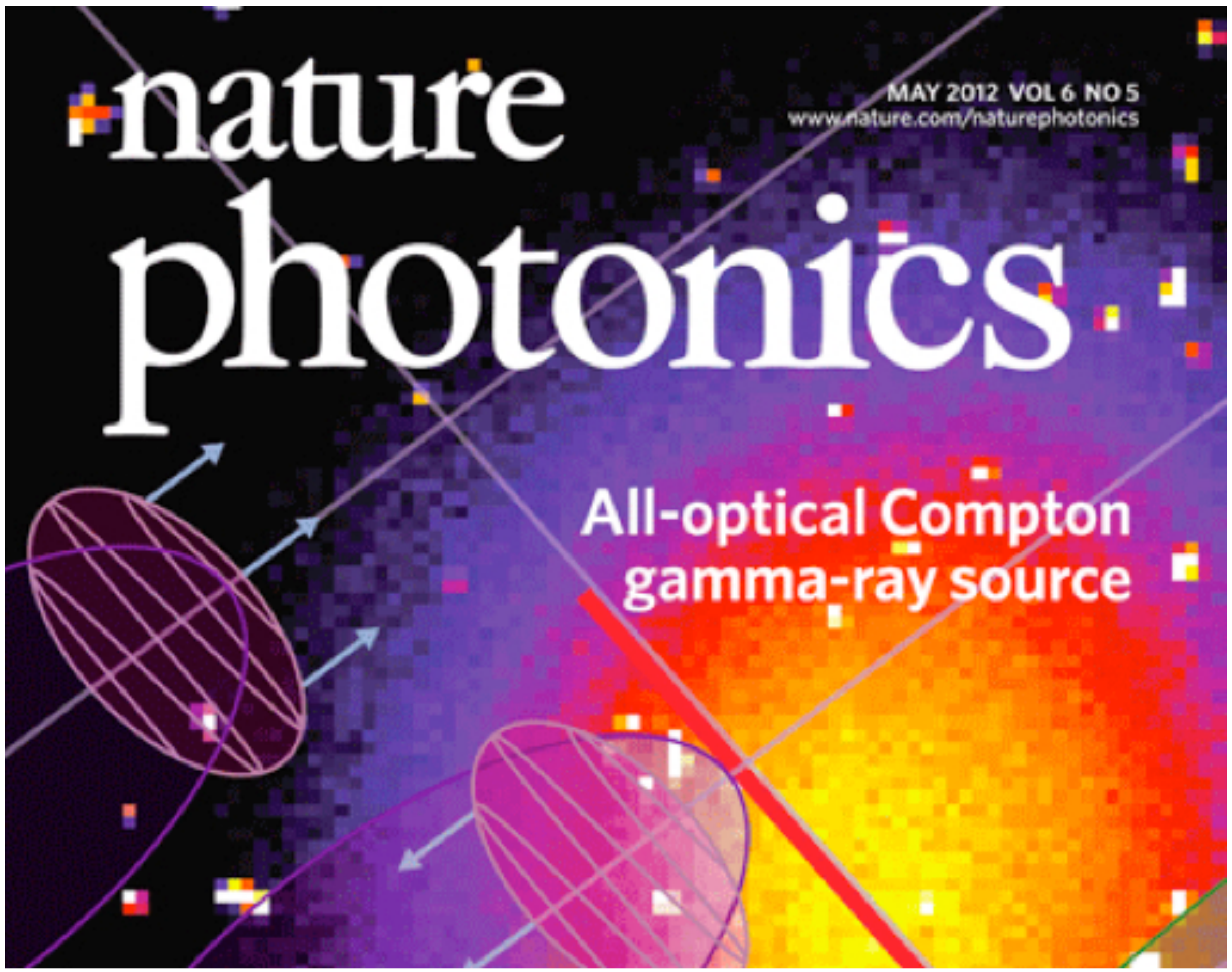
Ultra-Bright X-rays Beams from Laser Plasma Accelerators



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Conference on High Intensity Laser and Attosecond Science in Israel, Tel-Aviv, December 2-4 (2013)

X rays source with Laser Plasma accelerators

Nonlinear Thomson 2003

Betatron radiation 2004

Compton scattering 2011

Bremsstrahlung 2010

1 keV — **10 keV** — **100 keV** — **1 MeV** — **10 MeV**

Xuv — **X** — **γ**

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

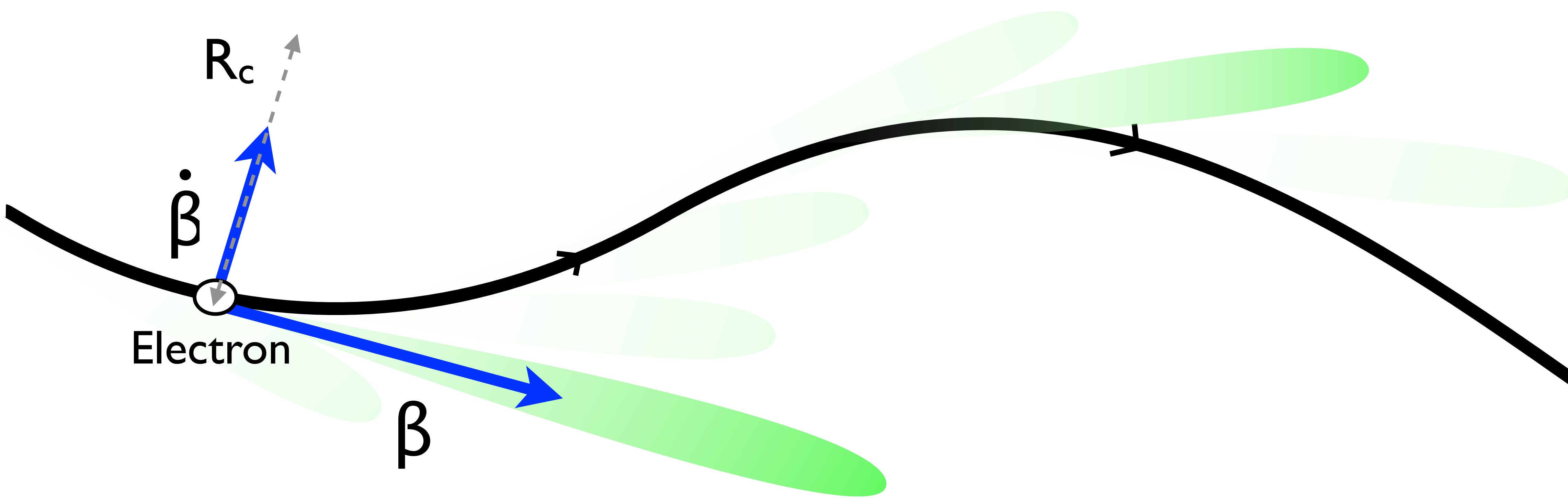
Moving charge radiation

Velocity — Acceleration

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

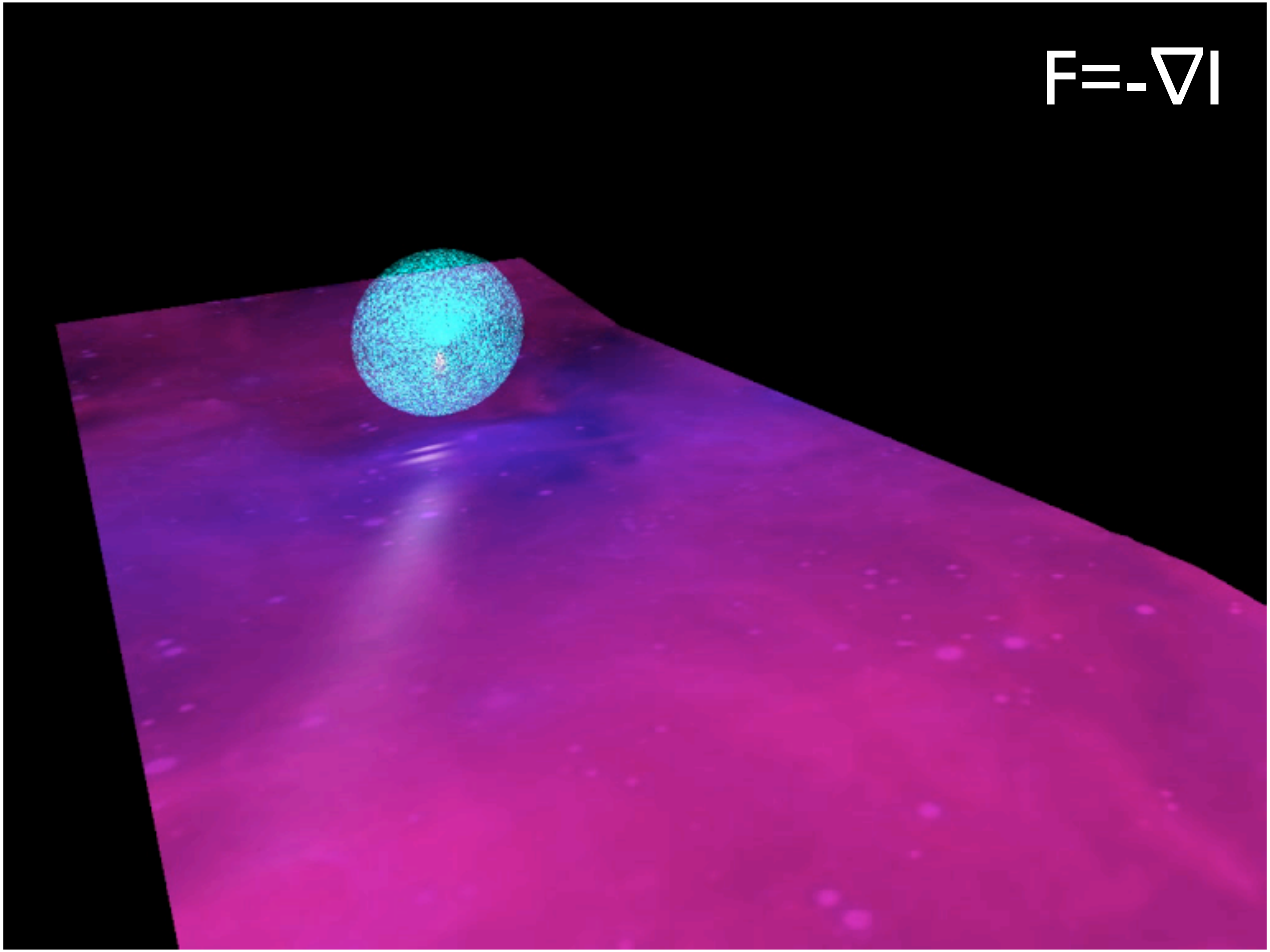
Radiated energy

n *unit vector in the observation direction*



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

The laser wakefield



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

X rays Source with Laser Plasma Accelerators : Outline

- Betatron radiation produced in LPA
  - Experimental characterization
  - Electron-X rays beams correlations
  - Diagnostics for LPA
  - Single shot contrast imaging
- All optical Compton gamma rays source
  - Principle
  - Experimental results
- Bremsstrahlung gamma rays source
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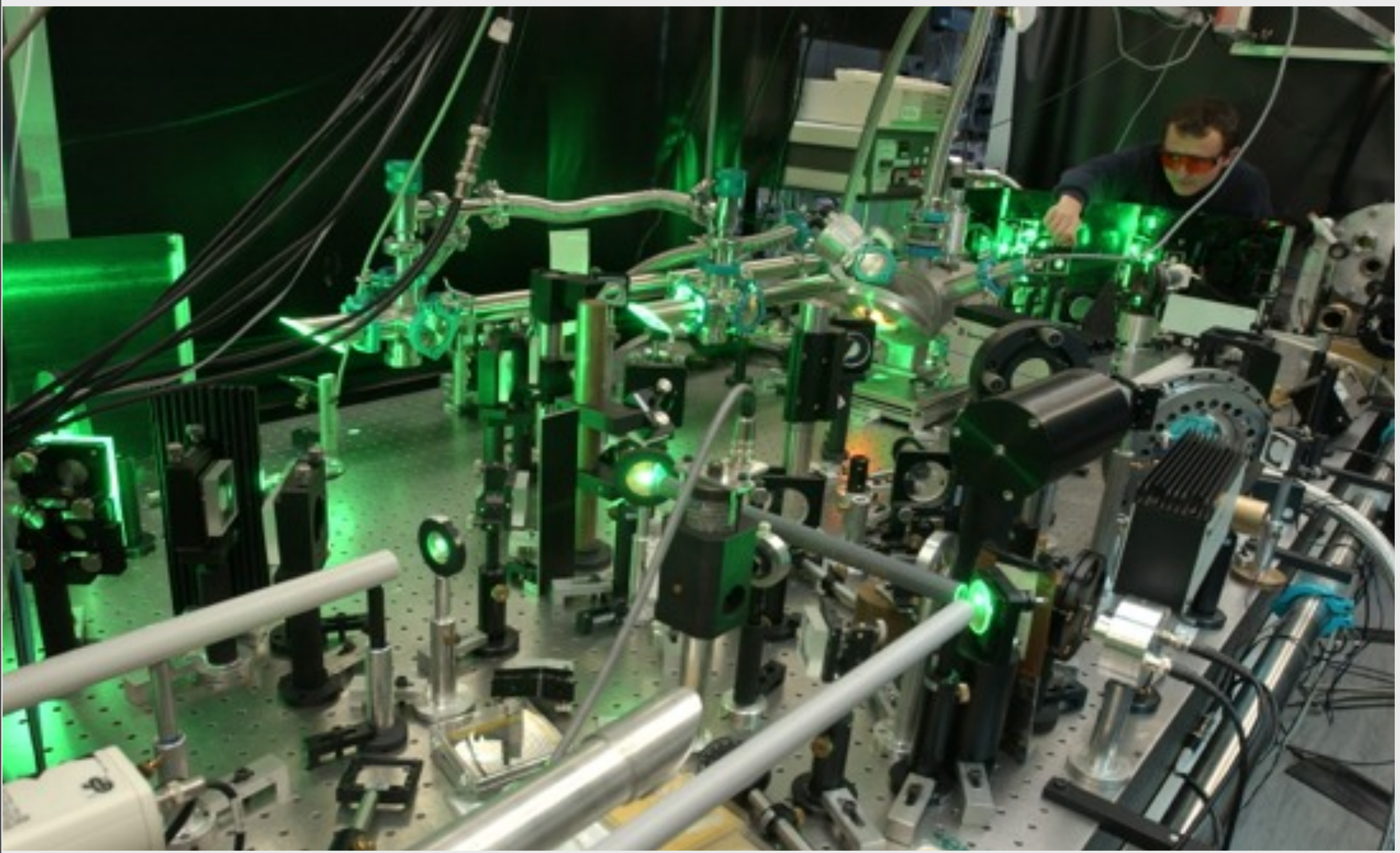
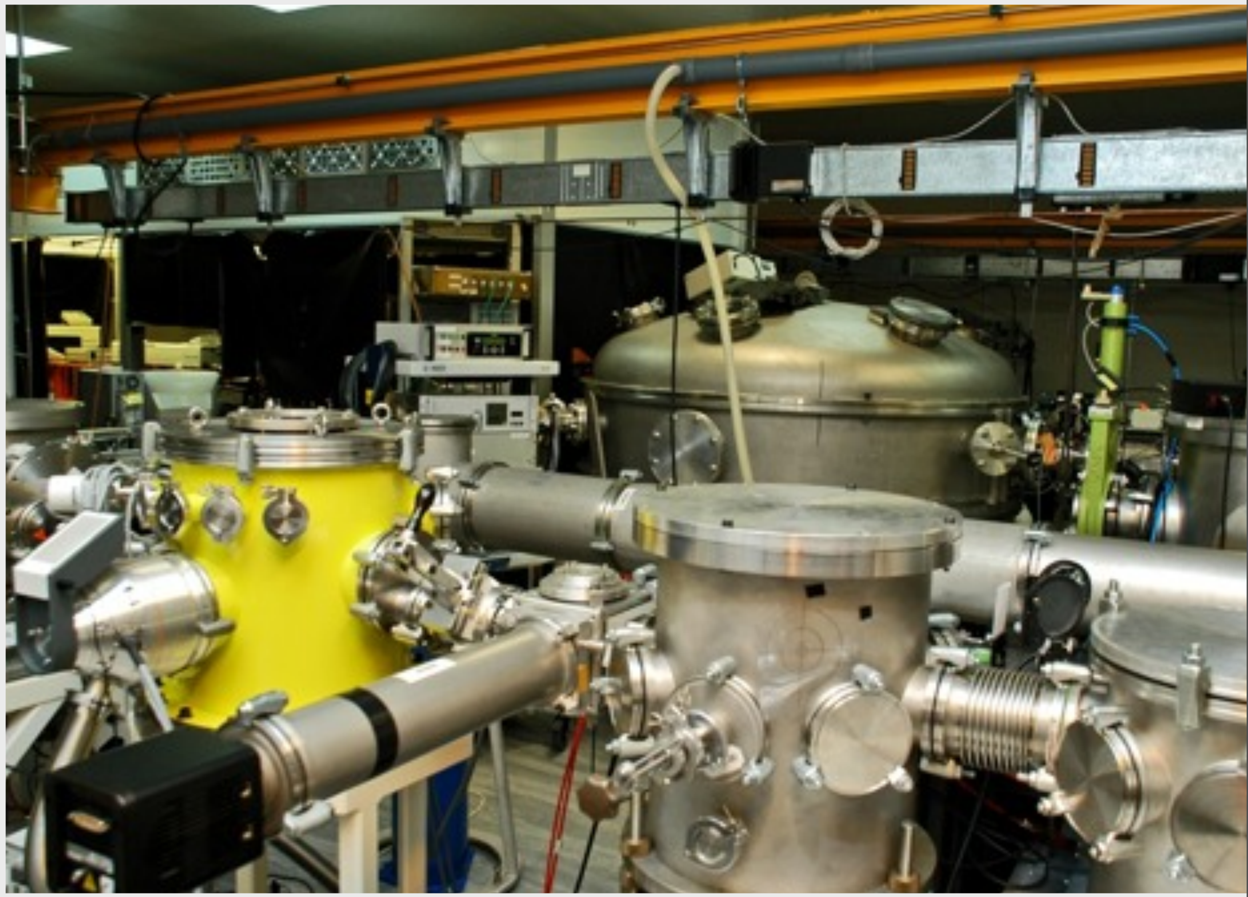
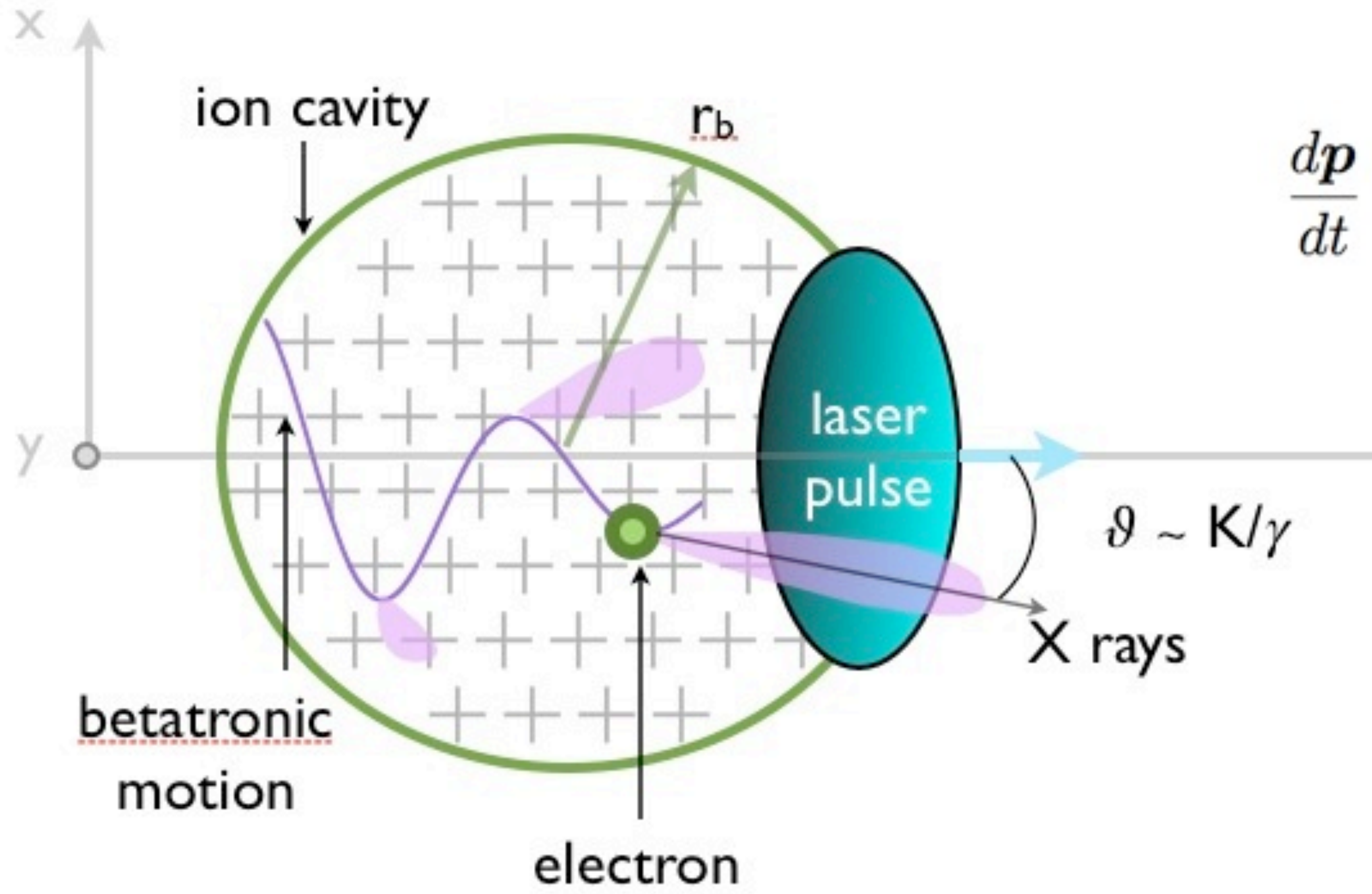
Laser "Salle Jaune"





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

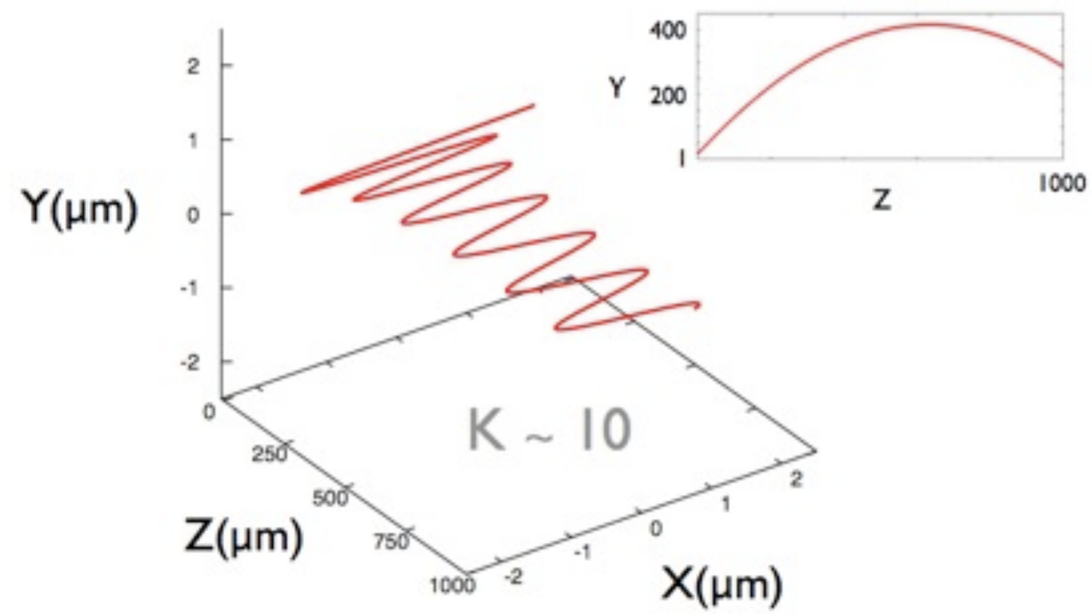
Betatron radiation properties



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



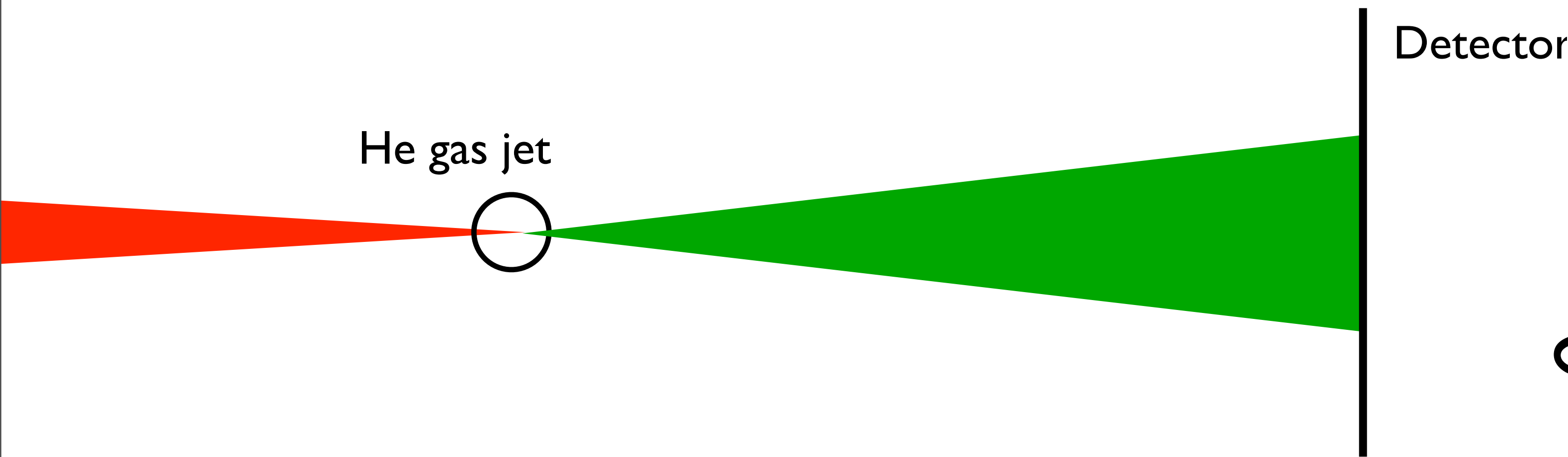
Betatron oscillation properties:

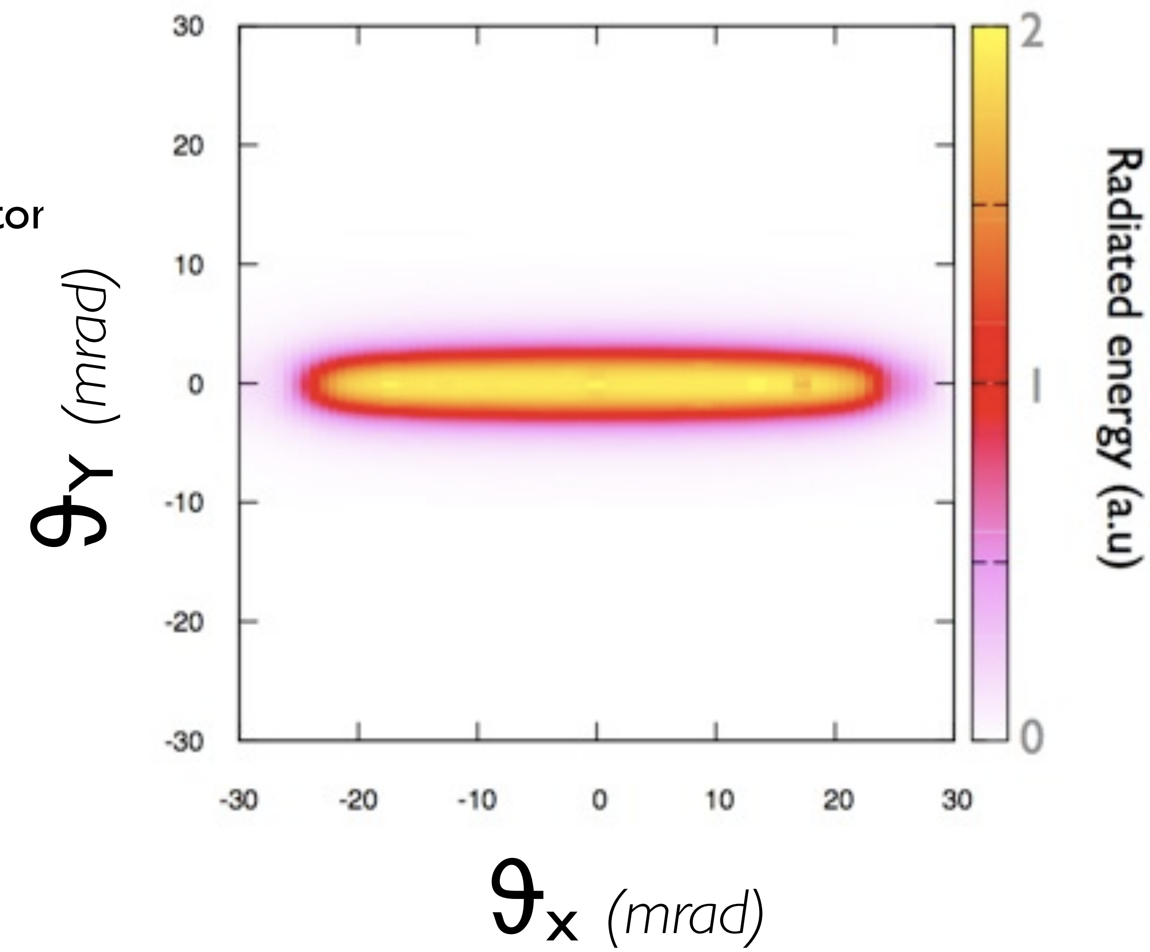
$$\lambda_u = \sqrt{2\gamma}\lambda_p \qquad K = r_\beta k_p \sqrt{\gamma/2}$$

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

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

Spatial distribution of the emitted radiation





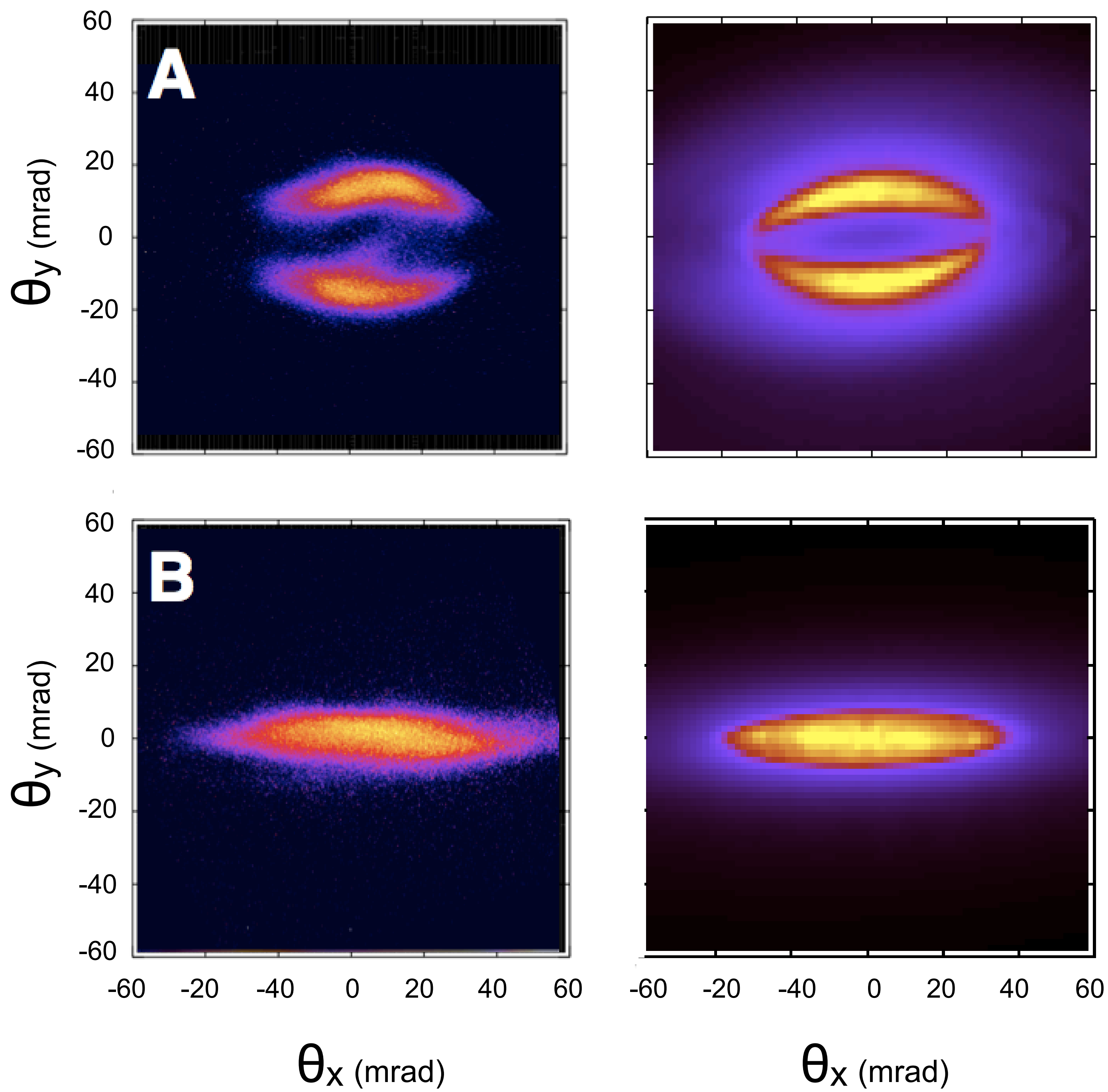
Scaling law

Cone aperture: $\vartheta_x = K/\gamma$ ~50 mrad for K = 10 and 100 Mev electrons

Cone width: $\vartheta_Y = 1/\gamma$ ~5 mrad

A more precise source size estimation

Experimental profiles | Calculated profiles | Electron orbits



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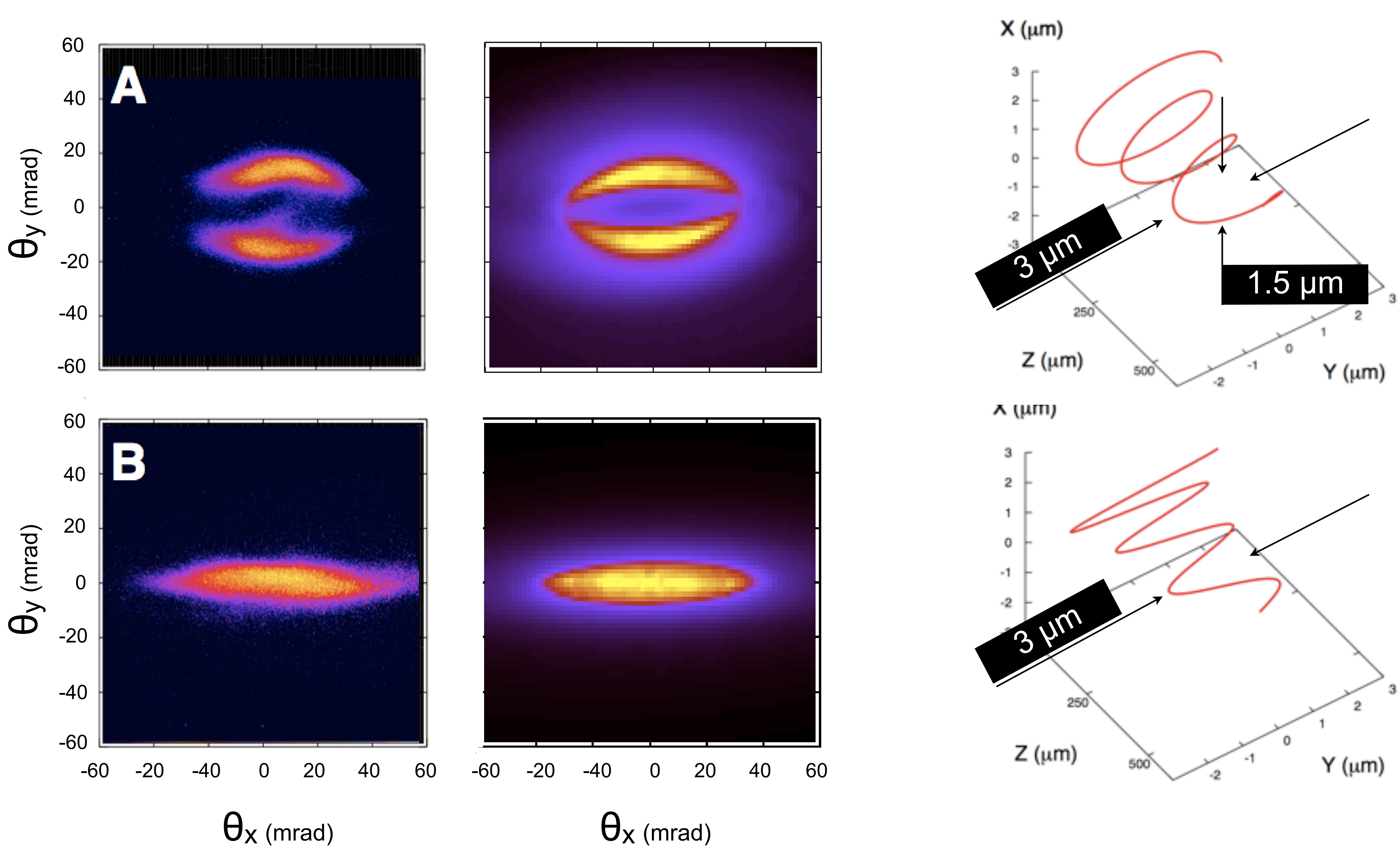
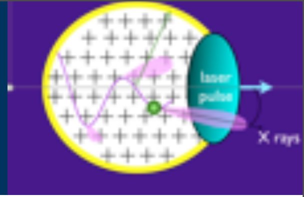
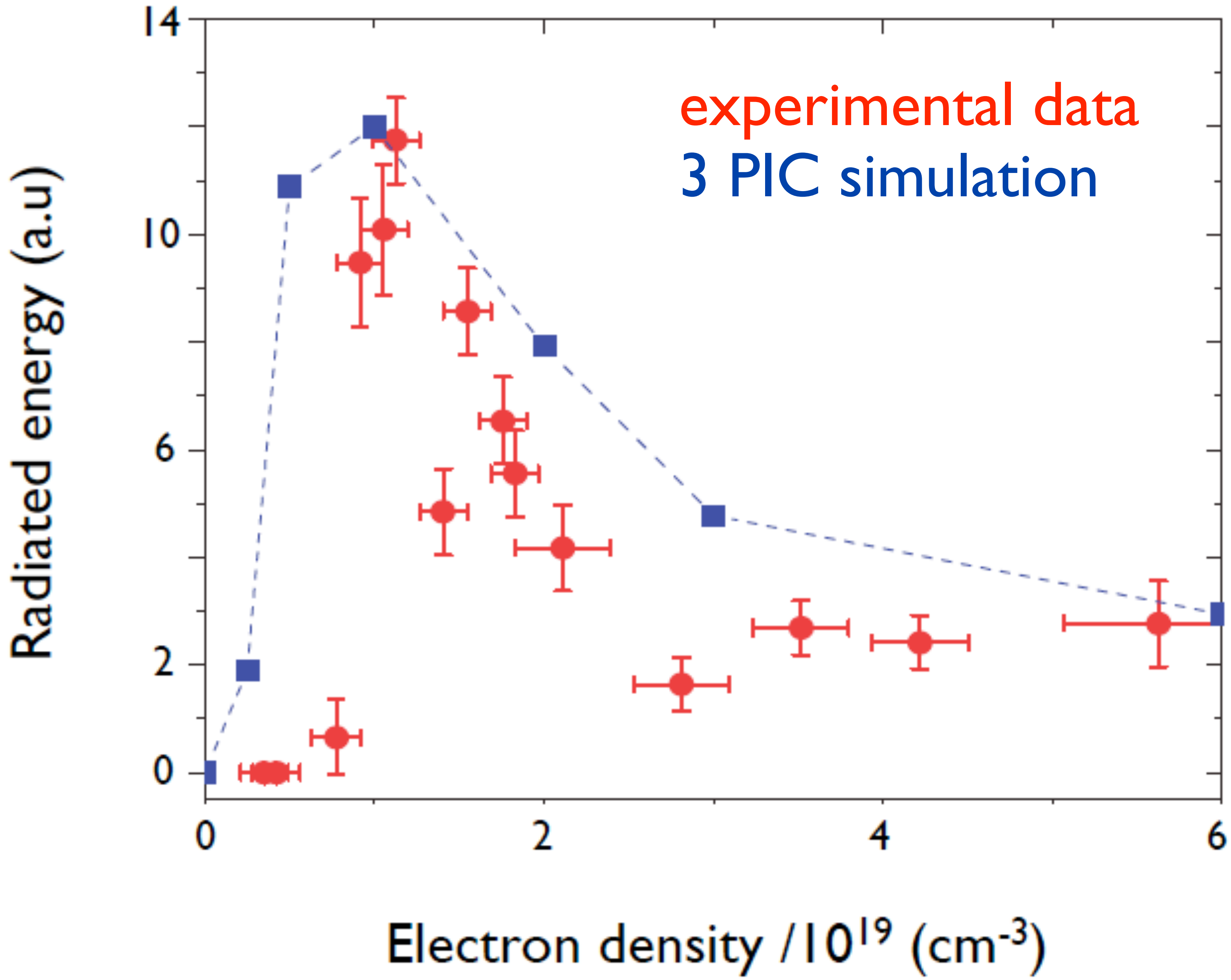


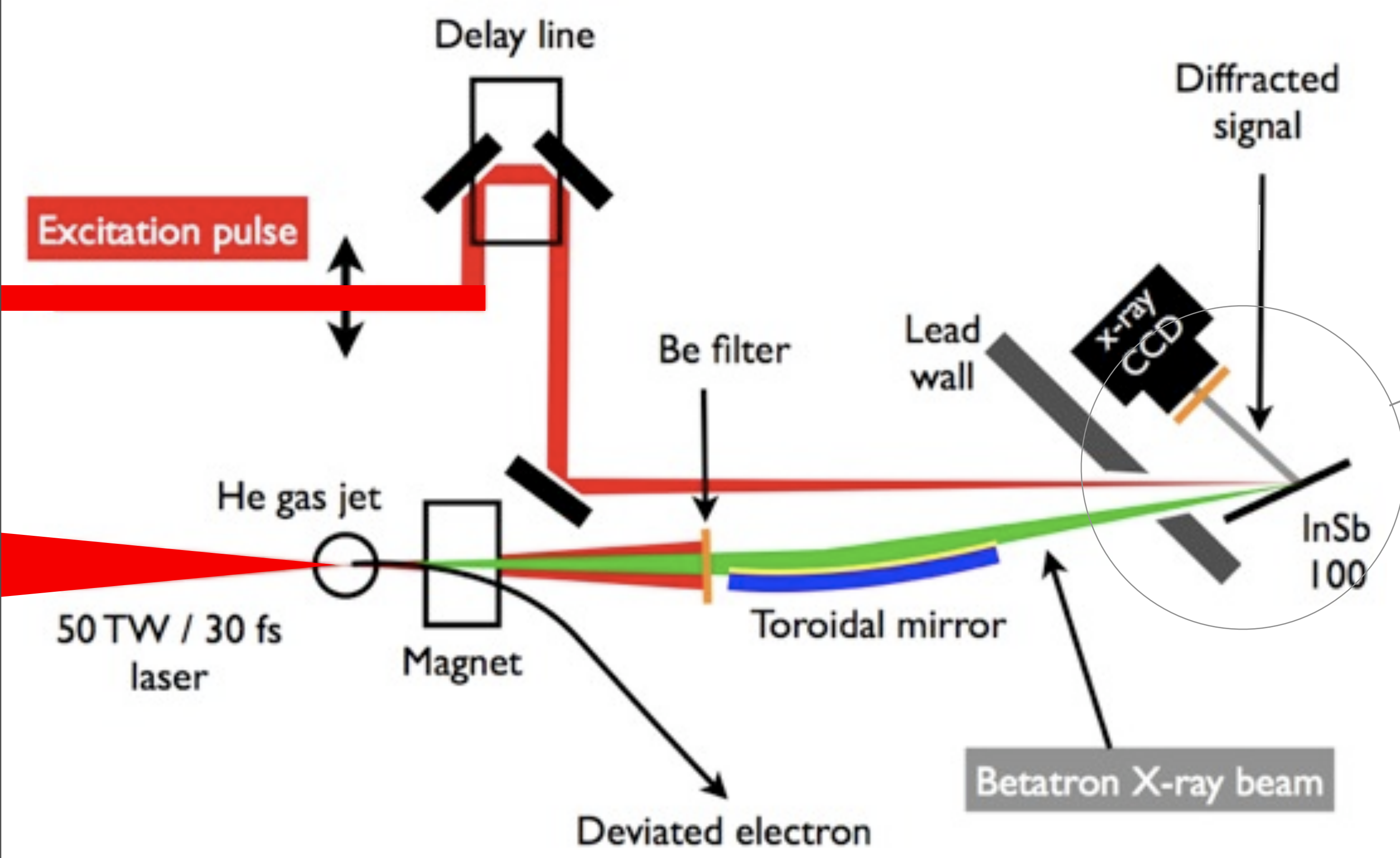
Betatron signal variation with density

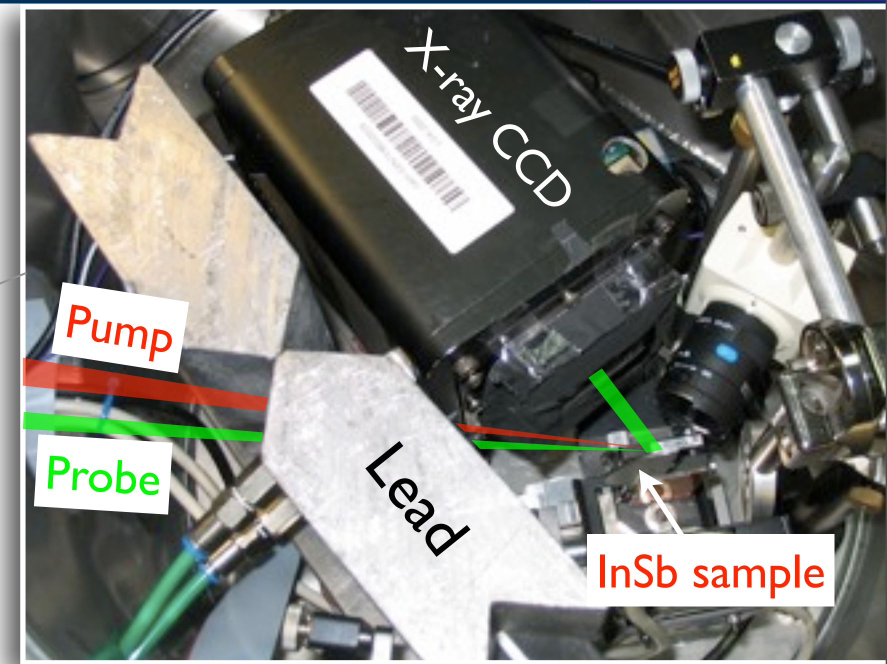




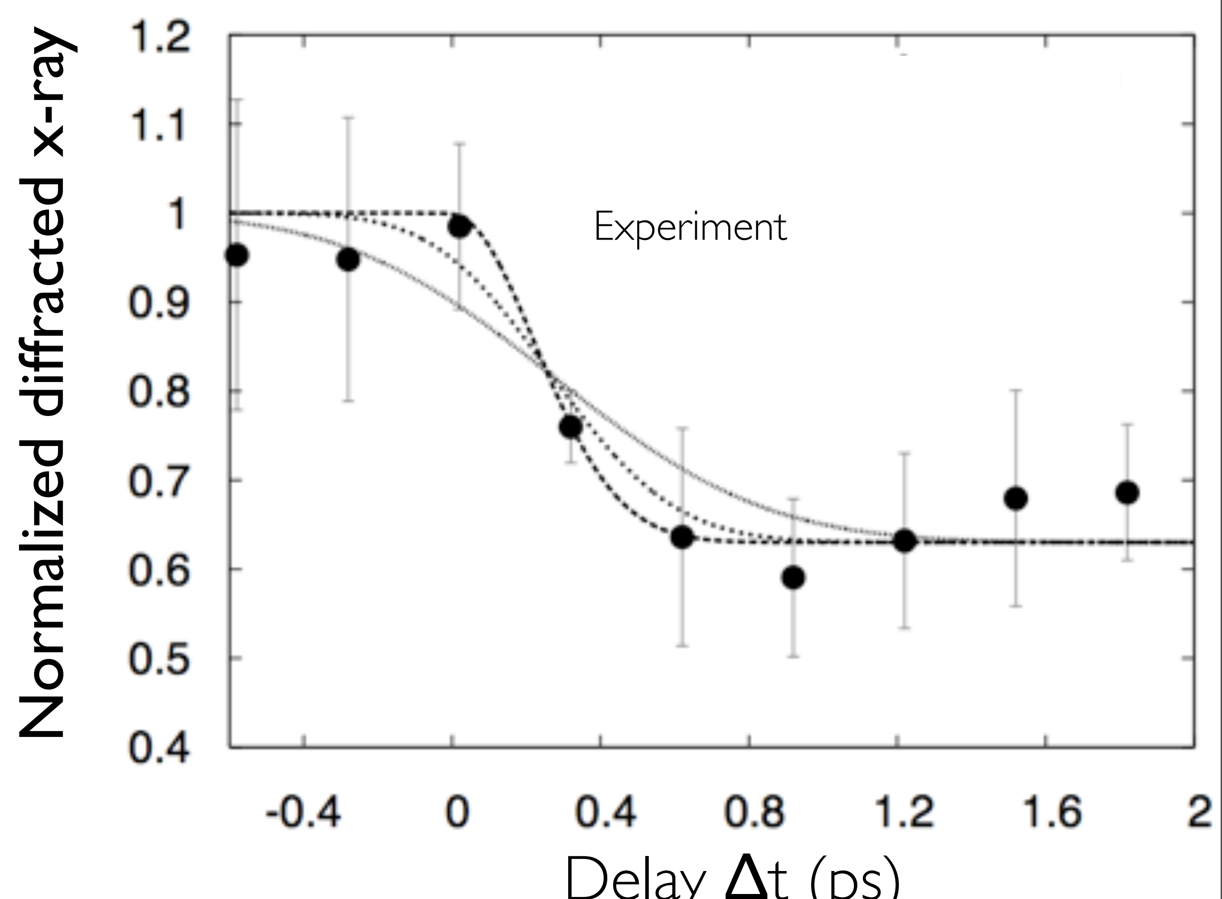
A. Rousse *et al.*, Phys. Rev. Lett., 93, 135005 (2004)

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

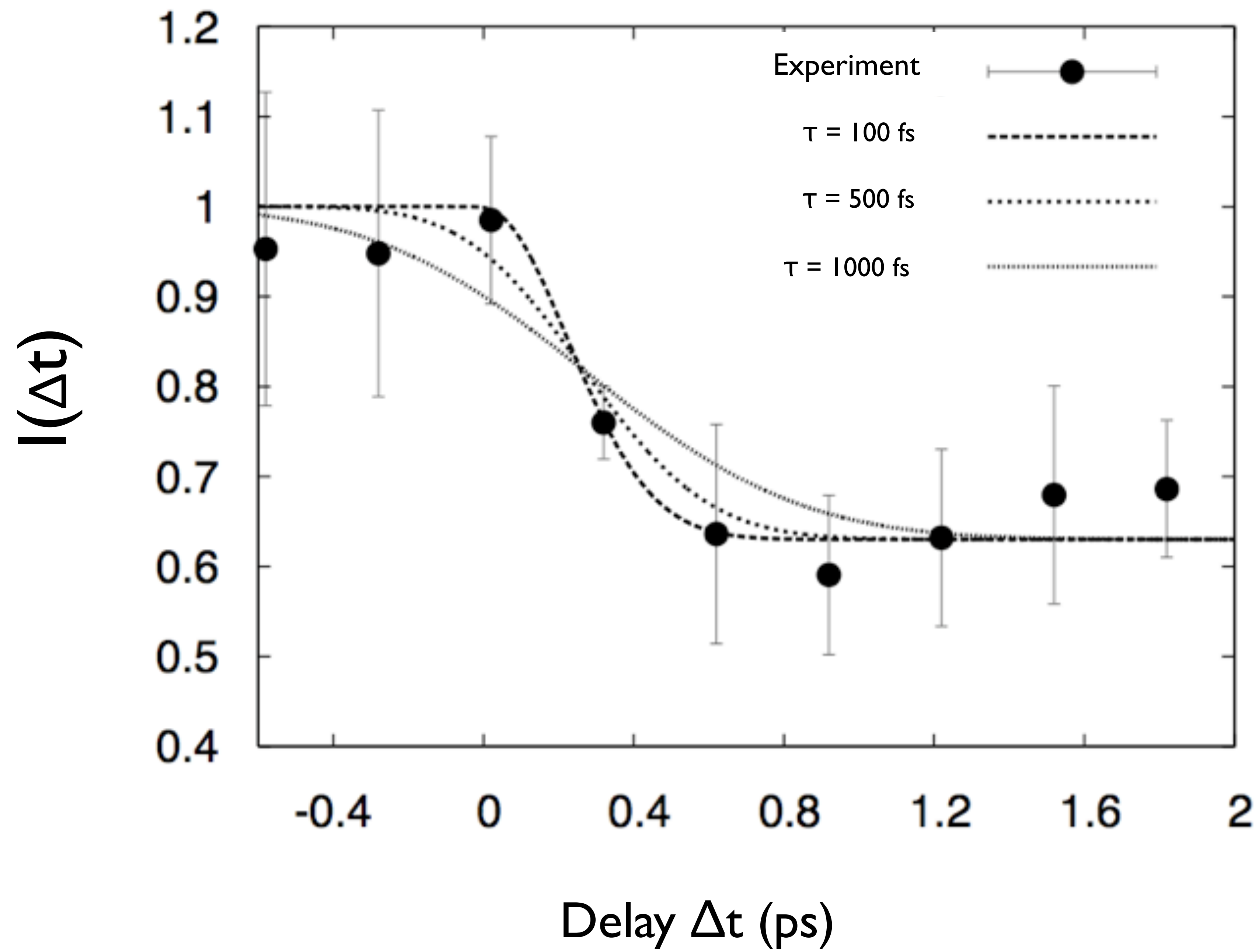




Ultrafast phase transition can be measured with tens fs resolution - limited by shot to shot fluctuations of the source



Estimation of the x-ray pulse duration: results

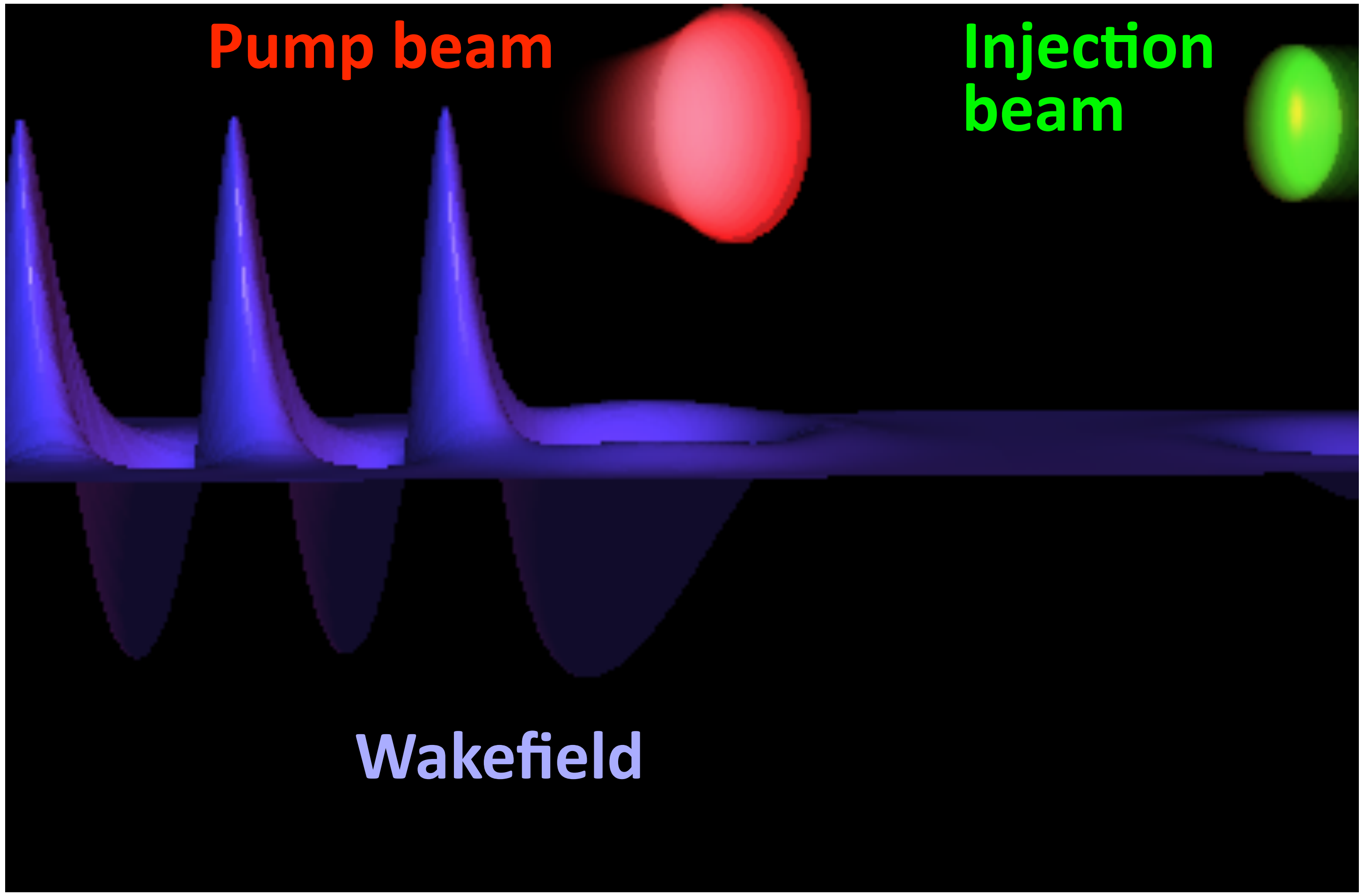


τ < 1 ps • Best fit for τ < 100 fs

K. Ta Phuoc *et al.*, Phys. of Plasmas, 14, 080701 (2007)

Colliding Laser plasma accelerator and Betatron

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)

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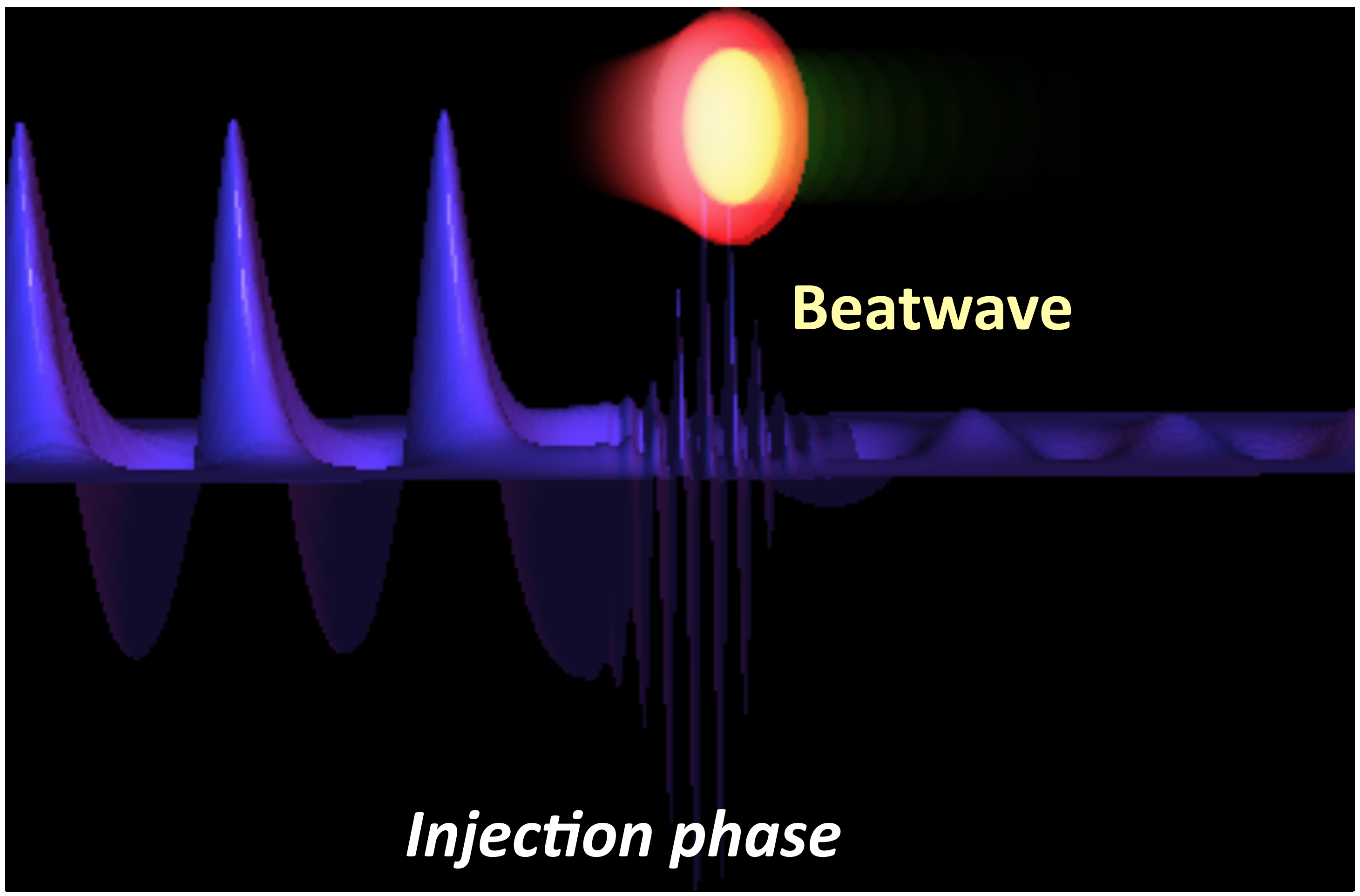

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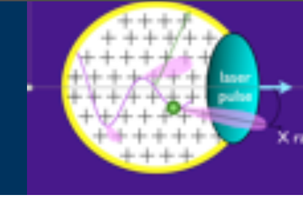

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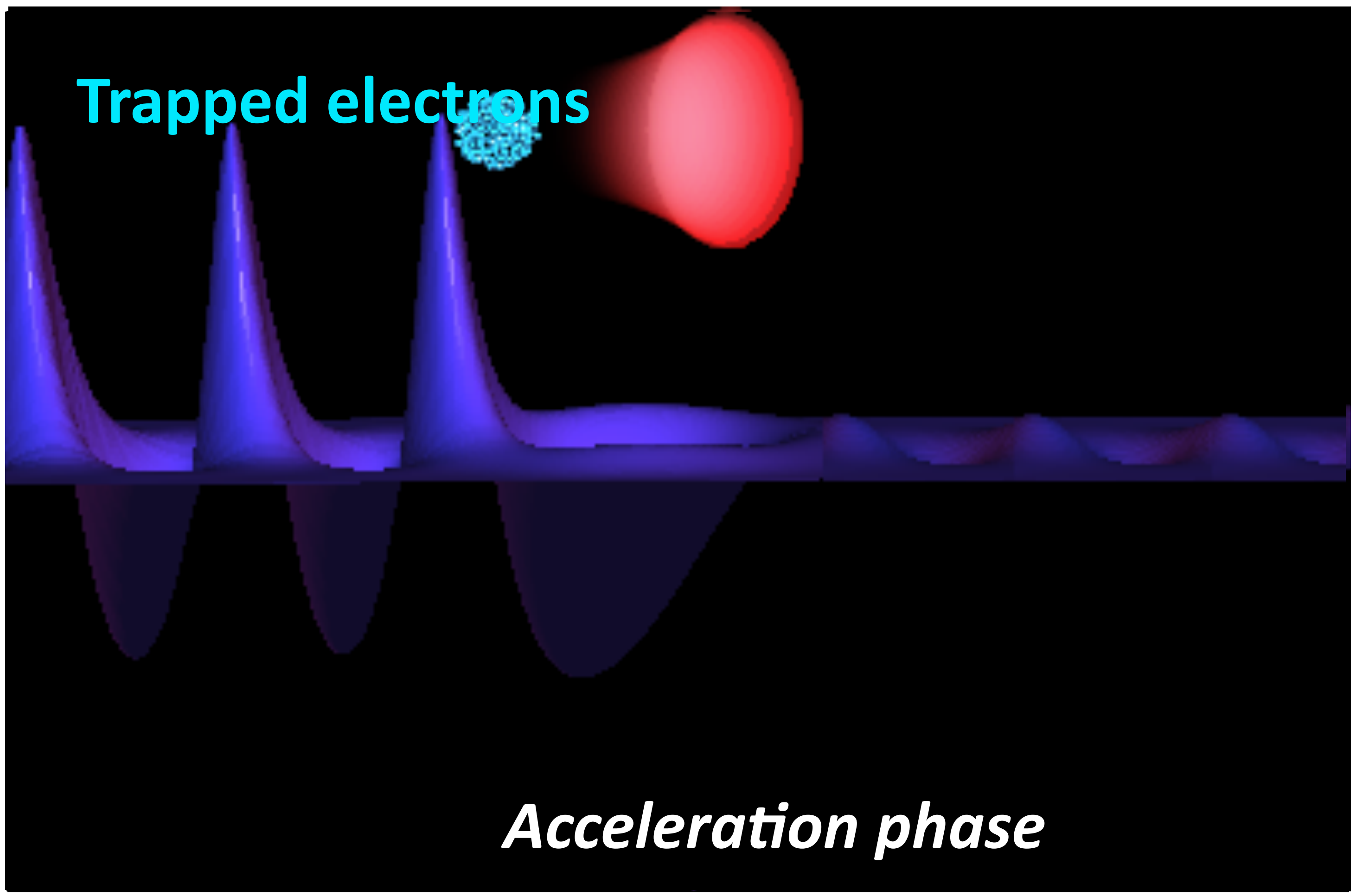

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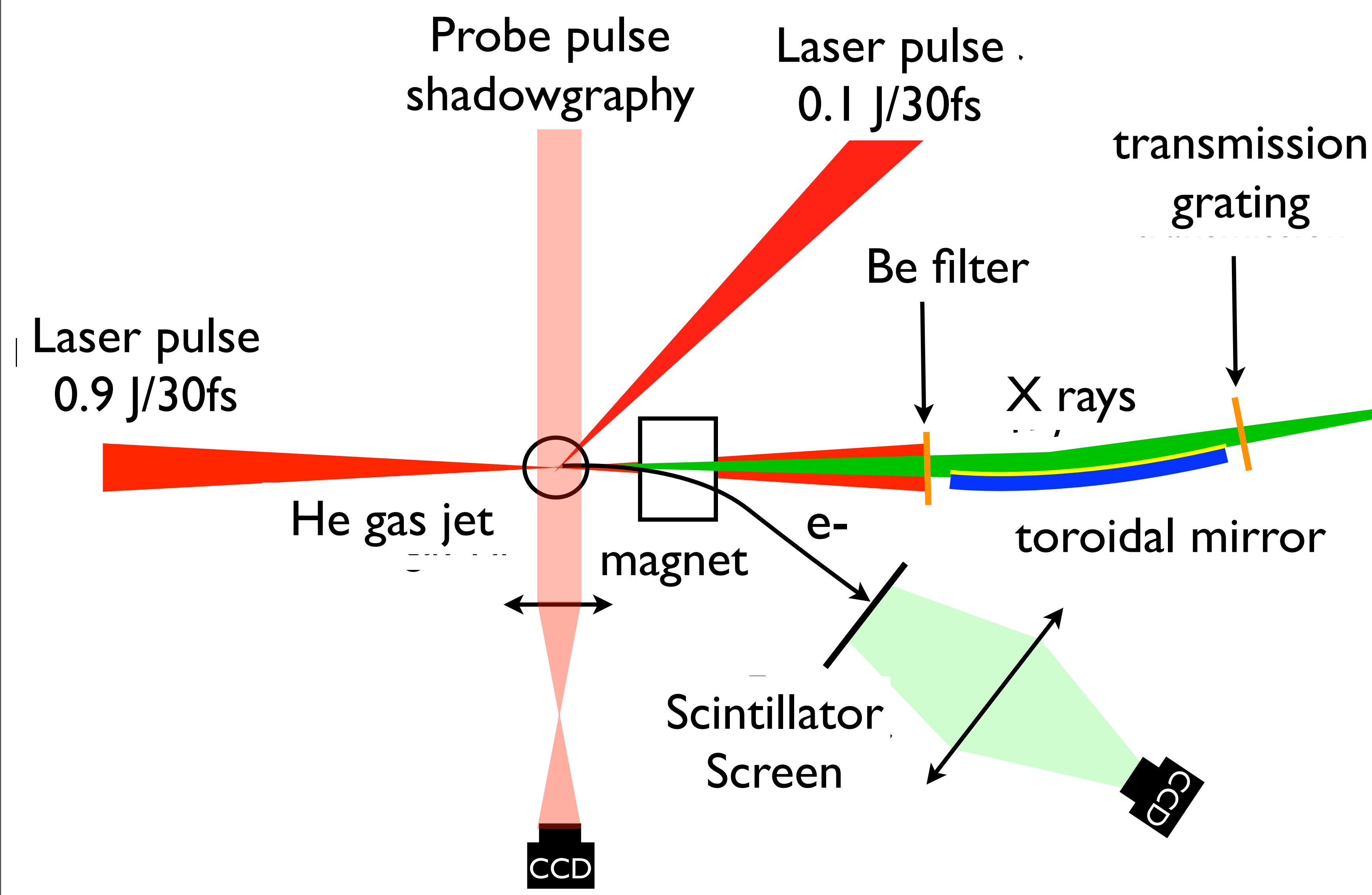
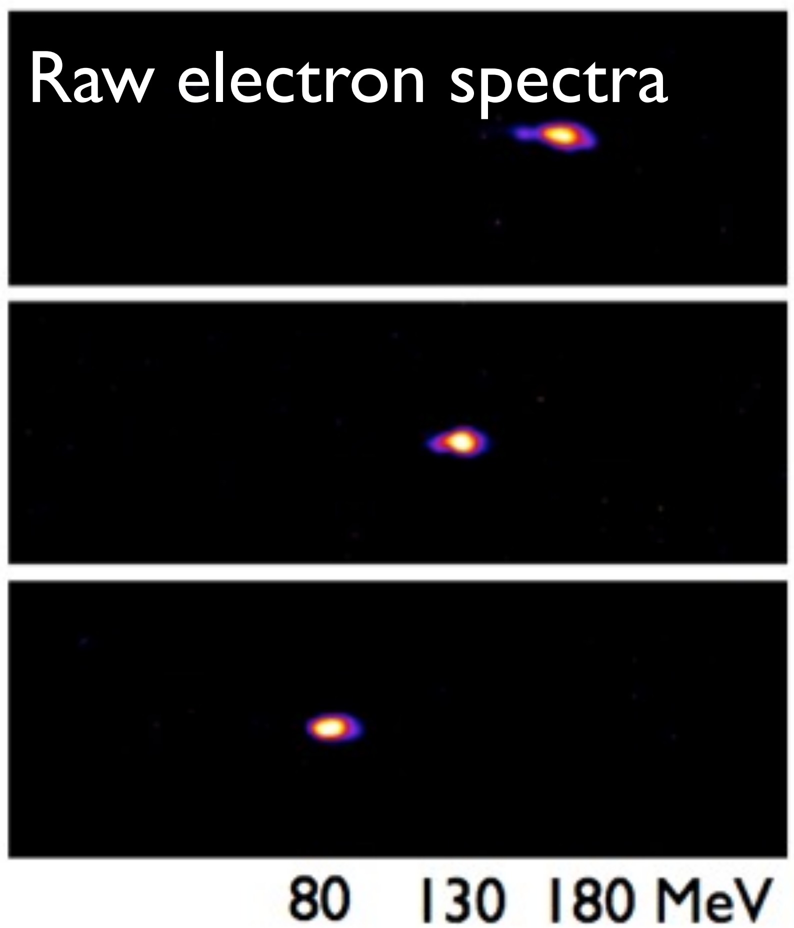
Electron and X ray correlation (LOA experiments)

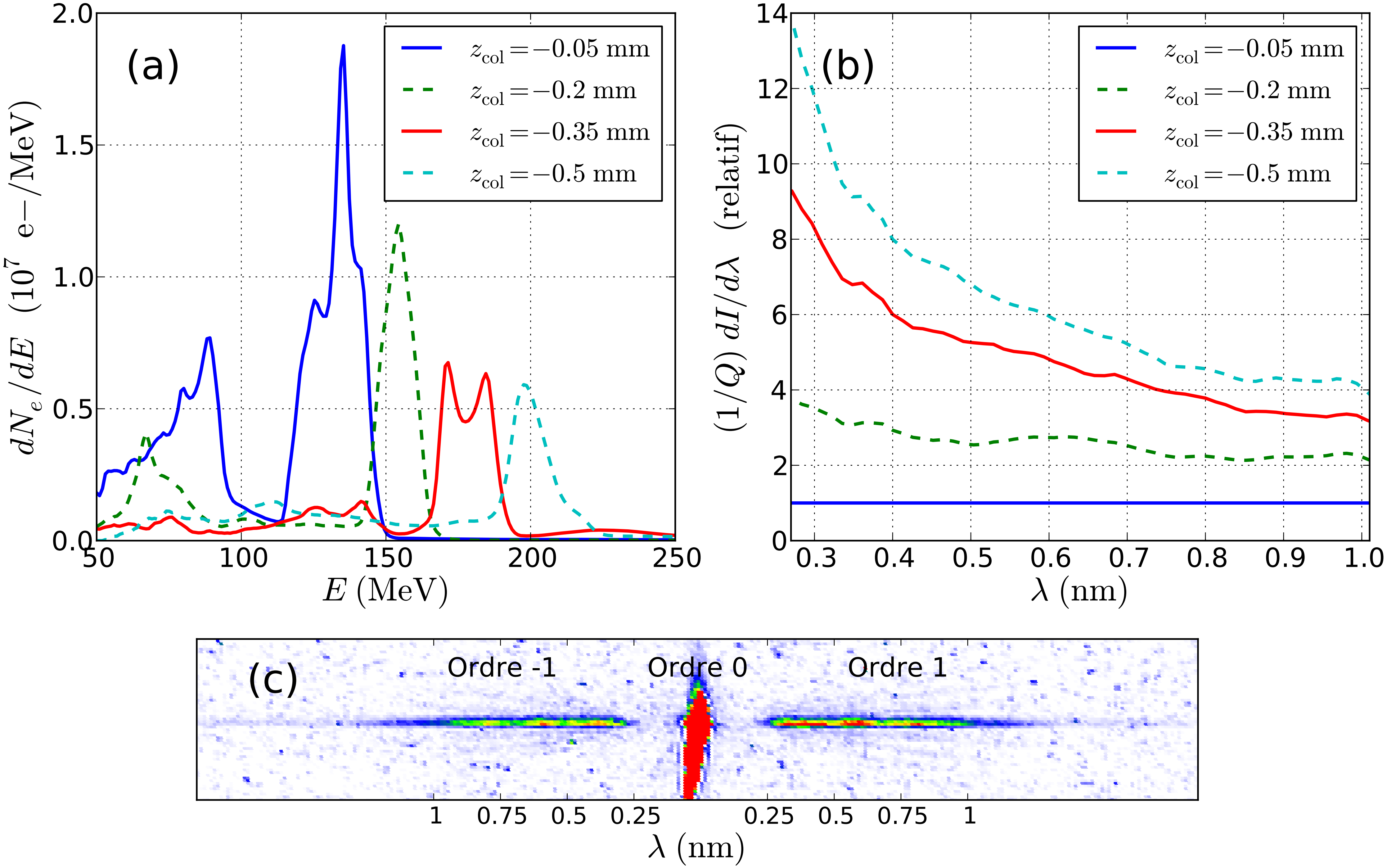


Collision angle :135°
$n_e = 8\times10^{18}$ cm^{-3}



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)



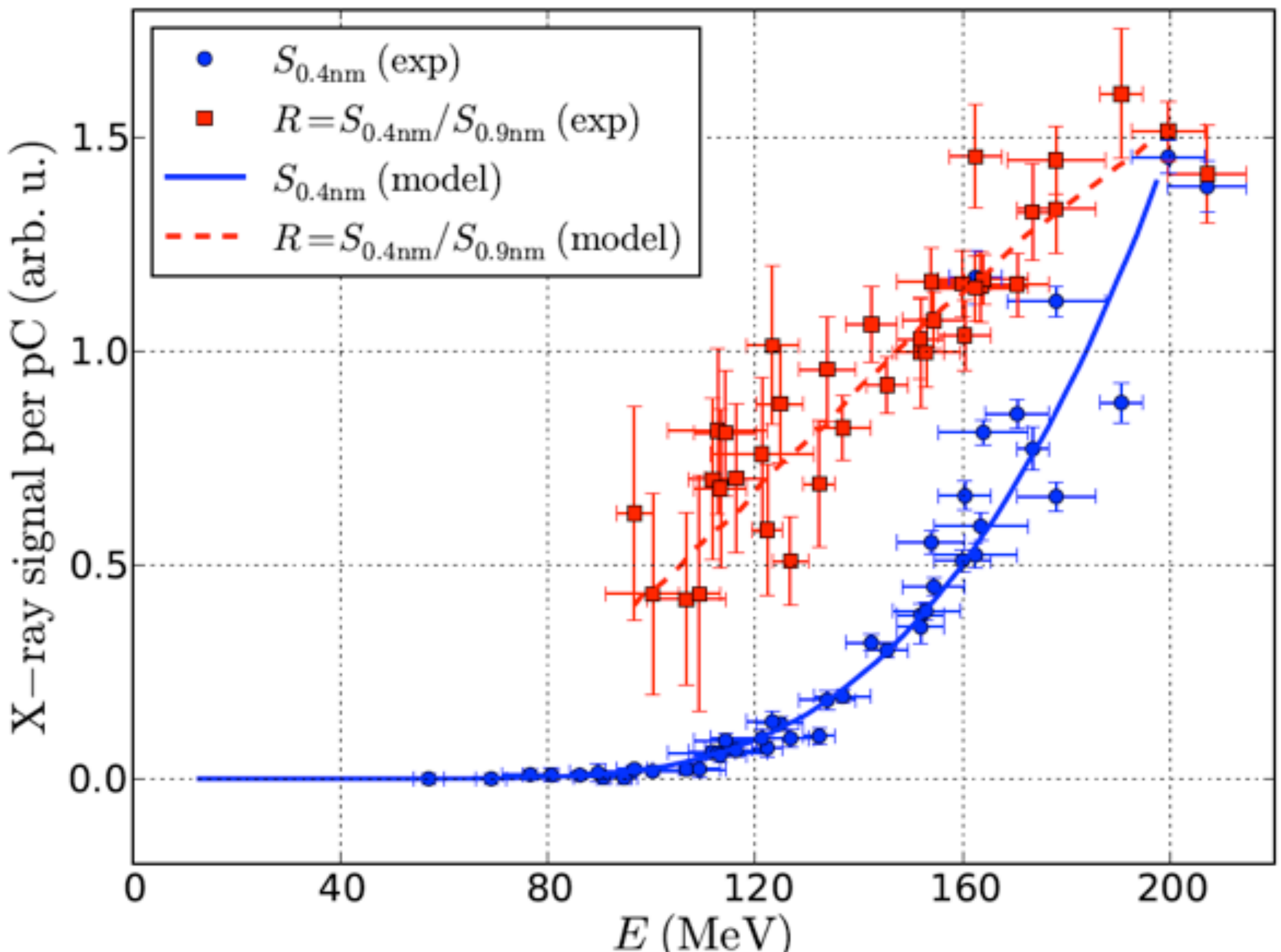
Thanks to the colliding laser pulses scheme, clear correlations between electron beam energy and betatron X ray distribution are observed

Electron and X ray correlation : comparison

The best agreement is obtained for :

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

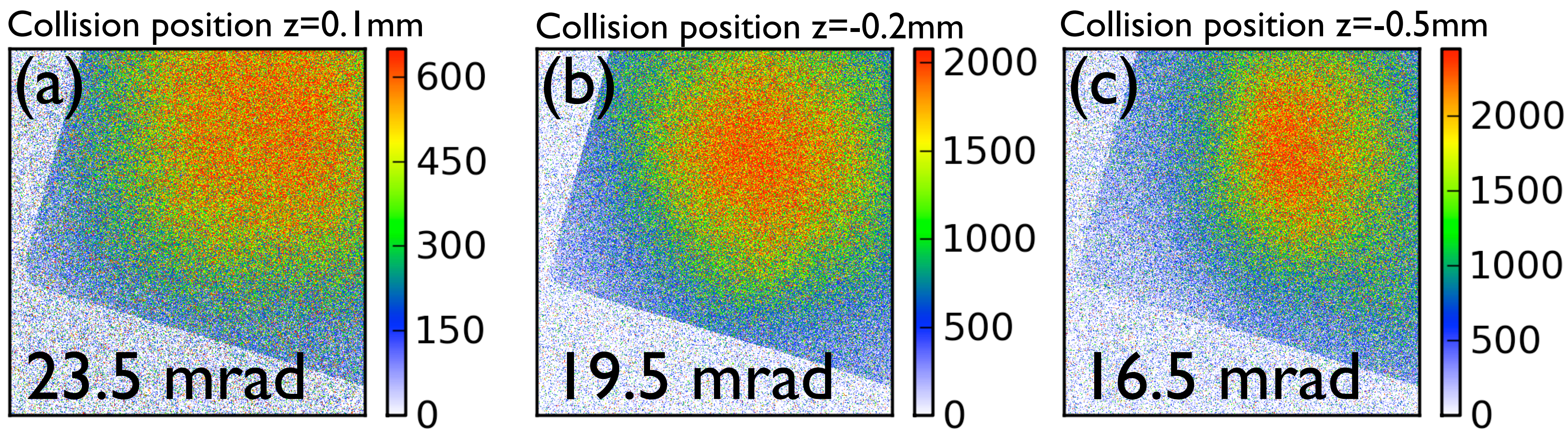
$$(\text{ or } \alpha\sigma = 0.23\ \mu\text{m})$$

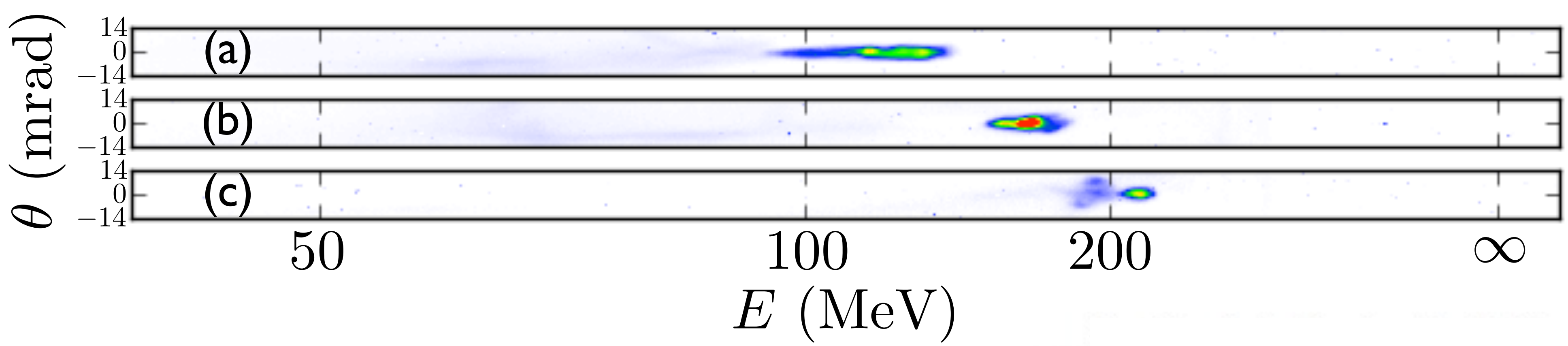


S. Corde *et al.*, Phys. Rev. Lett. **107**, 225003 (2011)

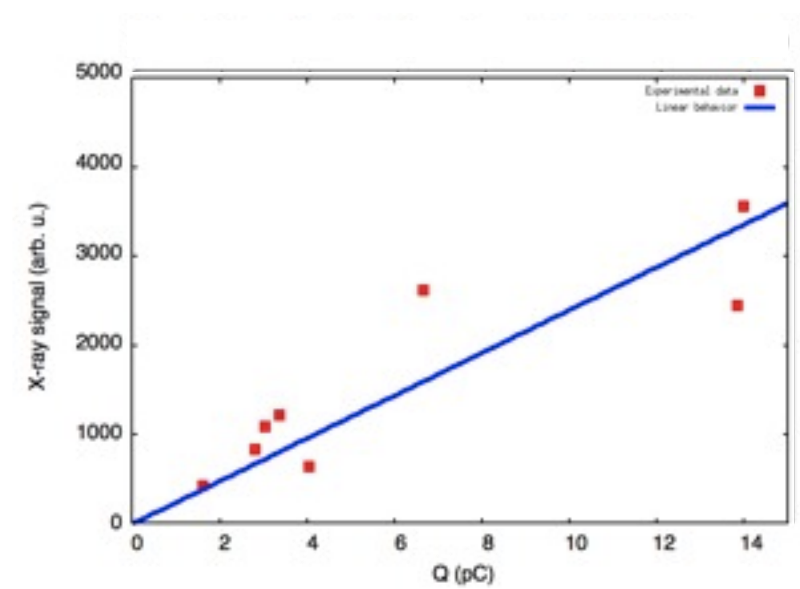
Electron & Xray correlation: divergence and charge

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

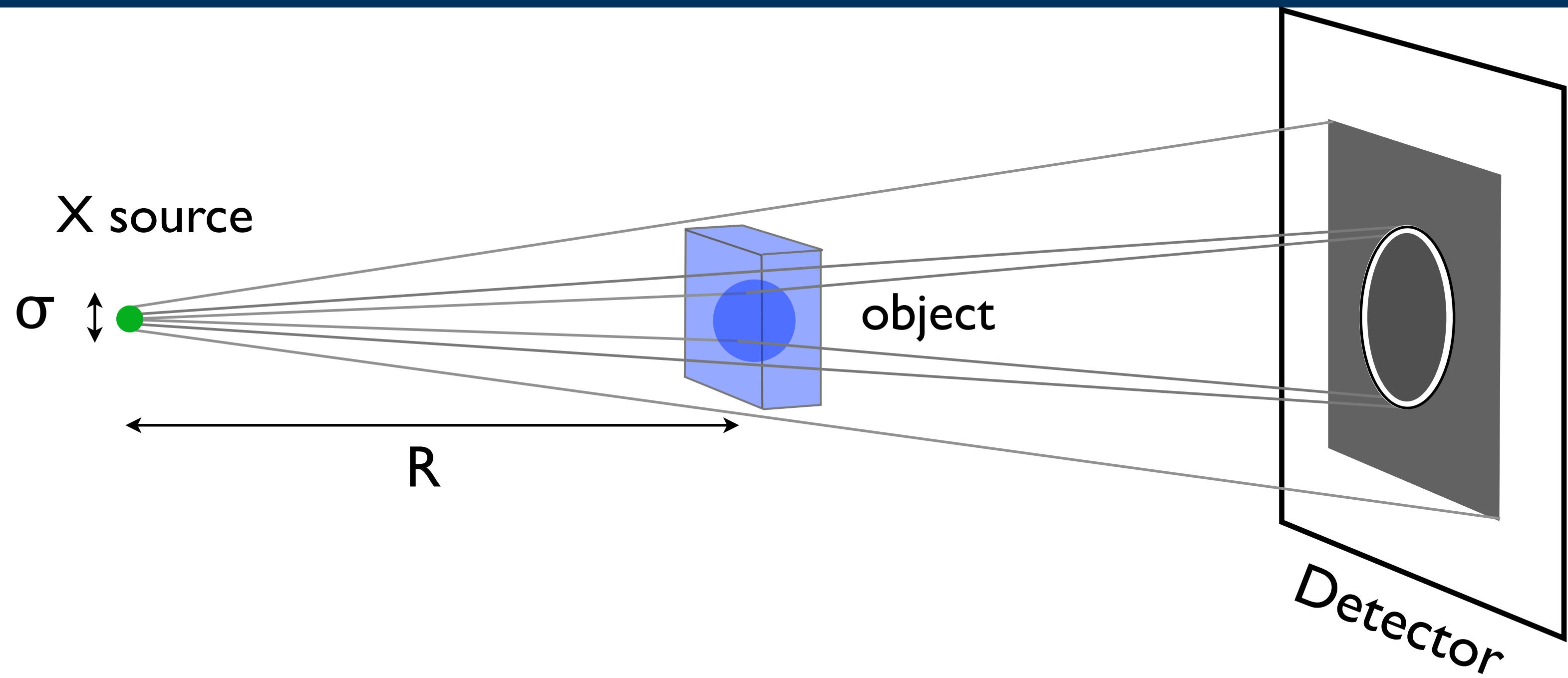




Linear dependency of the X betatron signal with the electron beam charge (for a fixed electron beam energy at ~220 MeV)



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

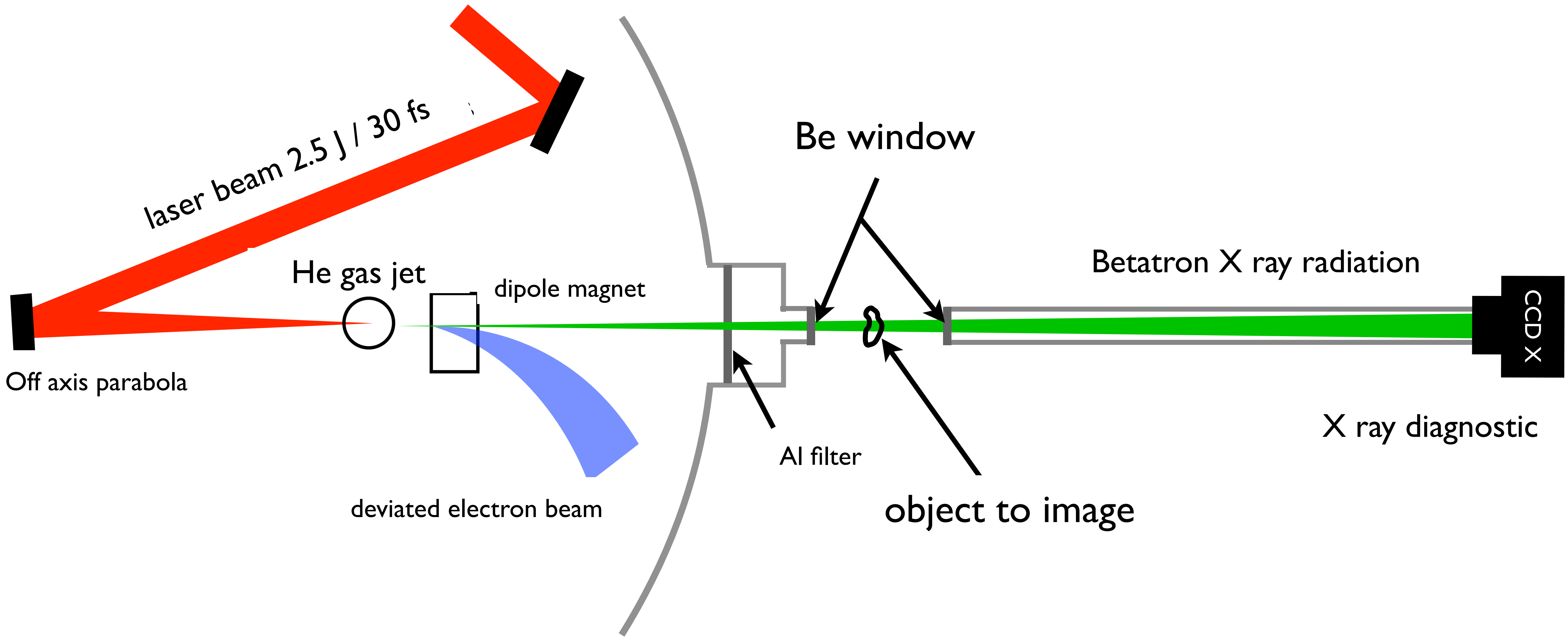
- **Phase contrast**

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 :

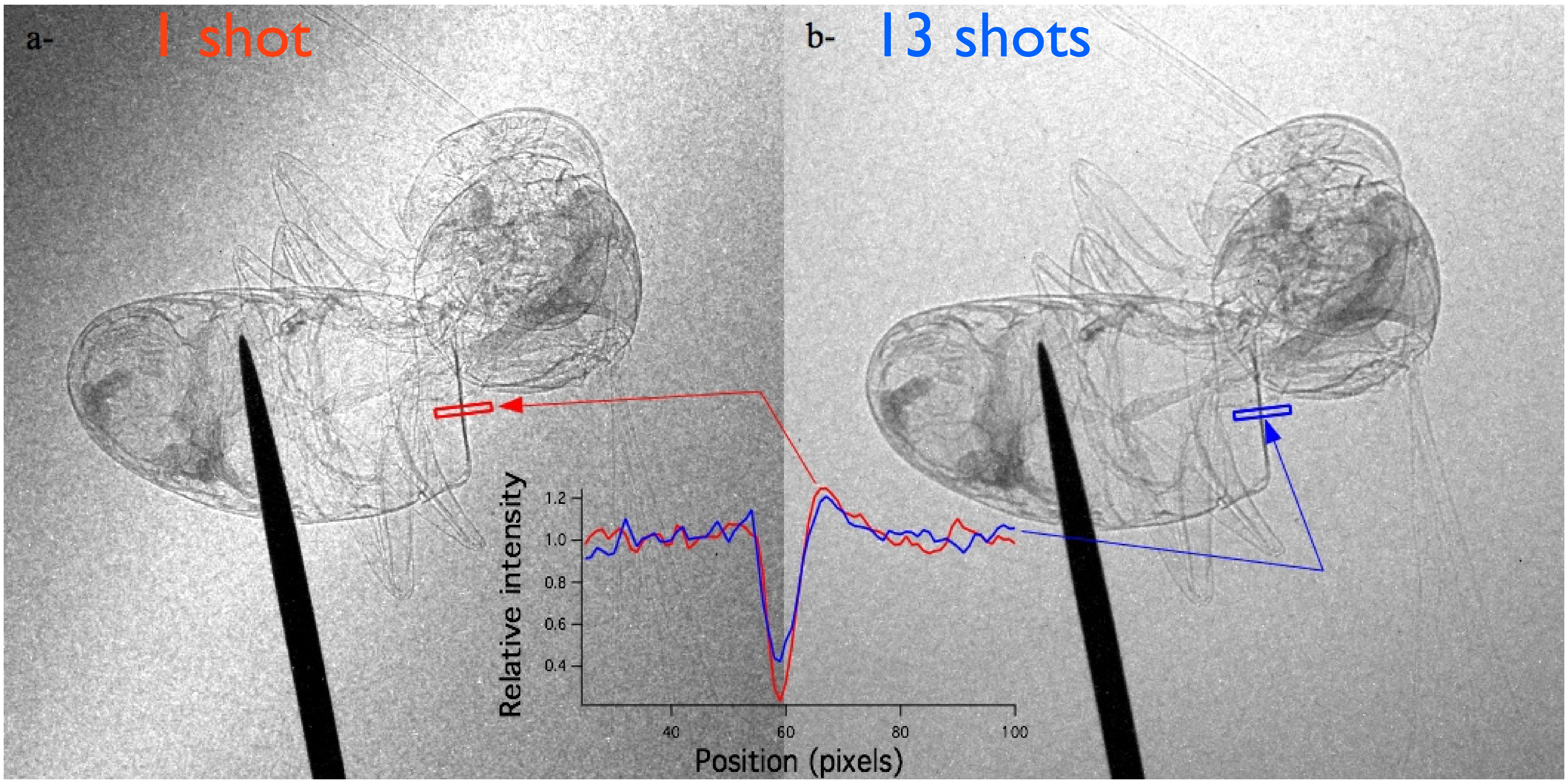
- E_c = 12.3 keV
- 2.2×10^8 photons/0.1%BW/sr/shot at 10 keV
- N = 10^9 photons in 28 mrad (FWHM) divergence beam

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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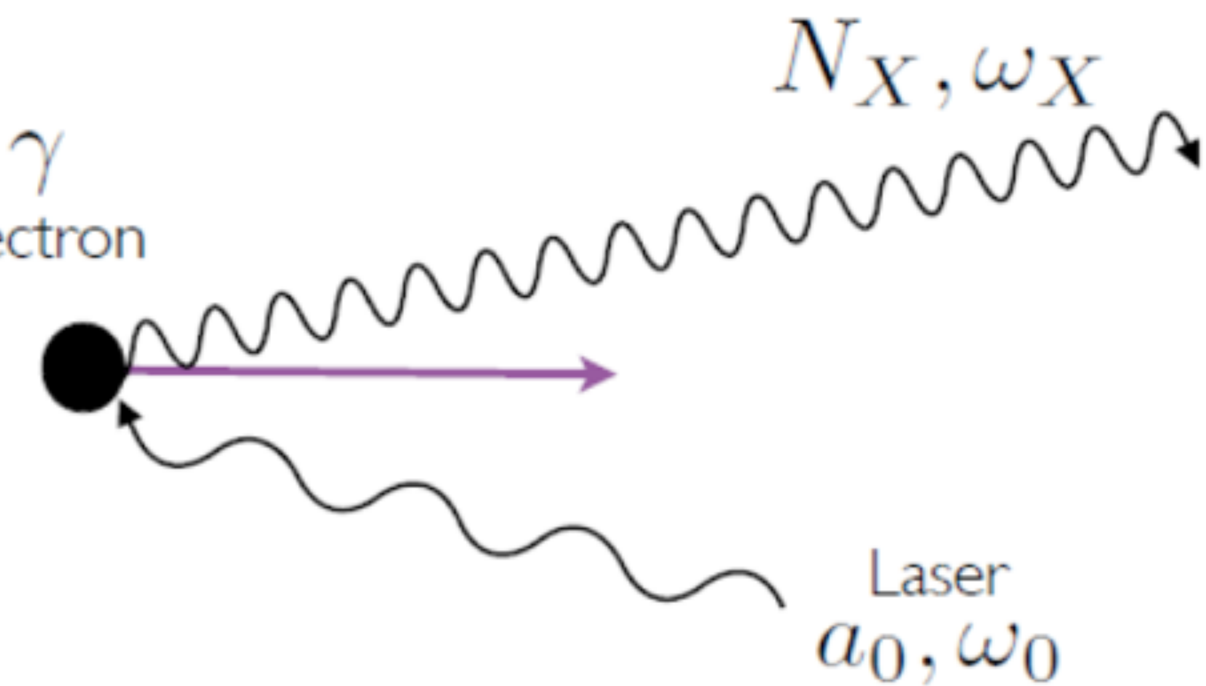


Doppler upshift : high energy photons with modest electrons energy : $\omega_x = 4\gamma^2\omega_0$

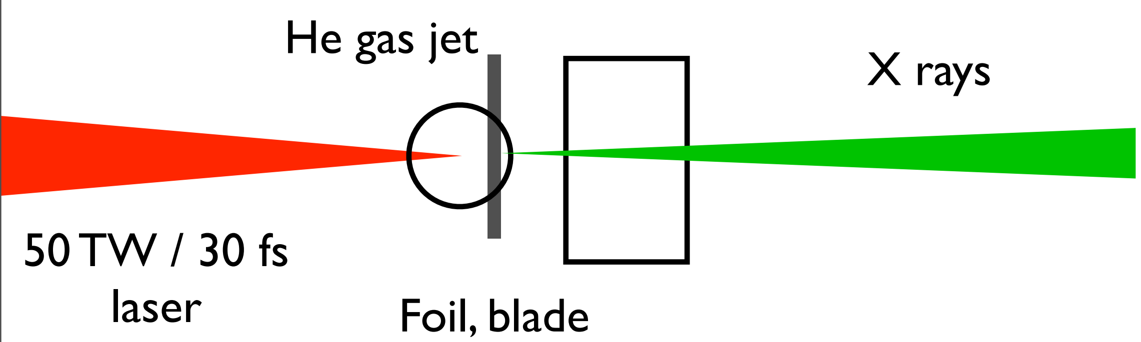
For example : 20 MeV electrons can produce 10 keV photons
200 MeV electrons can produce 1 MeV photons

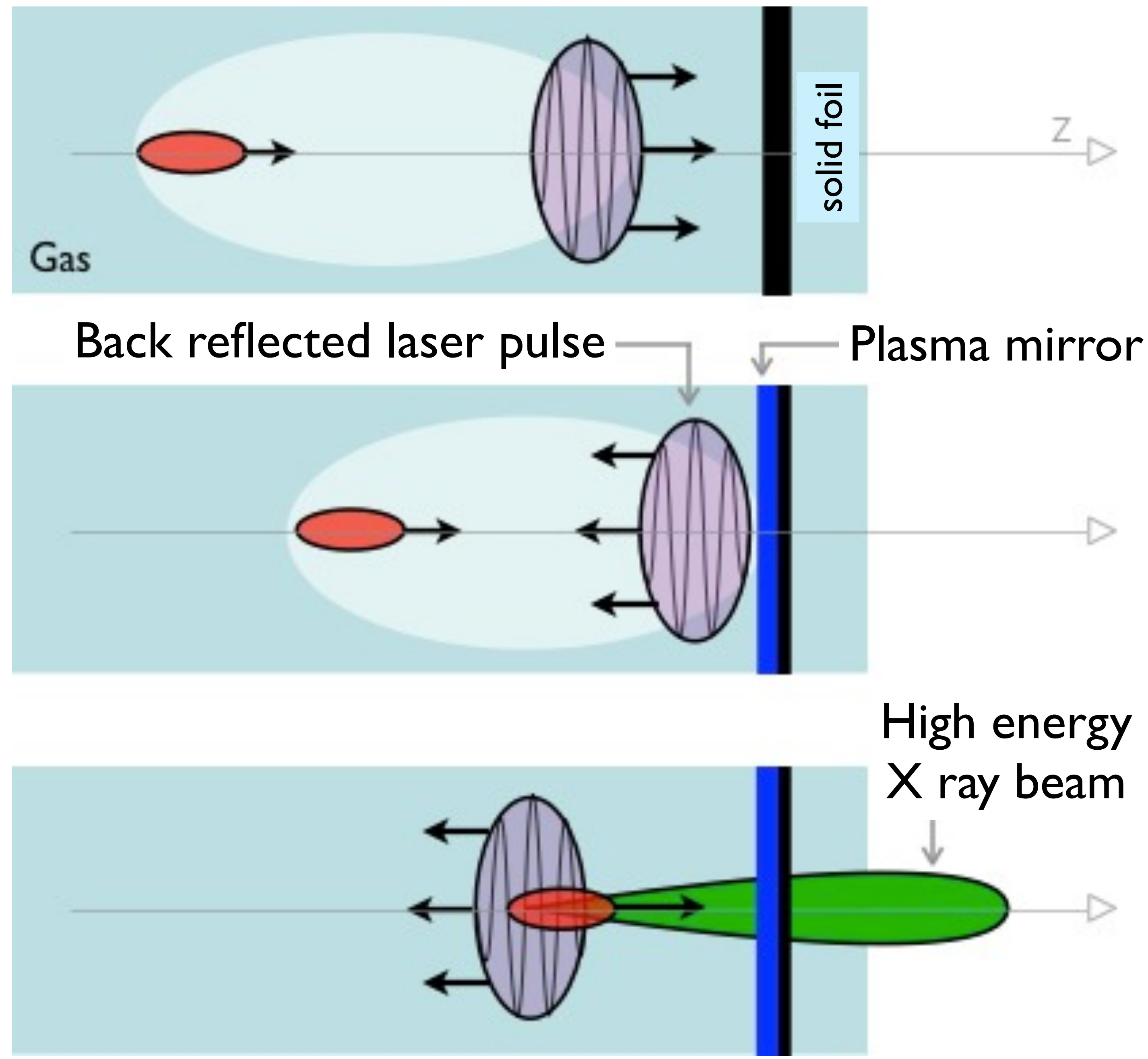
The number of photons depends on the electron charge N_e and a_0^2 : $N_x \propto a_0^2 \times N_e$

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

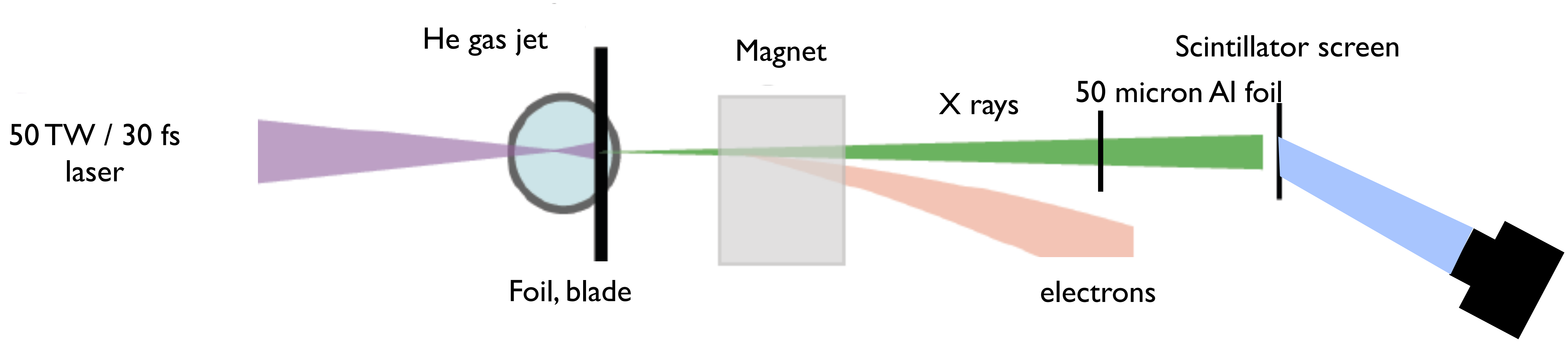
A plasma mirror reflects the laser beam

The back reflected laser collides with the accelerated electrons

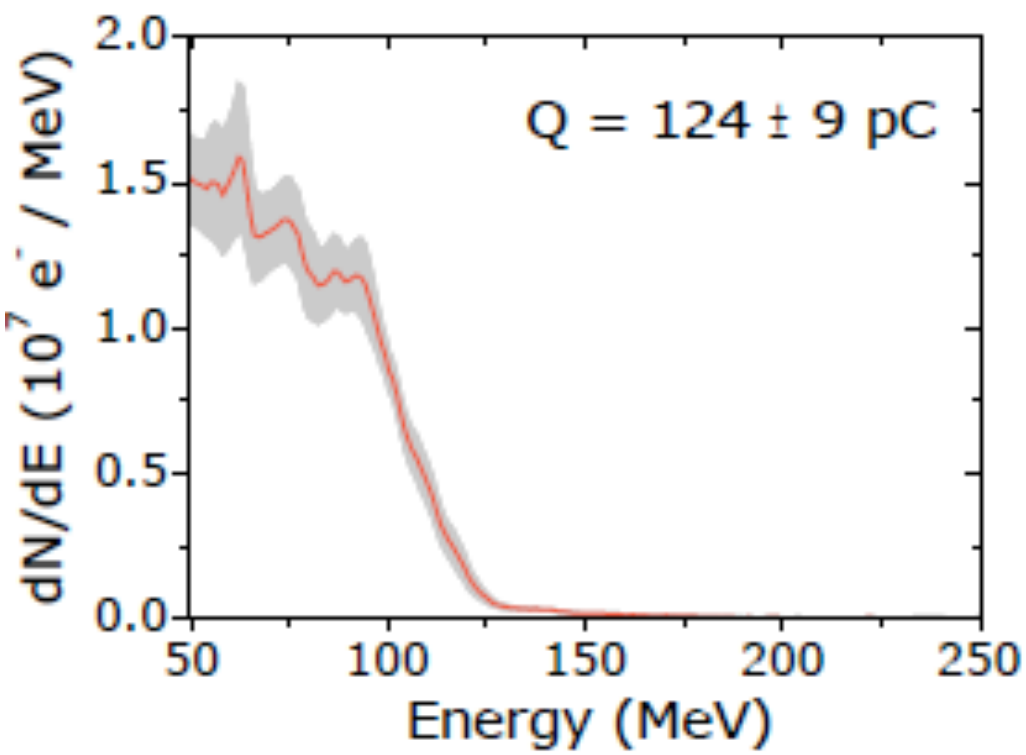
No alignement : the laser and the electron beams naturally overlap

Save the laser energy !

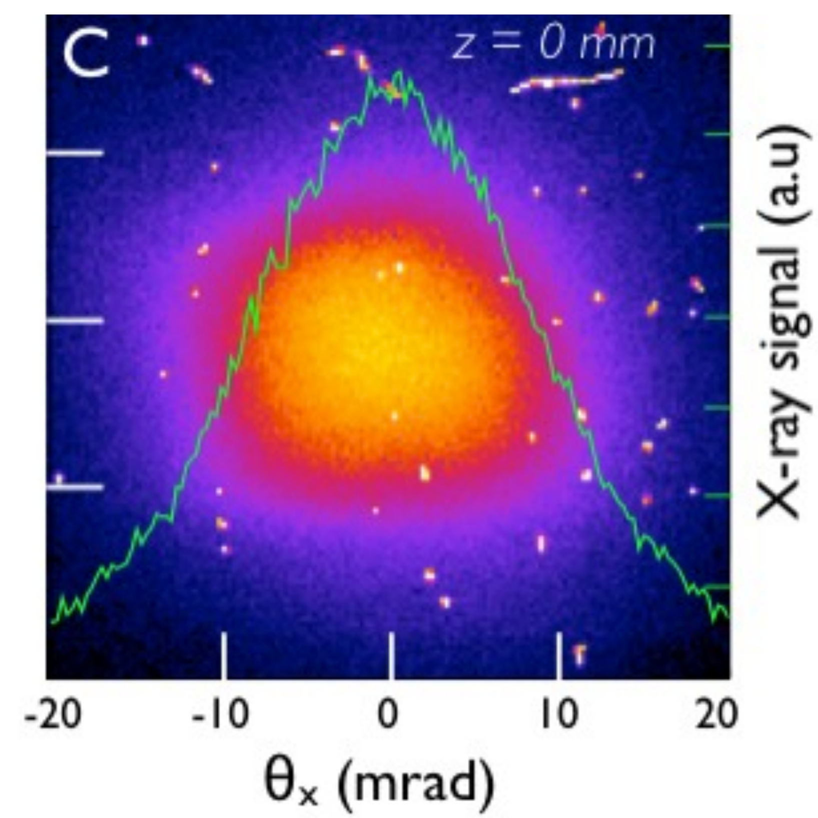
Inverse Compton Scattering : Experimental set-up



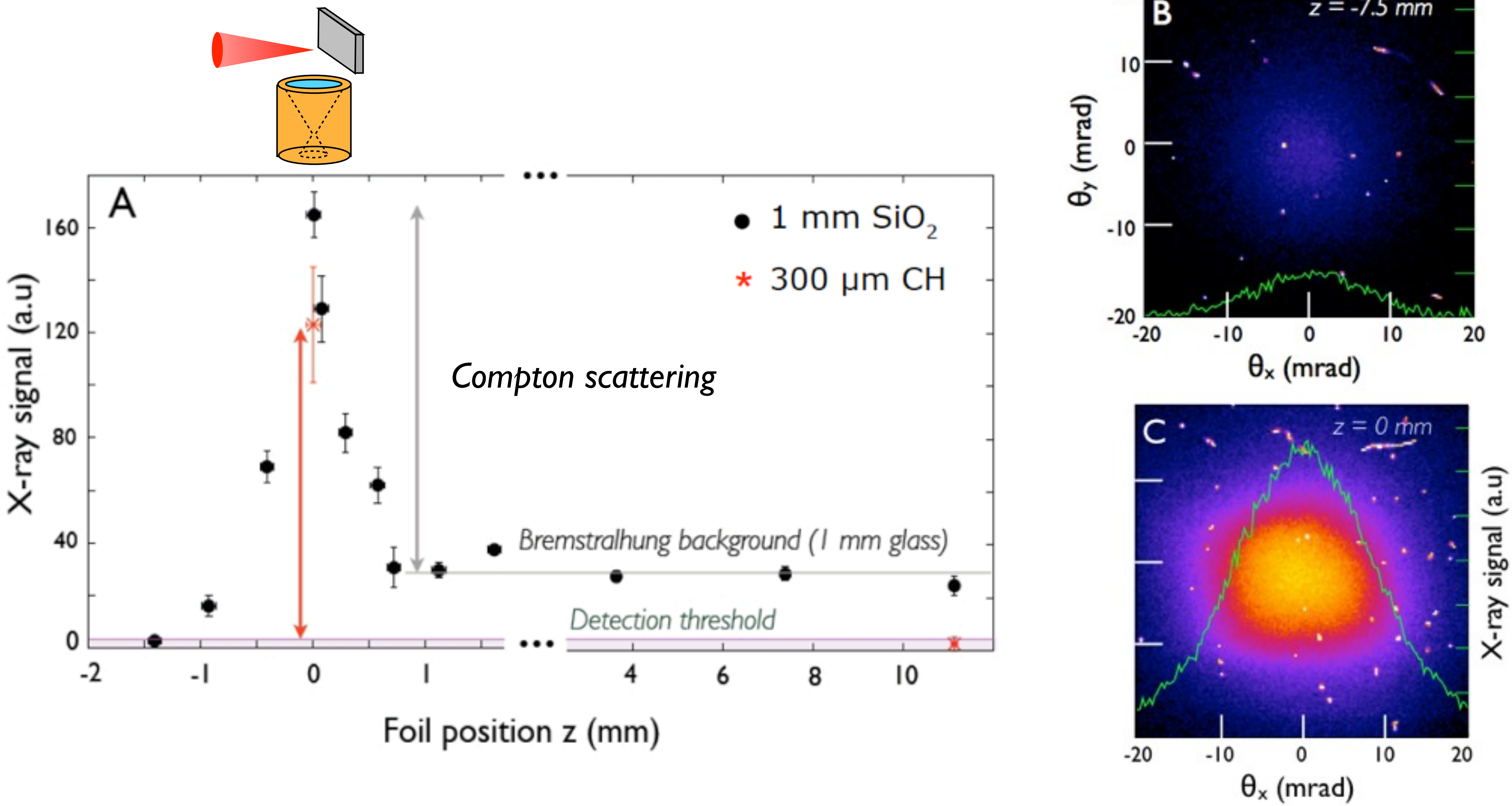
Electron spectra



X ray beam profile

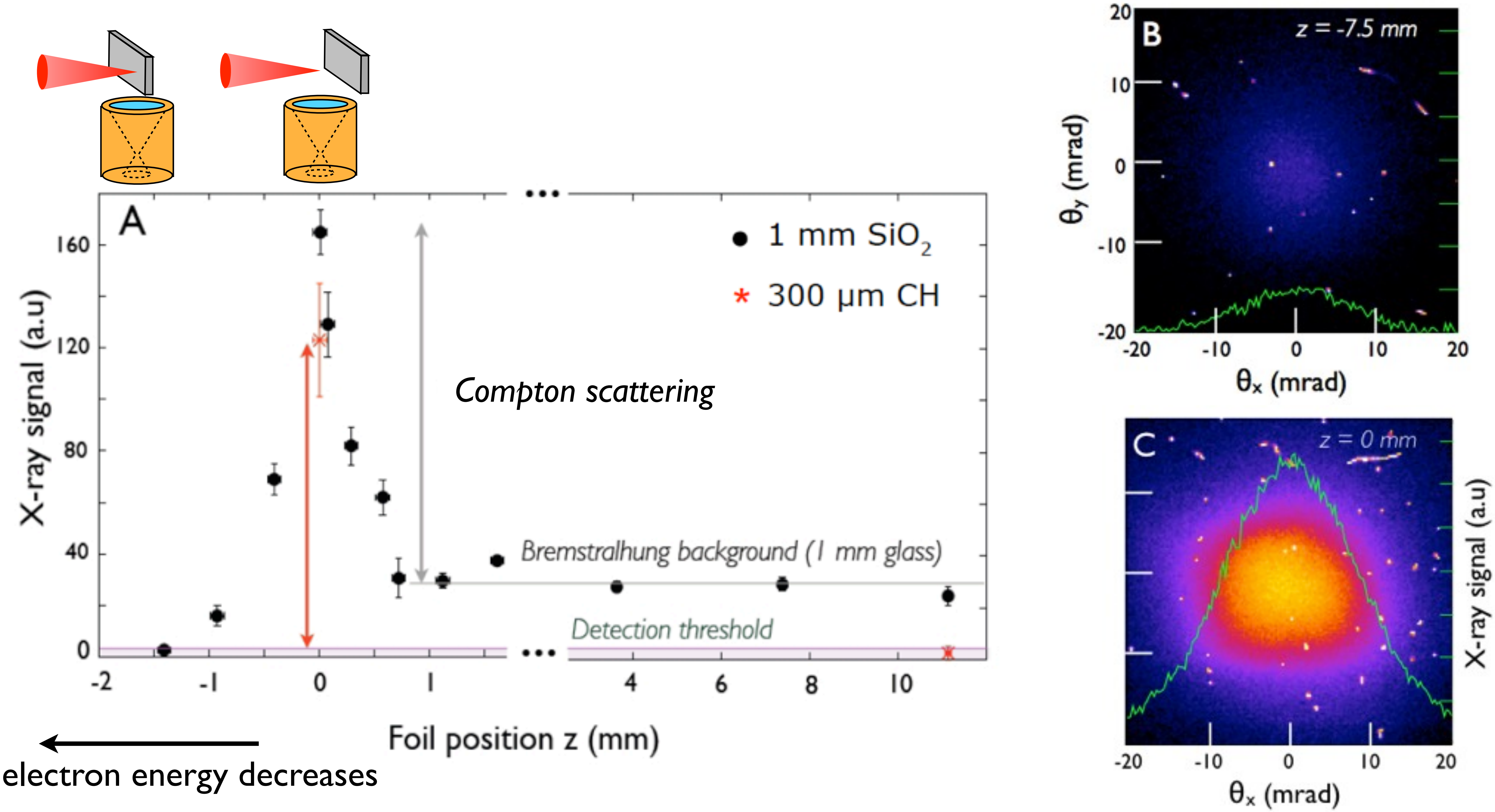


Inverse Compton Scattering : Experimental results



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

Inverse Compton Scattering : Experimental results



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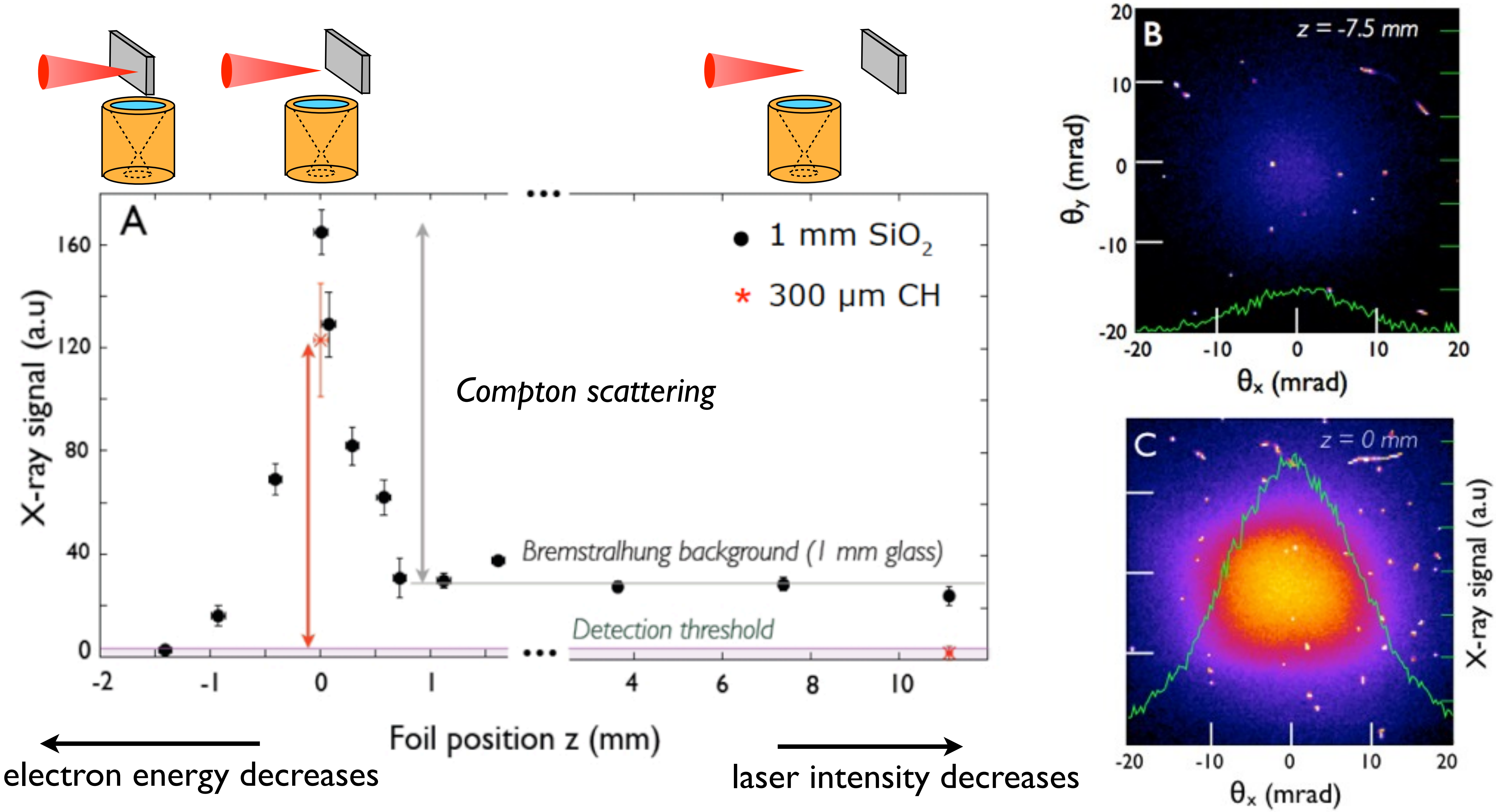

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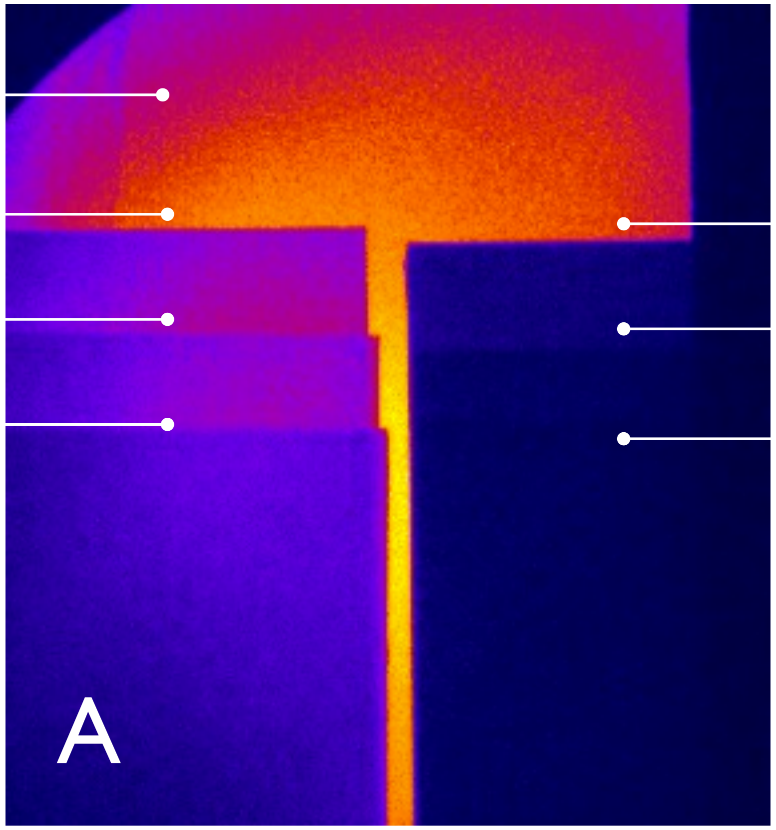
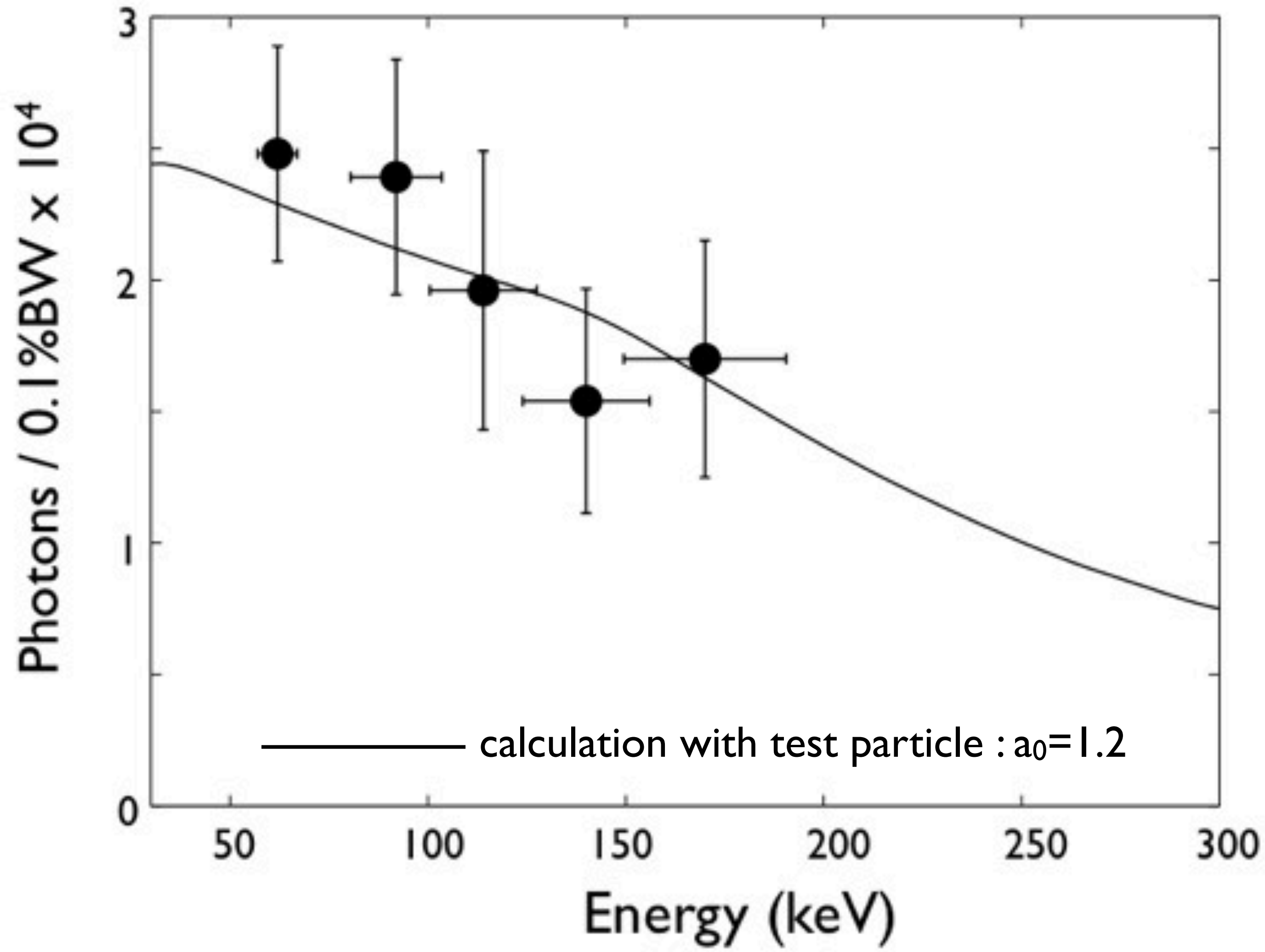
Inverse Compton Scattering : Compton Spectra

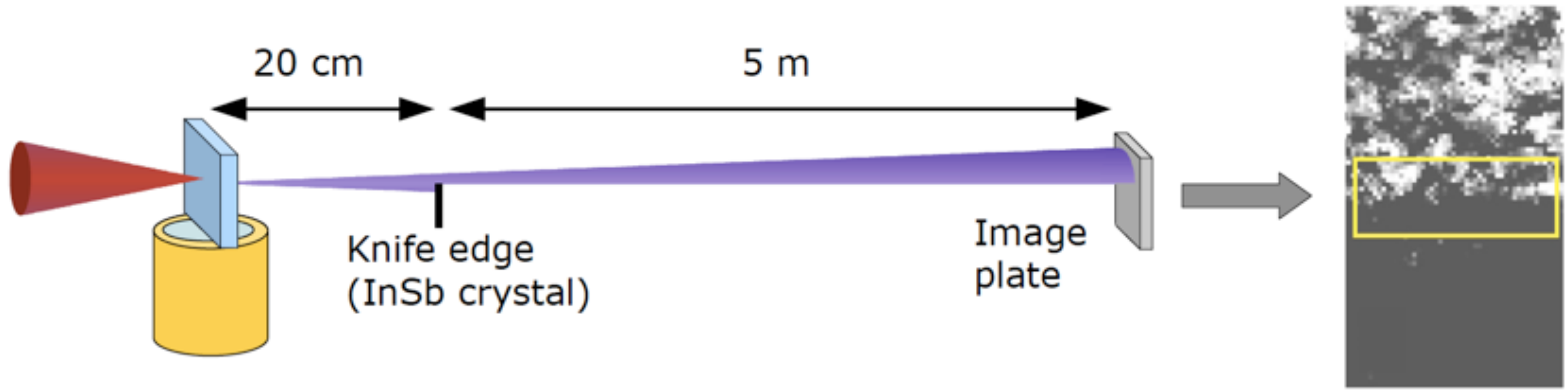


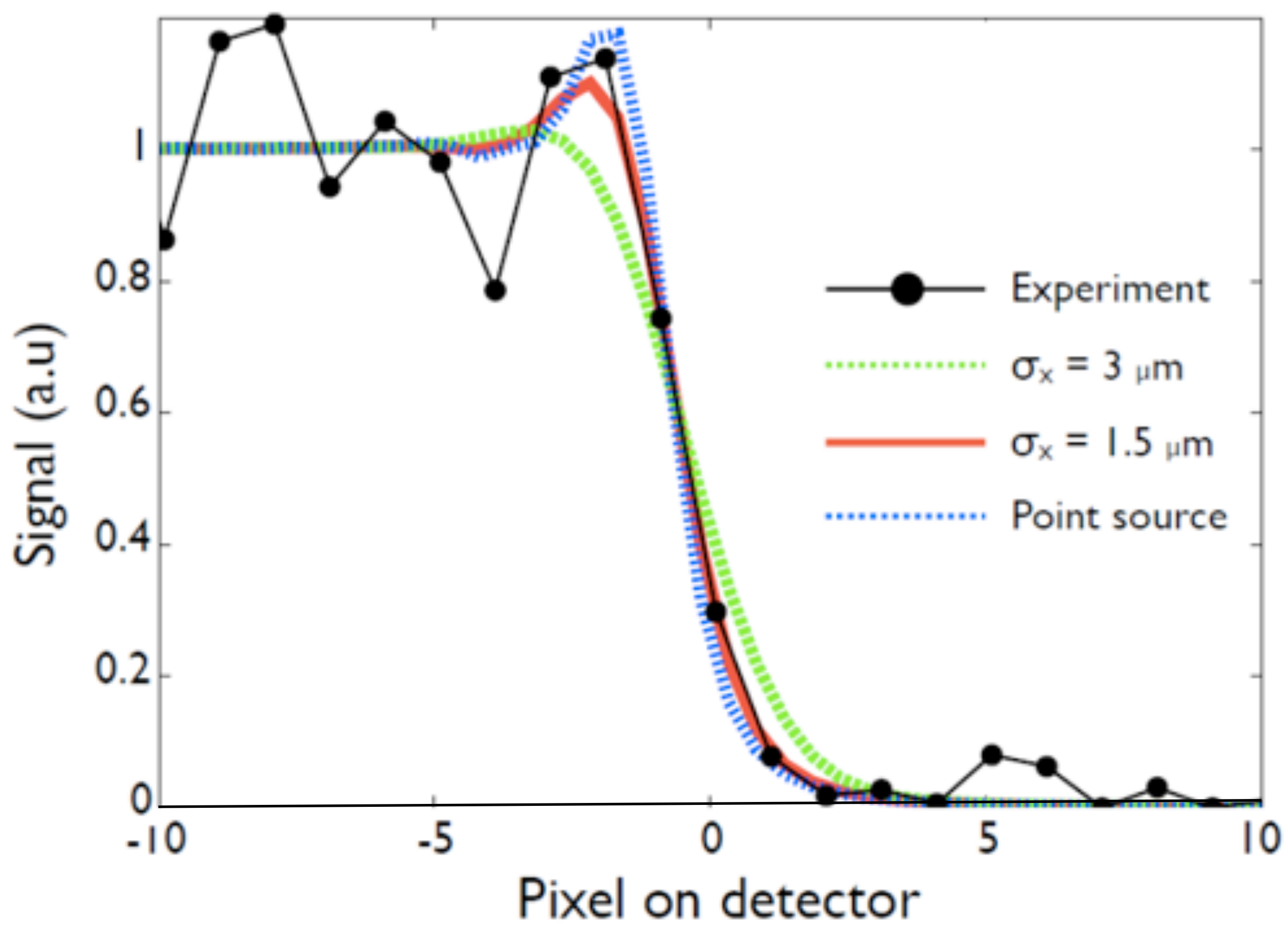


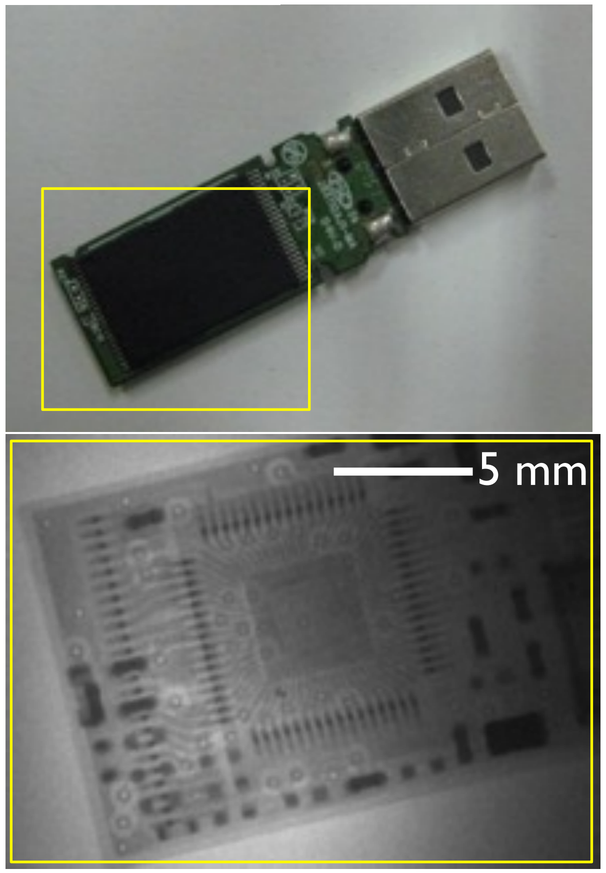
- About 10^8 ph/shot, a few 10^4 ph/shot/0.1%BW@100 keV
- Broad electron spectrum => broad X ray spectra
- Brigthness: 10^{21} ph/s/mm²/mrad²/0.1%BW @100 keV

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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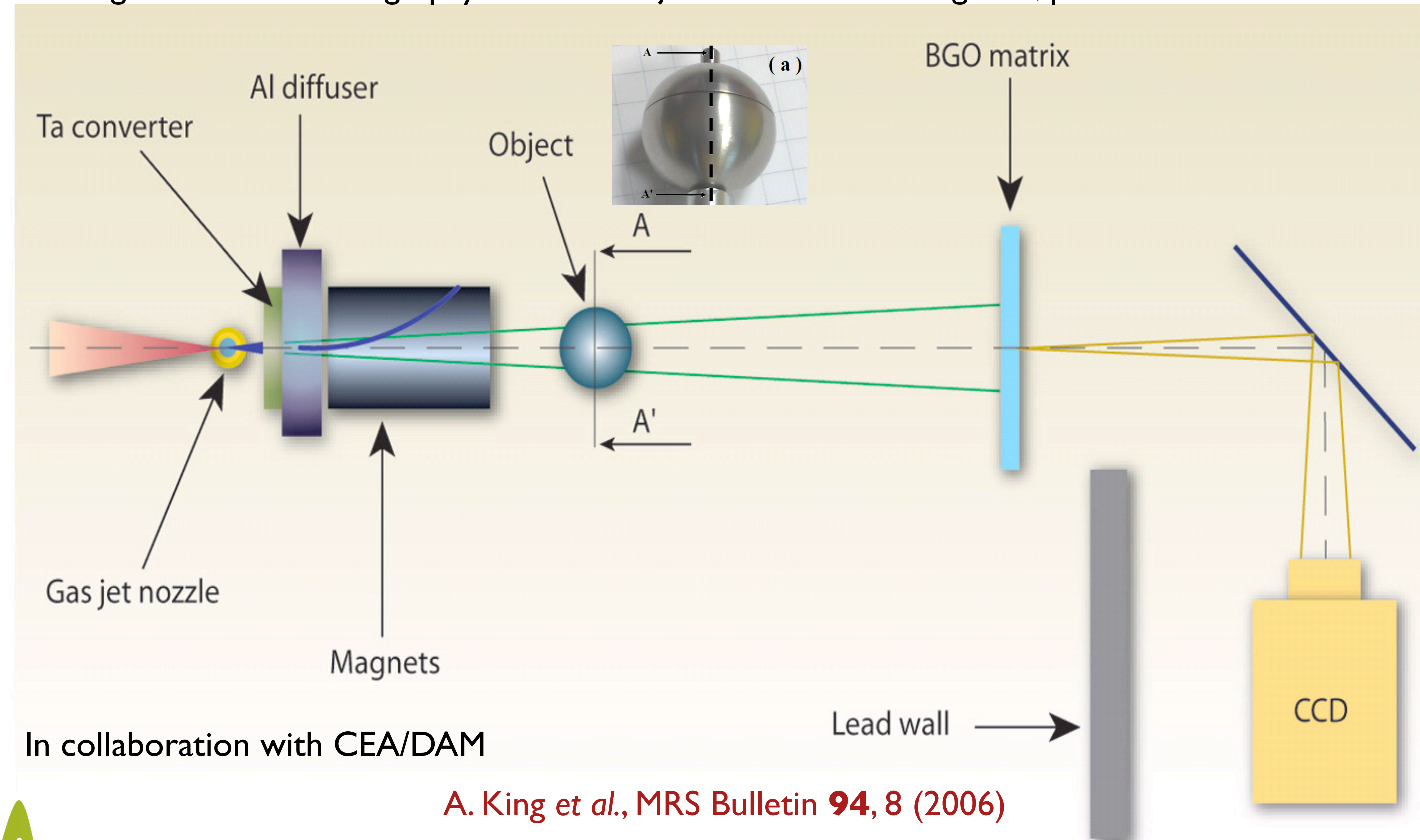
Some examples of applications : radiography

Non destructive dense matter inspection

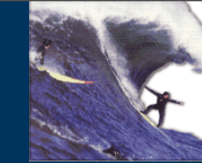
High resolution radiography of dense object with a low divergence, point-like electron source

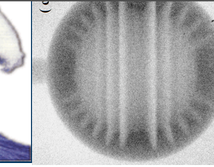


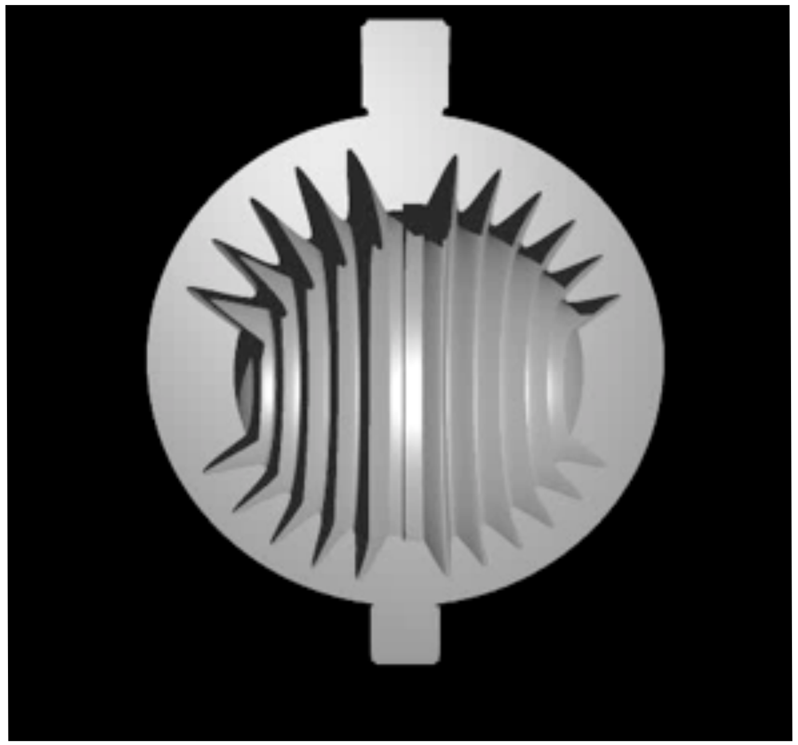
In collaboration with CEA/DAM

A. King *et al.*, MRS Bulletin **94**, 8 (2006)

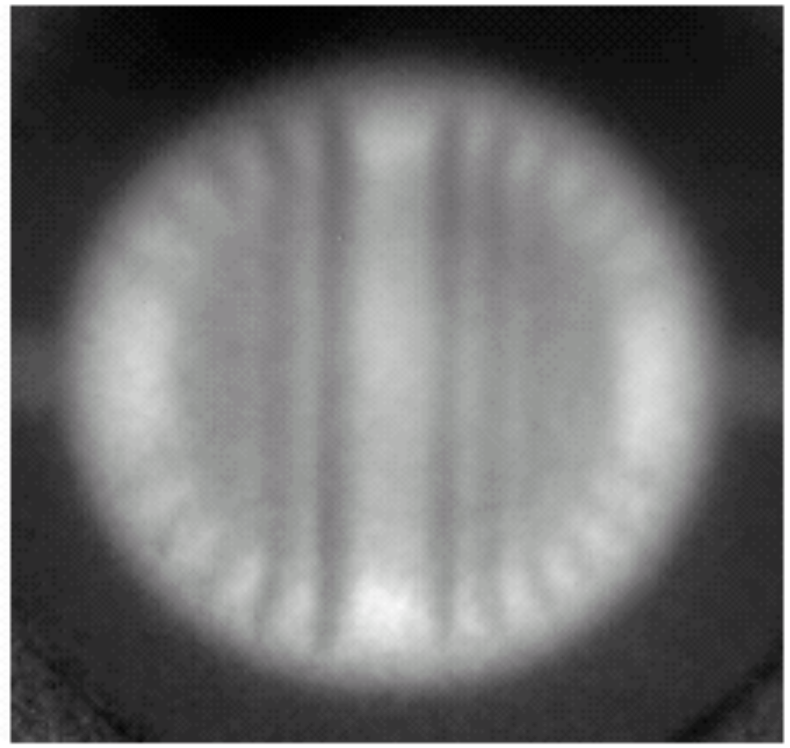
Some examples of applications : radiography results



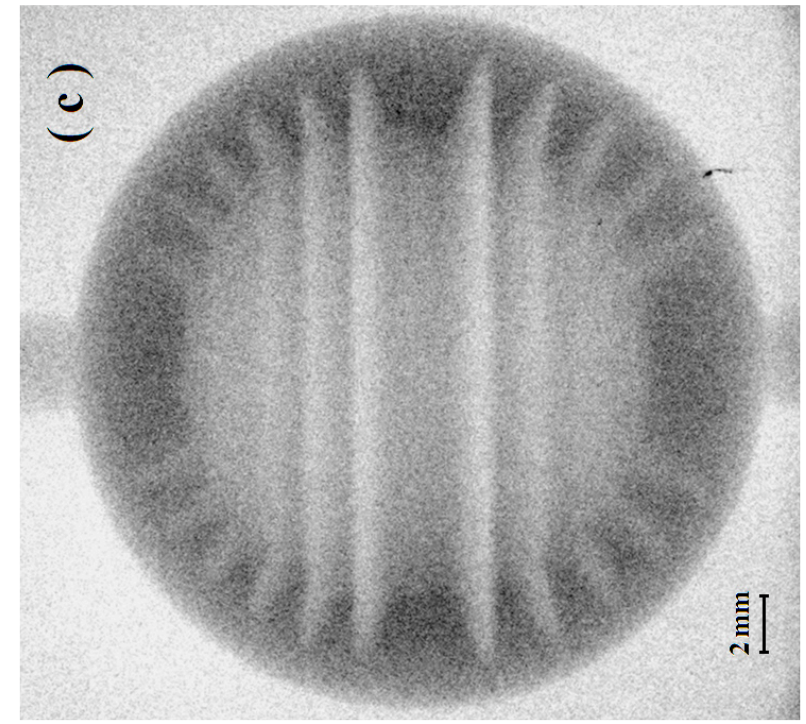




Cut of the object in 3D
Spherical hollow object in tungsten with sinusoidal structures etched on the inner part.



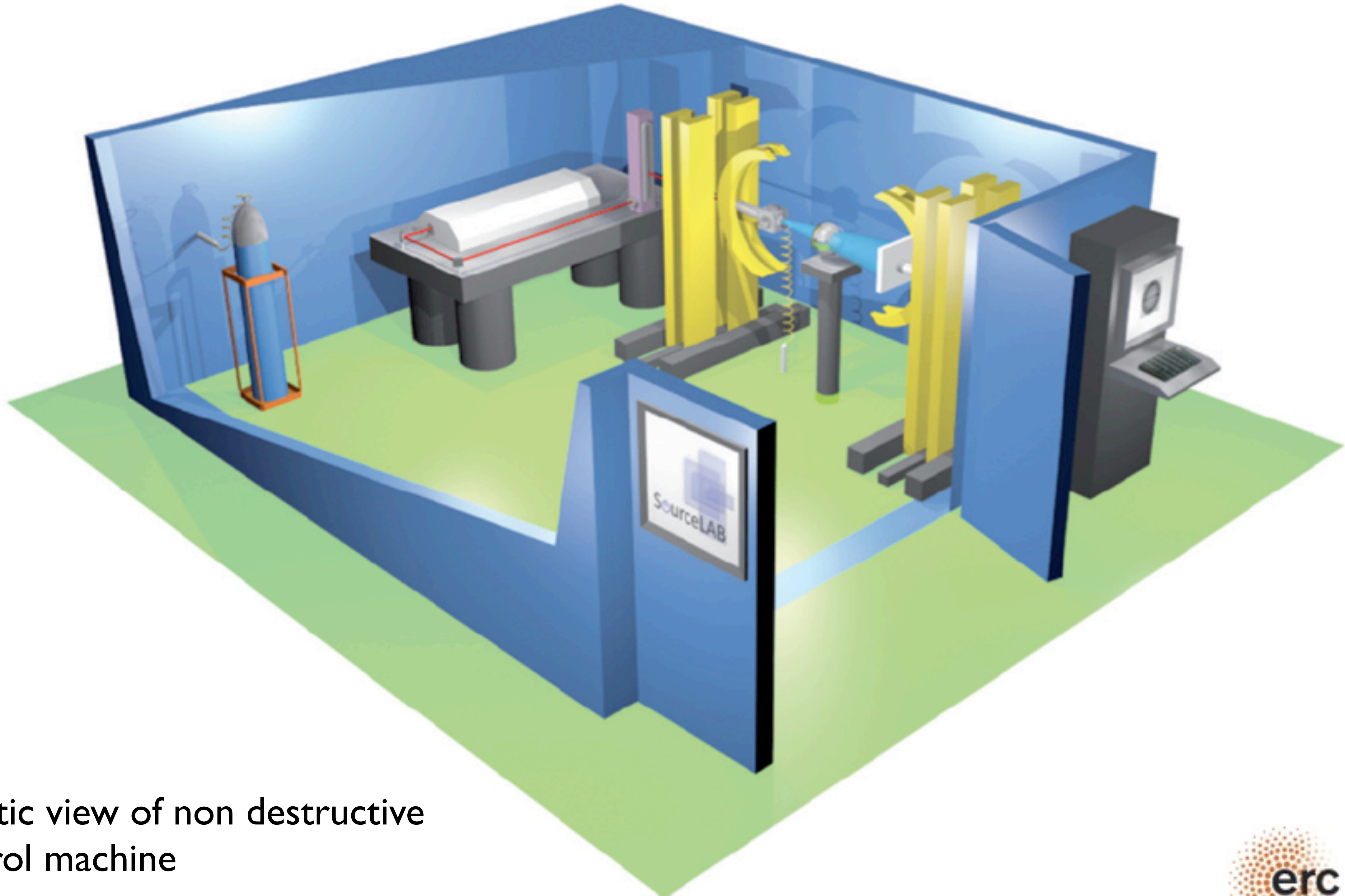
400 µm γ source size
2005



50 µm γ source size
2010

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

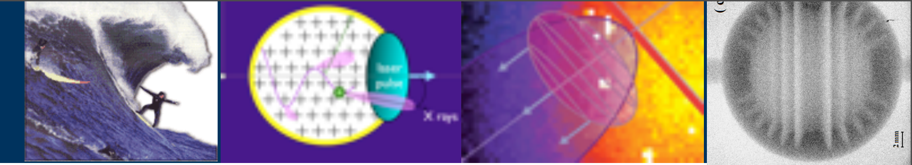
Application to Non Destructive Control



Artistic view of non destructive control machine

- Betatron radiation produced in LPA
  - Experimental characterization
  - Electron-X rays beams correlations
  - Diagnostics for LPA
  - Single shot contrast imaging
- All optical Compton gamma rays source
  - Principle
  - Experimental results
- Bremstralhung gamma rays source
  - Principle
  - Experimental results
- **Conclusion and perspectives**

Conclusion



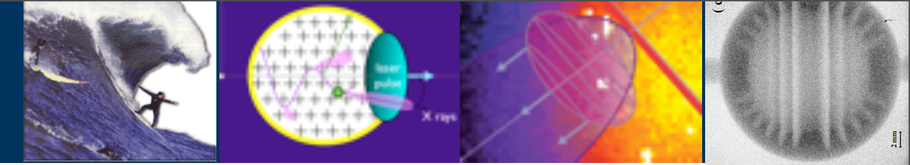
Laser plasma accelerators can deliver high quality X ray beams

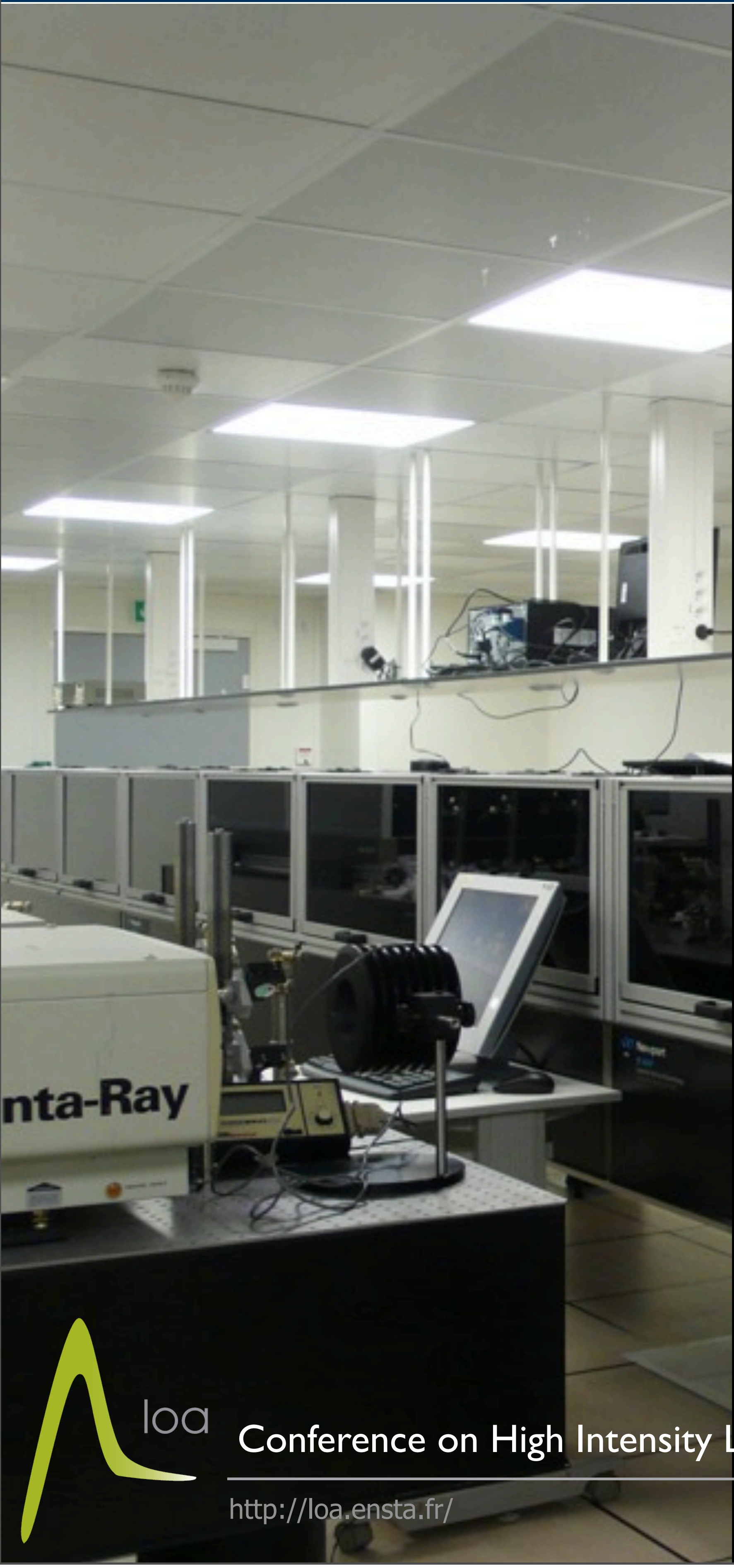
(i) Betatron : 10^8-10^9 ph/shot - fs - micron - 10's keV - 10's mrad

(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

Conclusion and Perspectives





- Betatron radiation:

Fully characterized, used for first applications

↦ High repetition rate keV source

↦ High energy radiation: 100s keV

- All optically driven Compton x-ray source:

First demonstration in the hard x-ray range

↦ Produce x-ray beams at higher repetition rates (compact lasers).

↦ Produce tunable monochromatic fs x-ray/gamma-ray beams.

- Applications:

Ultrafast x-ray absorption, diffraction experiments, radiography

↦ keep developing these applications

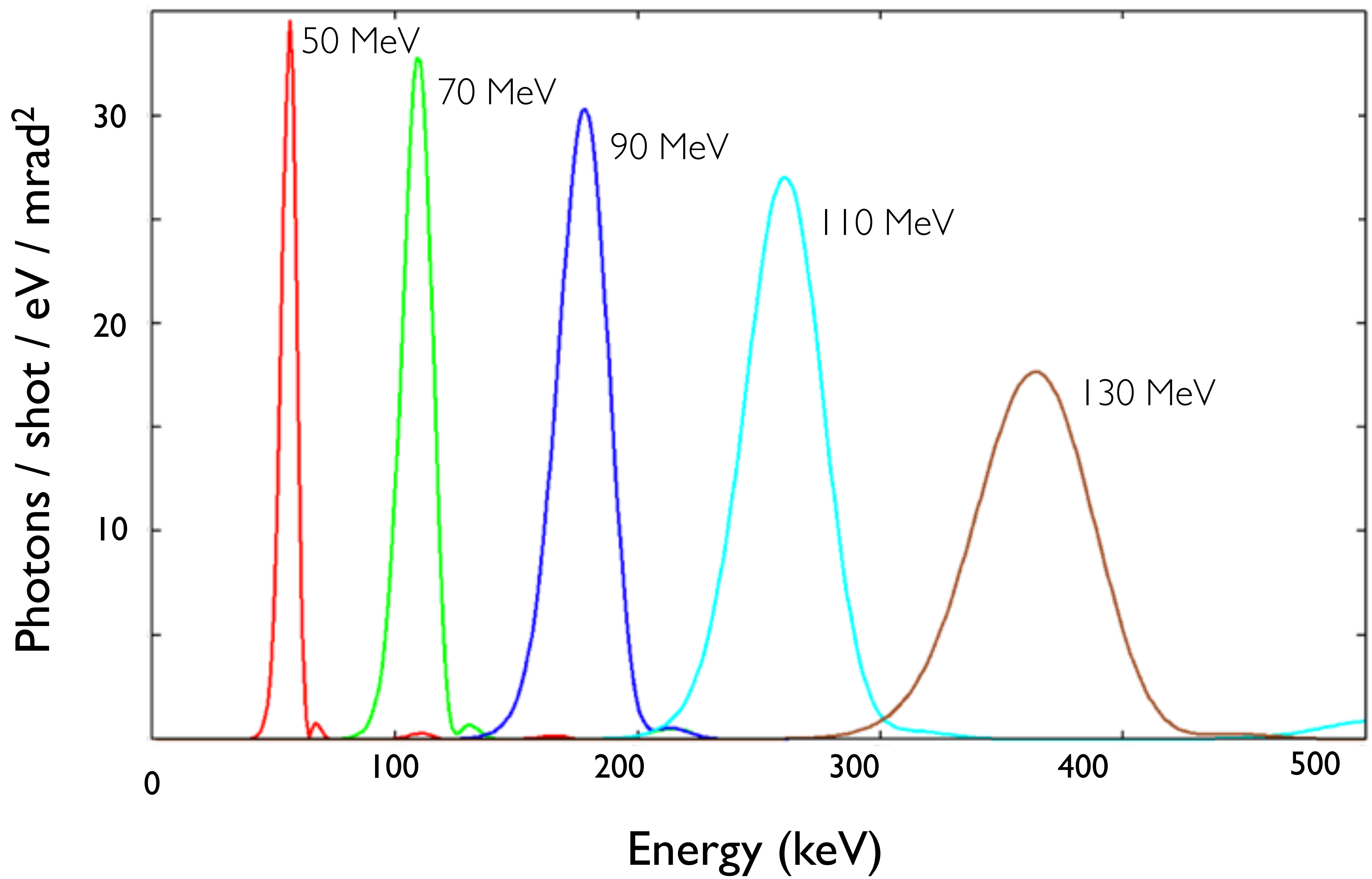
↦ Applications for ICF under consideration

Femtosecond X-rays from laser plasma accelerators
S. Corde *et al.*, Review of Modern Physics, 85, 1, 2013

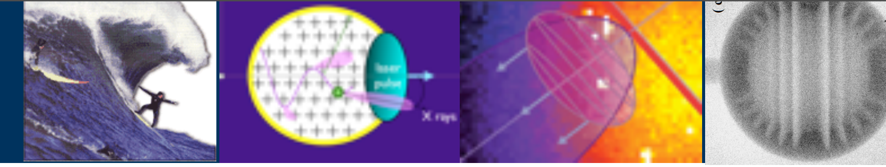
Produce a nearly monochromatic radiation source: from a few keV to a few MeV

To do so we will use monoenergetic electrons produced from a laser plasma accelerator

Expected x-ray spectra



Collaborators



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