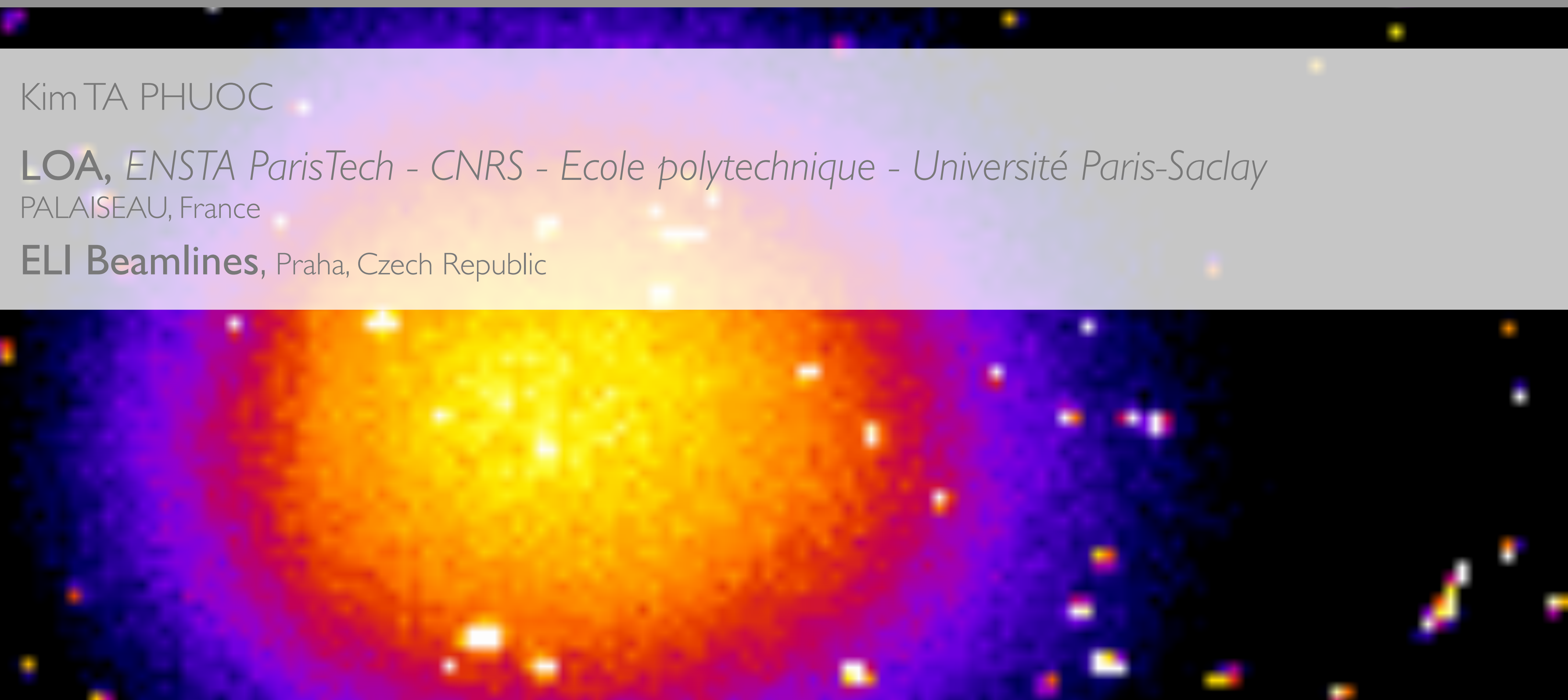
Review on Betatron and Compton sources from Laser Plasma Accelerators



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ELI Beamlines, Praha, Czech Republic

Why do we need novel x-ray sources ?

Multidisciplinary, novel and fundamental applications

Compact Femtosecond x-ray sources →

- To probe matter →
  - X-ray diffraction
  - X-ray absorption
  - Thomson scattering
  - ect...
- To excite matter →
  - Radiography
  - Phase contrast imaging
  - Ionization
  - Heating

→

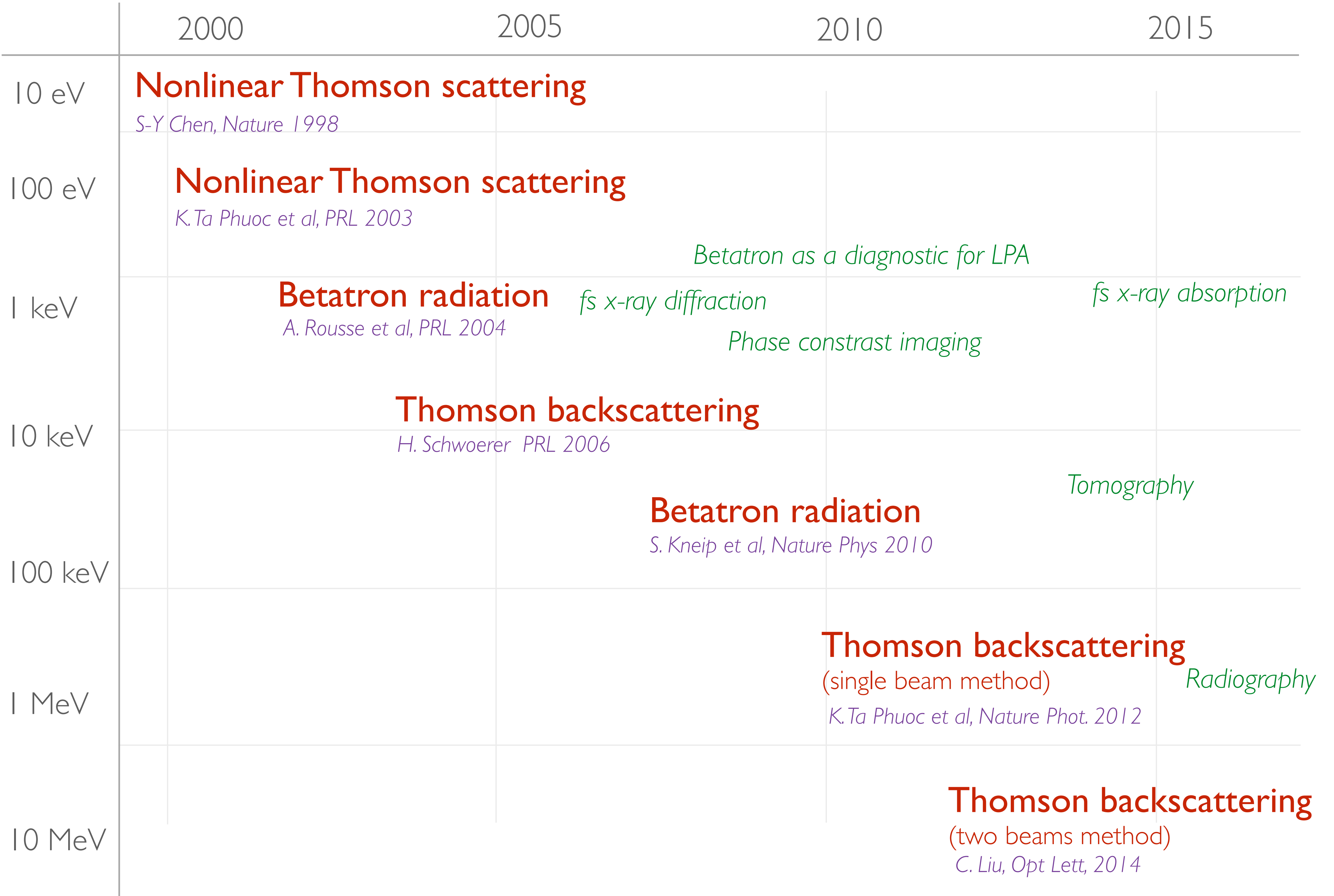
Physics
- Plasmas physics
- Solid State physics

Chemistry

Biology

Industry

Femtosecond X-ray sources from LPA



Outline

Betatron source

- Principle
- Experimental characterization of the source
- Applications experiments
- Recent progresses

Compton source

- Principle
- Experimental characterization of the source
- Applications experiments

Summary, conclusion & perspectives

Radiation from relativistic electrons

Sources based on moving charge radiation

Velocity

Acceleration

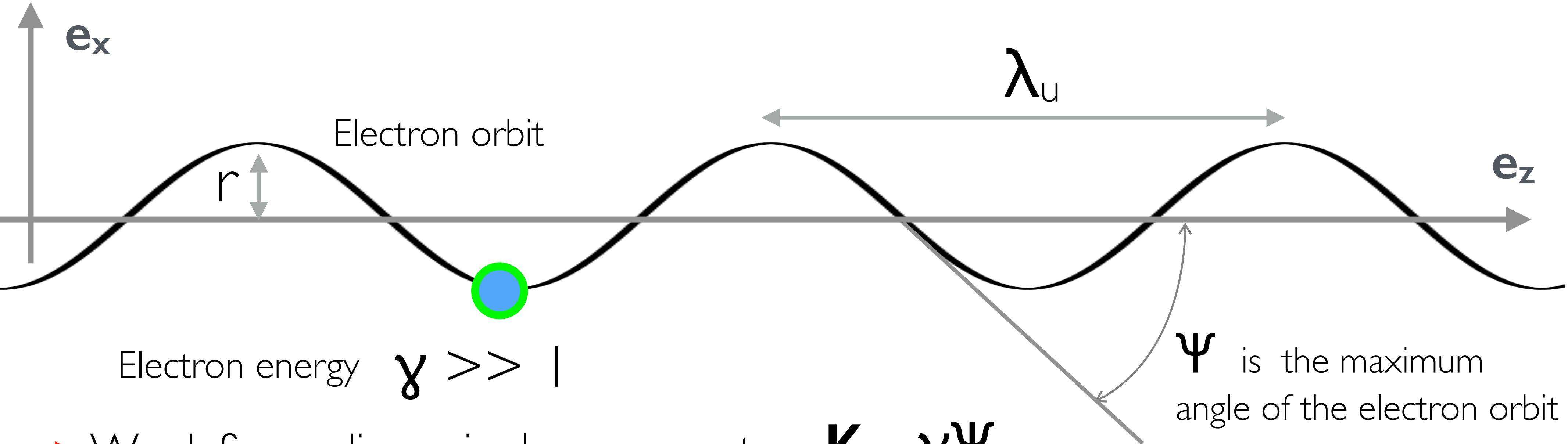
$$\frac{d^2 I}{d\omega d\Omega} = \frac{e^2}{4\pi^2 c} \left| \int_{-\infty}^{+\infty} e^{i\omega[t - \vec{n}.\vec{r}(t)/c]} \frac{\vec{n} \times [(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \vec{\beta}\,.\,\vec{n})^2} dt \right|^2$$

Radiated energy

- Transverse acceleration is necessary to efficiently produce radiation
- Relativistic electron emits order of magnitude more radiation than non relativistic electron
- Radiation is emitted in the direction of the electron velocity
- Radiation is emitted at the frequency $\omega \sim 2\gamma^2\omega_e$ and harmonics. ω_e is the frequency of the electron motion. X-ray radiation can be produced by wiggling electron relativistic at a frequency far below x-ray range.

Radiation from relativistic electrons

→ We need relativistic electrons undergoing transverse oscillations

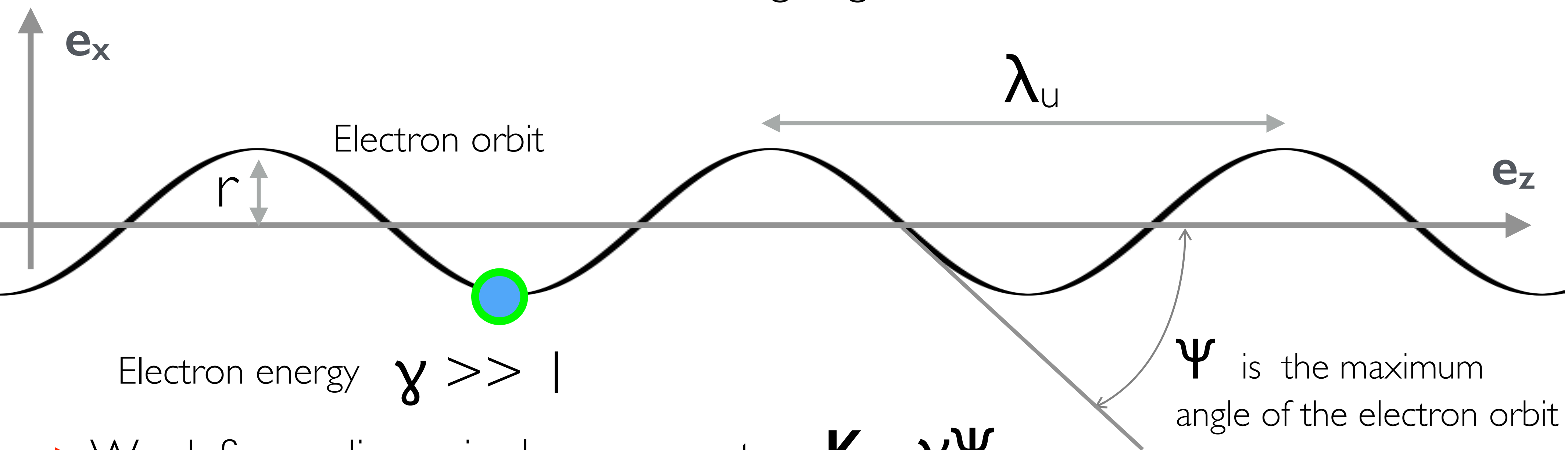


Electron energy $\gamma >> 1$

→ We define a dimensionless parameter : $\mathbf{K} = \gamma\Psi$

Radiation from relativistic electrons

→ We need relativistic electrons undergoing transverse oscillations



Electron energy $\gamma >> 1$

Ψ is the maximum angle of the electron orbit

→ We define a dimensionless parameter : $\mathbf{K} = \gamma\Psi$

→ This type of trajectory can be obtained using the following methods:

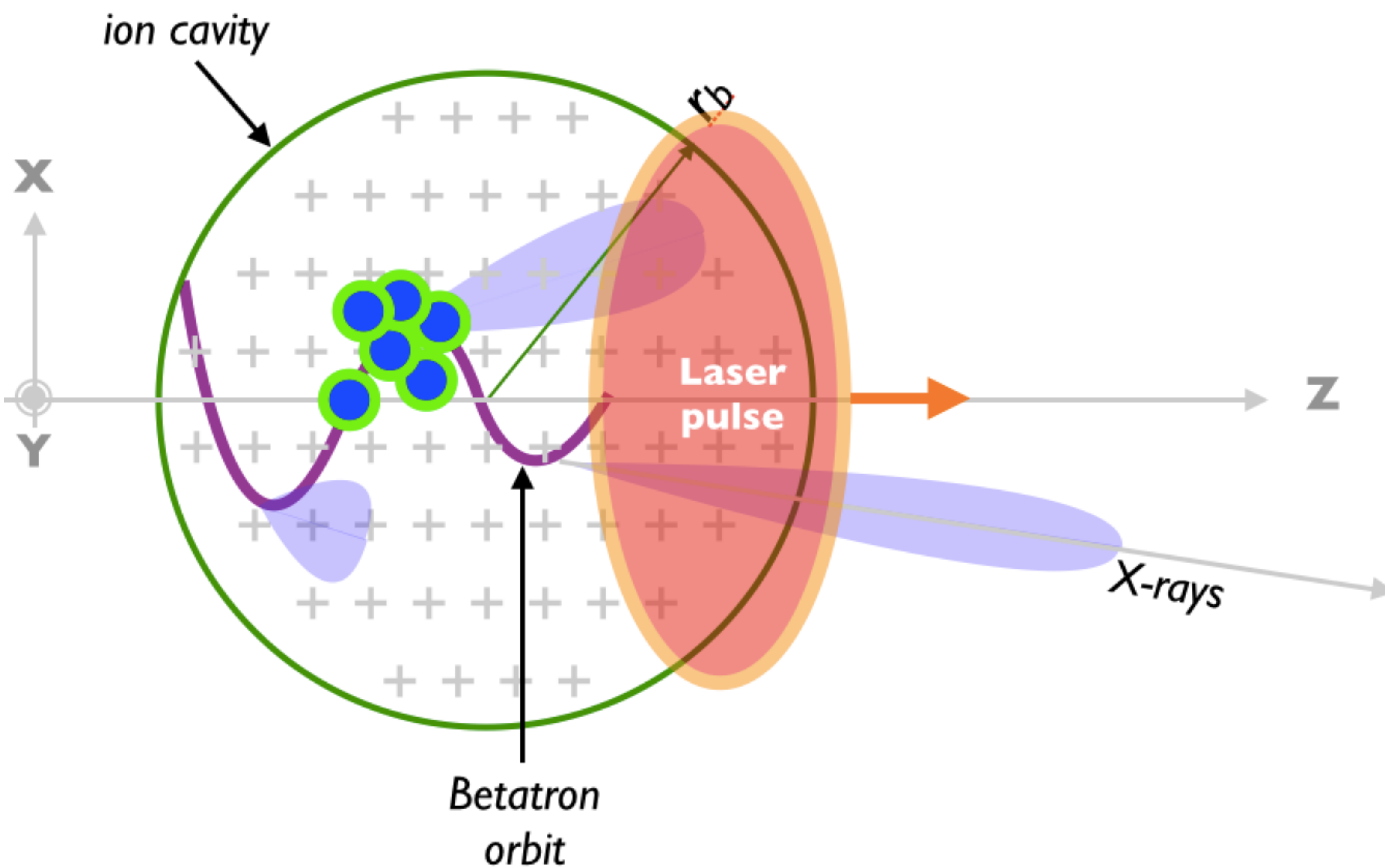
Laser → **Relativistic electrons** + **Wiggler** = **X-rays**

Relativistic electrons:
- Laser
- Laser plasma accelerator

Wiggler:
- Laser
- Plasma
- counter-propagating laser

X-rays:
- Nonlinear Thomson
- Betatron
- Compton scattering

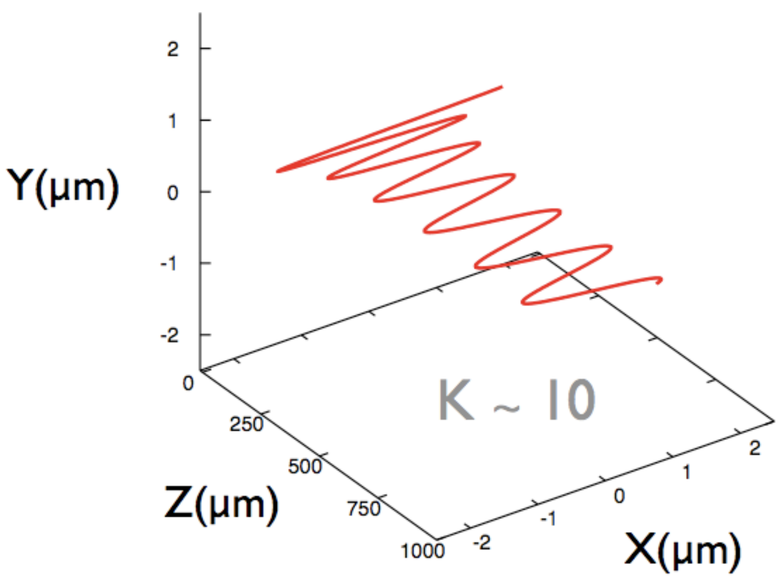
Betatron radiation

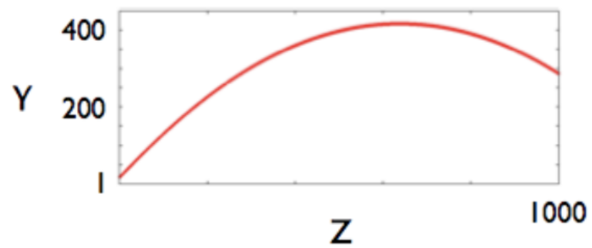


→ This is an appropriate motion to produce x-ray beams

→ To calculate the radiation features we first need to calculate the electron orbit

Betatron radiation: Electron orbit





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

acceleration ↑ ↑ wiggling

The spatial period of the electron orbit is:

$$\lambda_u(t) = \sqrt{2\gamma(t)}\lambda_p,$$

$$\lambda_u[\mu\mathrm{m}] = 4.72 \times 10^{10}\sqrt{\gamma/n_e[\mathrm{cm}^{-3}]},$$

λ_u ~ 150 microns,

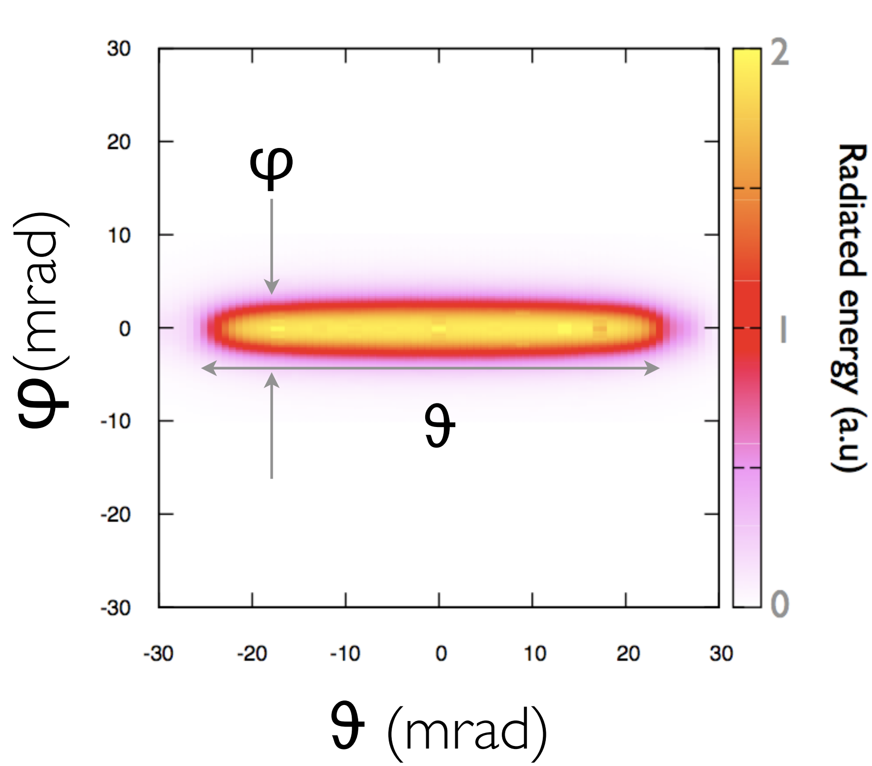
and the K parameter is:

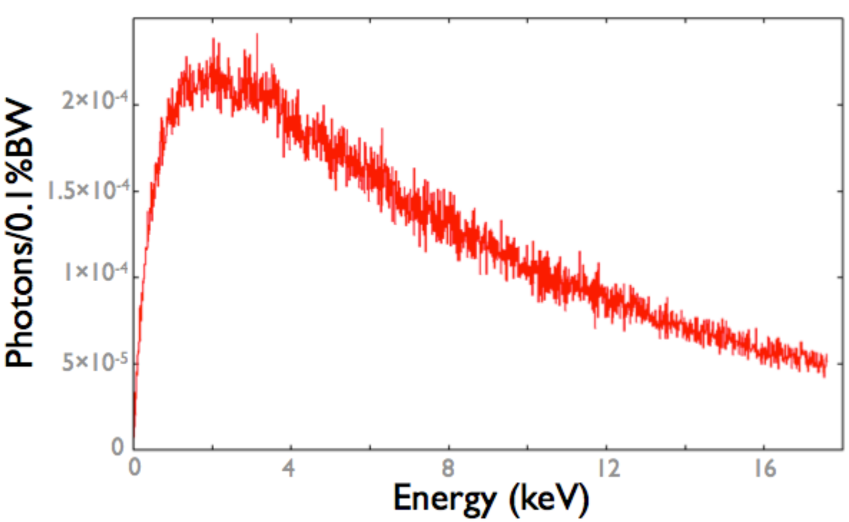
$$K(t) = r_\beta(t)k_p\sqrt{\gamma(t)/2},$$

$$K = 1.33 \times 10^{-10}\sqrt{\gamma n_e[\mathrm{cm}^{-3}]}r_\beta$$

K ~ 10

Betatron radiation features: for one electron





- Example for $a_0=2$, $n_e=10^{19}$ cm^{-3}
- Spectrum, critical energy

$$\hbar\omega_c[\mathrm{eV}] = 5.24 \times 10^{-21}\gamma^2 n_e[\mathrm{cm}^{-3}] r_\beta[\mu\mathrm{m}]$$

~9 keV

- Photon number / electron

$$N_\gamma = 3.31 \times 10^{-2} K \quad \text{for } K \gg 1.$$

~0.3 photon / electron

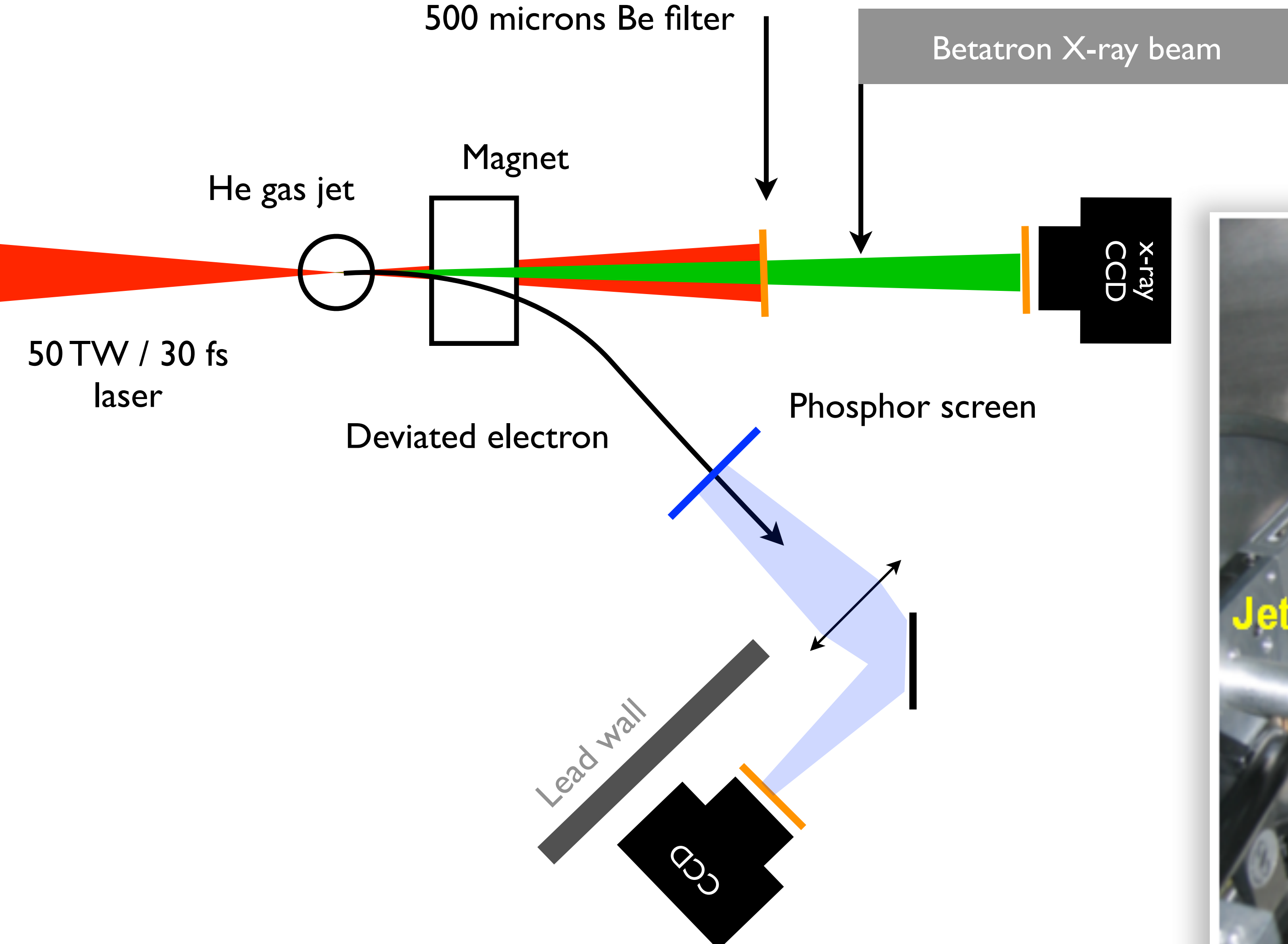
- Spatial distribution

$\vartheta = K/\gamma$ $\qquad$ $\varphi = 1/\gamma$

~30 mrad

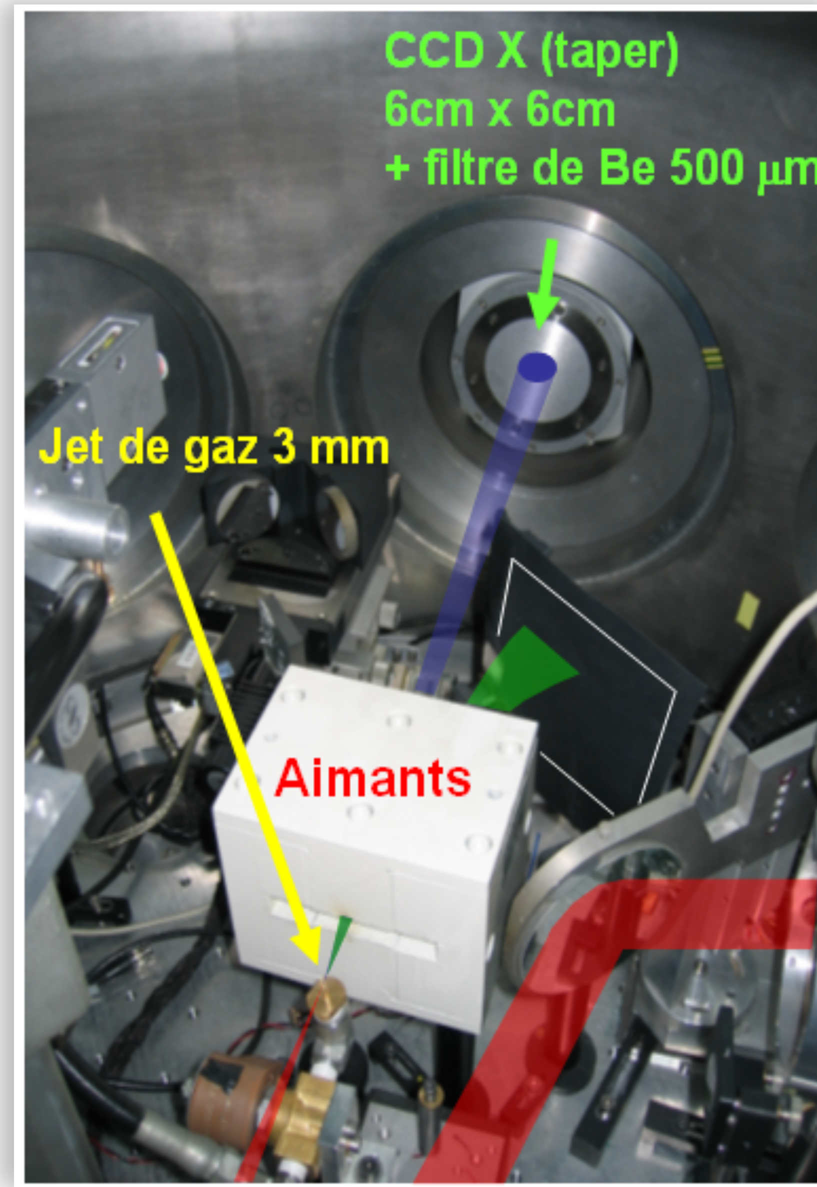
- Source size is a few microns
- Duration is a few femtoseconds

Typical Betatron experiment

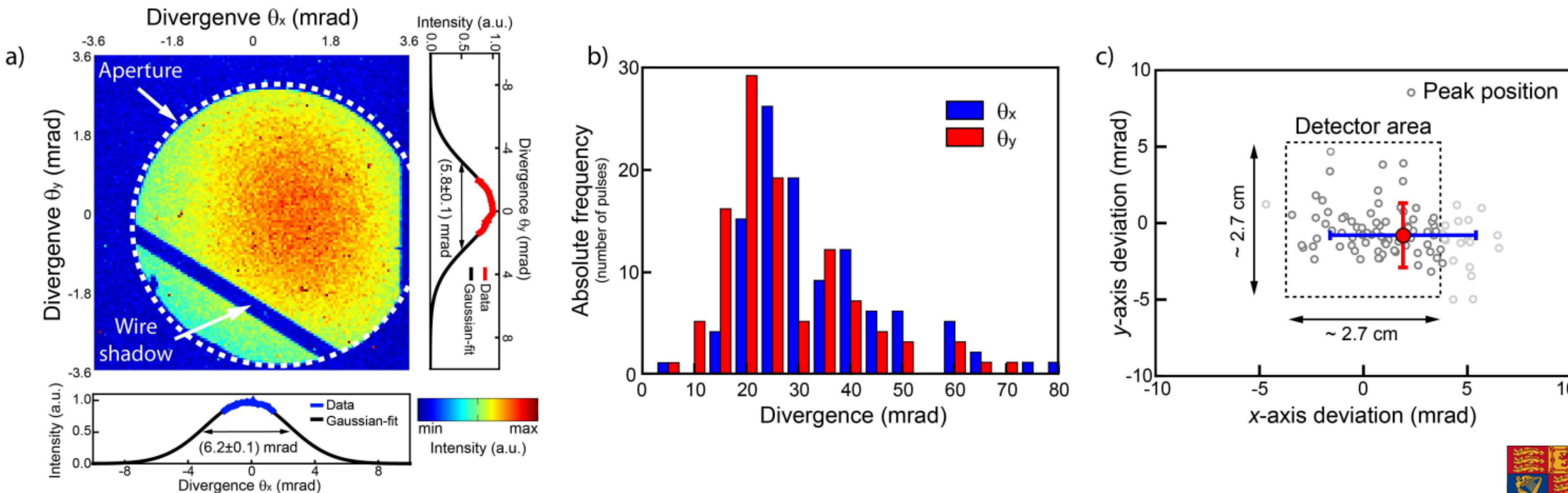


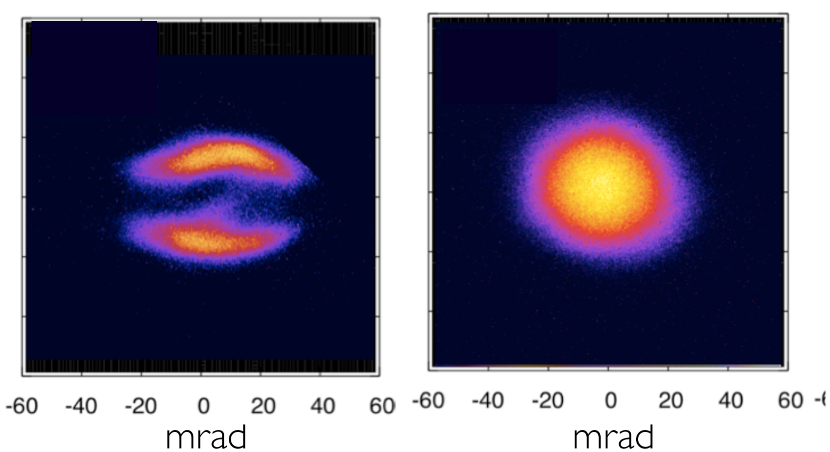
$a_0=2$

$n_e=1\times10^{19}$ cm^{-3}



Angular distribution





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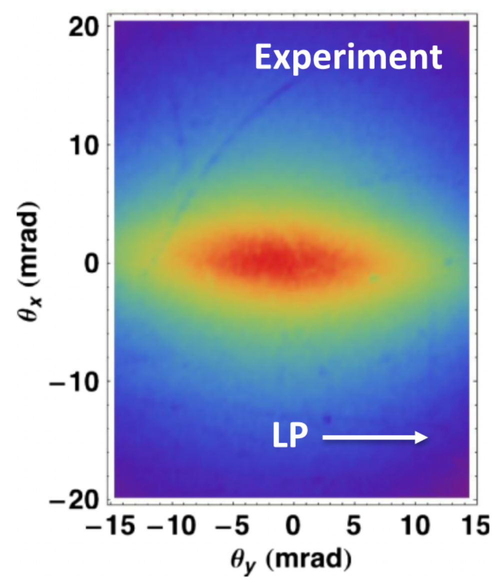
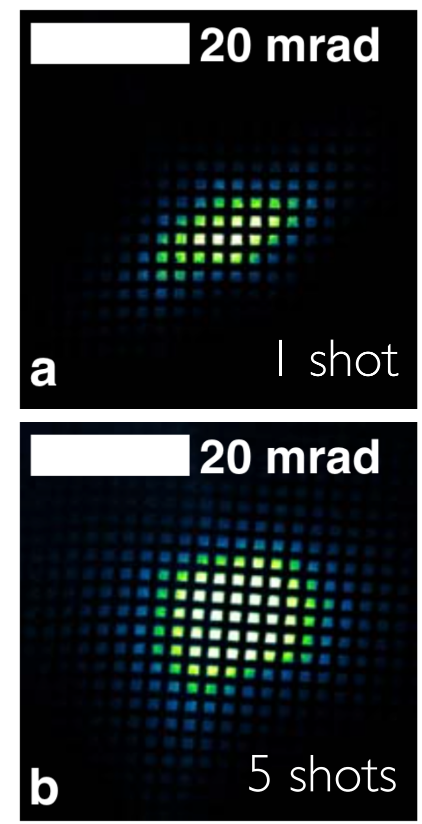
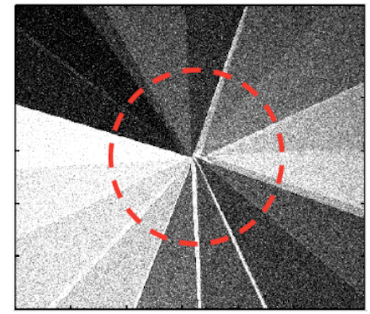




- Typical divergence 20 - 50 mrad
- Pointing fluctuations 5-10 mrad

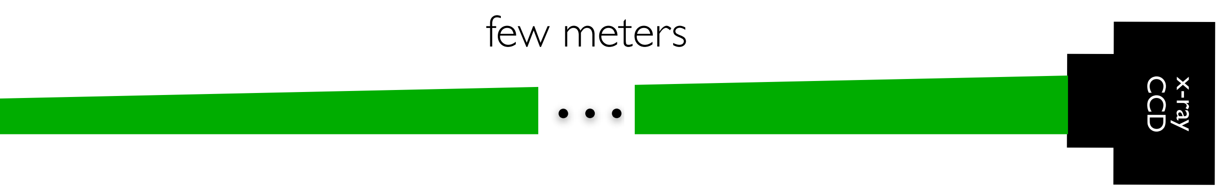
Spectrum measurement

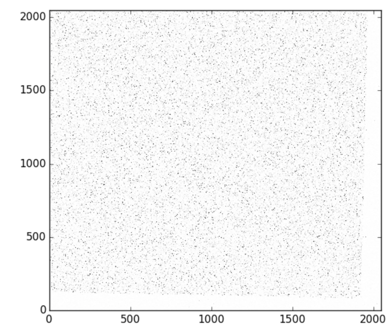
Filters set



Spectral resolution : few keV
Spectral range : keV to hundreds keV

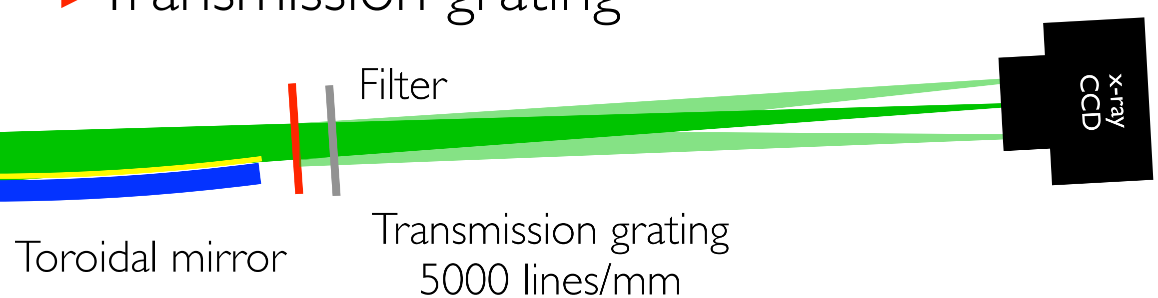
Single photon counting

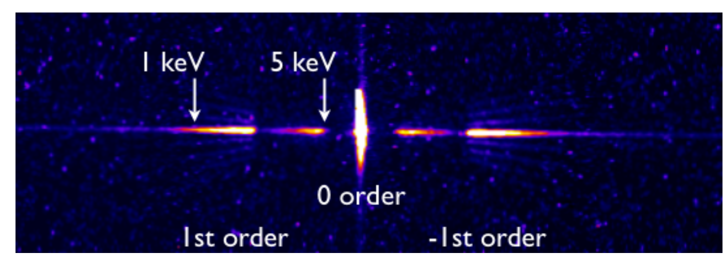




Spectral resolution : 100 eV
Spectral range : up to 30 keV

Transmission grating

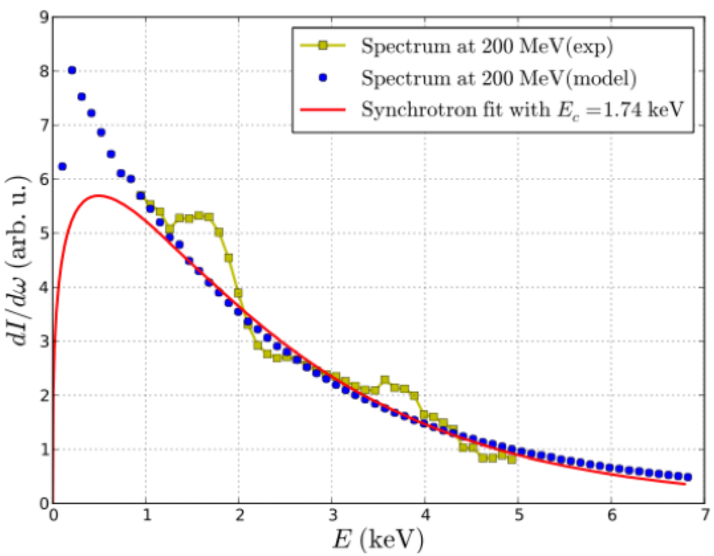




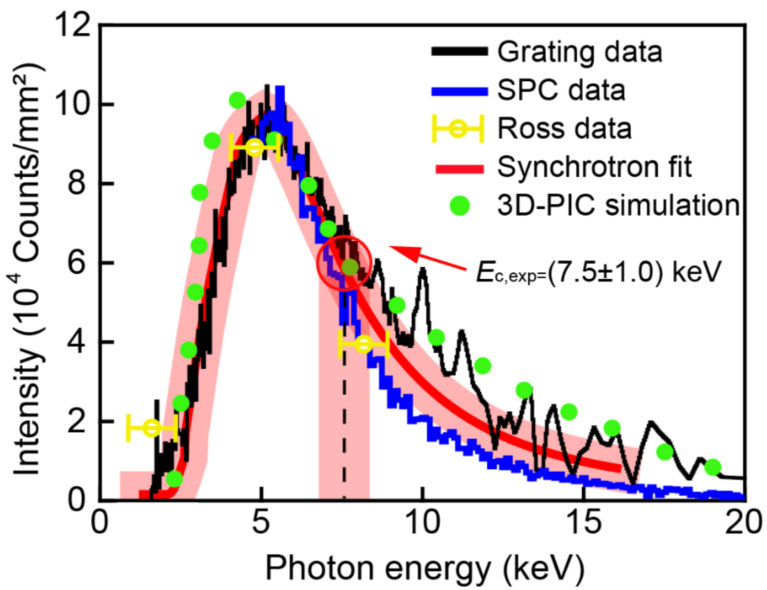
Spectral resolution : few eV
Spectral range : 100s eV to few keV

Betatron radiation spectrum (10s TW class lasers)

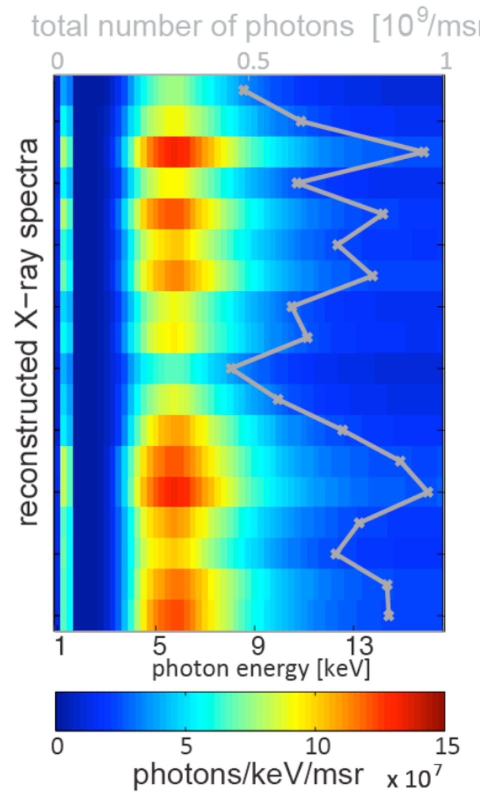
50 TW



30 TW



50 TW

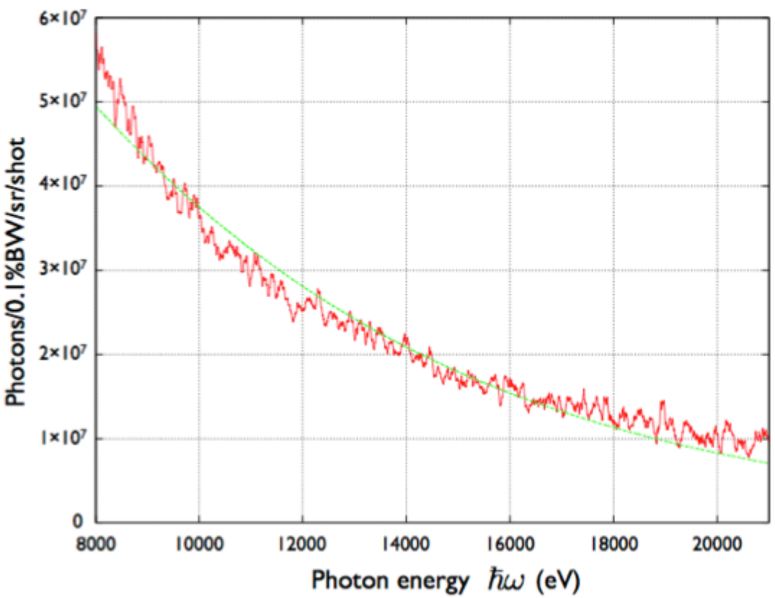


- Critical energy in the few keV range
- Flux is about 10^8 photons / Shot

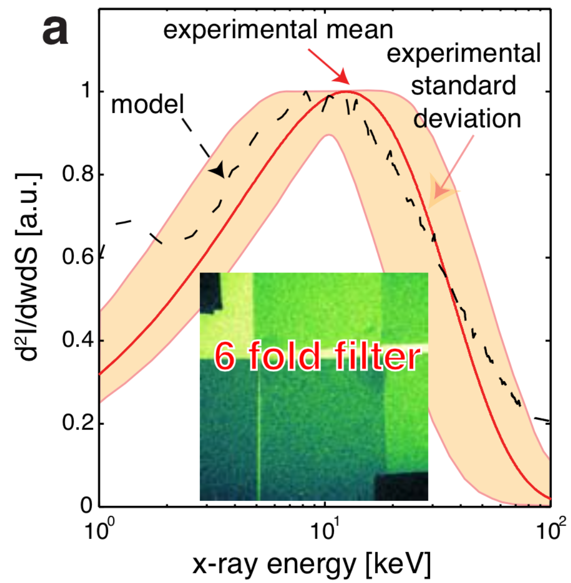
Betatron radiation spectrum (100s TW class lasers)

100 TW

ALLS Advanced Laser Light Source



100 TW



200 TW

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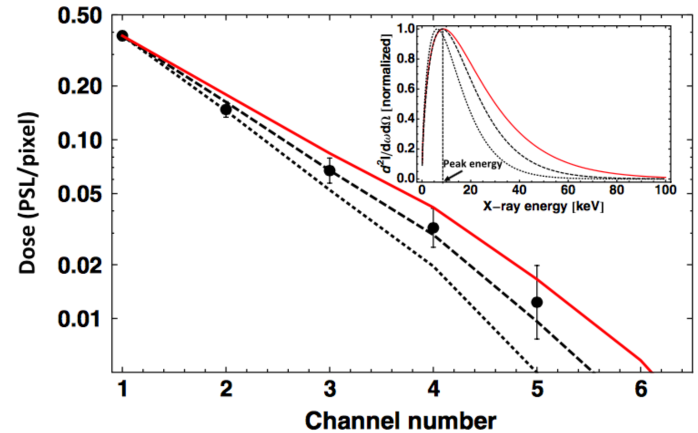
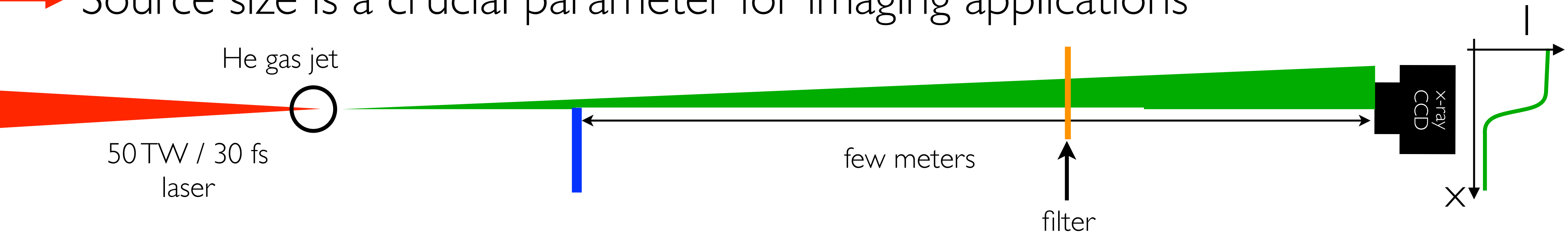


→ Critical energy of about a 10 keV

Source size measurement

→ Source size is a crucial parameter for imaging applications



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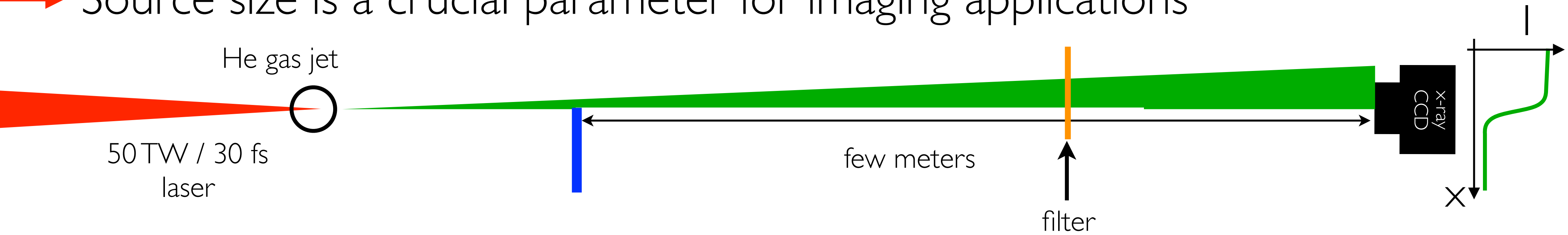
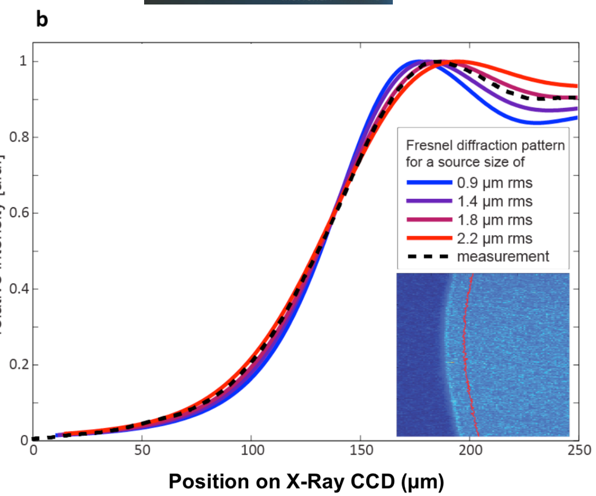
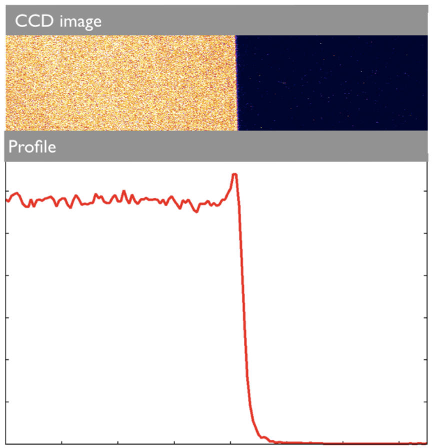
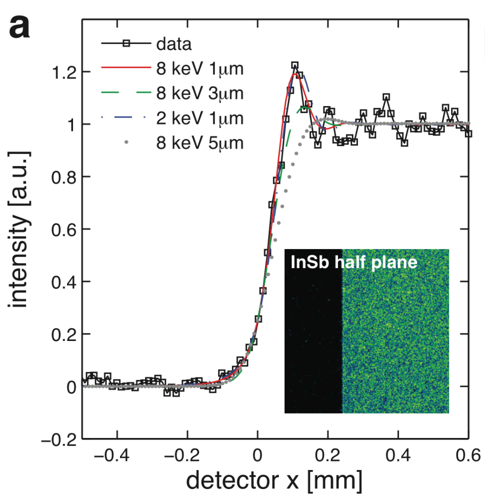
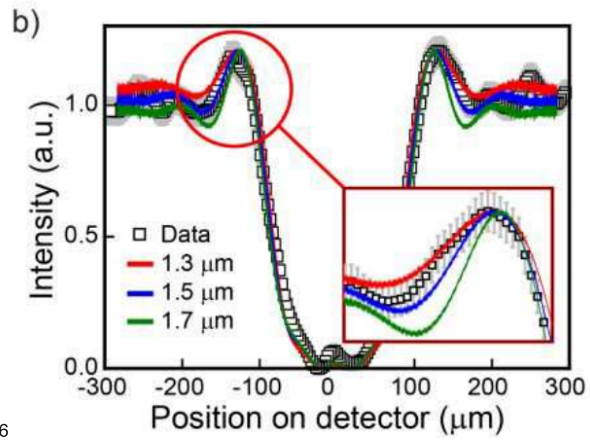










- Source size is about 1-2 microns
- It is usually limited by the resolution of the measurement

Summary of the source features

- 10^5 photons/shot/0.1% BW @ 1 keV
- 10^{8-9} photons/shots
- collimated: 10's mrad
- ultrashort: <10 fs
- broadband: 1-50 keV
- Micron source size: 1- 2 microns

Simple to produce, collect and use for applications.

Applications & recent progresses

- Imaging electrons orbits

- Betatron as a diagnostic for LPA

- Single shot phase contrast imaging

- Femtosecond x-ray diffraction and absorption

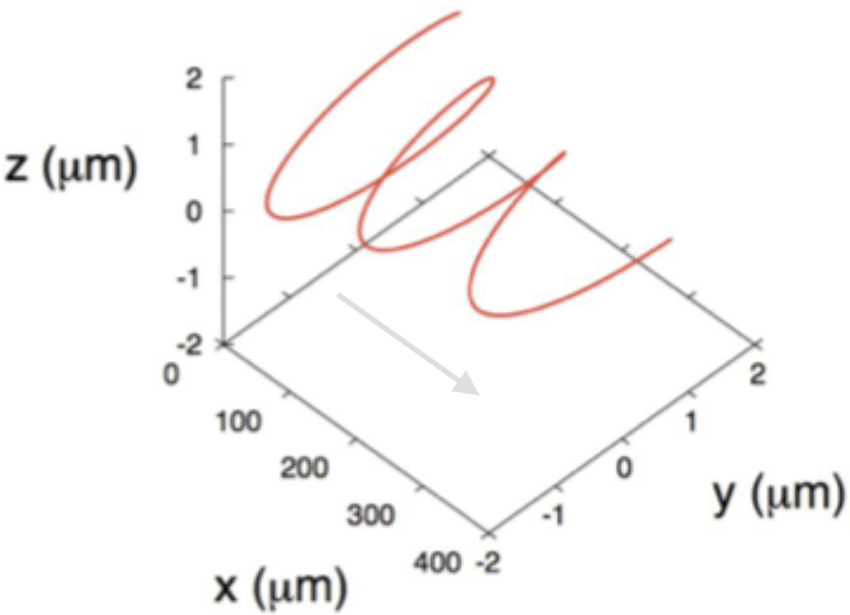
- Production of Stable and polarized Betatron radiation

- Decoupling accelerator and wiggler

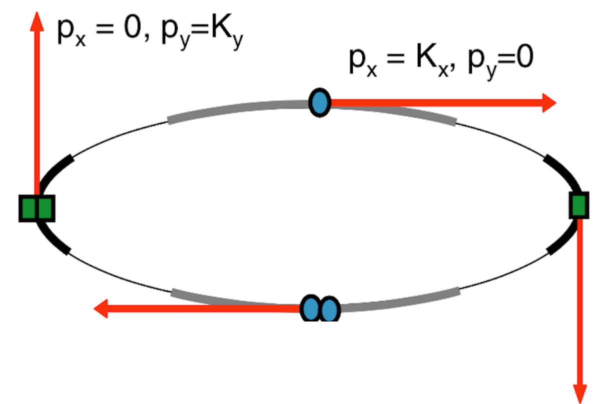
Transverse electrons orbits in the wakefield cavity

→ Betatron radiation can be used to determine transverse electrons orbits

We assume an helical orbit



Transverse electron orbit



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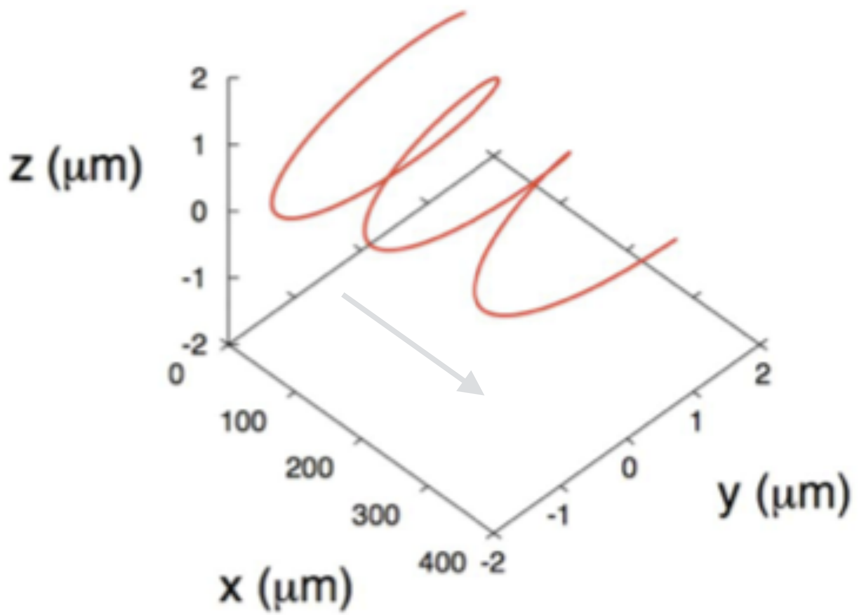
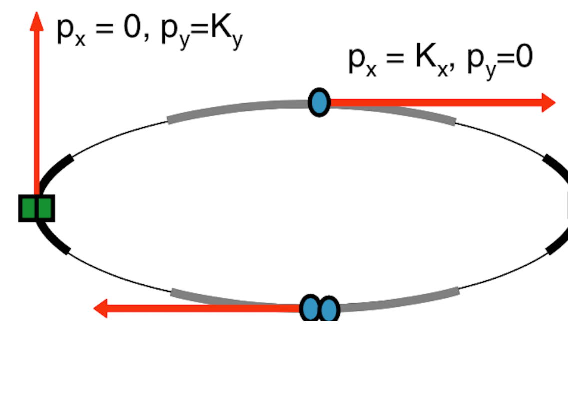
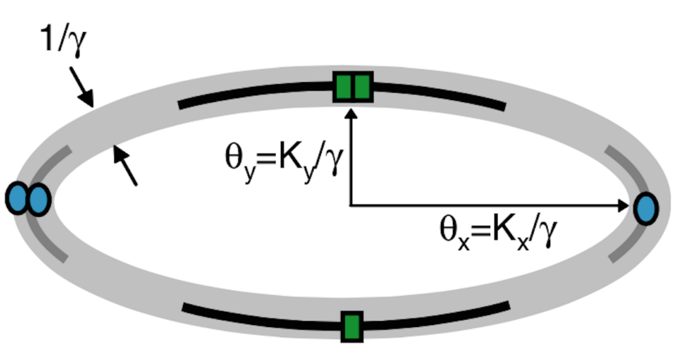


Transverse electron orbit



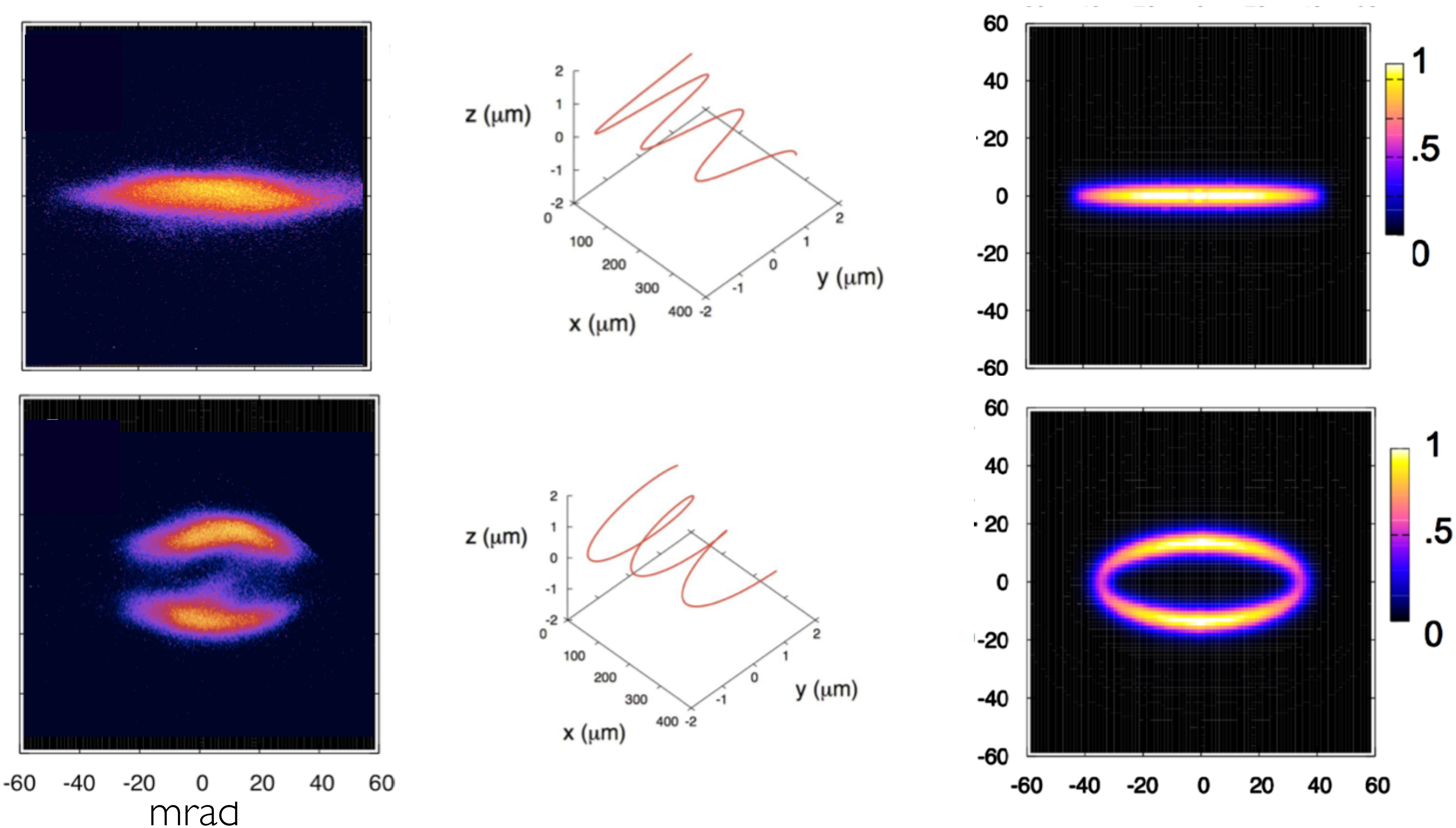
→ Corresponding x-ray beam profile



→ X-ray beam profiles are signatures of transverse electrons orbits

Transverse electrons orbits in the wakefield cavity

→ X-ray radiation is emitted in the direction of the electron velocity

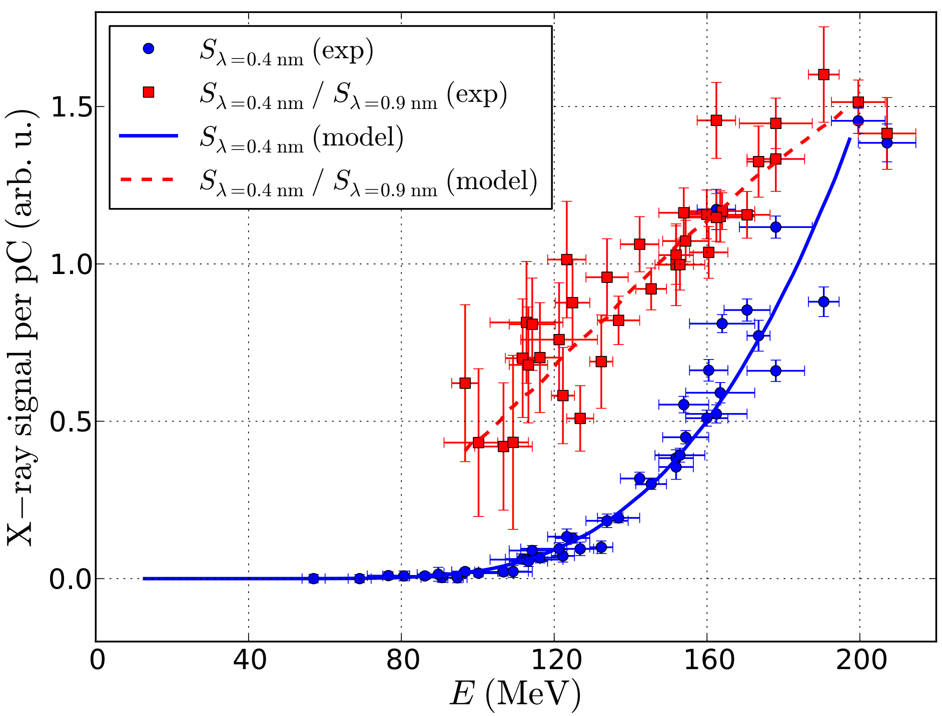


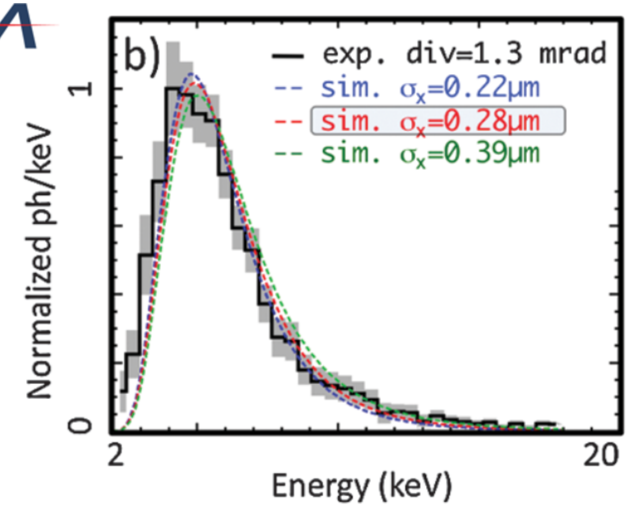
→ X-ray beam profile allows to estimate the transverse e- beam size

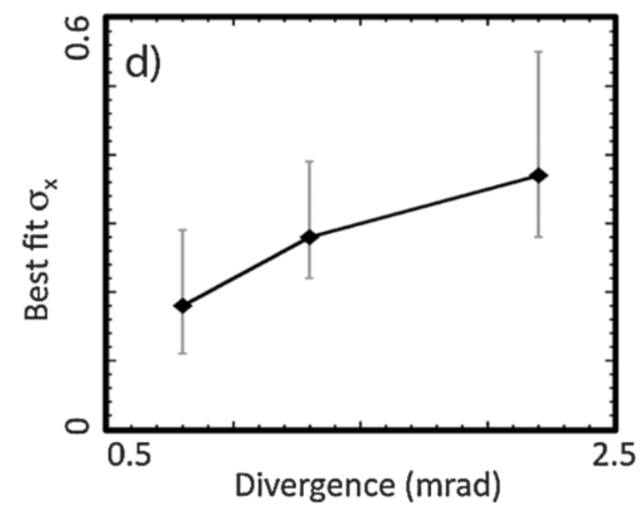
Estimation of the transverse e- beam size

- Fit of the evolution of the x-ray signal as a function of the electron energy (quasi-monoenergetic electrons)

- Fit of the measured x-ray spectrum



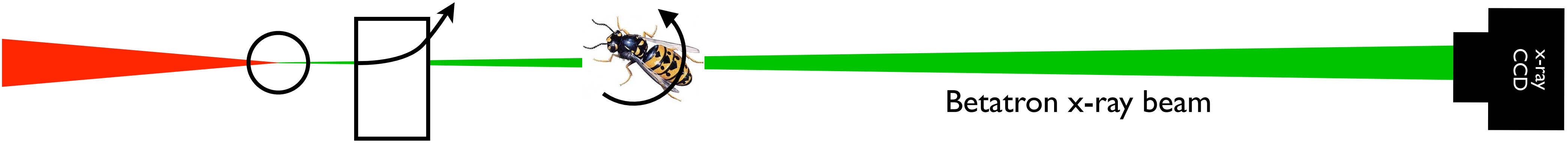




- σ_x = 0.23 microns RMS

- σ_x = 0.28 microns RMS

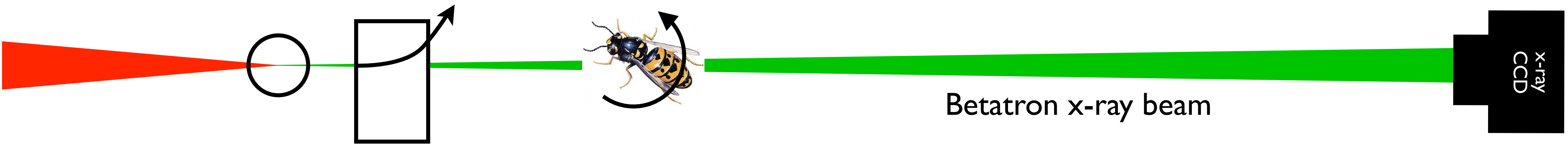
Absorption and phase constrast radiography



→ Betatron has the good features for this application:

- High brightness (10^{20} ph/s/mm^2/mrad^2/0.1%bw @1 keV)
- Micron source size
- Coherence length is a few tens microns at 1 m and 5 keV

Absorption and phase constrast radiography



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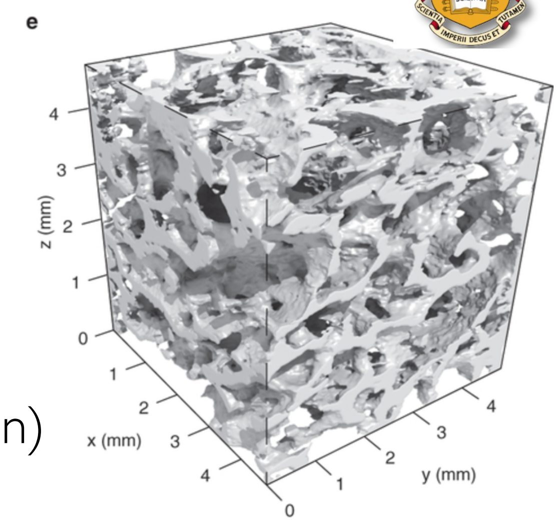
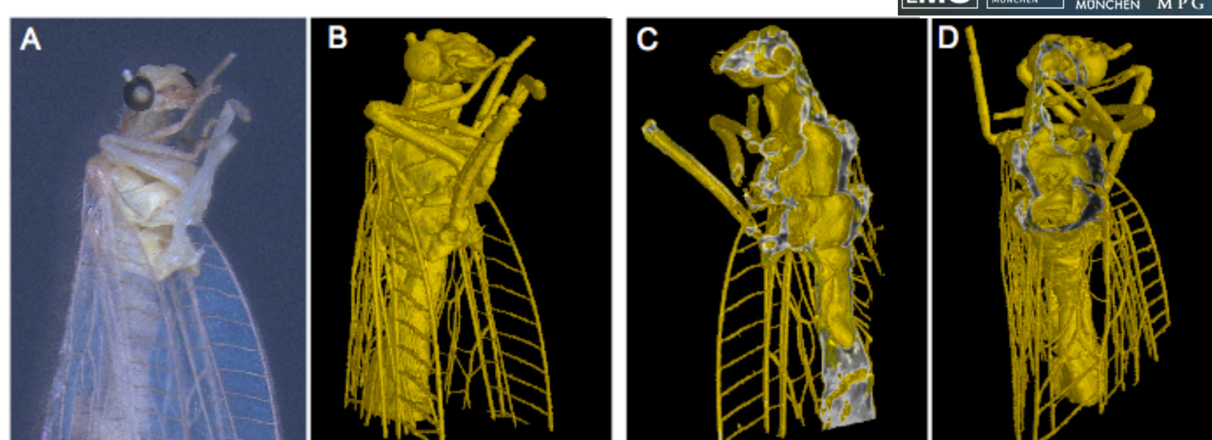


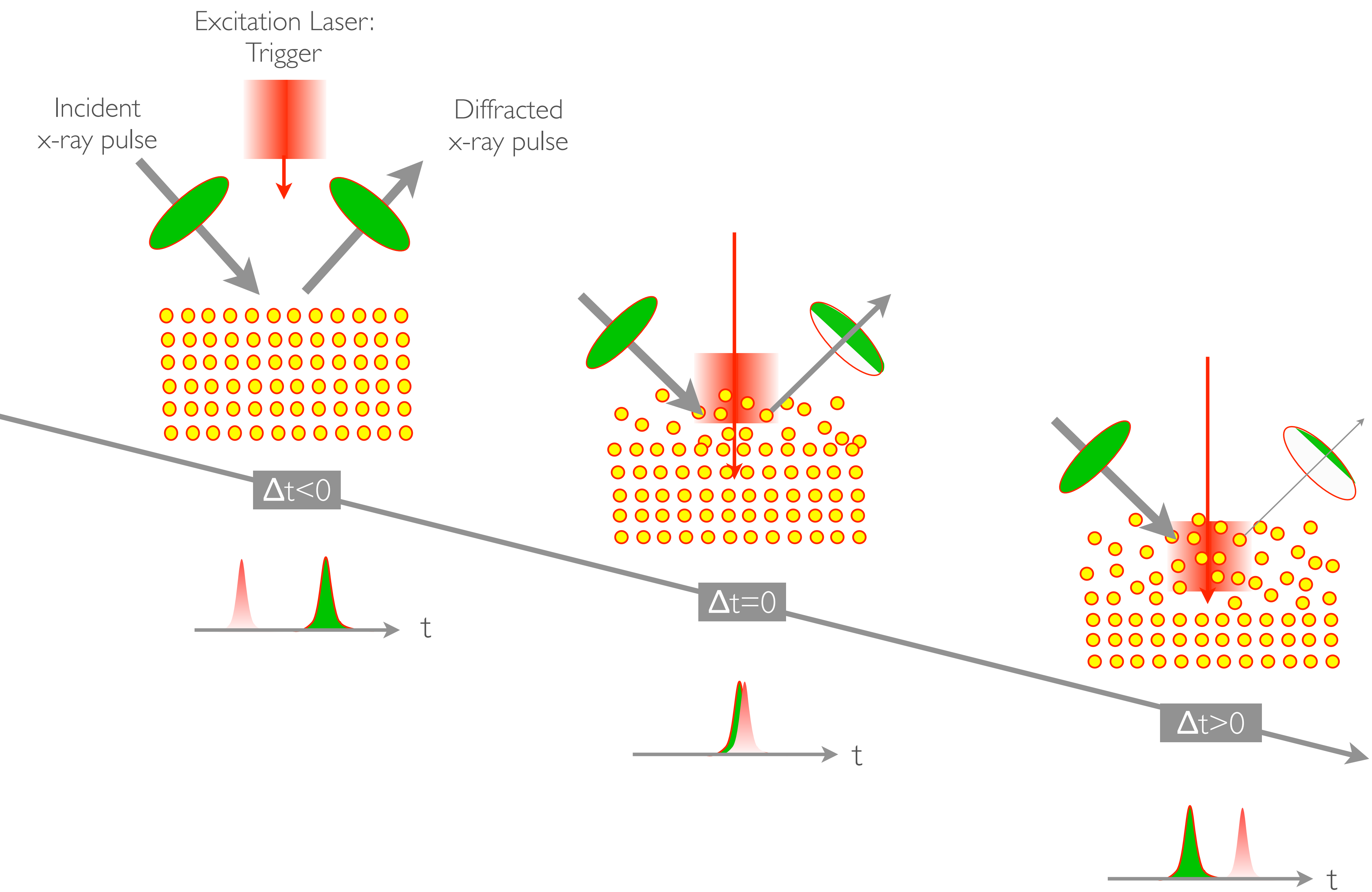
Bone tomography
(constrast absorption)

Radiograph of a bee (Phase contrast)

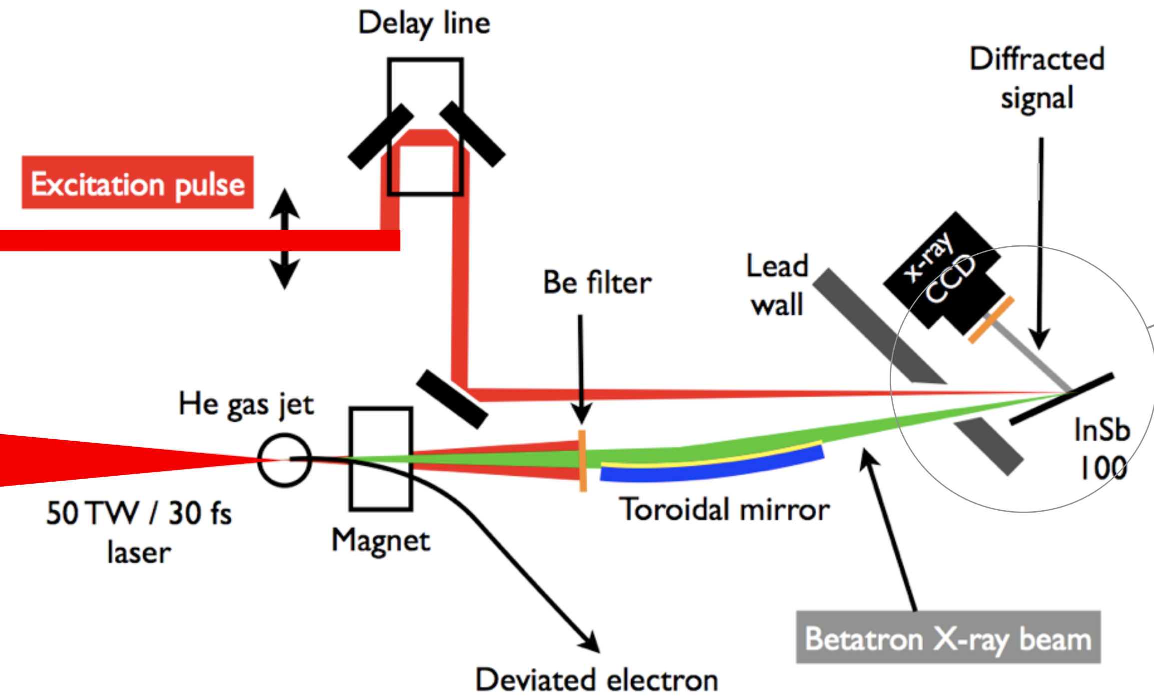
Tomography of a fly (Phase contrast)

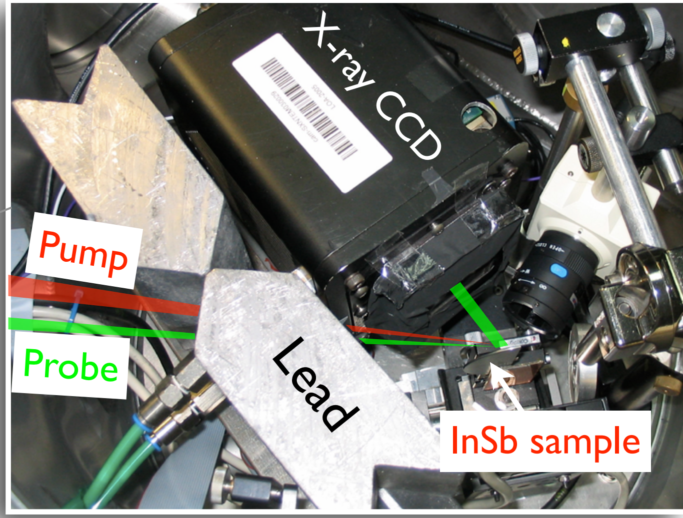


Femtosecond x-ray diffraction: pump-probe experiment

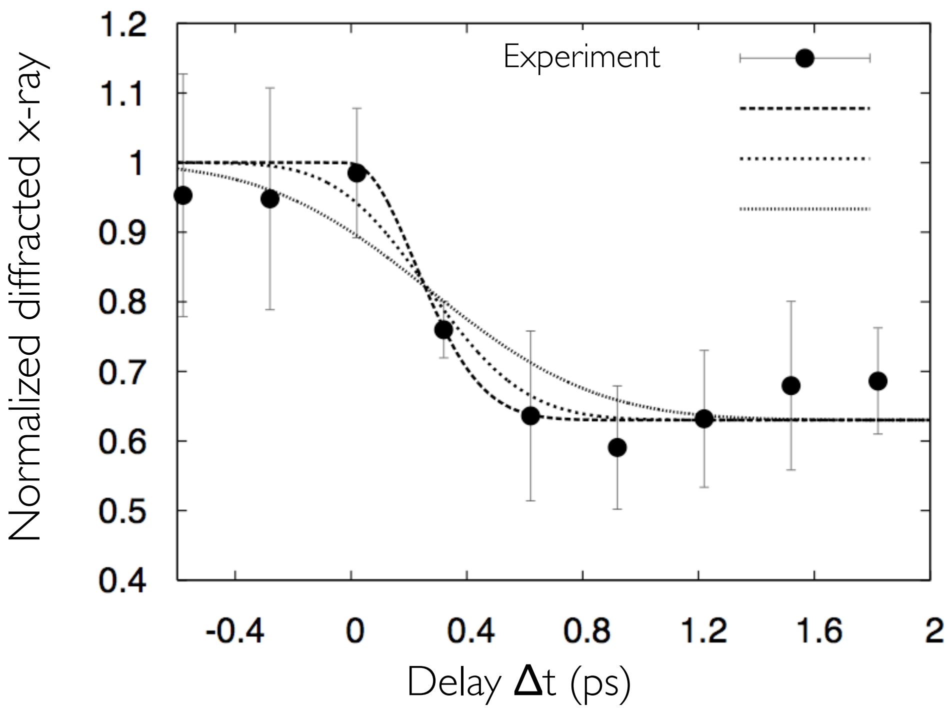


Femtosecond x-ray diffraction: Non thermal melting (InSb)

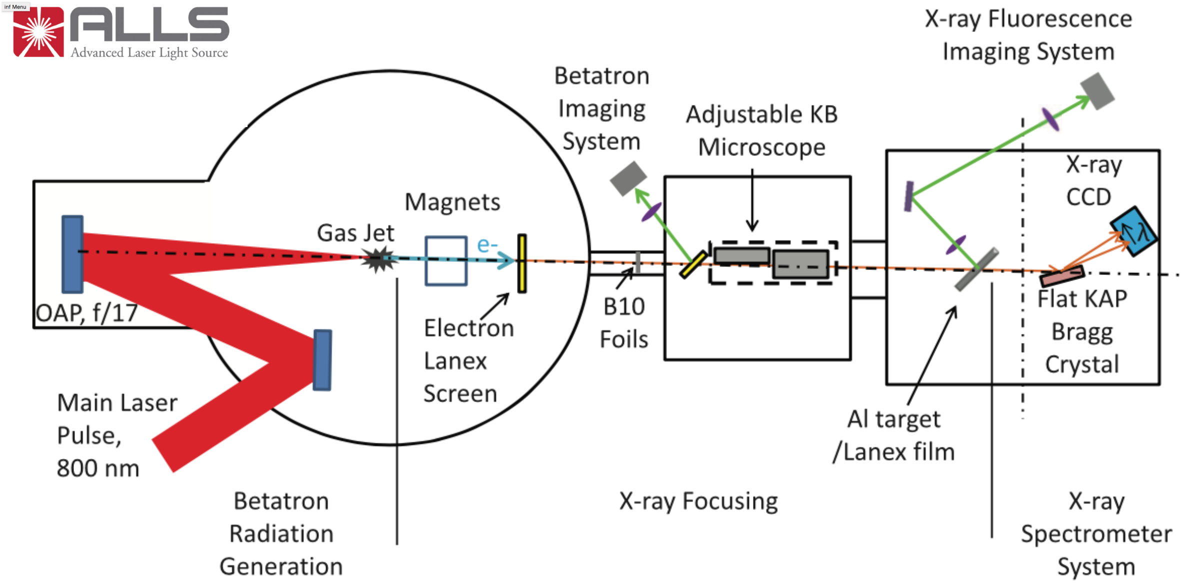




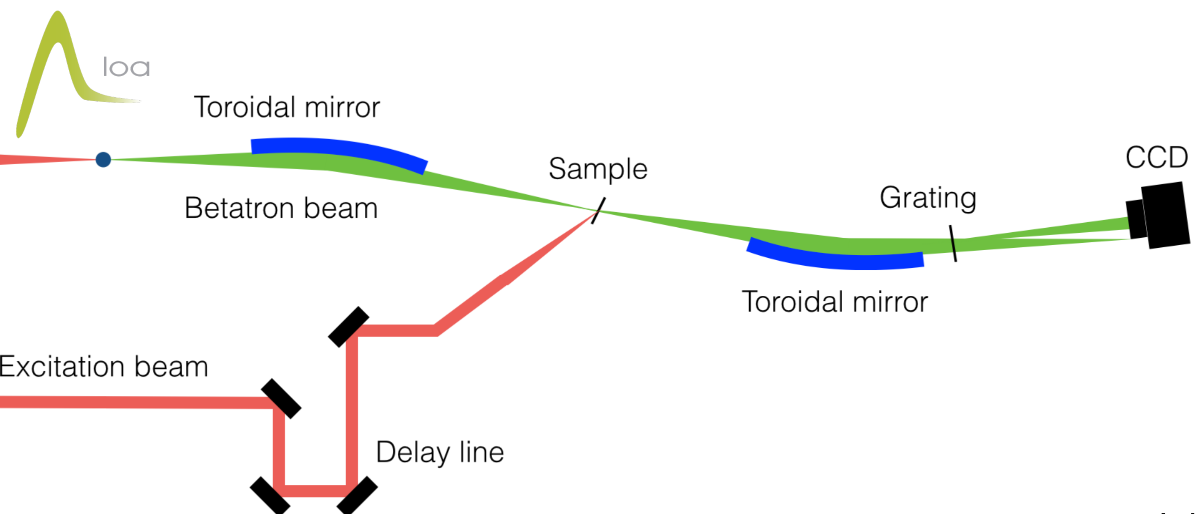
→ Ultrafast phase transition can be measured with tens fs resolution

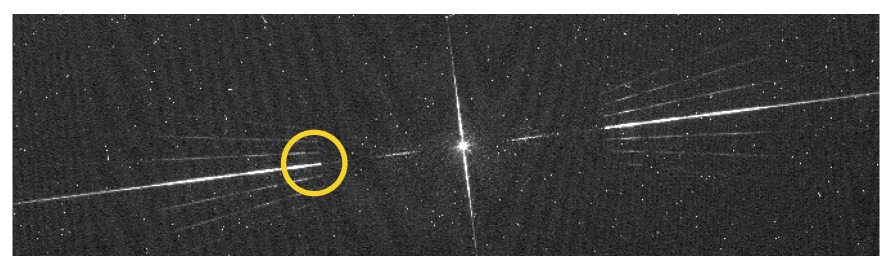


Development of fs x-ray absorption experiments



→ No time resolved study published yet



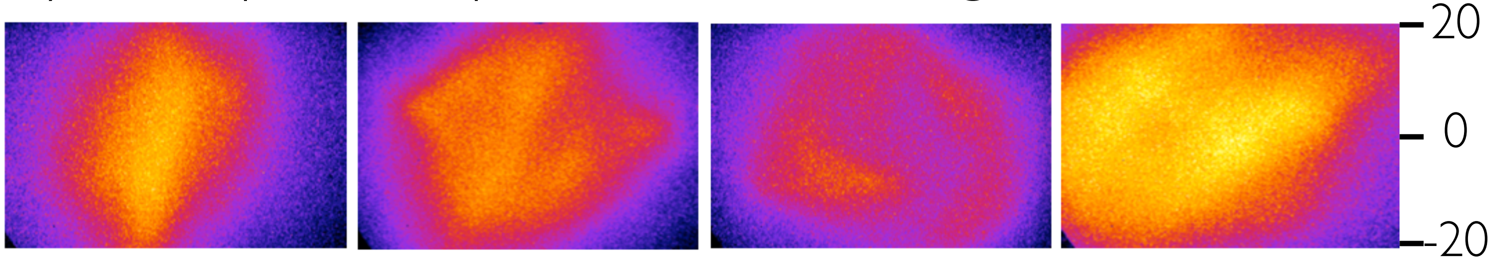


→ Limited spectral resolution

→ Significant shot to shot fluctuations

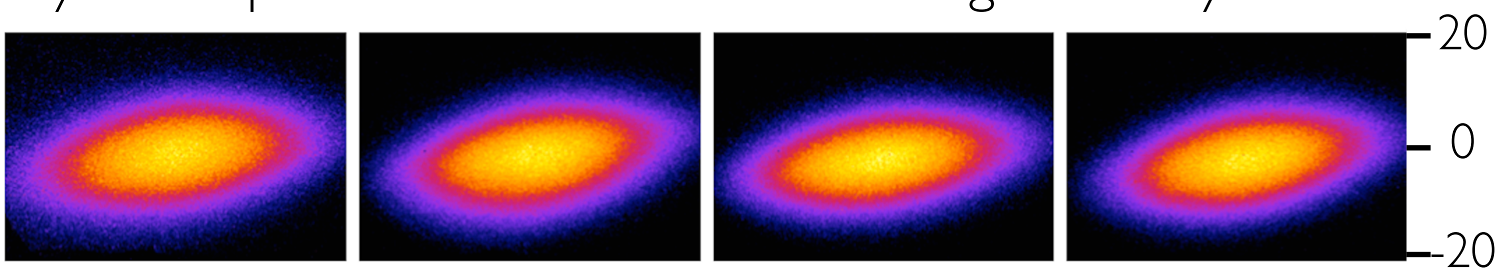
Stable and polarized Betatron radiation using gas mixture

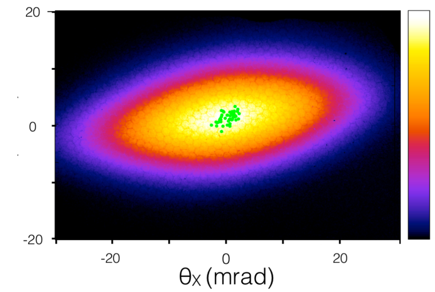
→ X-ray beam profile in pure He is fluctuating



Stable and polarized Betatron radiation using gas mixture

→ X-ray beam profile in 99% He + 1% Nitrogen is very stable

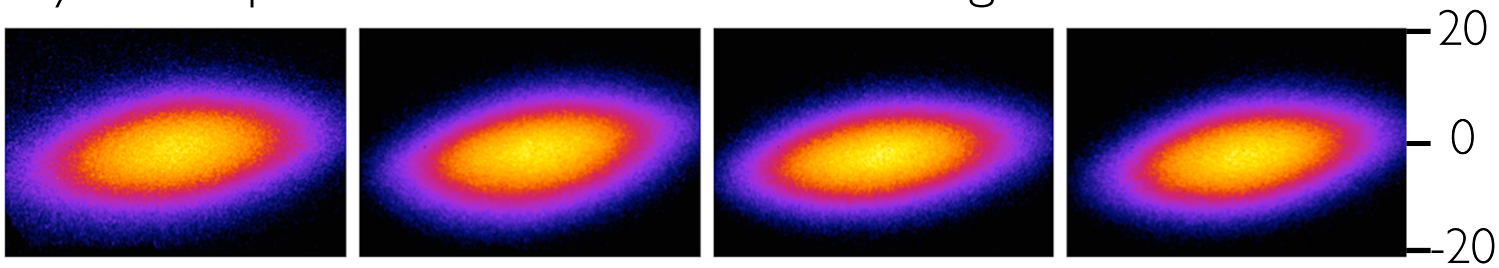


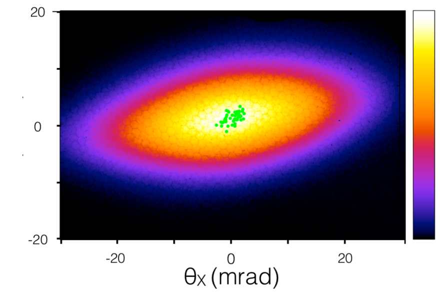


- → Pointing stability is 10% of the beam diameter
- → Beam shape is 100% reproducible

Stable and polarized Betatron radiation using gas mixture

→ X-ray beam profile in 99% He + 1% Nitrogen

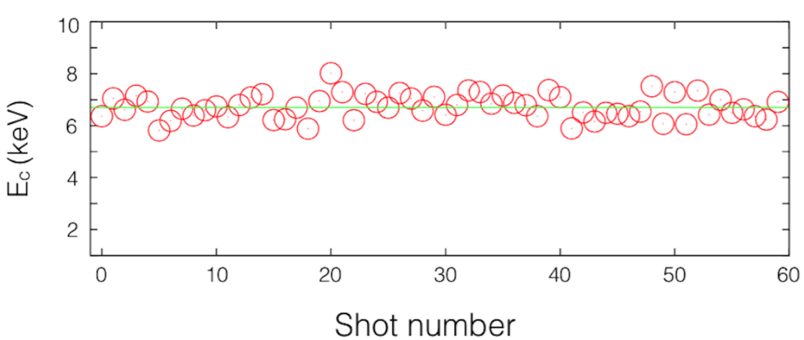


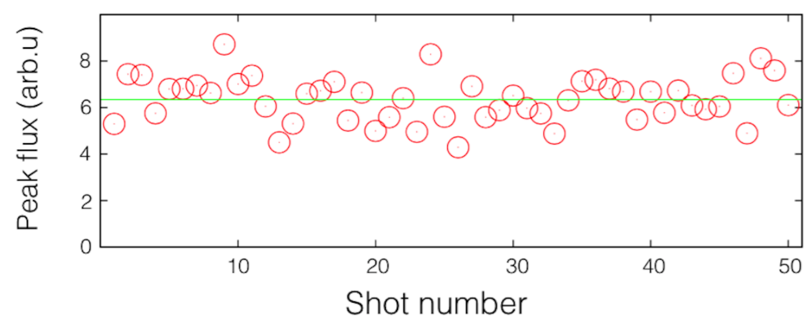


→ Pointing stability is 10% of the beam diameter

→ Beam shape is 100% reproducible

→ Shot to shot fluctuations of the critical energy and peak flux



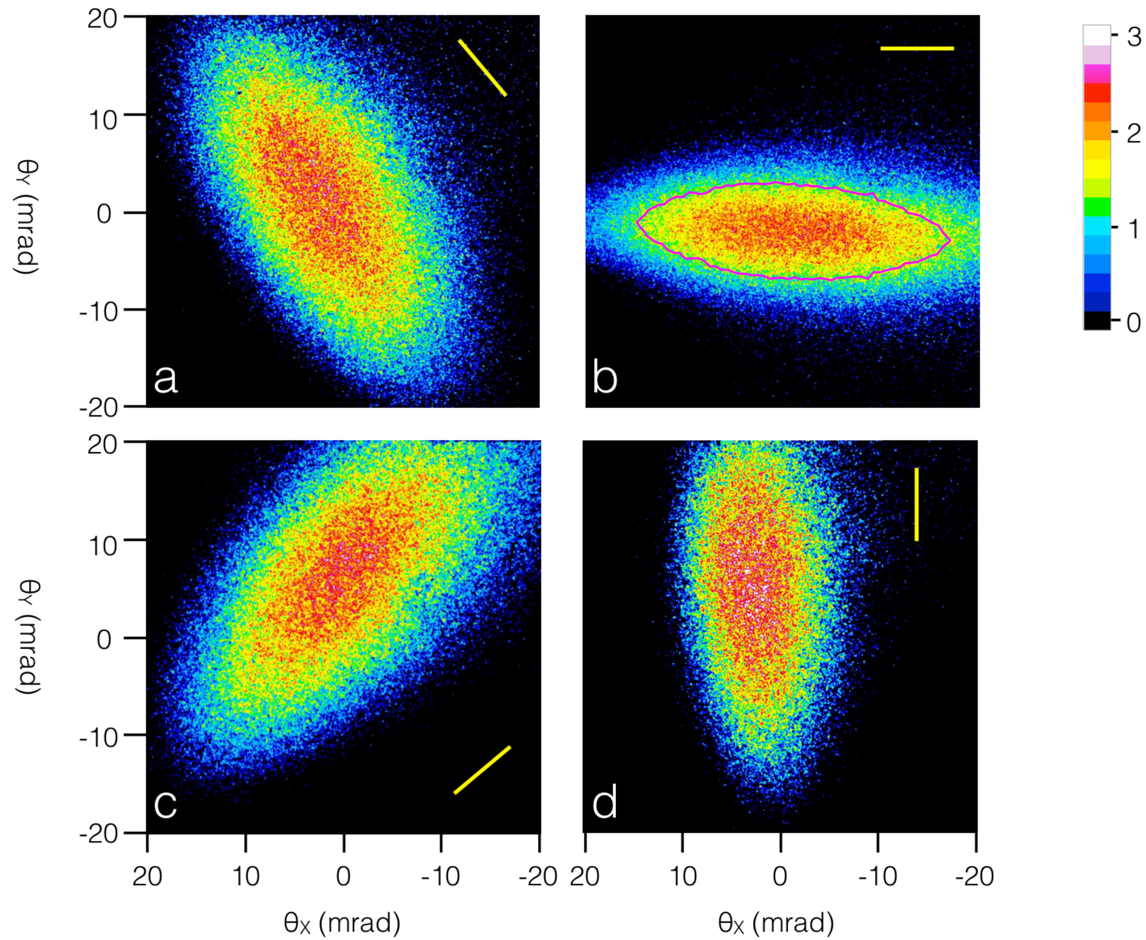


→ Energy stability (standard deviation)is about 10% of the mean energy

→ Energy stability (standard deviation) is about 15% of the mean flux

Stable and polarized Betatron radiation using gas mixture

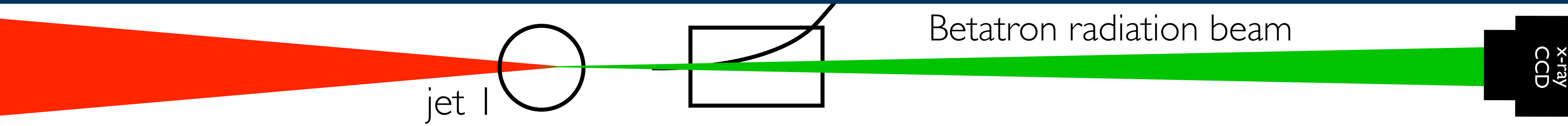
→ X-ray radiation is polarized & polarization

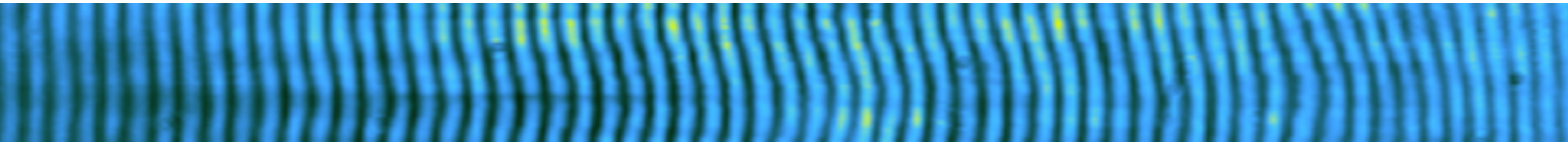


→ Polarization degree is about 80%

→ It is tuned by changing laser polarization (circular polarization produces circular beams)

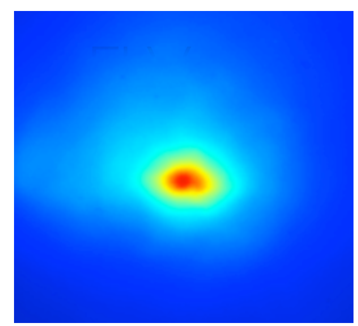
Decoupling accelerator and wiggler



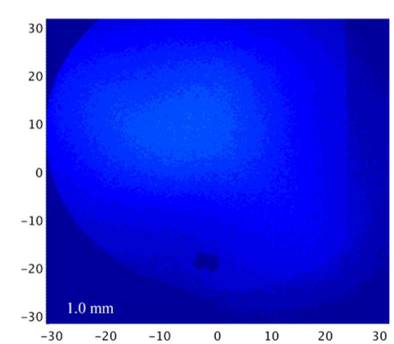


→ LPA is set to produce good quality e-beam

LPA

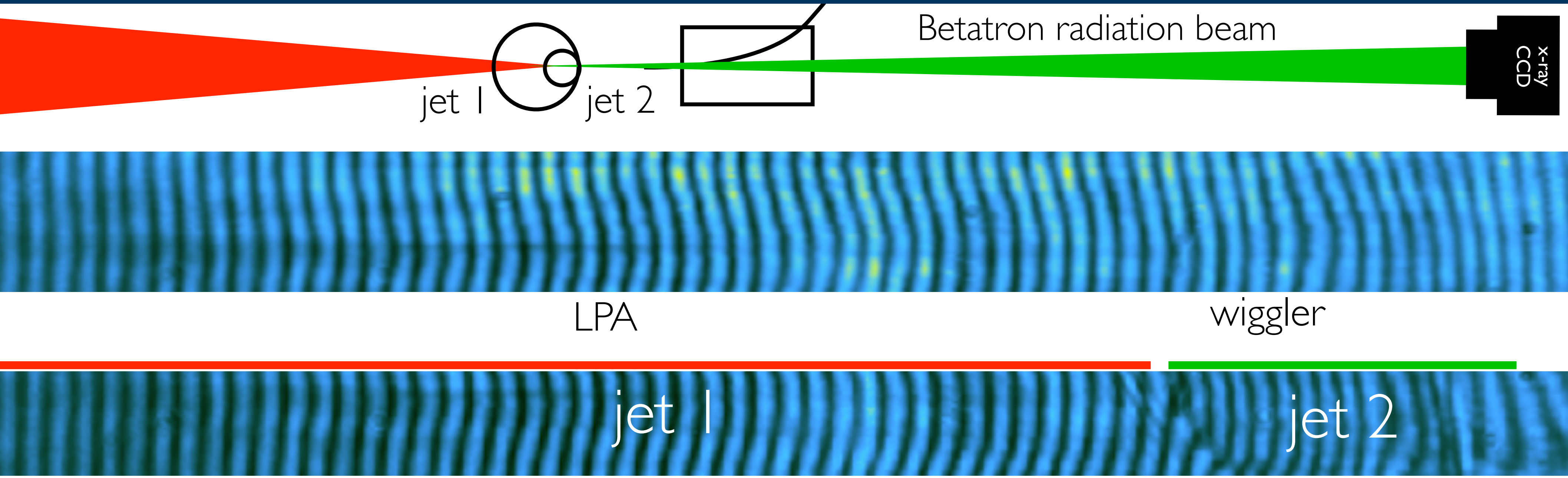


e-beam

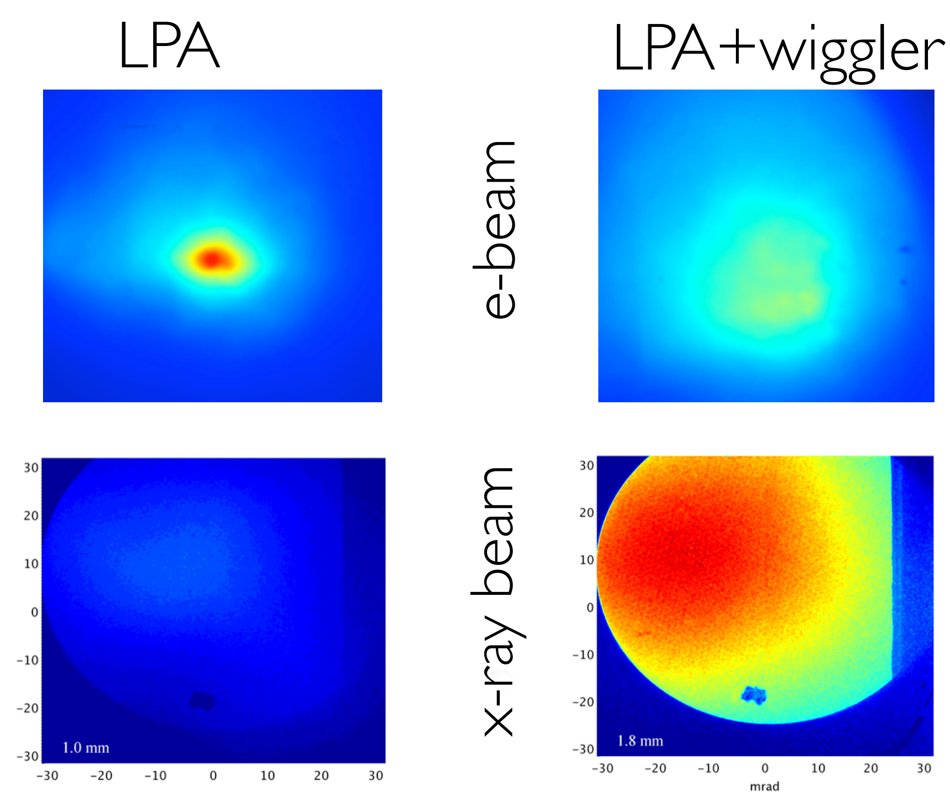


x-ray beam

Decoupling accelerator and wiggler



- LPA is set to produce good quality e-beam
- Independent control of LPA and wiggler
- Produce high energy and high quality electrons



Outline

Betatron source

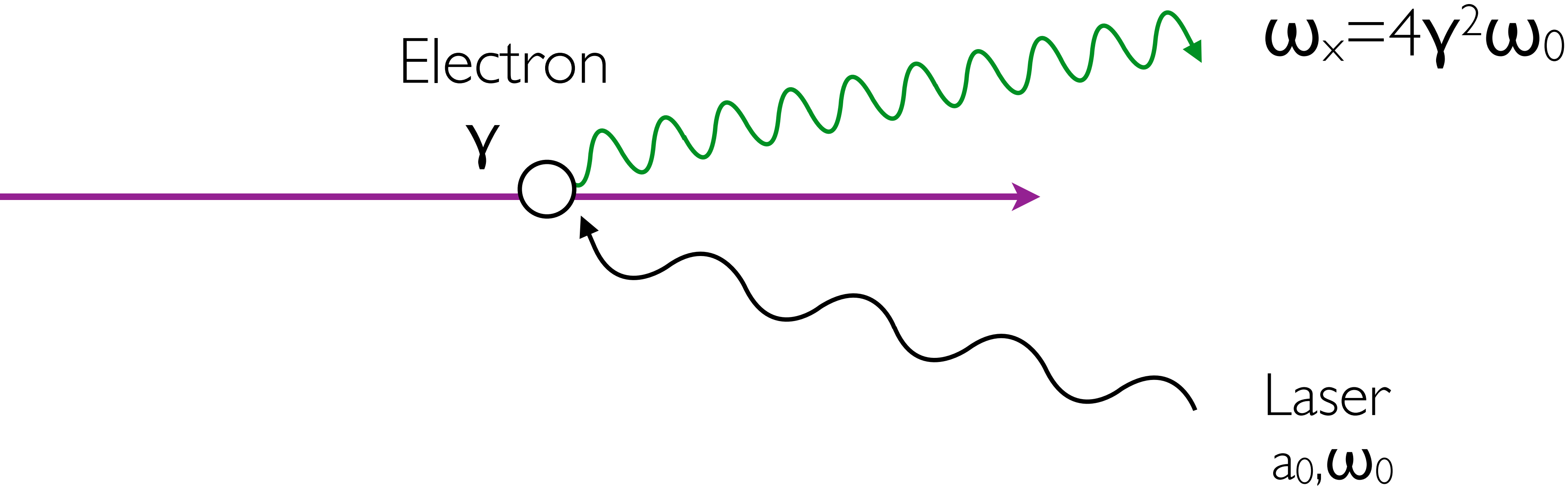
- Principle
- Experimental characterization of the source
- Applications experiments
- Recent progresses

Compton source

- Principle
- Experimental characterization of the source
- Applications experiments

Summary, conclusion & perspectives

X-ray Compton scattering: *Principle*



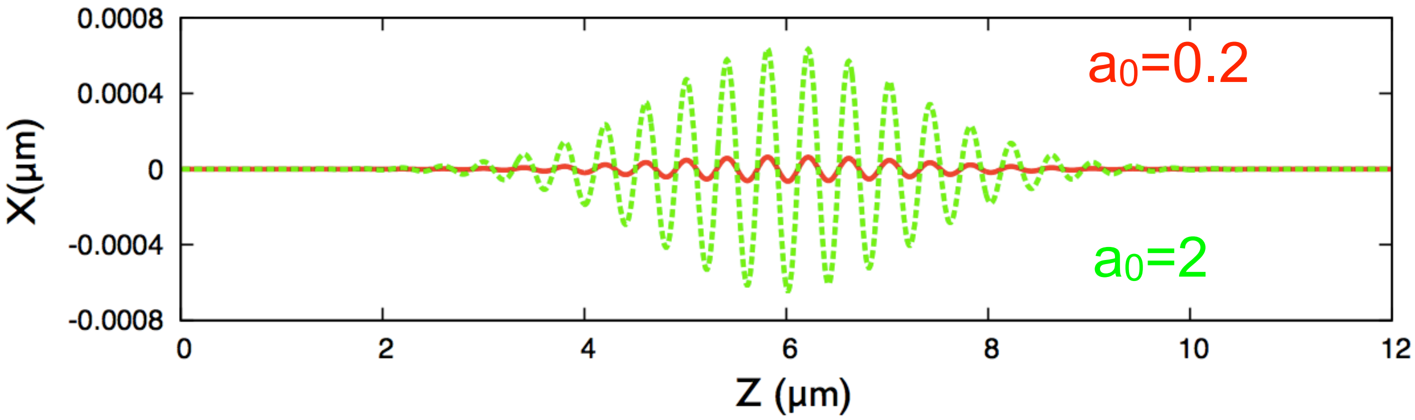
Modest electrons energies can produce high energy x-rays

20 MeV ⟶ 10 keV

65 MeV ⟶ 100 keV

200 MeV ⟶ 1000 keV

X-ray Compton scattering: *Test particle simulation*



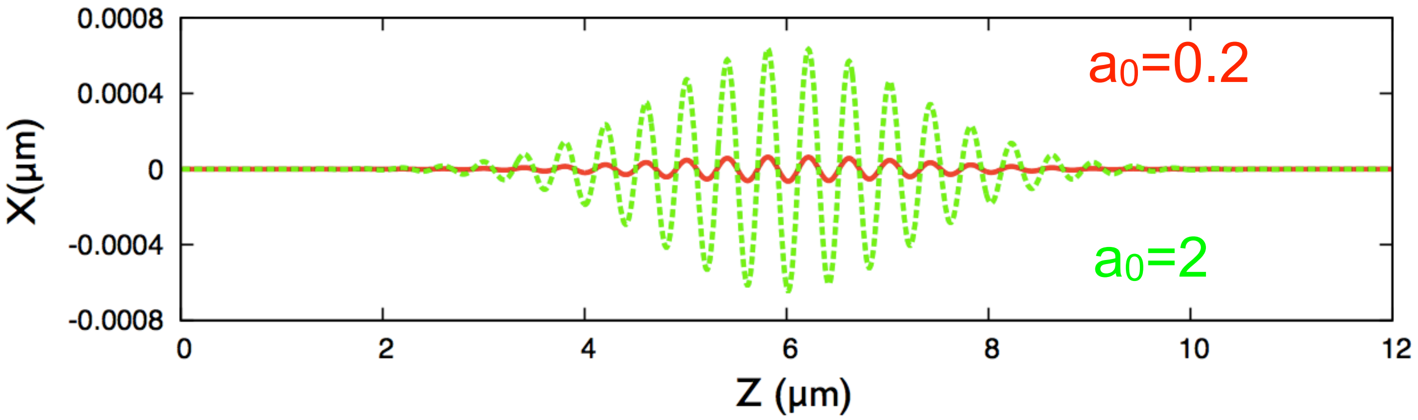
Electrons orbits

$\gamma \approx 200$

$\lambda_u \approx 1\ \mu m$

X-ray Compton scattering: *Test particle simulation*

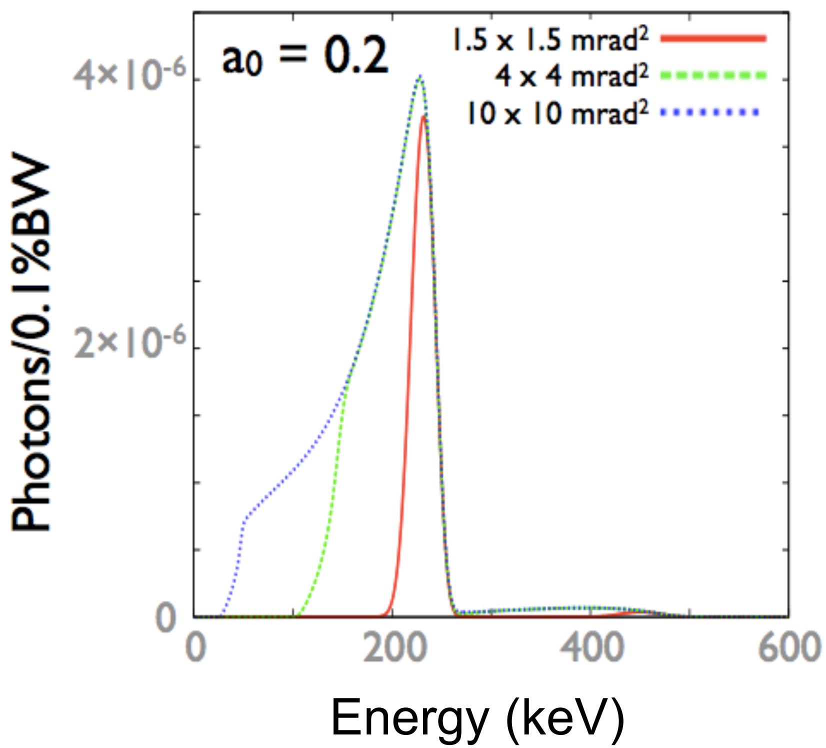
Electrons orbits

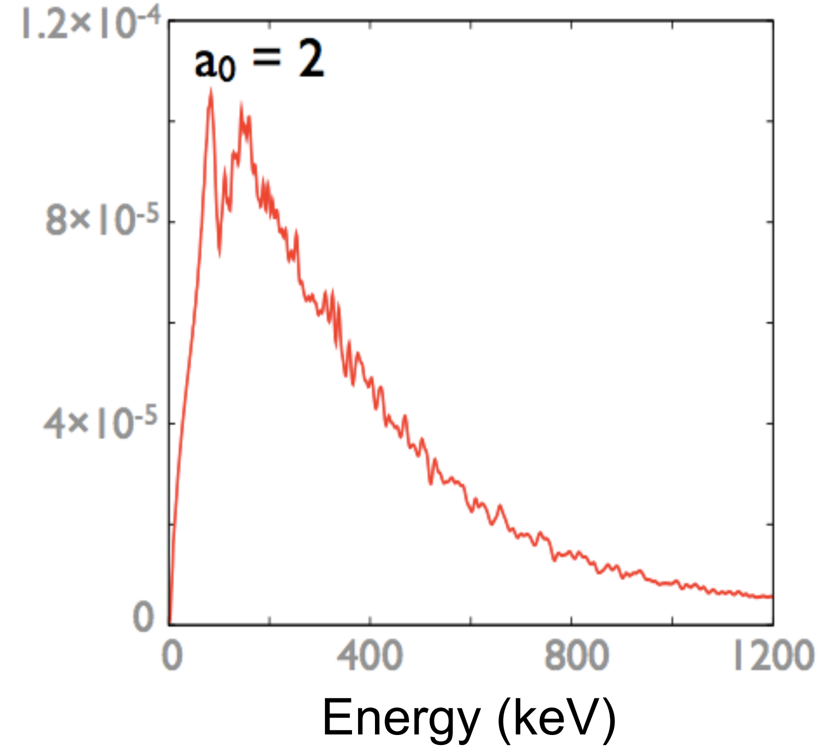


$\gamma \approx 200$

$\lambda_u \approx 1\ \mu m$

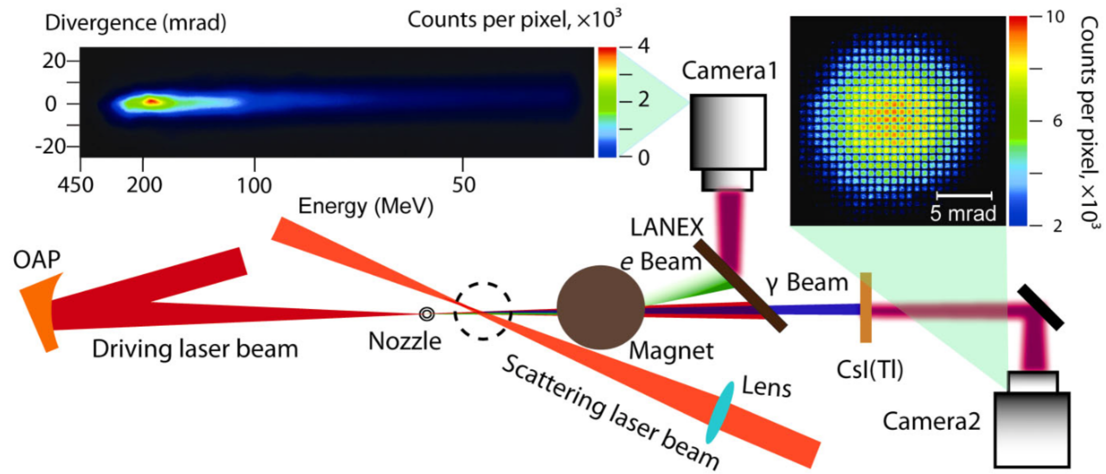
Spectra





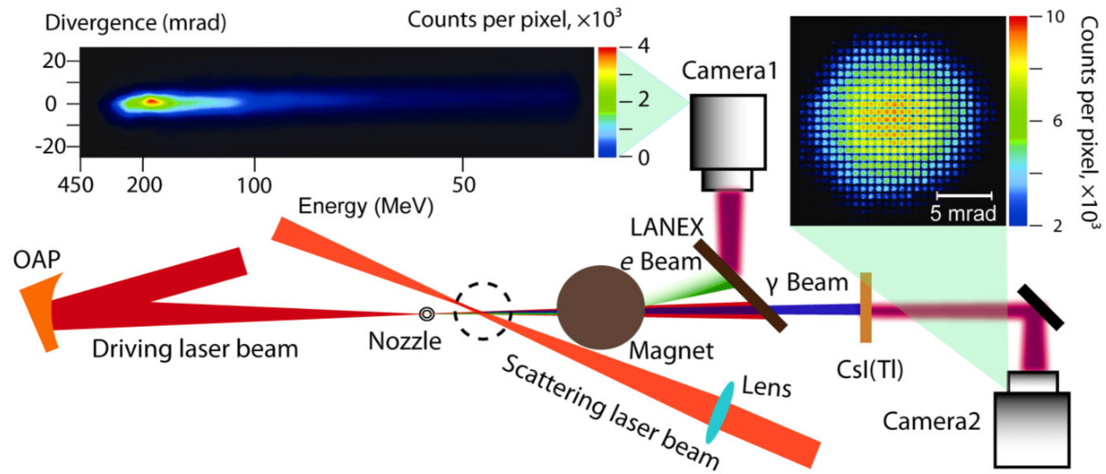
X-ray Compton scattering: *two laser beams method*

- Experiment setup

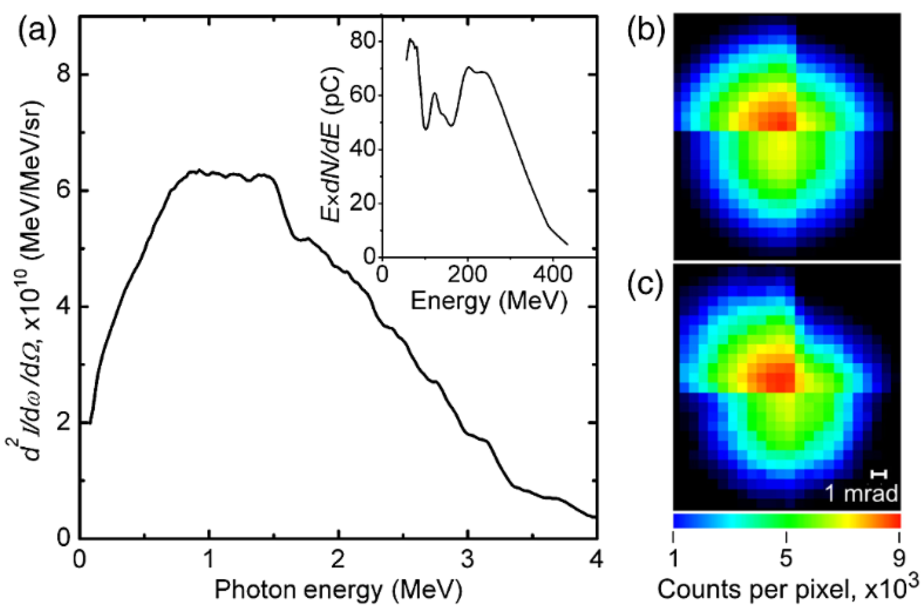


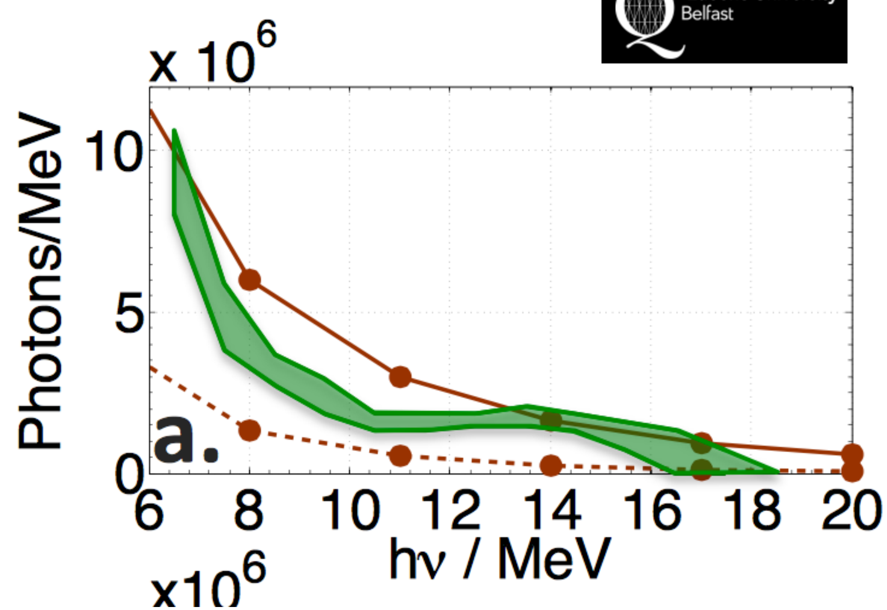
X-ray Compton scattering: *two laser beams method*

Experiment setup



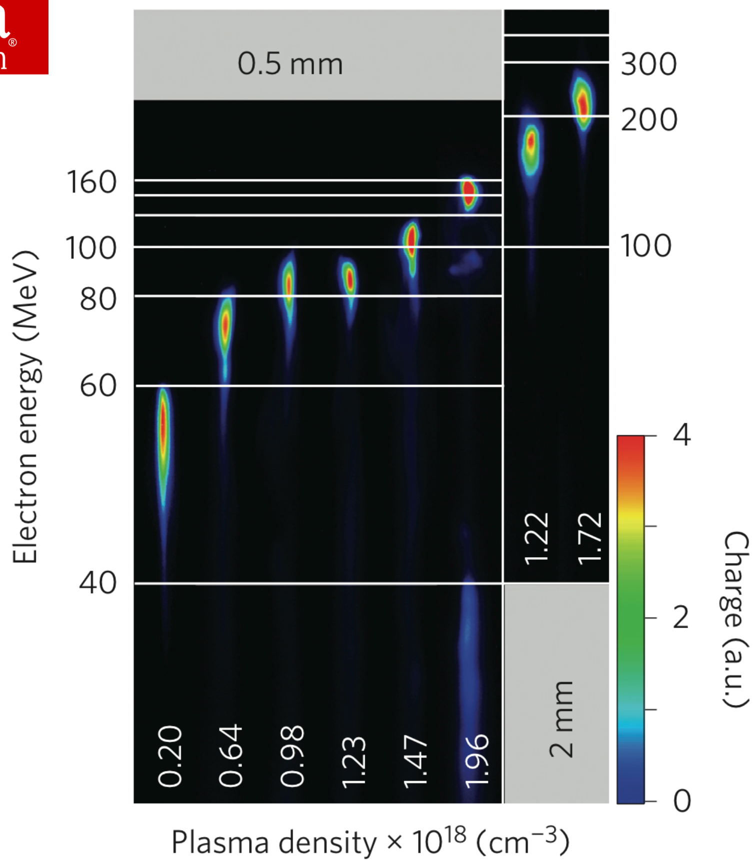
Spectrum and beam profile

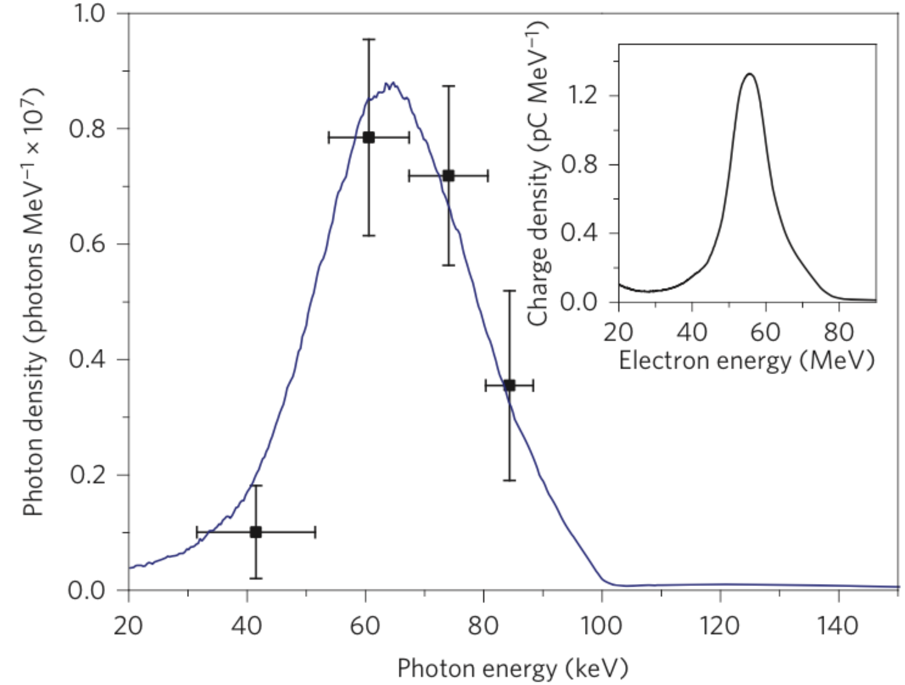


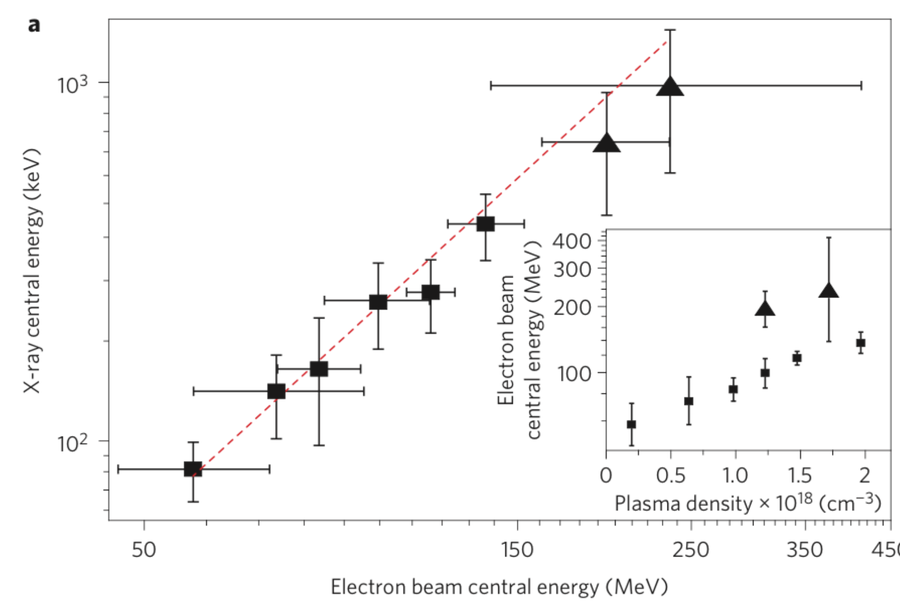


X-ray Compton scattering: *two beams method*

→ Production of narrow band radiation



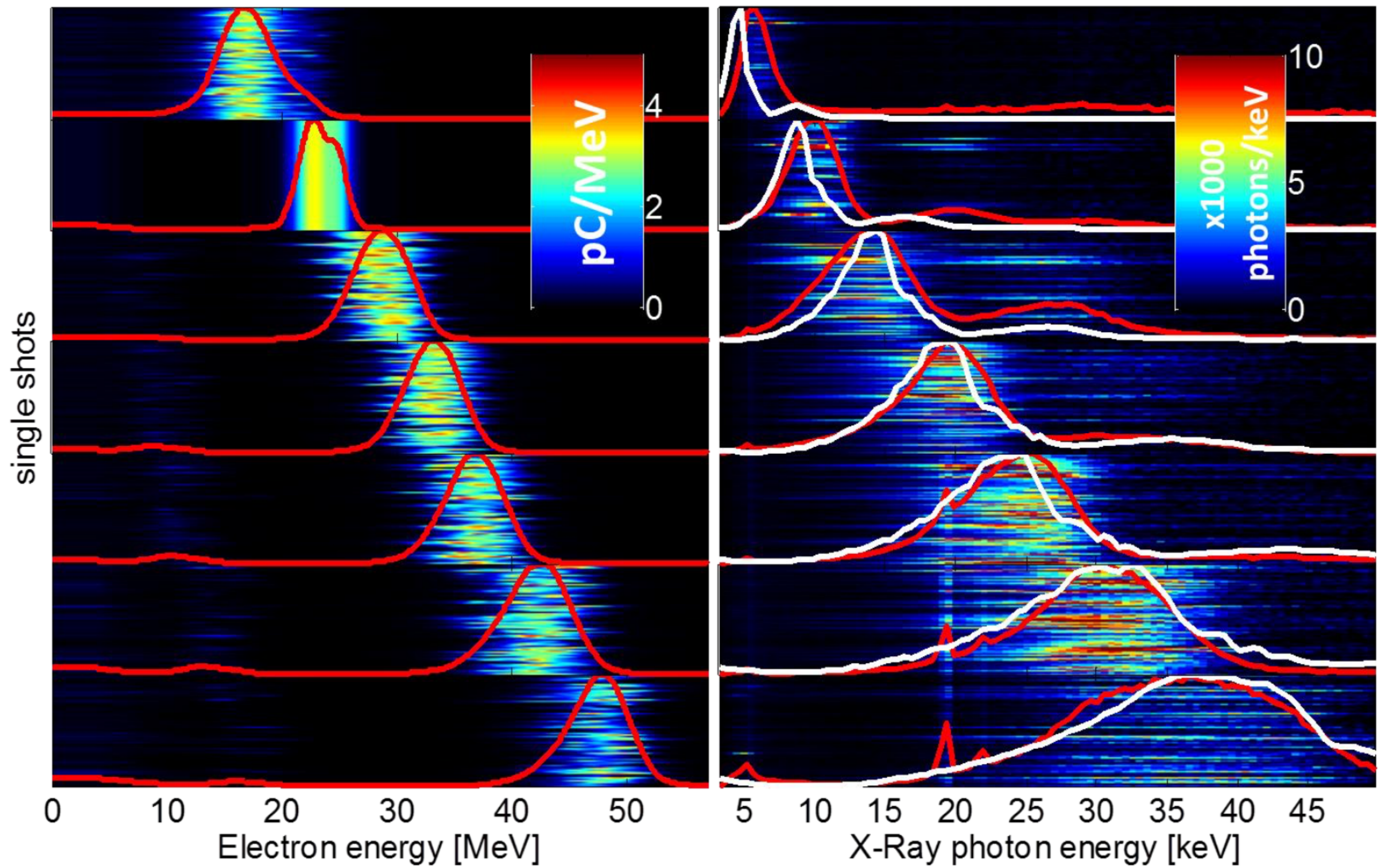




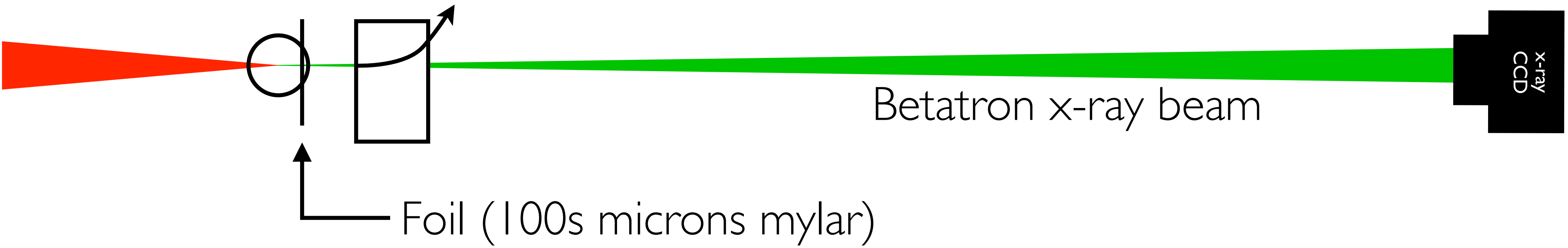
→ Central x-ray energy can be tuned by tuning electron energy

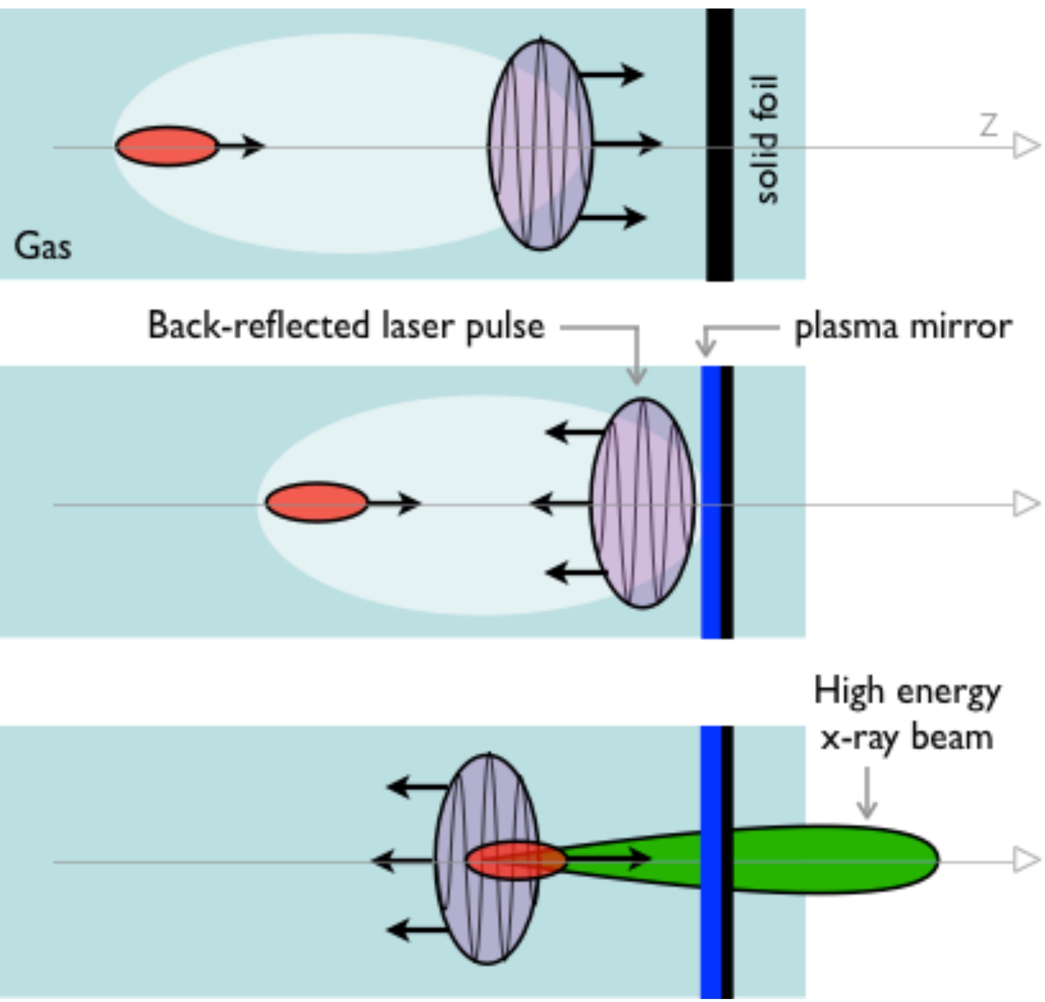
X-ray Compton scattering: *two beams method*

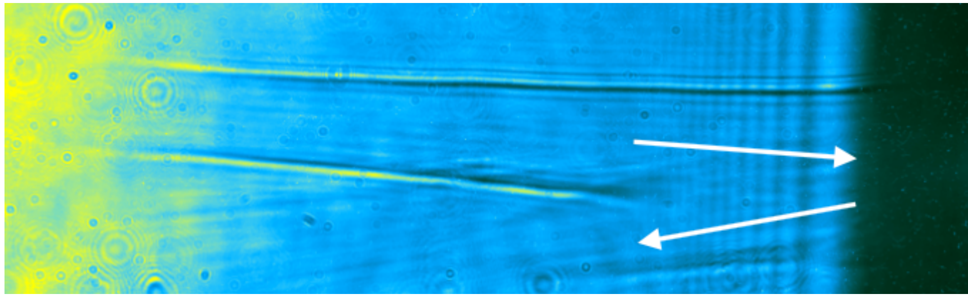
→ Narrow band x-rays from a stable and tunable LPA (shock injection)



X-ray Compton scattering: *Single beam method*

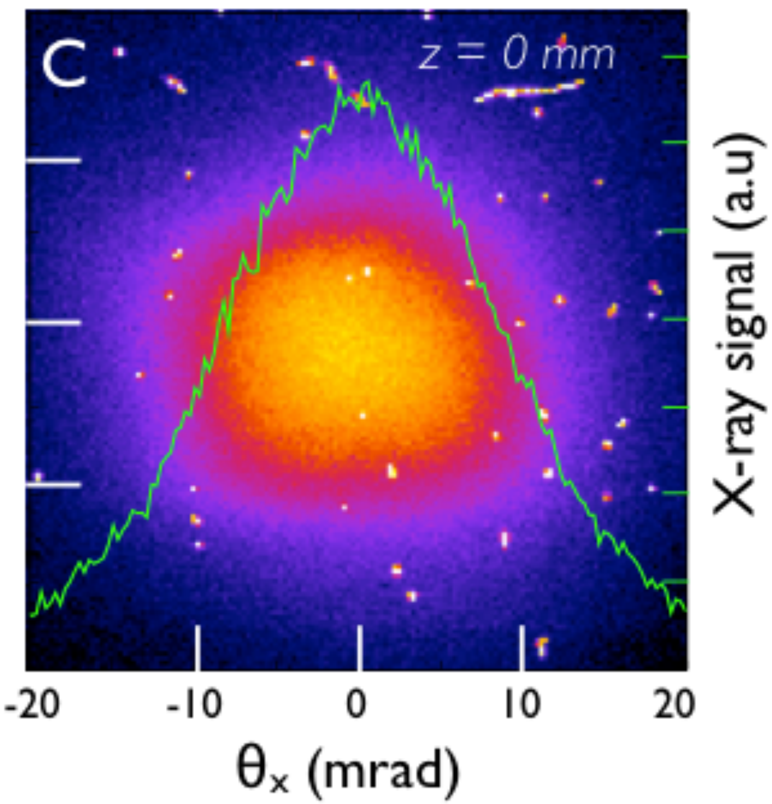


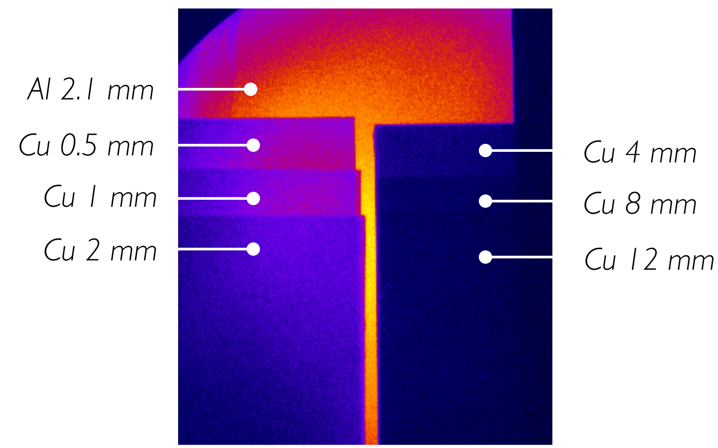


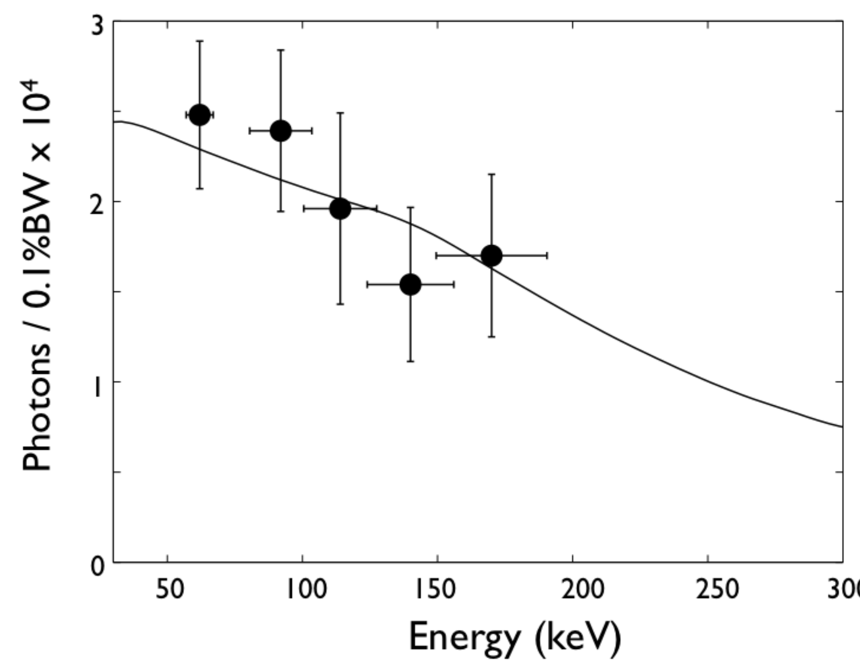


- Inherent synchronization
- No independent tuning of e- beam and laser beam

X-ray Compton scattering: *Single beam method*





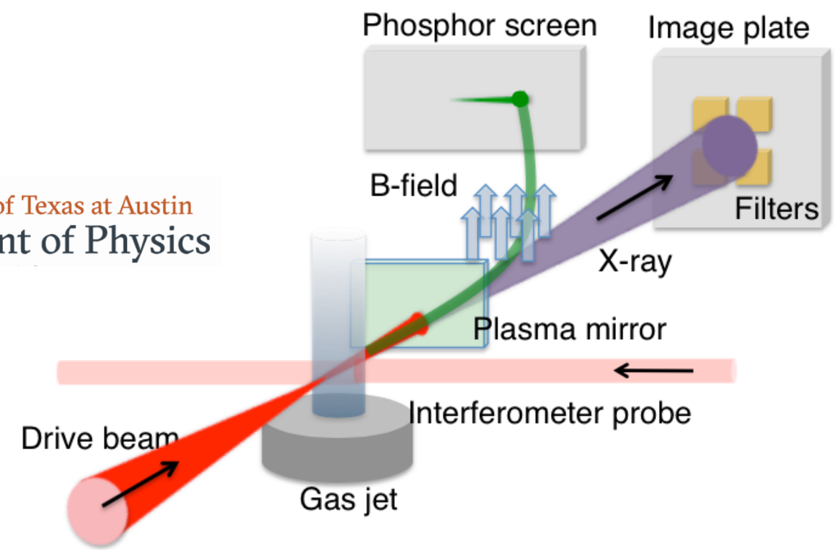


- Divergence is about 20 mrad
- the flux is about 10^8 photons / shot

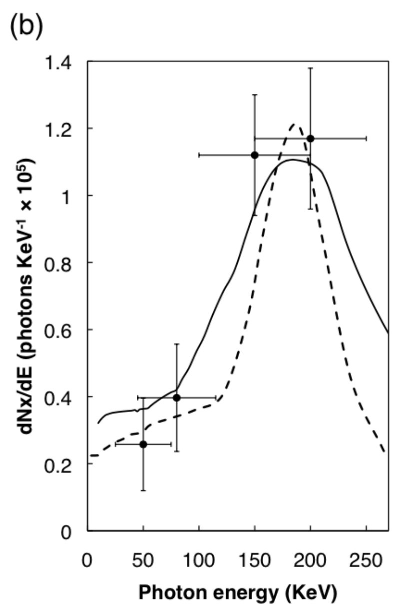
X-ray Compton scattering: *Single beam method*

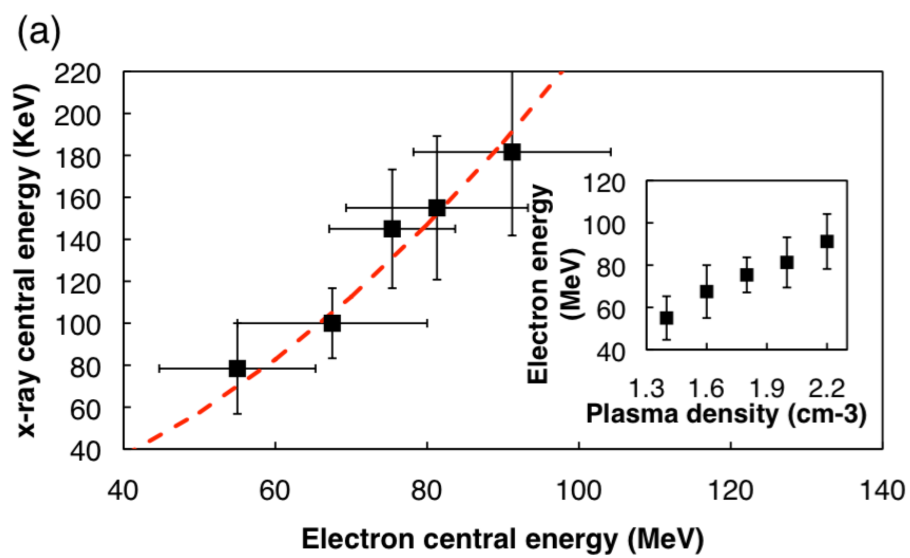
→ Production of narrow band radiation

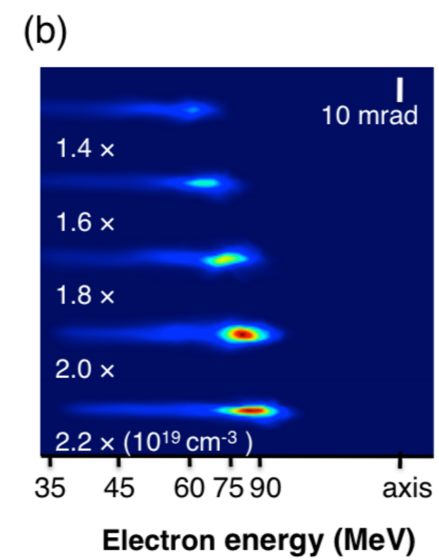
The University of Texas at Austin
Department of Physics



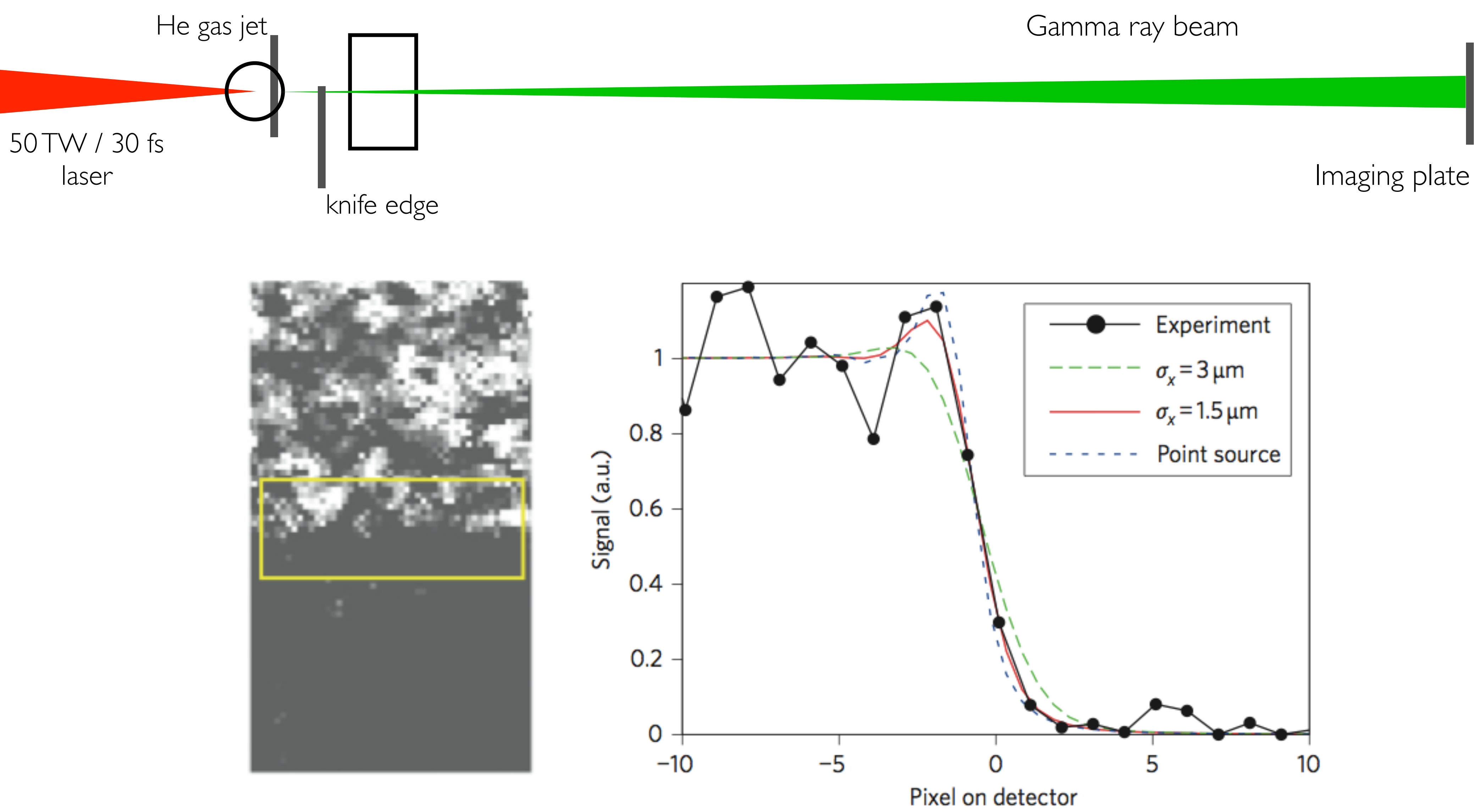
Central x-ray energy can be tuned by tuning electron energy





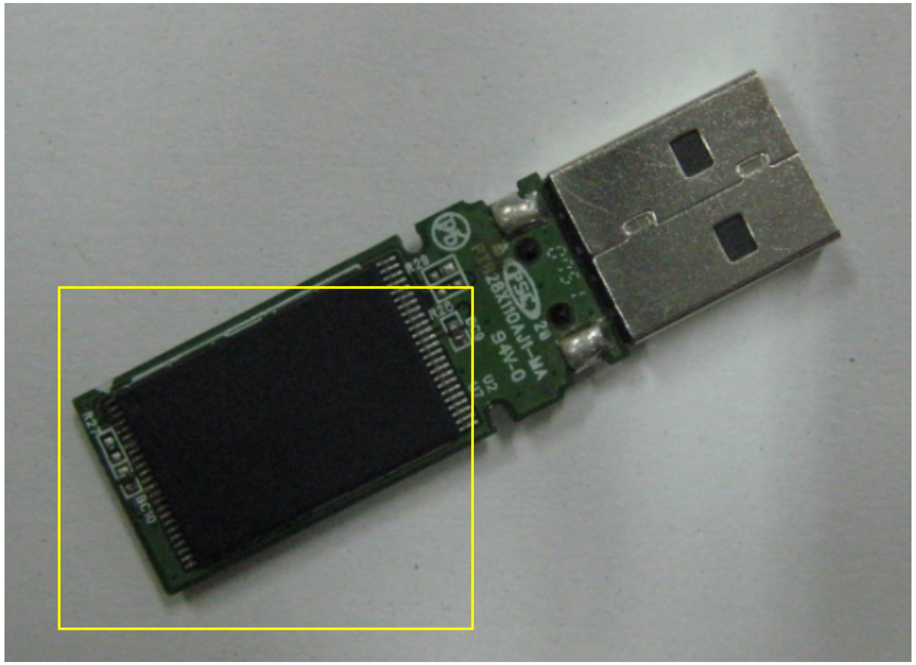


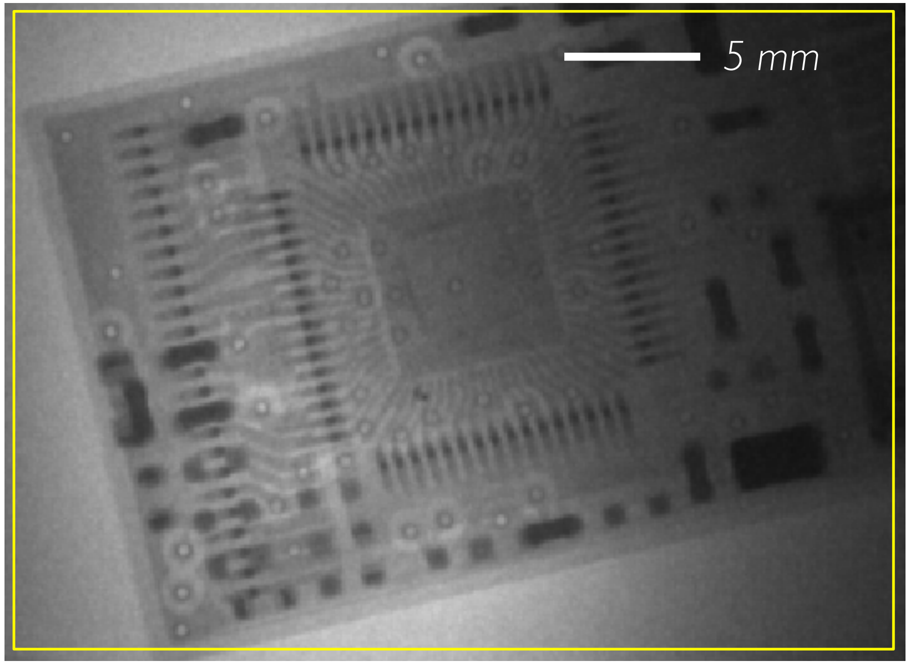
Source size

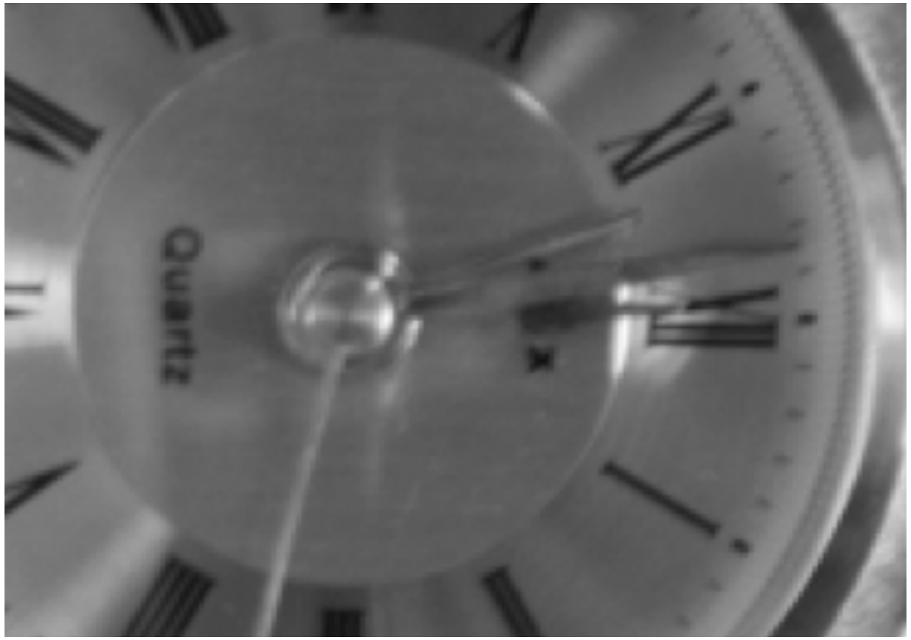


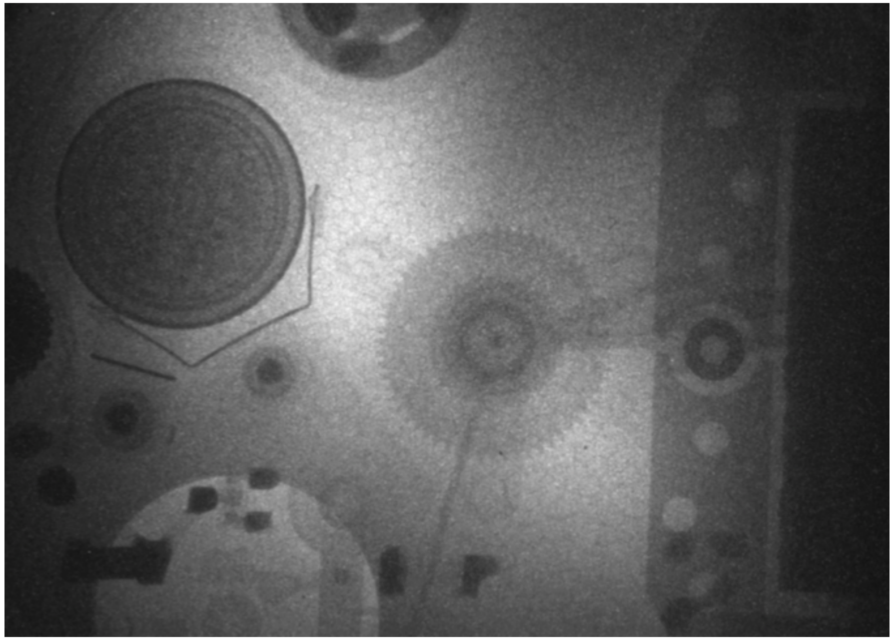
Micron order transverse source size

High energy x-ray radiography









Summary of the source features & perspectives

- 10^4 photons/shot/0.1% BW @ 100 keV
- $10^{8\text{-}9}$ photons/shot
- collimated: 10's mrad
- ultrashort: 10's fs
- broadband: 10s keV to few MeV or narrow band tunable
- small source size: 1- 2 microns

Collection of the high energy x-ray beam will be much more complicated

Summary

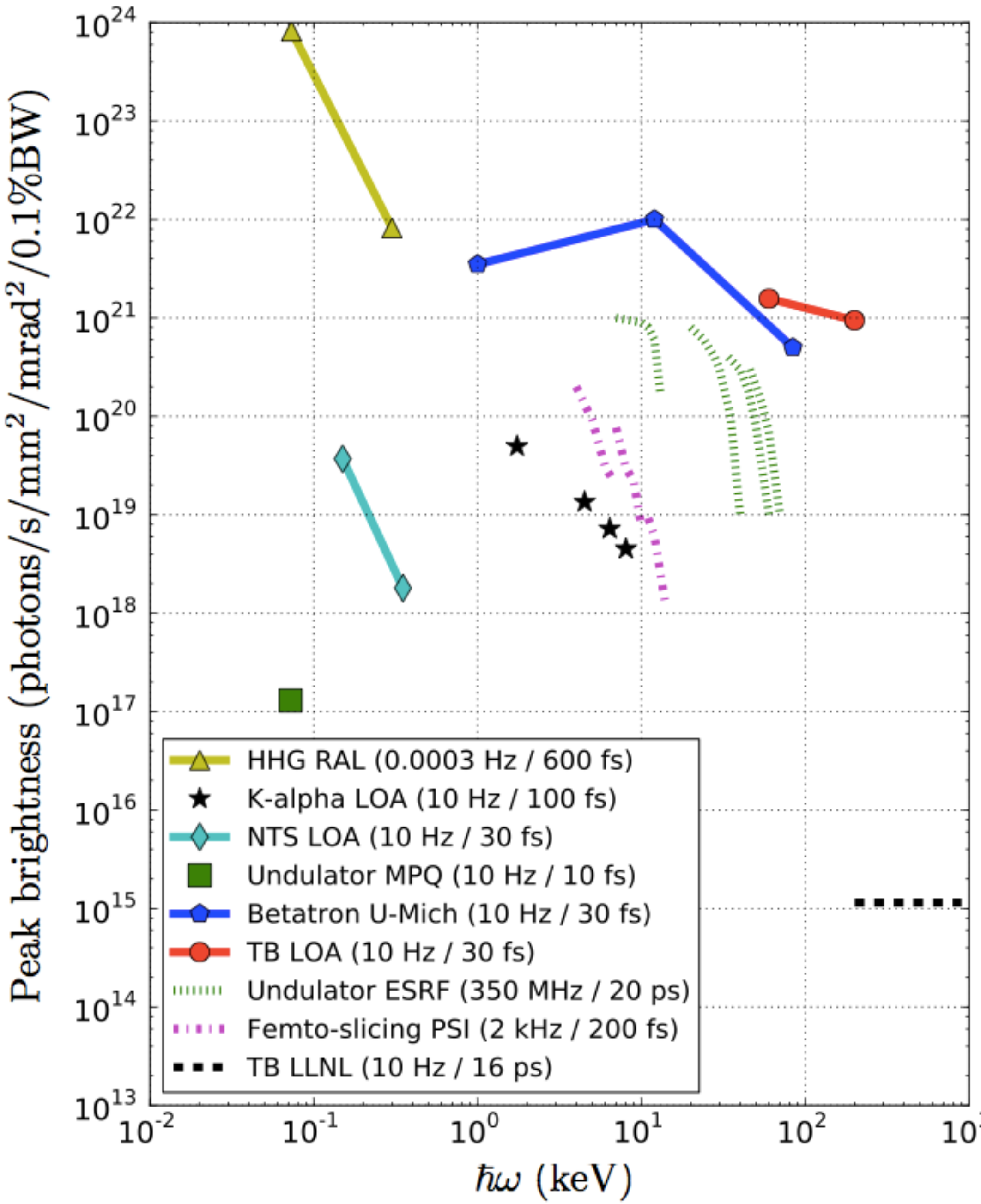
	Nonlinear Thomson scattering	Betatron	Compton scattering
Electron energy (MeV)	few 10s	few 100s	few 100s
λ_u (microns)	10	100	1
K	10	10	1
Radiation energy (keV)	0.1	1-10	100-1000
θ	100 mrad	10 mrad	10 mrad
n photons	10^9	10^8	10^8

Conclusion

Nonlinear Thomson scattering:
- 100 eV - 1 keV
- Large divergence
- femtosecond

- Betatron radiation:
- Up to several 10s keV
- Low divergence
- femtosecond
- micron source size

- Compton:
- Up to several 1 MeV
- Low divergence
- femtosecond
- micron source size



Perspectives

- Betatron radiation:

Control of the electrons orbits and increase the x-ray energy. Schemes based on density modulations are promising.

- All optically driven Compton source:

Produce x-ray beams with smaller laser at higher repetition rates in the 10-20 keV range

Reduce the spectral bandwidth (using for example beam transport)

- Applications:

Ultrafast x-ray absorption

High energy phase contrast radiography.

Betatron/Compton @ LOA is the work of

Sebastien CORDE, Andreas DOEPP, Cedric THAURY, Emilien GUILLAUME, Julien GAUTIER, Victor MALKA, Antoine ROUSSE, Stephane SEBBAN, Romuald FITOUR, Felicie ALBERT, Rahul SHAH, Jean Philippe GODDET, Amar TAFZI, Pascal ROUSSEAU, Jean Philippe ROUSSEAU, Benoit MAHIEU, Antoine DOCHE.

Reference: Femtosecond X-rays from laser plasma accelerators
S.Corde, et al.
Review of Modern Physics, 2013