Femtosecond X-ray from laser plasma accelerators

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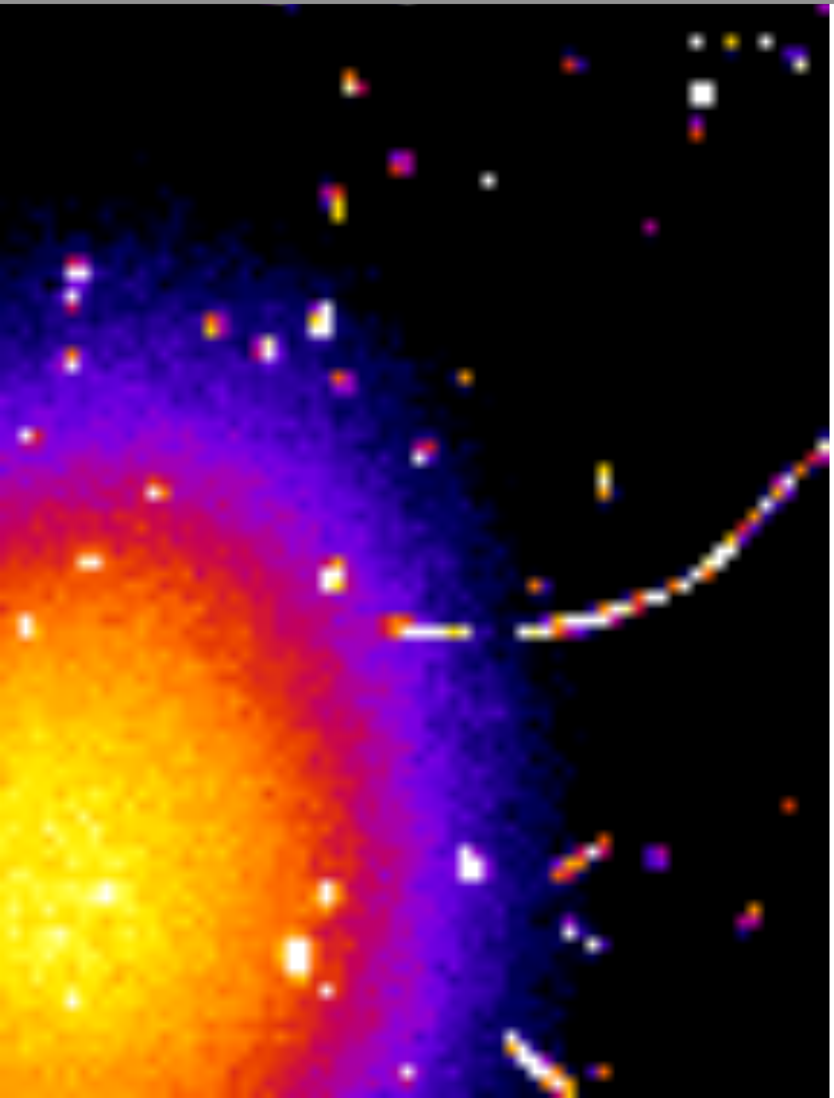

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Why do we need x-ray sources ?

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Femtosecond x-ray/Gamma-ray sources

- To probe the matter
- To excite the matter

Physics
- Plasmas physics
- Solid State physics

- X-ray diffraction
- X-ray absorption
- Thomson scattering
- ect...

Imaging

- Non destructive testing
- Phase contrast imaging

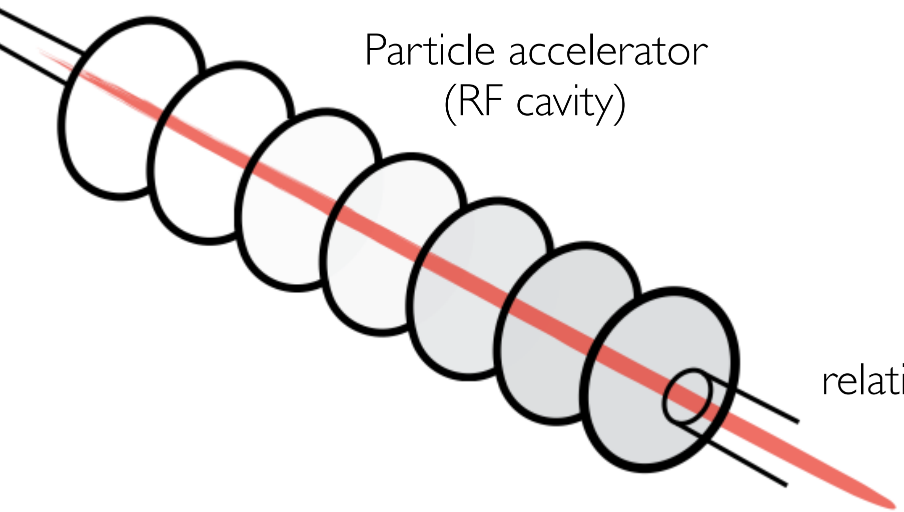
Chemistry

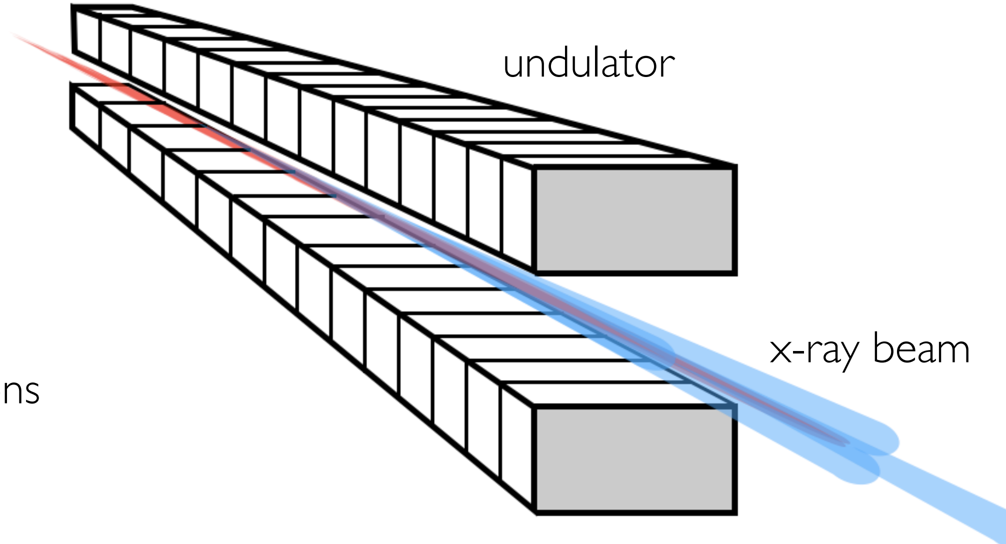
Biology

- Ultrafast x-ray science
- X-ray radiography
- etc...

→ There is a need for femtosecond x-ray sources

Femtosecond x-ray sources: Synchrotron / Free electron lasers





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- collimated x-ray beams
- picosecond duration at synchrotron
- femtosecond duration at FEL
- stable
- FEL are several orders of magnitude brighter than synchrotrons

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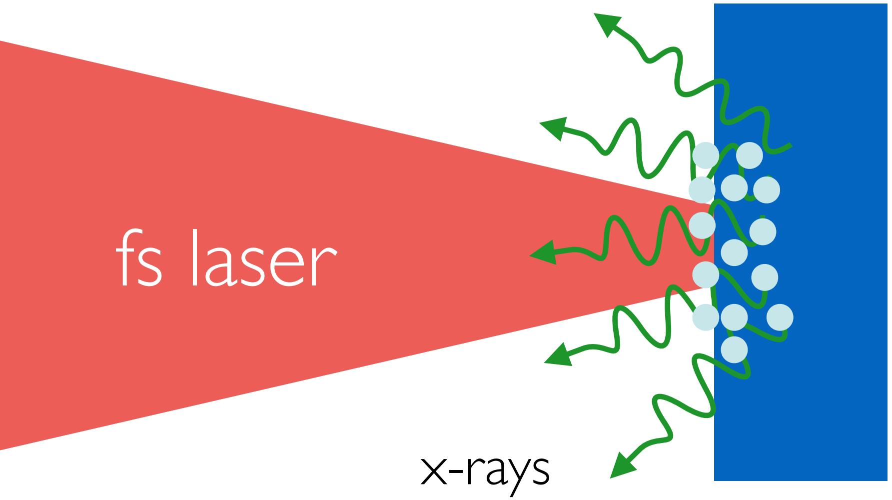
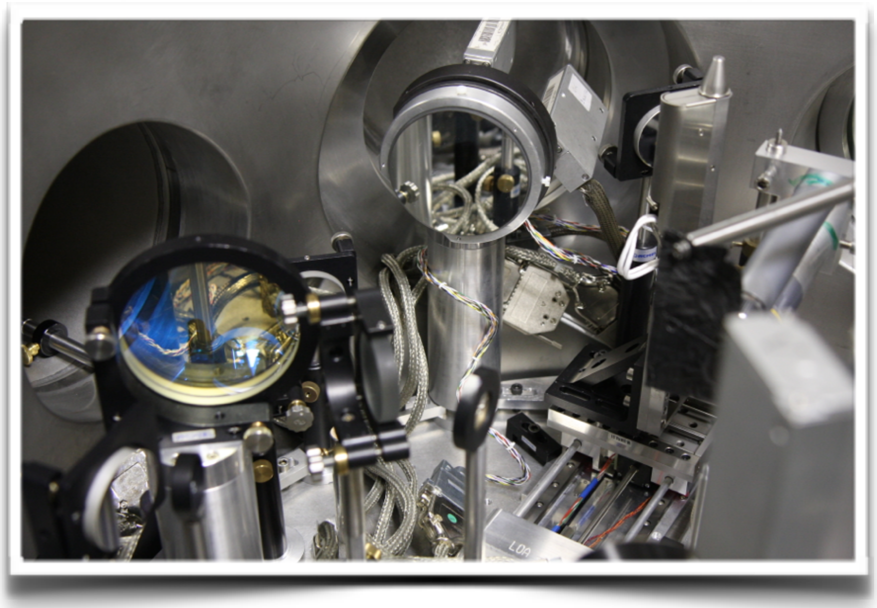
- Large facilities
- limited beam time

Femtosecond x-ray sources: Plasma sources





Hot electrons from laser solid interaction ionize inner shel atoms. Inner shell vacancy is filled by outer shell. This results in the emission of a short x-ray pulse

+

- femtosecond duration (few hundreds).
- Compact

-

- Isotropic emission
- Lines spectrum, not easily tunable
- Low brightness

Combine avantages of Synchrotron and plasmas sources

How can we produce a radiation source that is :

- Compact
- femtosecond
- Collimated

Combine avantages of Synchrotron and plasmas sources

How can we produce a radiation source that is :

- Compact
- femtosecond
- Collimated

→ Produce synchrotron radiation in a plasma

Produce relativistic electron beam	+	Wiggle the electron beam	=	X-rays
- Laser - Laser plasma accelerator		- Laser - Plasma - counter-propagating laser		- Nonlinear Thomson - Betatron - Compton / Thomson backscattering

Outline

1 - General formalism: Radiation from relativistic moving charge

2 - Non linear Thomson scattering

3 - Betatron radiation

4 - Compton scattering

5 - Conclusions & perspectives

The radiation mechanism

For all sources described here, the radiative mechanism is the radiation from relativistic electrons.

→ What are the required conditions to produce x-ray with relativistic electrons ?

Radiation from a relativistic electron

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

Position

Direction of observation

→ This is the general expression of the radiation emitted by a moving charge

From simple considerations we can determine the radiation features

Radiation from a relativistic electron

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

- Radiation is maximum for $\vec{\beta}.\vec{n} \rightarrow 1$. This is verified for $\beta \simeq 1$ and $\vec{\beta}$ and $\vec{n}$ parallel
- Radiation is emitted in the direction of the electron velocity.
- Relativistic electrons emit orders of magnitude more radiation than non relativistic electrons

Radiation from a relativistic electron

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

→ No radiation is emitted without acceleration

→ Acceleration is responsible for the emission of radiation

Radiation from a relativistic electron

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 more efficient than longitudinal acceleration to produce radiation

Radiation from a relativistic electron

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

Velocity

Acceleration

Radiated energy

- The phase term can be locally approximated by $e^{i\omega(1-\beta)t}$

The integration over time is non-zero only if the the phase term oscillates at the same frequency as the integrand.

If we assume that the electron oscillates at the frequency ω_e it is necessary to have $\omega\,(1-\beta) \sim \omega_e$

- Therefore an electron oscillating at ω_e produces radiation at $\omega = \omega_e/(1-\beta) \sim 2\gamma^2\omega_e$

What do we need to produce X-rays beams ?

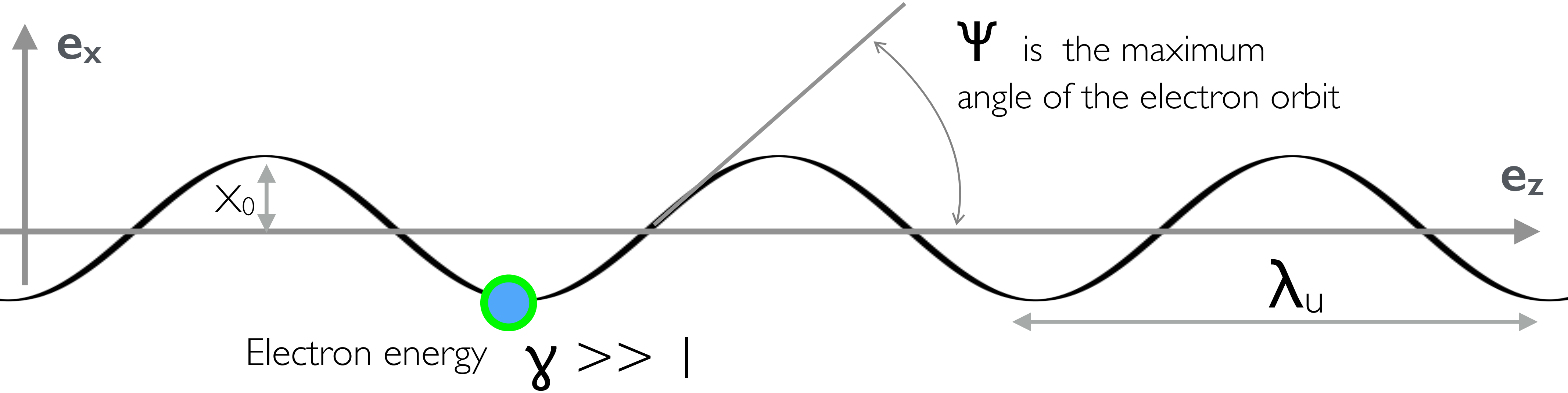
→ Relativistic electrons undergoing transverse oscillations

→ X-ray radiation can be produced by wiggling electrons at a frequency far below x-ray range $\omega_e \sim \omega_X/2\gamma^2$ (Spatial period is typically a cm for a few GeV e- beam)

→ The trajectory must be essentially longitudinal to produce an x-ray beam (because the radiation is emitted in the direction of electron velocity)

→ A sinusoidal trajectory with small transverse amplitude combines all these conditions

What do we need to produce X-rays beams ?



→ Relevant parameters to obtain the features of the radiation are :

The electron energy γ

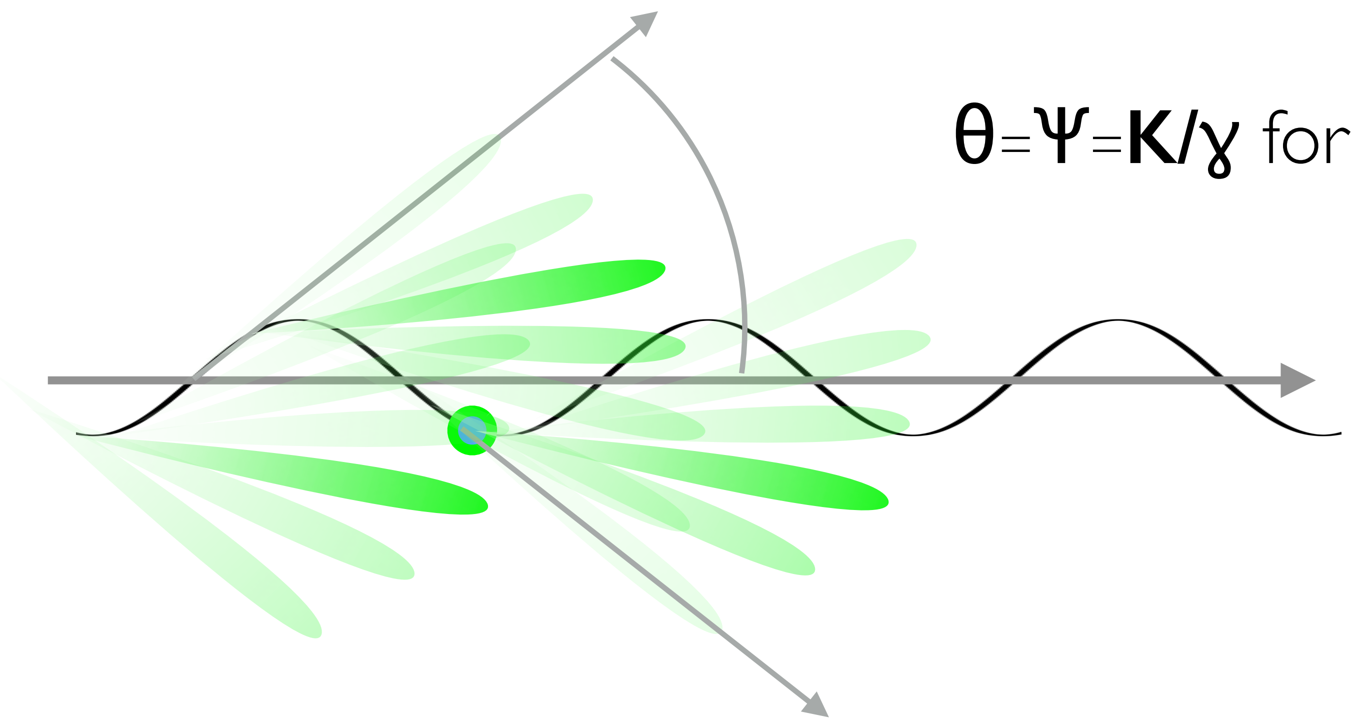
The spatial period of motion λ_u

The parameter $K = \gamma\,\Psi$.

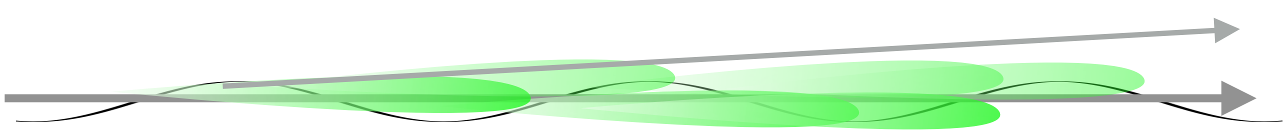
→ Radiation features will depend on these parameters

Radiation properties: Spatial distribution

→ The radiation is emitted in the direction of the electron velocity.

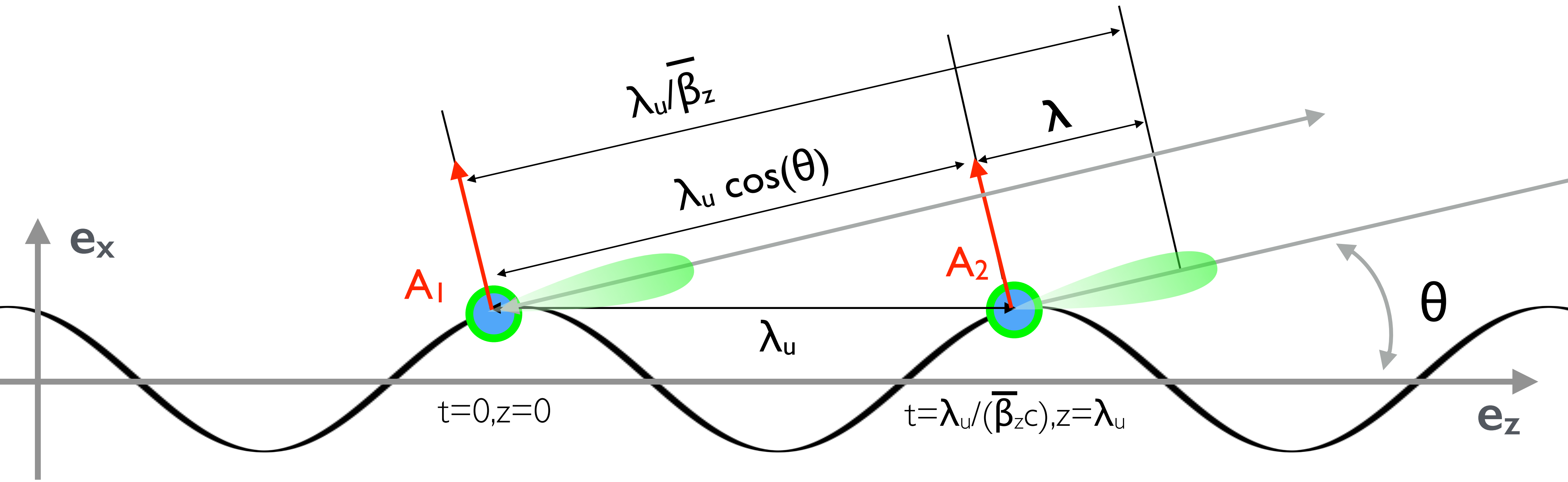


$\theta = \Psi = \mathbf{K/\gamma}$ for K>1



$\theta = 1/\gamma$ for K<<1

Radiation properties: Period of the radiation



The electron radiates the same field amplitude when it is a the same phase along the trajectory (A_1 and A_2 are identical).

The field amplitude A_1 radiated at t=0 and z=0 propagates at the speed of light
The amplitude A_2 is radiated at $z=\lambda_u$ and $t=\lambda_u/(\bar{\beta}_z c)$

→ The spatial period of the radiation emitted is therefore $\lambda = \dfrac{\lambda_u}{\bar{\beta}_z} - \lambda_u \cos\theta$

Radiation properties: Period of the radiation

For the calculation of β_z we assume a sinusoidal trajectory given by:

$$x(z) = x_0 \sin(k_u z) = \frac{\psi}{k_u} \sin(k_u z) = \frac{K}{\gamma k_u} \sin(k_u z) \quad \text{where} \quad k_u = 2\pi/\lambda_u$$

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The longitudinal electron velocity can be derived from the trajectory :

$$\beta_z \simeq \beta\left[1 - \frac{K^2}{2\gamma^2}\cos^2(k_u z)\right] \qquad \bar{\beta}_z \simeq \beta\left(1 - \frac{K^2}{4\gamma^2}\right)$$

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→ The spatial period of the radiation field is then:

$$\lambda = \frac{\lambda_u}{\bar{\beta}_z} - \lambda_u \cos\theta \simeq \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

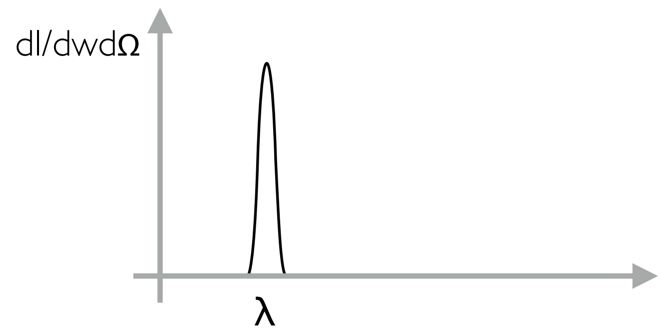
→ The radiation spectrum necessarily consists in the fundamental frequency $\omega = 2\pi c/\lambda$ and its harmonics.

Undulator and wiggler regimes

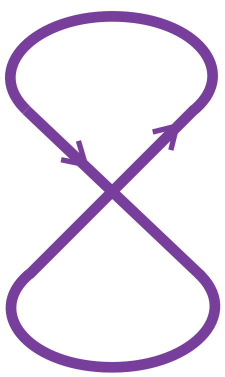
How do we know if we have harmonics in the spectrum ?
We can look at the electron orbit in the electron average rest frame where $\bar{\beta}_z=0$

→ **For K<<1**, the longitudinal velocity reduction due to the oscillation is negligible. The motion is harmonic in the electron averaged rest frame.

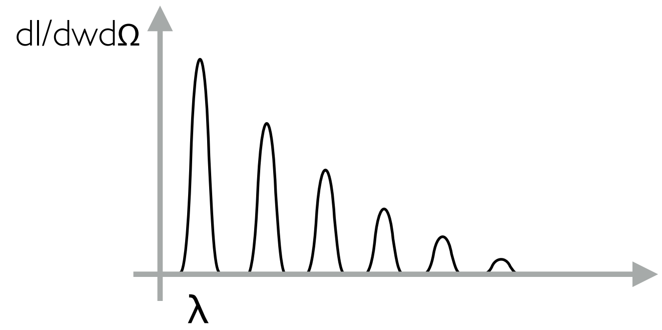
This is the undulator regime



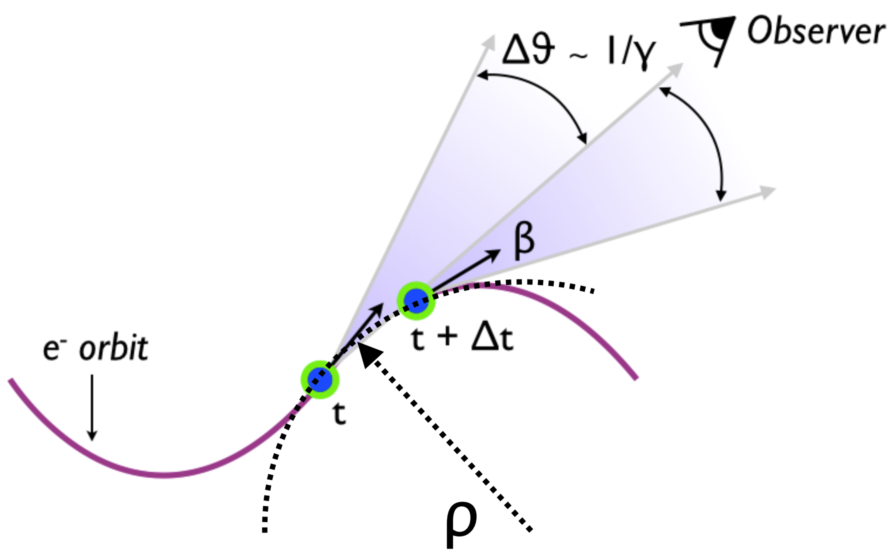
→ **For K>>1**, the longitudinal velocity reduction is significant. The motion is a figure eight motion in the electron averaged rest frame.

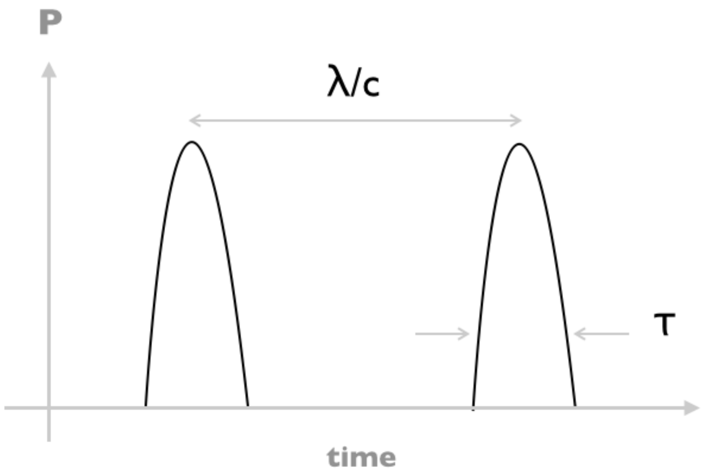


This is the wiggler regime



What is the critical energy in the wiggler regime ?





The observer receives bursts of radiation of duration τ separated by a time λ/c.

The burst duration is: $\tau \simeq \rho/2\gamma^3 c$

The Fourier transform of this temporal profile gives the the critical frequency:

$$\omega_c \sim 1/\tau \sim \gamma^3 \frac{c}{\rho}$$

For a sinusoidal trajectory we have $\rho_0 = \dfrac{\lambda_u}{2\pi\psi} = \gamma \dfrac{\lambda_u}{2\pi K}$, and $\omega_c = \frac{3}{2} K \gamma^2 2\pi c/\lambda_u$

Summary of radiation features

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- Radiation features depend on γ, λ_u, K

Fundamental radiation energy for undulator regime	$(2\gamma^2 hc/\lambda_u)/(1+K^2/2)$
Critical radiation energy for wiggler regime	$\frac{3}{2}K\gamma^2 hc/\lambda_u$
Typical divergence angle for undulators	$1/\gamma$
Typical divergence angle for wigglers	K/γ
Number of photons emitted / electrons for undulators	$1.53\times 10^{-2}K^2$
Number of photons emitted / electrons for wigglers	$3.31\times 10^{-2}K$

- Radiation flux and energy increase when increasing K, γ and/or decreasing λ_u.

- X-ray sources based on laser plasma accelerators will be described using this formalism. For each source we will define K, γ, λ_u and use these expressions to obtain the radiation features.

Outline

100 eV

1 keV

10 keV

100 keV

1 MeV

Nonlinear Thomson scattering

- Electron orbit
- Radiation features
- Experimental results
- Perspectives

Betatron radiation

- Electron orbit
- Radiation features
- Experimental results
- Perspectives

Compton scattering

- Electron orbit
- Radiation features
- Experimental results
- Perspectives

Method

Calculate the electron orbit

↓

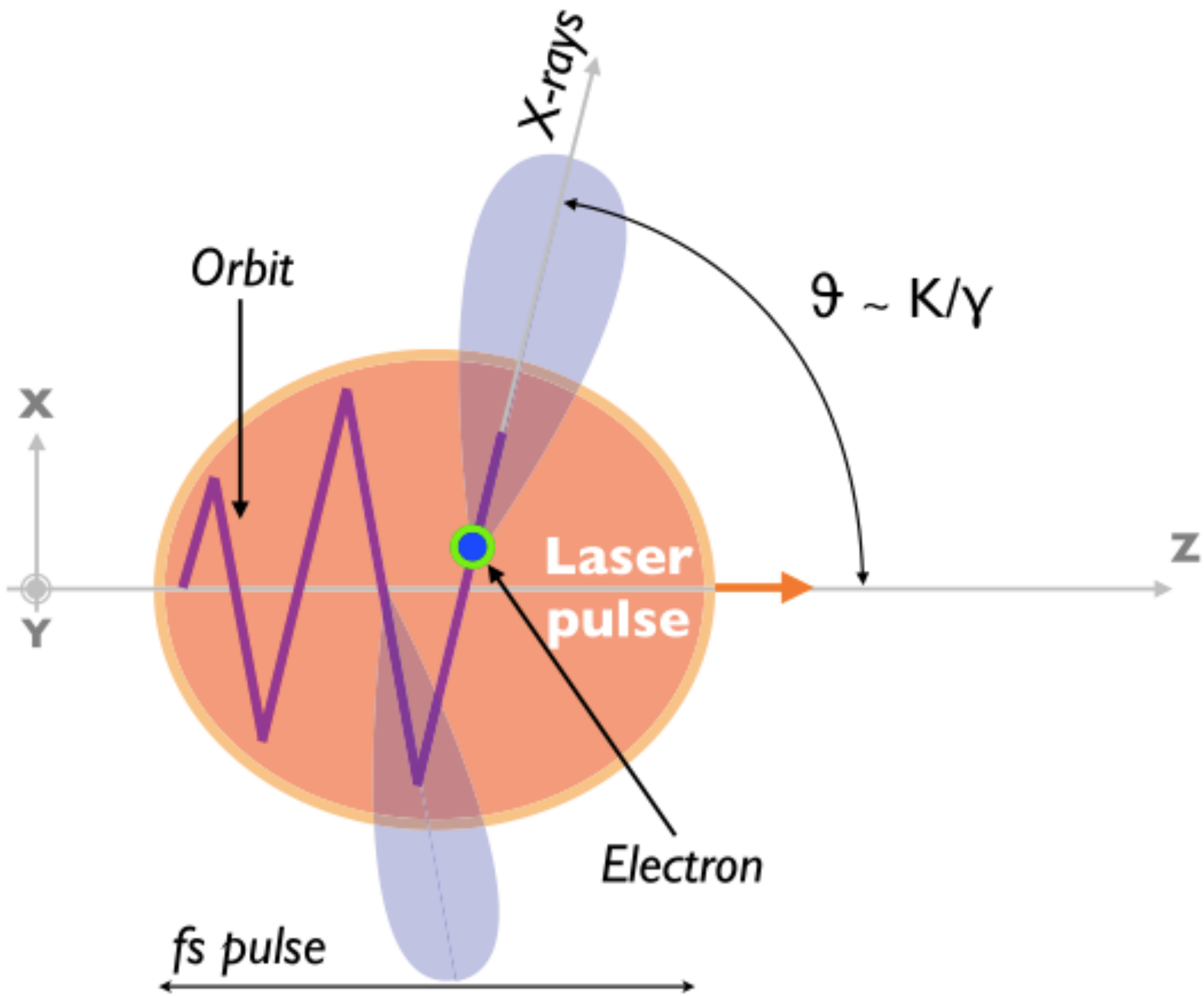
Obtain γ, λ_u, K

↓

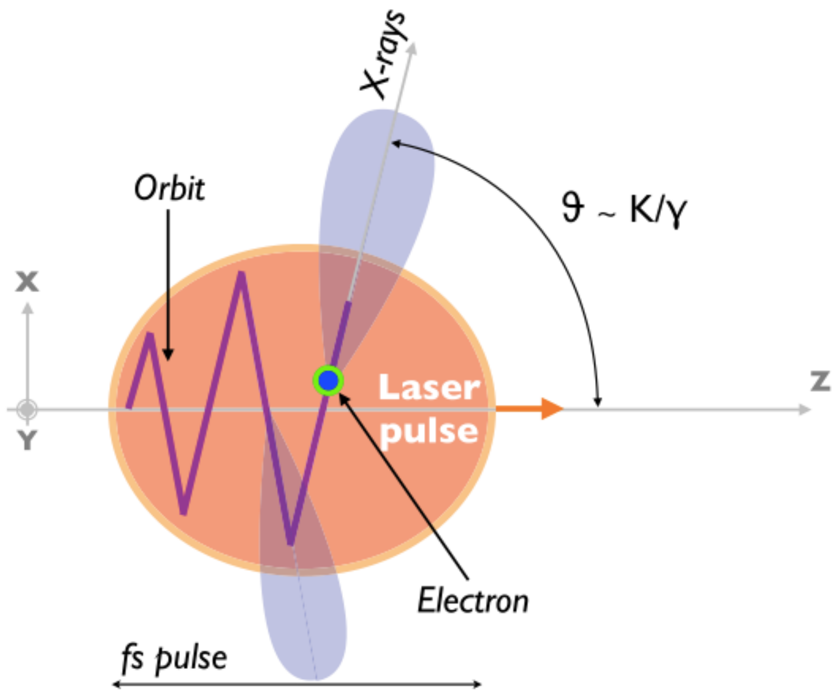
Use these γ, λ_u, K to obtain the radiation features

Nonlinear Thomson scattering: principle

It is the radiation produced by an electron oscillating in an intense laser field



Nonlinear Thomson scattering: Electron orbit



The electron, initially at rest is submitted to the EM laser field.

The equation of motion is :

$$\frac{d\vec{p}}{dt} = -e(\vec{E} + \vec{v} \times \vec{B}).$$

The Hamiltonian describing the electron dynamics is:

$$\hat{\mathcal{H}}(\hat{\vec{r}}, \hat{\vec{P}}, \hat{t}) = \gamma = \sqrt{1 + \hat{\vec{p}}^2} = \sqrt{1 + (\hat{\vec{P}} + \vec{a})^2}.$$

^ denotes a normalized quantity

We consider a circularly polarized field. The normalize potential vector is:

$$\vec{a} = a_0\left[\frac{1}{\sqrt{2}}\cos(\omega_i t - k_i z)\vec{e}_x + \frac{1}{\sqrt{2}}\sin(\omega_i t - k_i z)\vec{e}_y\right].$$

$$a_0 = 0.855\sqrt{I[10^{18}\ \mathrm{W/cm^2}]\lambda_L^2[\mu\mathrm{m}]}$$

Nonlinear Thomson scattering: Electron orbit

For an infinite plane wave and an electron initially at rest we have two constants of motion:

$\hat{\mathcal{H}}$ is independent of $\hat{x}$ and $\hat{y}$ ⇒ Conservation of the transverse canonical momentum:

$$\hat{\vec{P}}_\perp = \hat{\vec{p}}_\perp - \vec{a} = \vec{0}.$$

$\hat{\mathcal{H}}$ depends on $\hat{t}$ and $\hat{z}$ only through $\varphi = \hat{t} - \hat{z}$ .Thus $\partial\hat{\mathcal{H}}/\partial\hat{t} = -\partial\hat{\mathcal{H}}/\partial\hat{z}$

$$\gamma - \hat{p}_z = \text{Constant} = 1$$

This give the trajectory

$$\hat{x}(\varphi) = \frac{a_0}{\sqrt{2}}\sin(\varphi),$$

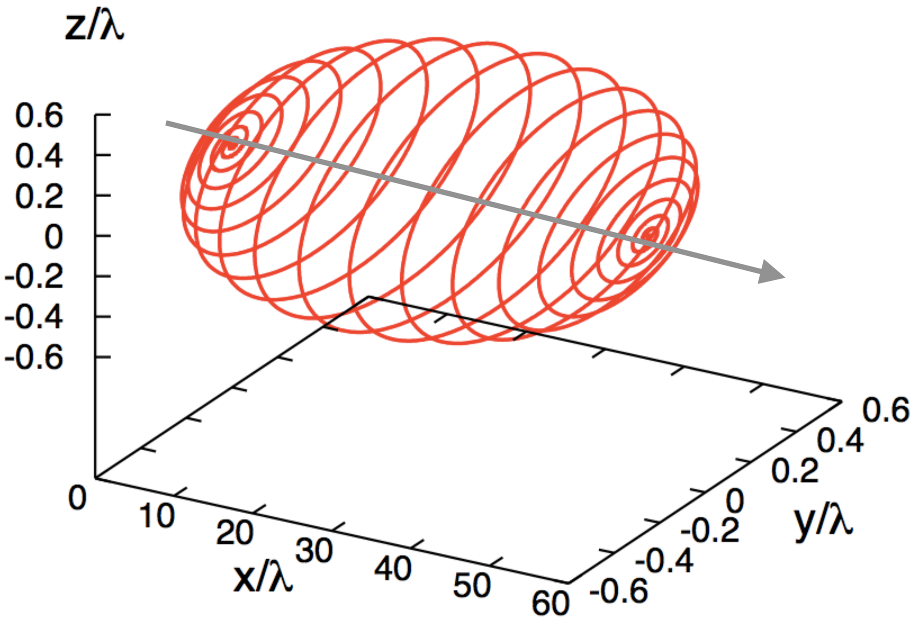
$$\hat{y}(\varphi) = -\frac{a_0}{\sqrt{2}}\cos(\varphi),$$

$$\hat{z}(\varphi) = \frac{a_0^2}{4}\varphi,$$

and $\gamma = 1 + \dfrac{a_0^2}{4}.$

→ The motion consists in transverse oscillations with a longitudinal drift

Nonlinear Thomson scattering: Electron orbit



The spatial period of the electron orbit is

$$\lambda_u = \frac{a_0^2}{4}\lambda_L.$$

and the K parameter is

$$K_X = K_Y = \frac{4}{\sqrt{2}a_0}(1 + a_0^2/4) \simeq a_0/\sqrt{2}$$

The radius of curvature is

$$\rho \simeq (\lambda_L/2\pi) \times \sqrt{2}a_0^3/16$$

→ For typical a typical laser (100 TW), we can reach $a_0 \sim 10$ and we have

$\gamma \sim 25$

$\lambda_u \sim$ 20 microns,

K ~ 7 (wiggler regime)

Nonlinear Thomson scattering: Radiation features

Using expressions from general formalism we have:

For $a_0 = 10$

→ Spectrum, critical energy:

$$E_{Xc}[\text{eV}] = 0.3\frac{a_0^3}{\lambda_i[\mu\text{m}]}$$

~350 eV

→ Spatial distribution

$$\theta = \psi_X = \psi_Y = 2\sqrt{2}/a_0$$

~280 mrad

$$\Delta\theta = 1/\gamma \simeq 4/a_0^2$$

~40 mrad

→ Photon number / electron

$$N_\gamma = 4.68 \times 10^{-2} a_0.$$

a few photons / electron

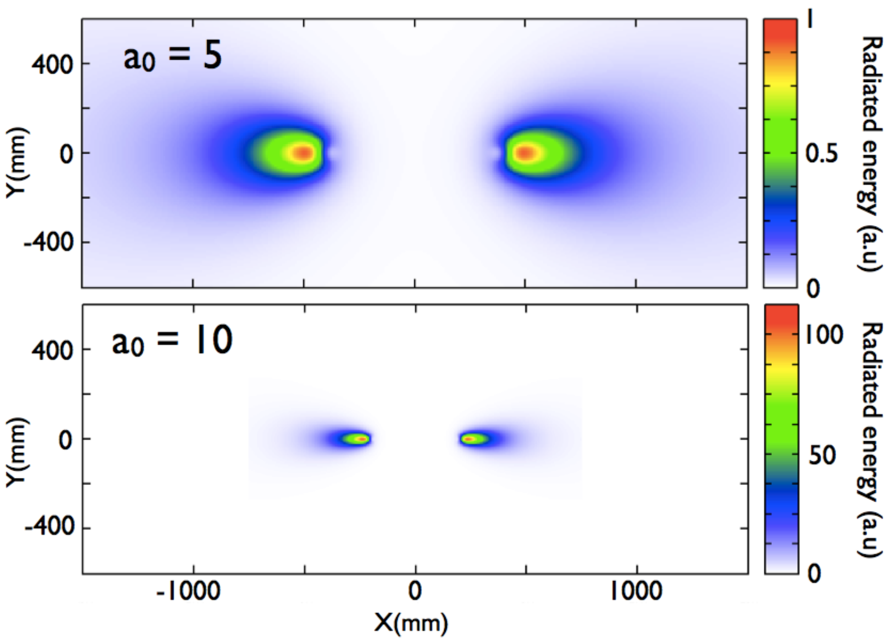
→ Source size is about ten microns

→ Duration is a few femtoseconds

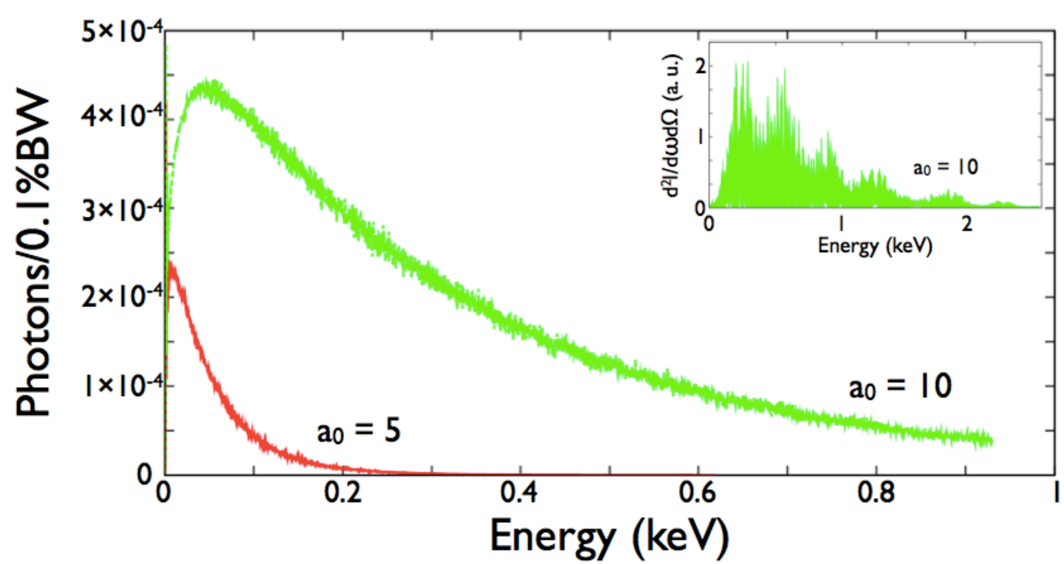
Nonlinear Thomson scattering: Radiation features

Numerical simulation for a_0=2 and 10, electron initially at rest, no ions background

Spatial distribution



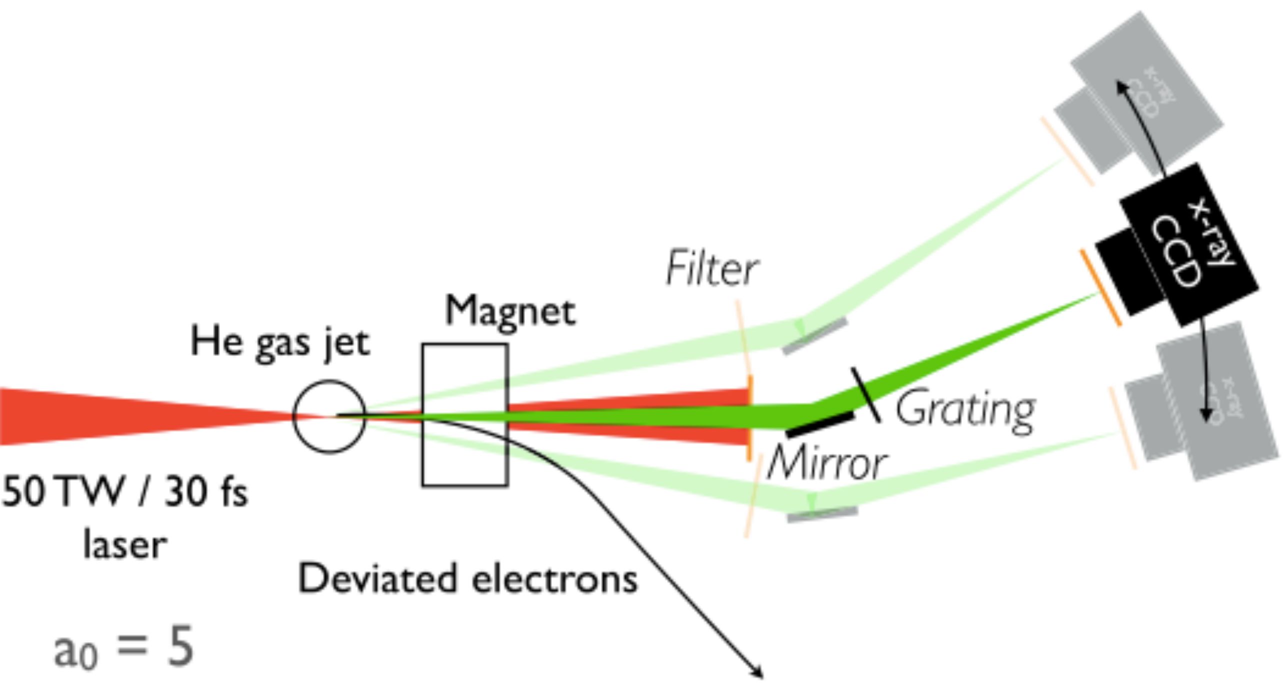
Spectrum

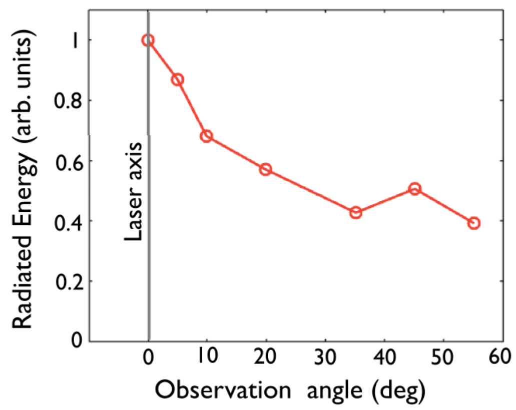


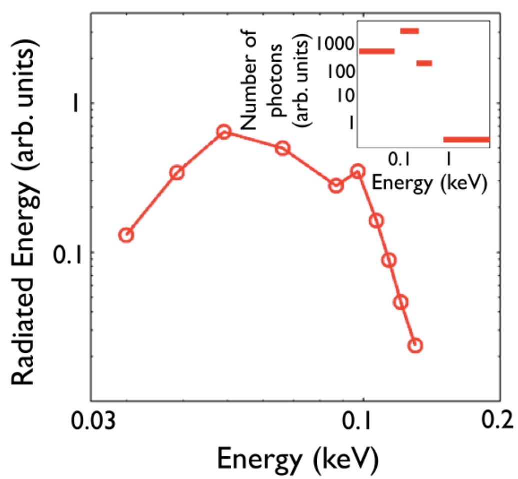
Nonlinear Thomson scattering: Experiment

1998 : First demonstration in (S.Y Chen et al., Univ Michigan). Measurement of the first few harmonics of non linear Thomson scattering radiation.

2003 : First demonstration of nonlinear Thomson scattering in the X-UV range (LOA).







Nonlinear Thomson scattering: Perspectives

→ Increase the energy, reduce the divergence

Use PW class lasers with a_0 ~20
We expect : ~few keV
High flux : ~1 photon / electron

→ Attosecond x-ray pulses production ?

A single electron produces an attoscond pulses train
However this disappears when summing over all electrons

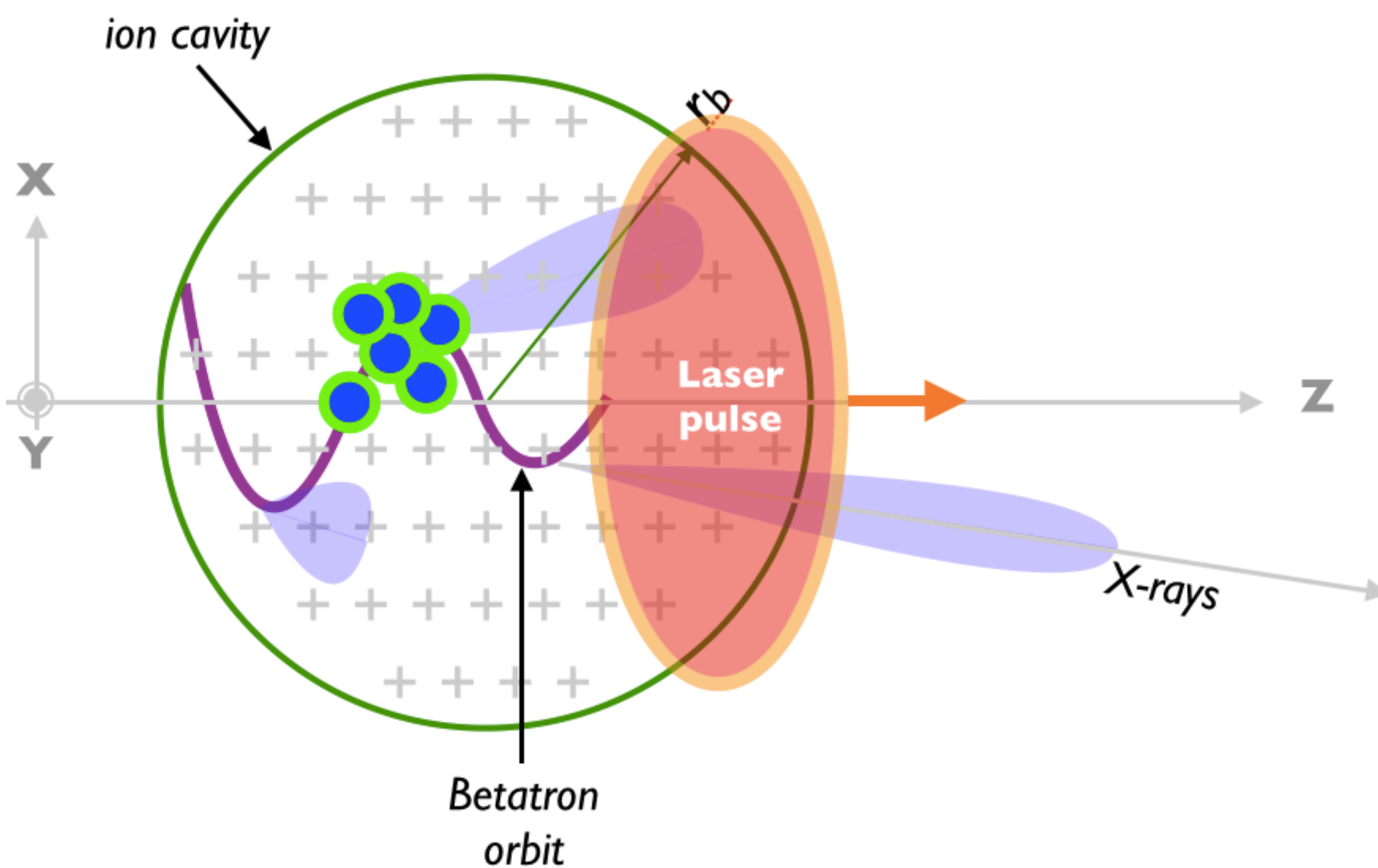
A solution ? Very thin solid target, complex schemes with counter propagating lasers to confine e- orbit in a thin layer.

Outline

100 eV	**Nonlinear Thomson scattering** $\lambda_u \sim 10$ µm and $\gamma \sim 20$ Electron orbit Radiation features Experimental results Perspectives
1 keV	
10 keV	**Betatron radiation** $\lambda_u \sim 150$ µm and $\gamma \sim 300$ Electron orbit Radiation features Experimental results Perspectives
100 keV	**Compton scattering** $\lambda_u \sim 1$ µm and $\gamma \sim 300$ Electron orbit Radiation features Experimental results Perspectives
1 MeV	

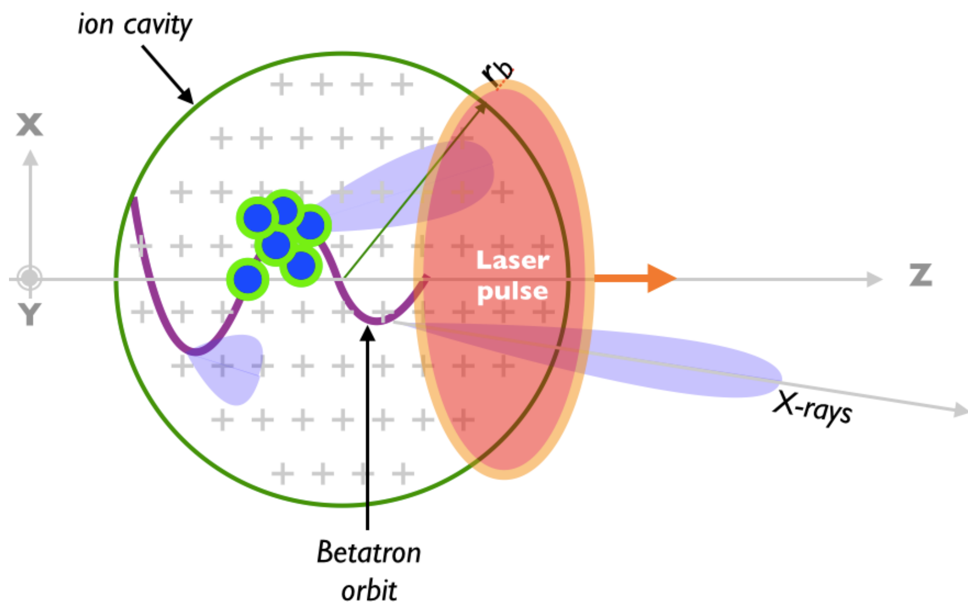
Betatron radiation: Principle

It is the radiation produced by an electron oscillating in a wakefield cavity



Betatron radiation: Electron orbit

Proposed by A. Pukhov et al. in 2004



The electron, is accelerated and wiggled in the ion cavity

The equation of motion is :

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

with $\zeta = z + r_b - v_g t$

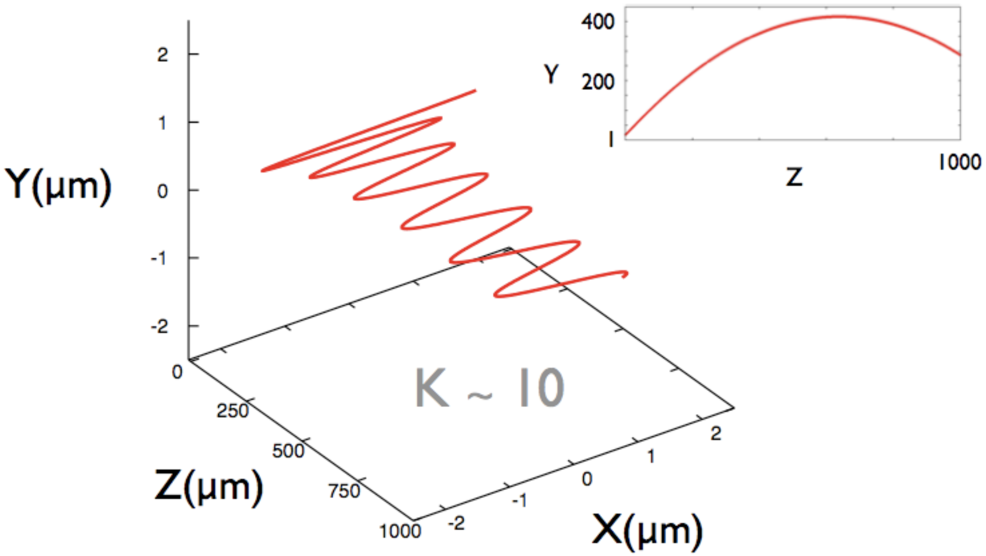
We can consider a propagation distance << dephasing length. The acceleration is linear

$$x(t) = \boldsymbol{r}_\beta \hat{x}\cos(\omega_\beta t), \quad y(t) = \boldsymbol{r}_\beta \hat{y}\cos(\omega_\beta t + \phi) \quad \text{and} \quad \gamma\beta = \frac{m\omega_p^2 r_b}{2}t + \gamma_0\beta_0.$$

where $\omega_b \sim \omega_p / \sqrt{2\gamma}$ is the Betatron frequency and r_β the transverse amplitude

→ The motion consists in a longitudinal acceleration and transverse oscillations across the cavity axis

Betatron radiation: Electron orbit



The spatial period of the electron orbit is

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

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

and the K parameter is

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

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

→ For typical typical parameters in a laser plasma accelerator we have:

γ ~ 300

λ_u ~ 150 microns,

K ~ 10 (wiggler regime)

Betatron radiation: radiation features

Using expression from general formalism we have:

- Spectrum, critical energy

$$\hbar\omega_c = \tfrac{3}{2}K\gamma^2 hc/\lambda_u$$

$$\hbar\omega_c[\mathrm{eV}] = 5.24\times10^{-21}\gamma^2 n_e[\mathrm{cm}^{-3}]r_\beta[\mu\mathrm{m}]$$

- Photon number / electron

$$N_\gamma = 3.31\times10^{-2}K \quad \text{for } K \gg 1.$$

- Spatial distribution

$$\vartheta = K/\gamma$$

- Source size is a few microns

- Duration is a few femtoseconds

For γ ~ 300, λ_u ~ 150 μm, K ~ 10

~9 keV

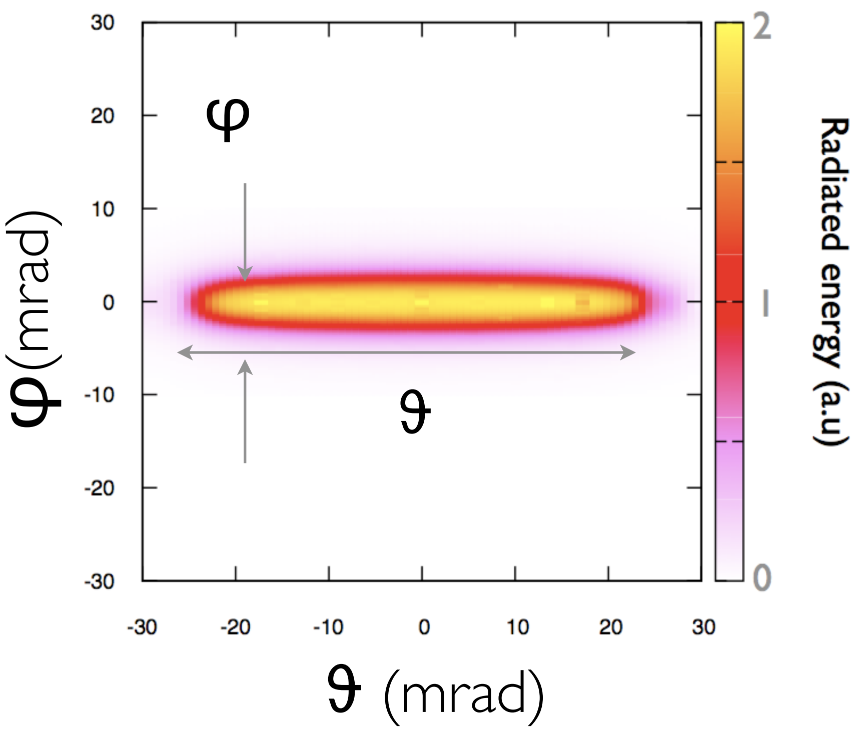
~0.3 photon / electron

~30 mrad

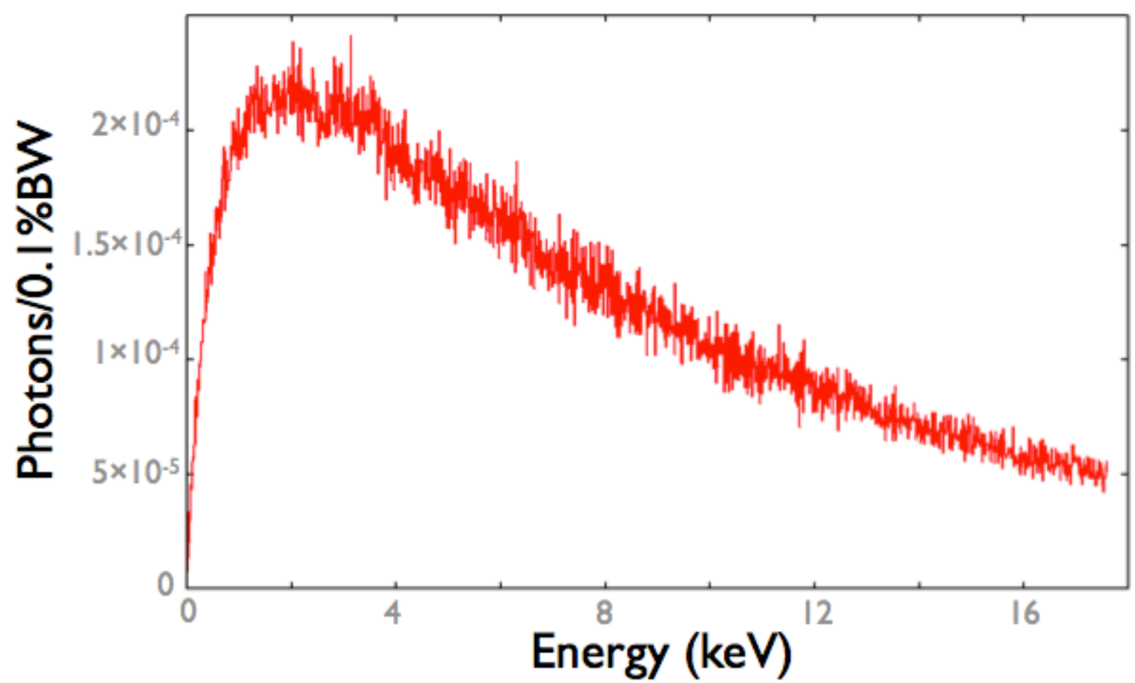
Betatron radiation: radiation features

Numerical simulation for $a_0=4$, $x_0=2$ µm, $p_{zi}=20$, $n_e=1.10^{19}$ cm^{-3}

Spatial distribution

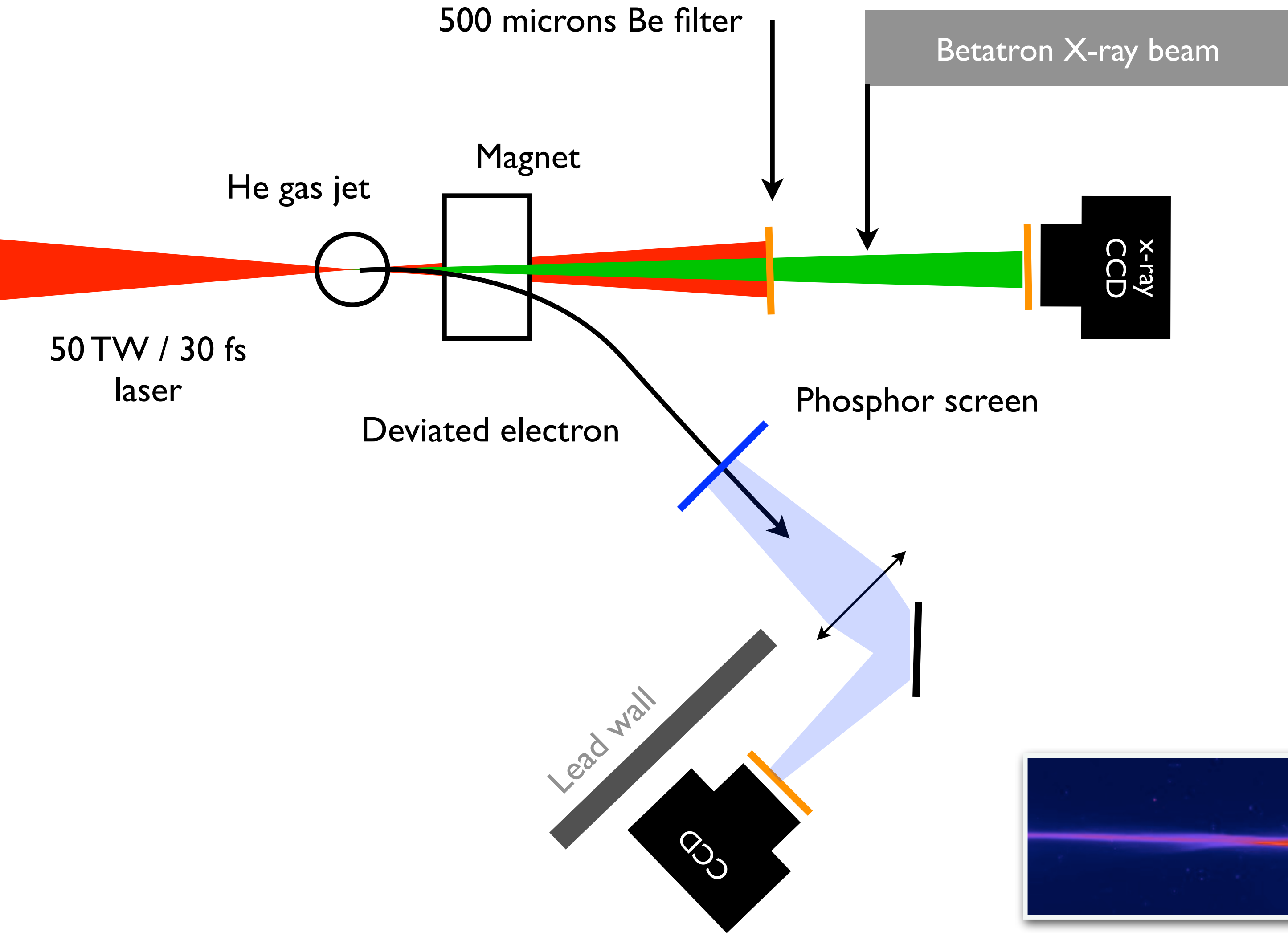


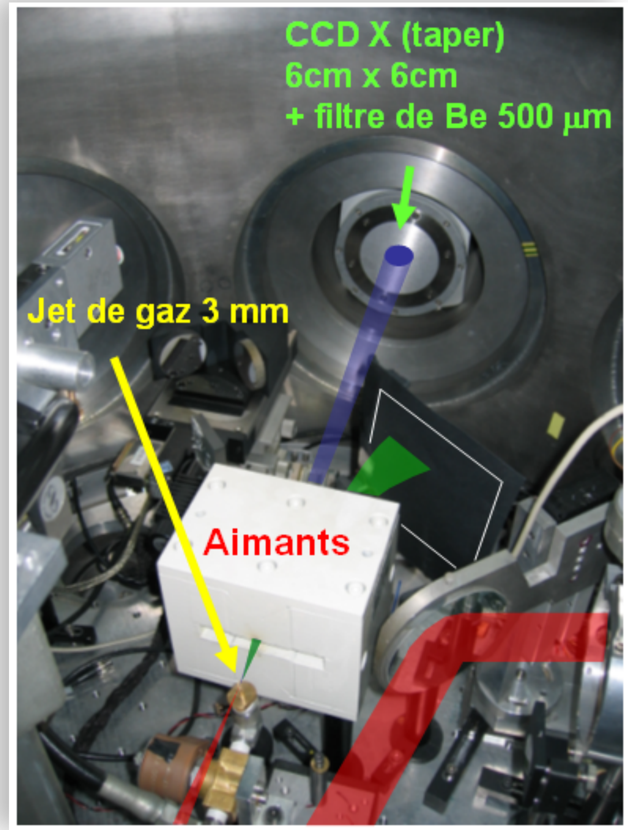
Spectrum integrated over spatial distribution

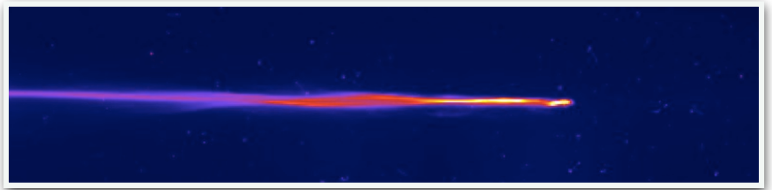


Betatron radiation: experiment

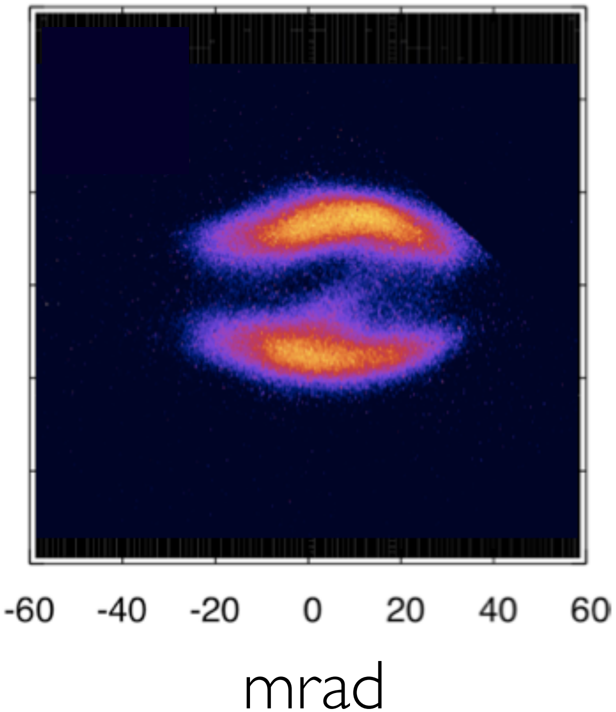
2004 : First demonstration (LOA, France)

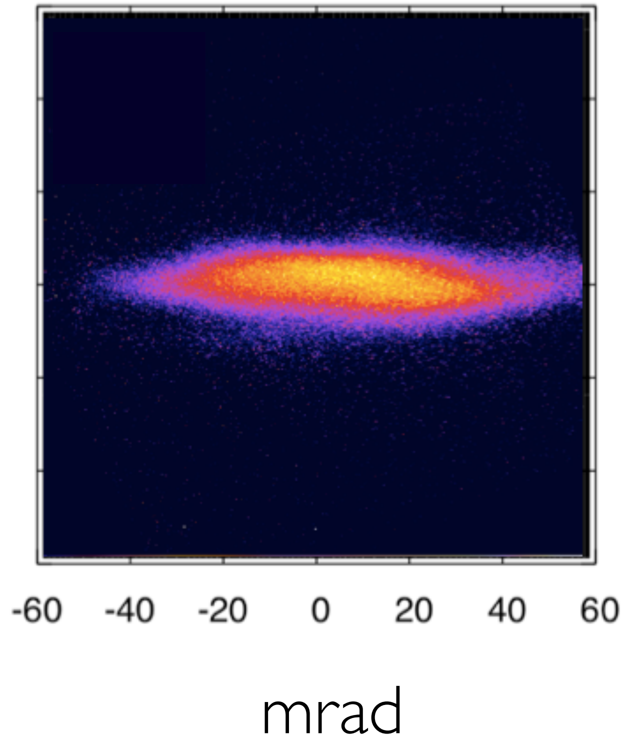


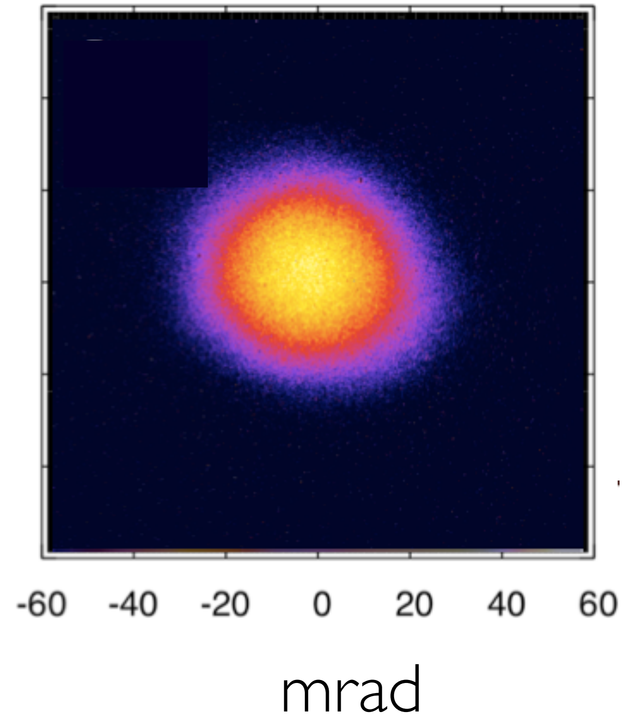




Betatron radiation: experiment - angular distribution



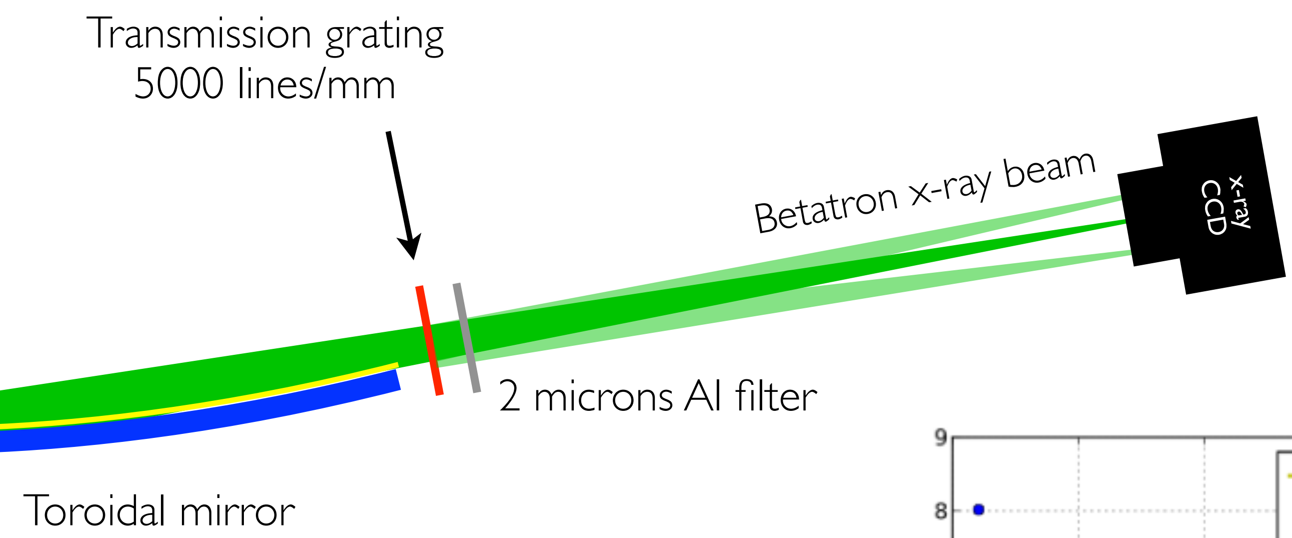


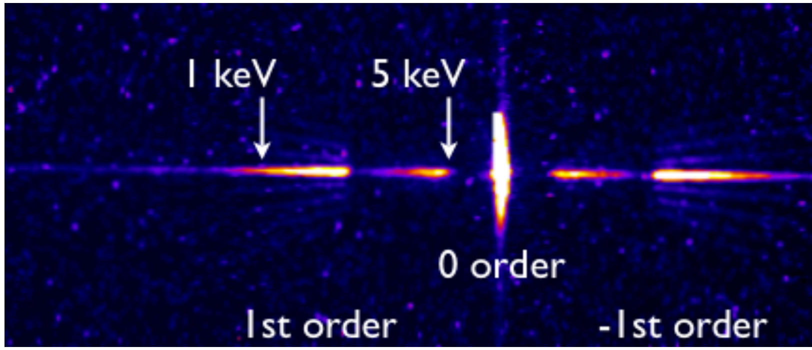


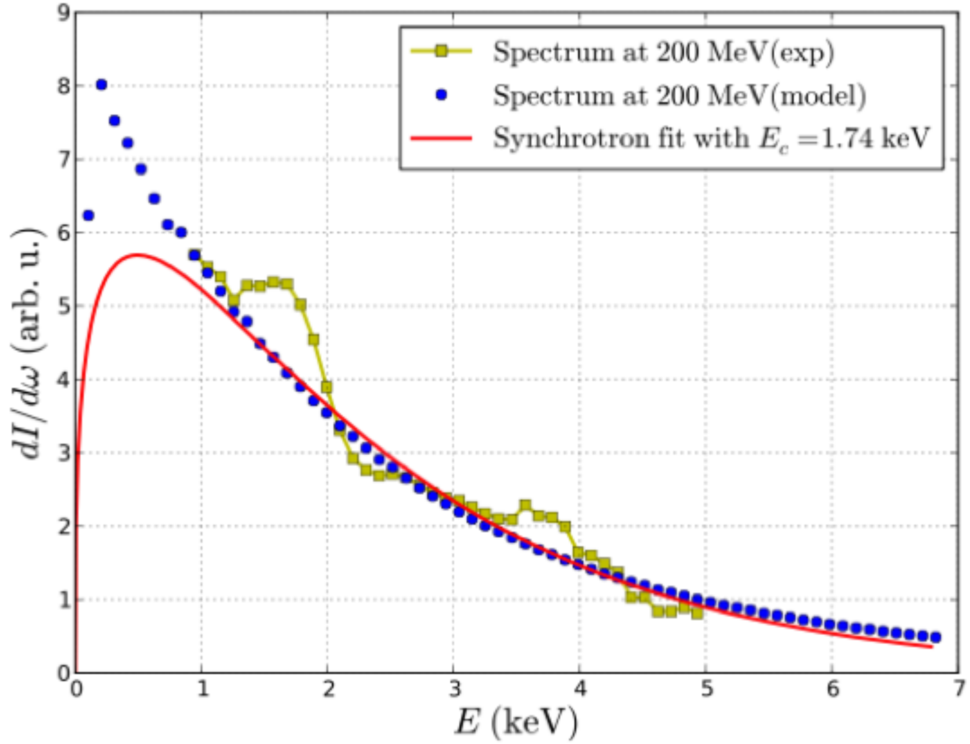
→ Beam profiles depend on the electron orbits

→ Typical divergence: 10-50 mrad

Betatron radiation: experiment - spectrum @ 50 TW



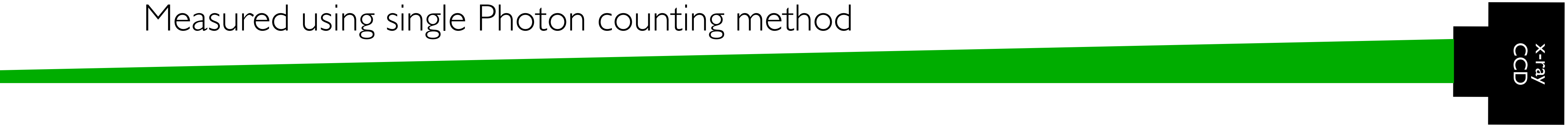


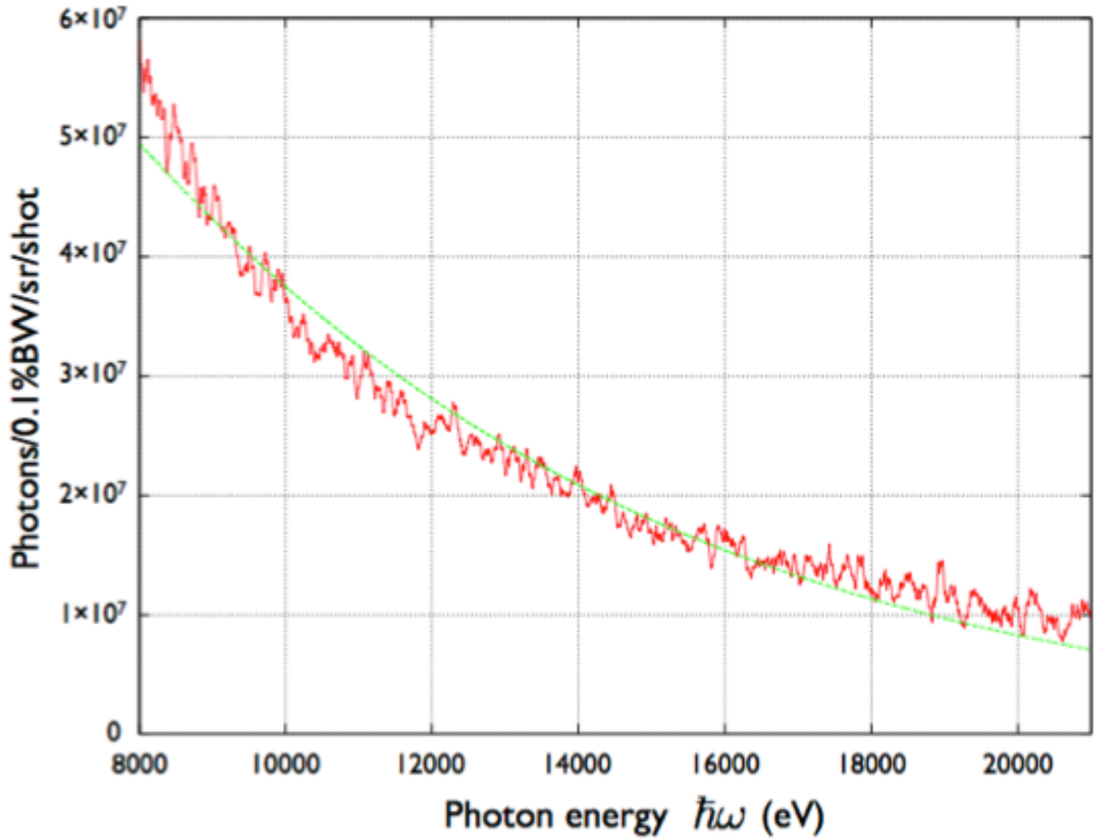


→ It is a Synchrotron type spectrum

Betatron radiation: experiment - spectrum @ 100 TW

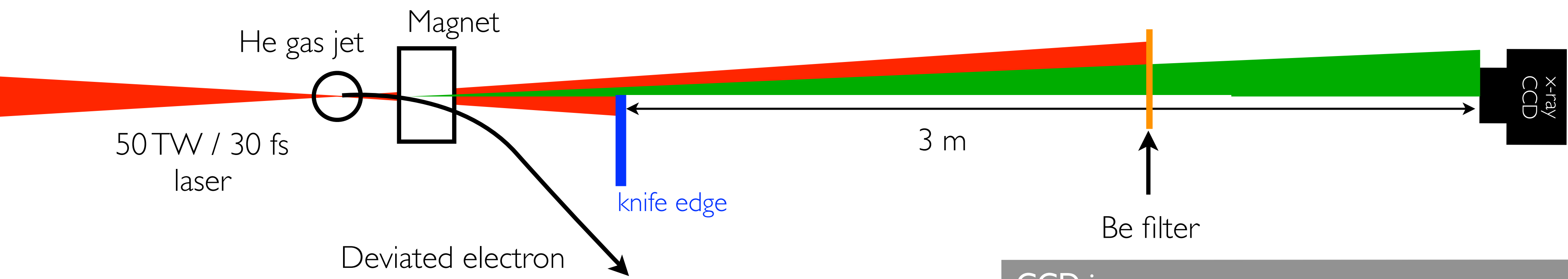
Measured using single Photon counting method

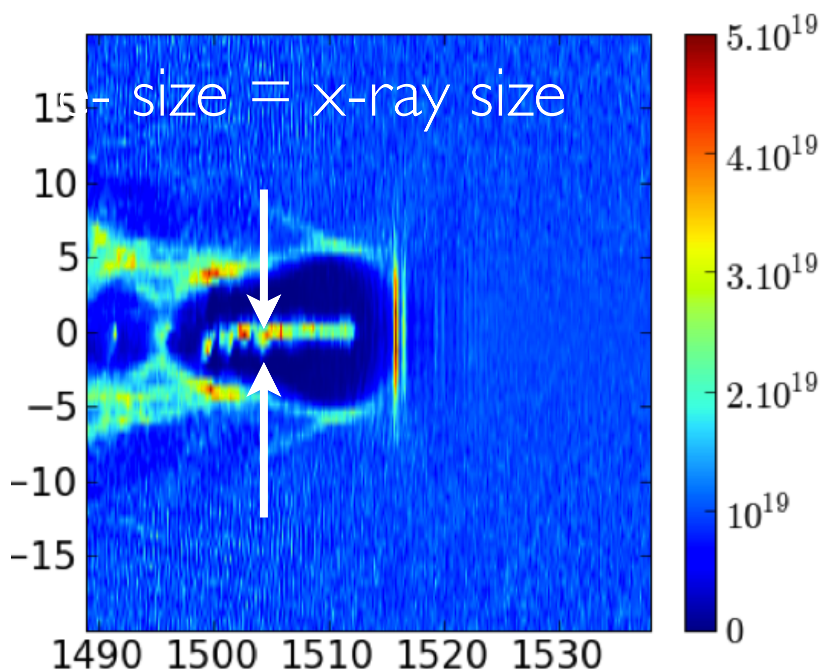


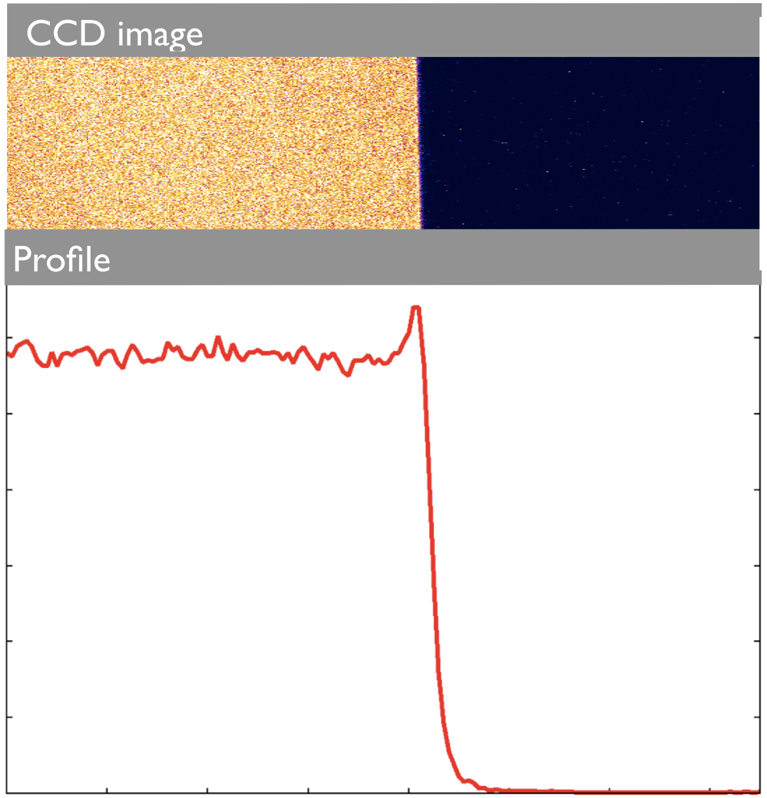


→ The spectrum extends up to a few tens of keV

Betatron radiation: experiment - source size



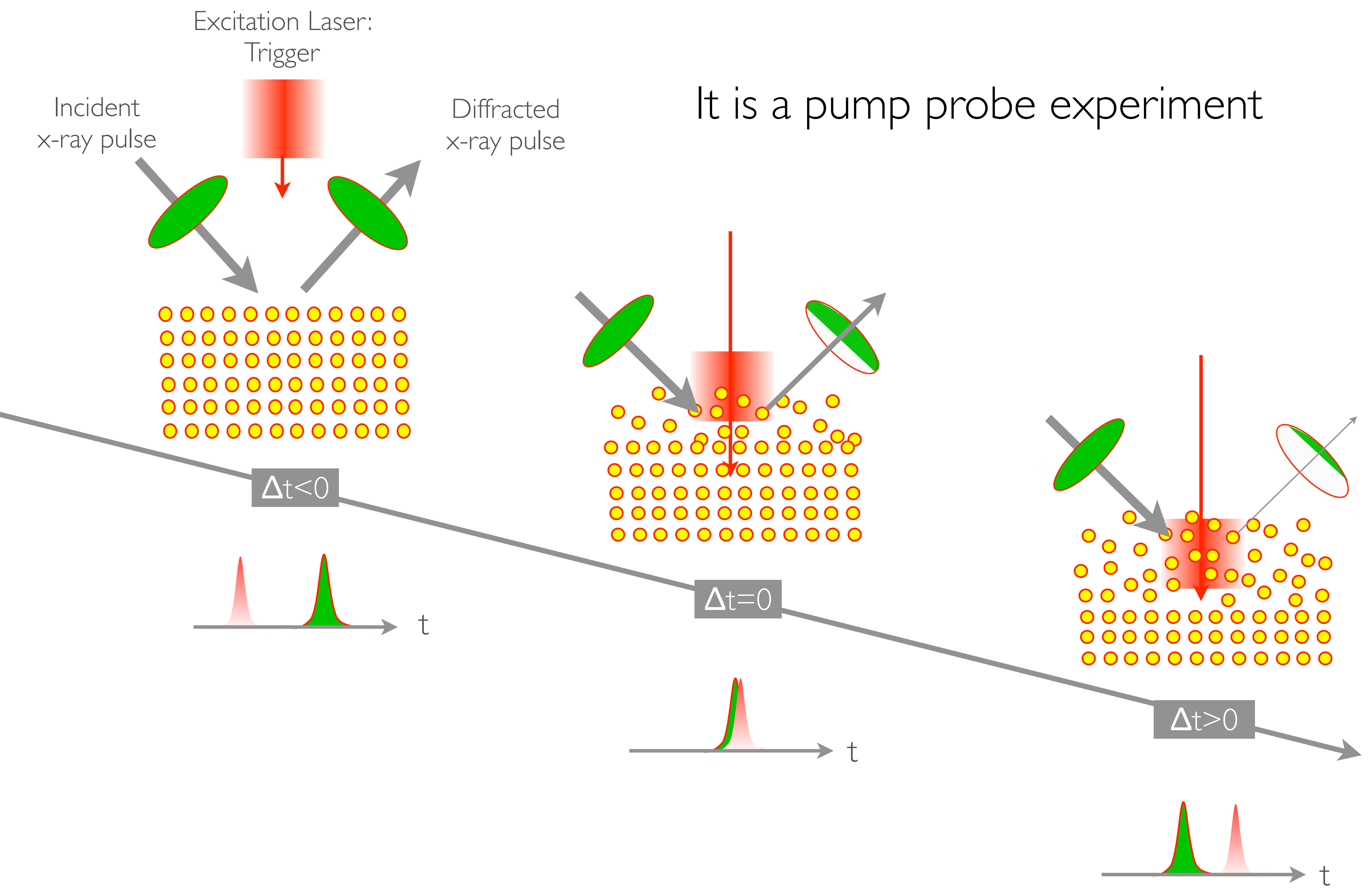




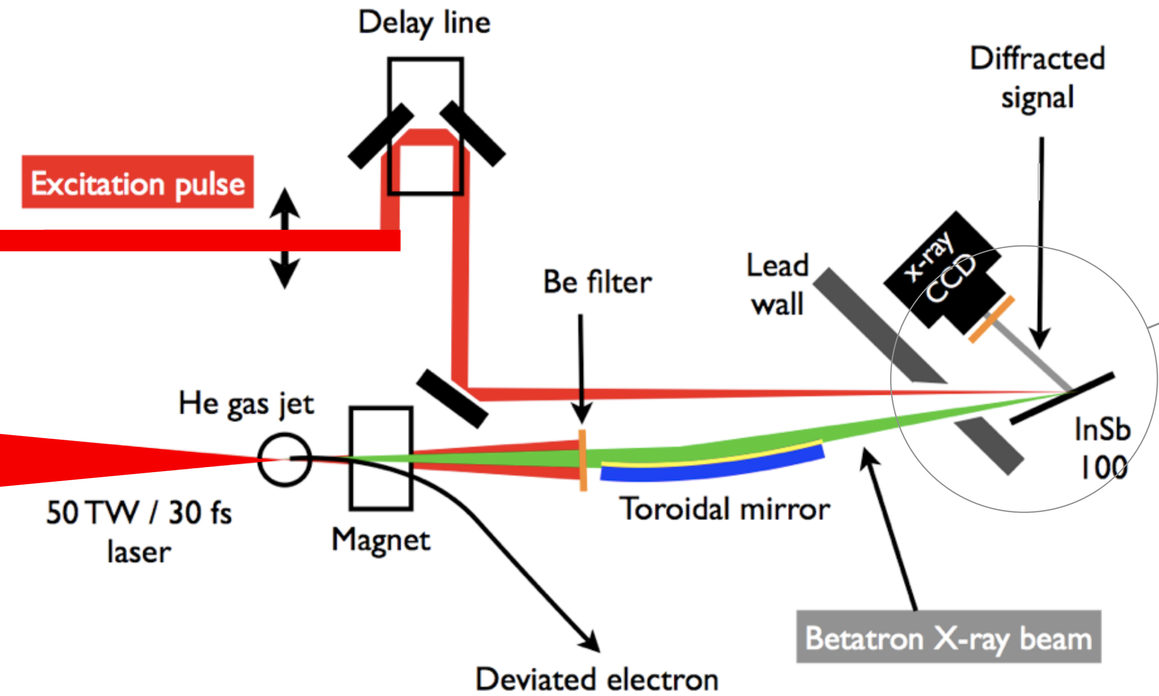
→ Source size < 2 microns

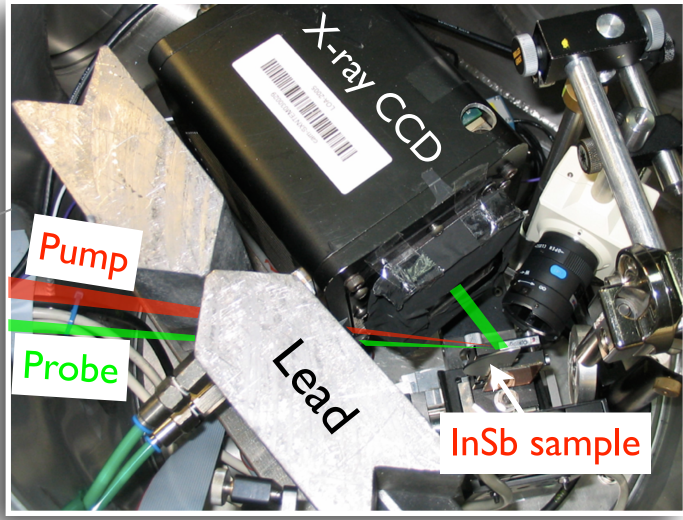
Betatron radiation: application - Femtosecond x-ray diffraction

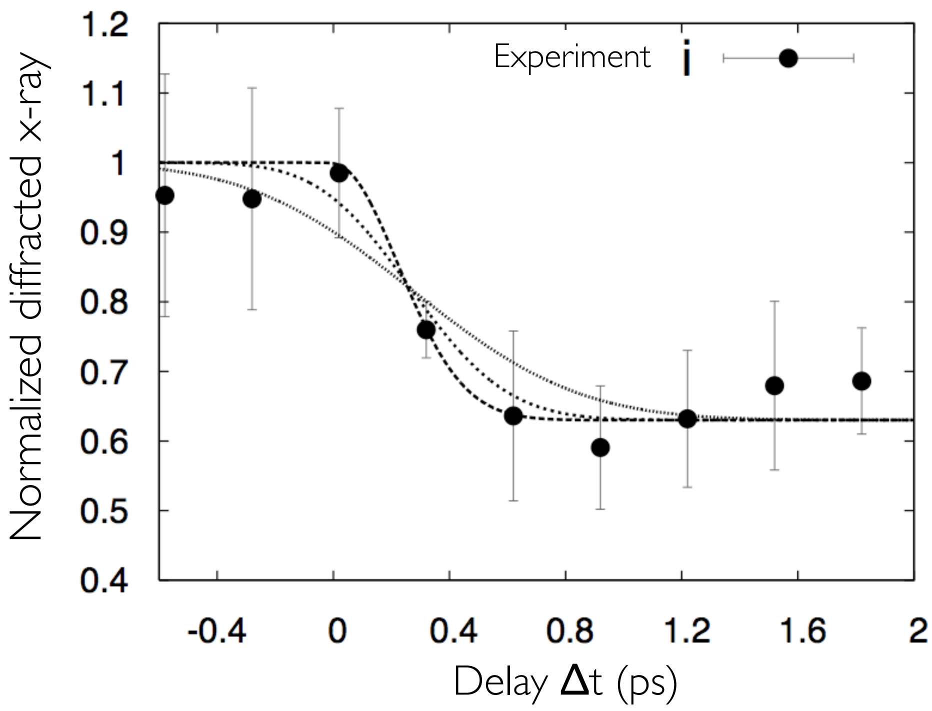
It is a pump probe experiment



Betatron radiation: application - Femtosecond x-ray diffraction





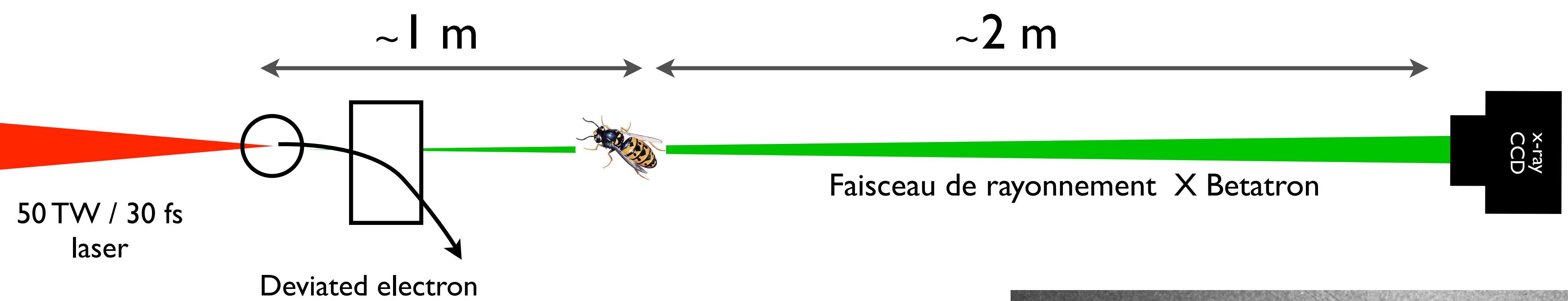


→ Ultrafast phase transition can be measured with tens fs resolution

Betatron radiation: application - radiography

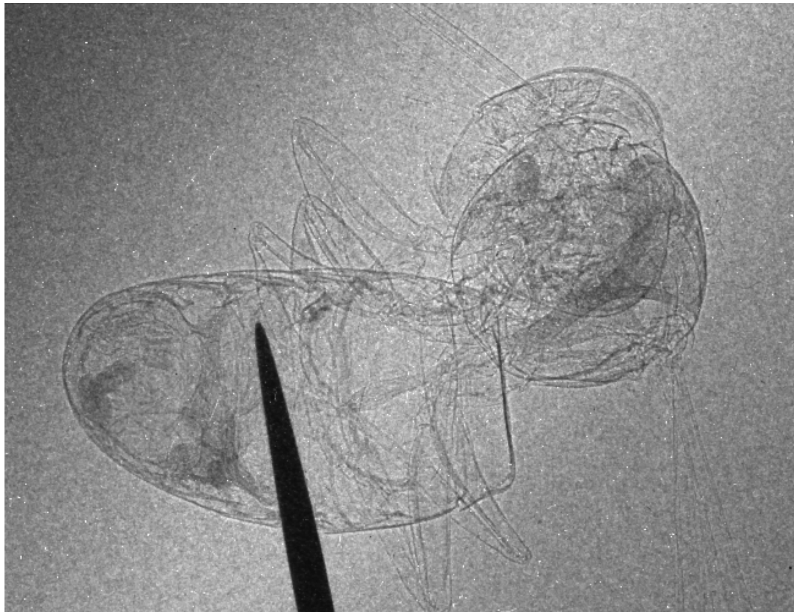
Betatron source has good features for this application:

- High brightness (10^{20} ph/s/mm^2/mrad^2/0.1%bw @1 keV)
- Source size about 1 micron
- Coherence length of the order of 50 microns at 1 m and 5 keV



→ Single shot image

→ Compact setup thanks to micron source size



Betatron radiation: Summary & Perspectives

- 10^5 photons/shot/0.1% BW @ 1 keV
- collimated: 10's mrad
- ultrashort: 10's fs
- broadband: 1-10 keV
- small source size: 1- 2 microns

simple to produce, collect and use for applications

→ Increase the energy, reduce the divergence

Use PW class lasers to increase the electrons energy
We expect : ~100 keV
High flux : ~1 photon / electron

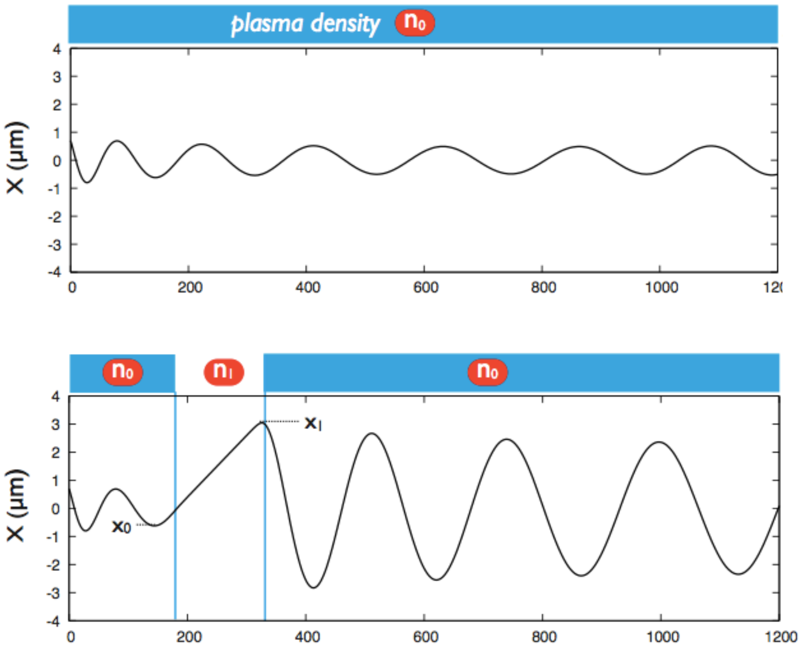
→ Control the electrons orbits and produce higher energy, higher flux radiation while keeping the laser energy constant.

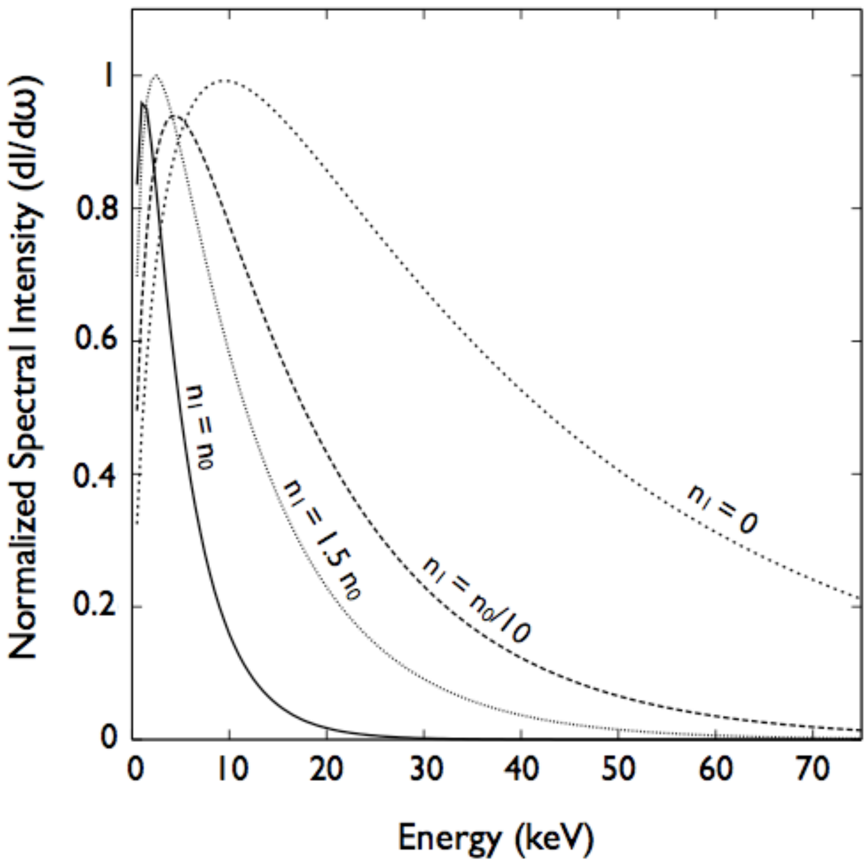
Can we increase the betatron energy ?

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

Photon number $$N_\gamma = 3.31 \times 10^{-2} K \quad \text{with} \quad K = 1.33 \times 10^{-10}\sqrt{\gamma n_e[\text{cm}^{-3}]} r_\beta$$

→ Increase the amplitude of oscillation → Use plasma with density modulation





Outline

100 eV	
1 keV	
10 keV	
100 keV	
1 MeV	

Nonlinear Thomson scattering $\lambda_u \sim 10\ \mu m$ and $\gamma \sim 20$

Electron orbit
Radiation features
Experimental results
Perspectives

Betatron radiation $\lambda_u \sim 150\ \mu m$ and $\gamma \sim 300$

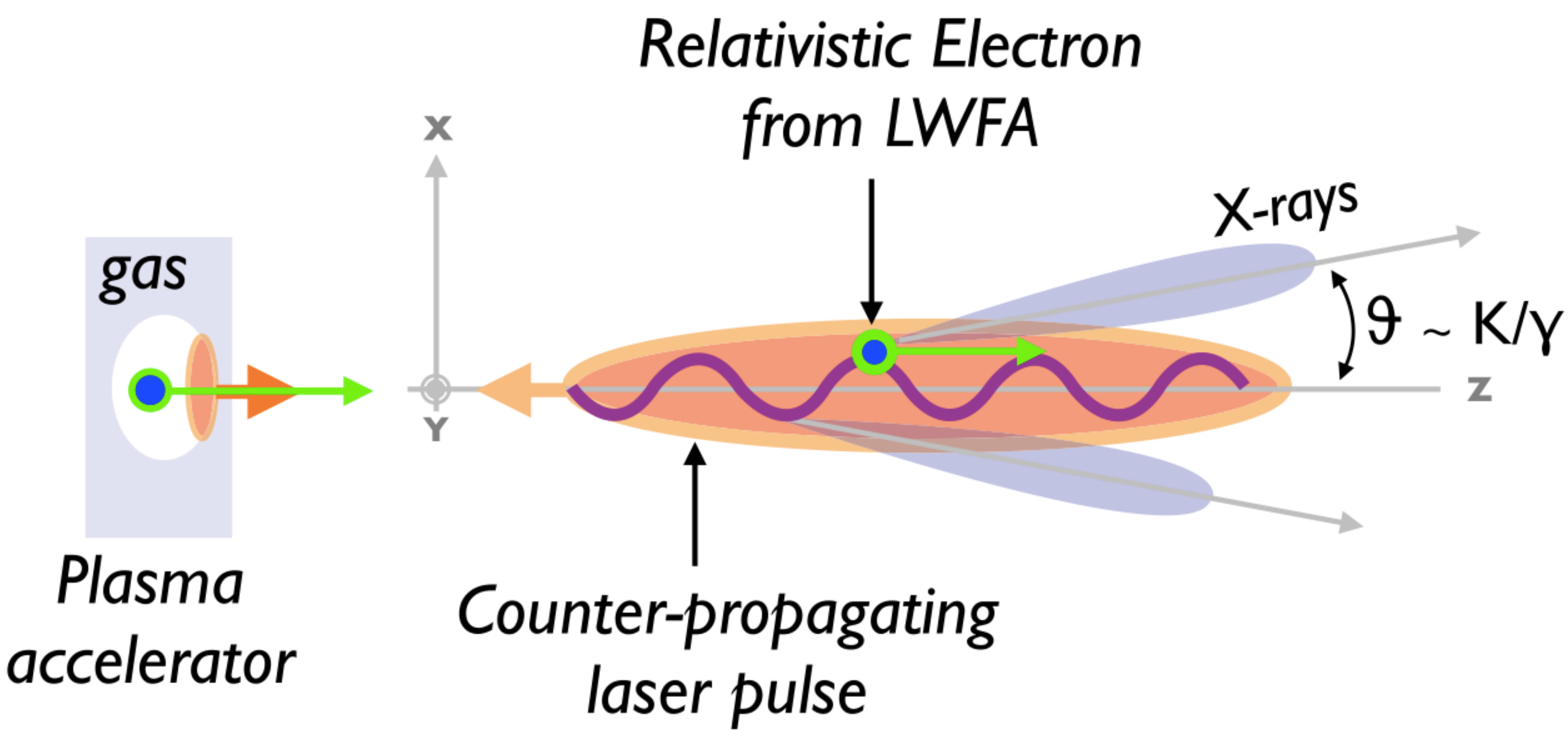
Electron orbit
Radiation features
Experimental results
Perspectives

Compton scattering $\lambda_u \sim 1\ \mu m$ and $\gamma \sim 300$

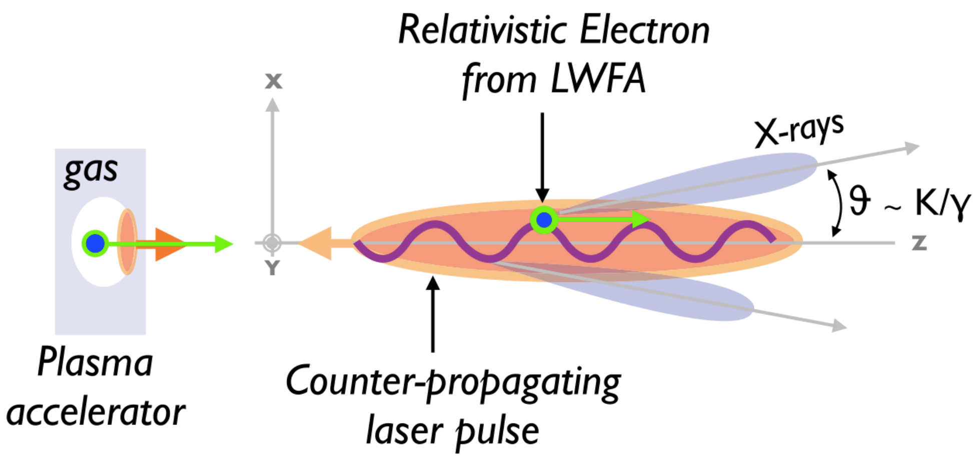
Electron orbit
Radiation features
Experimental results
Perspectives

Thomson backscattering (Compton): Principle

It is the radiation produced by a relativistic electron oscillating in a counter propagating laser field



Thomson backscattering (Compton): Electron orbit



The electron, initially at rest is submitted to the EM laser field.

The equation of motion is :

$$\frac{d\vec{p}}{dt} = -e(\vec{E} + \vec{v} \times \vec{B}).$$

The Hamiltonian describing the electron dynamics is:

$$\hat{\mathcal{H}}(\hat{\vec{r}}, \hat{\vec{P}}, \hat{t}) = \gamma = \sqrt{1 + \hat{\vec{p}}^2} = \sqrt{1 + (\hat{\vec{P}} + \vec{a})^2}.$$

^ denote a normalized quantity

We consider a linearly polarized field, counter propagating. The normalize potential

$$\vec{a} = a_0 \cos(\omega_i t + k_i z)\vec{e}_x$$

with

$$\omega_i = 2\pi c/\lambda_L$$
$$\vec{k}_i = -2\pi/\lambda_L \vec{e}_z$$

Nonlinear Thomson scattering: Electron orbit

There are two constants of motion:

$\hat{\mathcal{H}}$ is independent of $\hat{x}$ and $\hat{y}$ ⇒ Conservation of the transverse canonical momentum:

$$\hat{\vec{P}}_\perp = \hat{\vec{p}}_\perp - \vec{a} = \vec{0}.$$

$\hat{\mathcal{H}}$ depends on $\hat{t}$ and $\hat{z}$ only through $\varphi = \hat{t} + \hat{z}$ .Thus $\partial\hat{\mathcal{H}}/\partial\hat{t} = \partial\hat{\mathcal{H}}/\partial\hat{z}$

$$\gamma - \hat{p}_z = C. = \gamma_i + \sqrt{\gamma_i^2 - 1} = 2\gamma_i - 1/(2\gamma_i) + o(1/\gamma_i^2).$$

This give the trajectory

$$\hat{x}(\varphi) = \frac{a_0}{C}\sin(\varphi),$$

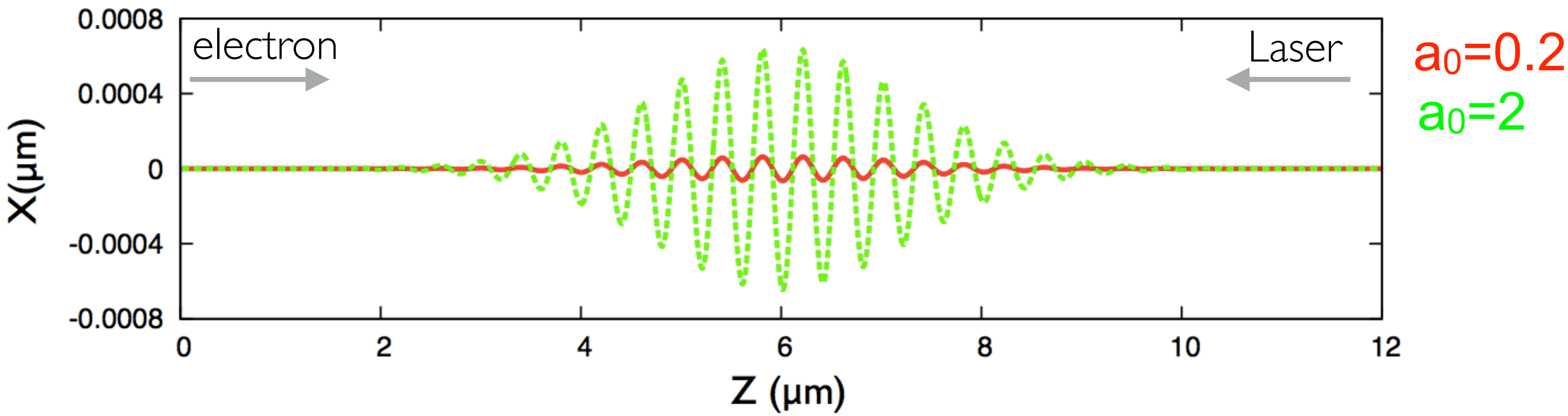
$$\hat{y}(\varphi) = 0,$$

$$\hat{z}(\varphi) = \left\{\frac{1}{2} - \frac{1 + a_0^2/2}{2C^2}\right\}\varphi - \frac{a_0^2}{8C^2}\sin(2\varphi),$$

and $\gamma(\varphi) = \dfrac{C}{2} + \dfrac{1 + a_0^2\cos^2(\varphi)}{2C}$,

→ The motion consists in a transverse oscillations

X-ray Compton scattering: *Test particle simulation*



The spatial period of the electron orbit is : $$\lambda_u = \lambda_L/2,$$

The K parameter is : $$K = a_0 = 0.855\sqrt{I[10^{18}\ \mathrm{W/cm^2}]\lambda_L^2[\mu\mathrm{m}]}$$

For typical a typical parameters we have

We have : γ ~ 300

λ_u ~ 0.5 microns,

K ~ 1 We can be either in undulator or wiggler regimes

X-ray Compton scattering: *Test particle simulation*

Using expression from general formalism we have:

- Spectrum :

$$\hbar\omega\ [\mathrm{eV}] = 4.96\gamma^2/\lambda_L\ [\mu\mathrm{m}] \quad \text{for } K \ll 1,$$

$$\hbar\omega_c\ [\mathrm{eV}] = 3.18\gamma^2\sqrt{I[10^{18}\ \mathrm{W/cm^2}]} \quad \text{for } K \gg 1.$$

- Photon number / electron

$$N_\gamma = 1.53 \times 10^{-2} K^2 \quad \text{for } K < 1,$$

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

- Spatial distribution

$\vartheta = K/\gamma$

$\varphi = 1/\gamma$

- Source size is a few microns

- Duration is a few femtoseconds

For $\gamma \sim 300$, $\lambda_u \sim 1\ \mu m$, $K \sim 1$

~500 keV

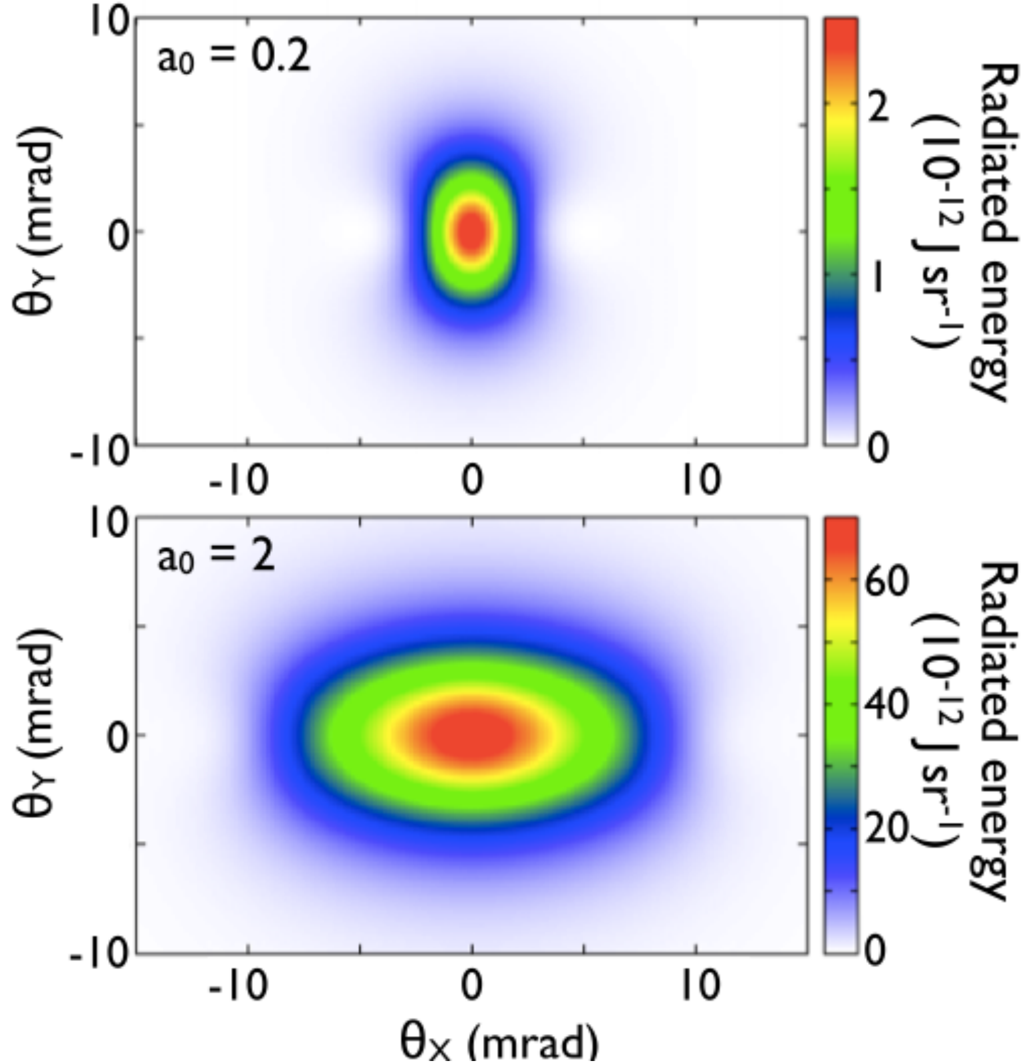
~0.1 photon / electron

~15 mrad

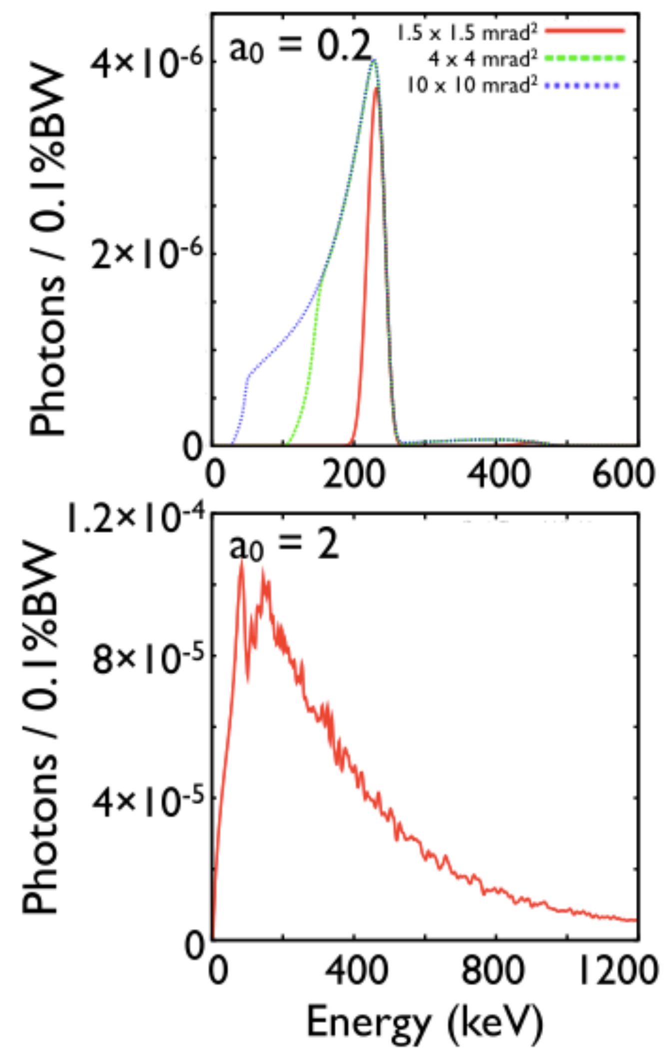
X-ray Compton scattering: *Test particle simulation*

Numerical simulation for a_0=0.2 and 2, electron energy is 100 MeV

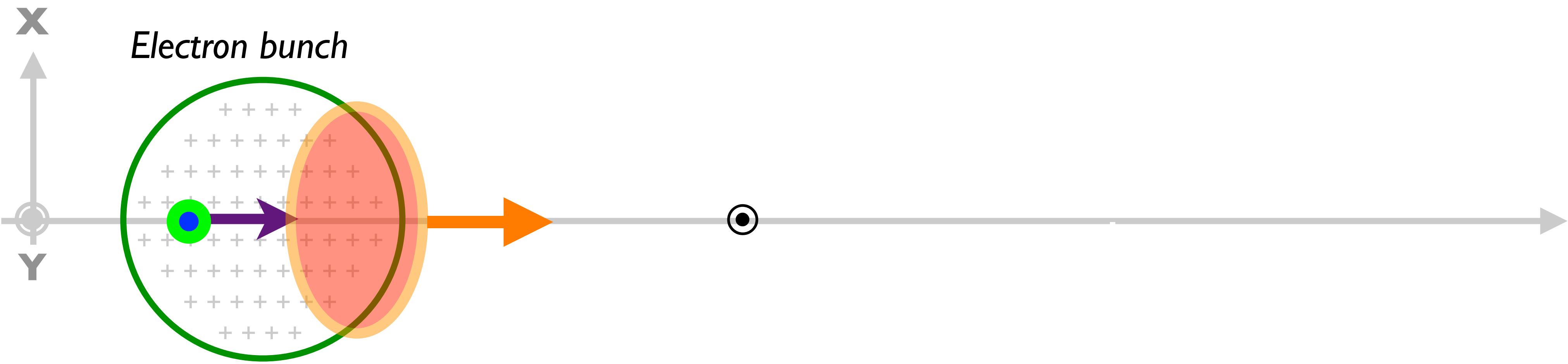
Spatial distribution



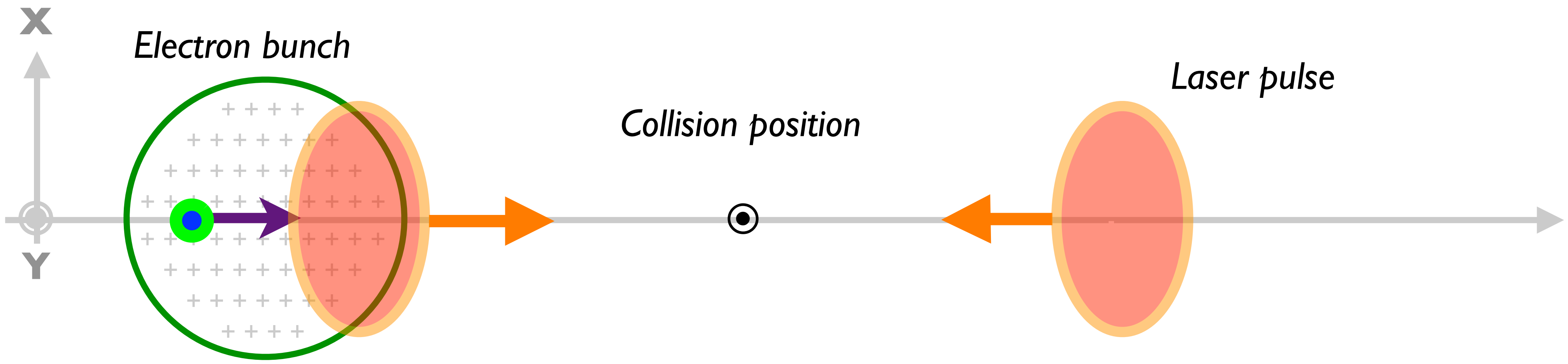
Spectrum



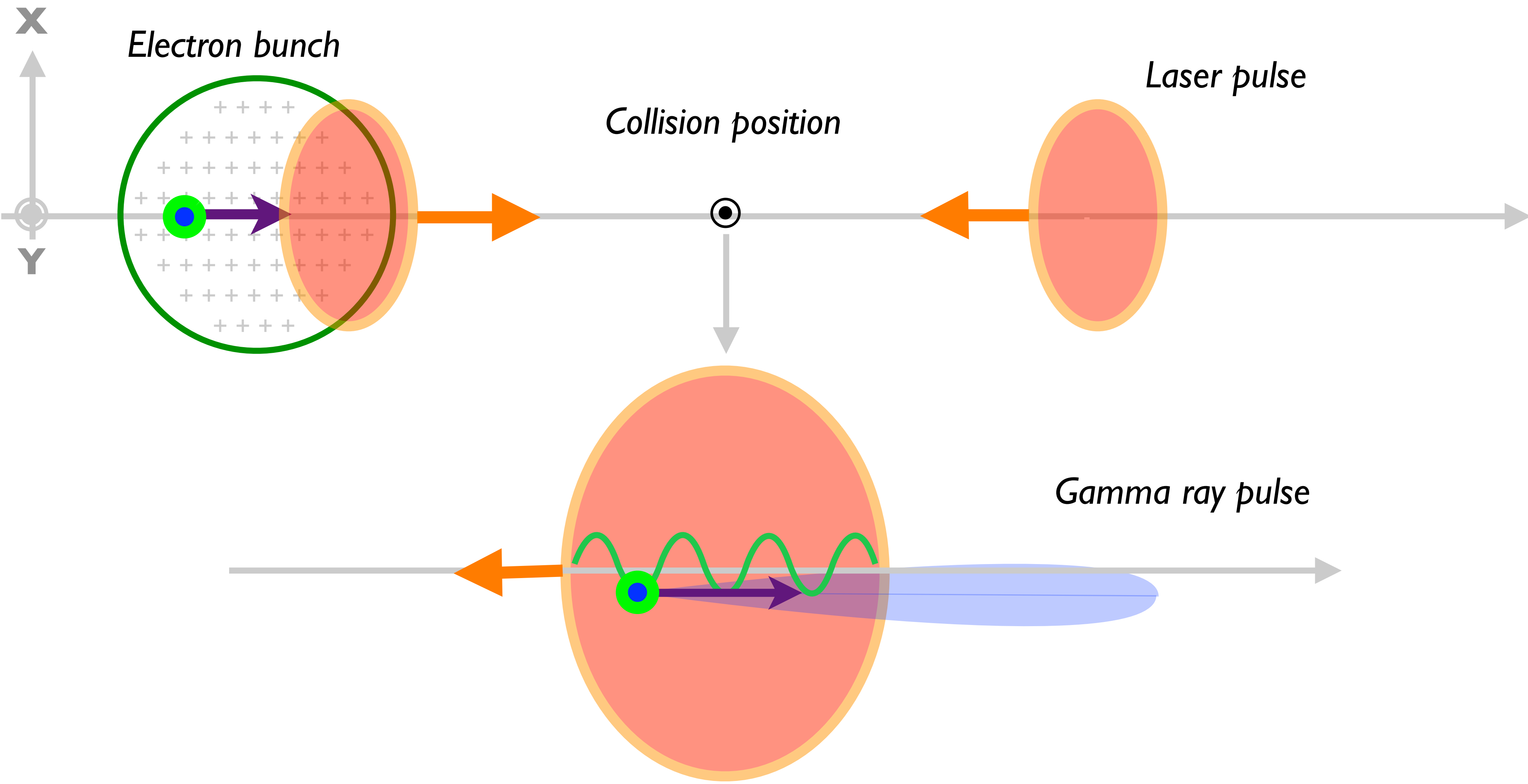
X-ray Compton scattering: *experiment*



X-ray Compton scattering: *experiment*



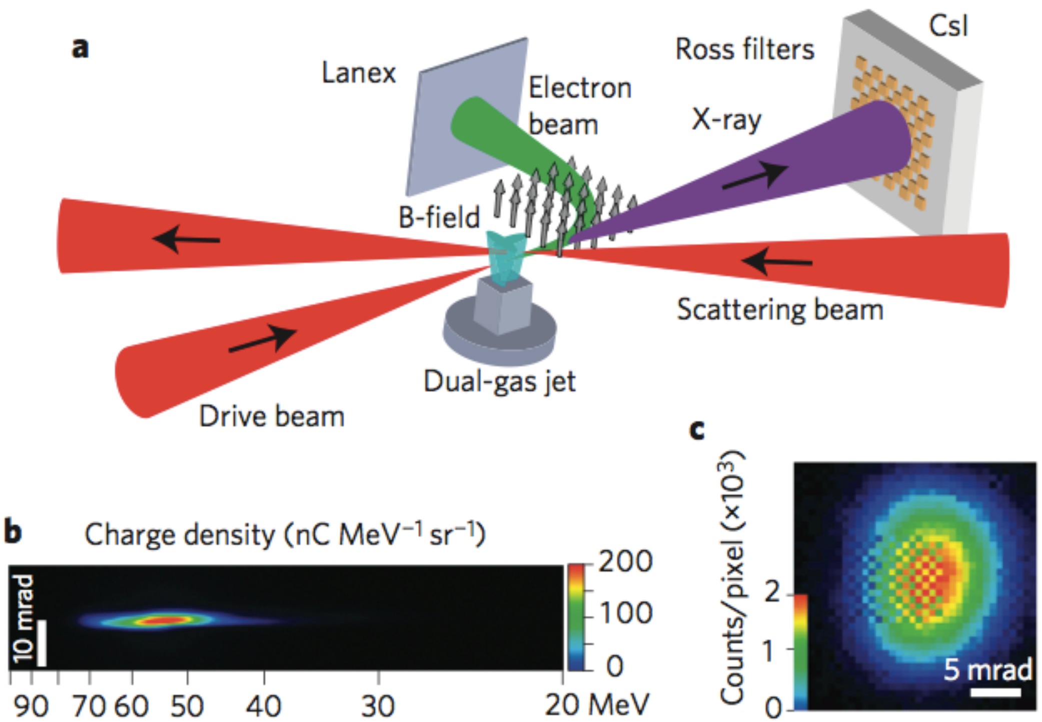
X-ray Compton scattering: *experiment*



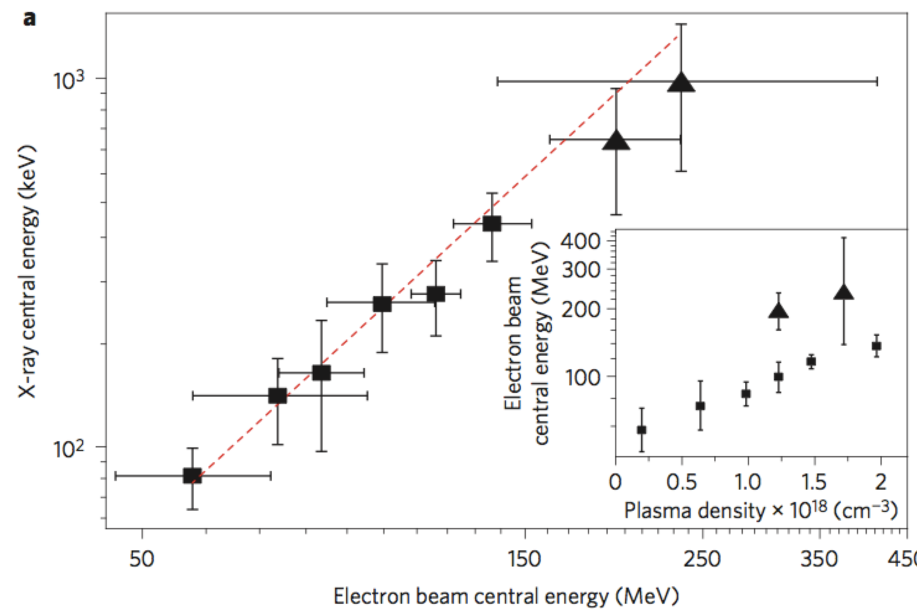
Advantages:

- Micron period (modest energies electrons can produce X-rays and Gamma-rays)

X-ray Compton scattering: *Two beams method*



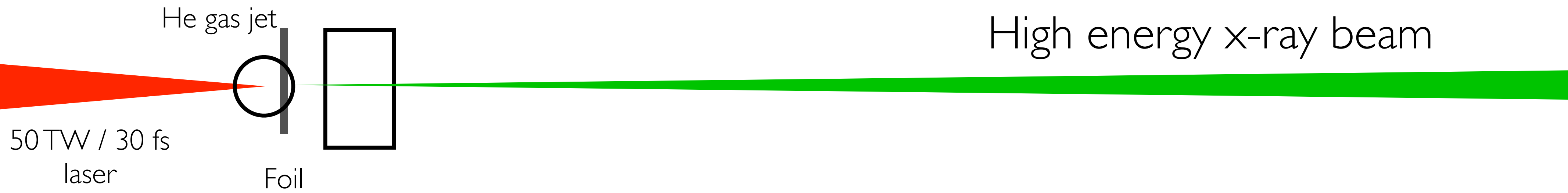
Experiment by
N. Powers et al.
D. Umstadter group , Univ. Nebraska



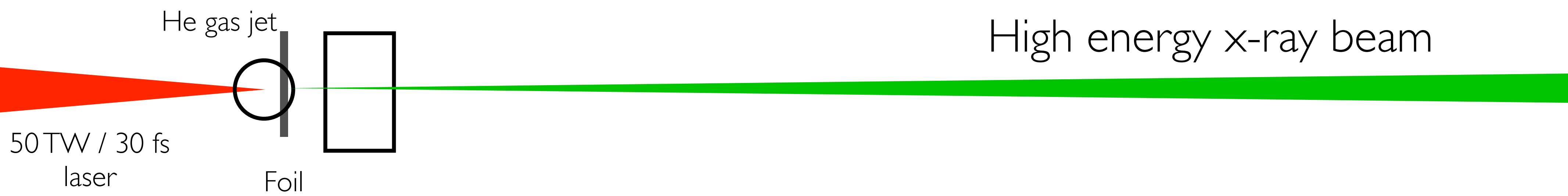
→ Production of tunable x-rays radiation in the few 100s keV range

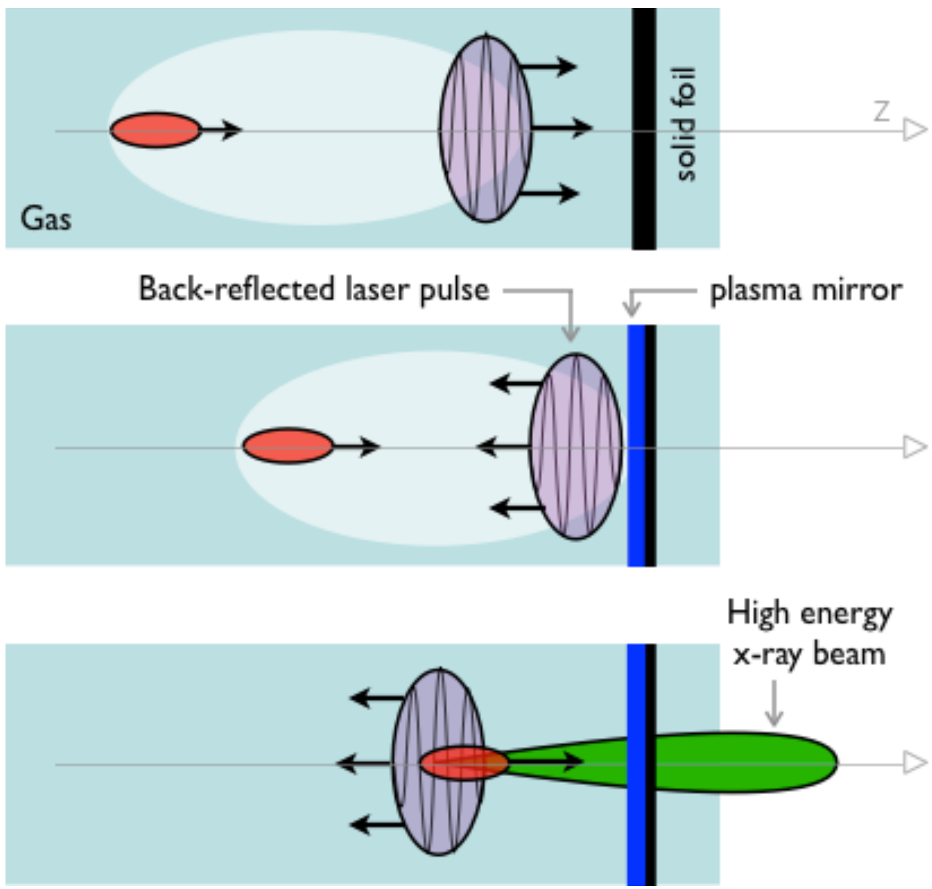
→ Production of high energy radiation: up to a few MeV

X-ray Compton scattering: *Single beam method*

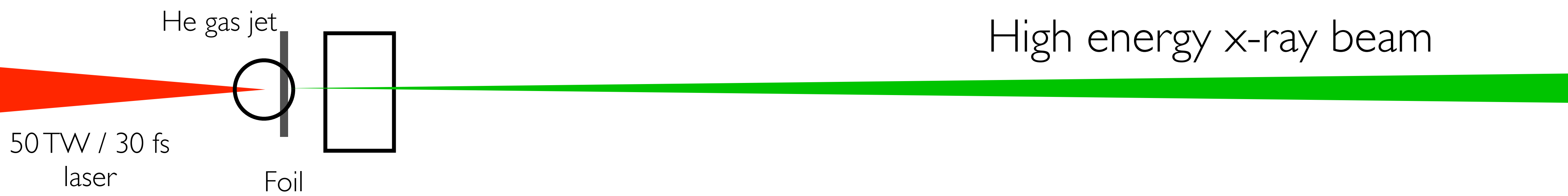


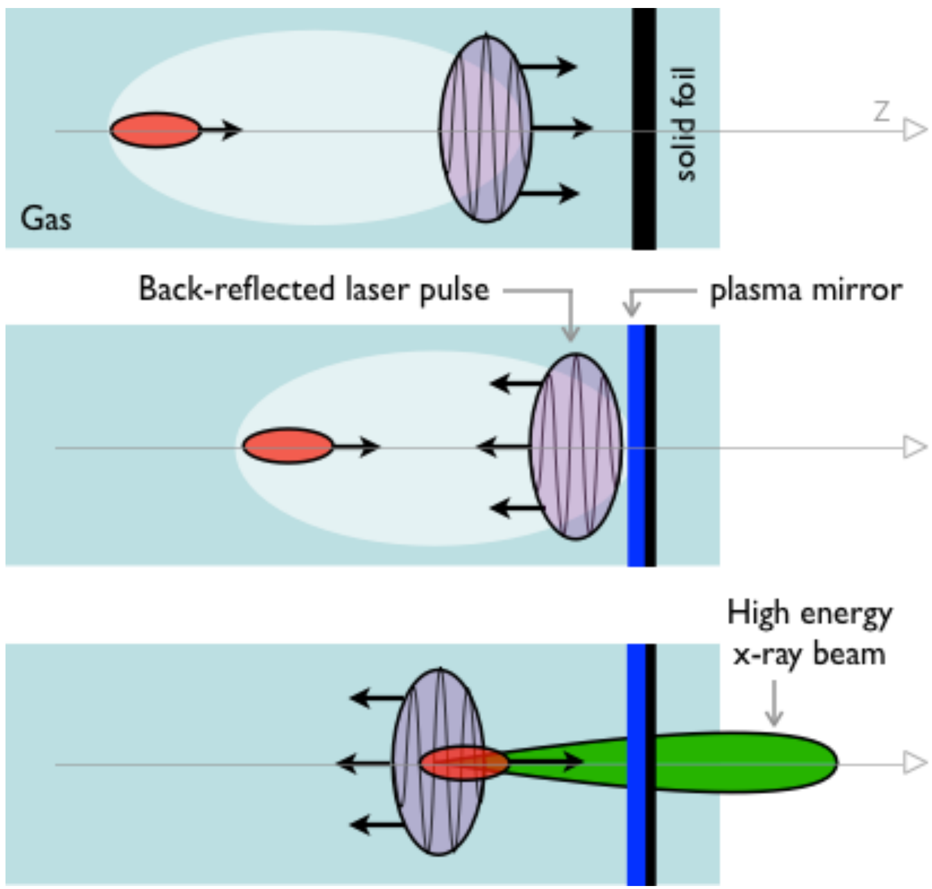
X-ray Compton scattering: *Single beam method*



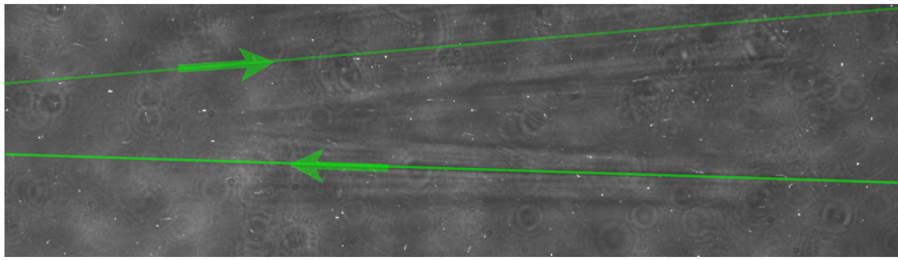


X-ray Compton scattering: *Single beam method*

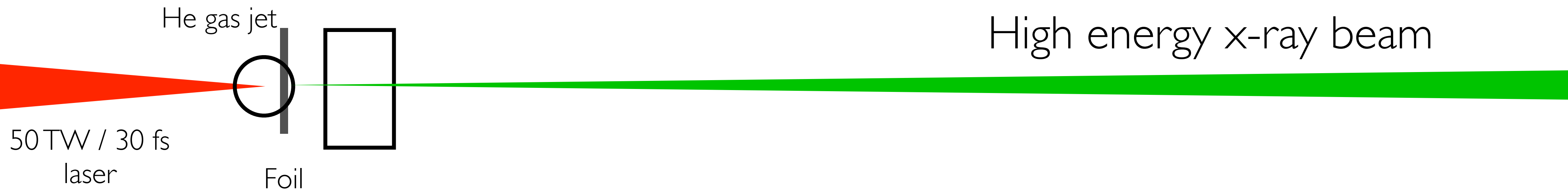


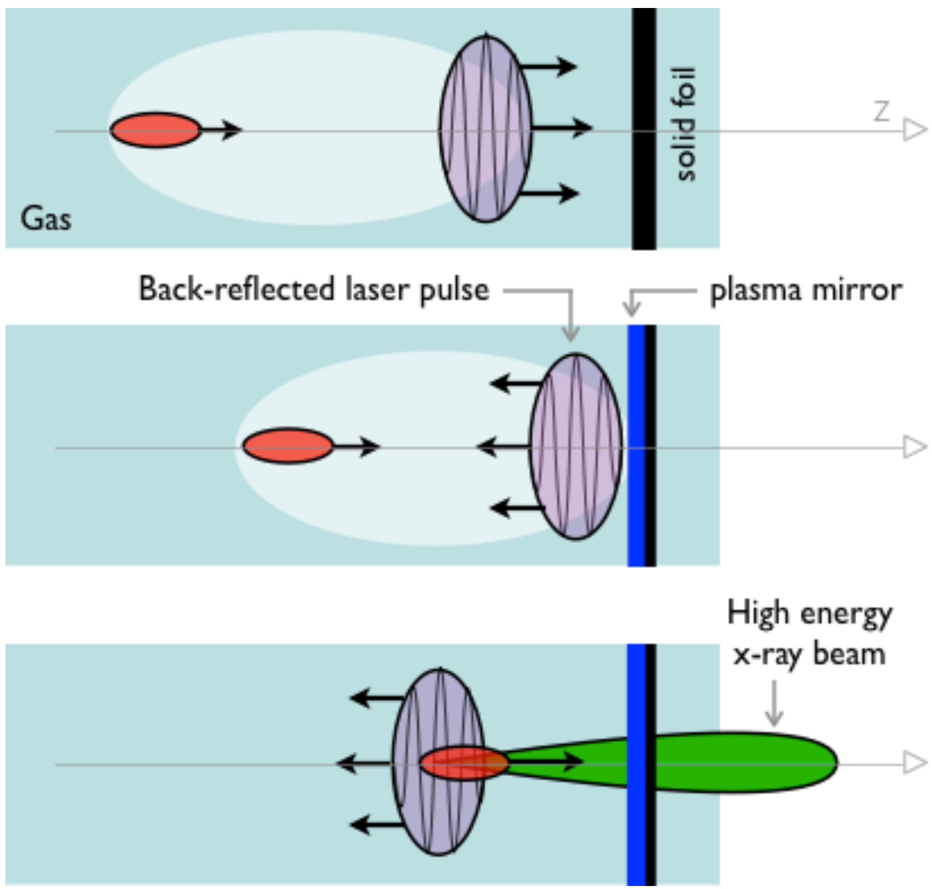


Shadowgraphy image

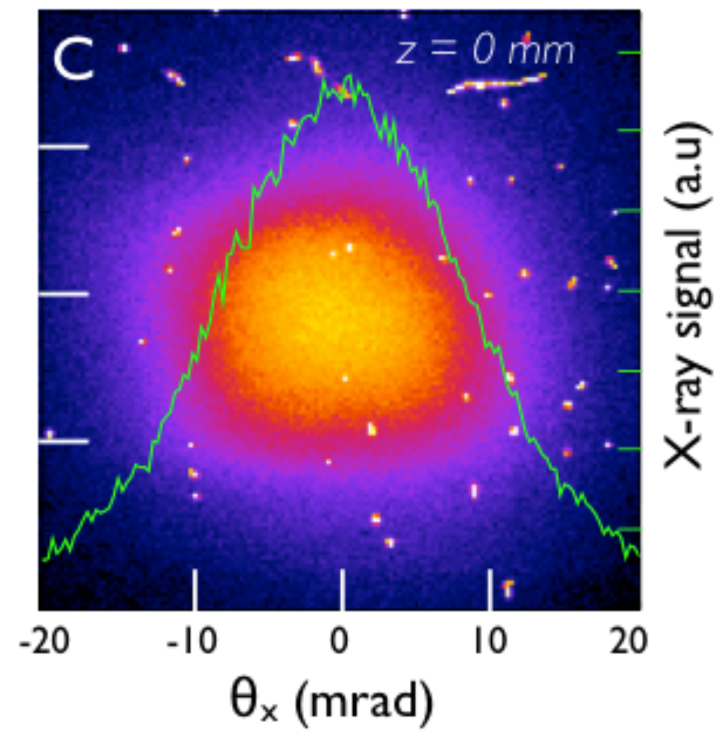


X-ray Compton scattering: *Single beam method*

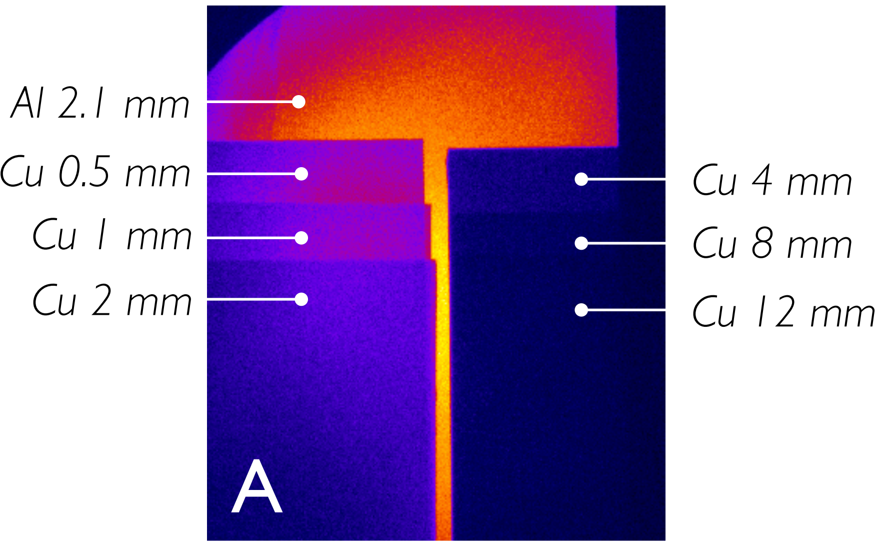


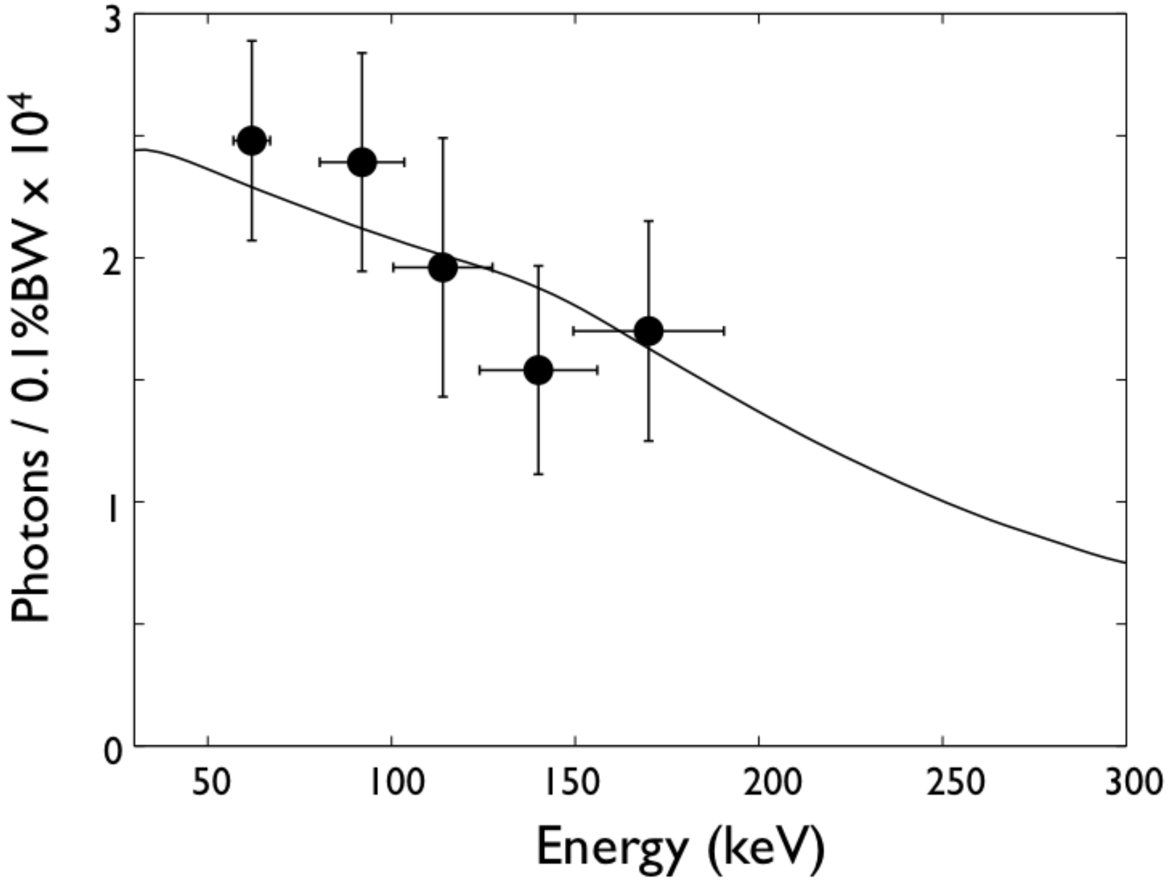


High Energy X-rays (100s keV)



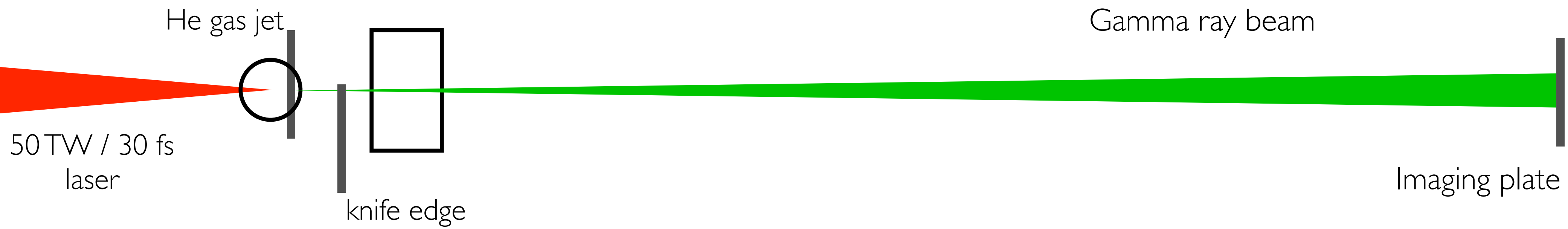
Spectrum

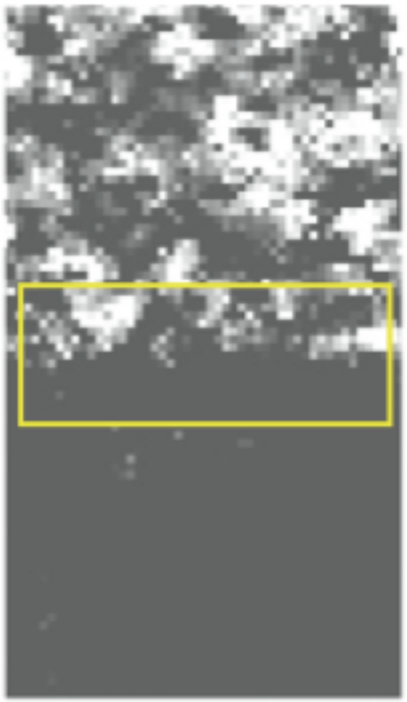


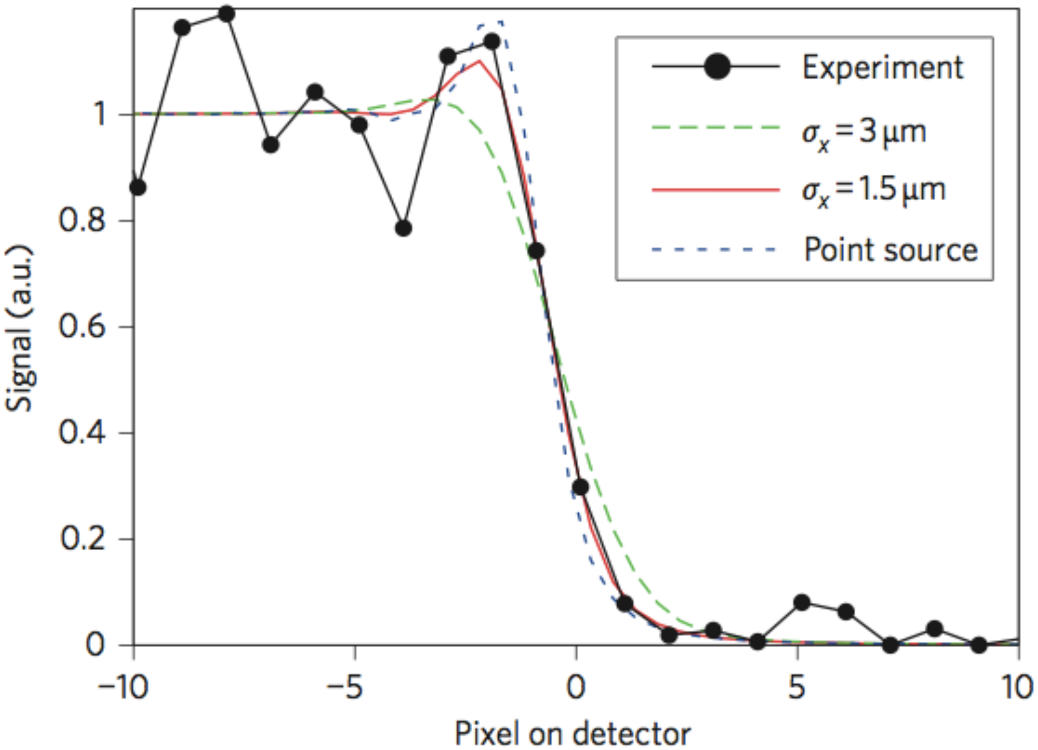


→ About 10^8 ph/tir, a few 10^4 ph/shot/0.1%BW @ 100 keV

Source size

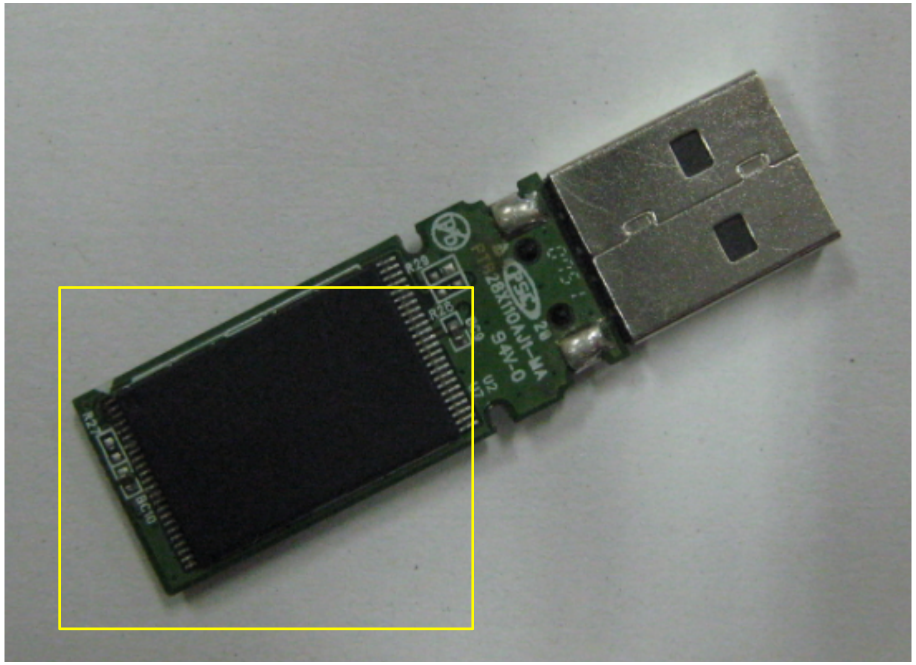


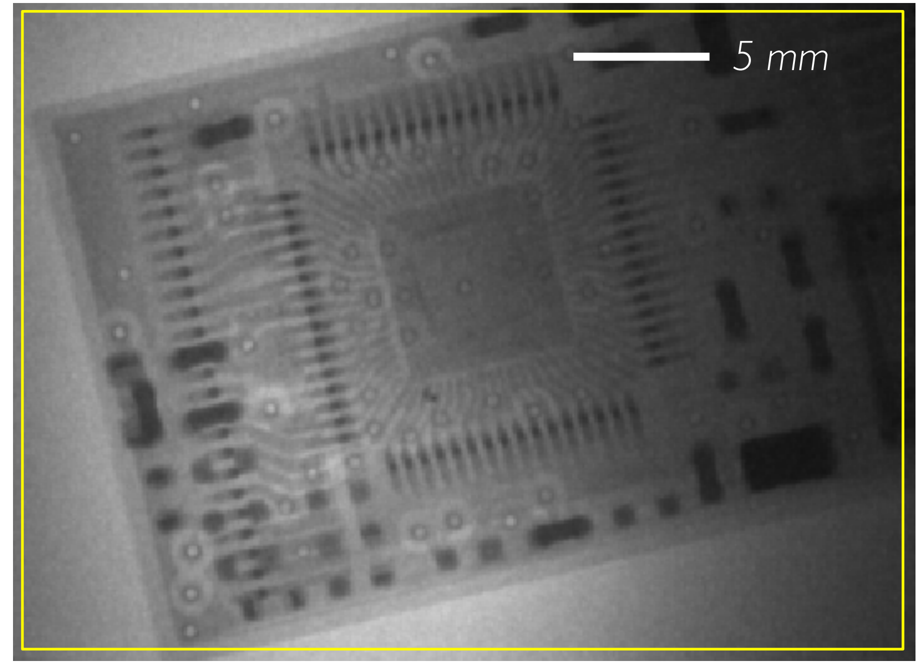


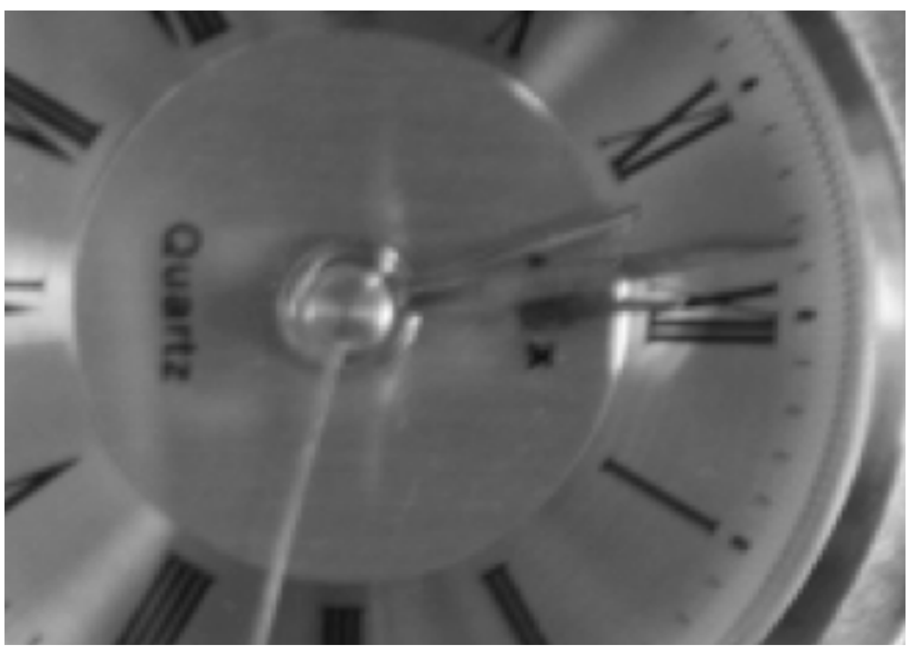


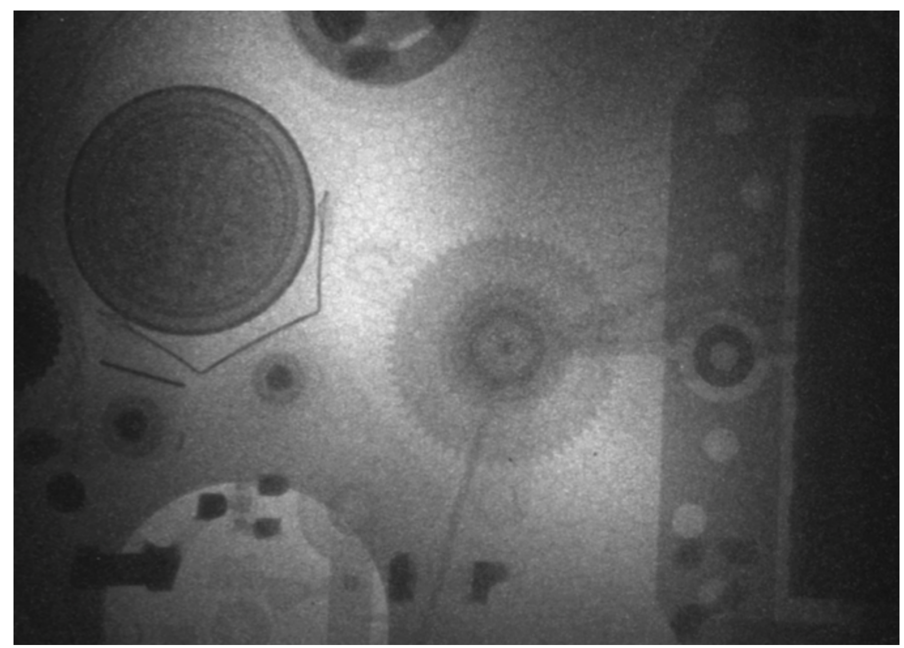
→ Micron order transverse source size

High energy x-ray radiography









Compton radiation: Summary & Perspectives

- 10^5 photons/shot/0.1% BW @ 100 keV
- collimated: 10's mrad
- ultrashort: 10's fs
- broadband: 10s keV -1 MeV
- small source size: 1- 2 microns

simple to produce

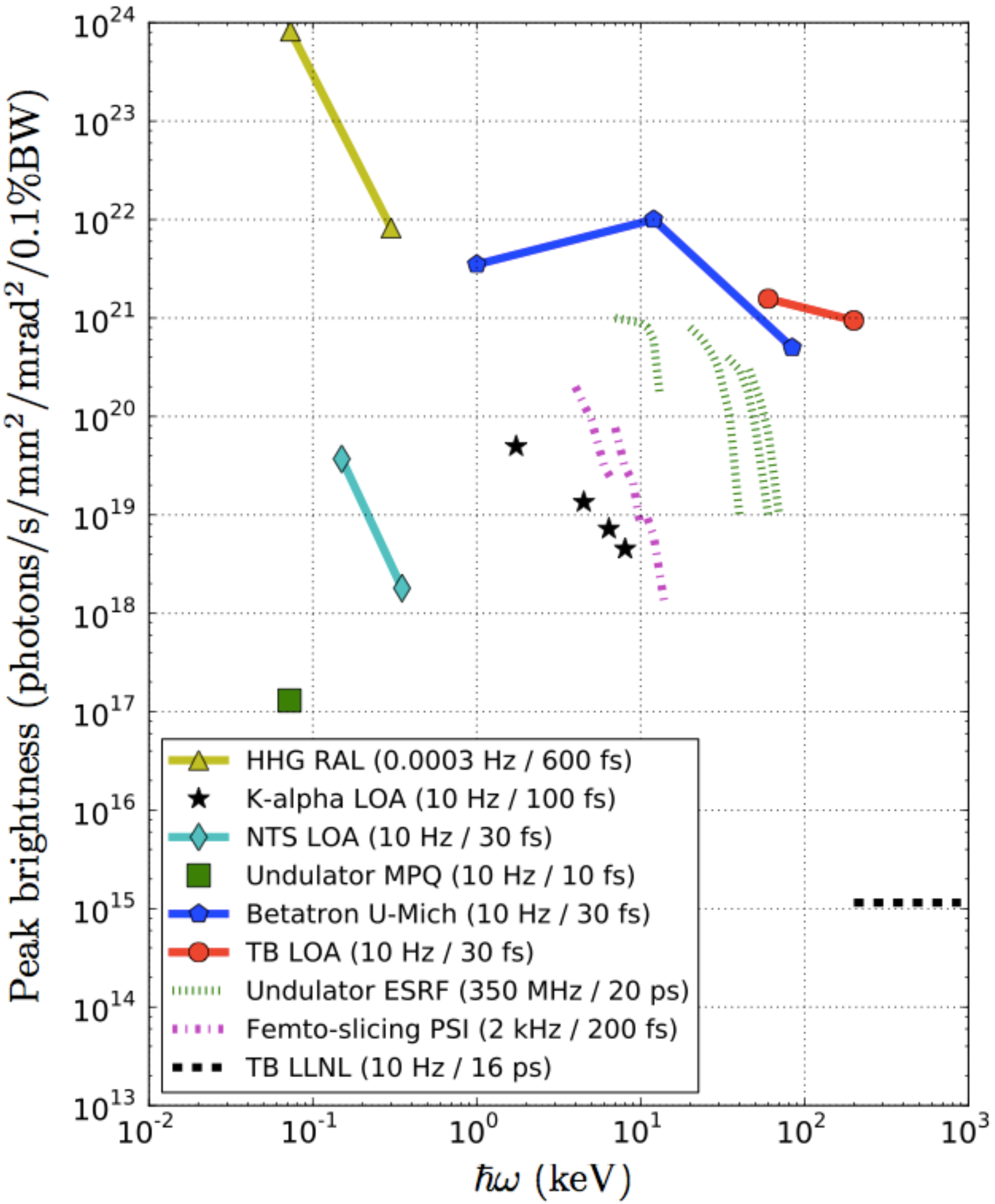
Increase the flux and reduce the spectral width
Produce high flux ten keV sources with small laser (10 TW class)

Application for high resolution radiography
High energy phase contrast imaging.

Summary

	Nonlinear Thomson scattering	Betatron	Compton scattering
Electron energy (MeV)	few 10s	few 100s	few 100s
λ	10	100	1
K	10	10	1
Radiation energy (keV)	0.1	1-10	100-1000
θ	100 mrad	10 mrad	10 mrad
n	10	10	10

Summary



Peak brightness (photons/s/mm²/mrad²/0.1%BW)
ħω (keV)
HHG RAL (0.0003 Hz / 600 fs)
K-alpha LOA (10 Hz / 100 fs)
NTS LOA (10 Hz / 30 fs)
Undulator MPQ (10 Hz / 10 fs)
Betatron U-Mich (10 Hz / 30 fs)
TB LOA (10 Hz / 30 fs)
Undulator ESRF (350 MHz / 20 ps)
Femto-slicing PSI (2 kHz / 200 fs)
TB LLNL (10 Hz / 16 ps)

Conclusion

→ We can produce femtosecond x-ray beams using laser plasma interaction

→ These sources are all based on radiation from relativistic oscillating electrons

→ These sources are easy to produce, compact, bright, synchronized with the laser.

→ These sources are not stable. The pointing, the flux and the spectrum vary shot to shot. It is necessary to work on these problems before the source can be delivered to users.

→ It is an important challenge to develop new schemes. In particular, would it be possible to produce a Free Electron Laser using electrons from a LPA ?

Acknowledgements

From LOA:
Romuald FITOUR*, Felicie ALBERT*, Rahul SHAH*, Jerome FAURE, Clement RECHATIN*, Jean Philippe ROUSSEAU, Victor MALKA, Jean Philippe GODDET, Amar TAFZI, Frederic BURGY*, Pascal ROUSSEAU, Philippe ZEITOUN, Guillaume LAMBERT, Greg LIAQUANIELLO.

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