Betatron radiation in Laser Plasma Accelerators

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cea

Why do we need x-ray sources ?

Multidisciplinary, novel and fundamental applications

Femtosecond x-ray/Gamma-ray sources →

- To probe the matter →
  - X-ray diffraction
  - X-ray absorplion
  - Thomson scallcring
  - ccl...
  - Radiography
  - Phase contrast imaging
- To excite the matter →
  - Ionization
  - healing

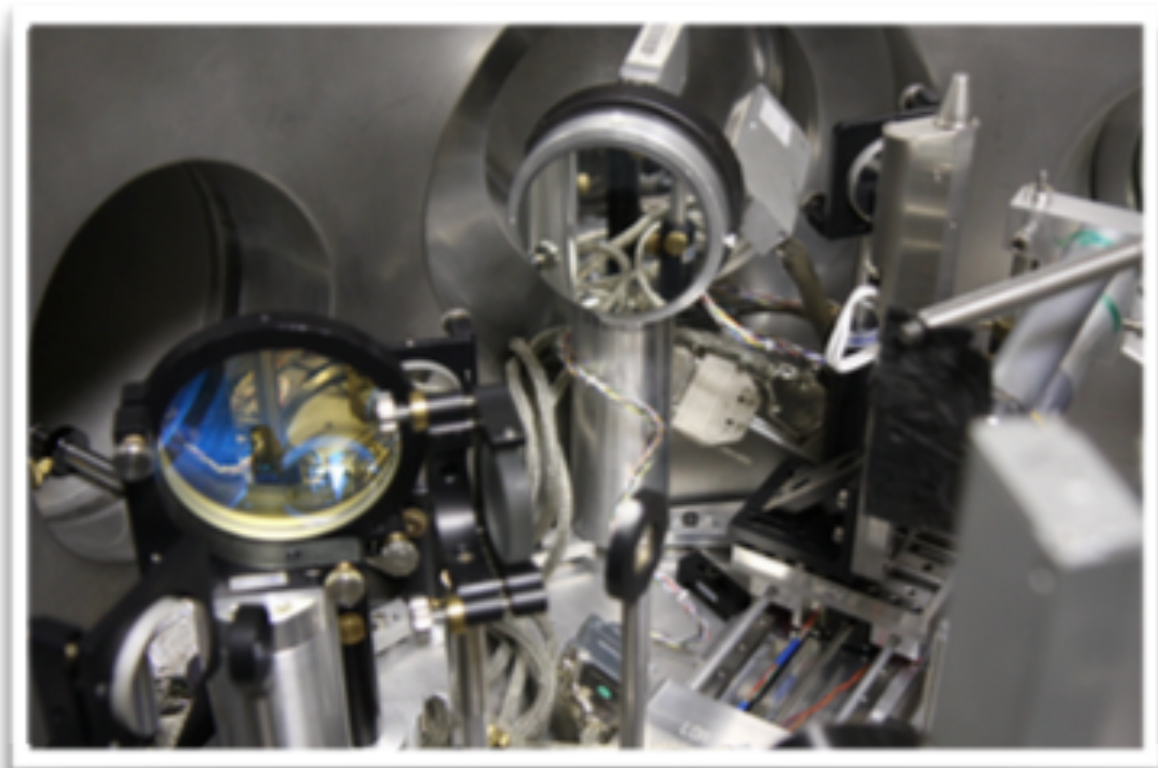
Physics
- Plasmas physics
- Solid State physics

Chemistry

Biology

Industry

Femtosecond x-ray sources



K-alpha Plasma Source

- Compact
- Low cost

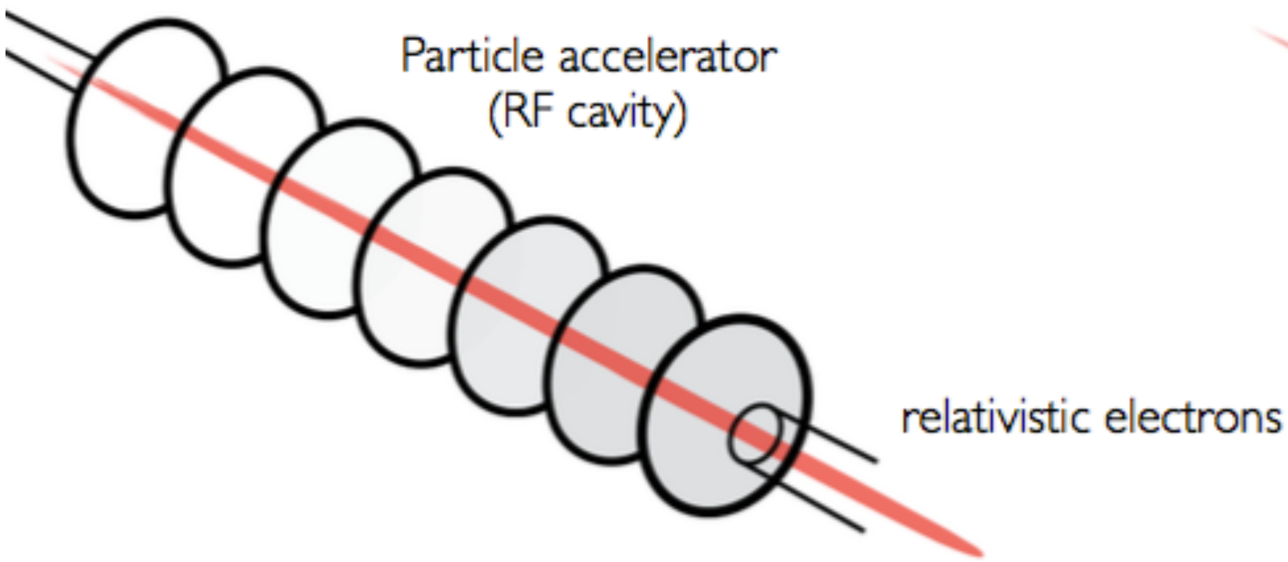
- Isotropic
- « long » 100s fs

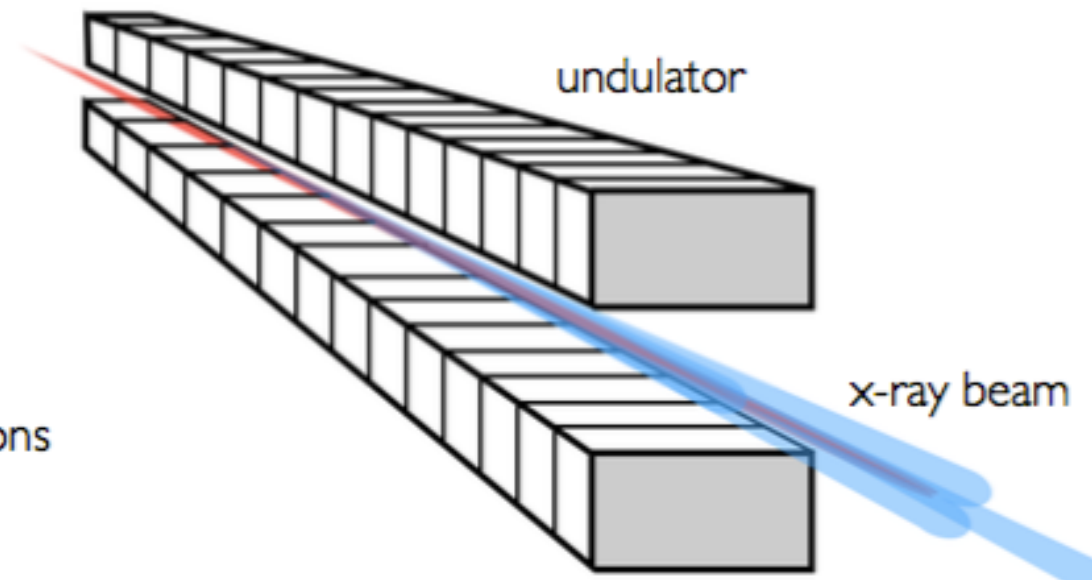
Free Electron Lasers

- Very high brightness
- high repetition rate

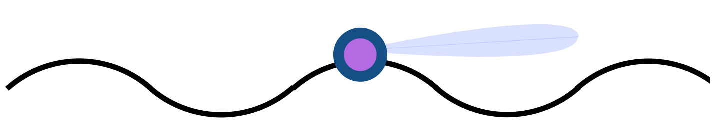
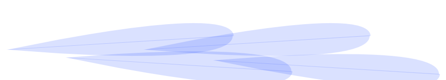
- Very high cost
- Poor spectral properties

Synchrotron radiation in a laser produced plasma ?

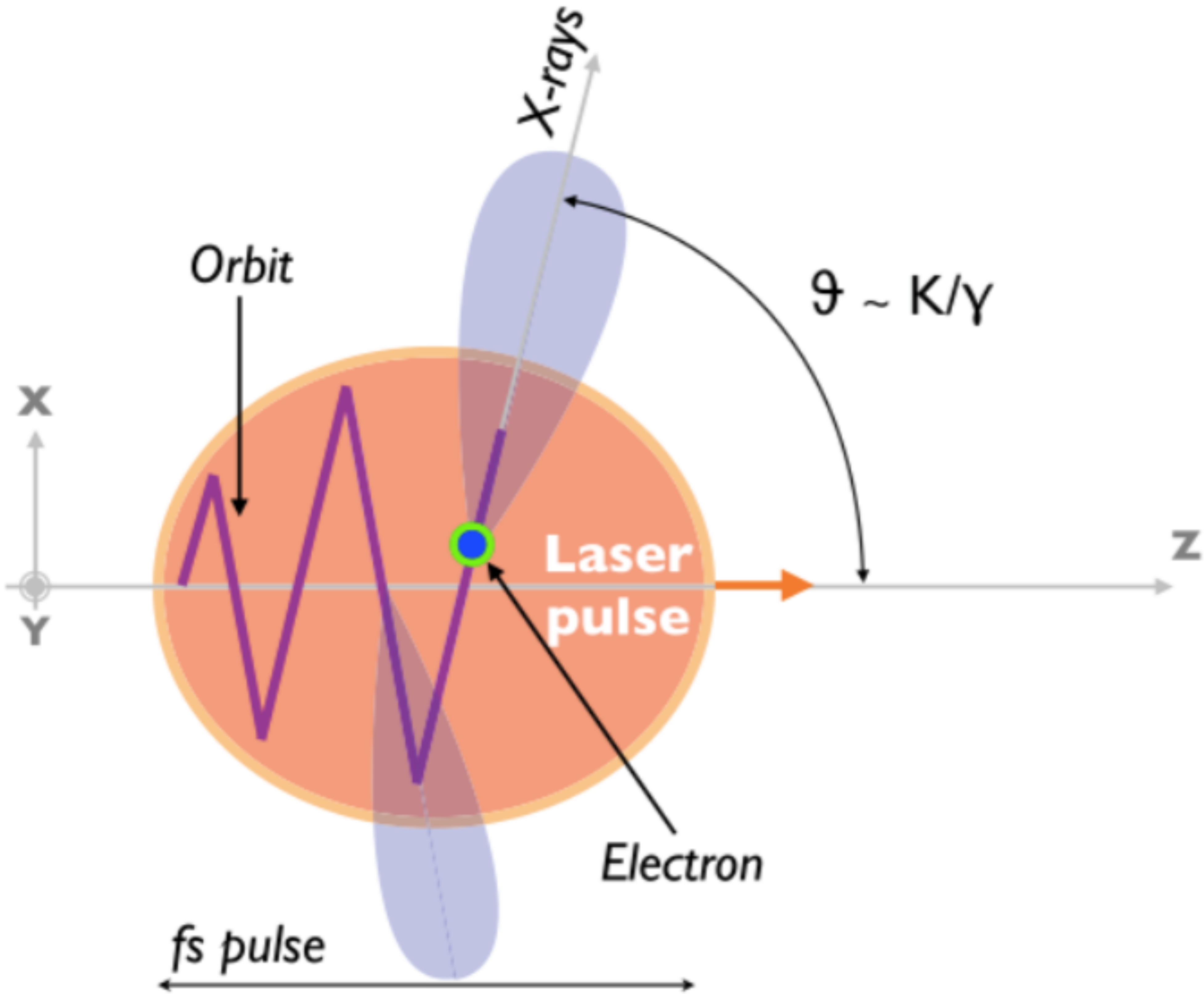




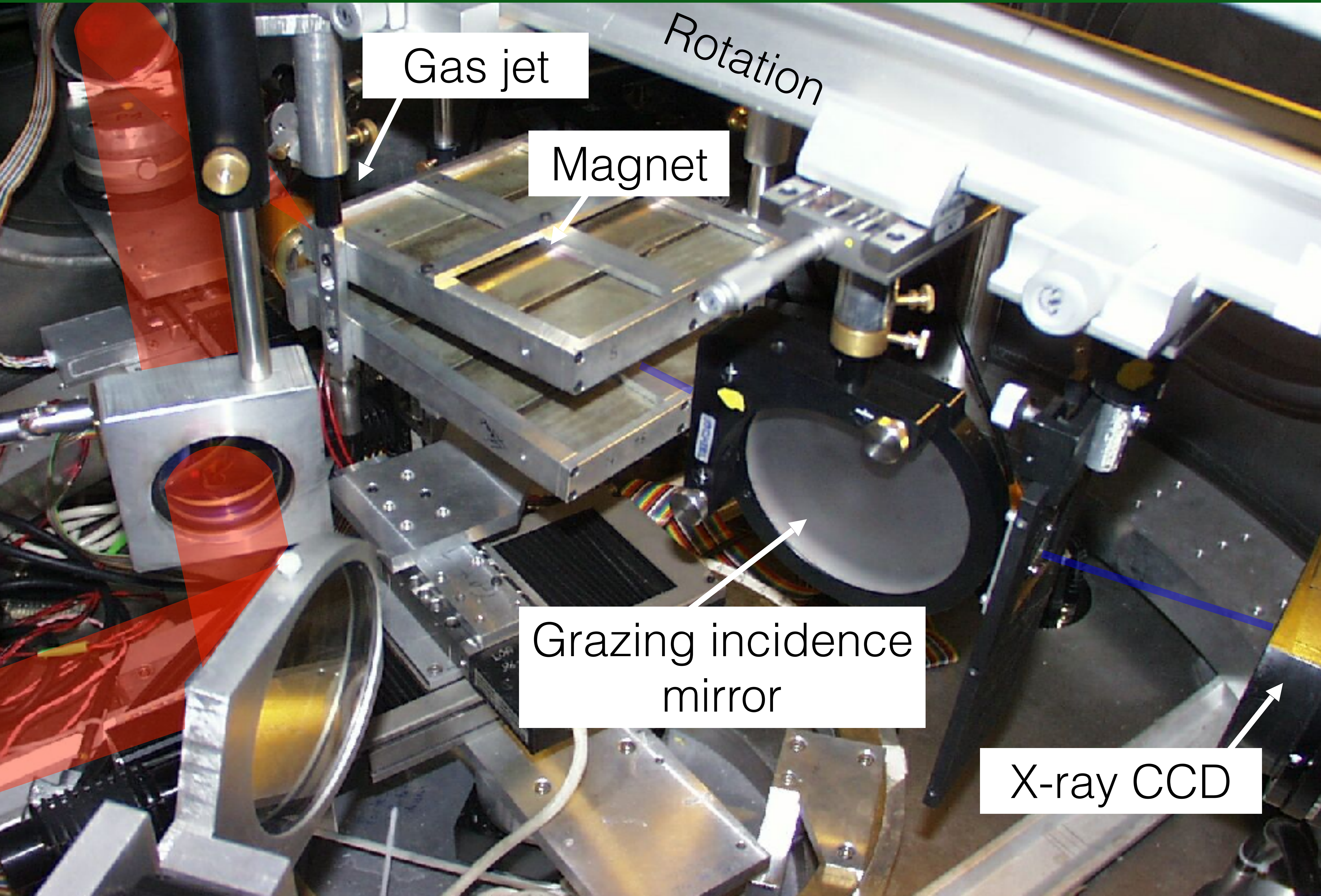
Relativistic electrons + Wiggling = X-ray radiation

Nonlinear Thomson Scattering

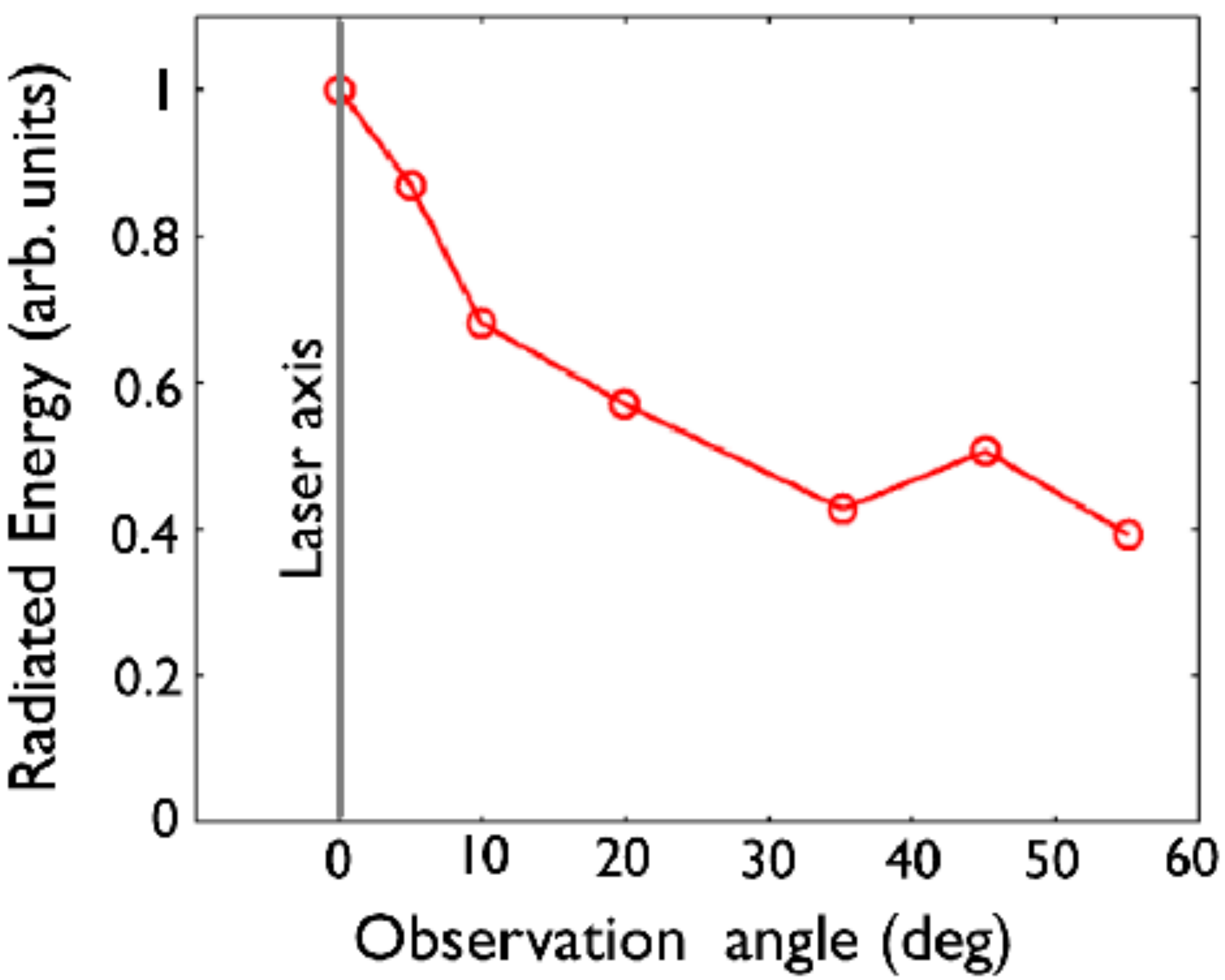


Nonlinear Thomson Scattering experiment (2003)

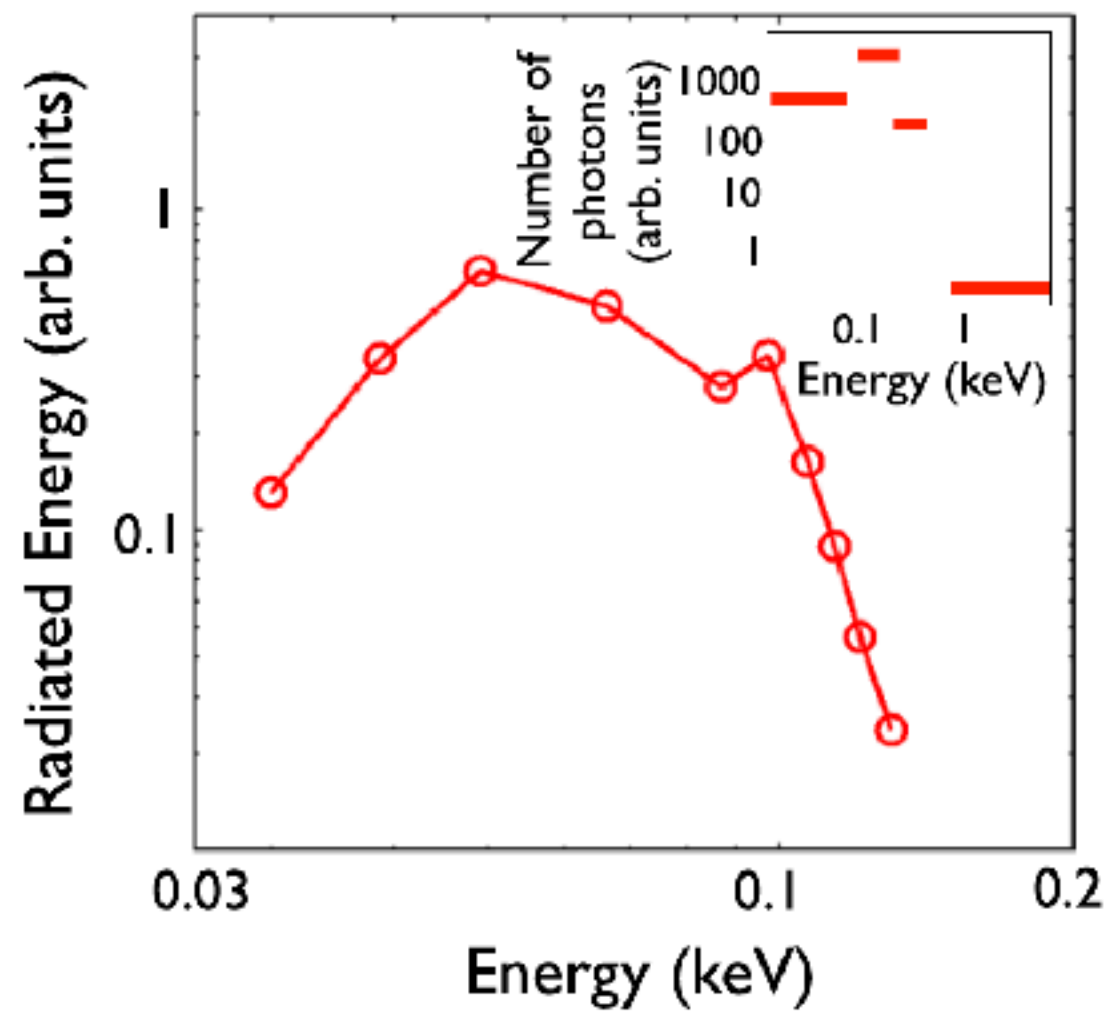


Nonlinear Thomson Scattering experiment (2003)

Angular distribution

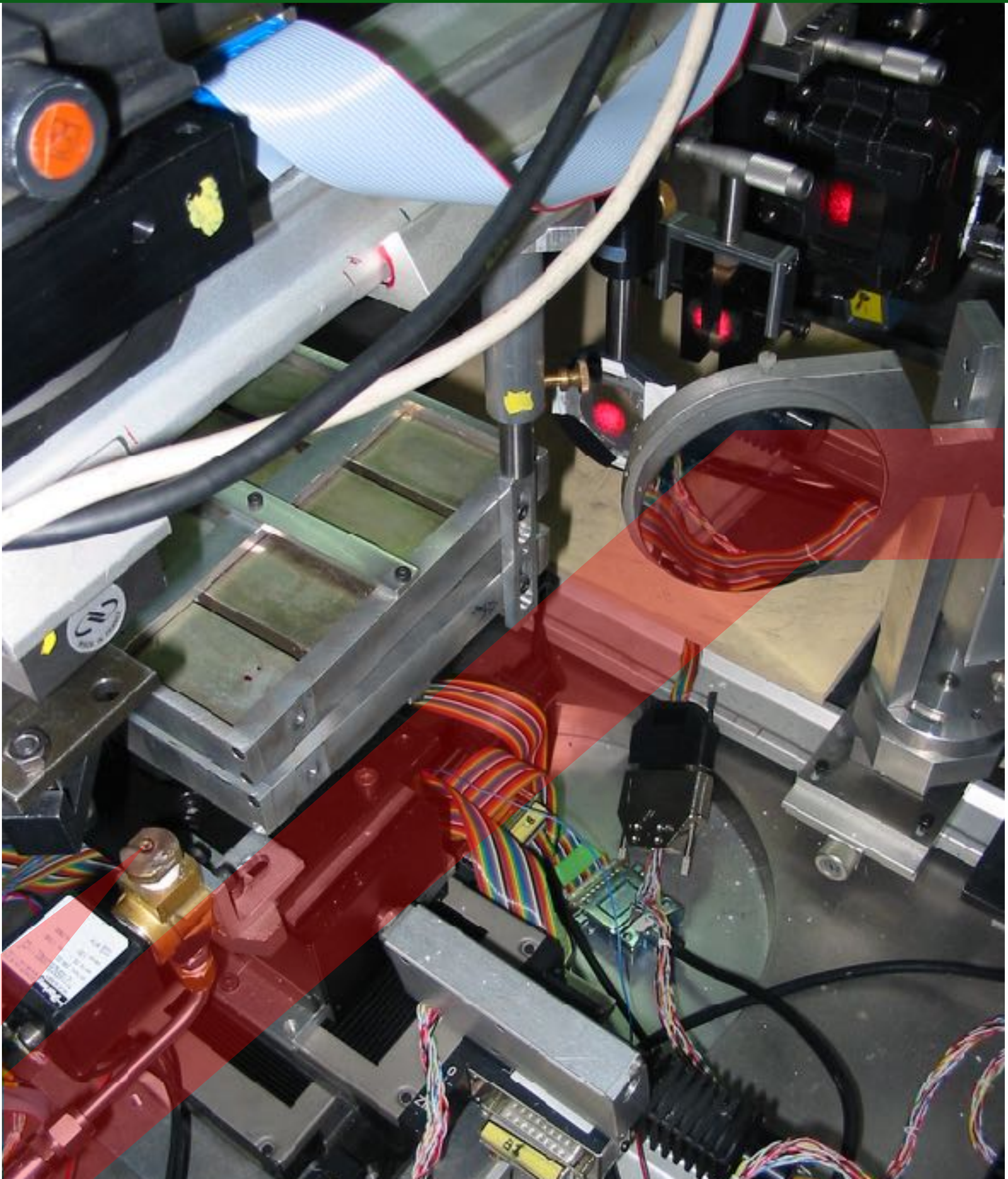


Spectrum

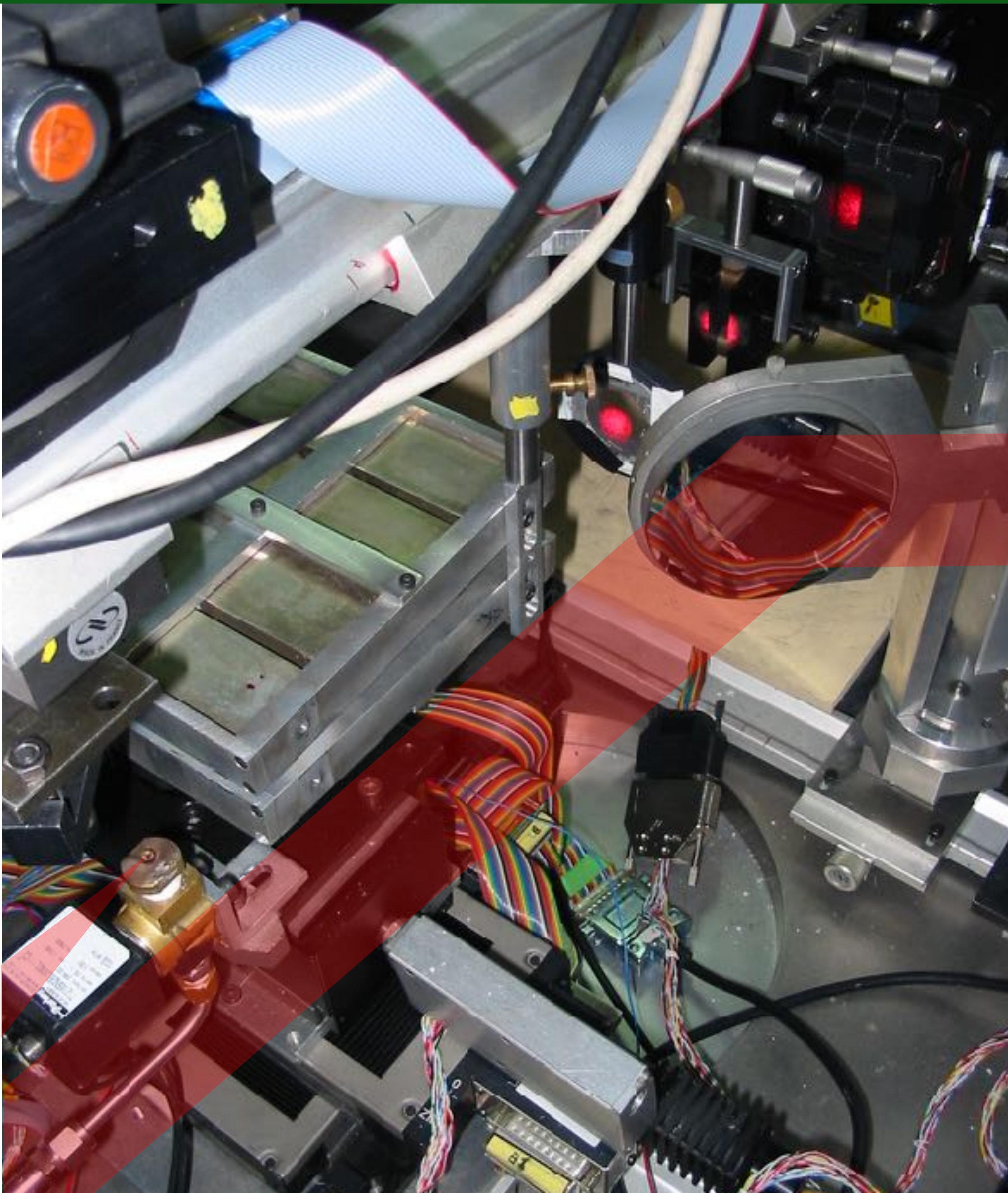


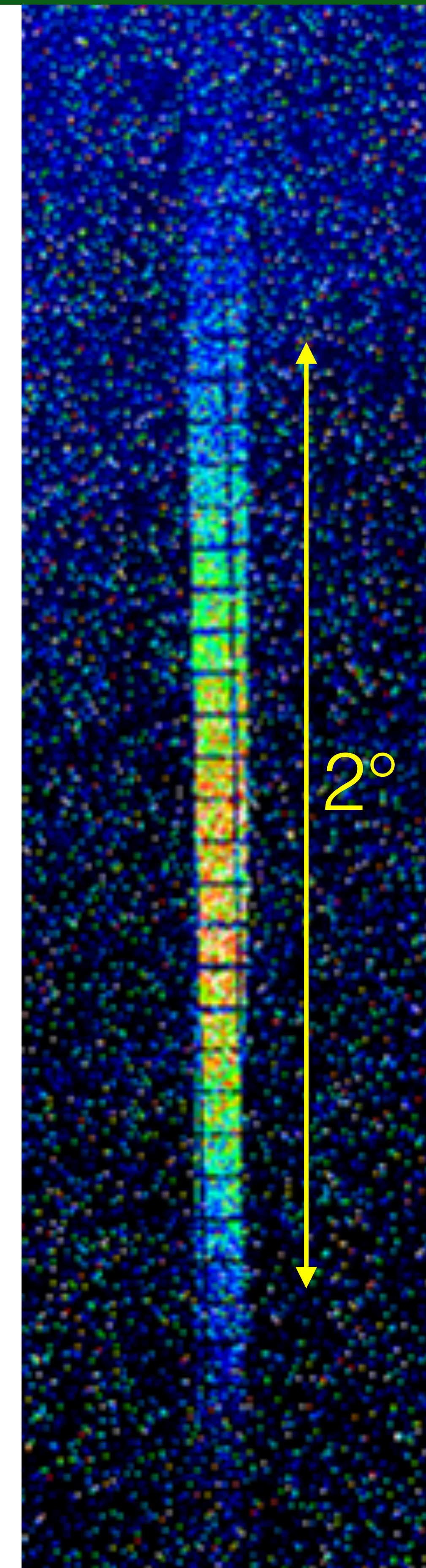
→ Few 10s degrees, up to a few 100s eV

Nonlinear Thomson Scattering experiment (2003)

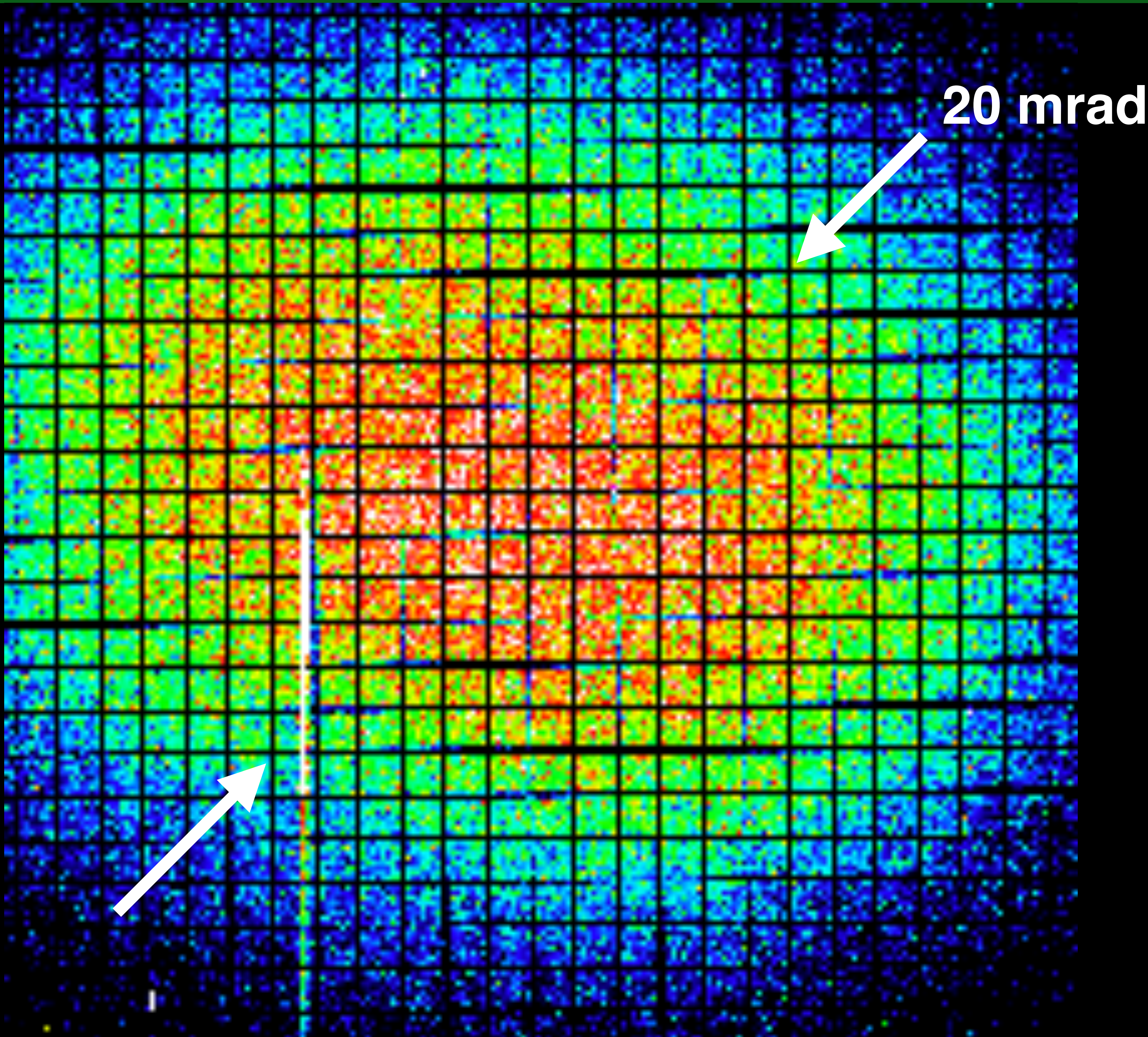


Nonlinear Thomson Scattering experiment (2003)





First observation of Betatron radiation



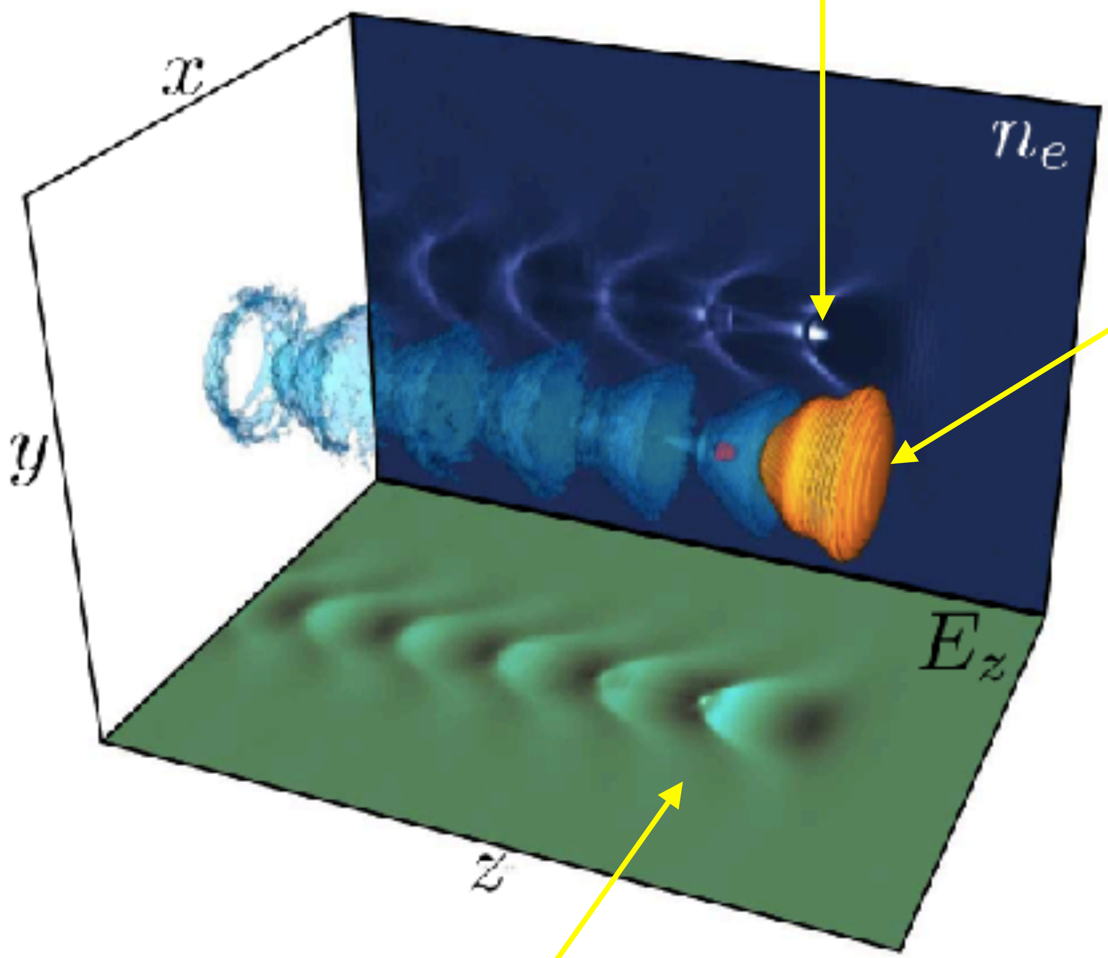
Outline

- Principle of laser Plasma Accelerator
- Principle of Betatron radiation source
- Characterization of the Betatron radiation source
- Applications of the Betatron radiation
- Latest improvements of the source

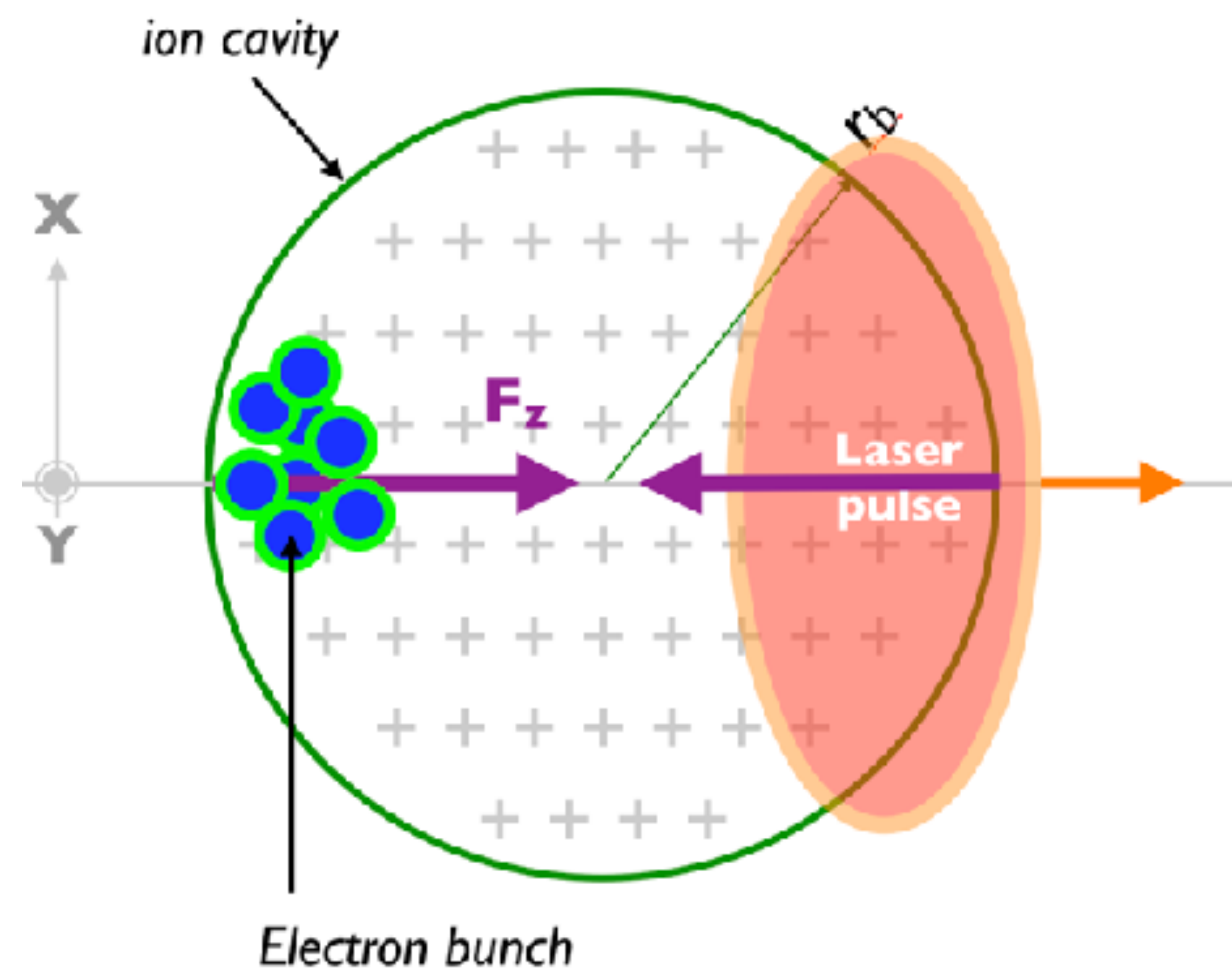
Laser Plasma Accelerator

Electron beam

>TW Laser pulse



Wakefield (100s GeV/m)



Relativistic electrons from a Laser Plasma Accelerator

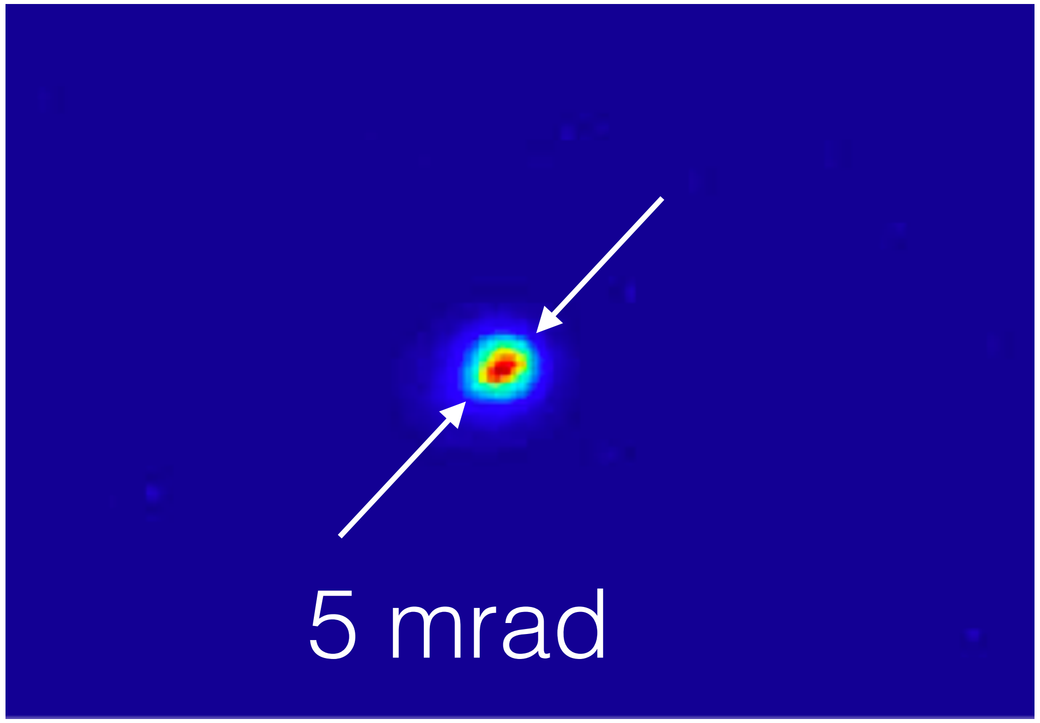
→ Electron beam features :

Charge : few hundreds pC

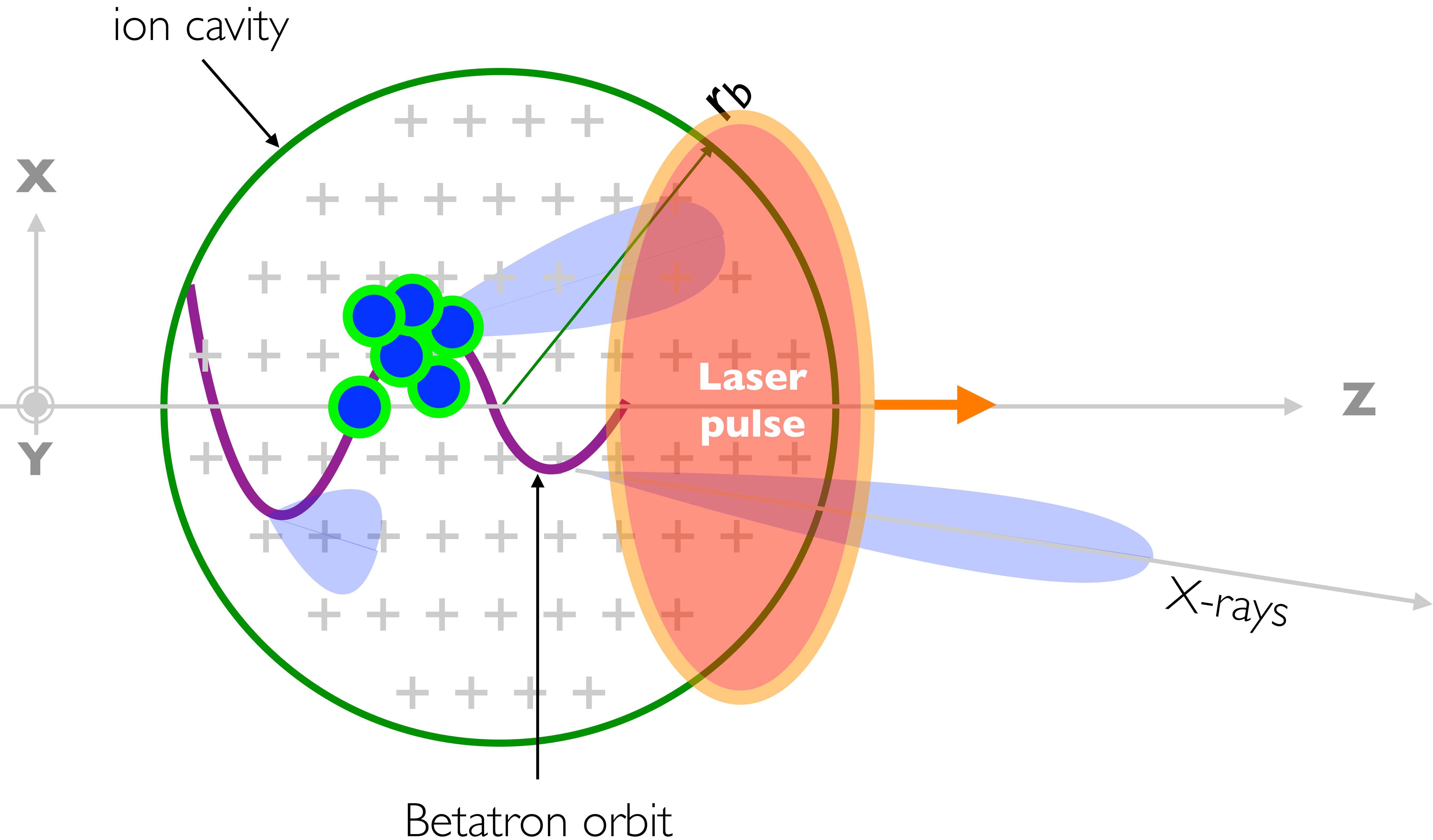
Energy : 100s MeV - GeV

Divergence : few mrad

Duration : few fs

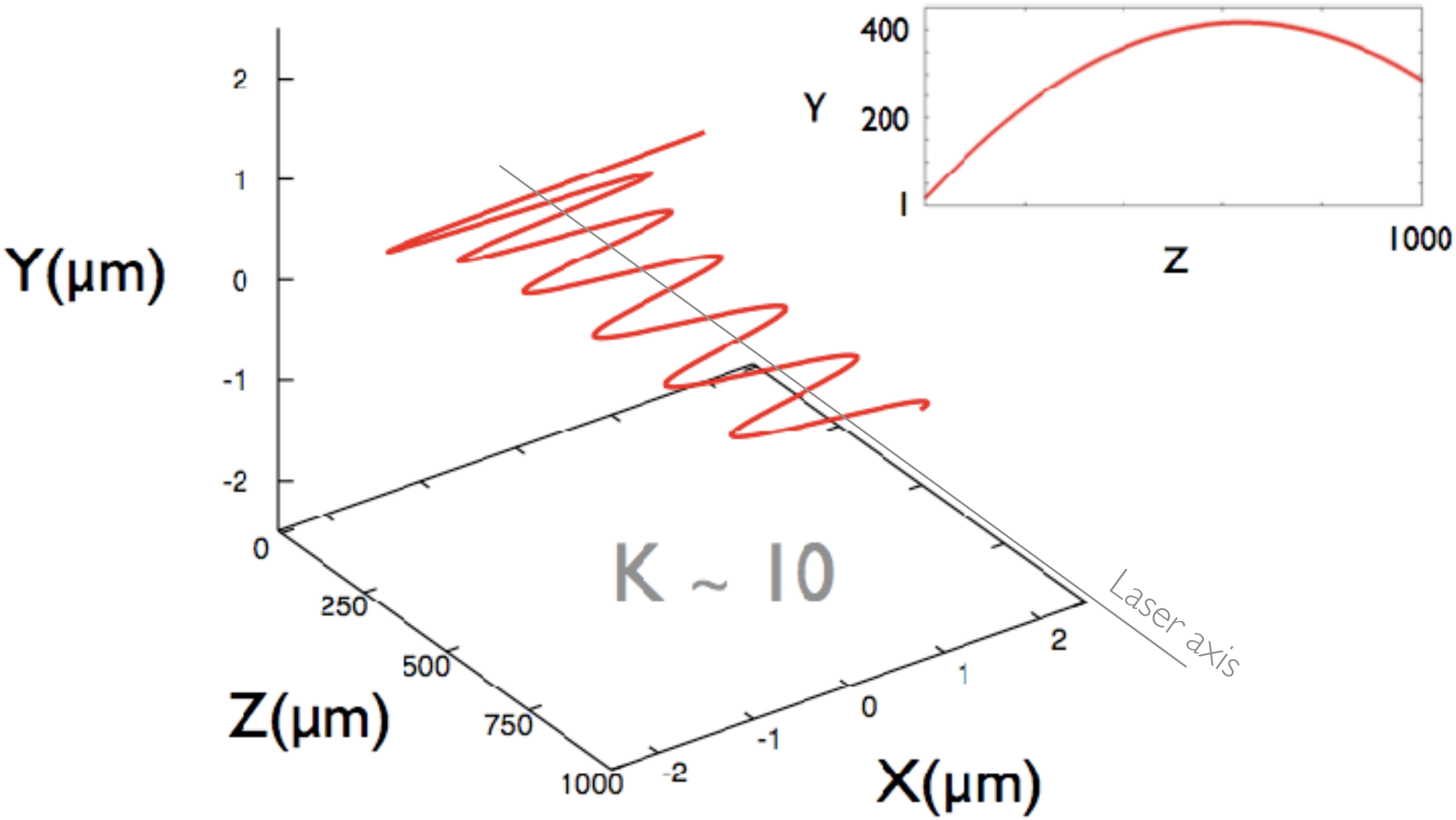


Betatron radiation = synchrotron radiation from laser produced plasma



Electron orbit in the ion cavity: Betatron oscillations

Example for $a_0=4$, $n_e=10^{19}$ cm^{-3}

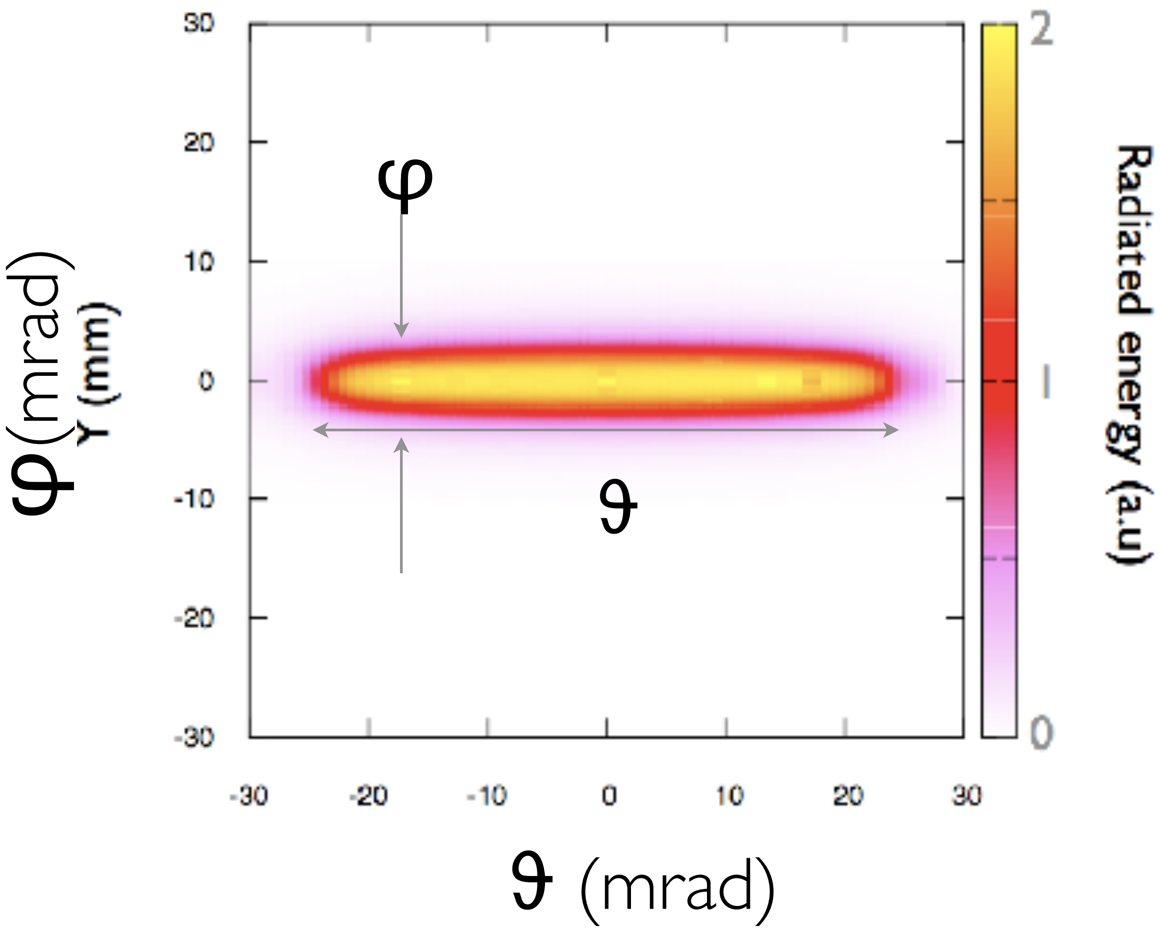


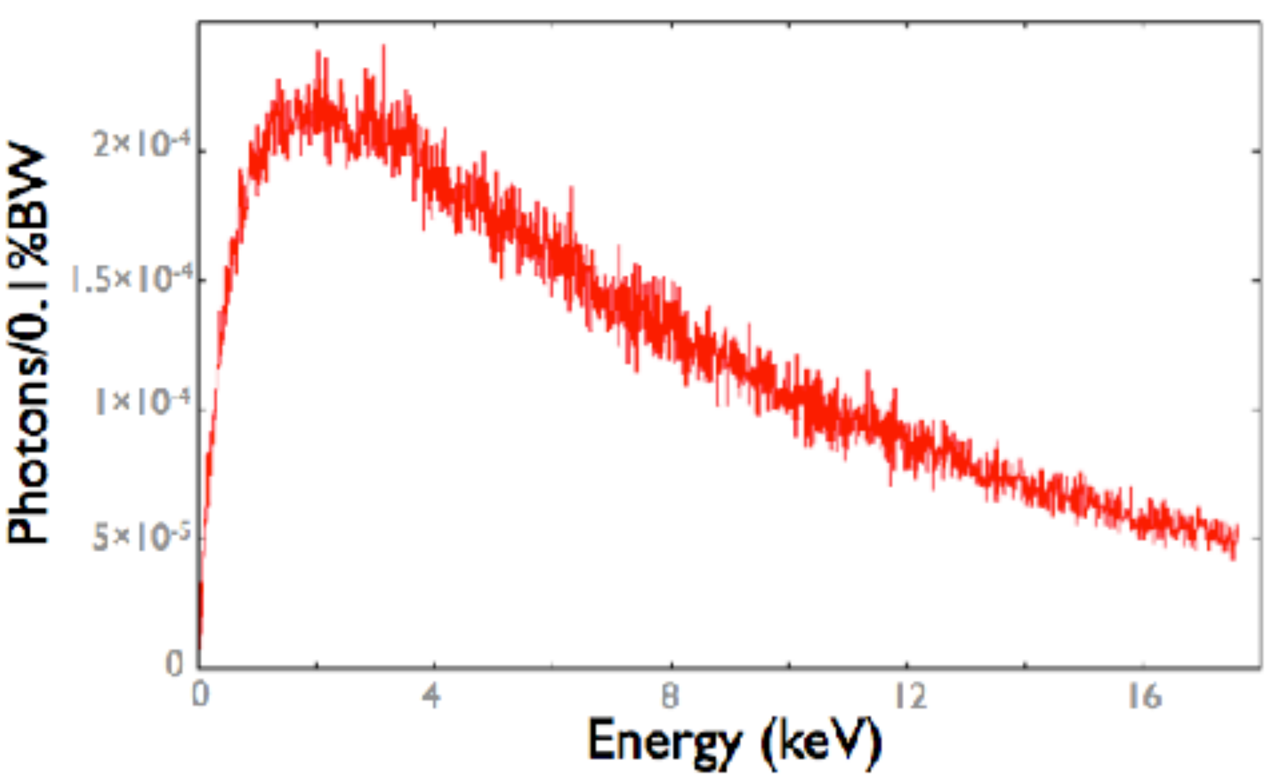
Characteristics of the trajectory

$\gamma \approx 300$ (150 MeV)

$\lambda_u \approx 150$ µm

Betatron radiation features: for one electron





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

Spatial distribution (beam profile)

$\vartheta = K/\gamma$

~3 degrees for K = 10 and 100 MeV e-

$\varphi = 1/\gamma$

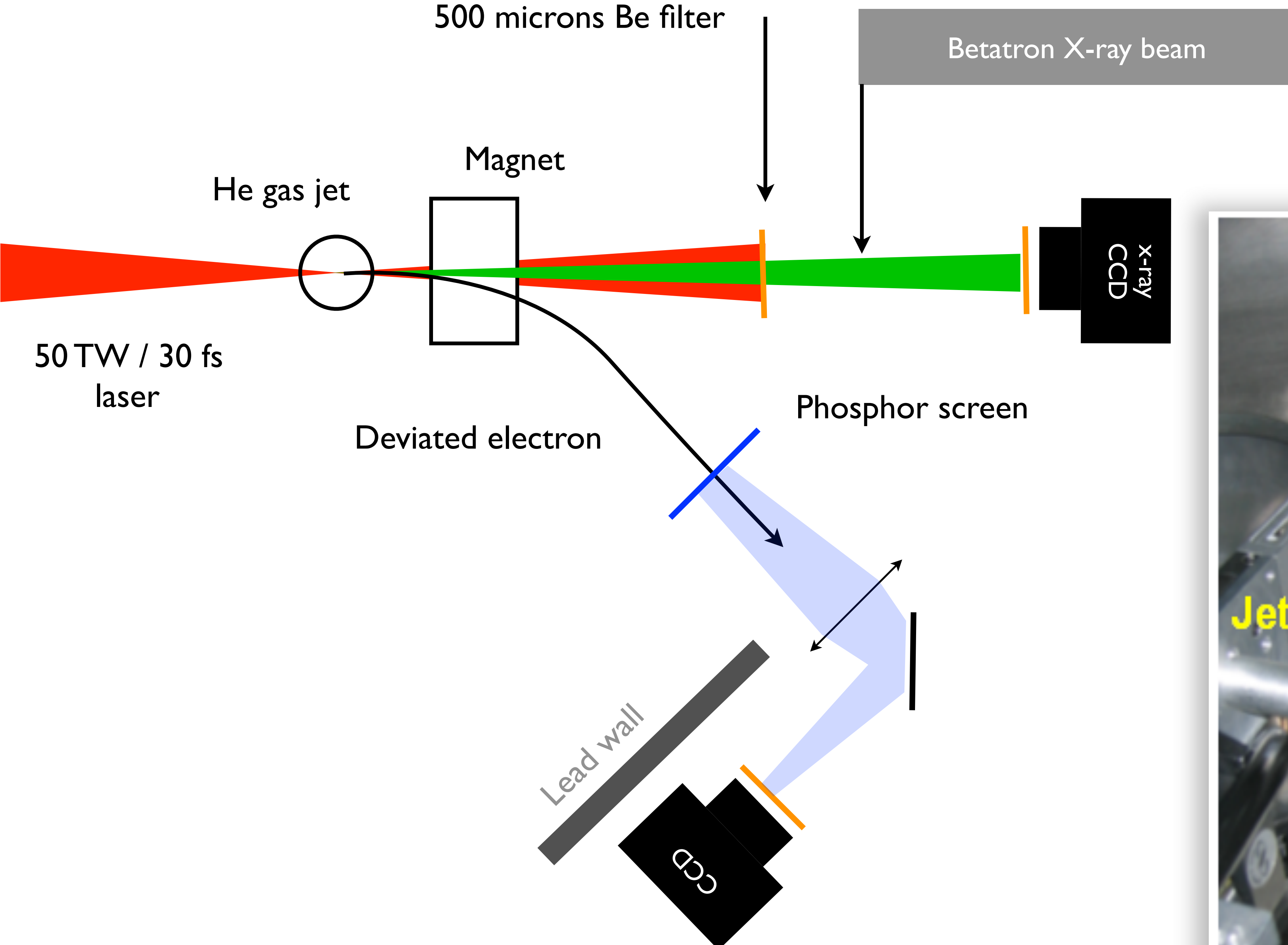
~0.3 degree

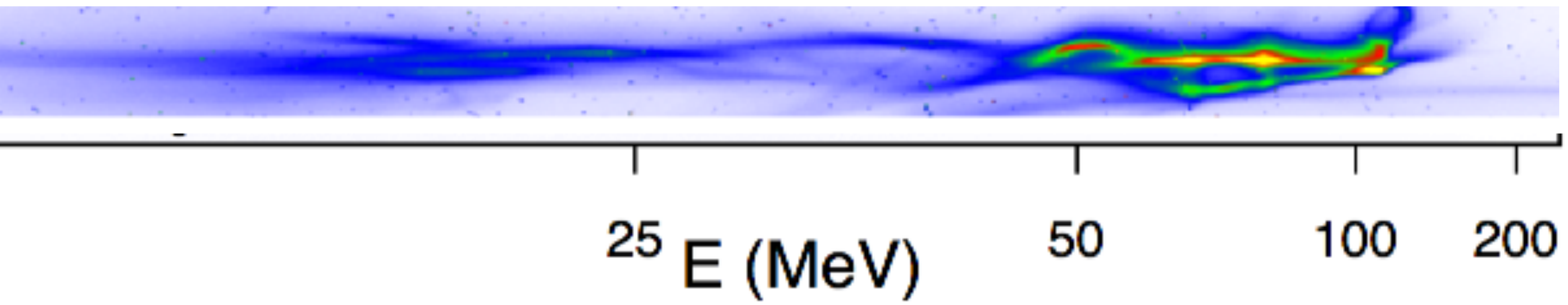
Spectrum

Energy $\propto \gamma\, n_e\, r_\beta$

Photons $\propto K$

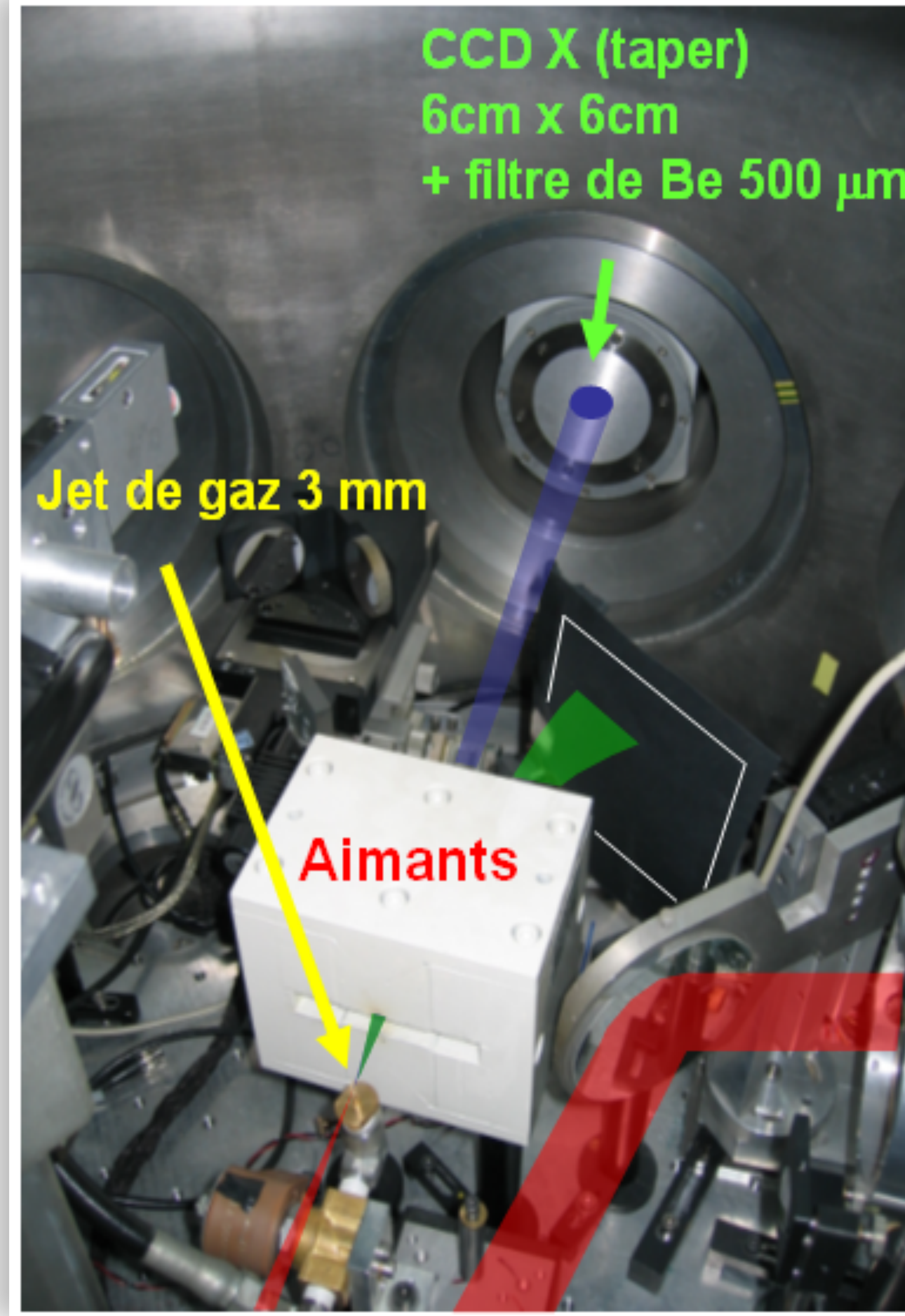
Production of Betatron radiation



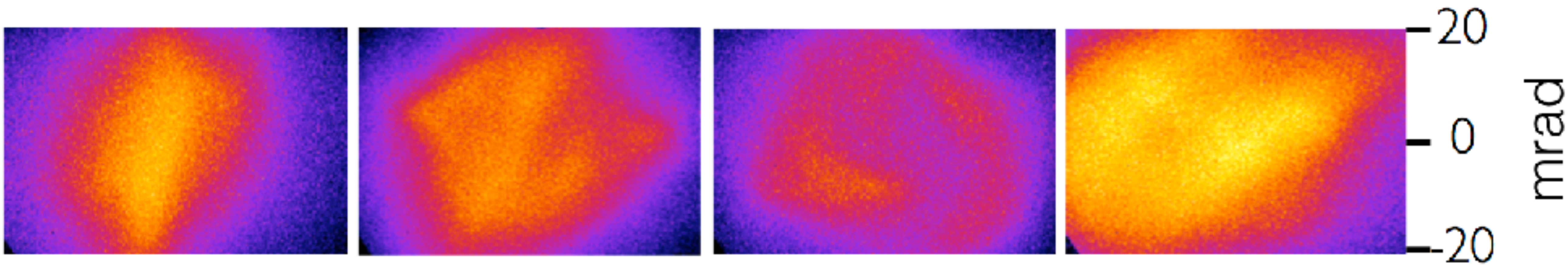


$a_0=2$

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

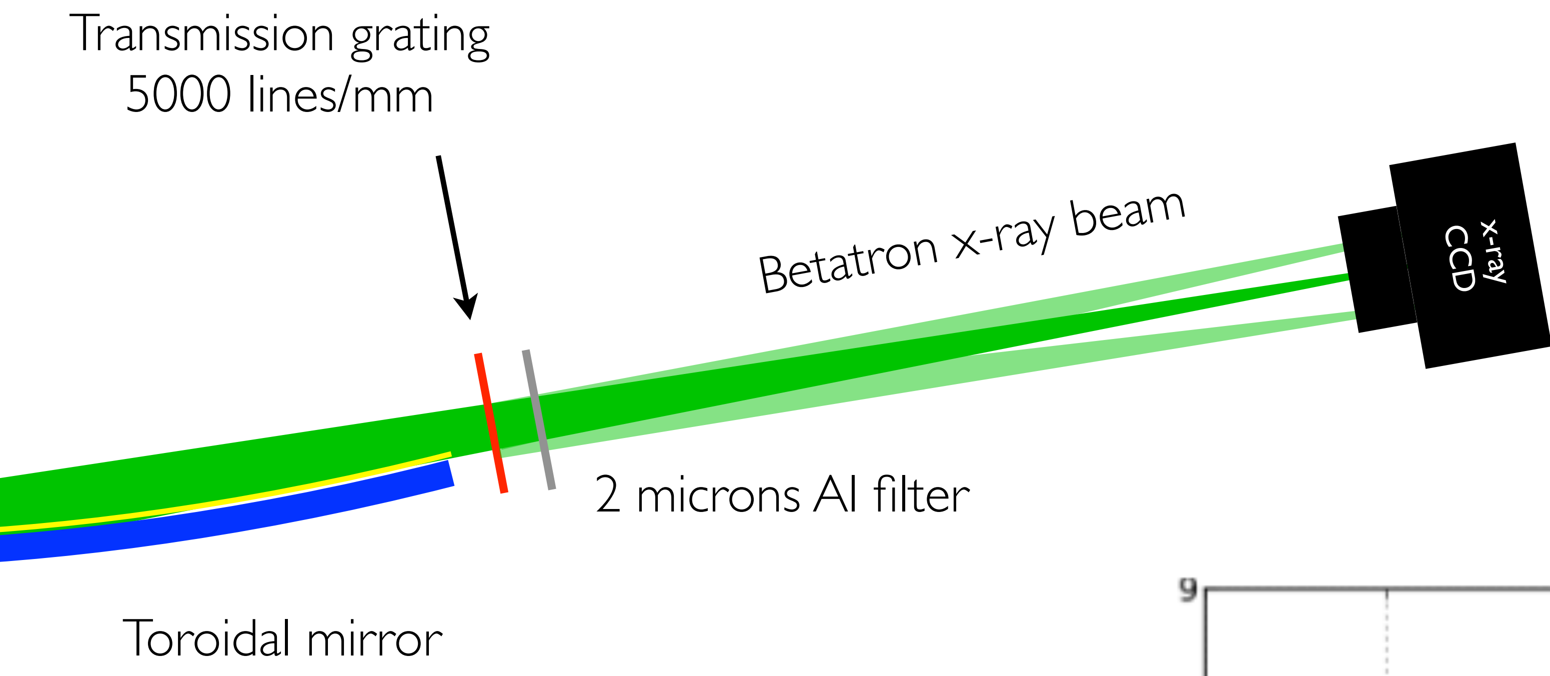


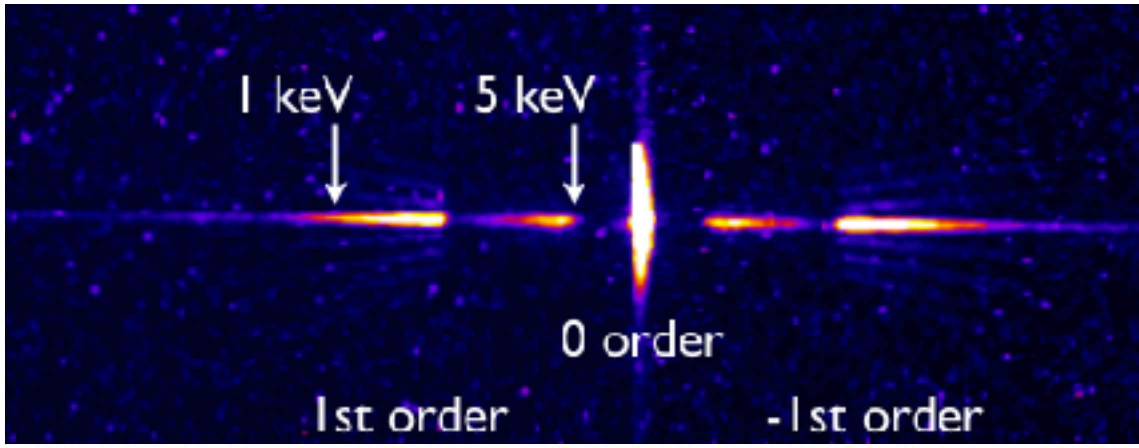
X-ray beams profiles

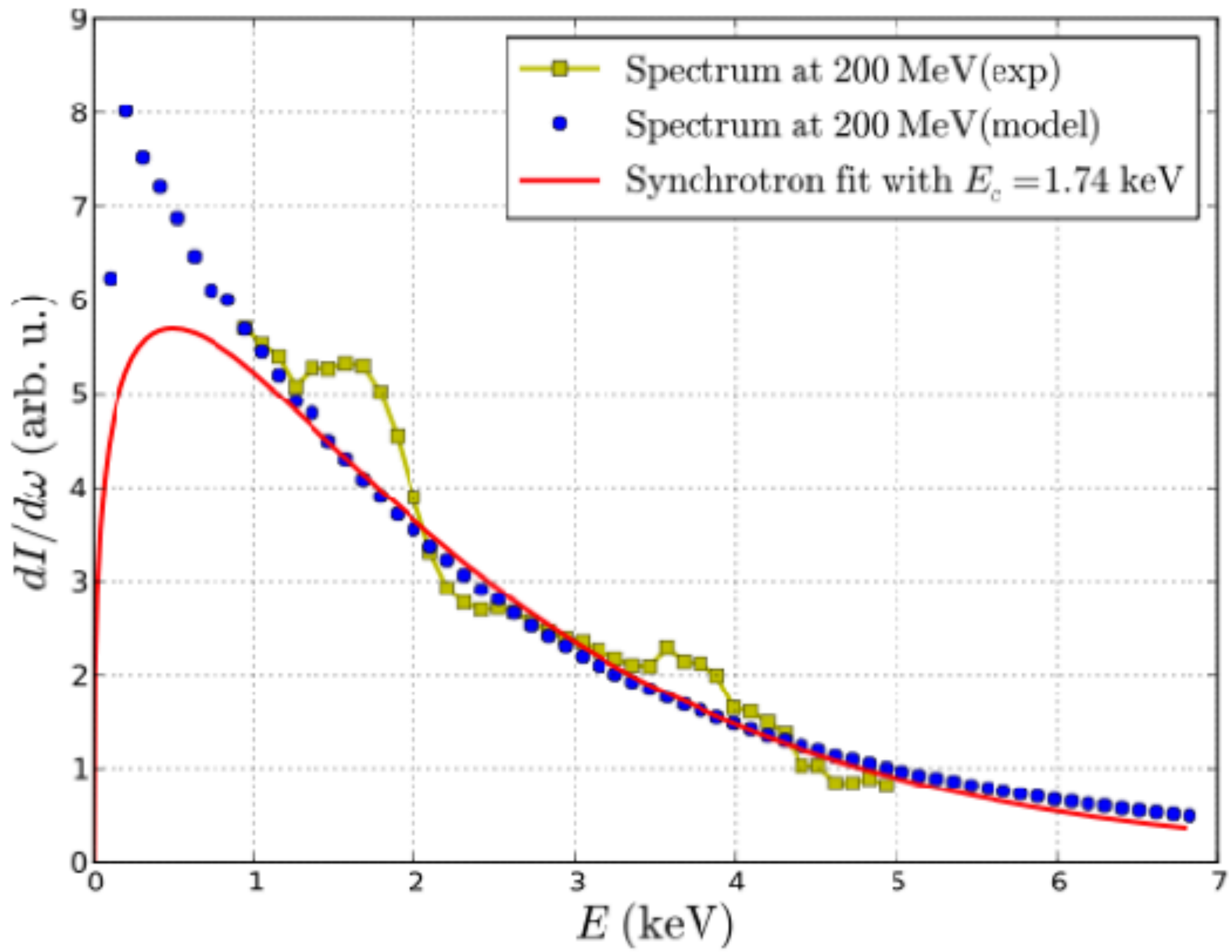


- Radiation is emitted in the forward direction. The beam divergence is typically 20 mrad.
- The beam profile significantly fluctuates shot-to-shot.
- Higher quality beams profile can be obtained but with lower x-ray flux.

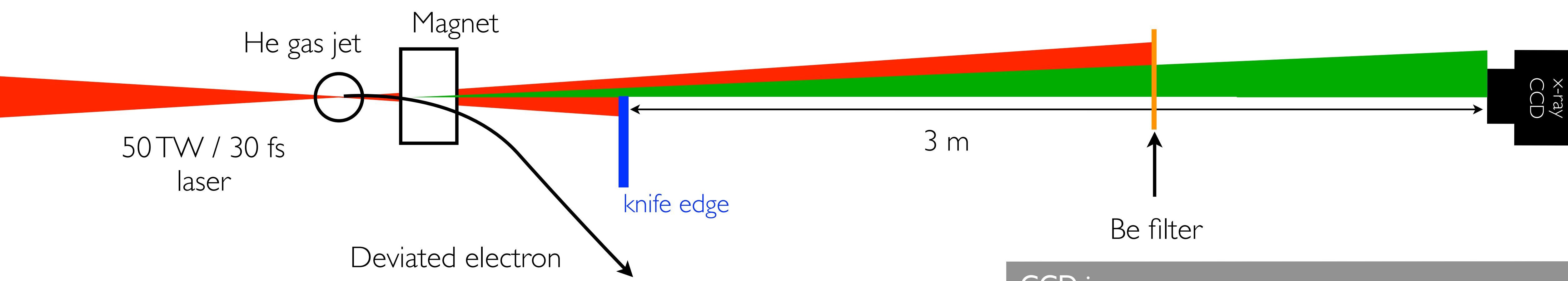
Spectrum measurement: @ 50 TW

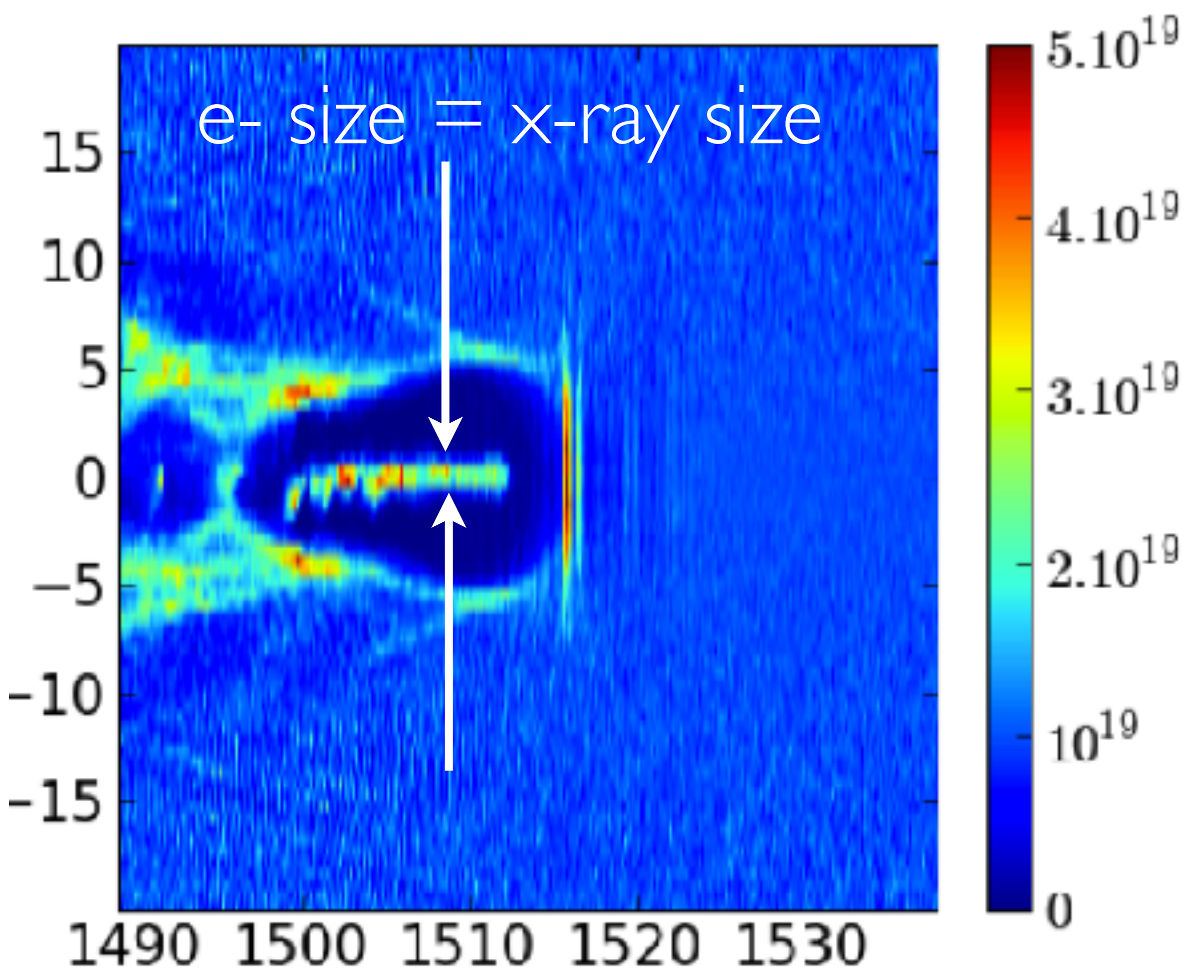


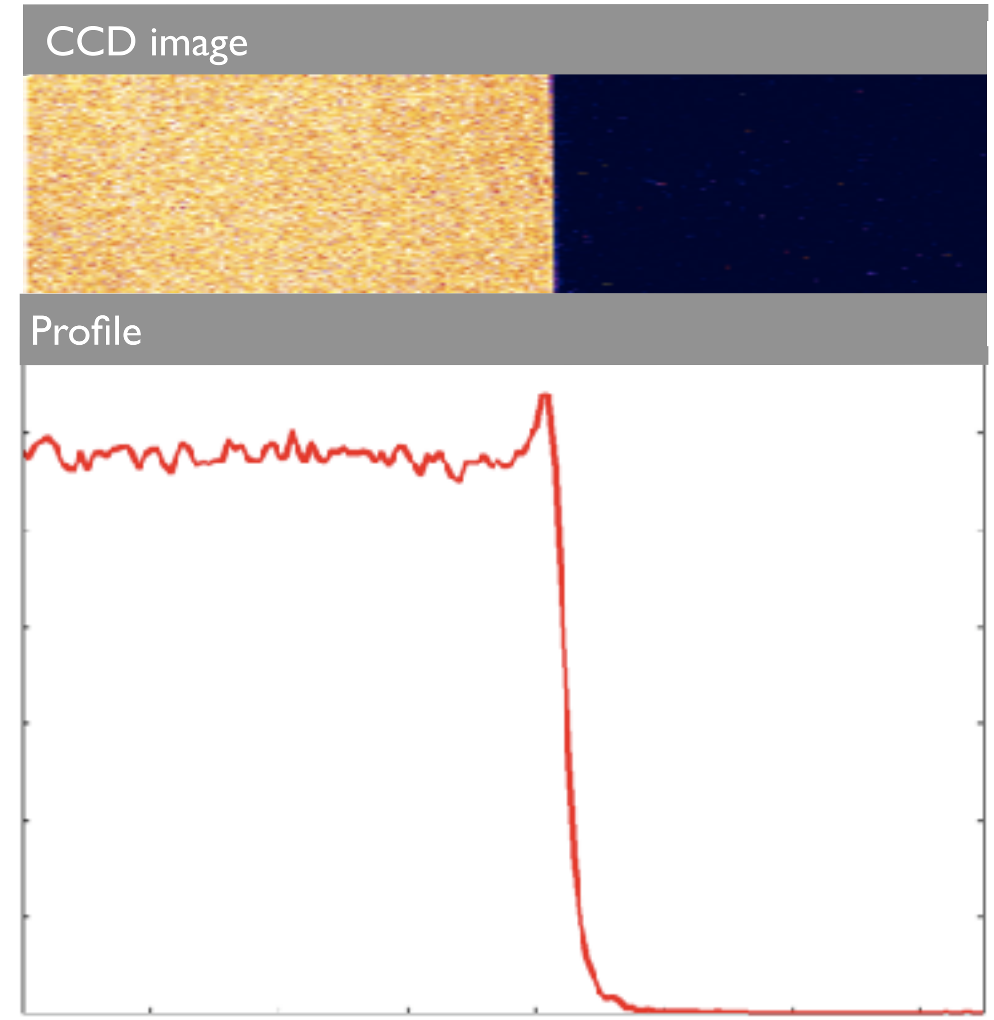




Source size measurement : knife edge



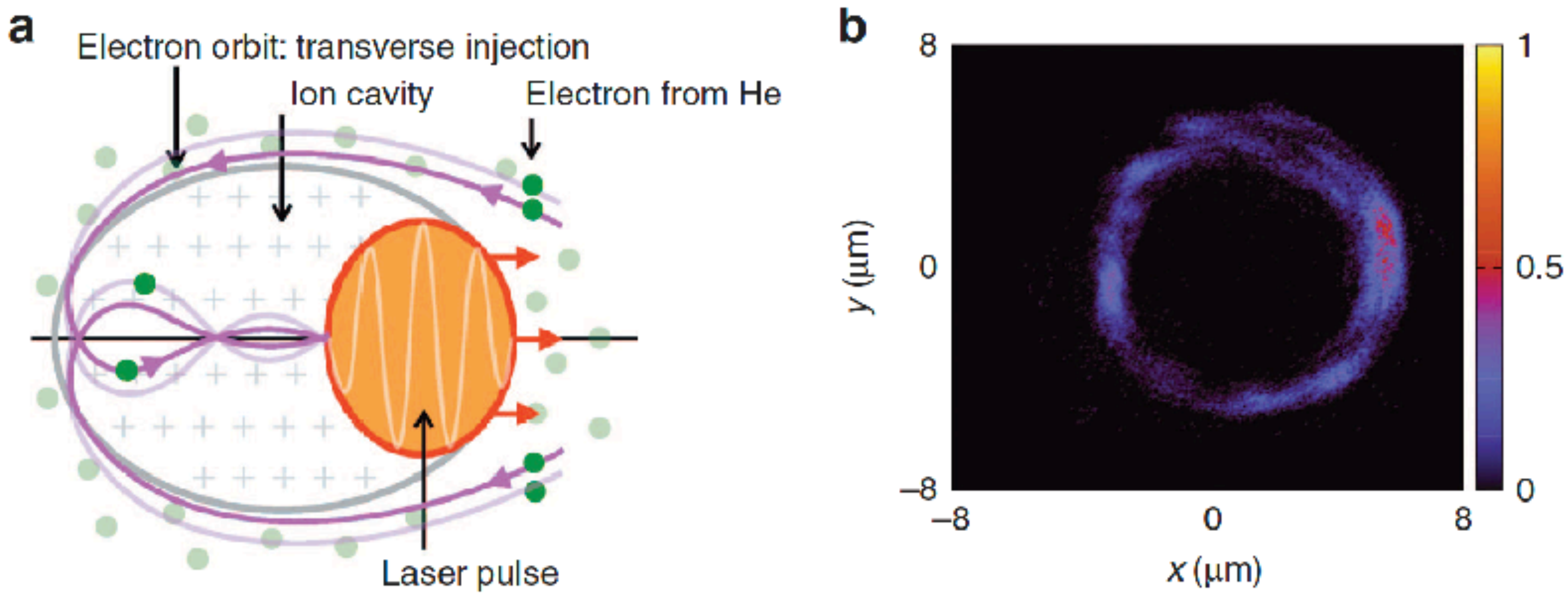




Source size < 2 microns

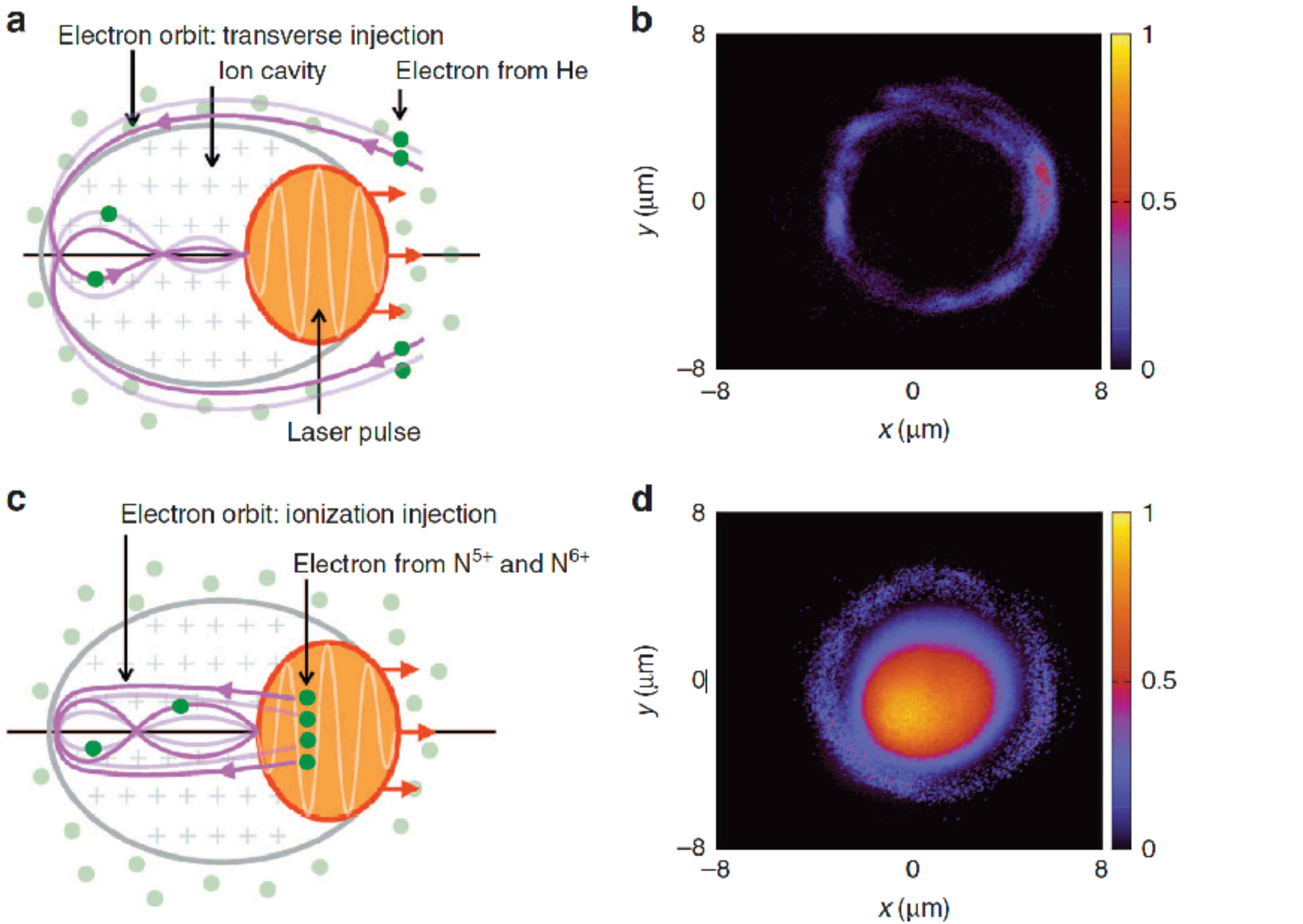
Betatron radiation in gas mixture (99%Helium+1% Nitrogen)

Initial traverse positon of injected electrons



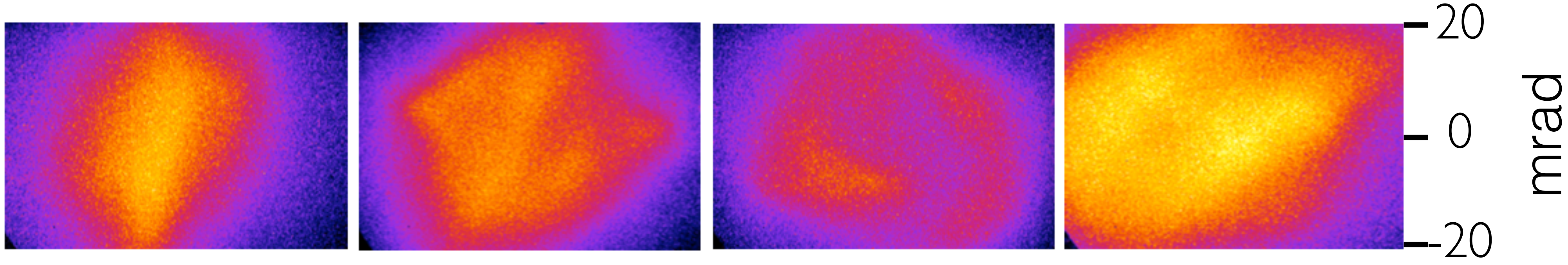
Betatron radiation in gas mixture (99%Helium+1% Nitrogen)

Initial traverse positon of injected electrons



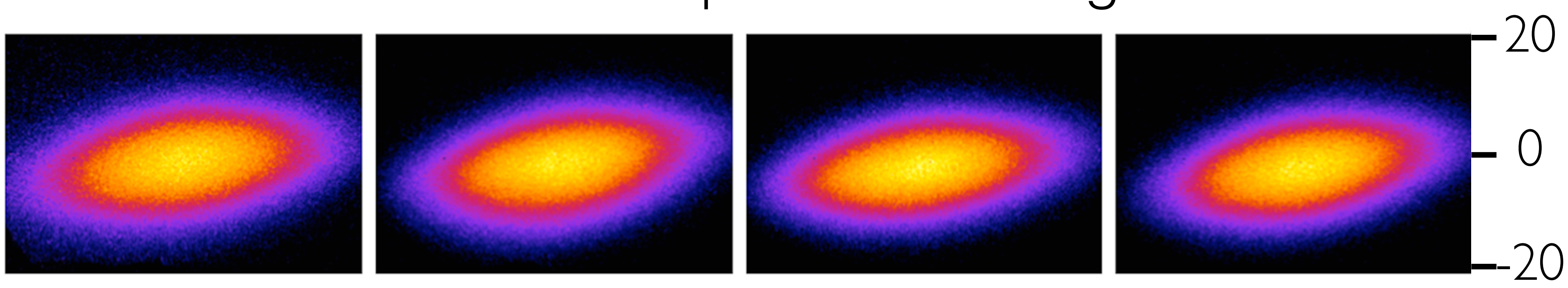
Betatron radiation in gas mixture (99%Helium+1% Nitrogen)

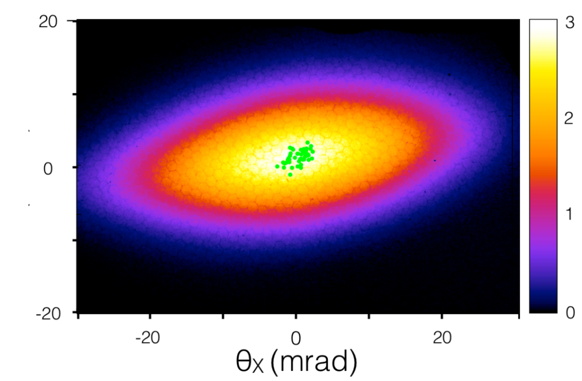
→ Betatron radiation produced so far is unstable with fluctuating



Betatron radiation in gas mixture (99%Helium+1% Nitrogen)

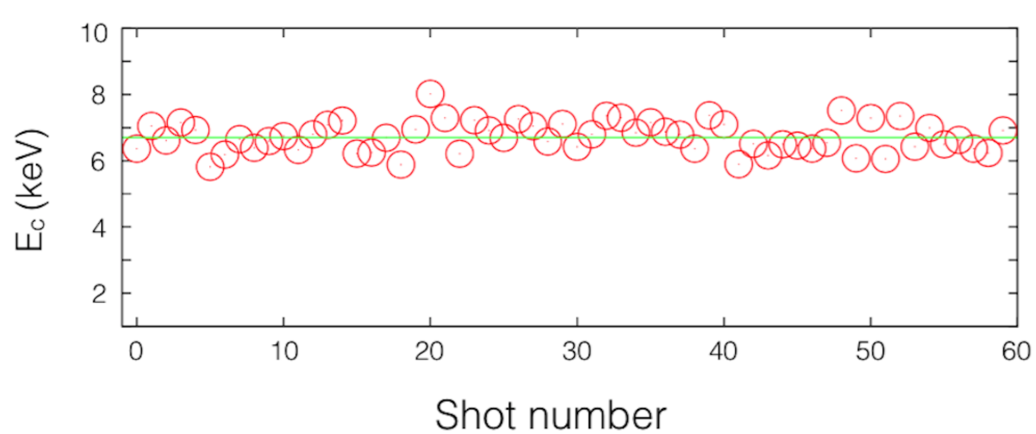
- It becomes stable when it is produced in a gas mixture

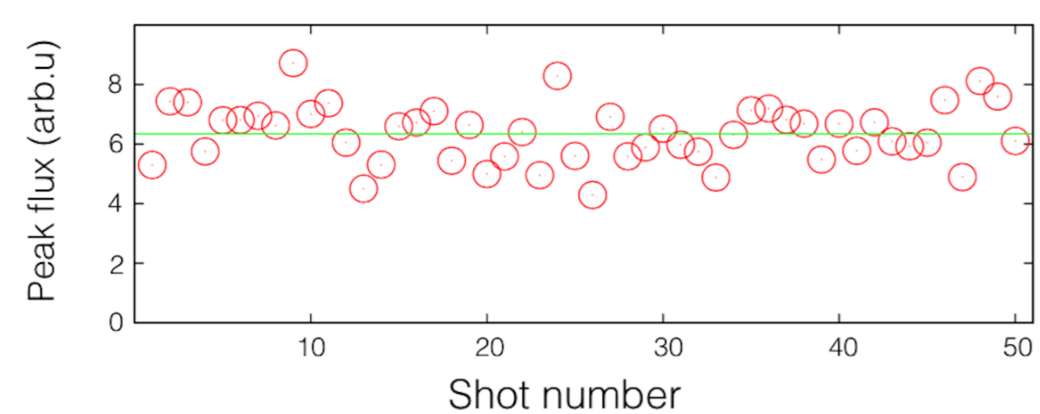




Fluctuation of the beam pointing is about 10% of the beam diameter

- Flux and energy become stable as well

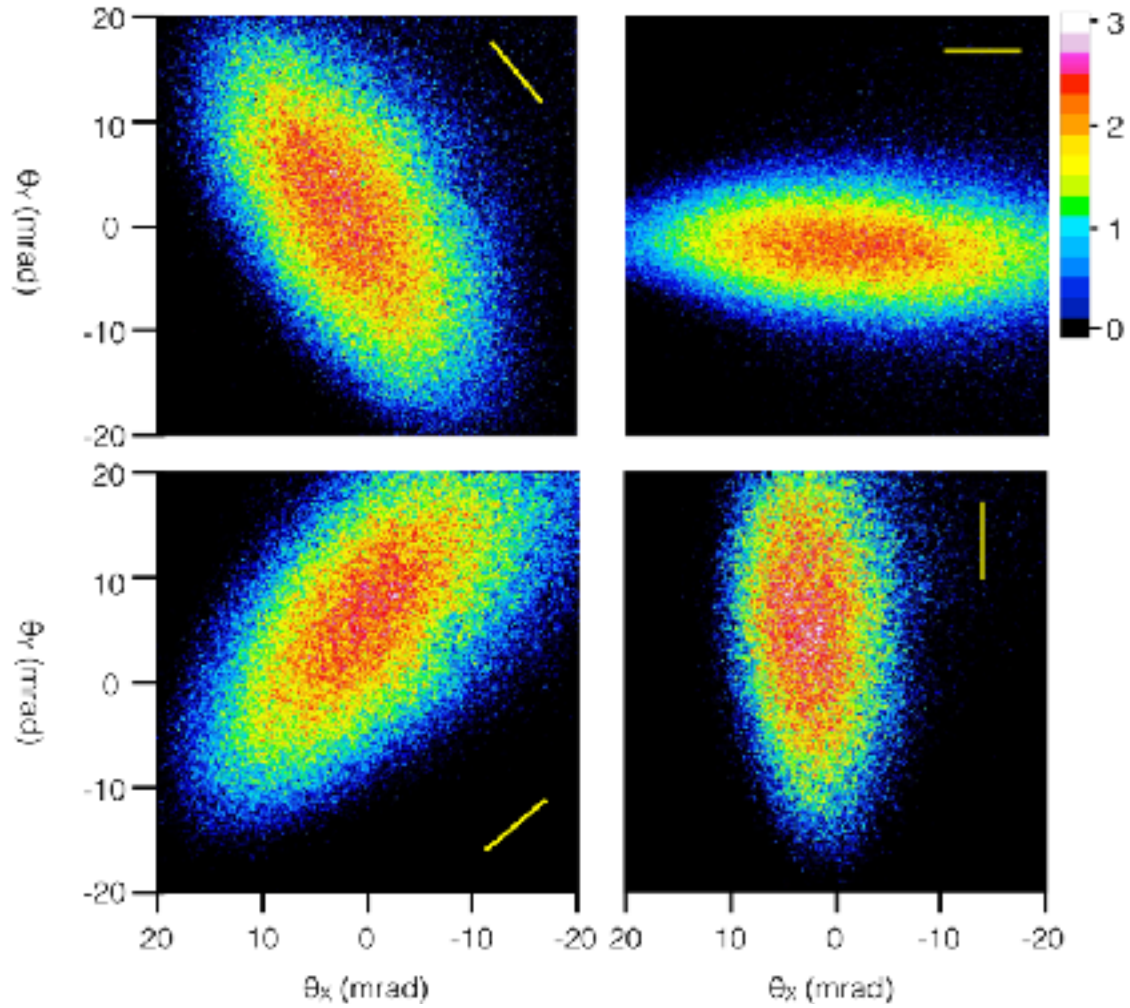




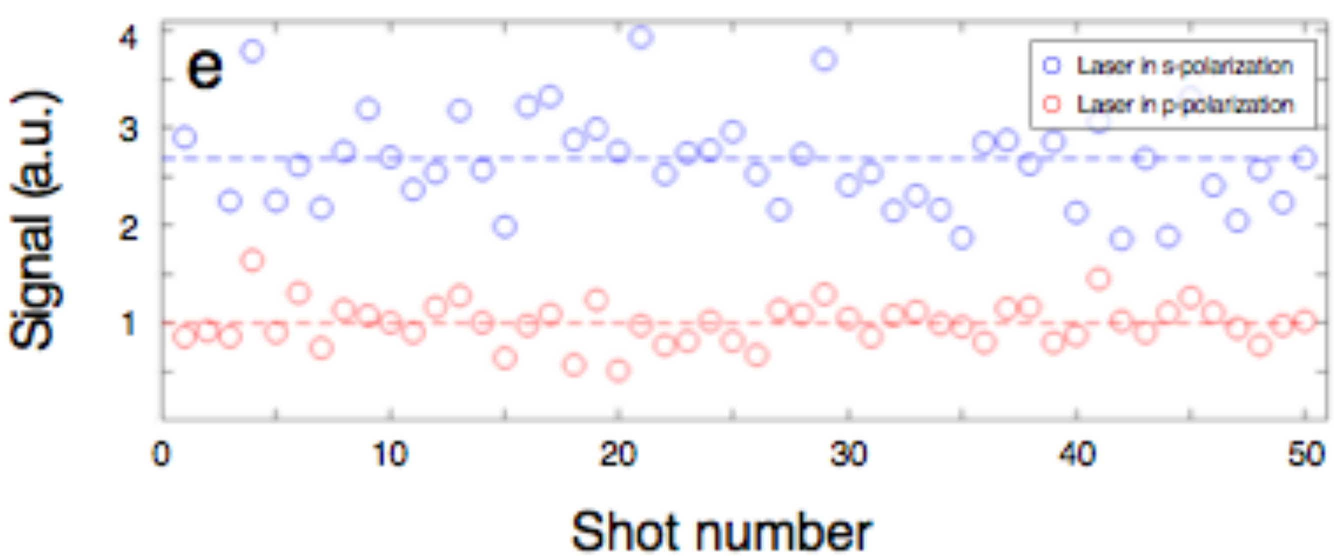
Flux and energy stability are of the order of 10%

The radiation is polarized

X-ray beam profiles as a function of laser polarization



X-ray signal in S and P polarization



- Radiation is polarized
- 75% of x-ray photons follow the laser polarization

Summary of the source features

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

→ The source has been used for applications:

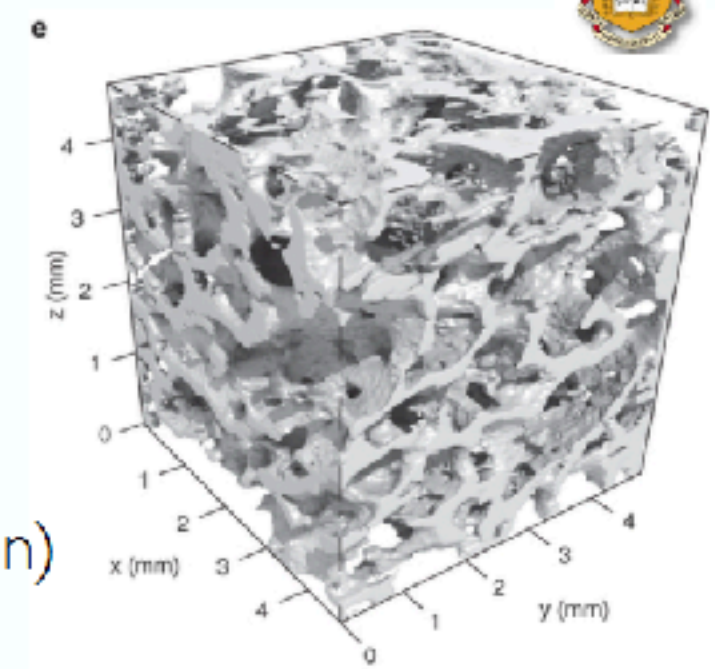
- Phase contrast radiography
- Femtosecond x-ray diffraction
- Femtosecond x-ray absorption

Absorption and phase constrast radiography

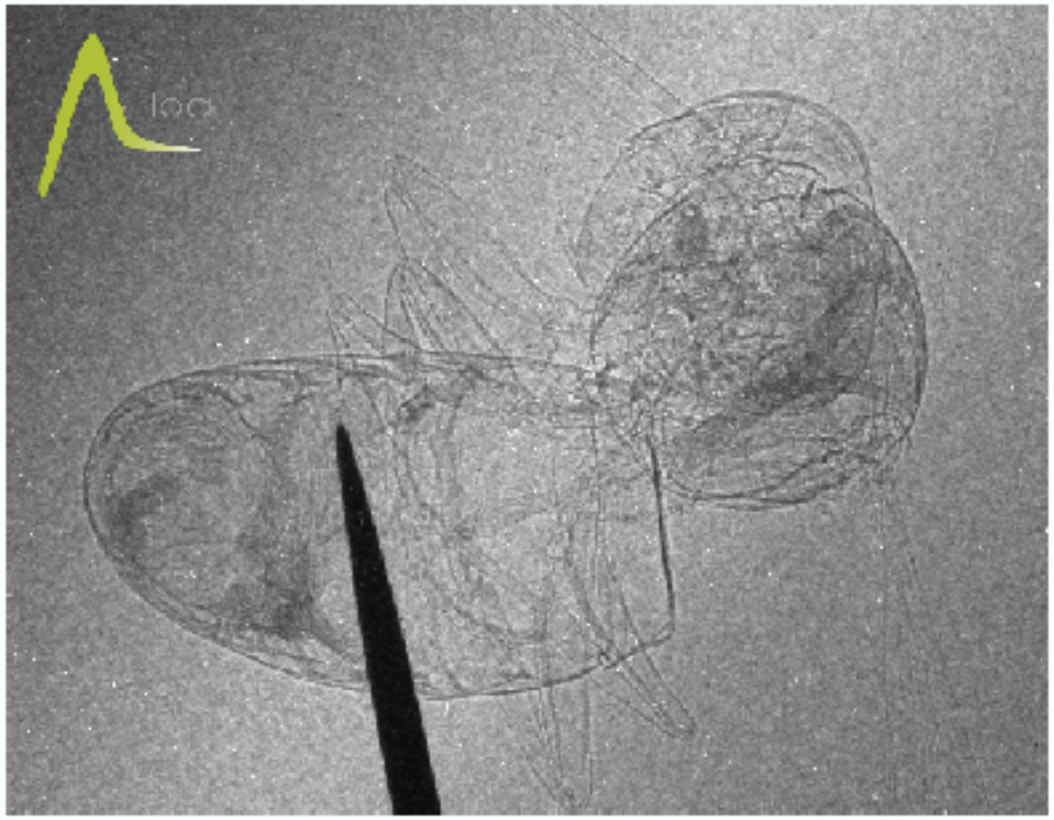
→ Betatron has the good features for this application:

- 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

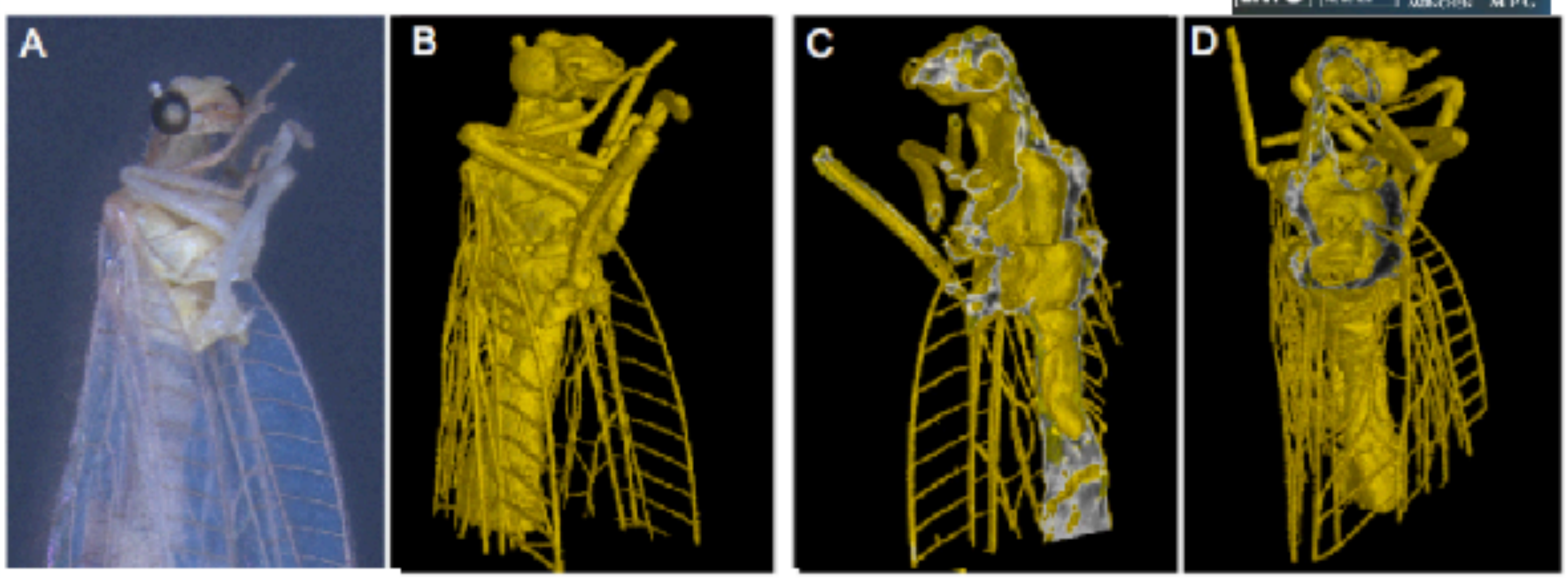
Bone tomography
(constrast absorption)



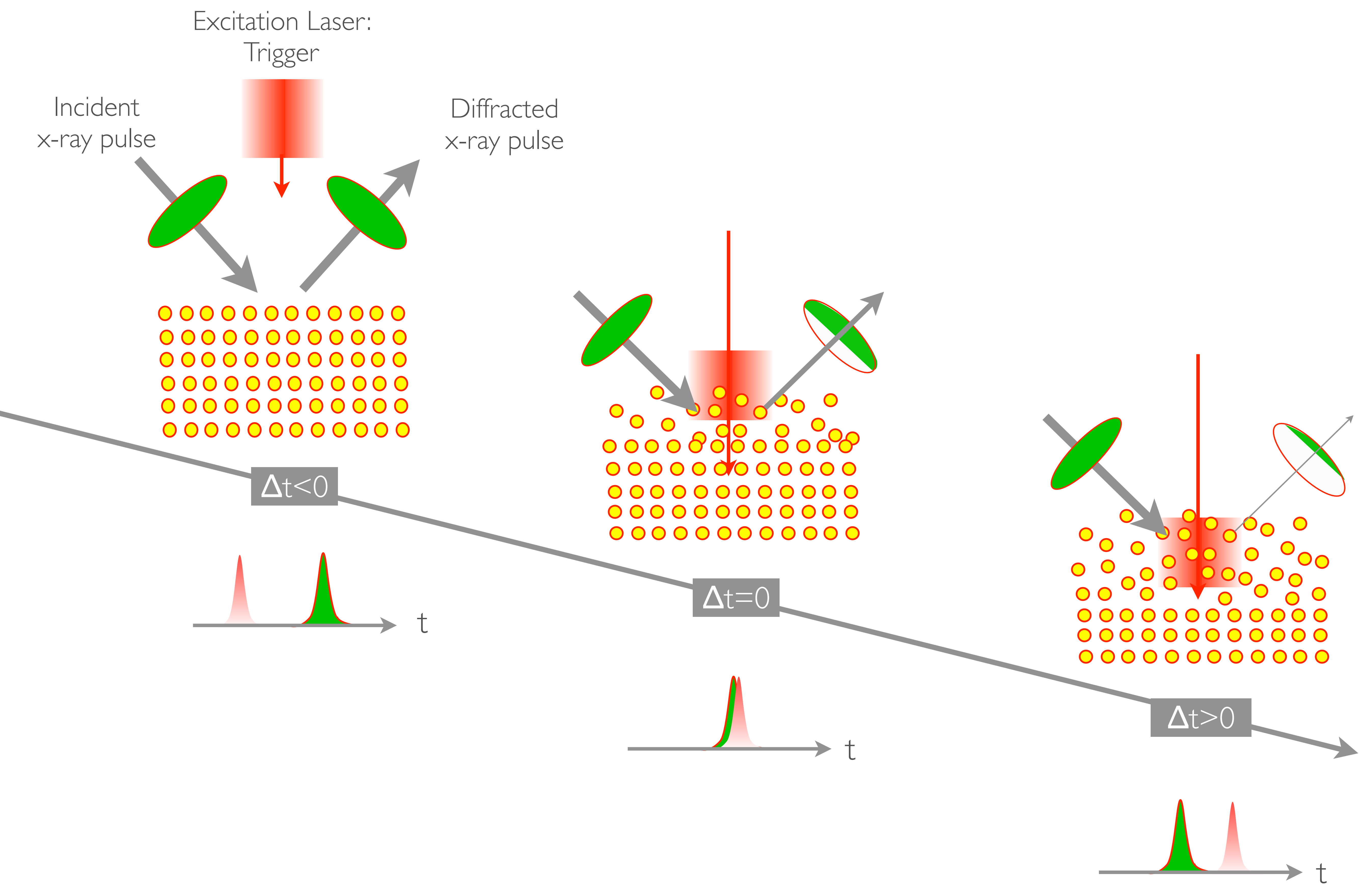
Radiograph of a bee (Phase contrast)



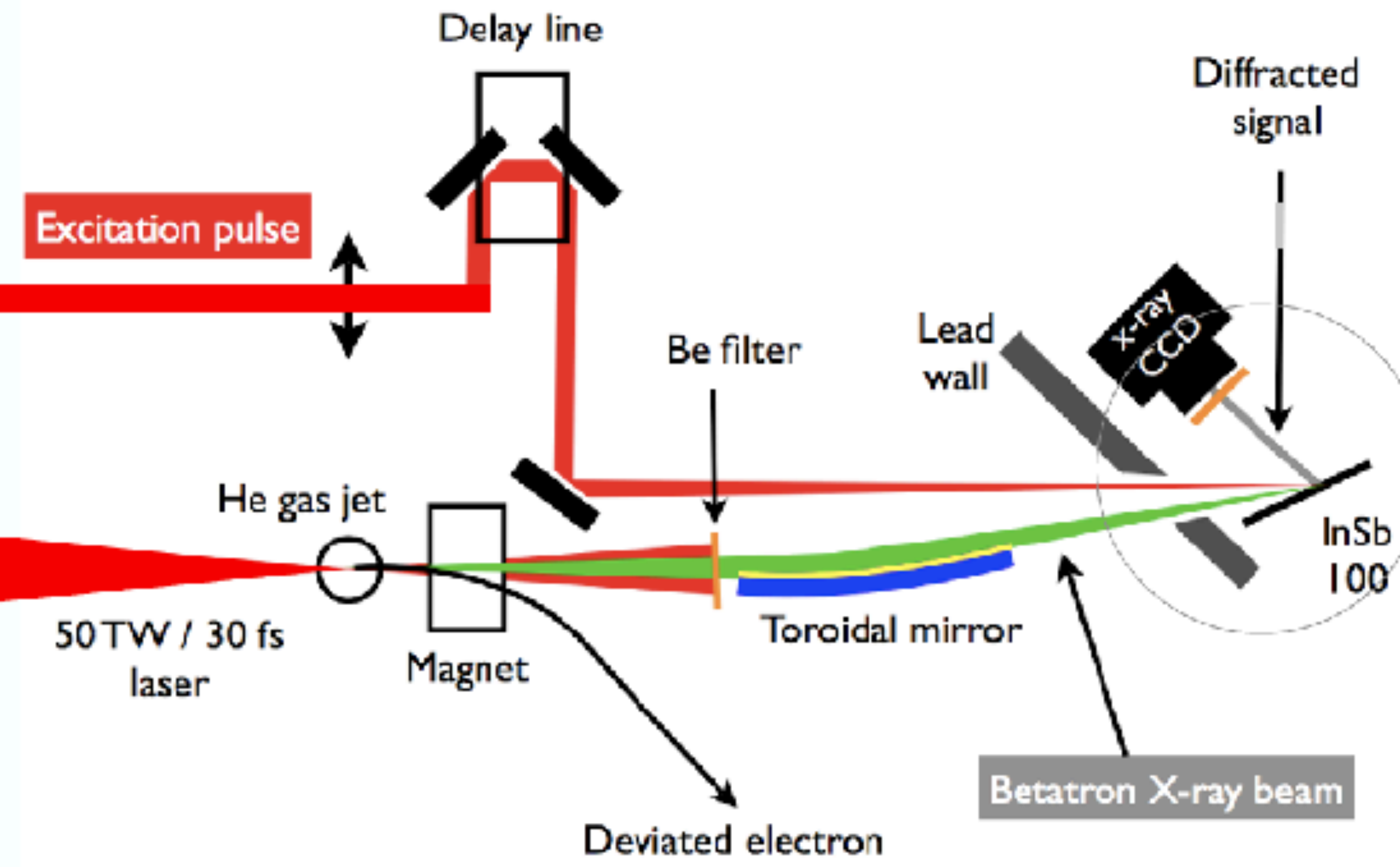
Radiograph of a fly (Phase contrast)

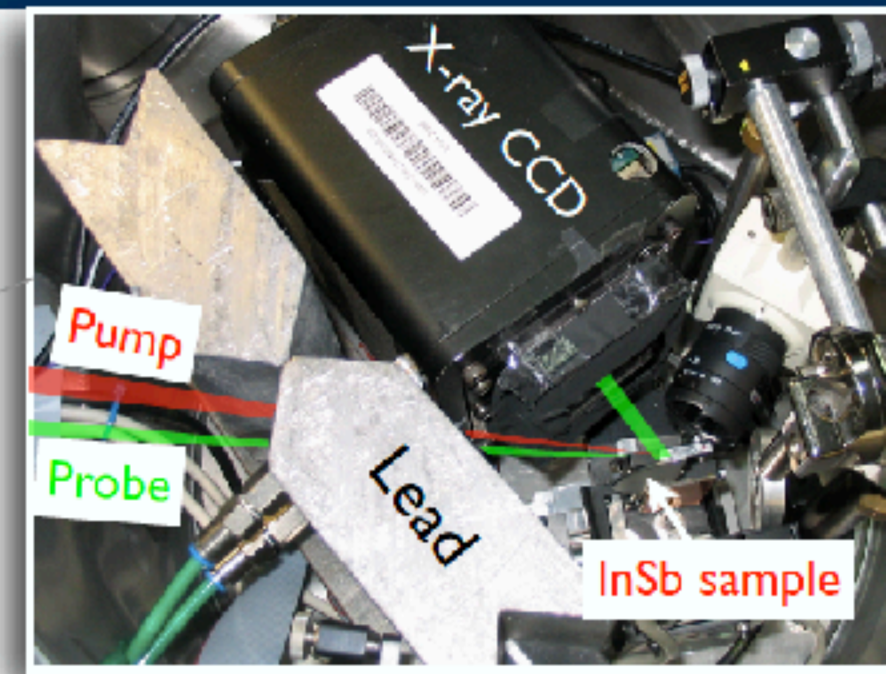


Femtosecond x-ray diffraction/absorption

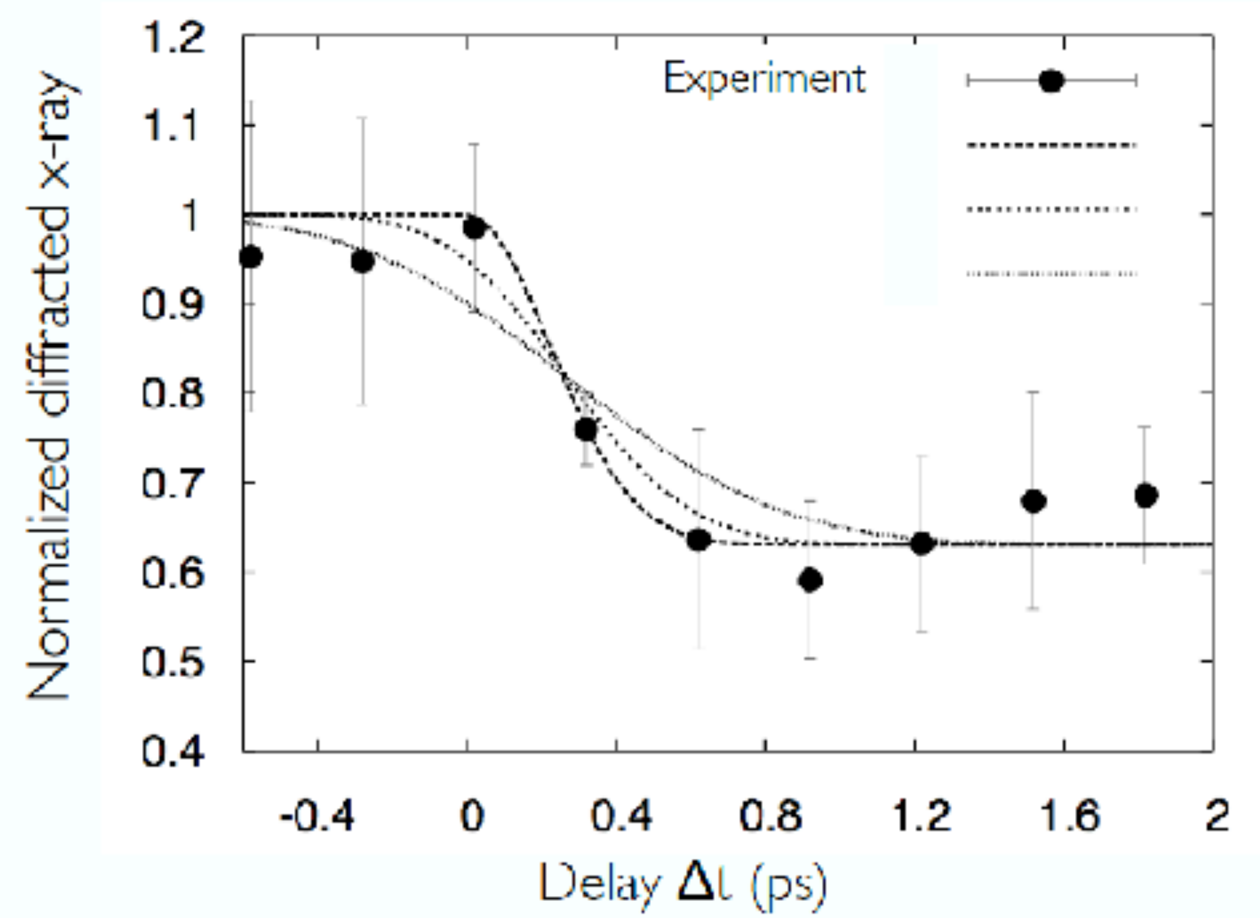


Femtosecond x-ray diffraction: Non thermal melting (InSb)

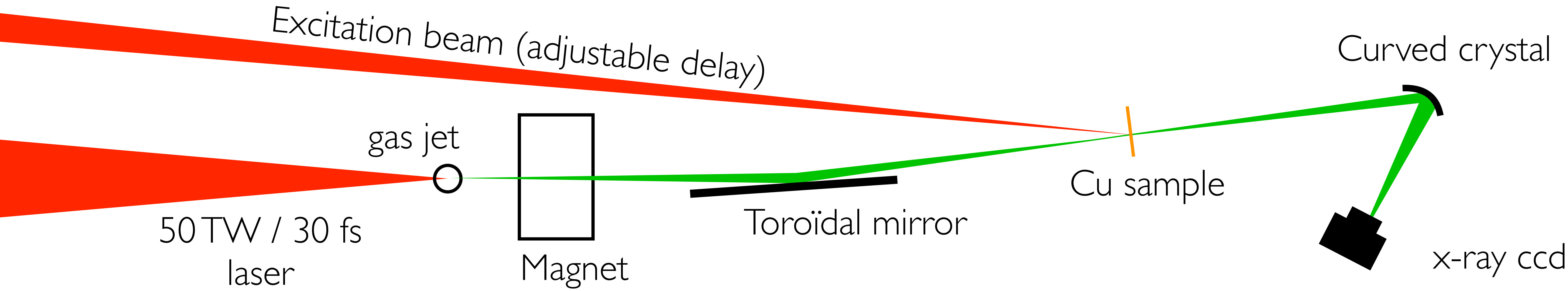


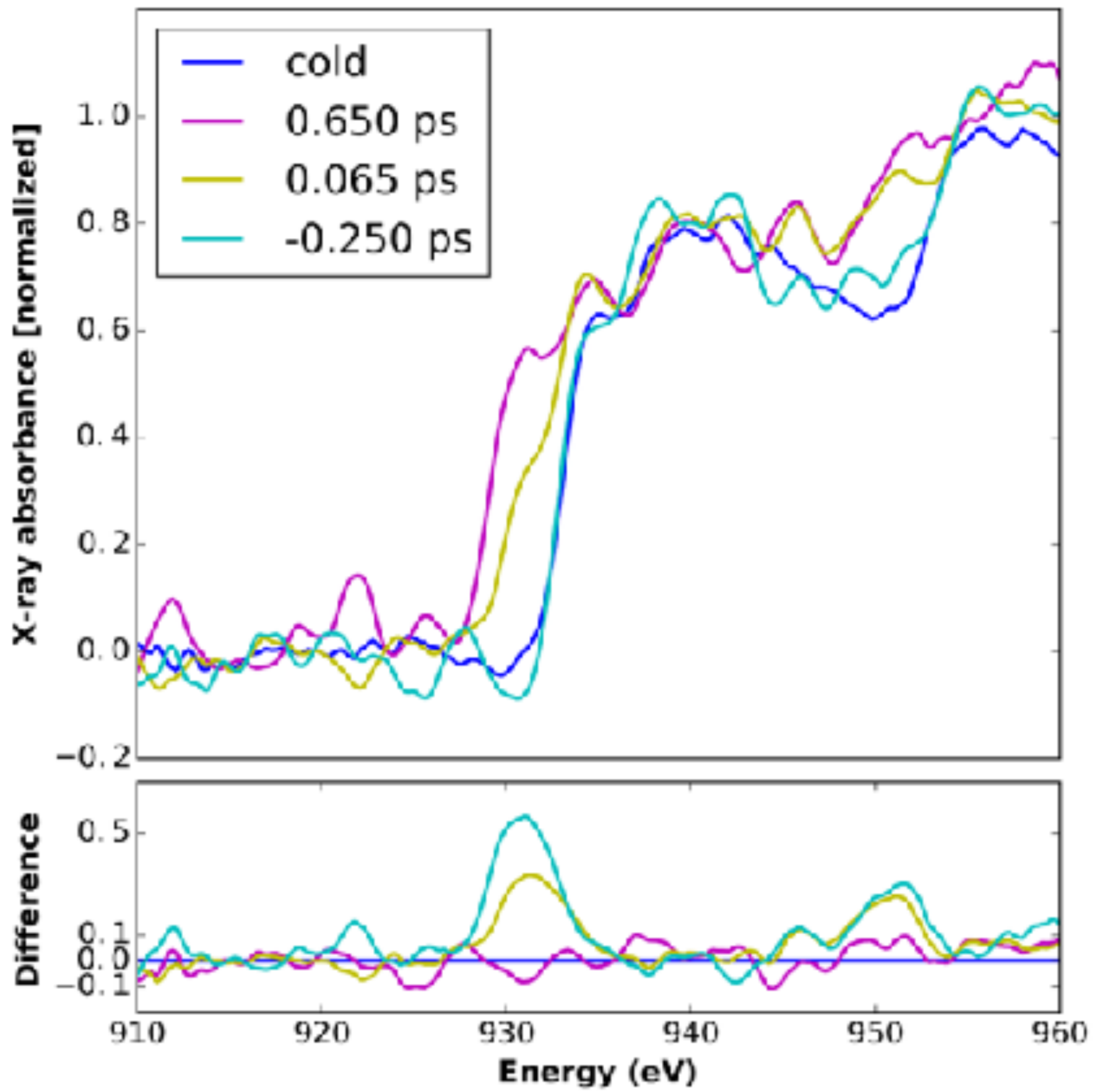


→ Ultrafast phase transition can be measured with tens fs resolution



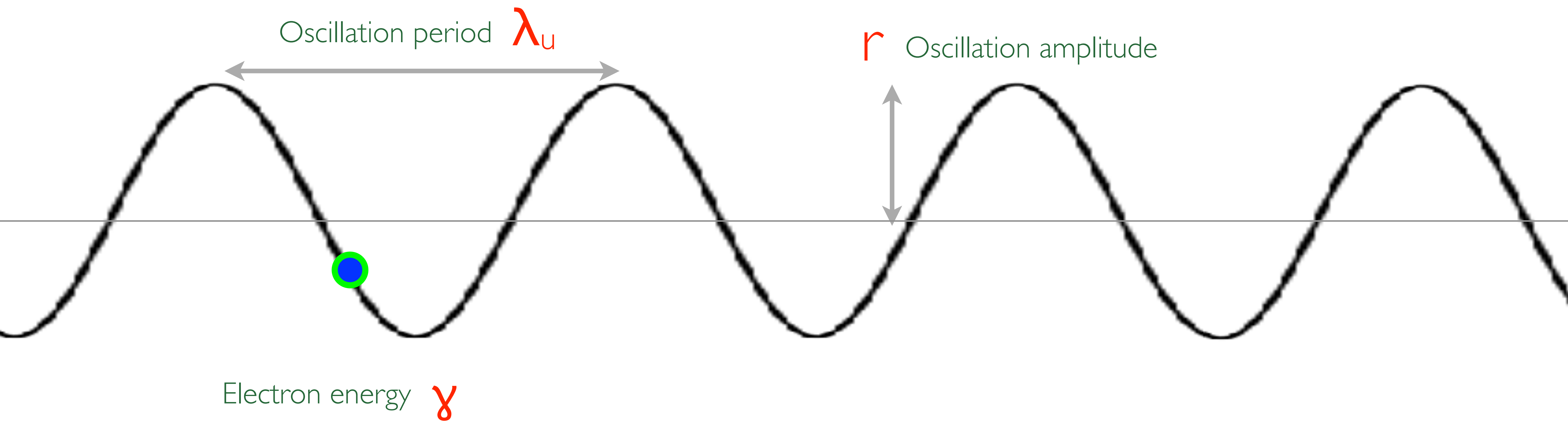
Fs X-ray absorption: Warm Dense Matter application





→ Unique features for fs x-ray absorption spectroscopy

How can we improve the source features ?



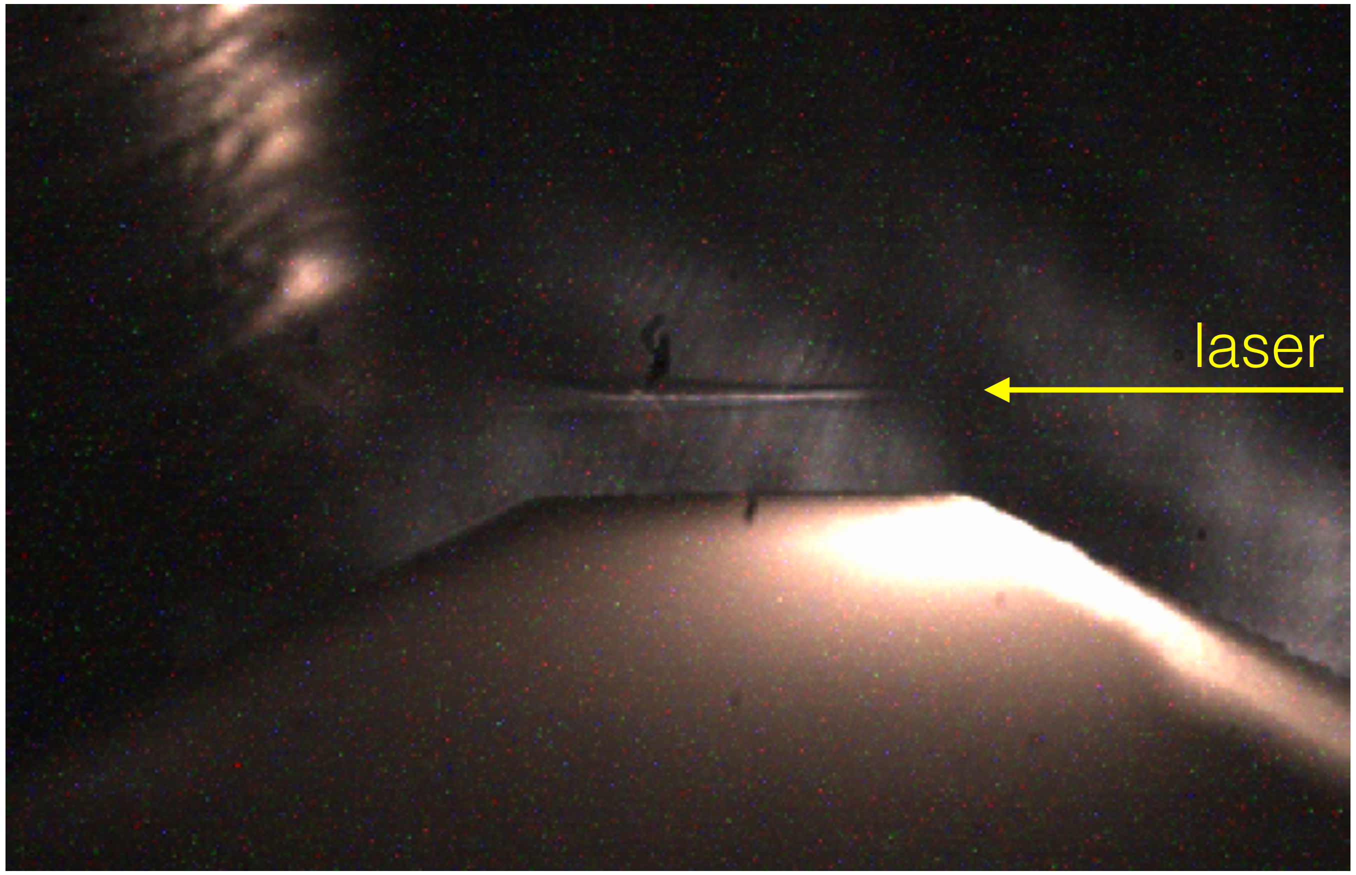
Radiation energy increases with: γ , λ_u^{-1} , r

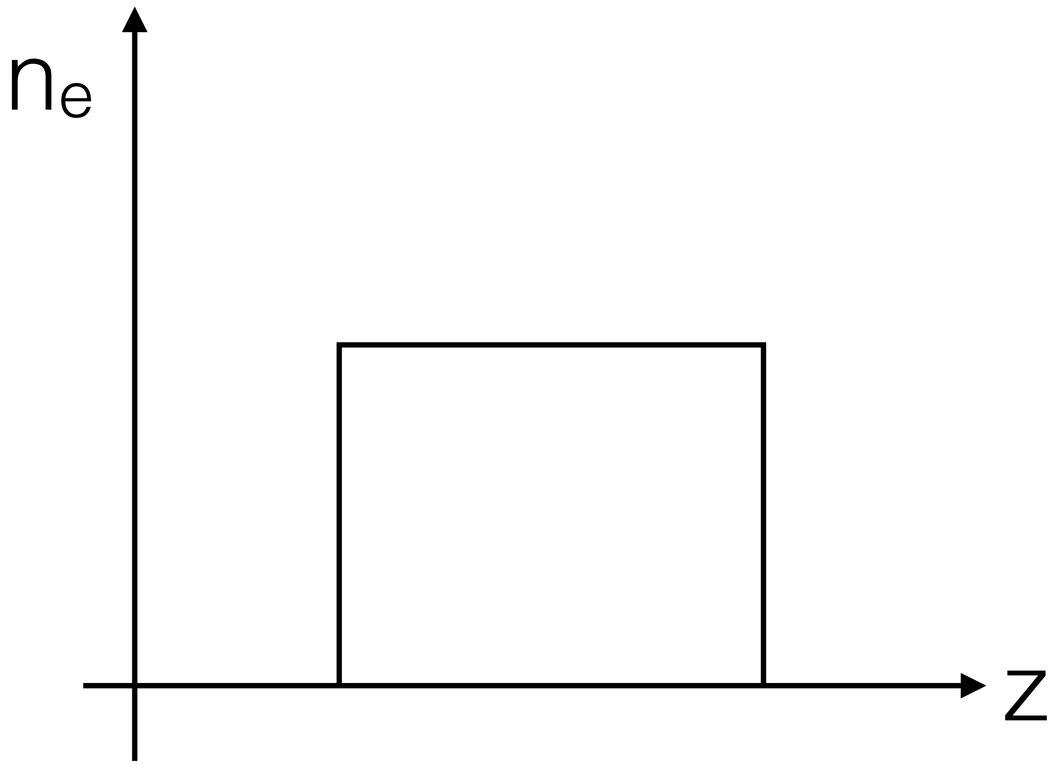
Flux increases with: γ, r and the number of periods

→ But, in a laser plasma accelerator, if γ increases, r is decreases and λ_u is increased

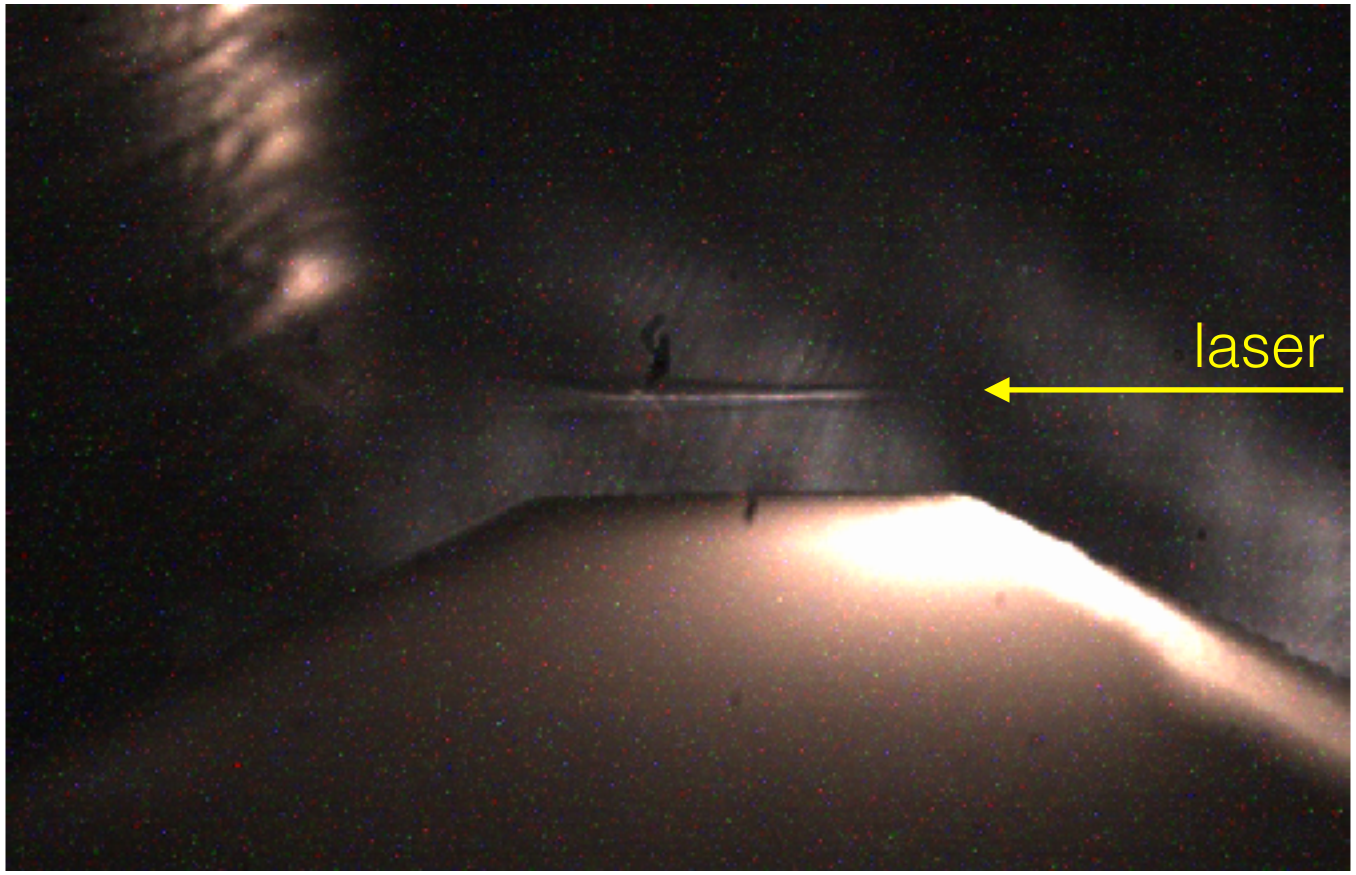
→ Decoupling acceleration and oscillation

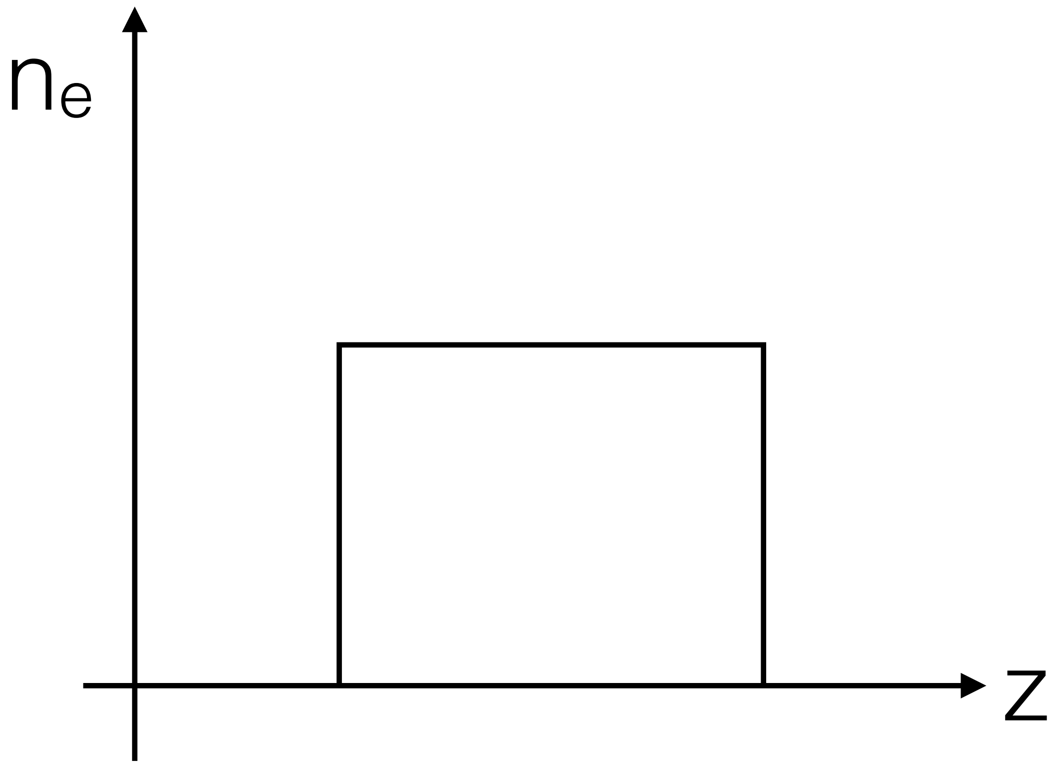
Betatron radiation using tilted nozzle

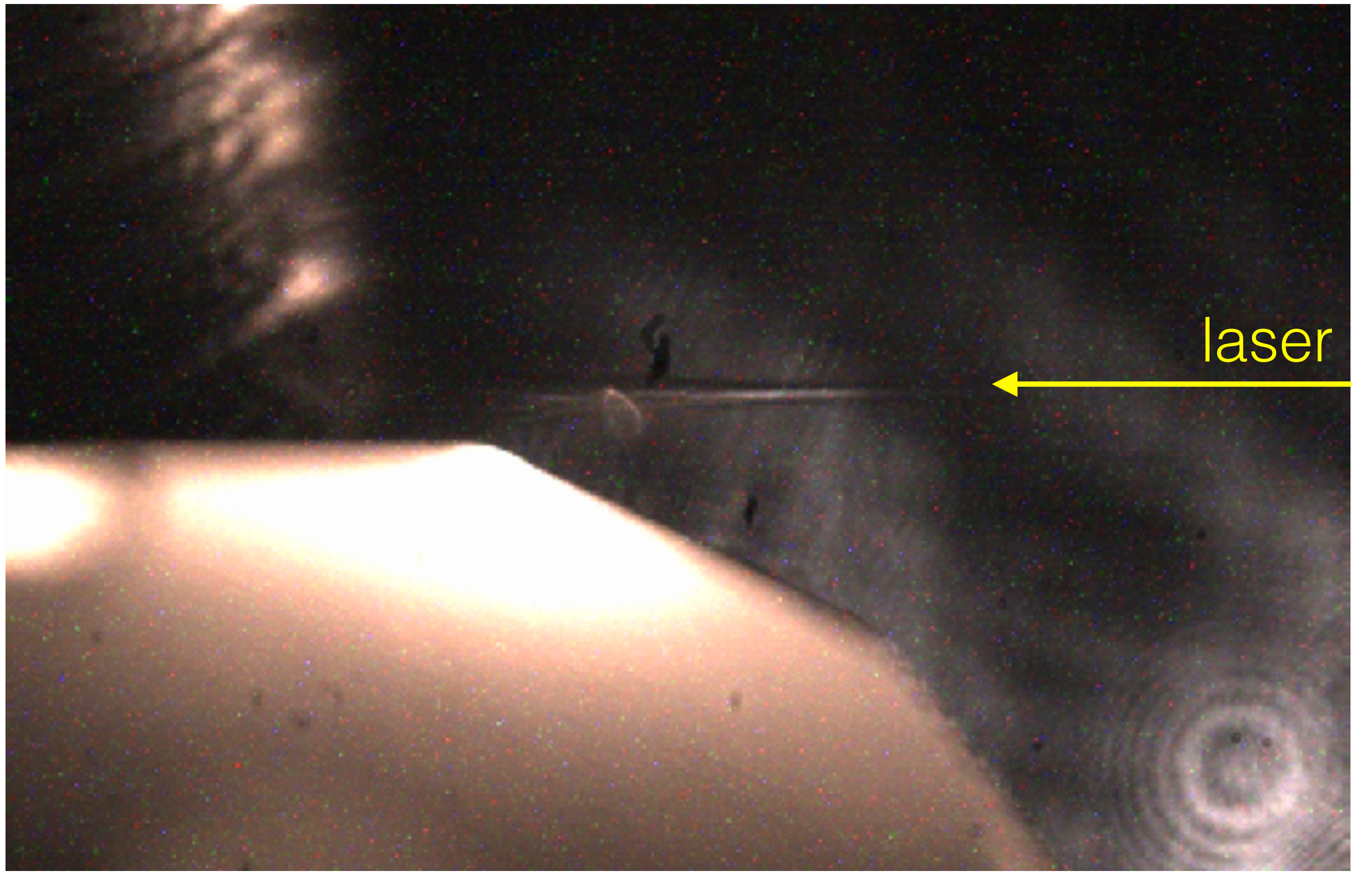


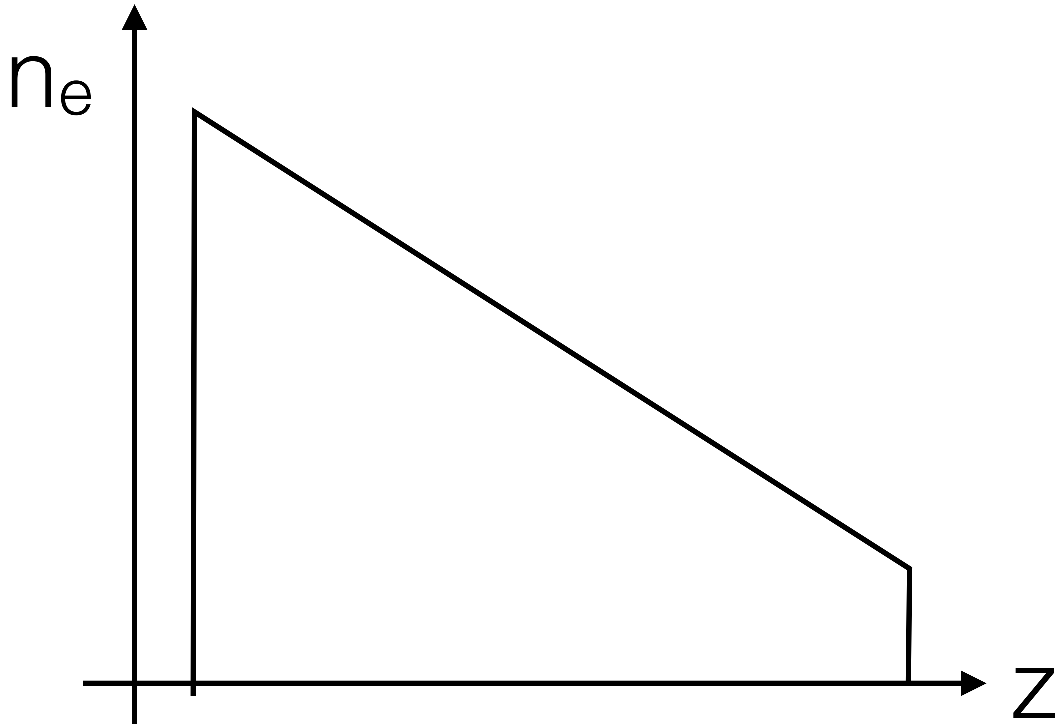


Betatron radiation using tilted nozzle

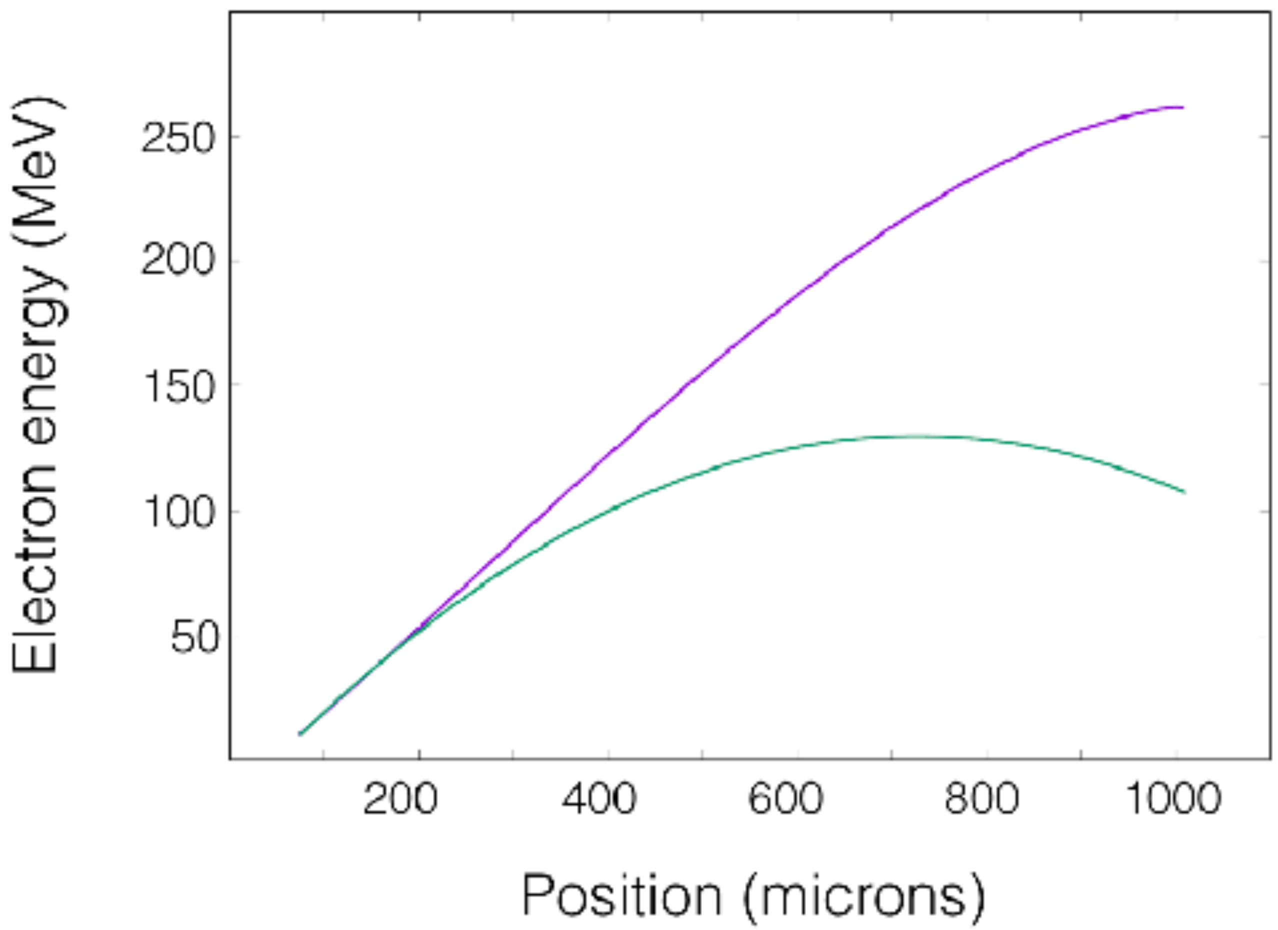


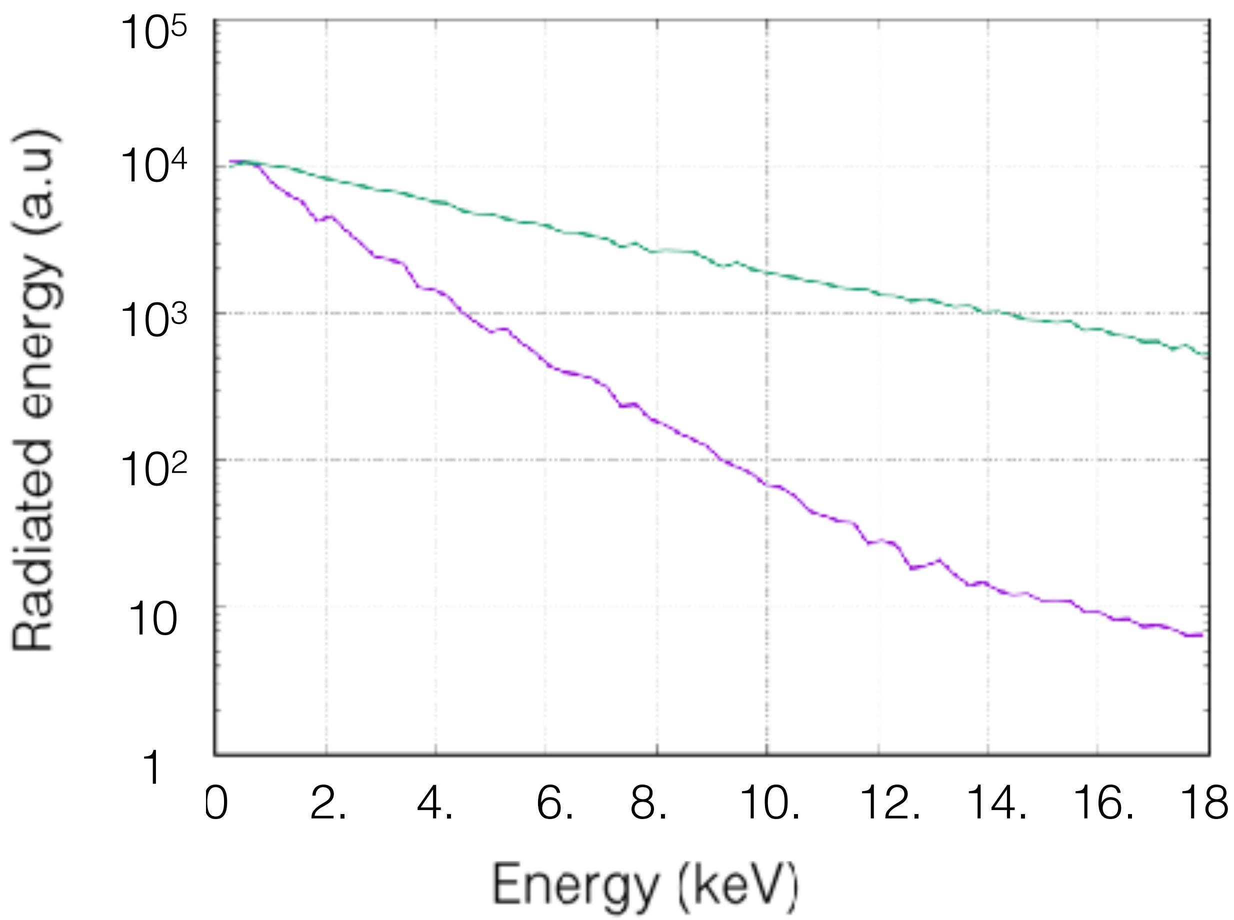






Numerical simulations of Betatron radiation

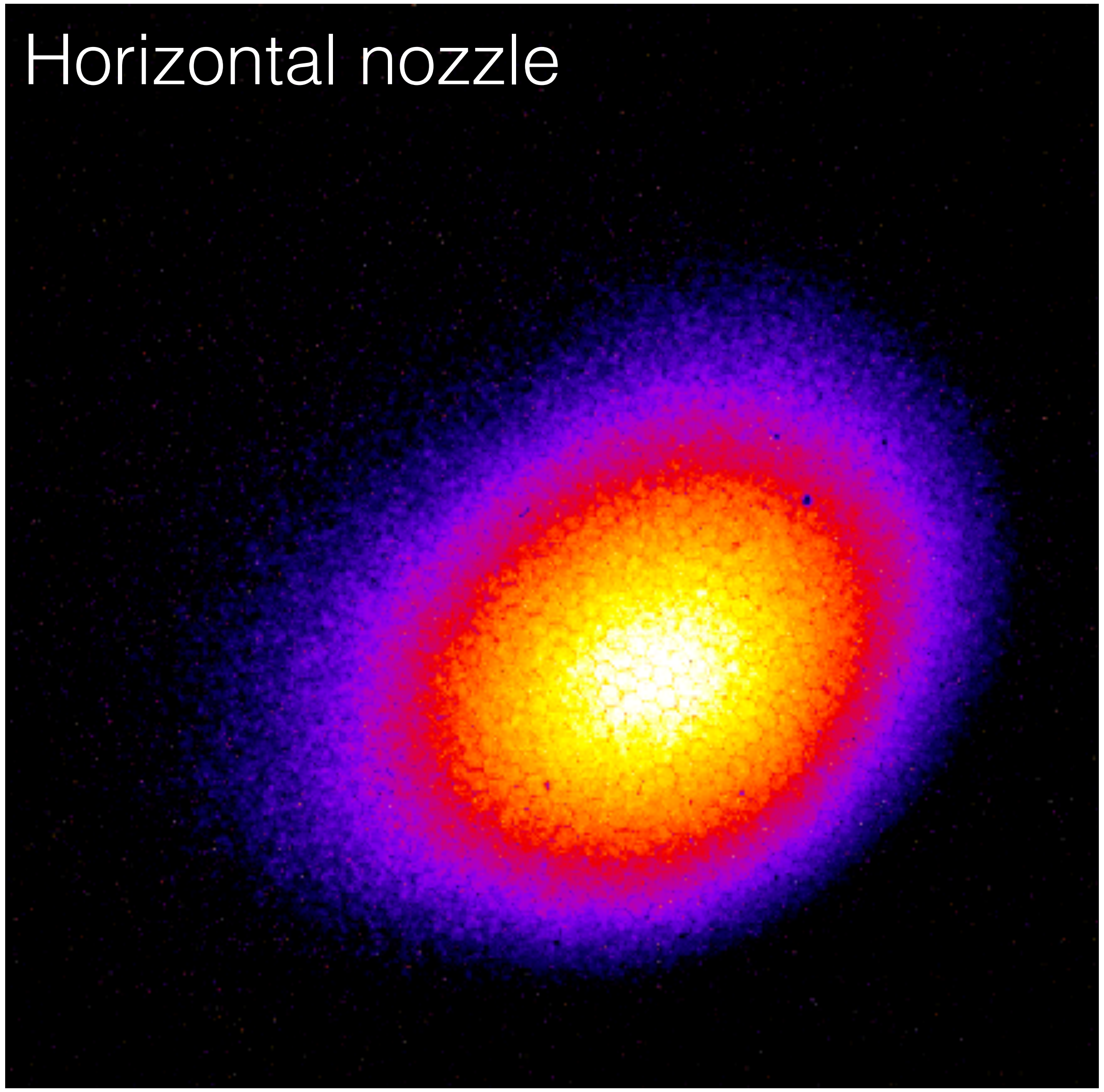




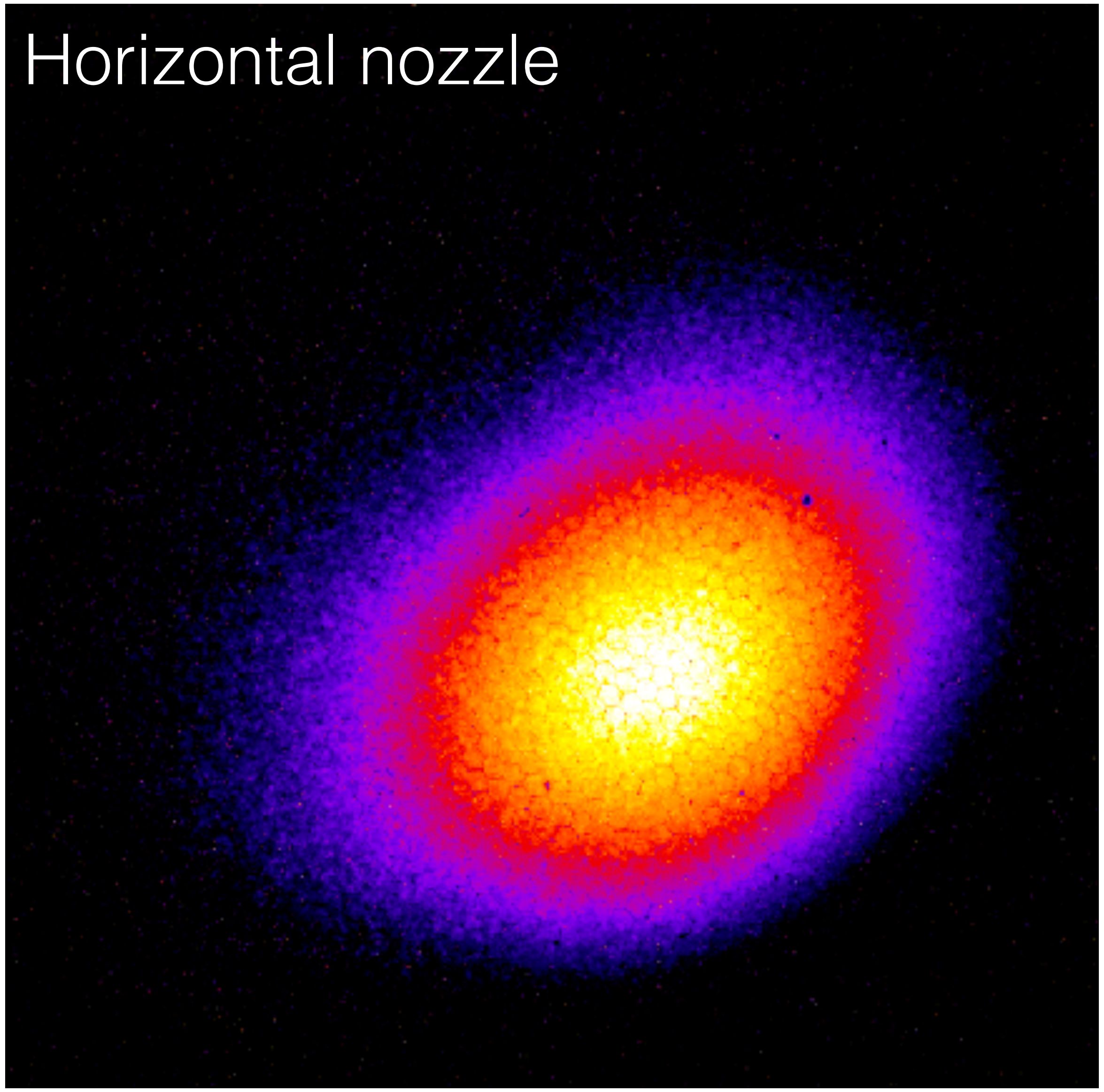
→ We expect an increase of the electron energy

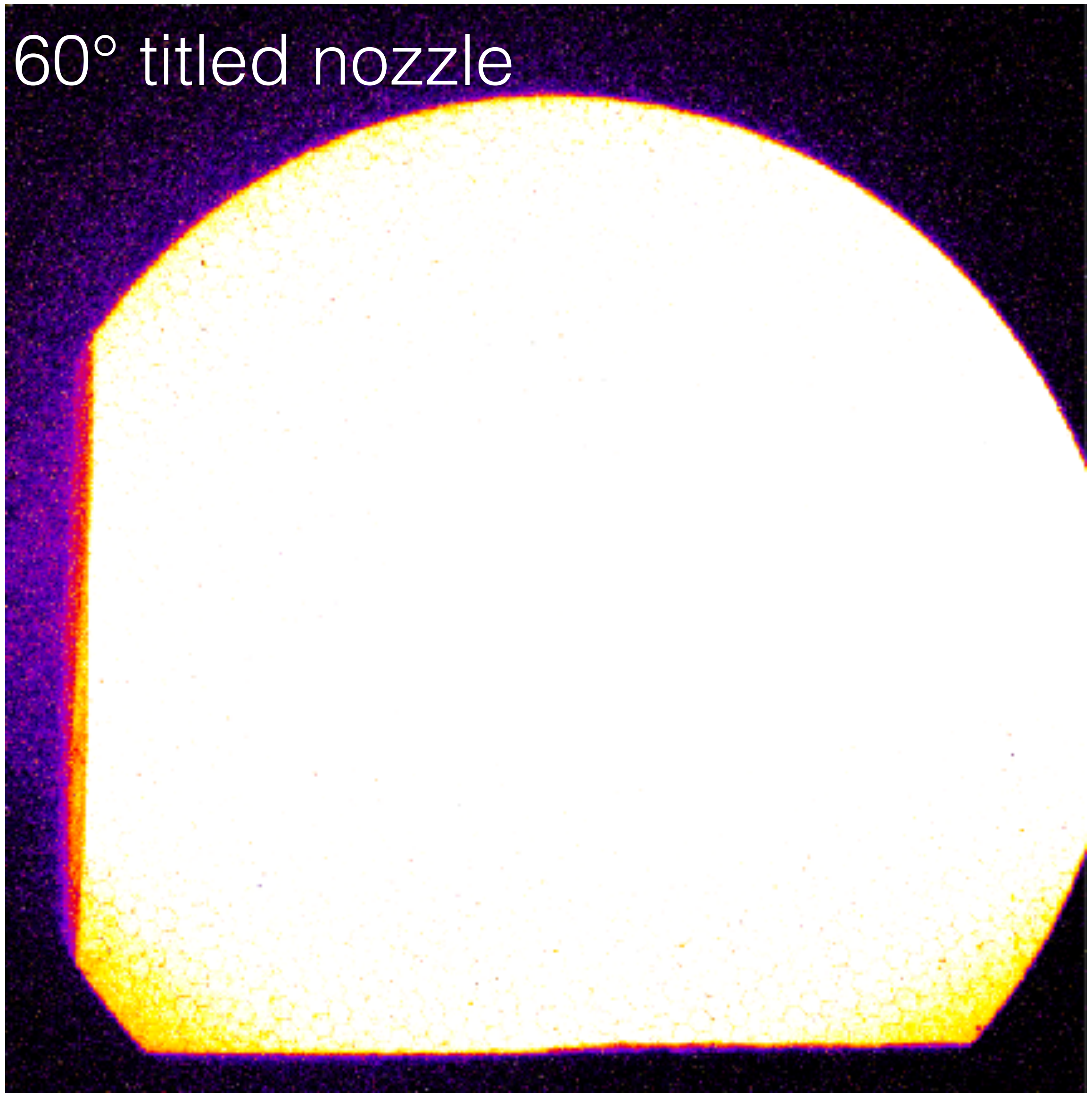
→ We expect a shift of the x-ray spectrum towards higher energies

Betatron radiation using tilted nozzle

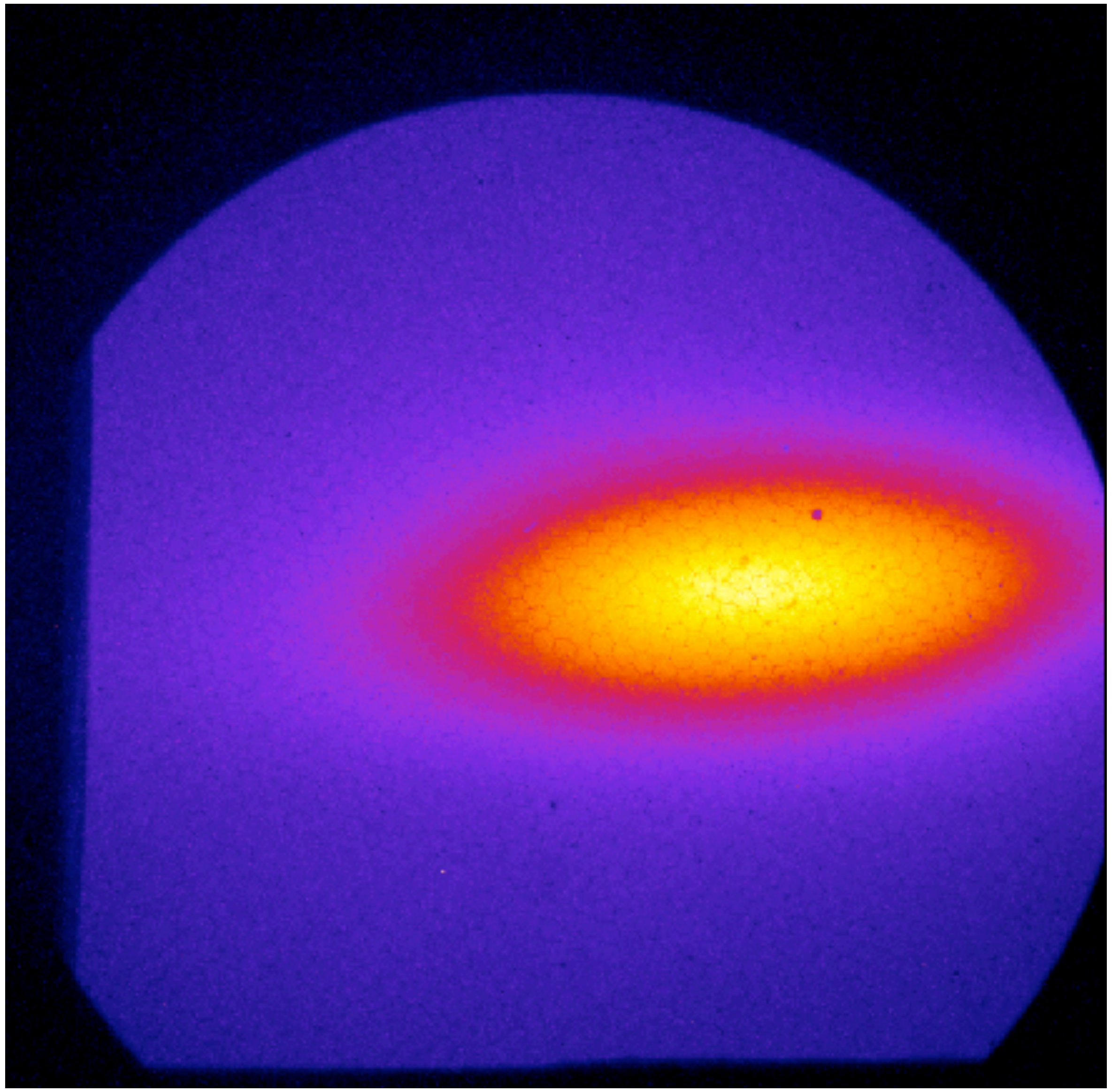


Betatron radiation using tilted nozzle



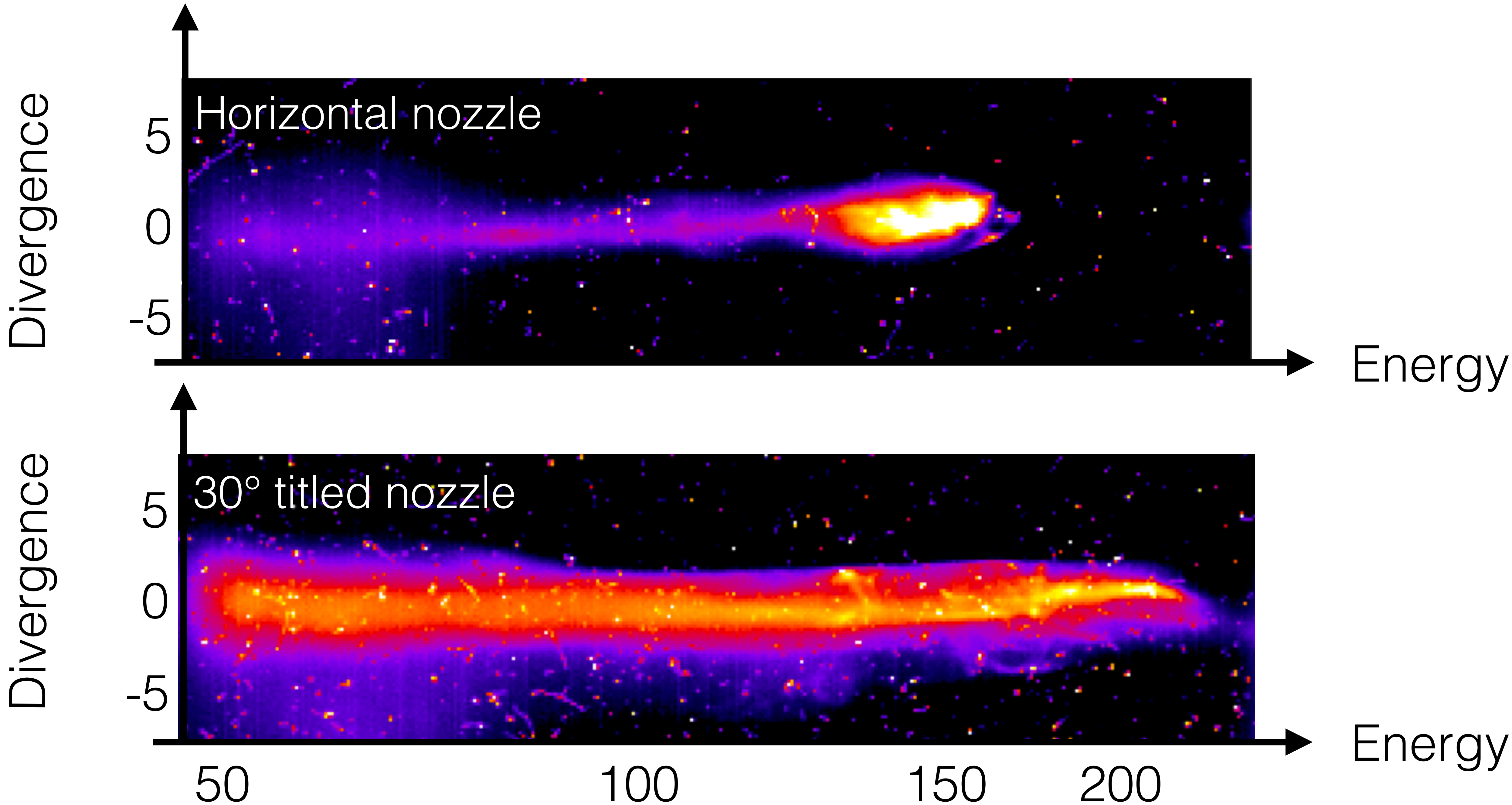


Betatron radiation using tilted nozzle



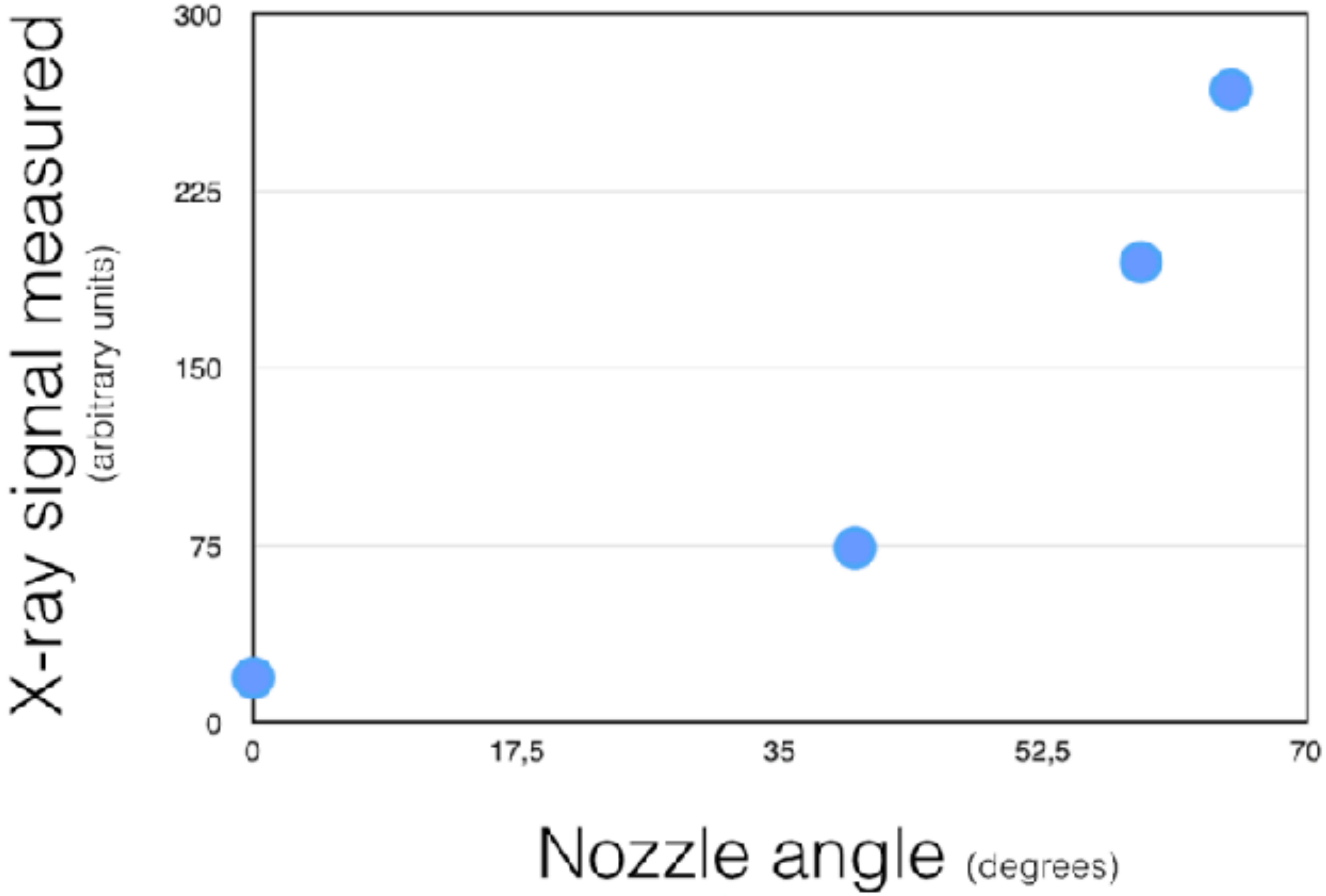
- Significant increase of the x-ray signal
- Decrease of the beam divergence

Electron beam spectrum



Signal as a function of nozzle angle

a 3 mm supersonic nozzle

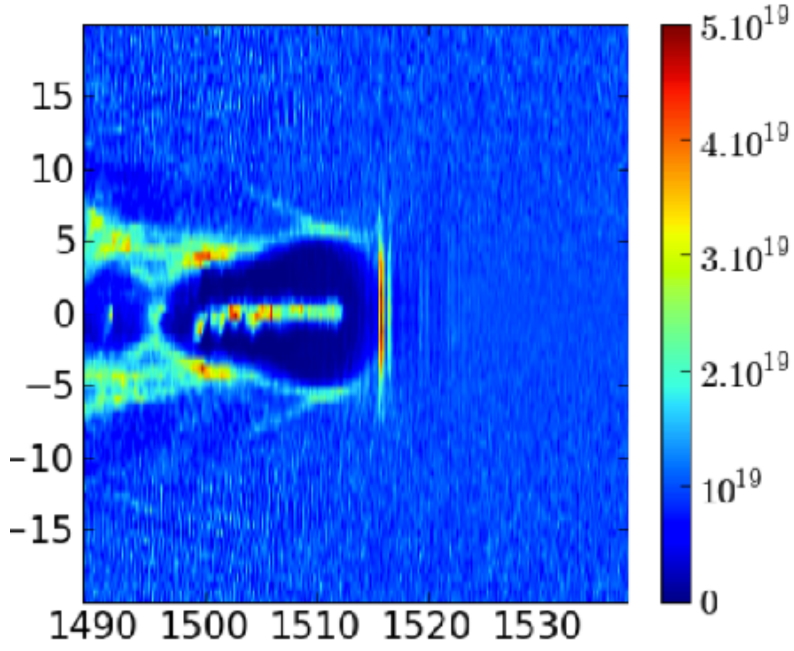


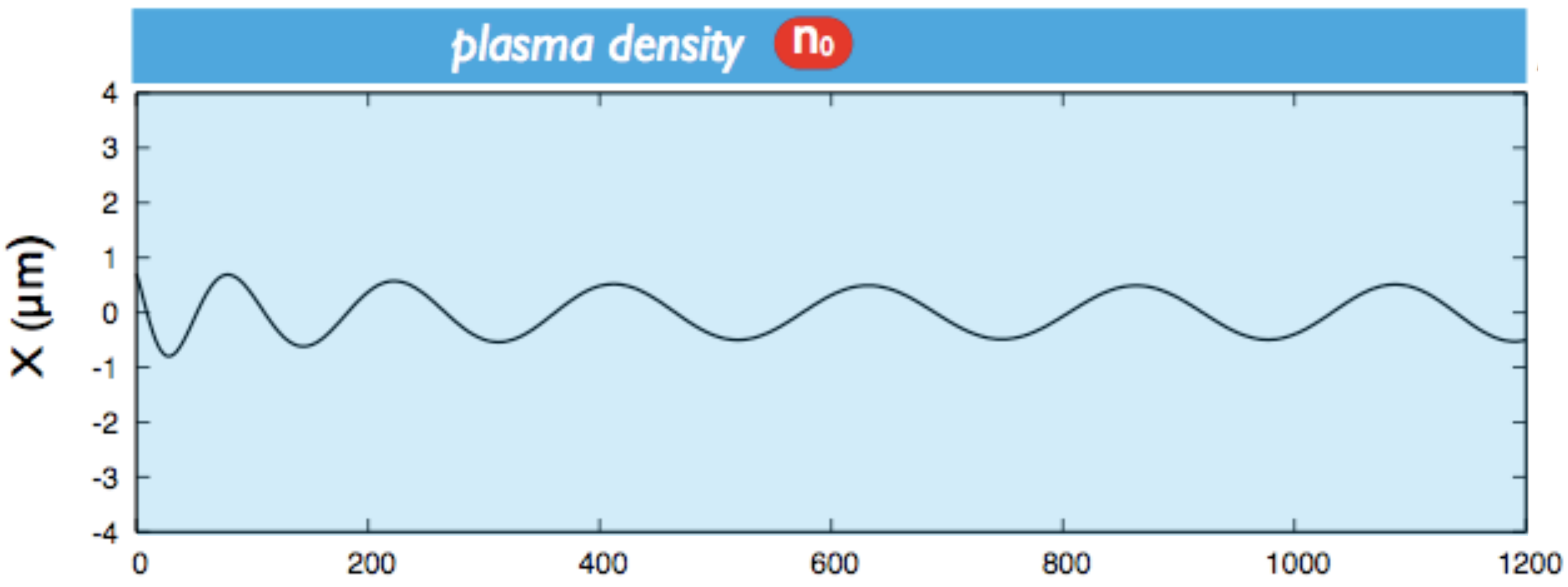
→ Signal above 3 keV can be increased up to 20x !

→ This method consists in increasing electron energy and reducing the oscillation period

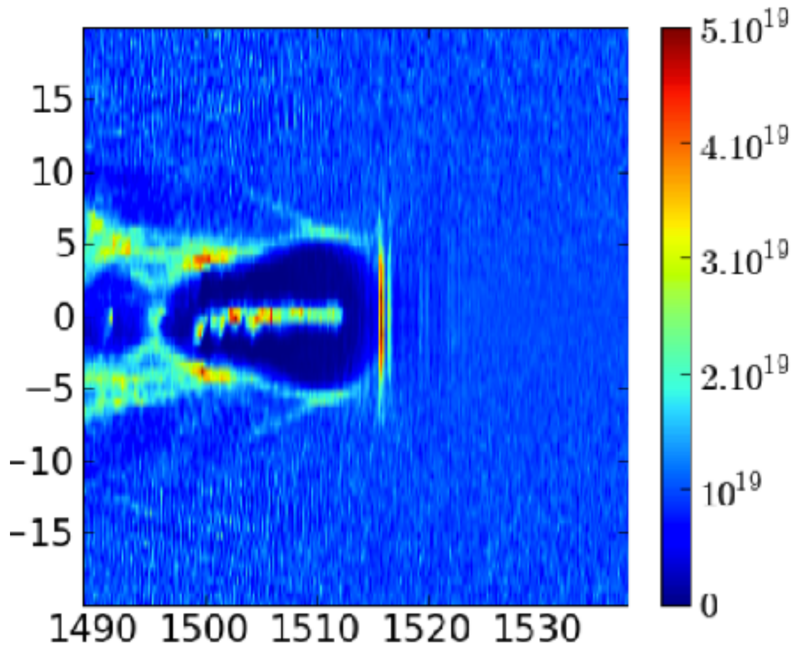
→ How can we control electron transverse motion and further increase the flux ?

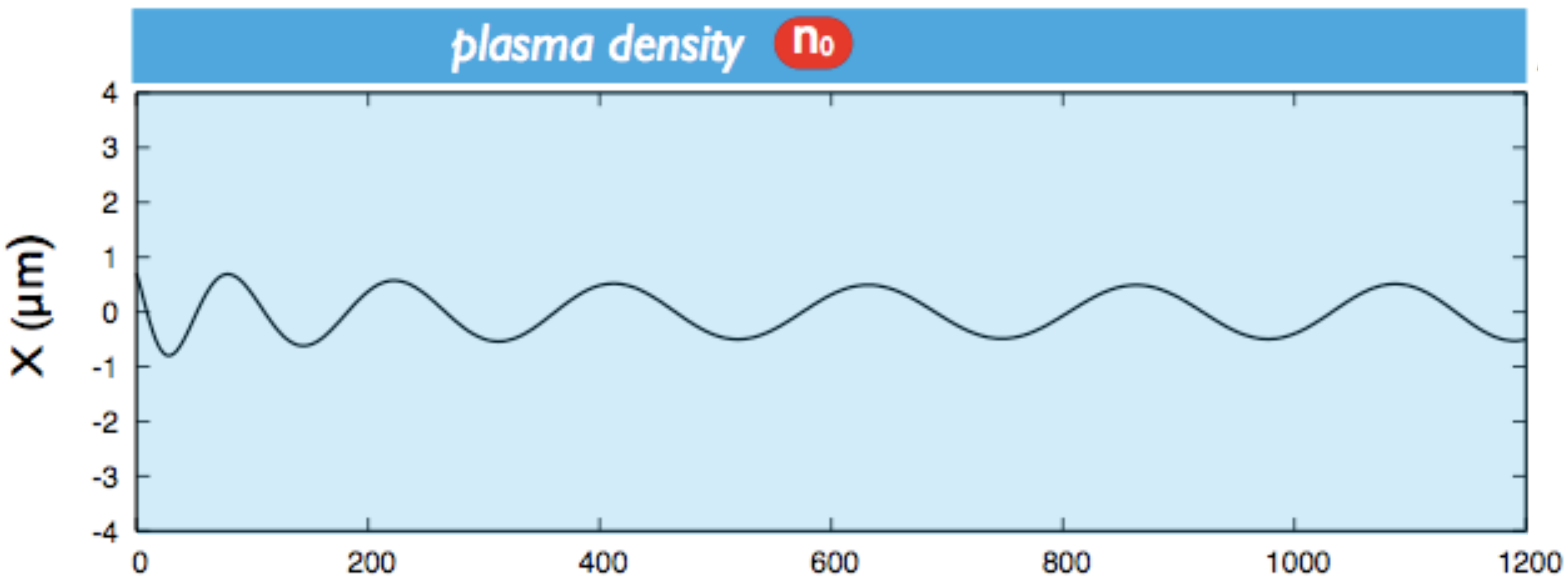
Density tailoring to control the electrons orbits

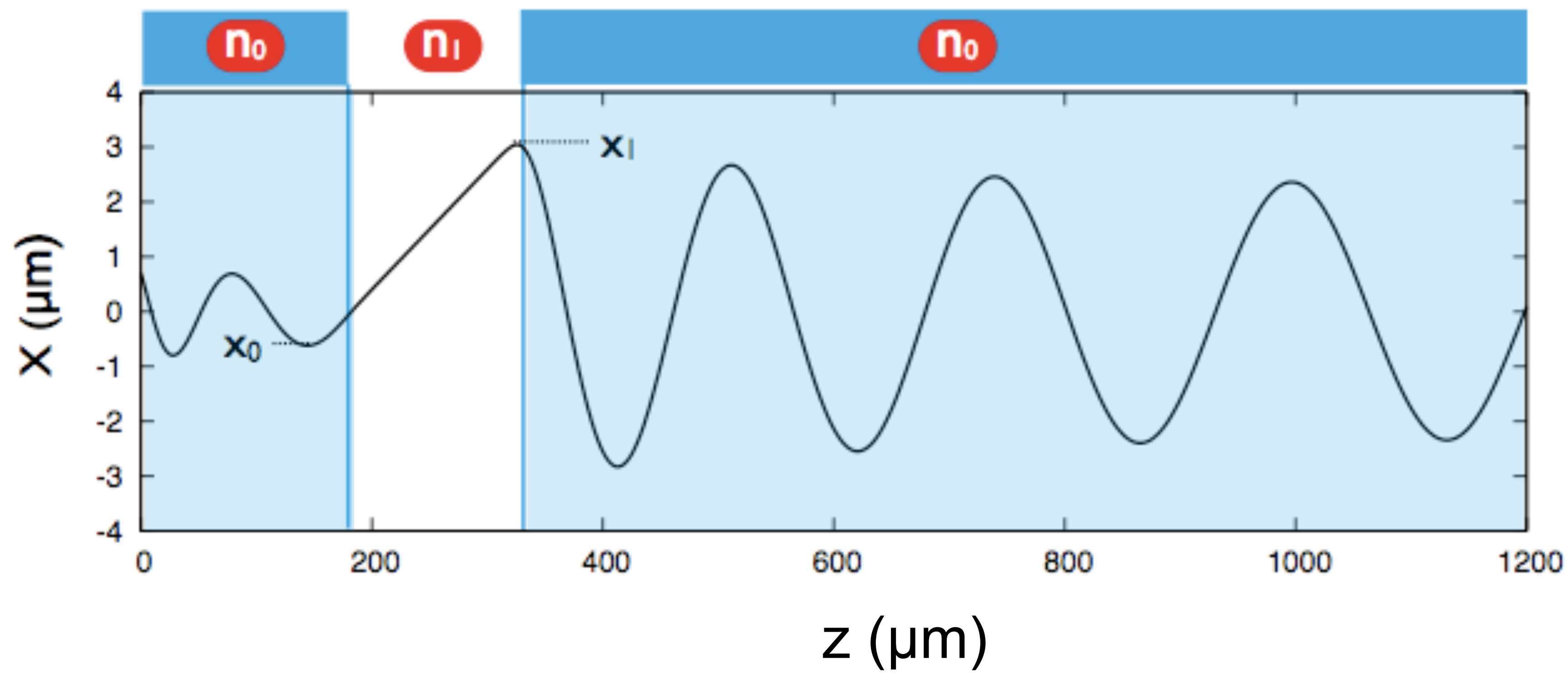




Density tailoring to control the electrons orbits

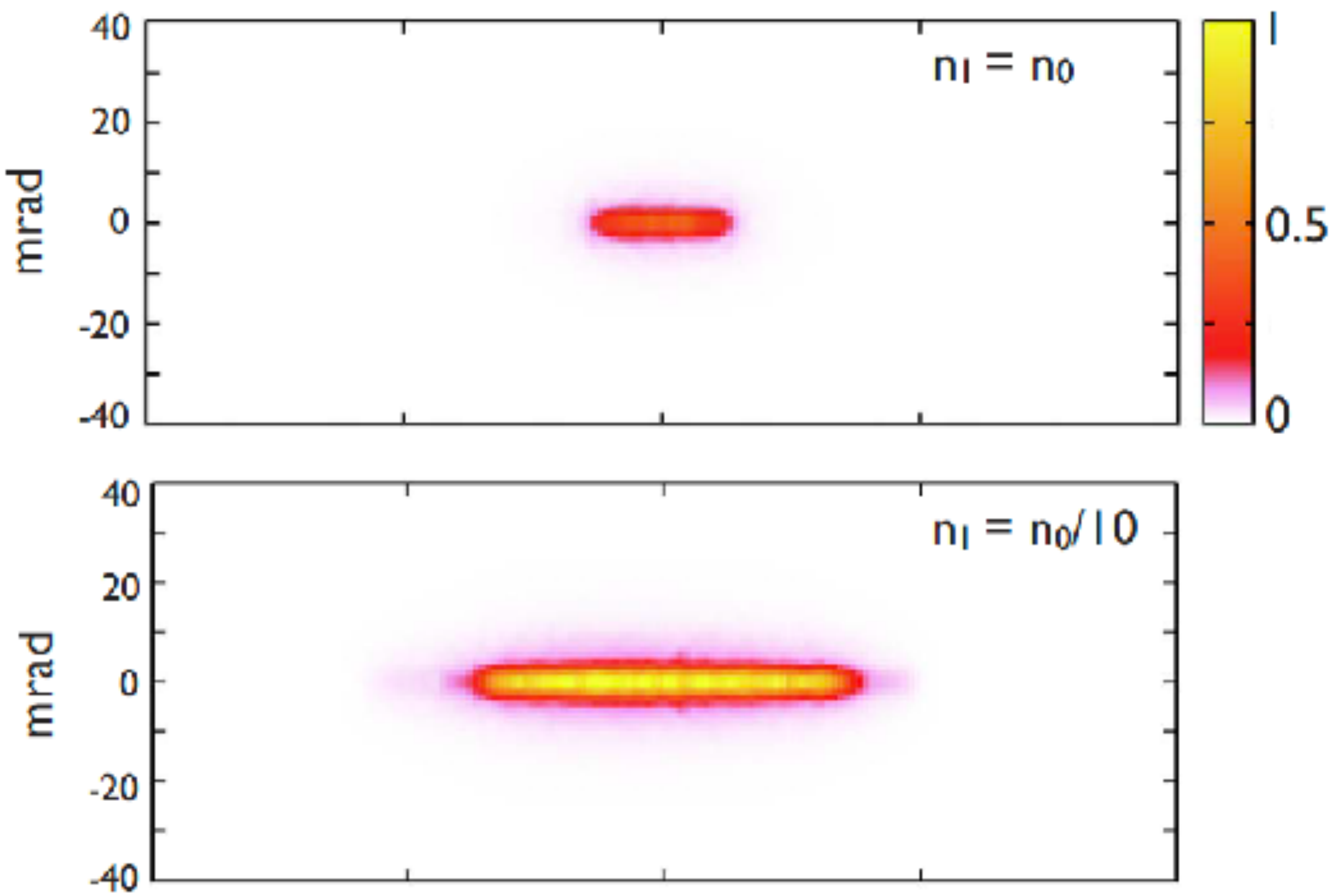




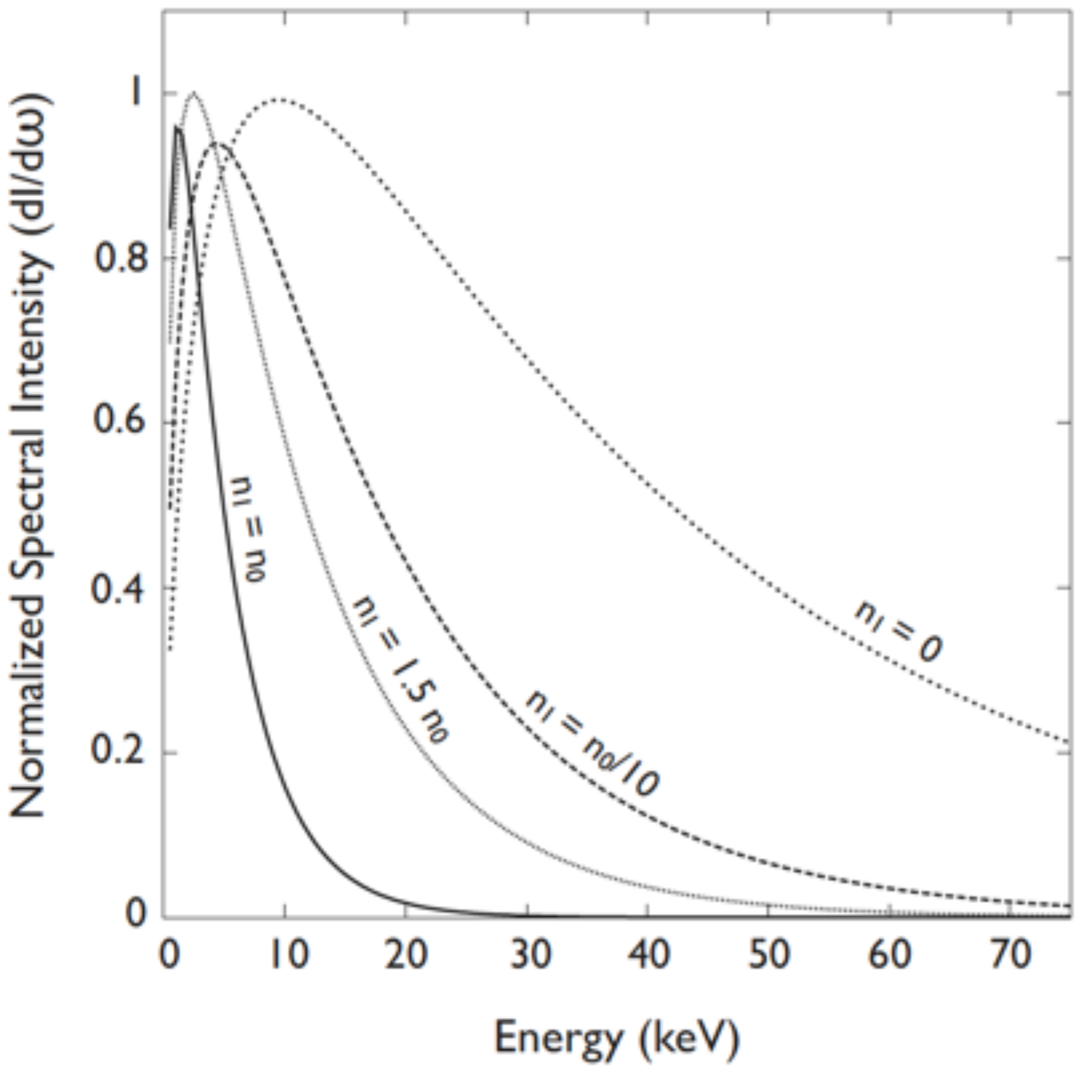


Density tailoring to control the electrons orbits

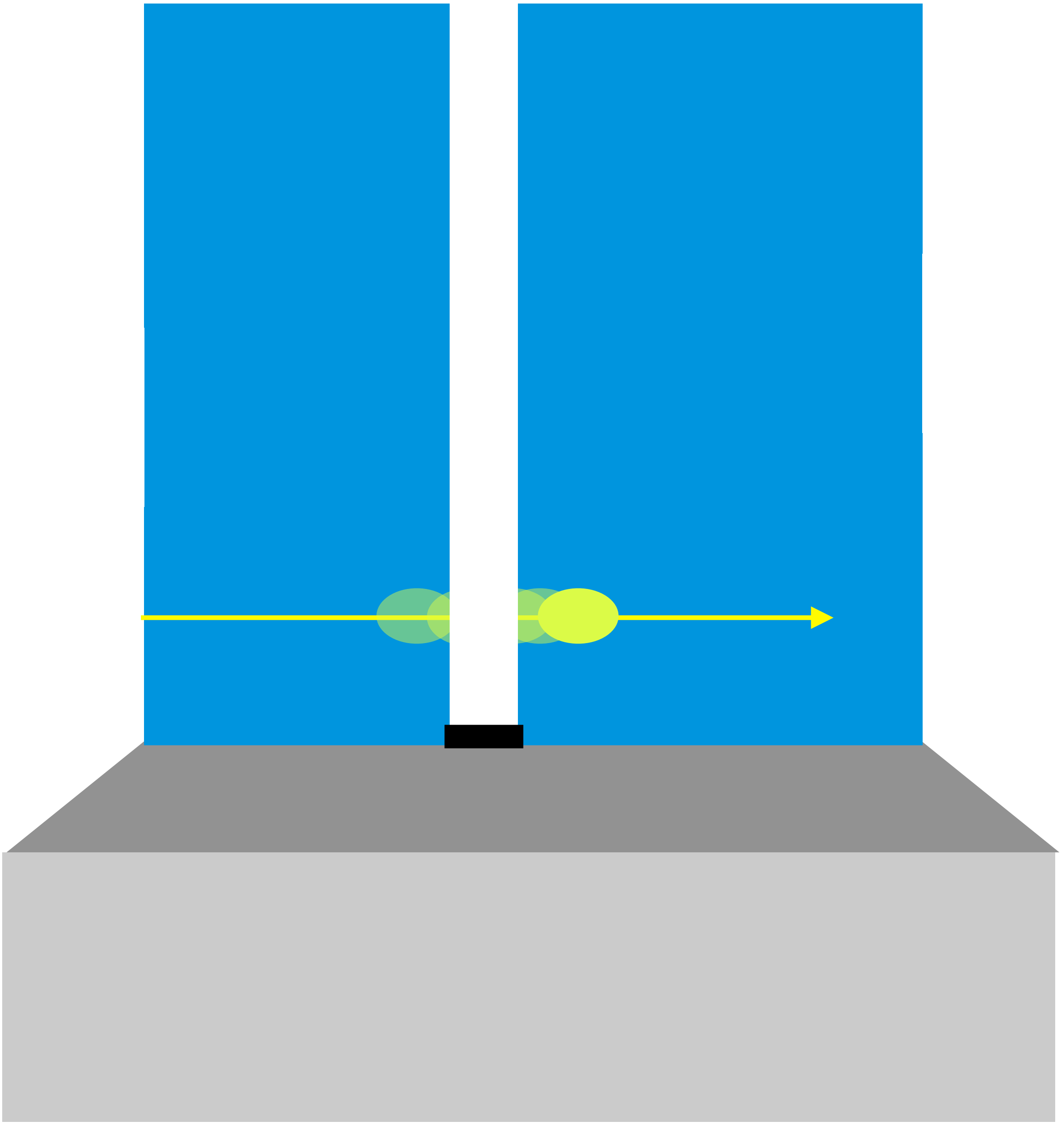
Angular distribution



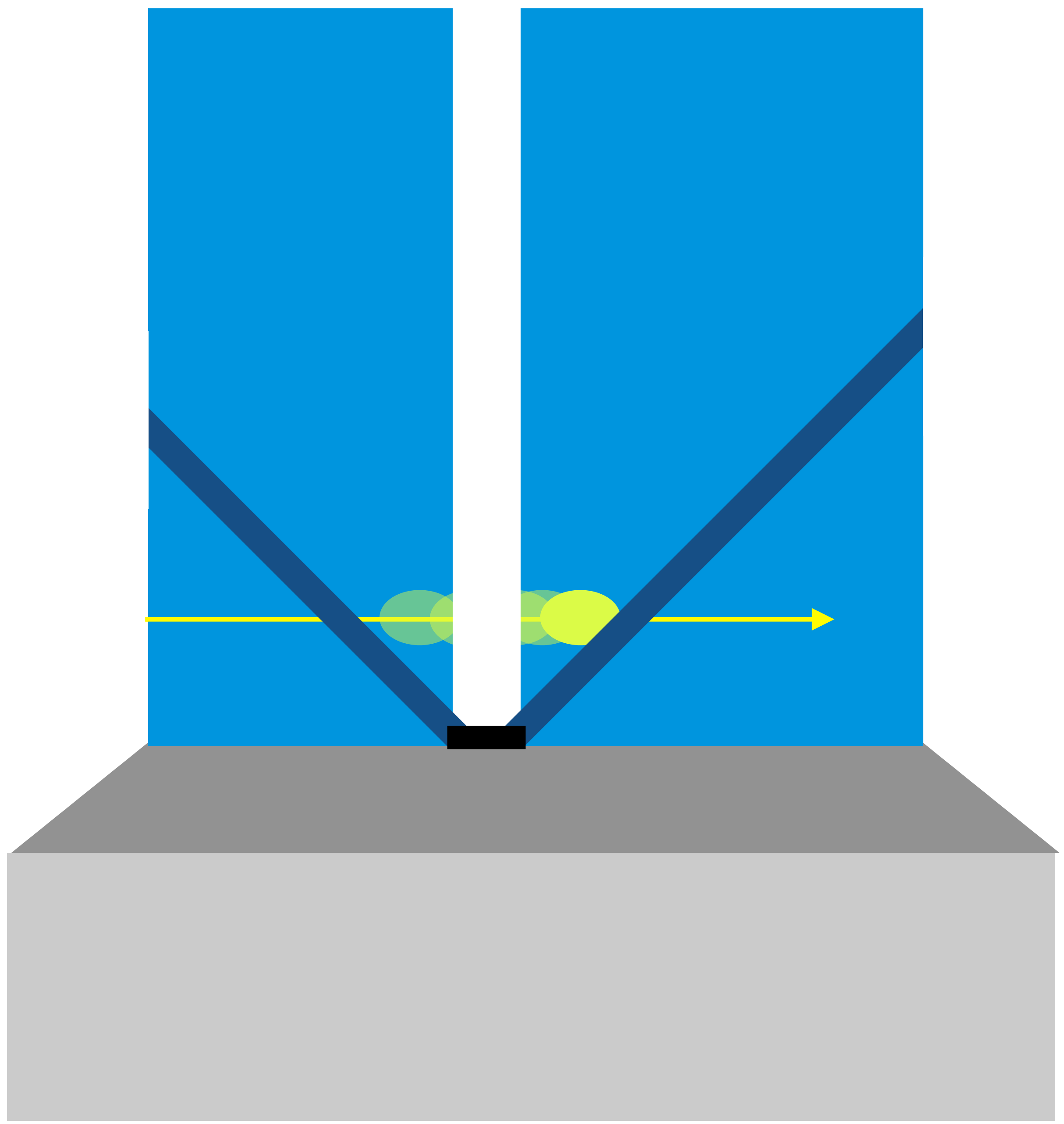
Spectrum



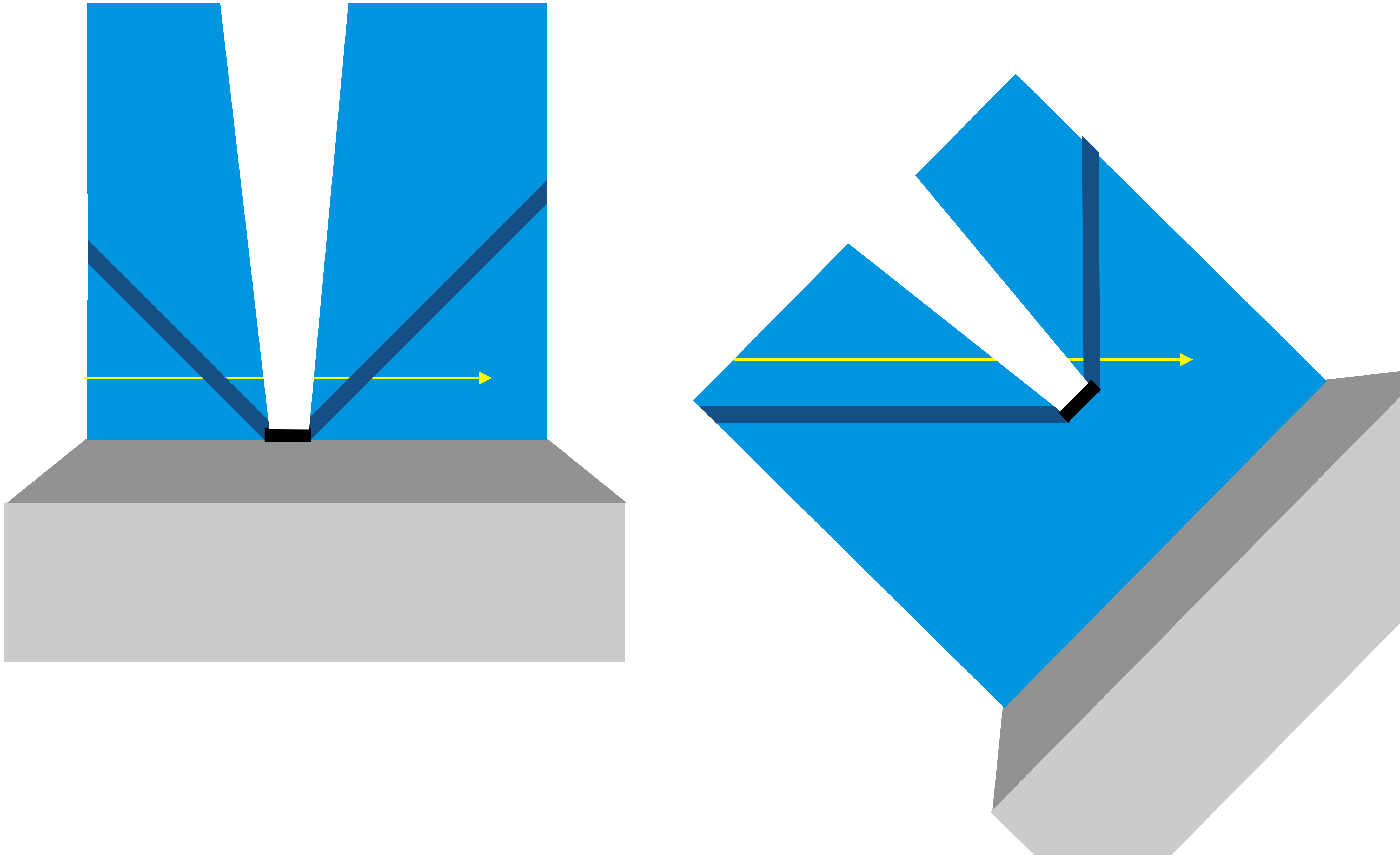
Density tailoring to control the electrons orbits



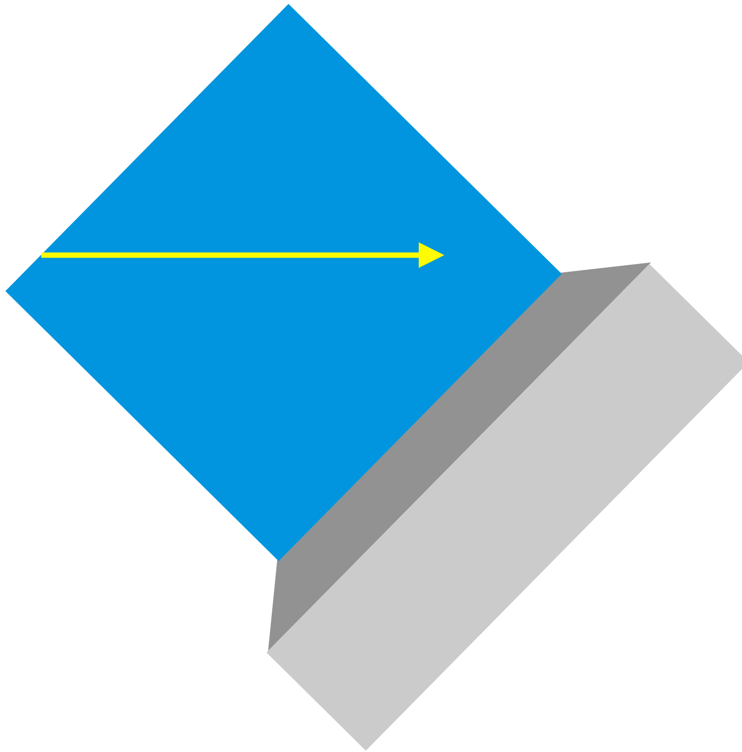
Density tailoring to control the electrons orbits

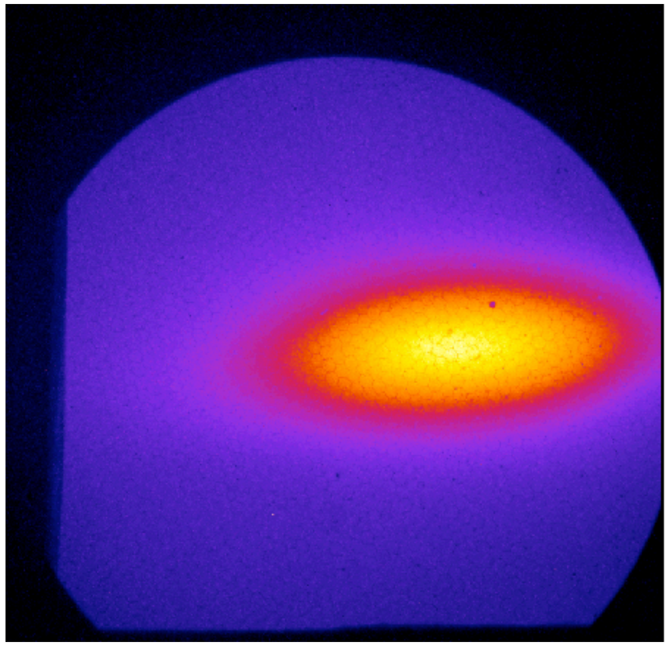


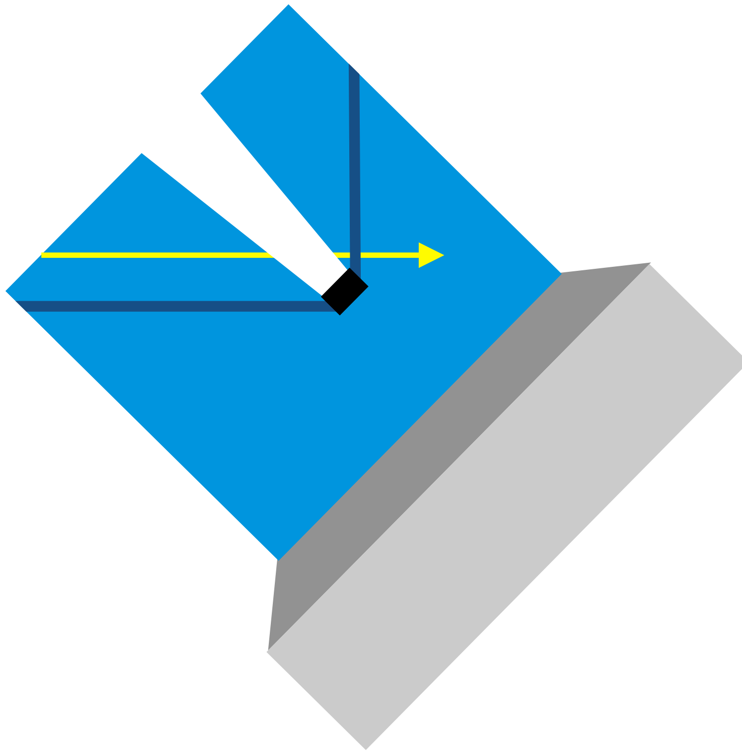
Density tailoring to control the electrons orbits

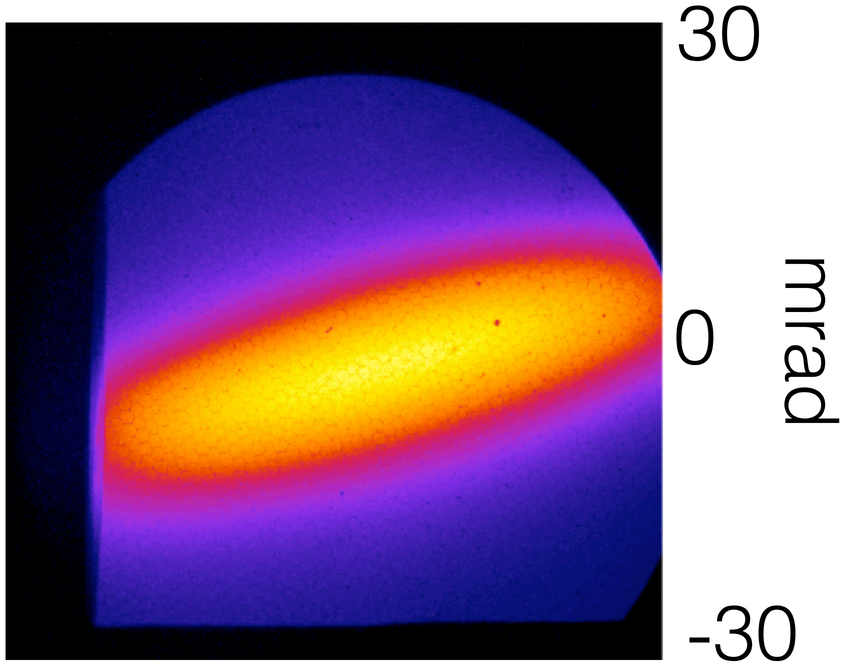


How can we increase the radiation energy ?









→ Integrated signal is increased by a factor 2

Conclusion & perspectives

Conclusion:

- We significantly increased the flux of the Betatron source.
- The source has been used for pioneering applications in fs x-ray science.

Perspectives:

- Laser Salle Jane has been improved. We expect even higher Betatron flux and energy.
- Keep developing methods to increase efficiency of the mechanism (use multiple laser beams to control electrons orbits, design gas targets with appropriate density profiles (cryogenic),…)
- Produce keV Betatron radiation using few TW class lasers with high repetition rate (100 Hz - kHz).
- Produce bright, tens keV Betatron radiation using PW class lasers.

And :

- Built a Betatron beam line for Femtosecond x-ray applications

Femtosecond X-ray sources from LPA