Gamma-ray spectrometer

Science at FACET II workshop

Presented by Félicie Albert

Lawrence Livermore National Laboratory

October 19th 2016

LLNL-PRES-XXXXXX

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Gamma-ray (and x-ray) spectrometer (and applications)

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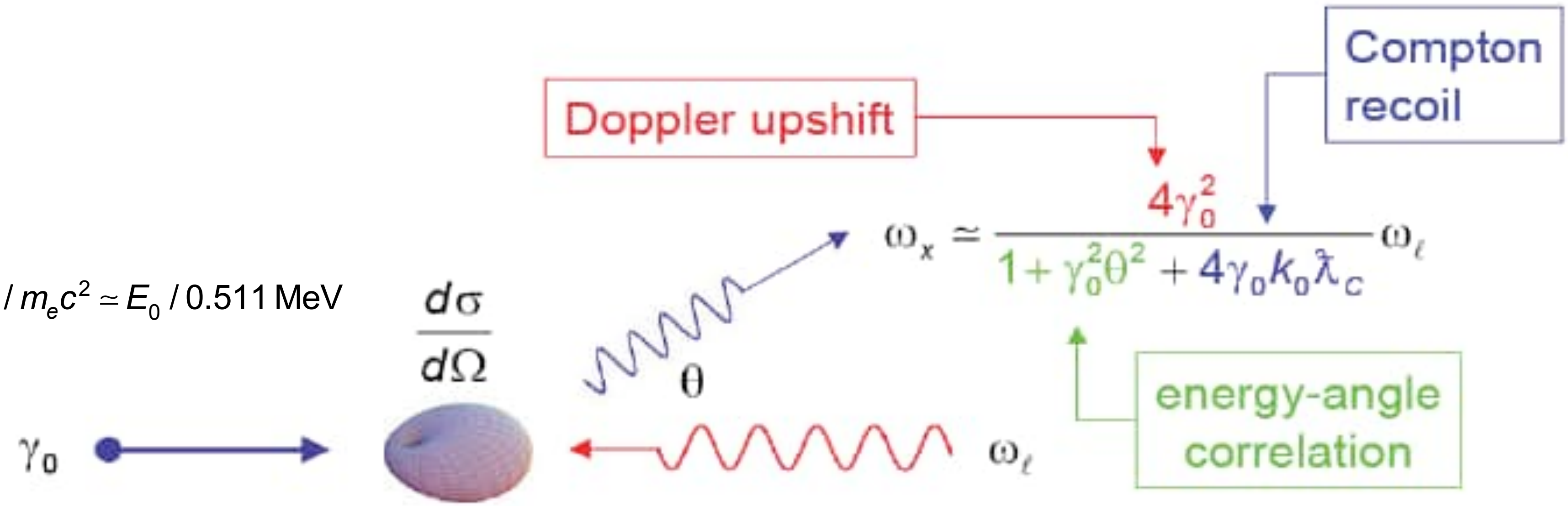
Outline

- Gamma-ray source based on Compton scattering
  - Performance
  - Gamma-ray measurements
  - Applications
- X-ray source based on betatron emission
  - Principle
  - X-ray measurements as a diagnostic of electron beam properties
  - Applications

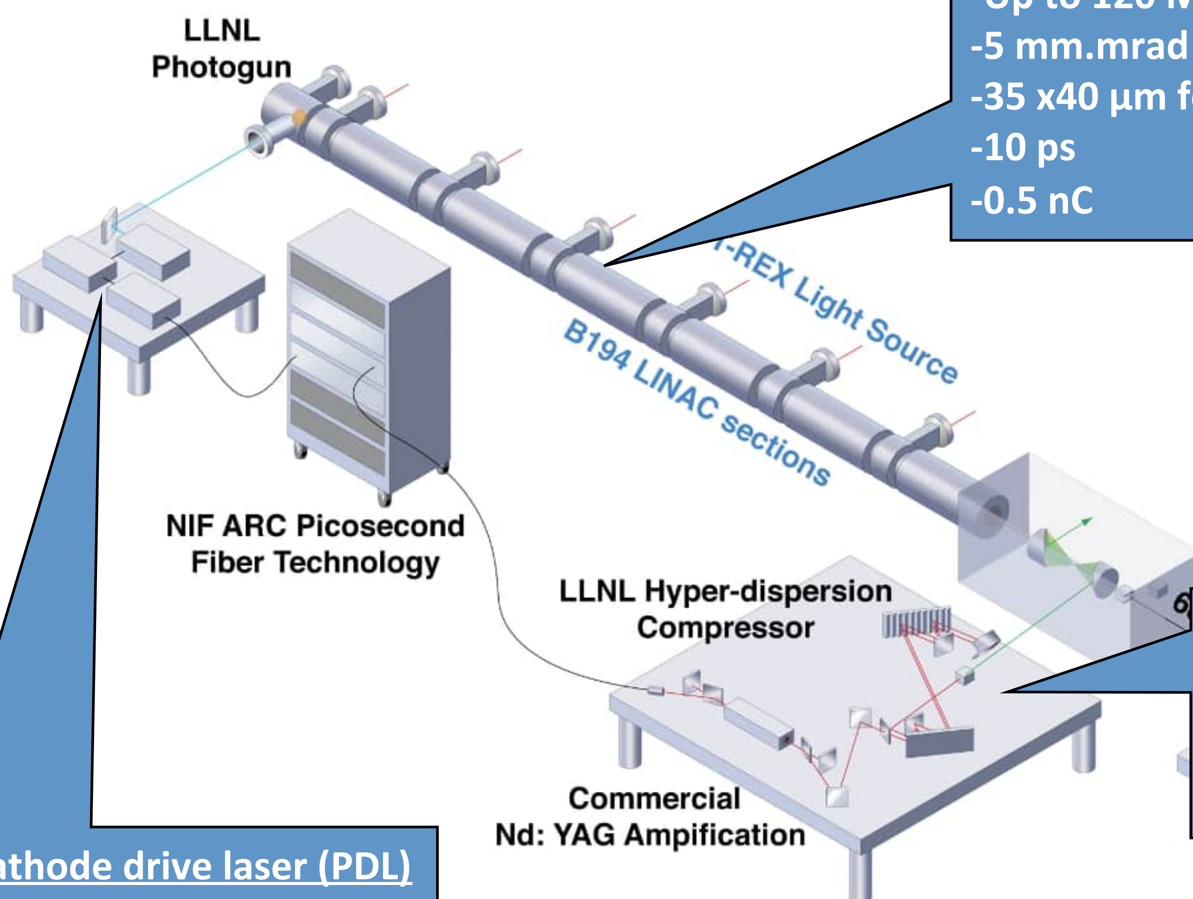
Narrow band gamma-rays from Compton scattering

$\gamma_0 = E_0 / m_e c^2 \simeq E_0 / 0.511\ \mathrm{MeV}$



Energy-momentum conservation yields $4\gamma^2$ upshift
Compton scattering cross section very small $6 \times 10^{-25}\ \mathrm{cm}^2$
High photon and electron densities required at interaction point

T-REX source components



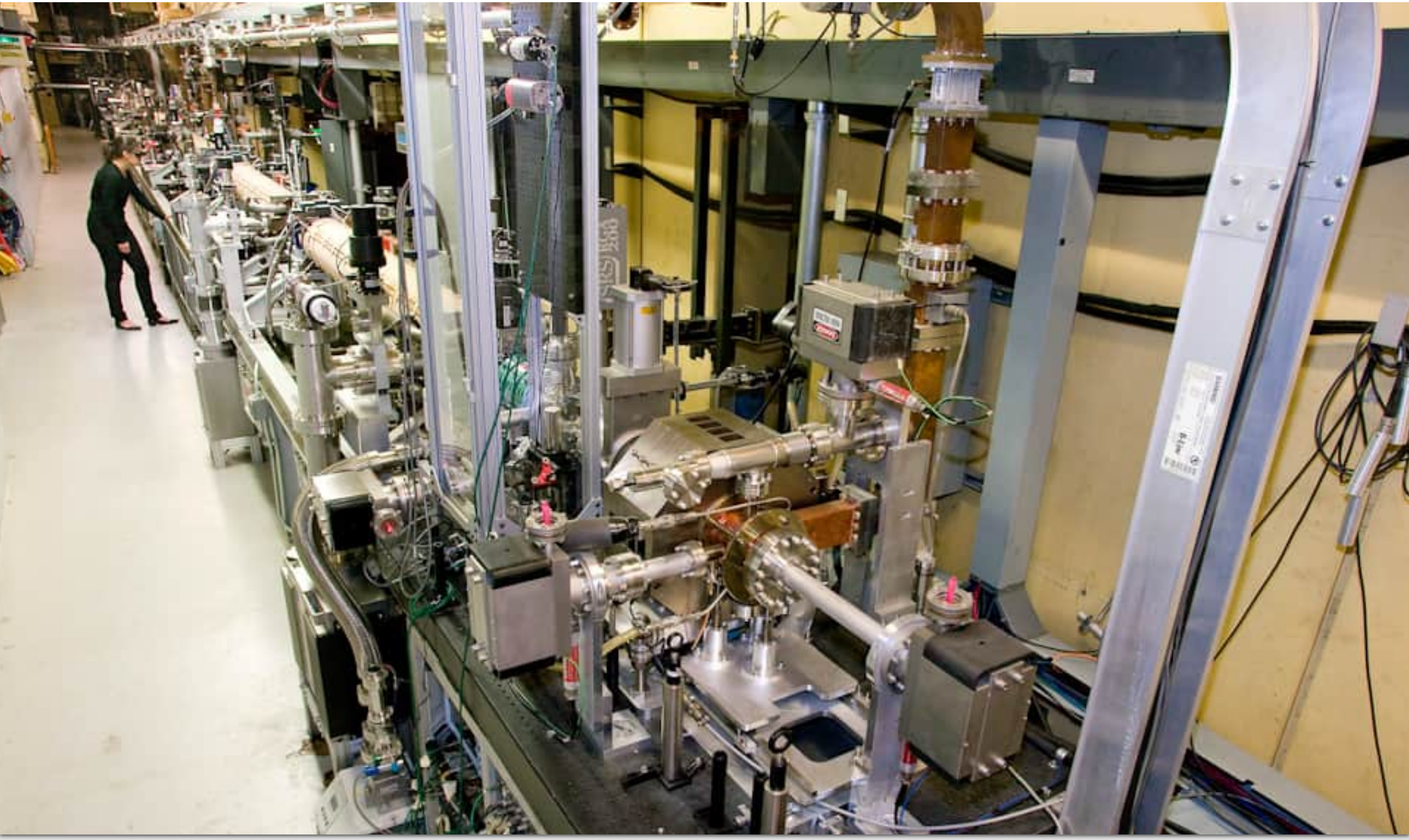
LINAC
- -Up to 120 MeV
- -5 mm.mrad
- -35 x40 µm focus
- -10 ps
- -0.5 nC

Interaction laser (ILS)
- -Up to 750 mJ (IR)
- -150 mJ (UV or green)
- -20 ps

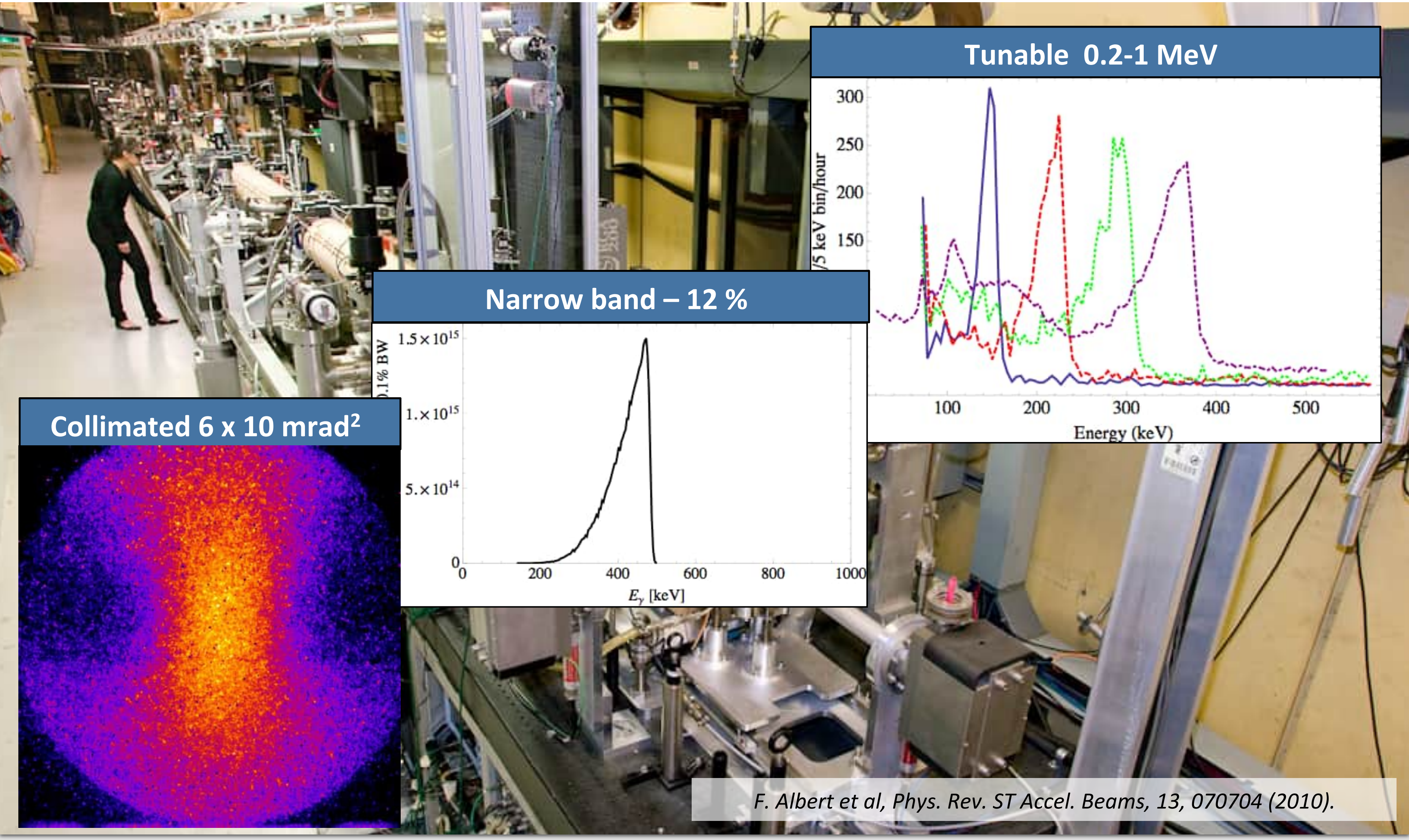
Photocathode drive laser (PDL)
- -261 nm
- -50 µJ flat top (space and time)
- -10 ps

D. J. Gibson et al, Phys. Rev. ST Accel. Beams 13, 070703 (2010).

T-Rex: LLNL's first Compton gamma-ray source

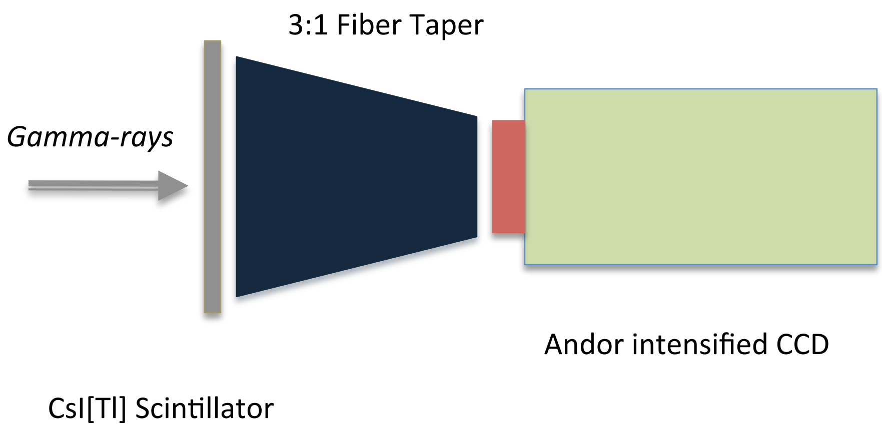


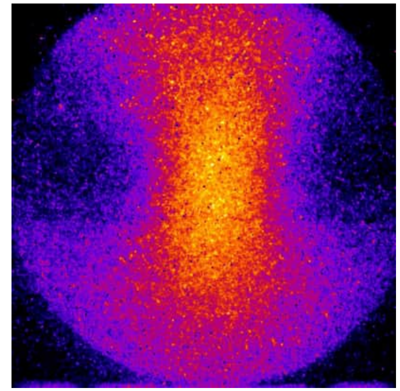
T-Rex properties



F. Albert et al, Phys. Rev. ST Accel. Beams, 13, 070704 (2010).

Photon flux and divergence



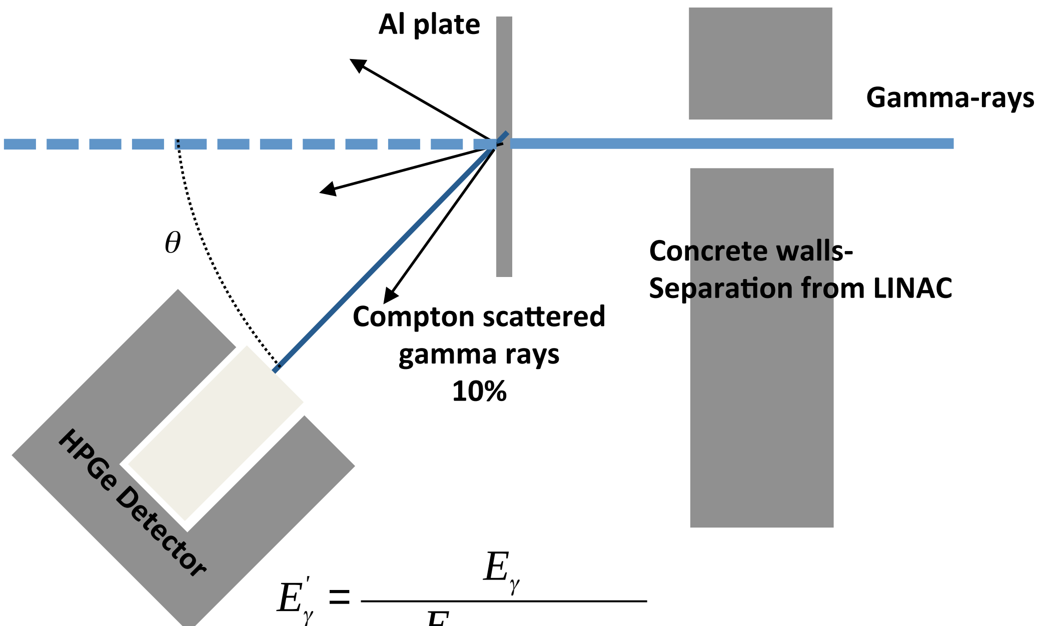


Electron beam and ILS
0.478 MeV gamma-rays

Electron beam only
No gamma-rays

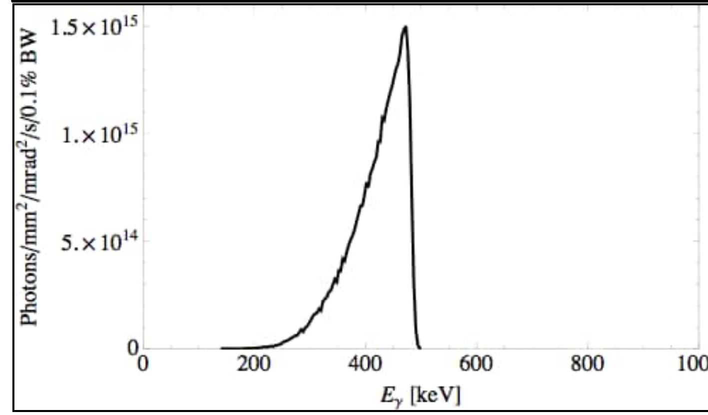
Estimations indicate 10^5 photons/shot (based on calibrations with ^{137}Cs source @ 662 keV)

Spectrum measurement

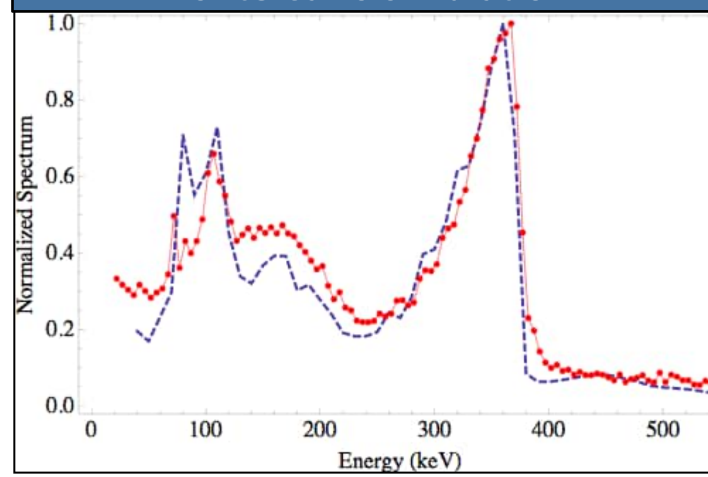


$$E_{\gamma}^{'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{E_0}(1 - \cos\theta)}$$

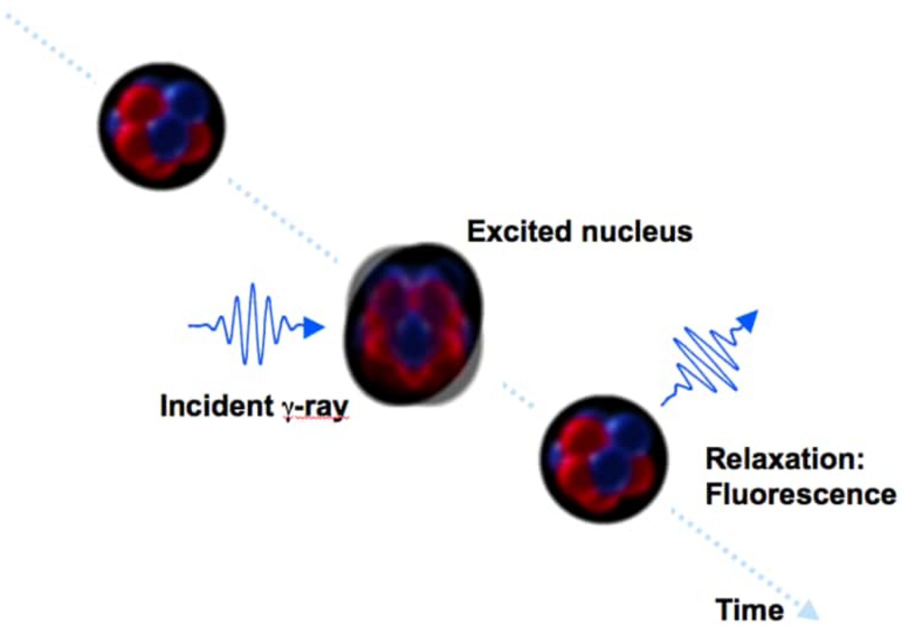
Input spectrum (simulation)



Indirectly measured spectrum and Monte Carlo simulation

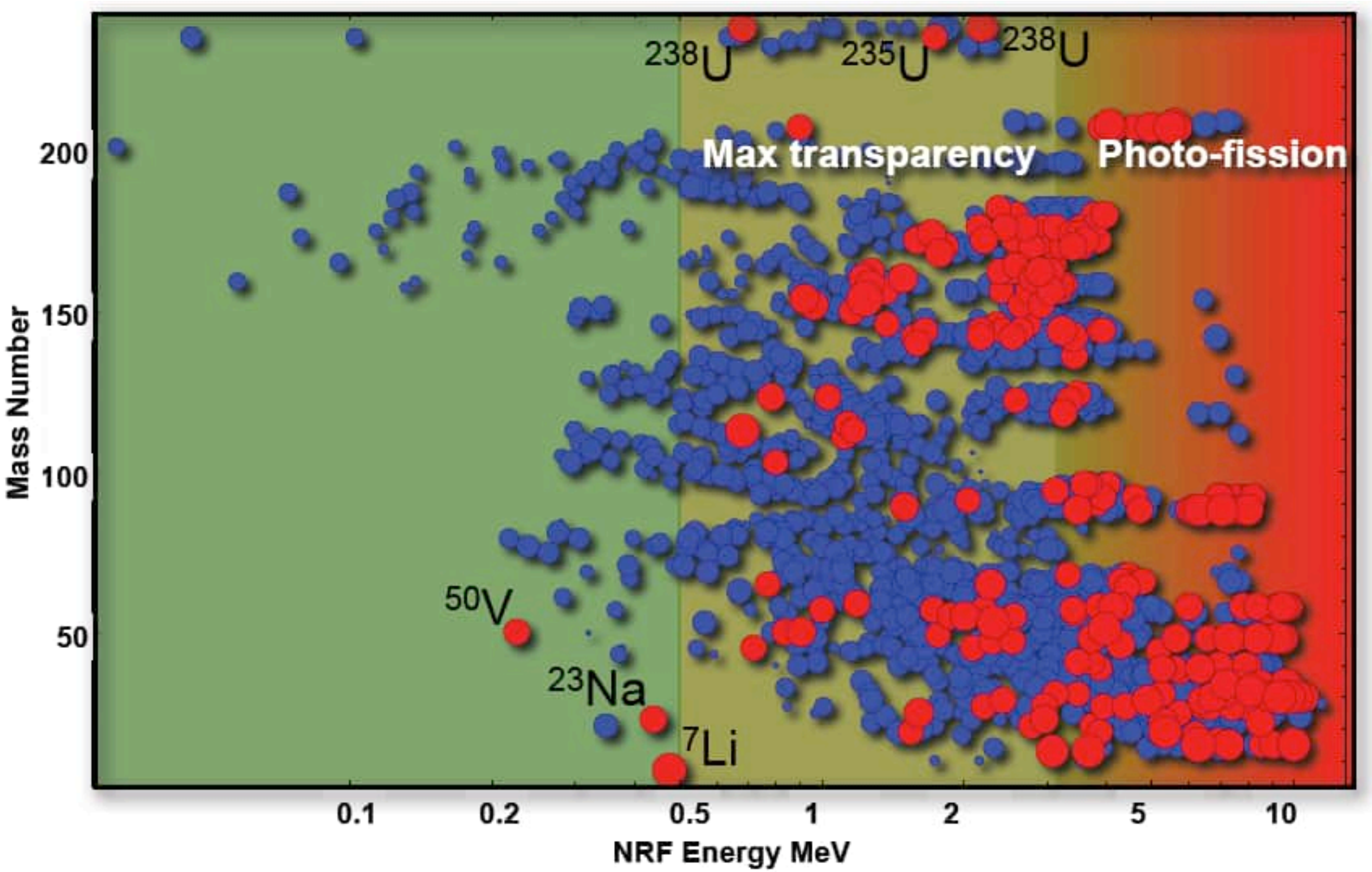


Nuclear Resonance Fluorescence (NRF) can provide isotope-specific contrast



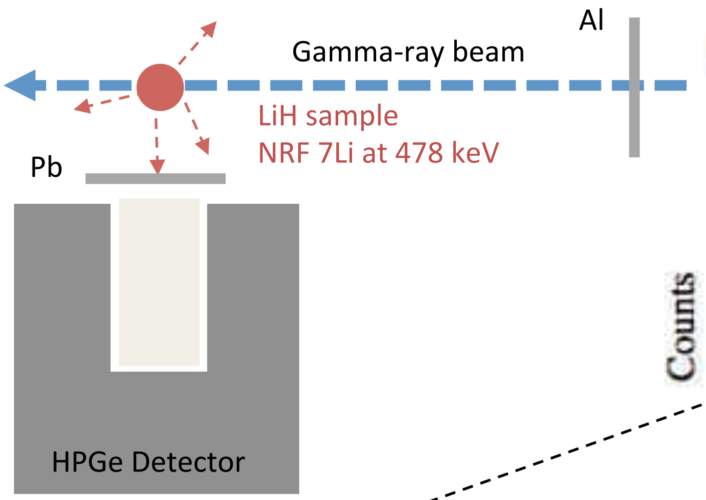
- Incident photon excites nucleus
  - MeV
  - Discrete energies
  - Isotope specific
- Nucleus subsequently re-radiates photons
  - NRF lines very sharp (1 eV)
  - Need high brightness narrow band source to detect them
- Applications
  - Isotope specific detection
  - Special Nuclear Materials detection (Homeland security)
  - Nuclear waste assay and detection

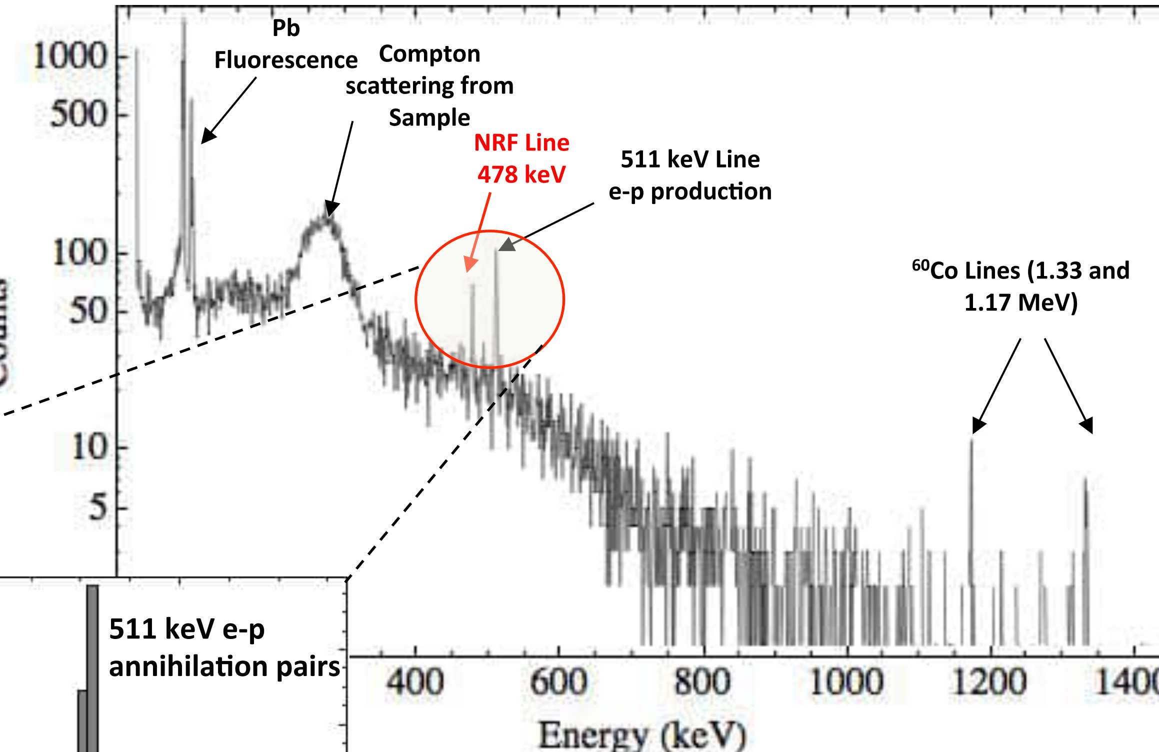
NRF transitions are isotope-specific and have large cross sections

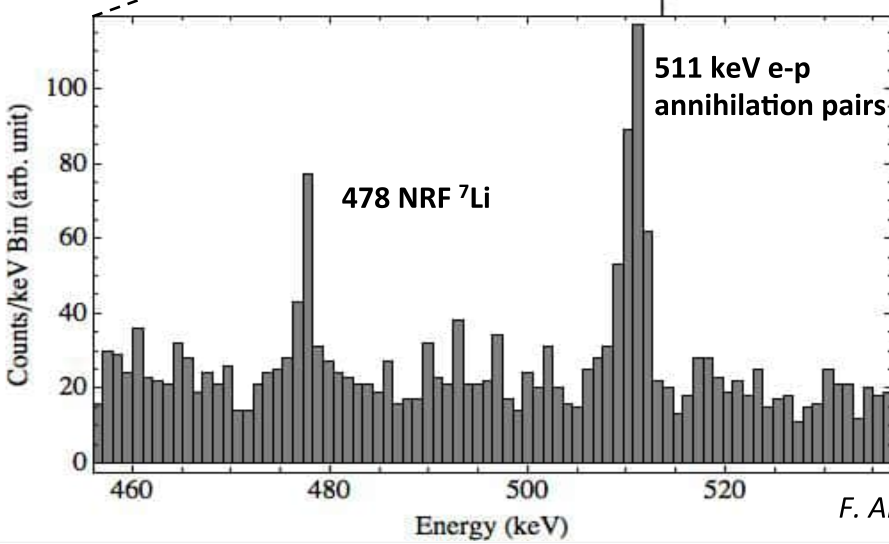


Gamma-rays in the 0.5-3 MeV range are both highly penetrating and non activating

Direct detection of ^{7}Li NRF line with T-REX



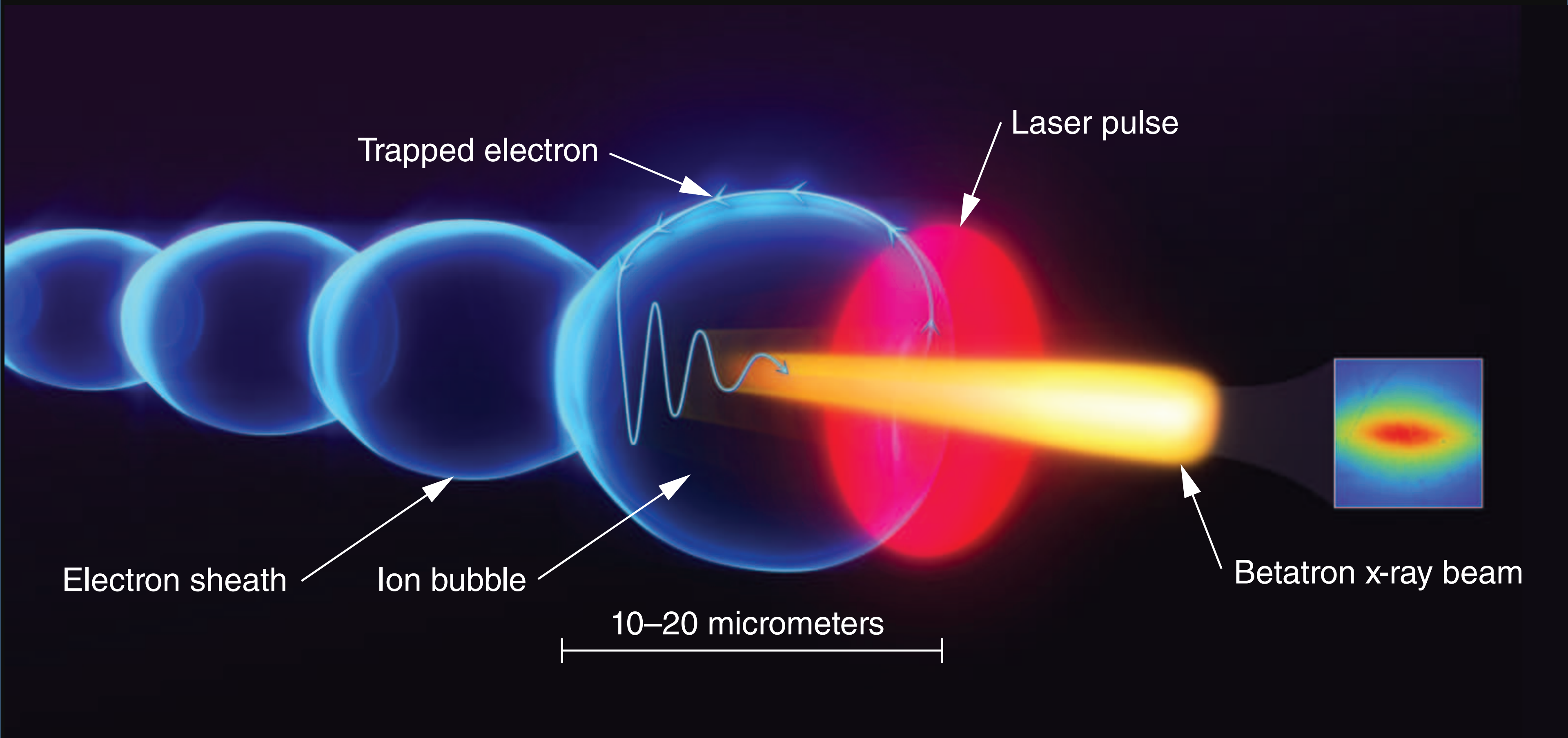




Drawback: 7.5 hours measurement

F. Albert et al, Phys. Rev. ST Accel. Beams, 13, 070704 (2010).

Betatron x-ray radiation



"Betatron x-rays bring focus to a very small, very fast world", LLNL S&T Review, January/February 2014

Modeling

Equation of motion

$$\frac{d\vec{p}}{dt} = -m\omega_p^2\frac{\vec{r}}{2} + \alpha\frac{mc\omega_p}{e}\vec{u_z}$$

Intensity per unit solid angle and frequence

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

Asymptotic limit

$$\frac{d^2I}{d\Omega d\omega} = \frac{e^2}{3\pi^2c}\left(\frac{\omega\rho}{c}\right)^2\left(\frac{1}{\gamma^2}+\theta^2\right)\left[K_{2/3}^2(\xi)+\frac{\theta^2}{(1/\gamma^2)+\theta^2}K_{1/3}^2(\xi)\right]$$

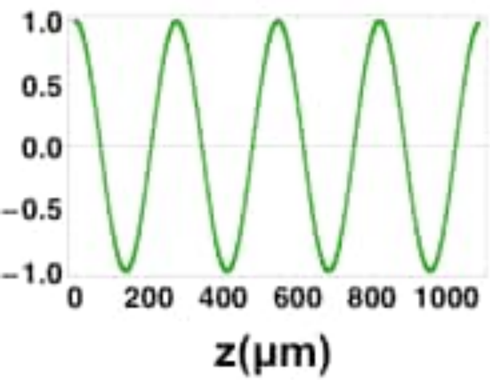
J.D. Jackson, Classical Electrodynamics, 3rd edition (1998)
E. Esarey, B. A. Shadwick, P. Catravas, and W. P. Leemans, Phys. Rev. E 65, 056505 (2002)

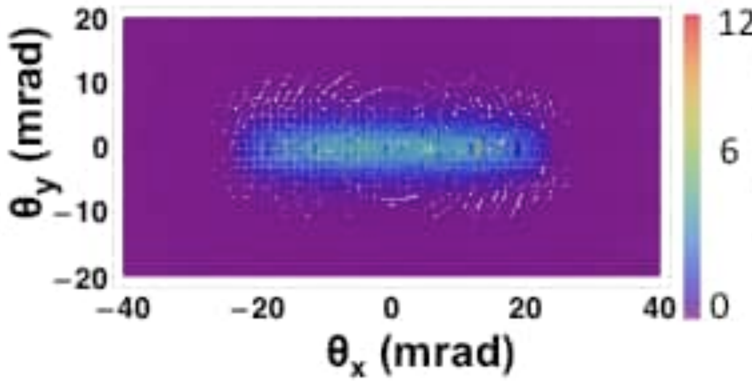
Modeling: example

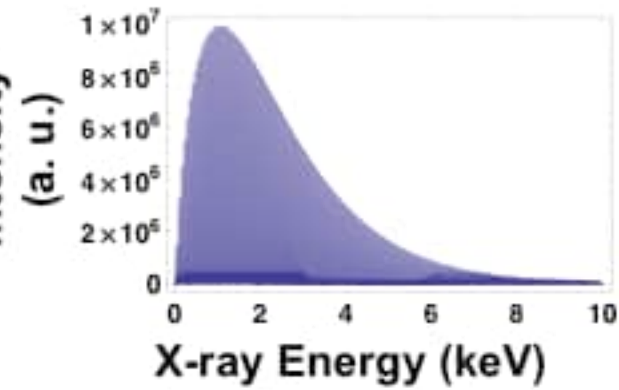
Trajectory

Beam profile

Spectrum







Parameters

n_e=10^{19} cm^{-3}

γ=200

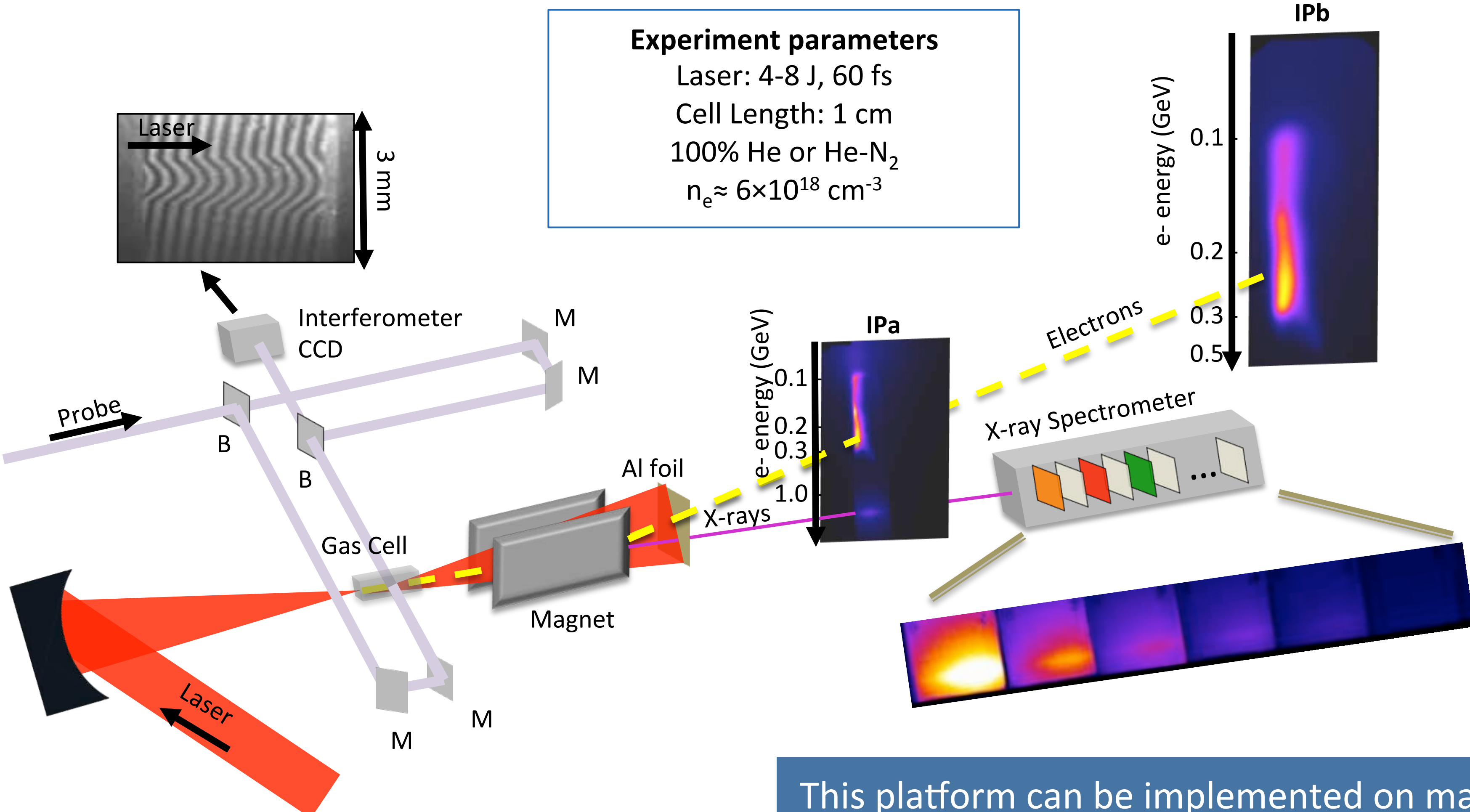
x_0= 1 μm

α=0

F. Albert et al., Proc. SPIE 2013

Betatron x-ray characterization

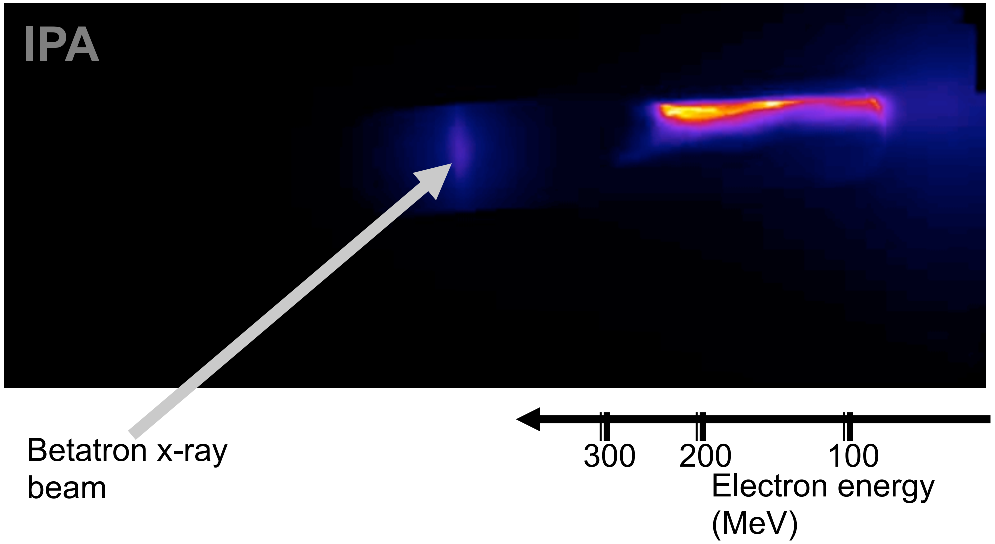
Experiment parameters
Laser: 4-8 J, 60 fs
Cell Length: 1 cm
100% He or He-N_2
$n_e \approx 6\times10^{18}$ cm^{-3}

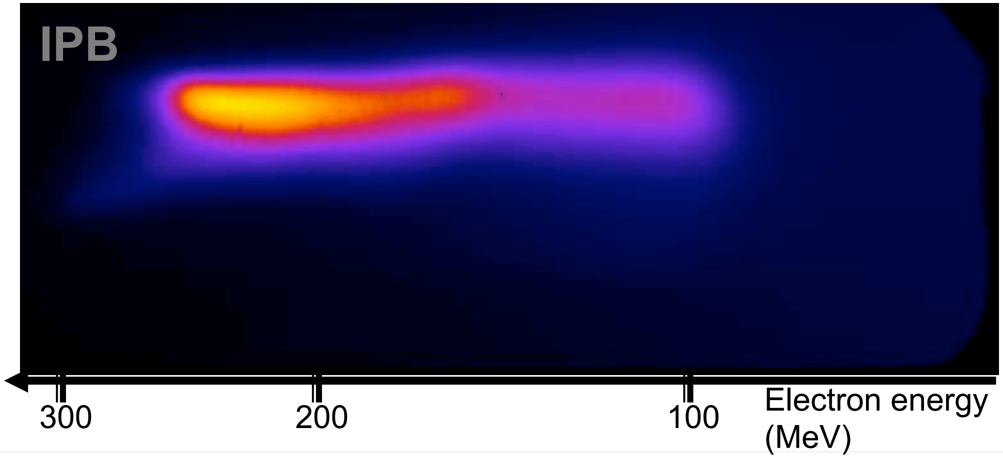


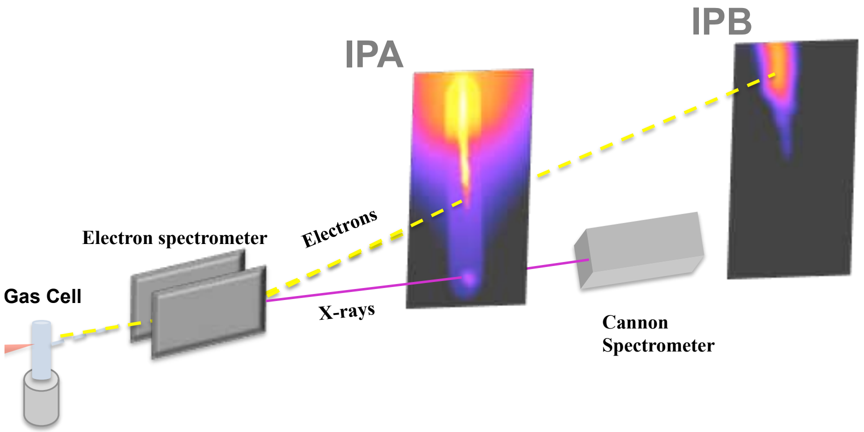
This platform can be implemented on many laser systems

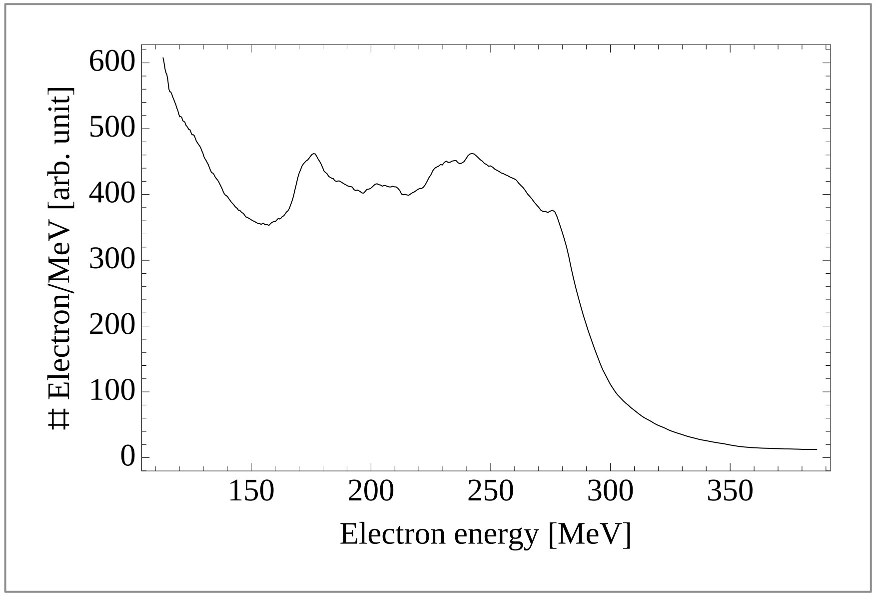
F. Albert, B.B. Pollock et al, Phys. Rev. Lett., 111, 235004 (2013).

Electron spectrum measured with two-screen spectrometer

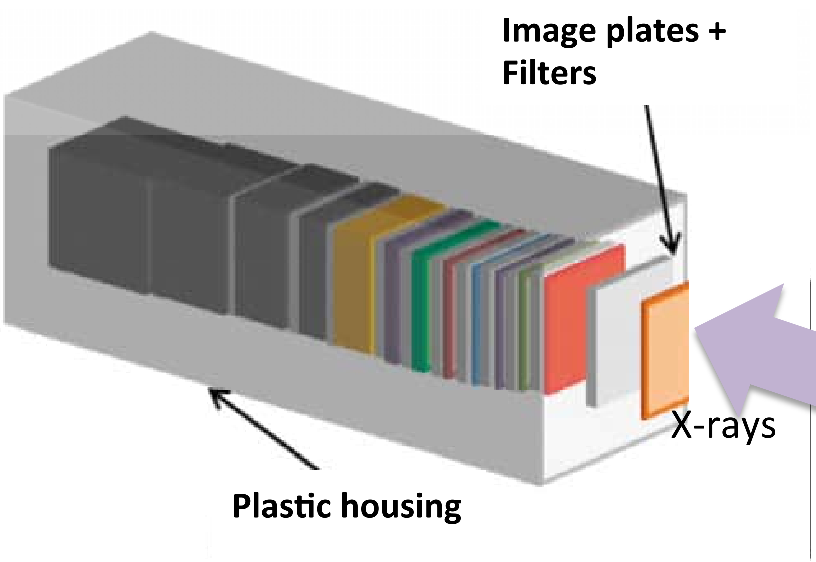


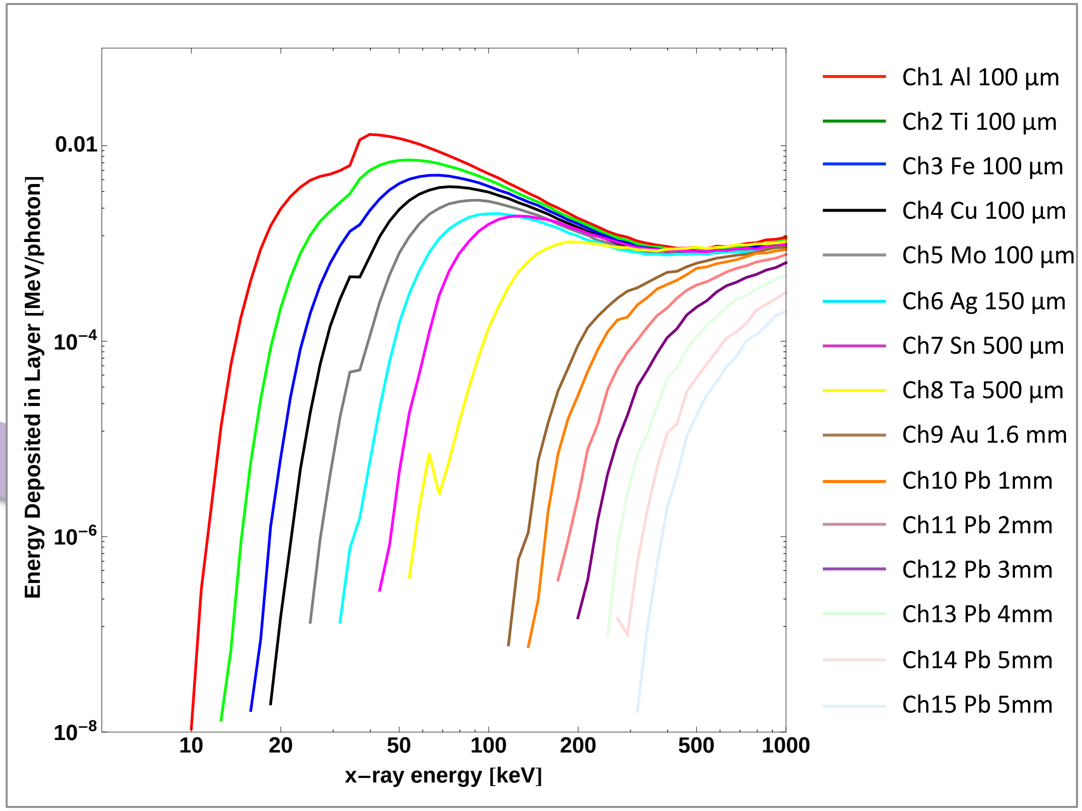






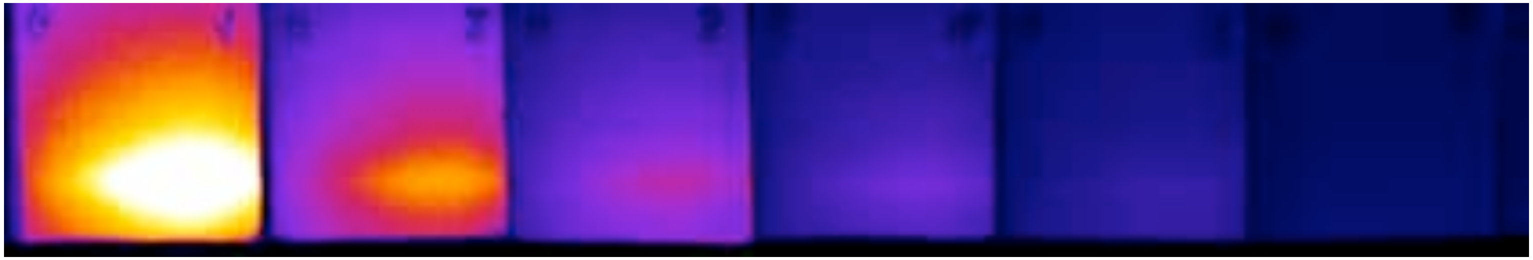
Stacked image plates spectrometer to measure spectral and spatial information on betatron beam



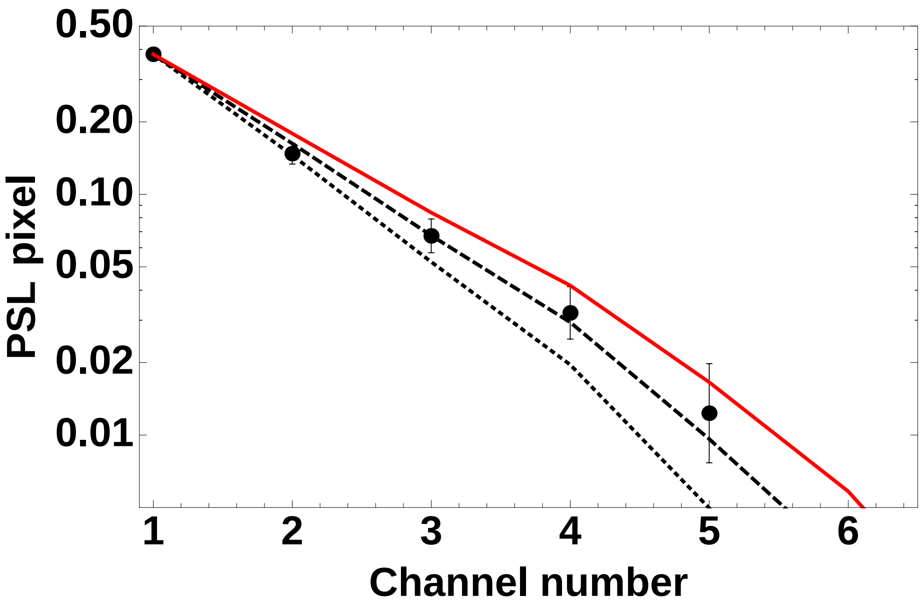


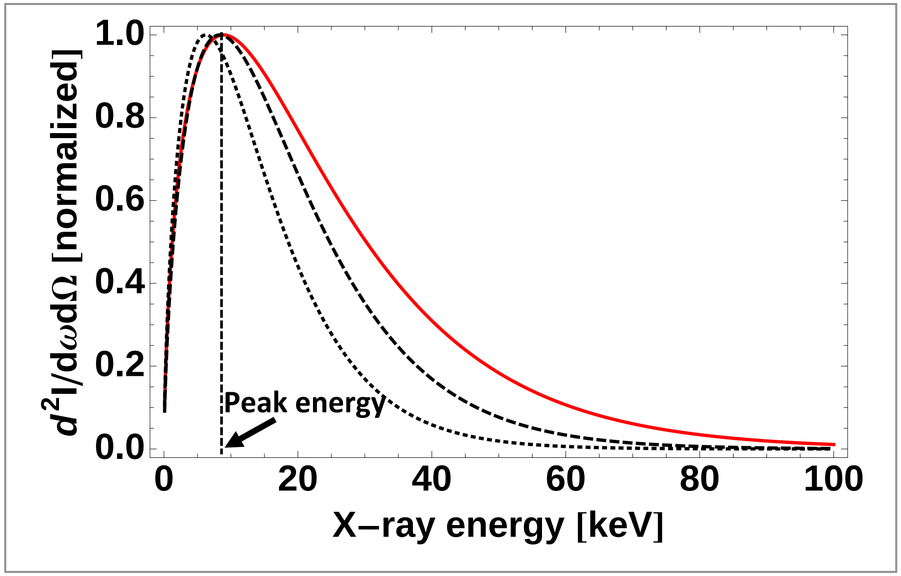
C.D. Chen et al, Rev. Sci. Instrum. 79, 10E305 (2008).
F. Albert et. al, Plasma Phys. Control. Fusion 56 084016 (2014).

Betatron on-axis spectrum measurement

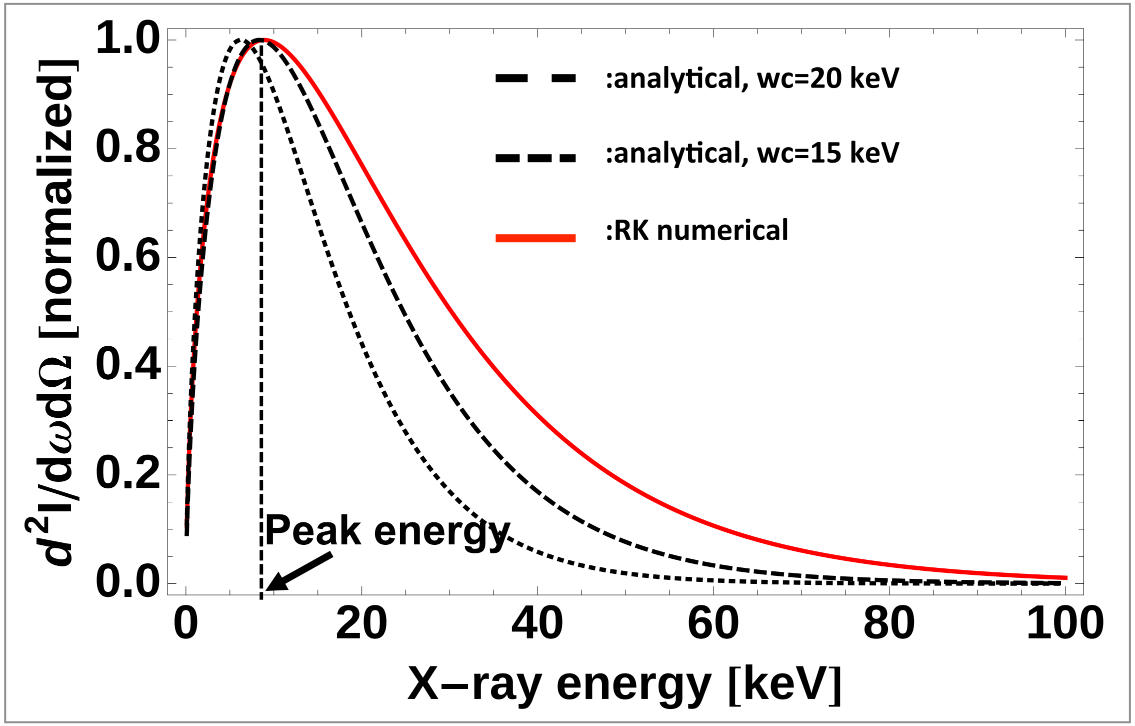


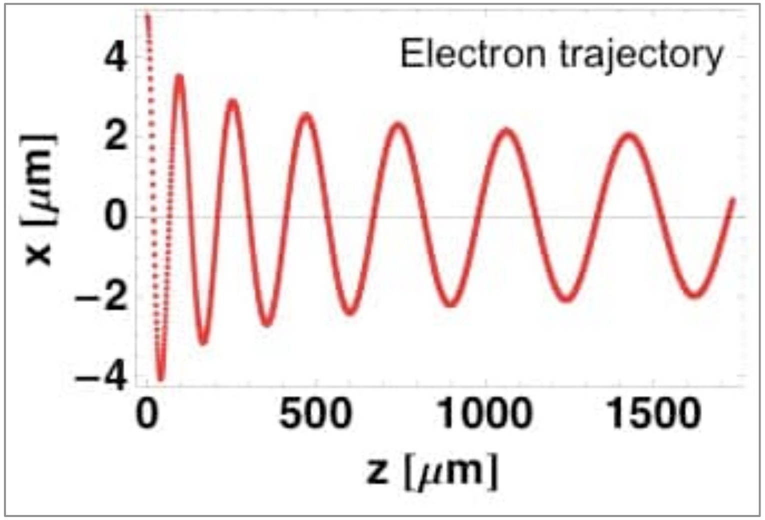
10 mm cell
n_e=6x10^{18} cm^{-3}
100 % He
E= 5.3 J
a_0= 2.33





Injection amplitude retrieved from the betatron spectrum





Analytical

$$\frac{dI}{d\omega d\Omega} \sim \frac{\omega}{\omega_c}^2 K_{2/3}{}^2\left(\frac{\omega}{\omega_c}\right)$$

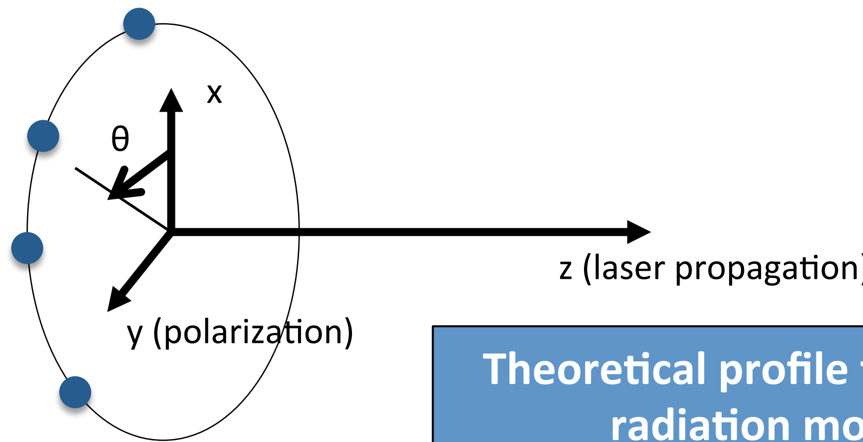
Numerical

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

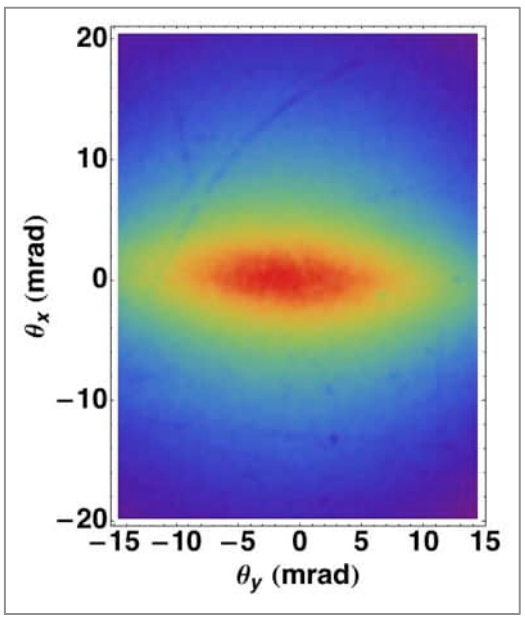
This spectral analysis provides information about betatron oscillation amplitudes without any spatial information

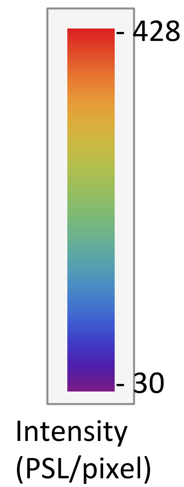
We use the beam profile to retrieve the spatial orientation of the oscillations

Electrons injected around the axis
r0=5 µm, π/30 steps

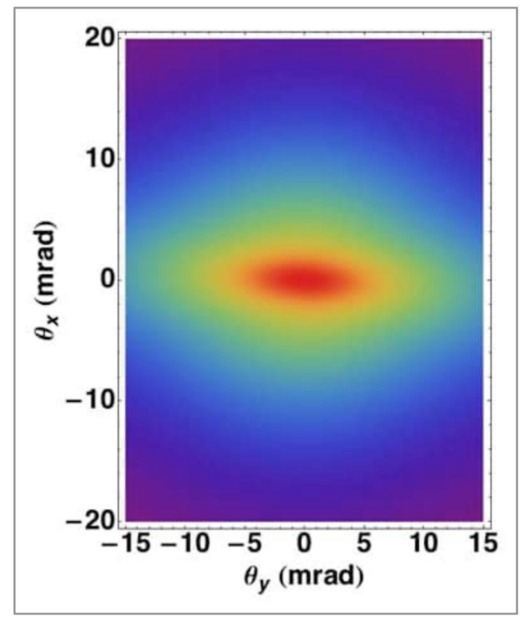


Experimental profile

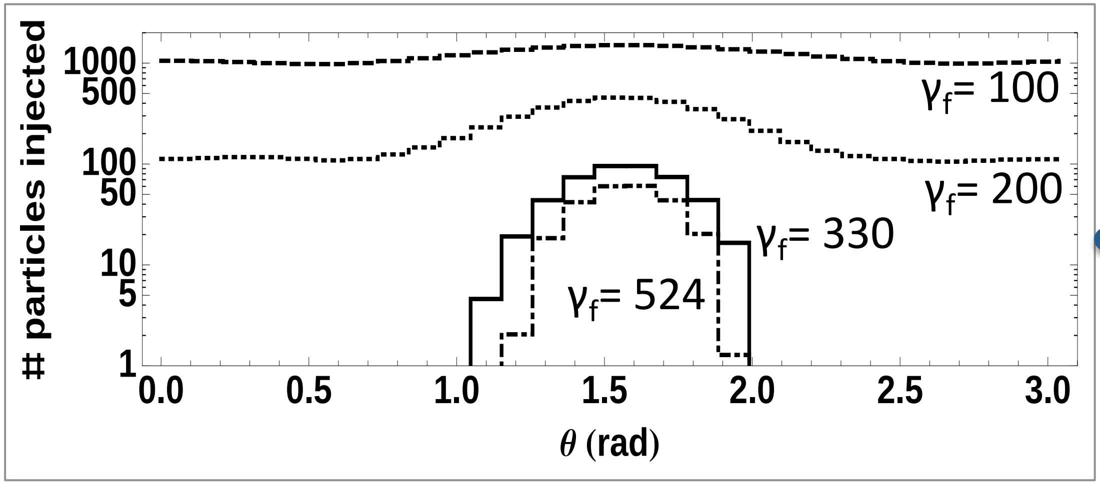


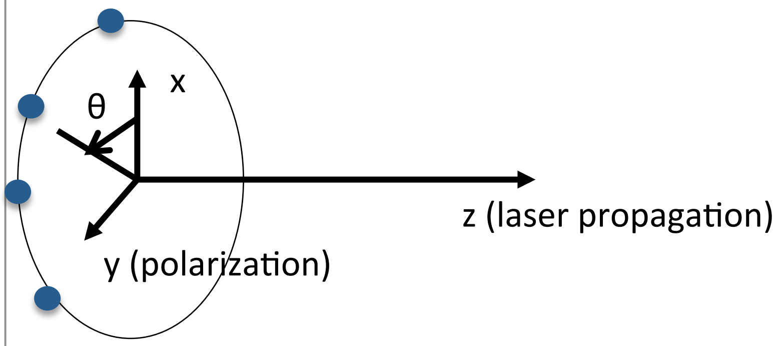


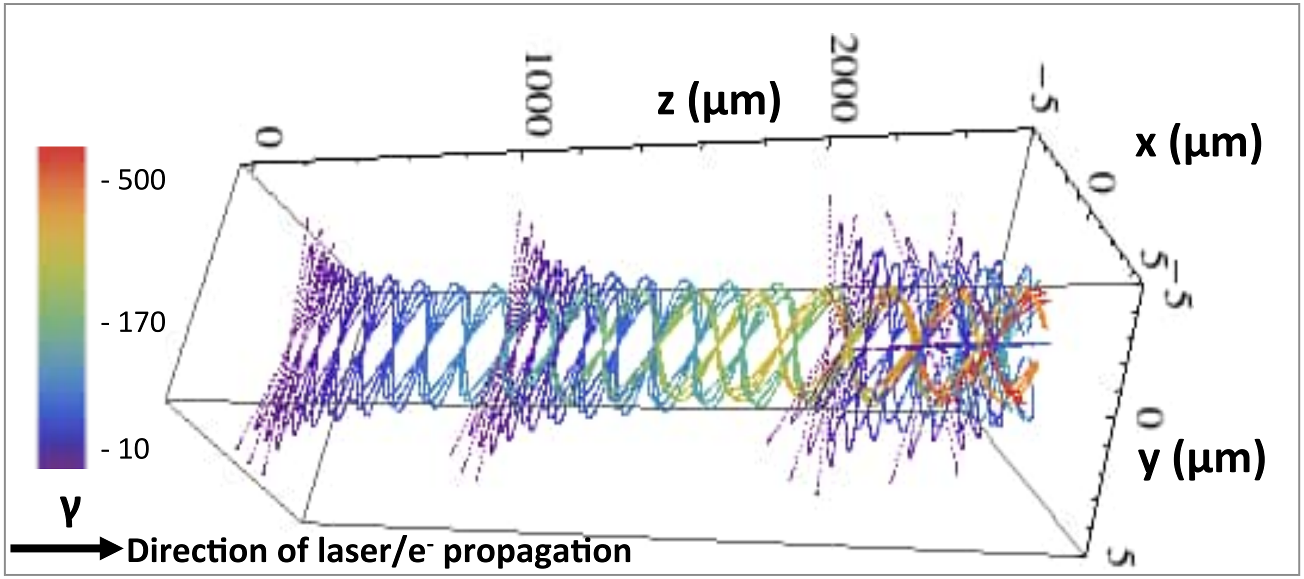
Theoretical profile from RK + radiation model



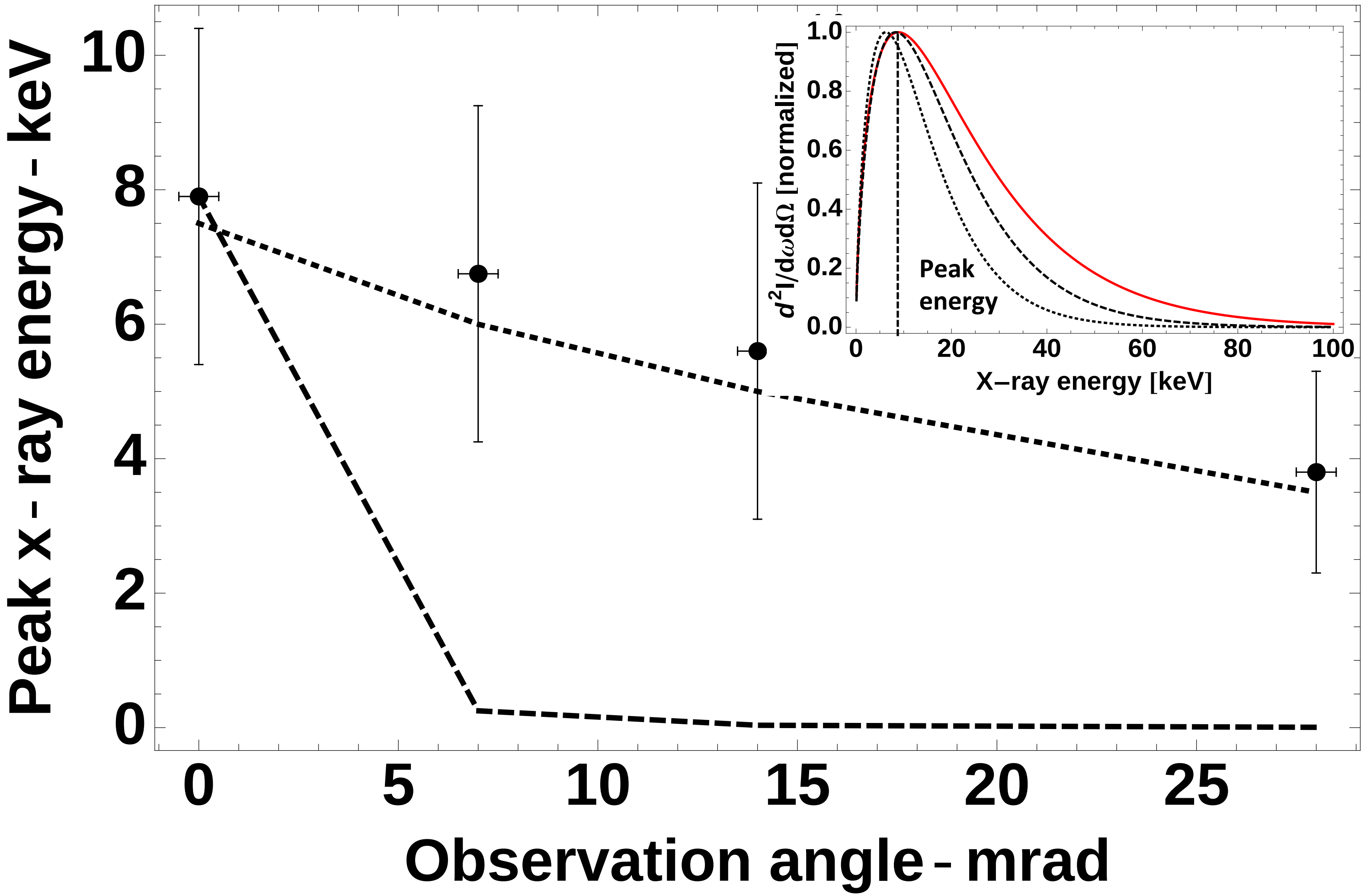
This spectral and spatial analysis provides a tomographic reconstruction of electron trajectories



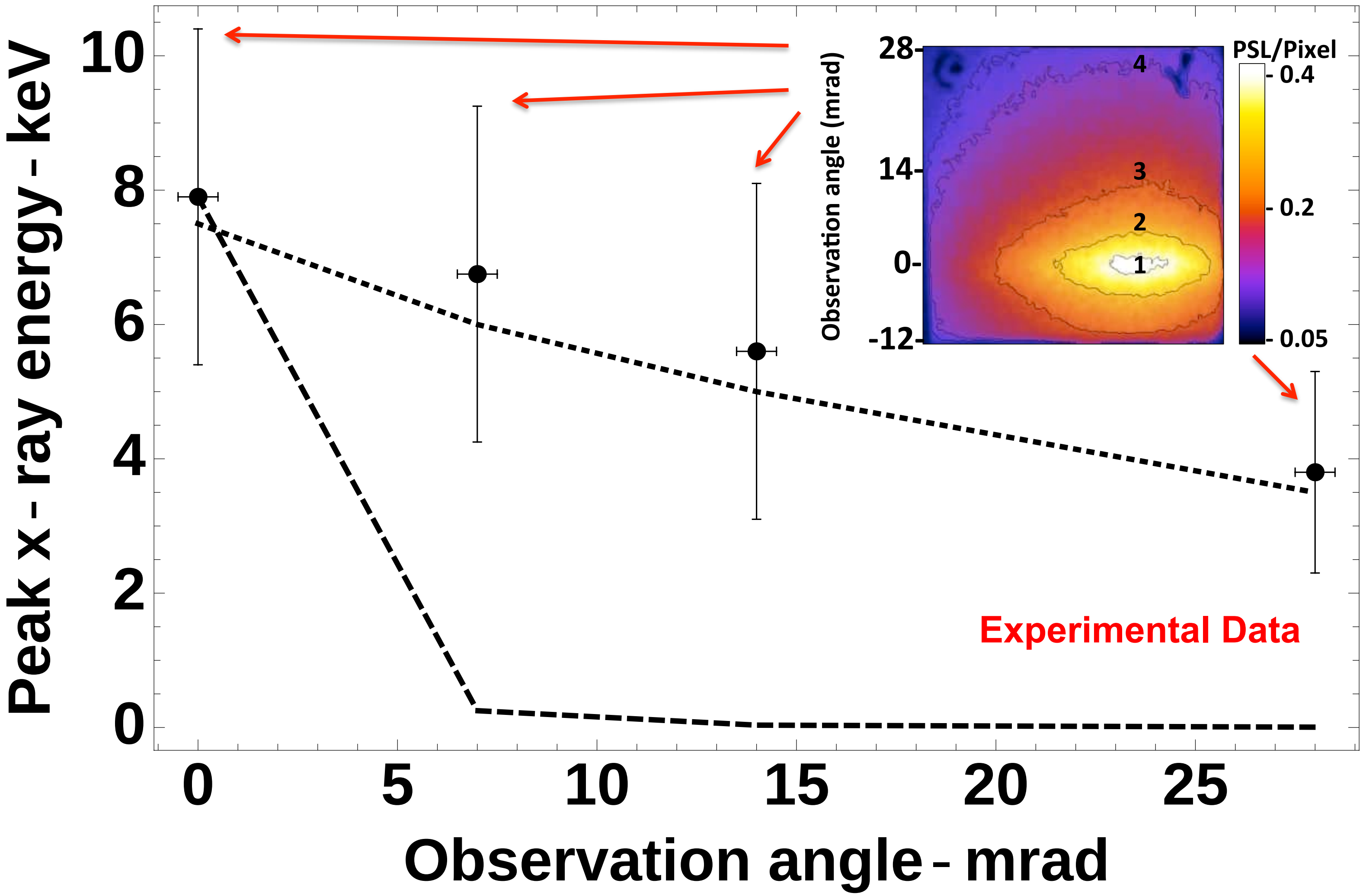




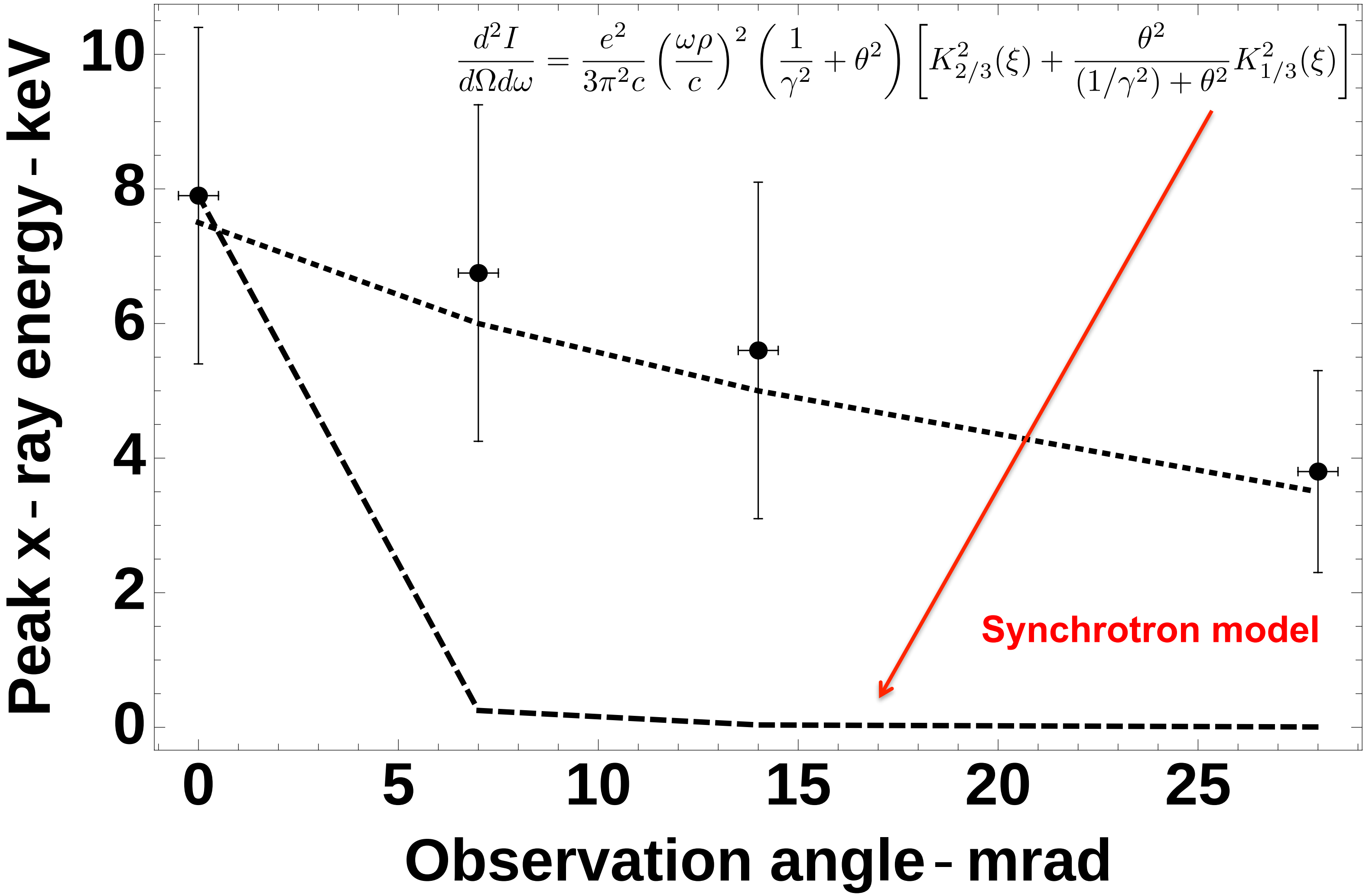
Angular dependence of betatron spectrum



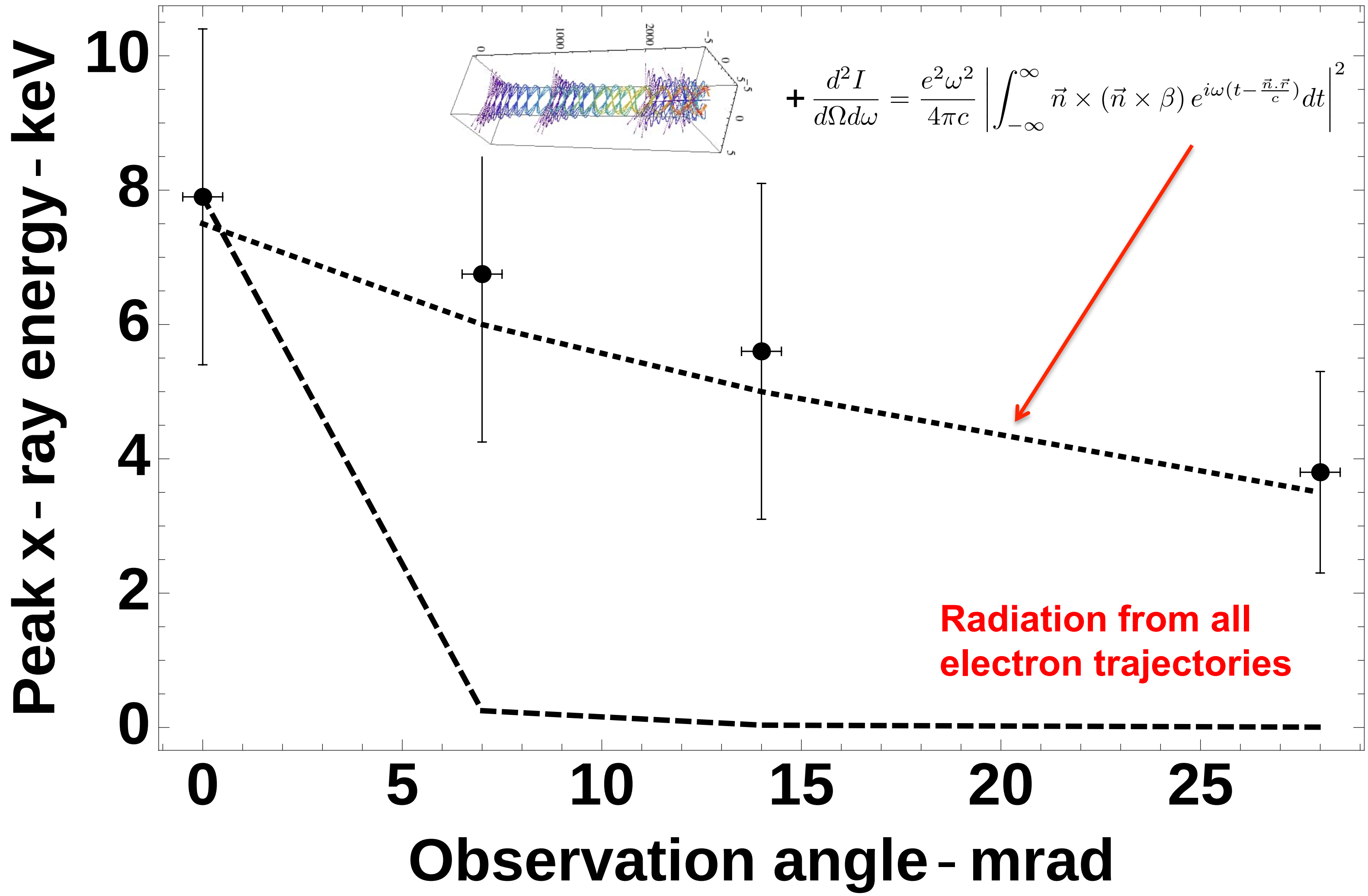
Angular dependence of betatron spectrum



Angular dependence of betatron spectrum



Angular dependence of betatron spectrum

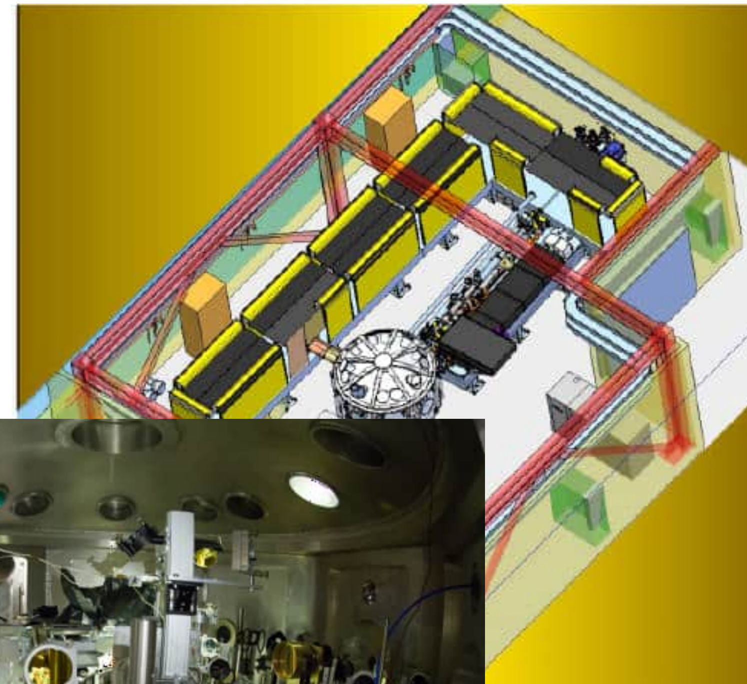


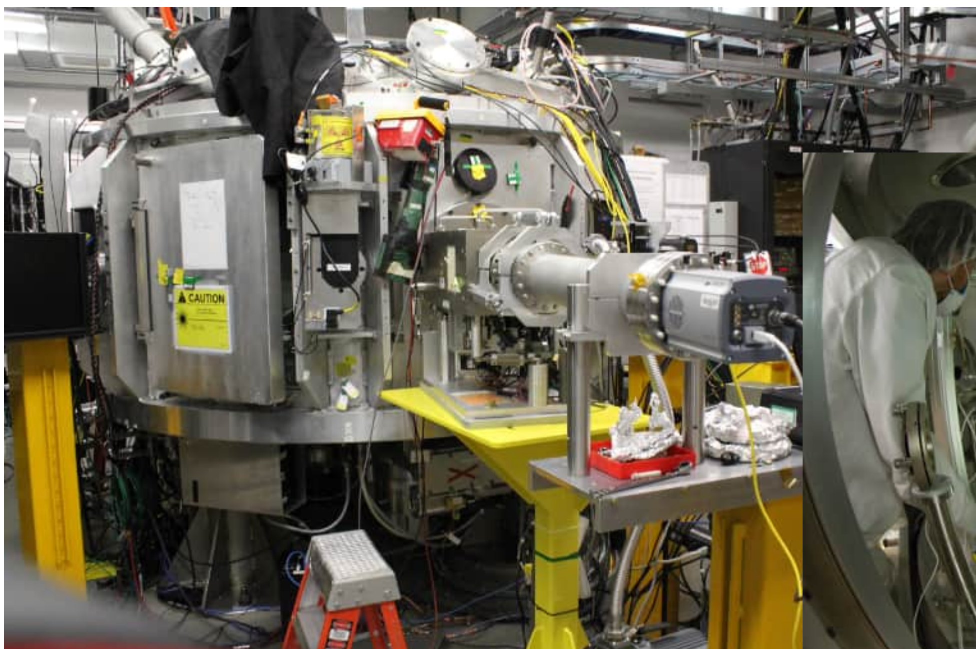
Development of a betatron radiation source at LCLS

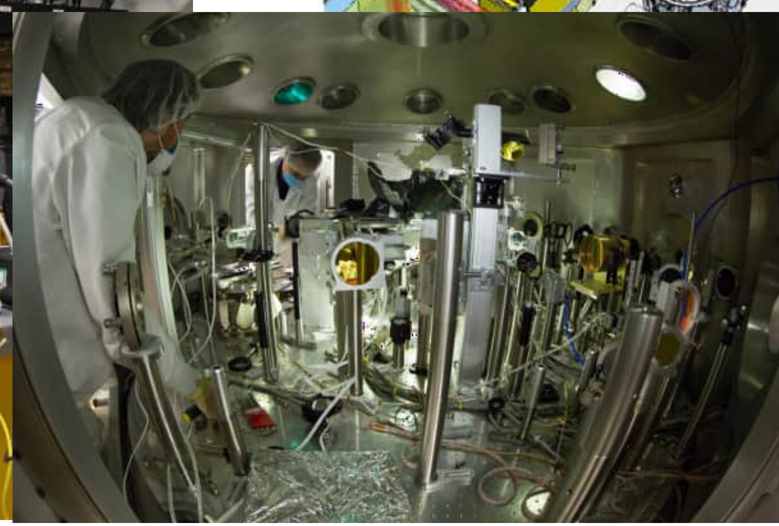
MATTER IN EXTREME CONDITIONS (MEC)

LCLS

- Colocation of three laser systems
  - XFEL (8 keV, 70 fs, 3 mJ)
  - ns optical laser (20 J, ns)
  - fs optical laser (1 J, 40 fs)

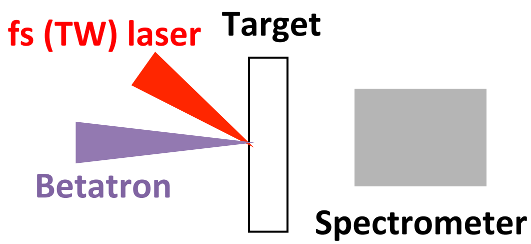


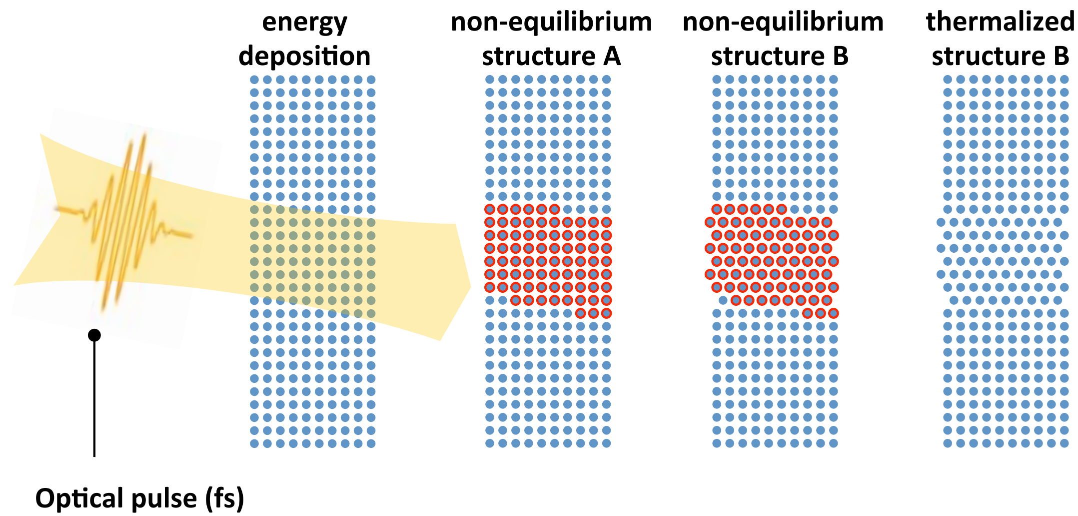




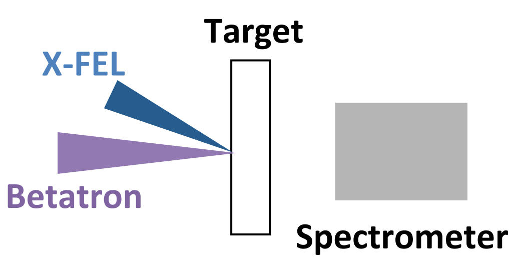
Physical mechanisms studied with betatron radiation at LCLS

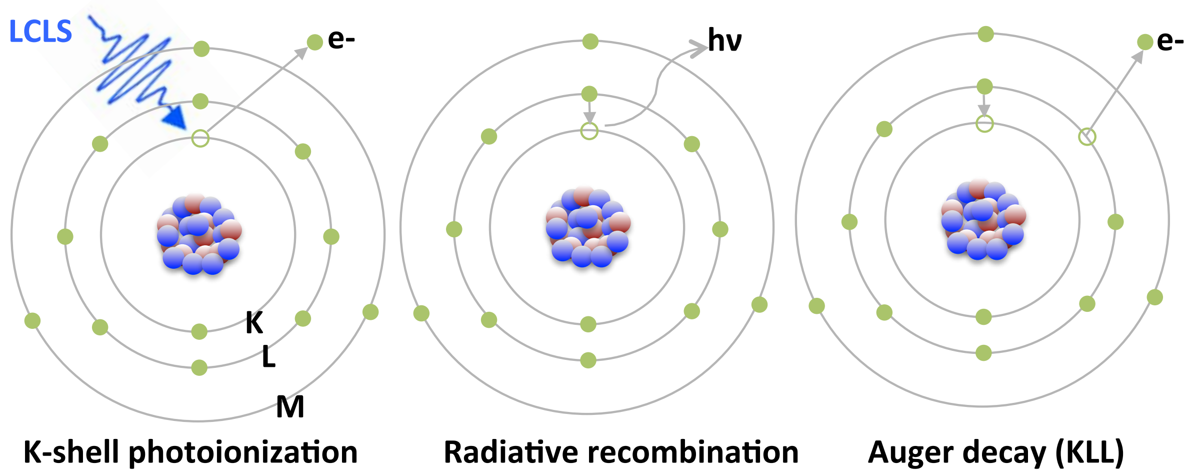
1 SiO2 heated by optical laser





2 Fe heated by X-ray FEL





Collaborators

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