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Transverse Profiling of an Intense FEL X-Ray Beam Using a Probe Electron Beam

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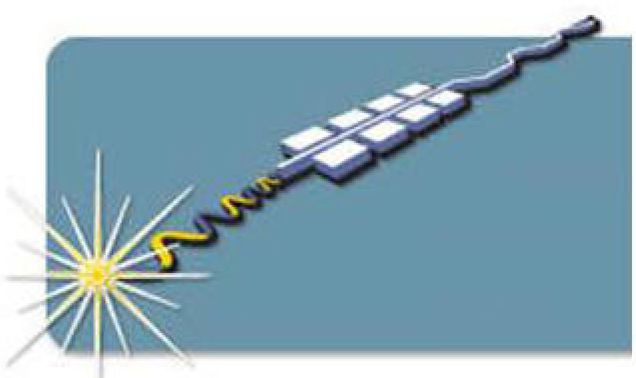
Diagnostics Requirements for Intense X-ray FEL Beams

The pulse to pulse energy output of an FEL is:

- A critical experiment parameter for the X-ray users
- It varies greatly shot to shot because of the stochastic nature of *SASE* FELs
- It depends on the electron drive beam charge, emittance, bunch length, peak current, energy, energy spread …
- And is the bottom line tuning parameter for optimization of the accelerator

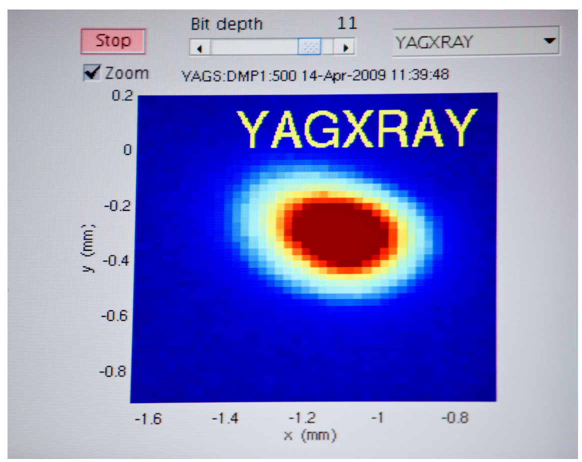
The transverse profile of the X-rays determines the source properties for all X-ray imaging experiments.



Difficulties in Diagnosing Intense X-ray FEL Beams

Insertable fluorescent YAG screen:

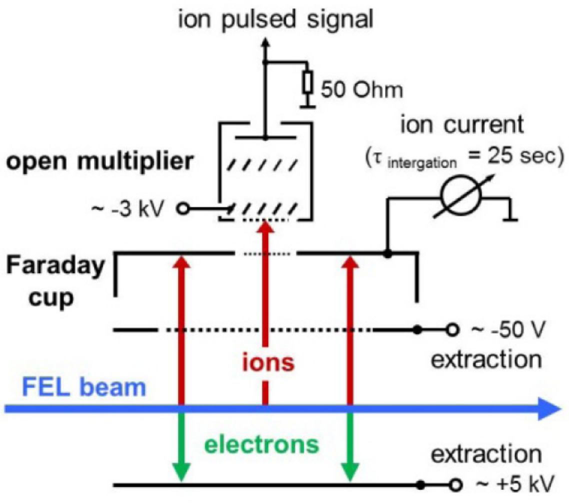
- Single shot measurement of transverse profile and intensity
- Invasive
- Limited in repetition rate by readout rate of camera
- Limited in single shot intensity by screen damage



Difficulties in Diagnosing Intense X-ray FEL Beams

Gas cell monitor:

- Single shot measurement of intensity
- Non-Invasive
- But no beam size measurement
- Limited in repetition rate by ionization build up in the gas
  - Not suitable for 1 MHz pulse repetition rate at LCLS-II
  - Transients at the start of pulse trains

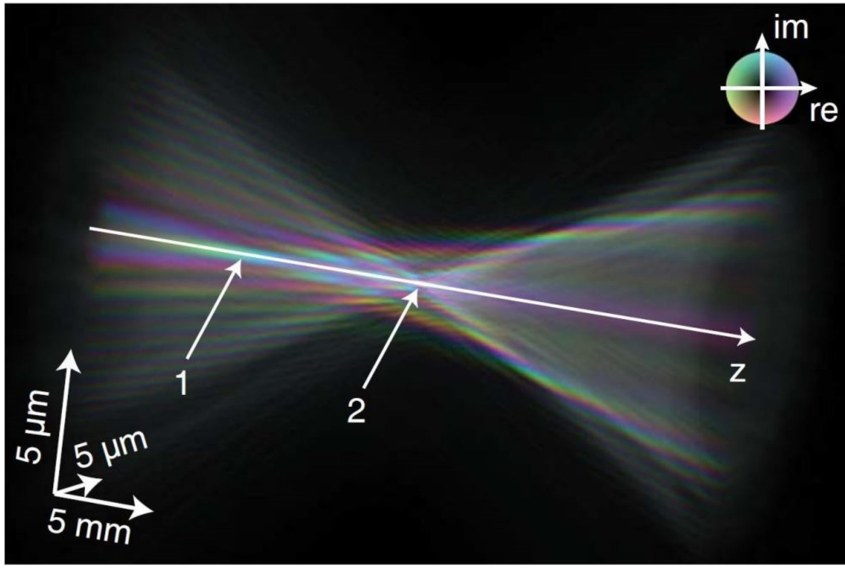


K. Tiedtke et al "Absolute pulse energy measurements of soft x-rays at the Linac Coherent Light Source," Opt. Express **22,** 21214-21226 (2014);

An Ideal FEL X-ray Diagnostic?

Should be:

- Single shot measurement of intensity
- Measure transverse profile
- Non-invasive
- Not susceptible to damage
- Not limited in repetition rate
- Not limited in intensity
- Also suitable for focused beams

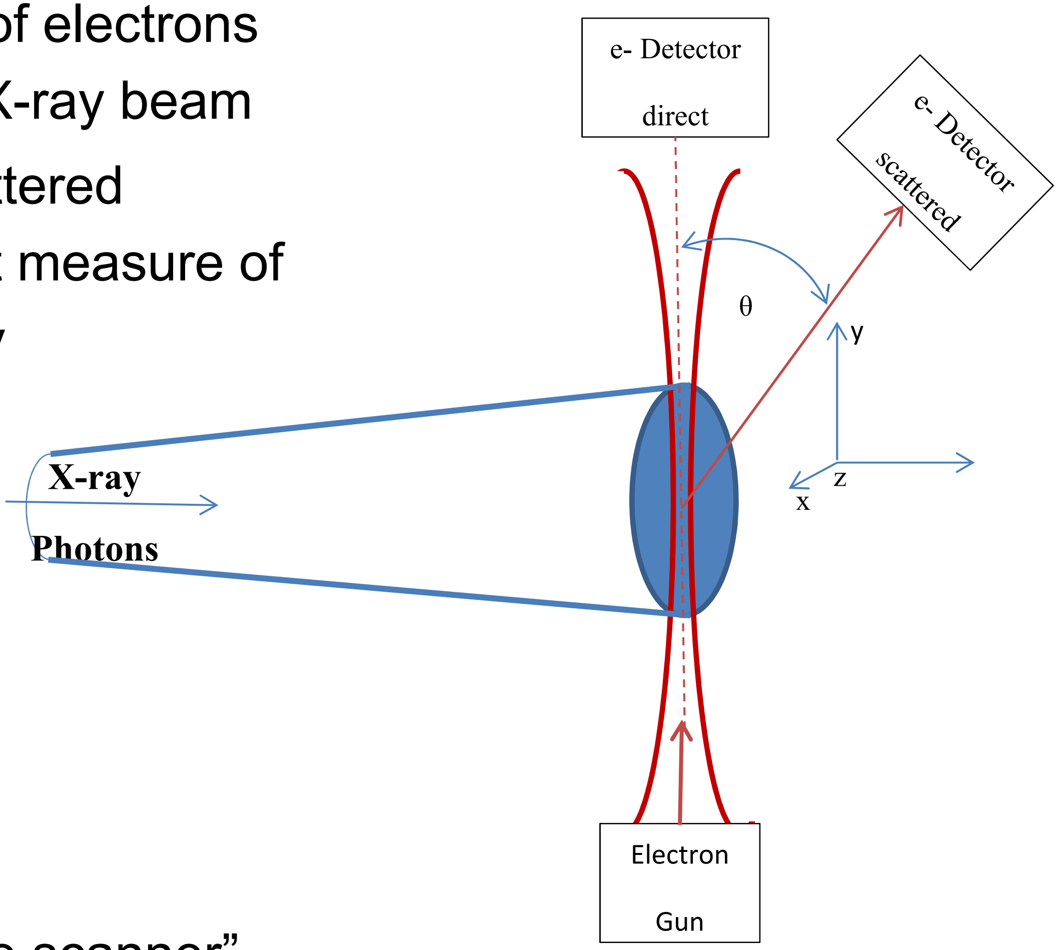


Wave field of a focused X-ray pulse at SLAC's LCLS, with colors indicating the phase of X-ray waves and amplitude encoded by brightness. (Credit: Andreas Schropp, Nature Scientific Reports)

An Electron Probe Beam to Measure the X-rays

A finely focused beam of electrons is scanned across the X-ray beam

- The number of scattered electrons is a direct measure of the photon intensity



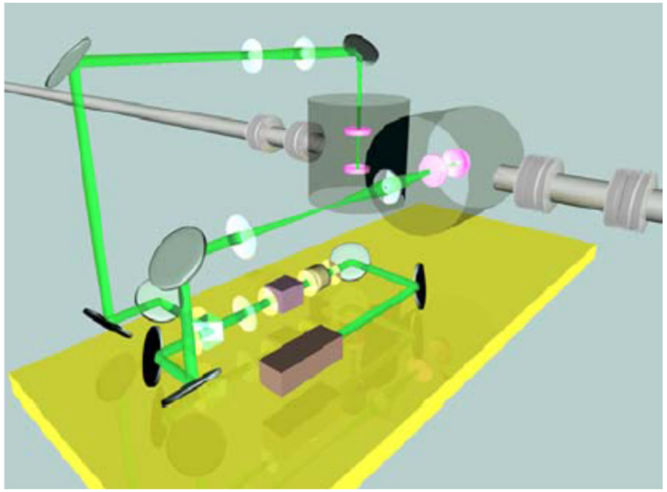
- A “free electron wire scanner”

Think of it as the converse to a laser-wire

Rather than probe a high energy electron beam with a laser,

we probe the X-ray laser beam with a low energy electron beam.

- But instead of detecting the downstream Compton scattered photons, it is more practical to detect the scattered electrons

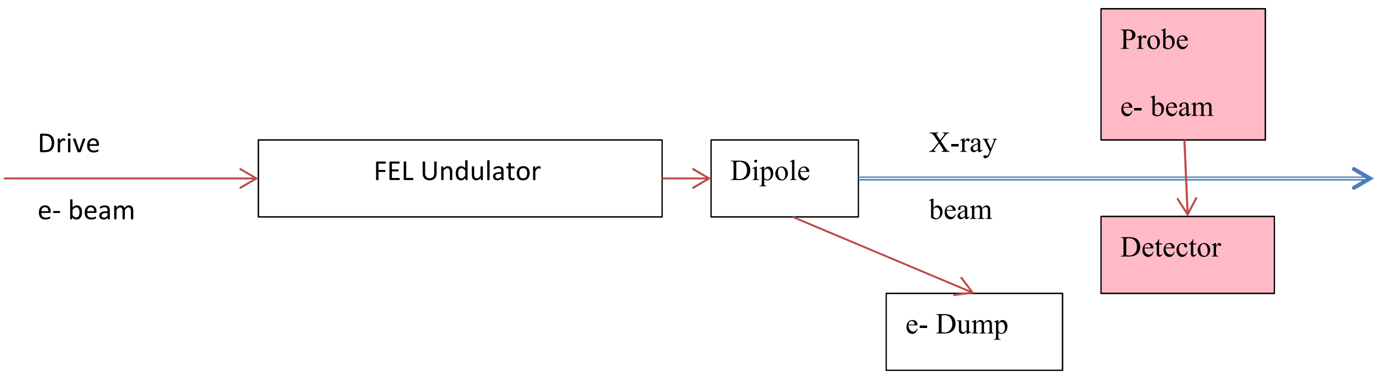


ATF laser-wire system

An Electron Probe Beam to Measure the X-rays

Located downstream of the undulator and electron dump

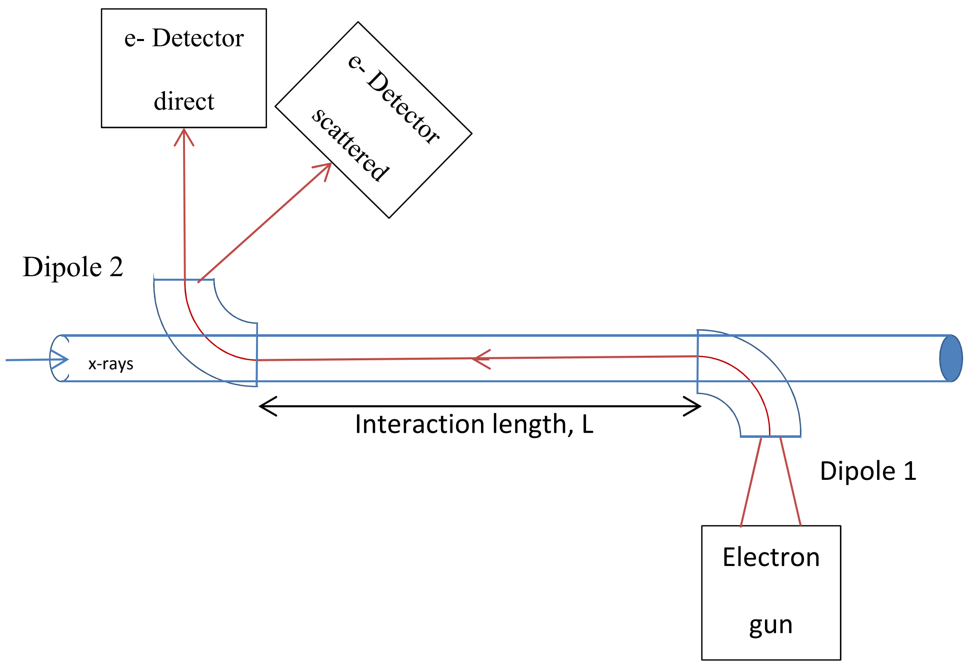
- The problem is that the photon pulse is very short duration, so the electron beam current density must be high to get sufficient interaction



Backscatter geometry

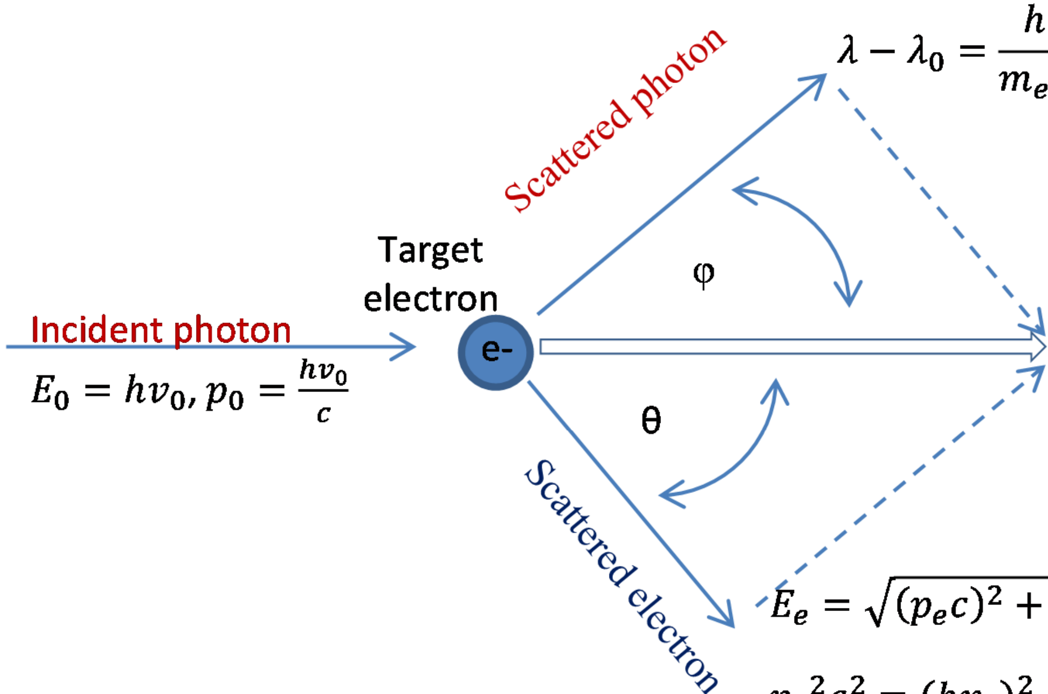
Probe electron beam geometry backscattered from the x-ray photons over an interaction length, L.

- Electrons that lose energy due to scattering can be measured in this spectrometer arrangement.



Electron-Photon Interaction

Compton scattering geometry



$$\lambda - \lambda_0 = \frac{h}{m_e c}(1 - \cos\phi) = \lambda_C(1 - \cos\phi)$$

$$E_0 = h\nu_0, p_0 = \frac{h\nu_0}{c}$$

$$E_e = \sqrt{(p_e c)^2 + (m_e c^2)^2}$$

$$p_e{}^2 c^2 = (h\nu_0)^2 + (h\nu)^2 - 2(h\nu_0)(h\nu)\cos\phi$$

Electron-Photon Cross-section

At low energies the cross section is energy independent

and is given by the Thompson cross section

$$\sigma_0 = \frac{8\pi}{3}\left(\frac{\alpha\lambda_C}{2\pi}\right)^2 \approx 66.5\ (fm)^2$$

The number of scattering events, N_γ, is

$$N_\gamma = N_b \frac{P_L \sigma_C \lambda}{c^2 h} \frac{1}{\sqrt{2\pi}\sigma_s}$$

where N_b is the number of electrons in the bunch
(or overlapping in time with the photon pulse)
σ_s is the beam overlap area.

The First Experiment

- Use a backscatter geometry with complete overlap of the two beams
- The number of scattered electrons is therefore a direct measure of the photon intensity
- Simple setup without the need to focus the electrons to a small spot, or scan the electrons across the beam.
- Compare the measurement with gas cell monitor on a low repetition rate machine like LCLS-I

Alternative schemes

Q: why not use an ion beam instead of electrons?

A: X-ray photons interact only with the electrons in an ion, so it is more a question of how to get the most electrons into the path of the x-ray beam.

- and it is easier to generate high electron beam current densities than ion

Typical parameters for an experiment at LCLS

The number of scattering events recorded per LCLS pulse

is $N_\gamma = N_b \frac{P_L \sigma_C \lambda}{c^2 h} \frac{1}{\sqrt{2\pi}\sigma_s}$

Where $P_L = 100\ GW, \sigma_C$ =66.5 (fm)^2 , $\lambda = 0.1$ nm, $\sigma_s = 1$ mm

Then, for 1 keV electrons, obtain

~ 50,000 scattering events

per meter interaction length per ampere of electrons

Conclusion

- A rich parameter space can be explored for measurement configurations
- The yield of scattered electrons can be increased by
  - Increasing the interaction length
  - Lowering the energy of the electrons
  - Increasing the peak current of the electrons

Thank you!