TRANSVERSE PROFILING OF AN INTENSE FEL X-RAY BEAM USING A PROBE ELECTRON BEAM*

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Abstract

Monitoring the pulse by pulse output intensity and profile of an FEL is a critical measurement both for users and for optimizing the accelerator drive beam. The diagnostic challenge is to find a technique that is not susceptible to damage at high output power, is noninvasive and can be performed at high repetition rates. Fluorescent screens are invasive, susceptible to damage and limited in repetition rate by the camera readout. Gas cell monitors are noninvasive but only yield intensity information and suffer from residual ionization at high repetition rates. The technique described here uses the scattering of a beam of low-energy electrons as they are scanned across the photon beam to measure the transverse intensity profile of the photon beam. Two different geometries are compared. One is where a finely focused electron beam is scanned transversely across the photon beam to measure the transverse profile. The second is where the electrons are bent onto the axis of the photon beam and are scattered by the counter propagating beam of photons. Here the electron beam is kept larger in diameter than the photon beam so that the photon pulse intensity can be measured by the scattering.

INTRODUCTION

The pulse by pulse photon energy output of an FEL is a vital parameter for both the experiment users of the photon beam and the operators tuning the electron drive beam to optimize the FEL performance. The energy output varies greatly shot to shot because of the stochastic nature of SASE FELs and experimenters need that information for each shot. The photon output energy depends on many parameters of the electron drive beam such as charge, emittance, bunch length, peak current, energy, energy spread and so on. The pulse energy is therefore the bottom line tuning parameter for optimization of the accelerator. The value is displayed prominently in the LCLS control room on a scrolling display to give an immediate indication of the overall machine performance.

Measurement of the photon beam size is also important in any photon experiment involving focusing of the beam so that knowledge of beam size, beam divergence and the virtual source position can be used to set up the x-ray optics.

The LCLS relies on two main measurement techniques to measure size and intensity. The first is an invasive technique where a fluorescent YAG screen is inserted in the photon beam and the image recorded by a camera[1]. Beam cannot be delivered to user experiments during this measurement process. The size and position of the beam can be measured on the screen with good precision to a few microns. The camera intensity also gives a good measure of the intensity of the x-ray beam at intensities below saturation of the YAG screen.

At high intensities the YAG output saturates, and this is readily observed if the screen is used with small or focused spots. At still higher intensities the YAG screen becomes permanently damaged with reduced light output, and at very high intensities the YAG crystal does not survive a single shot.

Although it can be regarded as a single shot measurement, the repetition rate is limited by the camera read out speed and would not keep up with the high repetition rate of superconducting machines like LCLS-II.

The intensity measurement of the YAG screen needs to be calibrated against an absolute measurement of the x-ray intensity such as with the gas cell monitor.

The gas monitor at LCLS is a low pressure gas cell separated from the photon beam line vacuum by differential pumping. The x-ray photons passing down the axis of the cell ionize the gas and the number of ions is counted by sweeping them to them side with a clearing electrode into a detector [2].

In this way the individual pulse energy of the FEL can be monitored continuously and non-invasively during beam delivery to users, making it a valuable diagnostic tool. No information on beam size or position is available though.

A problem arises when we move to the high repetition rate beams of superconducting machines such as LCLS-II. Ions in the gas monitor move relatively slowly and are not fully cleared by the time the next pulse arrives in a 1 MHz bunch train. There are therefore significant transient effects in the detector response at the beginning of the pulse train compared to later in the train when residual ionization builds up. A diagnostic with a faster response suited to LCLS-II parameters is therefore sought.

ELECTRON PROBE DETECTOR

In its simplest form an electron beam is directed across the beam of x-ray photons so that they scatter off each other, as shown in Figure 1. The interaction can be described by the Compton scattering process, but since the energies considered here are quite low it is in the Thompson elastic scattering regime.

Compton scattering measurements have been routinely performed at high energy accelerators, usually with a laser directed at the high energy electron beam in order to measure the transverse profile of the electron beam. A laser is used when the intensity of the electron beam is so

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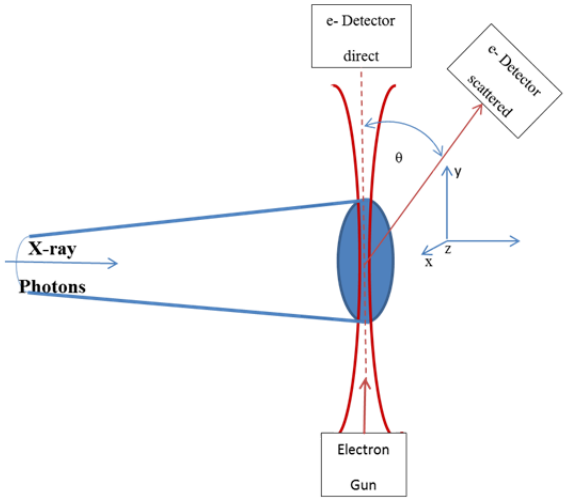

Figure 1: A high intensity x-ray beam from an FEL can be measured with a probe beam of low energy electrons by detecting the scattered electrons.

high that it would destroy a conventional scanning wire used for the beam profiling measurements, or the wire would be too invasive. For this reason such a device is often referred to as a 'laser wire scanner' [3]. In a laser wire scanner the usual procedure is to measure the number of Compton scattered photons. However, in the case of a low energy electron probe beam the electrons impart very little energy to the photons. In this case, detecting the scattered electrons instead becomes a more viable solution.

ELECTRON PHOTON INTERACTION

The Compton scattering process is usually analysed in terms of a photon striking a stationary electron and using conservation of energy and momentum to calculate the energy, as shown in Figure 2.

The incident photon has energy

$$E_0 = h\nu_0$$

and momentum

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

If the electron is assumed to have zero initial momentum

$$p_{e_0} = 0$$

The scattered electron energy is

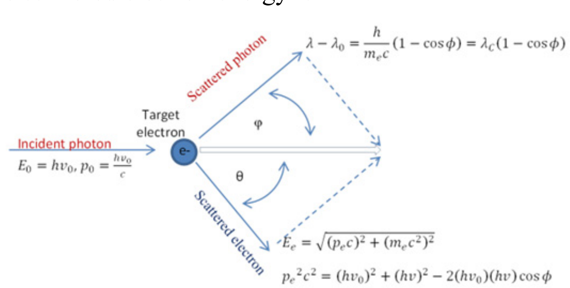

Figure 2: Compton scattering geometry for a photon scattered from a stationary electron.

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

where the magnitude of the scattered electron momentum is

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

and the change in wavelength of the scattered photon is

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

with the $\frac{h}{m_e c}$ term is usually referred to as the Compton wavelength, λ_C.

At low energies the cross section is energy independent and is given by the Thompson cross section

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

where α is the fine structure constant.

At high energies the cross section is modified according to the Klein-Nishina formula[4]

$$\sigma_C = \sigma_0 \frac{3}{4}\left\{\frac{1+\epsilon}{\epsilon^3}\left[\frac{2\epsilon(1+\epsilon)}{1+2\epsilon} - \ln(1+2\epsilon)\right] + \frac{1}{2\epsilon}\ln(1+2\epsilon) - \frac{1+3\epsilon}{(1+2\epsilon)^2}\right\}$$

where $\epsilon = \gamma\frac{\omega_0}{m_e}$ is the normalized energy of the laser photons in the electron rest frame and γ is the Lorentz factor associated with the incident electron beam energy.

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.

P_L is the FEL laser power output at wavelength λ.

Some typical photon parameters for LCLS are:

P_L = 100 GW

σ_C = 66.5 (fm)^2

λ = 0.1 nm

σ_s = 1 mm

For the electron beam, the number of electrons is related to the velocity, βc, of the electrons (and hence their energy) and to the electron beam current, I. Over an interaction length, L, the number of electrons is

$$N_b = \frac{L}{\beta c}\frac{I}{q_e}$$

As an example, for a 1 keV electron beam there are:

N_γ = 5.14x10^4 scattering events per ampere per meter of interaction length.

For the transverse scattering geometry shown in Figure 1with a photon beam diameter of 1 mm we obtain

N_γ = 5.14x10^2 total scattering events per ampere.

If, after various detector efficiencies are taken into consideration, we find that this number is too low, we can also consider alternative scattering geometries.

BACKSCATTER GEOMETRY

The electron beam in this case is bent onto the axis of the photon beam with a dipole magnet, as shown in Figure 3. The electrons counter propagate against the photon beam over a length, L, before being bent out of the way by a second dipole which directs the electrons towards a detector. The interaction length between the

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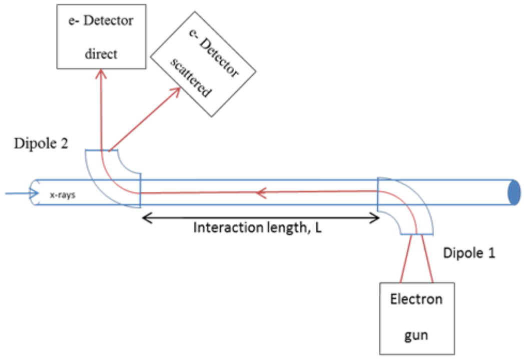

Figure 3: Back scatter geometry where the probe electron beam counter propagates over a length L against the x-ray beam.

dipoles can be chosen to ensure that sufficient scattering events occur to give a reliable signal. One detector measures the straight ahead unscattered component of the electron beam, and a second detector is placed at an angle to intercept lower energy electrons that have been scattered by the x-rays. The normalized scattered intensity can be determined by taking the ratio of these two detectors.

Measurement of the scattered fraction by detection in the energy spectrometer arrangement shown is not the only option. Some electrons are also scattered transversely and can be detected by annular detectors around the photon beam pipe. The x-ray photons are also scattered and although the bulk are forward directed some fraction is also scattered at an angle to the beam pipe and Compton shifted in wavelength.

Another possible geometry is to have the electrons and photons propagate in the same direction over a distance, L, as before. The electrons will gain energy in this geometry and be predominantly scattered in the forward direction.

IONS VERSUS ELECTRONS

It is worth considering whether other particles would have a higher cross section for interaction with the x-rays than the electron beams considered here. The gas monitor used at the LCLS relies on the detection of ions, so why not, for example, use an ion beam to interact with the photons. Since the photons always interact with the electrons, regardless of whether they are bound to an ion or are free electrons, the cross section of the interaction is the same. So the question becomes which technology allows the highest density of electrons to be delivered to the beam. Electron guns are by far the most efficient in this respect. However, ions travel much slower so that for a given energy and current the number of interactions over a length L is higher.

The electron gun design involves several trade-offs. High current operation requires pulsed operation, rather than dc operation, in order to keep the average power low. Although the electron density increases as the electron energy is lowered (increasing the number of scattering events) care must be taken in avoiding space charge effects that would limit the transverse size of the electron beam at very low energies.

Yet another approach would be to use a high brightness RF gun and use pulse compression techniques to achieve high peak electron currents.

SUMMARY

The electron probe technique permits single shot measurement of the x-ray intensity. At favorable electron-photon intensities it is also possible to scan the beam and measure the transverse profile. The technique is non-invasive and can be used while delivering beam to users. Since the electrons are “replenished” on each shot the technique is neither susceptible to damage nor limited in repetition rate. Since the technique is not limited by intensity it is also suitable for focused x-ray beams.

A rich parameter space exists that can be optimized for different measurement configurations. The challenge is to ensure that a sufficient number of scattering events can be recorded for each measurement. In general, 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

REFERENCES

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

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

[3] H. Sakai et al., “Measurement of a small vertical emittance with a laser wire beam profile monitor”, PRSTAB, Vol 5, 122801 (2002).

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

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