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ABSTRACT

The specifications of presently proposed x-ray free electron lasers (FELs) are for machines that will provide x-ray pulses as short as 100 fs with a photon energy as high as 12.3 keV. Since the pulse will contain as much as 5 mJ of energy, these devices will present the experimenter with an opportunity to expose matter to an unprecedented x-ray energy density. This high concentration of energetic x-rays presents both a promising frontier in energy-matter interaction, as well as a technological crevasse to be crossed by the experimenter attempting to use the FEL beam. We shall look at three possible problems confronting the experimenter: (1) synchronization of a detector, laser pulse, etc., to the FEL pulse; (2) radiation damage to the target sample; and (3) the presence of an electromagnetic pulse that could damage sensitive electronics located in the experimental area.

Keywords: x-ray, FEL, synchronization, radiation damage, electromagnetic pulse

1. INTRODUCTION

The advent of various x-ray FEL fourth-generation light source facilities that are proposed around the world will introduce a new arena for the study of energy-matter interaction. While the workhorse laser systems of today can deliver onto a target sample a focal intensity exceeding 10^{19} W/cm², the laser beam from these systems cannot penetrate into the depth of the sample material as freely as an x-ray beam will be able to do. Not only will new avenues for studying the bulk properties of matter become available, but the x-ray FEL will be a unique tool for studying the basic atomic physics of inner-shell electrons. When the x-ray FEL beam is focused to the diffraction limit, the electric field of the laser pulse will be many times the atomic field strength ($e/4\pi\epsilon_0 a_0^2 = 5.14 \times 10^{11}$ V/m corresponding to an intensity of 3.5×10^{16} W/cm²). This high-energy density environment will present new opportunities for the study of the physics of a plasma. The ultrashort pulse of the x-ray beam from the FEL will allow time-resolved studies of various processes at the subpicosecond level.

Each of these areas of study will bring technological challenges for the experimenter, presenting him with various questions. How does one synchronize the x-ray pulse with an external detector or laser pulse? What will be the damage to the target material resulting from the high x-ray intensity? Will the high photon flux or the ultrashort temporal nature of the x-ray pulse present the experimenter with difficulties not normally encountered in the laboratory environment of a synchrotron storage ring? Some suggestions on addressing these questions will be presented in the following discussion. For the examples used below, parameters for the Linac Coherent Light Source (LCLS)¹ to be built at Stanford and for TESLA² to be built at HASYLAB will be used.

2. SYNCHRONIZATION WITH A LASER PULSE

One of the principal features of the x-ray FEL is the short duration (~ 100 to 300 fs) of the intense x-ray pulse. This ultrafast pulse will be useful in time-resolved measurements exploring the dynamics of various phenomenon by using pump-probe techniques. A likely experimental setup would involve an external laser (possibly a Ti:sapphire system with a sub-100 fs pulse) acting as a pump to prepare the sample into some desired state and the x-ray FEL pulse acting as a probe of this state. If the experimental setup handles the prominent problem of how to synchronize these two pulses and introduce a fixed time shift between them, a time resolution approaching the x-ray pulse width will be possible. The uncertainty (or jitter) in the time shift between the two pulses will need to be minimized to less than 100 fs in order to perform time-resolved experiments with a time resolution approaching the time scale of the laser pulses, even for experiments using only a single FEL pulse. The solution to the problem of synchronization with minimum jitter will need to be addressed in the planning stage of the FEL and engineered into the final design of the FEL.

Several different solutions addressing the problem of synchronization, both optical and electronic, have been put forth and described in the Design Study Report for the LCLS.¹ Among these solutions is the optical technique of splitting the x-ray pulse from the FEL into two beams and sending both of them to the experimental area. With built-in delay paths for each of the two x-ray beams, pump-probe experiments could be performed. Additionally, there are electronic techniques for timing the trigger for the FEL relative to the trigger for an external laser. Of these solutions, only the optical solution of splitting the x-ray beam into two beams would result in a minimum jitter in overlapping the two pulses. However, there is still the issue of whether or not the beam splitting optics will survive the intensity of the incident x-ray pulse. Following is the description of another optical technique that will minimize the jitter between the x-ray pulse from the FEL and the pulse from an external laser. In addition this optical technique of generating two synchronous beams removes the need for beam splitting x-ray optics.

The photoinjector of the LCLS x-ray FEL will use a laser pulse from a Ti:sapphire laser system to fire onto the cathode of the photocathode gun. The electrons extracted from the cathode form the charge pulse to be accelerated in the linac and thus produce the x-ray pulse. The typical high-power Ti:sapphire laser³⁻⁴ consists of four sections, an oscillator, a stretcher, an amplifier and a compressor, as illustrated in Figure 1. As indicated in Figure 1, the laser beam for the photoinjector may be split into two beams by using a beam splitter after the stretcher section. One portion of the beam continues to the amplifier and compressor chain for the photoinjector. The remaining portion of the beam is sent to the experimental hall where it forms the seed beam for another amplifier-compressor chain to form a high-power laser pulse to be used in the target area. Since the two laser pulses, the one completing the track through the photoinjector and the one going to the experimental hall, originate from the same optical pulse out of the oscillator, in principle, there is no jitter between them. A delay path is positioned in one or both arms of the split beam path to adjust the relative time shift between the two laser pulses. In this way, either the x-ray pulse from the FEL or the external laser pulse could act as the pump in a suitable experiment. This technique is used in pump-probe experiments using conventional lasers. A difficulty in this method of synchronization for the FEL is immediately evident. The laser beam sent to the experimental area must travel a long distance, perhaps even into another building. In order to use this beam as a seed for another amplifier-compressor chain, the

Figure 1: The laser beam for the photoinjector of the FEL can be divided after the stretcher, with one part being sent to the photocathode gun for operation of the FEL, while the other part is sent to seed an external laser amplifier in the experimental hall. This method of synchronization of the x-ray FEL pulse with the pulse of an external laser minimizes the jitter between the two pulses.

beam quality would need to be preserved by using near-field image relaying optics to transport the beam through a vacuum beam pipe. But the benefit of no jitter between the two laser pulses should outweigh this technical difficulty.

3. DAMAGE TO A TARGET SAMPLE

The x-ray FELs that are currently proposed to come on line in the near future are expected to have pulse widths in the 200 fs (TESLA) to 300 fs (LCLS) range and have an energy content of 2.5 mJ (LCLS) to 13 mJ (TESLA) in each pulse. These facilities would produce pulses covering the spectral range from 1.5 nm to 0.1 nm. The x-ray beams from these facilities will be capable of producing two types of damage in target materials. One type of damage is that associated with the absorption of a high-energy photon resulting in bond breaking, free-electron generation, or the production of free radicals within the sample. This type of damage occurs with linear absorption in which the absorption of energy by the target sample scales with the incident x-ray flux (or energy E). The other type of damage is that associated with the absorption of energy on a short time scale resulting in the formation of a plasma at the sample surface or ablation to the target sample. This type of absorption of energy by the target material scales with the incident intensity ($E/(\text{Area} \times \text{Time})$). Needless to say, if a particular target material is damaged by the x-ray flux from existing storage rings, it will be damaged by the flux from future FELs, only faster and to a greater degree. If the intensity of the laser beam is sufficiently high, nonlinear absorption may occur in which the absorption scales as the power of the intensity (I^n where $n \geq 2$). The intensity level for the onset of nonlinear absorption of x-rays is unknown experimentally and will not be considered here.

Figure 2: The ratio of the attenuation coefficient at its maximum value (typically at 10 to 50 eV) relative to its value at 10 keV is plotted as a function of atomic number. The above ratios allow one to scale the threshold for ablation damage (formation of a plasma) due to absorption of a 10 keV laser pulse from the FEL to the threshold for ablation absorption using current laser systems.

Of particular interest for the question of target sample damage from the incident laser beam, as well as the onset of nonlinear optical phenomenon, is the intensity at which a plasma begins to form at the sample surface. The onset of plasma

formation can be estimated, in an order of magnitude fashion, by scaling the damage threshold results of present-day lasers operating at 1 to 5 eV to the energy level of the x-ray FEL (operating at up to 10 keV). This scaling can be achieved by using the absorption data for the elements and comparing the absorption at 10 keV to that at low energy (from 5 to 10 eV). With a Ti:sapphire or a KrF laser, for example, ablation of the target surface begins to occur at an intensity of about 10^8 to 10^9 W/cm². With conventional lasers, this target damage begins as linear absorption and quickly goes over to multiphoton, or nonlinear, absorption as the pulse width decreases or the laser intensity increases. This process of rapid absorption of the laser energy results from the increase in the free electron density at the surface where plasma is formed. With conventional lasers, several photons may be absorbed to liberate a single electron. However, with the x-ray FEL many electrons will be liberated by absorption of a single photon. Even though the absorption of the x-ray FEL beam is linear in intensity, it may be nonlinear in FEL photon energy since the higher energy photons will yield proportionally more free electrons to increase the plasma density.

The onset of the formation of a plasma by the x-ray FEL can be estimated from the published absorption coefficient data of the elements.⁵ In Figure 2 is plotted the ratio of the maximum absorption coefficient (typically at a photon energy of about 10 eV) to the absorption coefficient at 10 keV (the nominal maximum photon energy of the FEL). Scaling the damage threshold of current lasers according to this curve indicates that the damage threshold for 10 keV photons can be expected to occur at an intensity of 10^{12} to 10^{15} W/cm² for materials containing mainly elements lighter than calcium. For most other materials the damage threshold for 10 keV photons can be expected to occur once an intensity of 10^{11} to 10^{12} W/cm² is reached. Similar comparisons can be made for FEL photon energies less than 10 keV with the result that the damage threshold decreases as the x-ray photon energy decreases.

The unfocused intensity of the FEL beam from the LCLS or TESLA facility will be quite large. Assuming an x-ray beam size of 1 mm, the unfocused beam intensity will be greater than 10^{12} W/cm². Thus all target materials, except for the lightest, will be at risk to damage from absorption of the x-ray FEL beam. The level of damage will increase as the FEL beam is focused to higher intensity.

It is important to remember that the physical damage threshold considered here is not damage due to thermal absorption of the laser energy into the bulk material. Thermal absorption damage scales according to the absorbed energy (E) and usually manifests as melting of the target material. The ablation damage threshold considered above involves the formation of plasma at the target surface and scales as the laser beam intensity (E/(Area x Time)). Thus, while 5 mJ of energy absorbed over a surface area of 1 mm² in 100 ns ($\sim 10^{6-7}$ W/cm²) may not cause physical ablation damage to a sample material, unless it is repeated many times, absorbing the same energy in 100 fs ($\sim 10^{12-13}$ W/cm²) will result in ablation of most, if not all, known material.

4. ELECTROMAGNETIC PULSE

Experiments at synchrotron storage rings fall into two general design classifications regarding the x-ray flux exposure of the detector, indirect and direct. In indirect exposure situations, the detector may detect fluorescence resulting from interaction of the x-ray beam with the target sample, or the detector may record x-ray photons scattered from the x-ray beam by the target sample. For both situations, the full power of the x-ray beam is incident onto the target but is not incident onto the detector. In direct exposure situations, the full power of the x-ray beam transverses the target with little attenuation and is incident into the detector. Both experimental designs may result in an electromagnetic pulse (EMP) being induced into the detector circuit.

Consider an x-ray beam incident onto a material, either the target sample under study or the detector, see Figure 3. Photoelectrons are ejected predominantly normal to the target surface giving rise to a photoemission current and instantaneously to a giant dipole. This current results in a time-varying magnetic field that can produce an induced *emf* (voltage) into a nearby detector circuit. Carron and Longmire⁶ have obtained a general solution to the equations of Maxwell for the magnetic field. Limiting the general solution to one dimension allows for insight into the physical process that gives rise to the magnetic field and allows for approximation of the induced *emf*. Following the derivation of reference 6, the magnitude of the magnetic field is proportional to the second time derivative of the magnitude of the dipole moment formed by the charge separation as the photoemission current is produced, i.e.,

$$B \propto \frac{\partial^2 P}{\partial t^2}. \quad (1)$$

A closed loop, representing any circuit, positioned in this time-varying magnetic field will experience an induced *emf* proportional to the time derivative of the magnetic field. Hence

$$emf \propto \frac{\partial B}{\partial t} \propto \frac{\partial^3 P}{\partial t^3} \propto \frac{E}{t^3}, \quad (2)$$

where E is the magnitude of the energy content of the x-ray pulse and t is the duration of the pulse. From equations (1) and (2), one can estimate the relative strength of the induced *emf* from an x-ray FEL compared to that present at a synchrotron storage ring. The magnitude of the dipole moment is proportional to the magnitude of the charge generated by absorption of a single x-ray photon and hence to the magnitude (time integrated) of the energy (E) contained in the x-ray pulse. At the Advanced Photon Source, the energy contained in an x-ray pulse (of about 4×10^7 photons) from an insertion device beamline, at 10 keV, is about 70 nJ. The x-ray FEL pulse will have an energy content of 3 to 12 mJ, so let us say 5 mJ for this example. The pulse width (FWHM) of the APS x-ray pulse is about 50 ps. The pulse width of the FEL pulse from either the LCLS or from TESLA will be as short as 200 fs. Hence the magnitude of the magnetic field generated by the EMP at the x-ray FEL will be

$$\frac{5 \times 10^{-3} \text{ joules}}{70 \times 10^{-9} \text{ joules}} \times \left(\frac{50 \times 10^{-12} \text{ sec}}{200 \times 10^{-15} \text{ sec}} \right)^2 \cong 4 \times 10^9 \quad (3)$$

times larger than that encountered at the APS storage ring and the induced *emf* will be 10^{12} times larger. For example, if several 100 picovolts of induced *emf* are produced at the APS (a quantity too small to be easily measured), then several 100 volts may be expected to be produced at the x-ray FEL. As evident from equation (3), this dramatic increase in the induced *emf* is primarily due to the scaling with the x-ray pulse width.

Figure 3: An incident x-ray beam produces a photoelectron current normal to the target surface. This photocurrent produces a magnetic field that can be approximated as a series of dipoles (a dipole array). The magnetic field has a time variation corresponding to the lifetime of the dipole. An electrical circuit positioned near the target plane would experience an induced *emf* resulting from the time-varying magnetic field.

5. CONCLUSION

The proposed x-ray FEL fourth-generation light sources will present many challenges for the experimenter in his effort to handle the enormous x-ray energy density contained in a pulse. Three of these problems, synchronization of laser pulses,

damage threshold for target materials, and damage to electronics resulting from an EMP, have been introduced with a possible solution or an indication of where the problem may occur. The person designing experiments for the FEL will need to anticipate these problems and work for methods to minimize their effect.

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