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Technological Challenges to X-Ray FELs*

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Abstract

There is strong interest in the development of x-ray free electron lasers (x-ray FELs). The interest is driven by the scientific opportunities provided by intense, coherent x-rays.

An x-ray FEL has all the characteristics of a fourth-generation source: brightness several orders of magnitude greater than presently achieved in third-generation sources, full transverse coherence, and sub-picosecond long pulses.

The SLAC and DESY laboratories have presented detailed design studies for X-Ray FEL user-facilities around the 0.1 nm wavelength-regime (LCLS at SLAC, TESLA X-Ray FEL at DESY). Both laboratories are engaged in proof-of-principle experiments at longer wavelengths (TTF FEL Phase I at 71 nm, VISA at 600-800 nm) with results expected in 1999.

The technologies needed to achieve the proposed performances are those of bright electron sources, of acceleration systems capable of preserving the brightness of the source, and of undulators capable of meeting the magnetic and mechanical tolerances that are required for operation in the SASE mode.

This paper discusses the technological challenges presented by the X-Ray FEL projects.

1. INTRODUCTION

The intensity of x-ray sources has increased at a rapid rate since the late 1960s by 10 orders of magnitude and more through the use of synchrotron radiation produced by bending magnets, wigglers and undulators. Three generations of radiation sources have been identified depending on amplitude and quality of the radiation provided. While user facilities of the third generation were being constructed a new concept of radiation generating devices was being developed that offers an even larger increase in peak and average brightness than had been achieved till than. The new concept of the X-Ray Free Electron Laser (FEL) based on the principle of Self-Amplified Spontaneous Emission (SASE) will be the basis of fourth generation x-ray source user-facilities of the next century.

Existing FELs are operated in resonator configuration from the Infrared to the UV region, limited by the availability of good reflecting mirrors. The new SASE FELs get around this problem and open the door to the x-ray wavelength regime. Lasing is achieved in a single pass of a high brightness electron beam through a long undulator. No mirrors are needed.

The SASE concept was developed in the 1980s [1, 2, 3]. Advances in undulator technology, the development of the photocathode rf gun [4], and achievements in linac wakefield control during linear collider developments led to the proposal of linac-based x-ray FELs [5] in 1992. Experimental verification of the SASE-FEL theory in the Infrared regime has only recently been achieved [6, 7, 8]. The experiments verified all critical physics issues like gain length, slippage, optical guiding in the presence of large diffraction and photon statistics. Other important characteristics such as the saturation length and the power level at saturation have not been measured yet. Experiments are being prepared to complete the verification of the theory and to extend it towards the 1000 Å region and below [9, 10, 11, 12]. None of these experiments will be able to explore the SASE physics in the x-ray region near 1 Å. This will be done by the Linac Coherent Light Source (LCLS) X-Ray FEL R&D and User Facility [13] to be constructed at SLAC starting about 2003.

The DESY laboratory is proposing to build even brighter x-ray sources using 50-GeV-electrons and superconducting linac technology at the "500 GeV e^+e^- Linear Collider with Integrated X-ray Laser Facility (TESLA)" [14] which is expected to be constructed around 2009.

Some of the major technological challenges that face the design teams are described in the following section.

2. TECHNOLOGICAL CHALLENGES

2.1 Low Emittance Photo-Injector

Based on the requirements for a hard x-ray FEL, the design goal of low emittance photo-injectors currently under development at various laboratories is an electron beam of 3 ps (rms) bunch length with a 1 nC charge and a normalized rms emittance of 1 π mm mrad. The core of the injector is a photocathode radio-frequency (rf) gun [13].

In a photocathode rf gun electrons are emitted when a laser beam strikes the surface of a cathode. The factor that makes it difficult to extract a low emittance beam from an electron gun is space charge. Unfortunately, Coulomb forces tend to blow up the emittance of the high-density charged beams launched from the cathode. The most efficient way to overcome this tendency is to accelerate the electron bunch as quickly as possible to relativistic energies by placing the cathode in the center of an rf cavity with very high accelerating field, as proposed by Fraser, Sheffield and Gray in 1986 [4].

Gun development programs are under way at the Gun Test Facility (GTF) at SLAC, at the Accelerator Test Facility (ATF) at BNL [both 1.6 cell S-band], at UCLA [PWT, multicell S-band], at LANL [multicell, L-band] and at Fermilab for the TTF FEL [1.5 cell L-band]. S-band guns with a small number

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cells require fields of up to about 150 MV/m, which can generate strong dark currents that are a problem. Multicell guns can provide the same performance at about half the field. Metal cathodes require little maintenance but due to their low quantum efficiency (QE) require high power laser pulses that can stress these lasers to their technical limits. Semiconductor cathodes need load-lock mechanisms. Recently it was suggested to use coded semiconductor cathodes to avoid this design complication [15].

The increase of projected bunch emittance, i.e., the variation of the phase space distribution along the bunch, caused by the varying transverse space charge fields, can be compensated with an appropriate solenoidal focusing field (Emittance Compensation) [16, 17].

The lowest measured emittance (performed with the Los Alamos Advanced FEL photoinjector) for a beam charge of 1 nC was 1.6 π mm mrad integrated over the whole bunch, and 1.2 π mm mrad over 4 ps slices [18] .

2.2 Linac

2.2.1 Bunch Compression

The purpose of bunch compressors is to reduce the bunch length, thereby increasing the peak current to a level required to saturate the FEL. Accelerating the beam off the crest of the rf waveform in the linac creates an energy-phase correlation that can be used by a chicane to shorten the bunch by appropriate energy-path-length dependence. It is preferable to utilize two rather than one chicane. This reduces the sensitivity of the final bunch length to the phase jitter in the photocathode laser timing. The choice of energies of the various compression stages is the result of an optimization that takes into account beam dynamics effects, the most relevant ones being the space charge forces in the early acceleration stage, the wakefields induced by the electromagnetic interaction of the beam with the linac structure, and the coherent synchrotron radiation emitted by a short bunch [13].

2.2.2 Wakefields

One of the main challenges for a linac based x-ray FEL is the emittance conservation during the transport in the linac. Wakefields generated by resistive wall and chamber impedances can greatly increase the normalized transverse emittance and the longitudinal emittance, i.e., the projected energy spread. In general, the increase in projected emittance and energy spread comes from correlated chirping of transverse position and average energy of bunch slices. The intrinsic emittance and energy spread of individual slices is practically not effected. Due to the development of linac technology in linear collider R&D, the wakefields are well understood and mechanisms exist to suppress their effect on the beam to a few percent. Among the techniques used are off-crest acceleration and emittance bumps.

2.2.3 Coherent Synchrotron Radiation (CSR)

Coherent Synchrotron Radiation (CSR) is an enhancement of part of the broad spontaneous synchrotron radiation spectrum that is generated when the electron bunch is bent in deflecting magnets as used in chicanes. For those wavelengths that are longer than the bunch length, the radiation contributed by the individual electrons is emitted within a small phase interval. The total intensity of the emitted radiation is therefore no longer proportional to the number of electrons but becomes proportional to the square of the number of electrons. Since there are about 10^{10} electrons in a bunch, the intensity enhancement is quite large. Radiation from the tail of the electron bunch can catch up to the head of the electron bunch due to the curved electron path. This radiation field interacts with the bunch while travelling through the bending magnet, potentially adding correlated energy spread and emittance to the electron bunch. If a small enough vacuum chamber height is used in the deflecting magnets, the effects of CSR may be shielded. Practical limitations often limit the minimum chamber height to values larger than required for full shielding. Experimental verification that these effects can be controlled at the required level has not yet been achieved [13].

2.2.4 Low Charge Pulses

Initially the x-ray FEL designs concentrated on 1 nC bunch charge with a normalized emittance of 1 π mm mrad. Recently it has been shown that it can be better to operate at a lower charge level [19, 20]. Gun studies indicate that the gun emittance can be expected to be reduced as a function of lower bunch charge. Lower charge bunches generate smaller wakefields in the linac and in the undulator and are simpler to transport. For the FEL performance the reduced emittance can compensate the reduced peak current, leaving the saturation length unchanged. The peak power, and thus the brightness of the x-ray beam, will be reduced proportional to the charge.

Diagnostics instrumentation presently in use for optimizing linac beams are limited to bunch charges at or above 1 nC. Instrumentation needs to be further developed to enable the handling of low charge beams with comparable precision.

2.3 Undulator

2.3.1 Beam-Based Alignment

While the magnetic field amplitude in the undulator is typically of the order of 1 T, the tolerances on the field errors must still be tight enough to guarantee straightness of the entire beam trajectory within some 10 micrometers tolerance. (Note that the electron oscillation amplitude due to the design undulator field is well below this value for GeV beam energies.) This requirement sets new standards for undulator alignment procedures and beam position monitors. Only beam-based alignment techniques appear to be capable of achieving the required level of alignment precision.

The beam-based alignment technique uses electron beam position monitor (BPM) readings as a function of large, deliberate variations in the electron energy. The measurements are analyzed and then converted to (1) quadrupole magnet transverse position corrections, (2) BPM offset corrections, and (3) adjust-

ments of the incoming beam position and angle at the undulator entrance (initial launch conditions). The alignment procedure is repeated 2 - 3 times in succession for the initial machine startup, and then reapplied only once per few weeks or months as necessary [13].

2.3.2 Helical vs. Planar Undulator

All undulator designs presently under consideration use a planar hybrid undulator with a fixed gap. The proposed devices for the very short wavelength are rather long, i.e., up to 100 m of undulator structure [13, 14]. To saturate within those distances, the undulator gap needs to be small, i.e. not larger than 6 mm, with a period length of a few centimeters. Those hybrid device have the advantage of simplicity. They use a well-known and matured technology. The on-axis field can easily be measured and corrected using well-established shimming procedures.

The small gap requires a beam pipe with a very small diameter, which will be the source of wakefields that will interfere with the electron beam and can negatively affect beam quality.

The LCLS group is evaluating the use of a superconducting helical undulator as an alternative. Such a device would allow a larger diameter for the vacuum chamber which would reduce wakefields effects.

The DESY design for the TESLA x-ray FELs uses helical undulators to reach the highest brightness levels at saturation length below 100 m for 50 GeV electron energies [14]

2.3.3 Wall Roughness Wakefields

The impedance generated by the scattering the field of the electron beam on the disturbances of the conducting surface of the vacuum chamber creates wakefields that can increase the projected emittance and energy spread of the electron beam as it travels through the undulator. Again, as was said for the effect of the linac wakefields, the increase in emittance and energy spread comes from a change of the average transverse position and energy of beam slices as a function of the slices' position within the electron bunch. The intrinsic emittance and energy spread of narrow beam slices is not affected. Of greatest concern is the energy spread of the beam generated by the longitudinal impedance of the roughness on the inside surface of the beam tube. The projected emittance growth of the beam due to the roughness transverse wakefields imposes smaller tolerances. The effect of the surface resistance is much less important and can be neglected in the study of the roughness impedance. Roughness tolerances of the order 100 nm have been imposed for the LCLS beam pipe with an inner diameter of 5 mm [13]. A detailed study of the nature of wall roughness, its reduction and the wakefields associated with it is being carried out at SLAC as part of the LCLS R&D program [21]

2.3.4 Spontaneous Synchrotron Radiation

Besides the line spectrum of the FEL fundamental and its harmonics, the electron beam also emits a continuous spectrum of spontaneous synchrotron radiation. Its power increases proportional to the product of the square of the electron energy and the square of the undulator field. As the FEL design is pushed towards shorter wavelength, where higher electron energy and higher undulator fields are needed, the total spontaneous power increases tremendously. For the LCLS and TESLA FEL proposals the estimated total peak power levels of spontaneous radiation are 81 GW and 540 GW, respectively. The statistical emission process will increase energy spread and emittance. The effect of total power loss, which will lower the bunch energy, needs to be corrected by micro-tapering of the undulator.

2.4 X-Ray Optics

During the commissioning of the x-ray FEL, several characteristics of the radiation pulse, such as the total power and the temporal and spectral structure, need to be measured as a function of the total charge of the electron beam on a single shot or a pulse-by-pulse basis. In order to enable these measurements, it will be necessary to separate the FEL radiation from the background of spontaneous synchrotron radiation. The first separation filter is likely to be a variable diameter pinhole, making use of the fact that the opening angle of the spontaneous radiation is much larger than that of the spontaneous radiation. Further spectral purification can be achieved with monochromators.

The full intensity of the remaining FEL x-radiation can still not be handled by presently existing optical components. This situation is not likely to change in the forseeable future. The x-ray optics relies on the development of Gas Absorbtion cells that can be used to attenuate the intensity of the x-ray beam by several orders of magnitude.

2.5 Scientific Experiments

2.5.1 X-Ray Pulse Compression

Although the x-ray FEL pulse is extremely short, i.e., of the order of 100 fs rms, it still consists of a large number of spikes, each of which has a sub-femtosecond pulse width [13]. This time scale is of great interest for a number of experiments. Isolation of these spikes is technically very difficult and the pulse-to-pulse fluctuation amplitude of the spikes is 100 %. Recently, C. Pellegrini proposed to compress the x-ray pulse to the spike scale [22]. This could be done by chirping the energy of the electron bunch by off-crest acceleration. This in turn would chirp the wavelength of the x-ray pulse, allowing to use common laser pulse compression techniques. The resulting x-ray pulse could be about as short as one spike but it would have the increased pulse-to-pulse stability of the entire uncompressed x-ray pulse.

2.5.2 Pulse-to-Pulse Stability

The fluctuations of the pulse intensity from shot to shot are expected to be large for the x-ray FELs. They are driven by two sources (1) the statistical nature of the SASE process itself and (2) the amplification of jitters in the electron beam parameters, such as peak current and emittance [13]. The first mechanism is a property of SASE. It causes the intensity of each of the coherent radiation spikes to fluctuated by 100 %, the fluctuation of the total pulse intensity is reduced by the square root of the number of spikes. The second mechanism can produce much

larger pulse fluctuations than the first, due to unavoidable jitter in electron bunch parameters that are generated as an amplification of gun timing jitter by the bunch compressors. Shot-to-shot diagnostics for the x-ray pulse intensity is being considered that will allow to either select pulses that fall within a narrow intensity window or to use the intensity information when analysing the experimental data.

2.5.3 Longitudinal Coherence

The SASE x-ray pulses are not fully longitudinal coherent. The coherence length is normally only a small fraction of the pulse length. The methods that are considered to increase longitudinal coherence, which is a desired x-ray pulse property for a number of experiments, are all based on seeding, i.e. providing a radiation field of sufficient power and with a sufficiently narrow bandwidth to dominate the bunching process. All micro-bunches would than be spaced exactly by one optical wavelength and would thus be radiating in phase. The problem is that there is no strong tunable source at x-ray wavelengths ready to be used. Two paths for providing seed radiation are being considered (1) the use of harmonic generation and (2) monochromatization of radiation from a SASE pre-FEL. The first method has been theoretically studied by L.H. Yu at BNL, the latter method will be tried at the TESLA TTF FEL [23] or at the LCLS.

3. CONCLUSION

Linac-based x-ray FELs have been recognized as the most promising path to fourth generation light sources. It has been predicted that they will deliver a tremendous increase in brightness compared to presently existing sources.

A number of technological challenges are encountered during the design process. For many of the challenges, satisfactory solutions have been proposed. Remaining major issues include (1) electron beam brightness, (2) bunch compression, (3) test of SASE at 1 Å, and (4) delivery of x-ray radiation to the scientific experiments.

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