Title
Enabling instrumentation and technology for 21st century light sources

Author
Byrd, J.M.

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J.M. Byrd [a,*], T.J.Shea [b], P.Denes [a], P.Siddons [c], D.Attwood [d],
F.Kaertner [e], L.Moog [f], Y.Li [f], A. Sakdinawat [d], R.Schlueter [a]

[a] Lawrence Berkeley National Laboratory, One Cyclotron Road , Berkeley, CA 94720,USA

[b] Oak Ridge National Laboratory, Oak Ridge, TN 37831,USA

[c] Brookhaven National Laboratory, Upton, Long Island, New York 11973,USA

[d] University of California Berkeley, Berkeley, CA 94720, USA

[e] Massachusetts Institute of Technology, Cambridge, Massachusetts 02139,USA

[f] Argonne National Laboratory, Argonne, Illinois 60439,USA

ABSTRACT
We present the summary from the Accelerator Instrumentation and Technology working group, one of the five working groups that participated in the BES-sponsored Workshop on Accelerator Physics of Future Light Sources held in Gaithersburg, MD September 15–17, 2009. We describe progress and potential in three areas: attosecond instrumentation, photon detectors for user experiments, and insertion devices.

1. Introduction

As part of the Workshop on Accelerator Physics of Future Light Sources sponsored by the Department of Energy Office of Basic Energy Sciences, a working group was organized to examine the state of the art of accelerator instrumentation and technology for

*The Corresponding authors Telephone: 1-510-486-6329.
E-mail address: JMByrd@lbl.gov (J.M.Byrd).

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future light sources and to recommend a few topics for which directed R&D funding could help enable the tremendous potential of the next generation. These future light sources will achieve significant improvements in brightness, peak brightness, time resolution and stability. To reach these goals, advances are required in accelerator instrumentation and technology in many diverse areas, such as: RF acceleration, component alignment and stability, attosecond instrumentation and optics, photocathodes, pulsed power components, photon detectors, halo monitors, collimators, lasers, insertion devices, noninvasive profile monitors, high resolution position monitors, trapped ion diagnostics, and feedback systems.

To cull a few R&D topics from this long list, we applied the following criteria: impact, viability, uniqueness, and applicability. Technological developments with high impact will significantly enhance the performance and scientific output of future machines. Viable R&D programs should show results in five years and lead to deployable systems within about 10 years. Many of the technologies listed in the previous paragraph would be developed specifically for certain light source types and several are covered in publications by other working groups. We identified unique topics that were not fully addressed by the other working groups, and that were applicable to multiple types of future light sources. By consensus of the working group, our final selections are: attosecond instrumentation and optics, detectors, insertion devices, and photocathodes. The first three will be discussed in the following sections while the photocathode technology was singled out for a more detailed treatment in a separate paper.

2. Attosecond instrumentation

Free electron lasers are emerging as the 21st century source for high brightness ultrafast X-rays. To date, two facilities are operational with several more planned to come online in the next few years. With the recent operation of the LCLS with electron bunch lengths of less than 10 fs, the possibility of sub-fsec, or attosecond, pulses is approaching. We have identified three areas where development is needed to be able to take advantage of these pulses. These include electron bunch length, photon pulse length and spectral diagnostics, timing and synchronization, and X-ray optics. Each of these is discussed in further detail in the following subsections.

2.1. *Ultrashort electron and photon bunch length measurements*

One of the challenges facing the next generation of ultrafast X-ray FELs is the characterization of electron and photon pulses with femtosecond time scales. This includes both measurement of the longitudinal current distribution and energy spread for the electron bunches and the time and spectral distribution of the photon pulses. Since both of the pulses are expected to reach below 10 fs in the near future, sub-fsec, or attosecond, resolution will be required. In addition, a measurement of the arrival time of each of the pulses is necessary with respect to the pump laser in a pump/probe experiment. Furthermore, the ideal measurement is nondestructive and is made on every electron and photon pulse.

For measurement of electron bunches, several approaches are continuing development to address the above needs. These approaches include electro-optic sampling [1,2], coherent synchrotron terahertz radiation [4], streak cameras [8,9], transverse deflecting structures [3], and fluctuational interferometry [5–7]. A comparison of these techniques is beyond the scope of this paper. As an example, we examine below the resolution of the transverse deflecting structures (TDS).

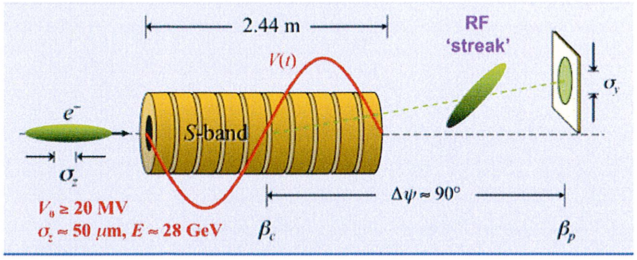

Fig. 1. Schematic view of a transverse deflecting structure for bunch length measurement.

A schematic view of the transverse deflecting structure is shown in Fig. 1. A high-frequency electromagnetic field exerts a time-dependent transverse force on the electrons, analogous to the sawtooth voltage in the oscilloscope, and converts the temporal profile of the bunch into a transverse (here vertical) streak on an observation screen. The bunch charge density profile can thus be measured single shot. Furthermore, appropriate variations of quadrupole strengths in the beam line upstream of the TDS allow for time-resolved horizontal phase space tomography. A crucial quantity that can be deduced from such a measurement is the horizontal slice emittance. A second screen mounted behind a dipole magnet is utilized to measure the energy distribution along the bunch axis and to carry out a longitudinal phase space analysis.

The longitudinal resolution of the TDS can approximated as the vertical beam size at the screen divided by the vertical deflection along the bunch given by the cavity. This can be written as [3]

$$\sigma_{long} = \frac{\sqrt{\varepsilon_y}}{\sqrt{\beta_{yTDS}}\sin\Delta\phi_y}\frac{\lambda_{TDS}E/e}{V_{TDS}} \tag{1}$$

where ε_y is the vertical beam emittance, β_{yTDS} is the vertical beta function at the center of the TDS, $\Delta\phi_y$ is the betatron phase advance between the TDS and observation screen, λ_{TDS} is the wavelength of the TDS, and V_{TDS} is the vertical deflecting voltage. A given configuration is optimized by maximizing the beta function in the center of the TDS and by choosing a betatron phase advance of an odd multiple of 90°. From this point, the longitudinal resolution can be increased by reducing the RF wavelength of the TDS and increasing the deflecting voltage. An example of a measurement at FLASH [3] is shown in Fig. 2.

For measurement of X-ray photon pulses, several approaches are continuing development to address the above needs. These approaches include optical streak cameras [10,11], conventional RF streak cameras [8,9], and fluctuational interferometry [12]. As in the case for electron bunches, a comparison of these techniques is beyond the scope of this paper. As an example, we examine in more detail recent advances in streak cameras operating at THz frequencies.

Streak cameras are proven tools in ultrashort pulse metrology and have single-pulse capability. In conventional streak cameras, photocathodes are used to generate electron bunches with temporal structures identical to that of the light pulses. The electrons are accelerated, transversely deflected by a rising electric field and then detected on a phosphor screen. Such schemes are limited in their time resolution to a few hundred femtoseconds. This limitation is mainly due to the spread of the initial momenta of the electrons released from the photocathode, which leads to a significant temporal broadening of the wave packet upon propagation to the deflector. This limitation can be overcome by using techniques recently developed for attosecond metrology [10]. A photoemitter is immersed in an electromagnetic field as shown in Fig. 3, transforming the time of

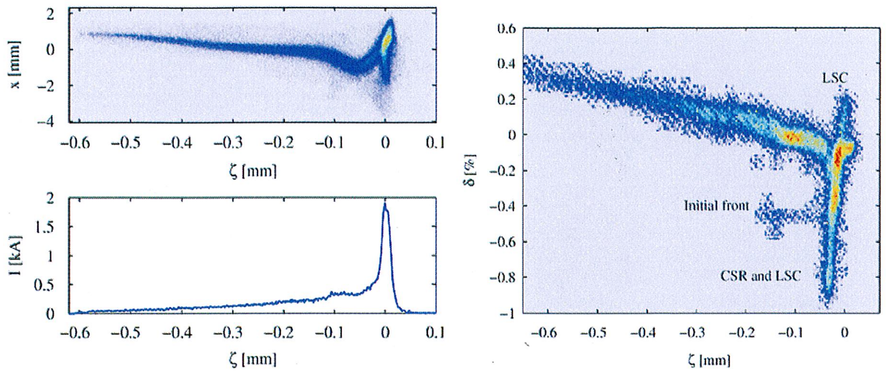

Fig. 2. Example longitudinal distribution from FLASH measured with the TDS (from Ref. [3].) The longitudinal phase space reconstructed from the measurement is shown in the right.

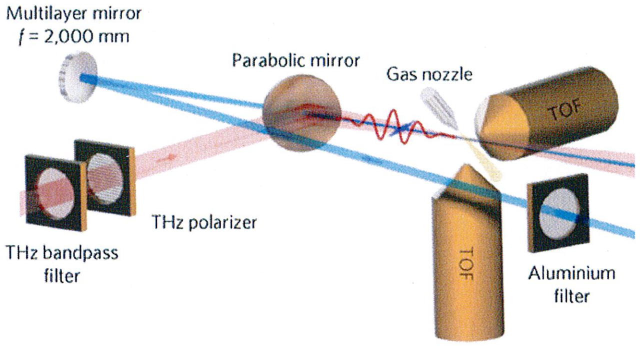

Fig. 3. Horizontally polarized soft X-ray (blue beam) and vertically polarized terahertz (red beam) pulses are focused and collinearly superimposed in a krypton gas target (from Ref. [10].) Photoelectrons are detected with two time-of-flight (TOF) spectrometers, one parallel and one perpendicular to the terahertz polarization. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

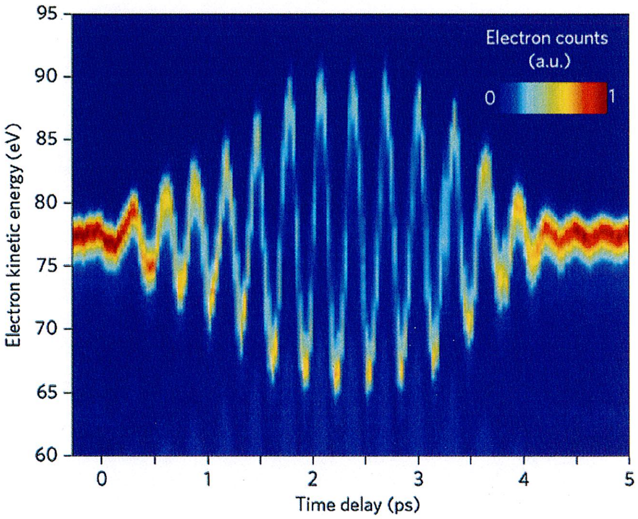

Fig. 4. Series of kinetic energy spectra of 4p photoelectrons detached from krypton atoms by a 13.5-nm soft X-ray pulse in the presence of an intense pulsed terahertz field (false-colour representation). The energy shift of the electrons versus the X-ray/terahertz delay directly represents the strength of the X-ray field (from Ref. [10].)

prompt ionization into an energy shift of the resulting photoelectrons. In this example, a deflecting field in the THz regime allows measurement of pulses up to tens of fs long. A measurement of this deflecting THz field is shown in Fig. 4.

2.2. High precision timing distribution

Fourth-generation light sources such as seeded FEL require a whole array of femtosecond lasers and synchronization techniques between low-level RF-systems, photo-injector laser, seed lasers as well as potential probe and diagnostic lasers. A layout of a generic seeded FEL facility and its synchronization needs is shown in Fig. 5. One of the main challenges in reaching the level of synchronization required for next generation light sources is transmission of a timing signal over a relatively large facility. For example, in a facility of a kilometer in length, diurnal temperature variation results in cable length variation from several hundred ps to a nanosecond. The master clock for the overall facility is an ultrastable oscillator. This could be either an ultra-low noise master microwave oscillator or a mode-locked fiber laser, locked to a microwave oscillator. The second option combines the superior high frequency noise characteristics of the fiber laser with the superior low-frequency noise characteristics of the microwave oscillator. The timing signals are distributed over stabilized fiber links throughout the facility and used to derive secondary synchronized sources, and lock critical optical and RF subsystems [13]. Several approaches have been used for stabilizing the fiber links. The two approaches that have been implemented at light sources are typically referred to as "pulsed" and "CW" (continuous-wave). In the pulsed approach, optical pulses from the master fiber laser are transmitted directly on the fiber and stabilization is achieved by locking the reflected pulse repetition rate to the master clock. RF timing signals are derived from harmonics of the pulse repetition rate. In the CW approach, each link comprises one arm of a optical Michelson interferometer which senses the variation in the link. RF timing signals are transmitted as modulations of the optical carrier with a phase adjusted by the correction sensed with the interferometer. Alternatively to the use of a mode-locked laser as the optical master oscillator also a highly stable continuous wave (cw)-laser could be used to length stabilize the optical fiber links and for transmission of optical as well as microwave signals [14,15].

Rapid advances over the last few years in frequency metrology based on ultrafast lasers and, therefore, also in laser stabilization and synchronization, show that the requisite low timing jitters between different laser and rf-systems can be achieved and maintained over long times and distances of several hundred meters [16].

2.2.1. Optical master oscillator

Over the last years high repetition rate (200–250 MHz), 100 fs fiber lasers have been developed [17] and are also commercially

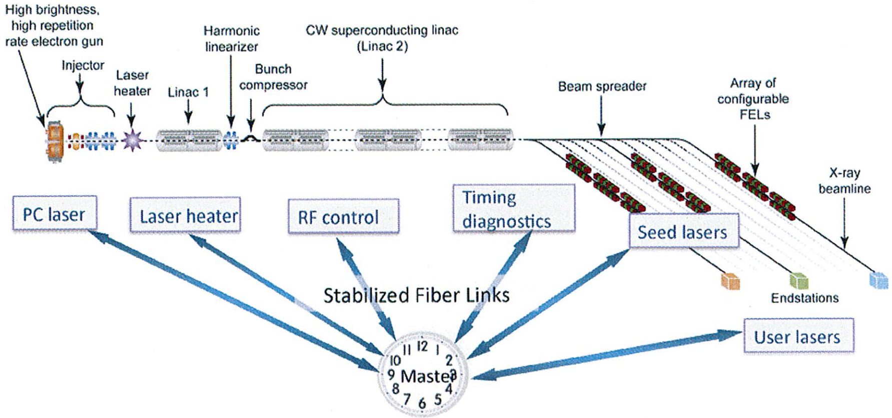

Fig. 5. Schematic outline of the timing distribution and synchronization for a seeded FEL facility.

available with several hundred mW of output power after amplification. These laser sources are, in terms of pulse parameters such as pulsewidth, repetition rate and output power, ideally suited to serve as the master oscillator for the intended facility. There high frequency timing jitter is below 1 fs and therefore these sources are well suited for timing distribution with 1 fs jitter level or even below [18].

2.2.2. *Timing distribution via length stabilized fiber links*

The use of optical signals as a means for timing delivery in an accelerator environment has many advantages compared to conventional temperature-stabilized coaxial cables, such as better robustness against electromagnetic interference (EMI), ease of installation, and space efficiency. Furthermore, the use of pulse trains enables direct stabilization of the group-delay of the fiber link while suppressing of Brillouin scattering and residual reflections. It also adds more flexibility in the operation and diagnostics of FELs by using the delivered ultralow-jitter pulse trains for direct seeding of optical amplifiers or down-conversion of microwave signals. Most importantly, optical cross correlation can be used to detect drifts in the length of the fiber link with high precision and robustness. Therefore, such drift detectors can be used to feed back on the length of the fiber link and keep it constant with better than 10 fs precision over many days of operation [13] demonstrated sofar for links up to 300 m in length. Compact single-crystal balanced cross-correlators for timing error detection and long-term stable timing link stabilization have been developed [19].

2.2.3. *Femtosecond synchronization techniques: optical to RF and optical to optical*

Tight synchronization is necessary not only for all the ultrafast lasers in the FEL facility, but also for the RF sources driving the accelerator sections. The electron beam dynamics is controlled by the microwave fields in the accelerator cavities. Therefore, highly stable microwave signals, tightly synchronized with each other in different accelerator sections, are an indispensable prerequisite for the control of electron beams with higher timing accuracy. High-quality RF signals can be extracted from the optical pulse trains delivered by timing-stabilized fiber links. However, the extraction of drift-free RF signals, which is tightly locked with the pulse trains, is a highly nontrivial task. Excess noise in the photodetection processes and thermal drifts of photodetectors [20] seriously compromise the achievable timing stability of RF-signals. On the other hand, tight synchronization of a mode-locked laser to a microwave frequency standard (Fig. 5) is also necessary for the optical master oscillator.

These issues have been addressed by the development of the balanced optical-microwave phase detector (BOM-PD) [21]. This device is based on a differentially biased Sagnac-loop interferometer for sensitive timing detection with electro-optic sampling. This PLL can be operated either by using an optical pulse train as a reference and a voltage-controlled oscillator (VCO) as a slave oscillator (optical-to-RF synchronization) or by using a RF signal as a reference and a mode-locked laser as a slave oscillator (RF-to-optical synchronization), see Fig. 6.

Use of the BOM-PDs has allowed synchronization of a 10.225-GHz VCO to a 200.5-MHz optical pulse train from an Er-fiber mode-locked laser. The measured short-term jitter was about 5 fs (1 Hz 1 MHz), and the long-term stability is below 7 fs rms, integrated over 10 h [13]. When all necessary components and sub-systems are well synchronized, the final issue is to precisely measure and monitor the achieved stability at critical points in the facility. For example, the electron beam stability at the bunch compressor and the phase stability of the microwave fields driving the accelerator structures must be continuously monitored. Availability of ultralow-jitter pulse trains at many positions in the facility allow the demonstrated techniques to support these diagnostic tools. For example, an electron bunch arrival time monitor [22] can be implemented based on electro-optic sampling. The down-conversion of microwave signals in the GHz range using BOM-PDs can be used to verify synchronism with the pulse trains at various points in the RF-system of the facility.

2.3. *Optics*

Experiments at new soft and hard X-ray free electron lasers (FELs) will require the use of specialized optics that are both tailored to the unique qualities of the FEL beam and to the specific experiment being performed. Crystal optics for hard X-rays will require special attention to assure that absorbed energy in ultrashort pulses does not cause short term heating sufficient to affect spectral selectivity. Optical components for focusing soft X-rays, such as zone plates, diffractive structures for holography, polarization control optics, femtosecond/attosecond mirrors, and pulse shaping optics will need to be properly designed and optimized for use with the intense soft X-ray FEL beam. Currently, there has been limited development and utilization of optics with ultrafast EUV sources such as laser high harmonic generation (HHG) and the FLASH FEL facility. In order to be prepared for the wide range of new scientific opportunities, much research and development in the optimal design, material selection, fabrication, efficiency, and radiation damage thresholds of the optics is needed. Indeed there is some experience in the EUV region, but essentially nothing in the soft and hard X-ray regions, and little quantitative studies of distortion and damage effects in any of these regions.

2.3.1. *Optics and diffractive structures for lens based and lenseless nanoscale imaging with femtosecond/attosecond FEL pulses*

Wavefront preserving focusing optics can be used in many ways: lens-based full field microscopy, keyhole coherent diffractive imaging, and formation of a nanometer-scale, intense probe. The main advantage of using a lens-based imaging system is that the image of a complex sample can be obtained directly and with high resolution. However, a typical configuration for a transmission X-ray microscope at 3rd generation synchrotrons, where Fresnel zone plate objectives are used with partially coherent illumination, cannot be directly translated for use in the spatially coherent beam from the FEL since coherent artifacts would affect the image. Alternatives include direct imaging using diffractive optics which can utilize the spatially coherent X-rays or use of an optic to reduce the spatial coherence of the illuminating beam within a single shot. Imaging using diffractive optics that can utilize the spatially coherent X-rays has been demonstrated with the DIC, spiral, and Zernike zone plates, shown in Fig. 7, using spatially coherent X-rays at the Advanced Light Source in Berkeley, CA. These zone plates are sensitive to both the amplitude and phase properties of the sample. For example, the DIC zone plate has been used to image phase contrast in magnetic samples. These zone plates are single-element imaging objectives in the microscope and are trivial to align. SEM images of the zone plates are shown in Fig. 7. The zone plates shown in Fig. 7 can utilize spatially coherent light from the FEL to form high resolution full-field real-space images. They are phase sensitive and can be used to detect phase contrast in a sample, potentially reducing radiation dose to the sample. Experiments designed to quantitatively describe conditions for survivability of these types of zone plates using various imaging geometries are required to predict their best use. Initial calculations suggest that survivability is possible in situations such as full-field zone plate imaging where only the direct zeroth order beam is avoided and a lens of many zones is used so as to minimize absorbed energy per unit mass. On the other hand, such lenses can play a valuable role even when destroyed in use, such as the zone plate lens array used in sequel keyhole coherent diffractive imaging experiments at FLASH. Examples of a lens before use, and portions of the array showing absent lens positions after use, are shown in Fig. 8. Mass production methods for producing large arrays of disposable zone plates cheaply should be investigated for such studies.

An additional form of diffractive structure likely to play a very useful role in nanoscale, ultrashort pulse imaging is the uniformly redundant array (URA), as seen in Fig. 9. The URA is designed for holographic soft X-ray imaging, offering the advantage of increased reference beam intensity, equal or greater than the object beam, while maintaining the high spatial resolving capability. These attributes are important for image quality, linearity, and accurate image fidelity, while making better use of available coherent photon flux. Again, flux related distortion and damage thresholds must be understood well in advance of experimental planning to achieve the best scientific results.

2.3.2. *Mirrors for femtosecond/attosecond pulses*

Conventional multilayer mirrors are generally not optimized for FEL sources and ultrafast experiments in the femtosecond/attosecond time domain. According to Heisenberg Uncertainty limits, very short pulses require appropriately wide spectral bandwidths, as expressed below.

$$\Delta E \Delta t_{FWHM} \leq 1.82\ \mathrm{eV{-}fs} \qquad (2)$$

To support such very short pulses mirrors with appropriately broad spectral bandpass are required, generally broader than typical required for longer pulse experiments. Tradeoffs between overall reflectivity and bandwidth need to be carefully considered. Fig. 10 shows an example of a multilayer mirror designed to

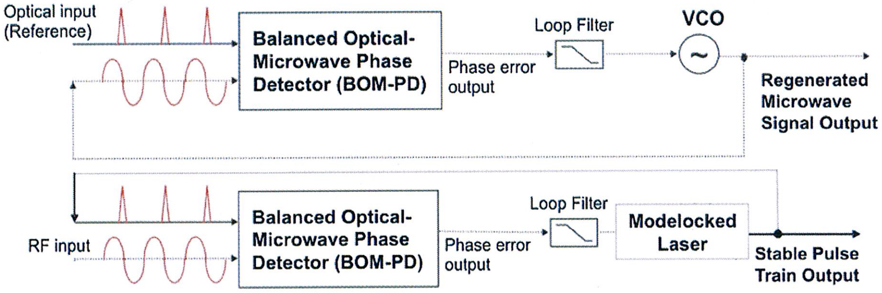

Fig. 6. Schematic of optical-to-RF and RF-to-optical synchronization using a balanced optical-microwave phase detector (BOM-PD).

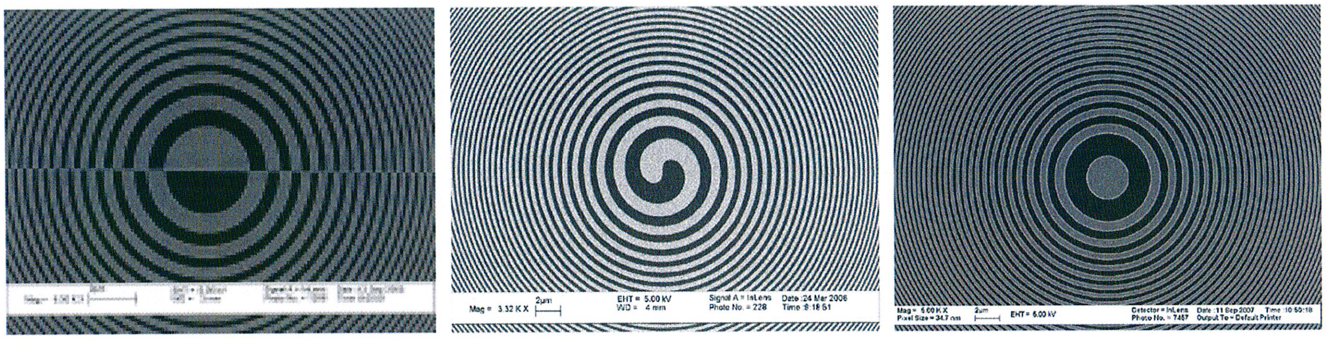

Fig. 7. SEM images of DIC (left), Spiral (center), and Zernike (right) zone plates. (Sakdinawat).

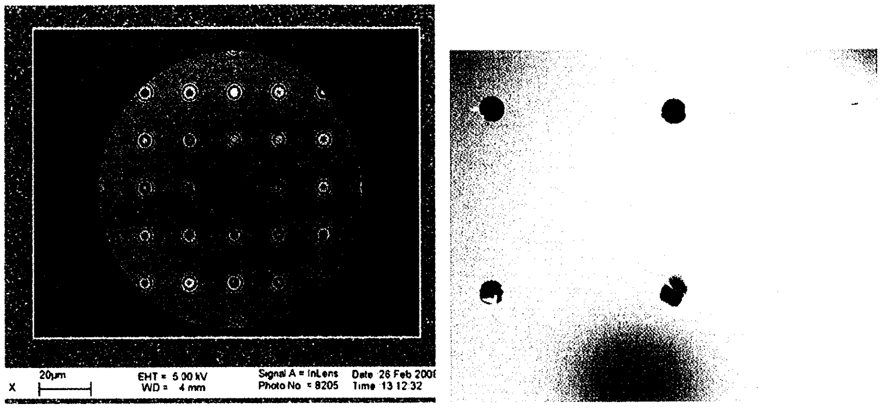

Fig. 8. SEM image (left) of one of over 200 zone plates fabricated in an array using electron beam lithography for keyhole coherent diffractive imaging. These zone plates were used in single-shot CDI experiments at the FLASH FEL. The right image shows the location of destroyed zone plates after use in the direct FEL beam. (Sakdinawat).

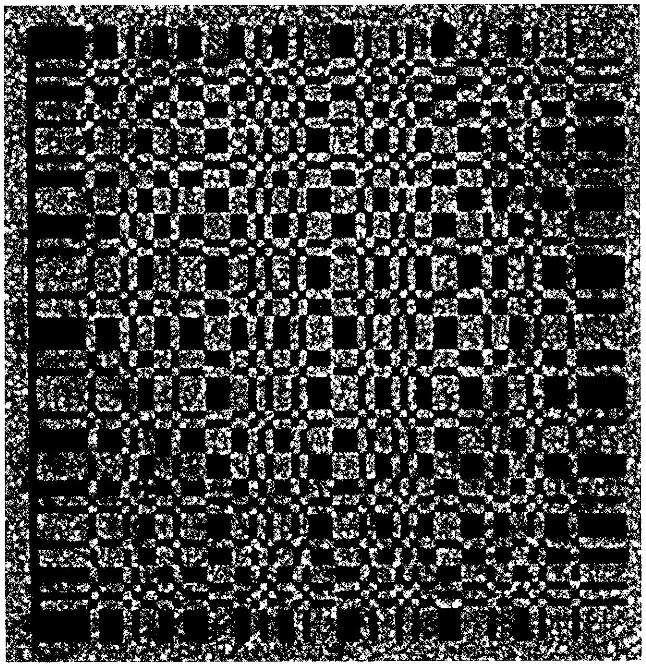

Fig. 9. An SEM image of a uniformly redundant array diffractive element used as a reference for high resolution holographic imaging. The highly parallel nature of this type of reference enables an improvement in resolution over pinhole-based Fourier transform holography. (Sakdinawat and Marchesini).

have sufficient bandwidth to support 100 as pulses at a photon energy of just under 100 eV. Further optimizations are required to explore the available material combinations for ultrashort EUV to X-ray pulses for a wide range of applications, including mirrors for two-color pump–probe experiments, etalons for sequential pulse generation at specified sub-femtosecond separation.

3. Detectors

New (and existing) synchrotron light sources can benefit enormously from R&D on X-ray detectors [23]. Whereas older experiments simply accepted the limitations of existing, commercial detectors, many experiments at newer synchrotrons simply cannot work without detectors beyond the commercial state of the art. Experiments at the latest FEL facilities illustrate escalating detector requirements even more starkly. At the Linac Coherent Light Source, diffract and destroy experiments must record two-dimensional diffraction patterns on a shot-by-shot basis, with a wide dynamic range over the detector, and no memory of the previous pulse [24]. At the European X-ray Free Electron Laser, the complex bunch structure requires storing and tagging X-rays, and then reading them out between bunches [25]. In both of these examples, micro-electronic enabled detector technologies, originally developed for High Energy Physics, were at the root of the solution. Such detectors are likely to continue to provide beyond-the-state-of-the-art solutions to new (and existing) sources. The development of such sophisticated systems is not a trivial undertaking, and typically demands many years to fully complete. For the machines currently under construction it is already too late to start a development program to have things ready for day-one operations. The LCLS and XFEL projects fortunately have programs in place, but as we learn about these exciting new sources and how to best use them, we will need to build different systems from those conceived currently.

For non-FEL sources, it is becoming clear that the next generation of X-ray detectors will add spatial resolution in two dimensions to whatever other properties they may have. Detectors having excellent energy resolution or good time resolution already exist, but the next generation must be multidimensioned. For example, energy resolving detectors currently have relatively few elements. The next generation will offer megapixel designs with per-pixel energy resolution similar to that of current single-element devices. Similar comments will relate to other property combinations, such as position and time. In order to achieve these goals, direct detection will become mandatory, and current devices relying on indirect detection via a scintillator will become obsolete. Achieving these goals will inevitably demand more complex circuitry be compressed into smaller pixel areas. The physics of charge collection will require intelligent reconstruction of the charge cloud in order to achieve good energy resolution and/or spatial resolution. This in turn will demand even more pixel complexity. All of this will require innovation in sensor physics, integrated circuit technology and device packaging. In order to reach the required level of sophistication, we must build infrastructure which can support it. This means bringing the US sensor foundries up to modern standards, providing the best software tools to US chip designers, and bringing in and educating new talent to take us forward. With the exponential progress in semiconductor processing, modern detectors are increasingly based on direct detection in semiconductors. Hard and soft X-rays present challenges for which R&D on materials and processes are needed.

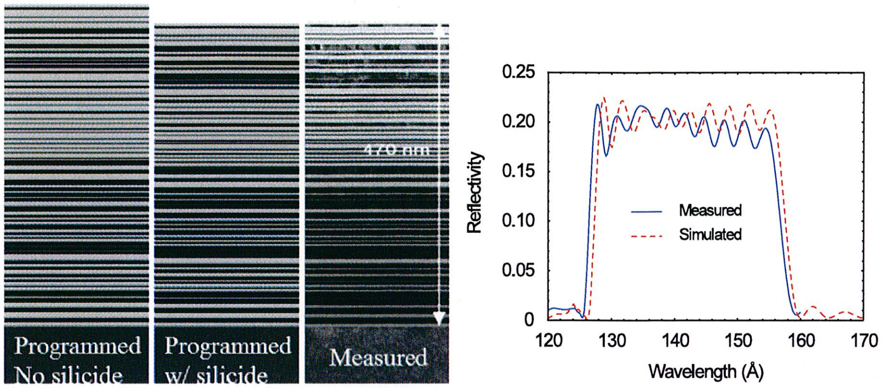

Fig. 10. An aperiodic multilayer mirror with 18 eV bandwidth, wide enough to support a 100 as pulse at 88 eV photon energy (Aquilar, Liu and Gullikson).

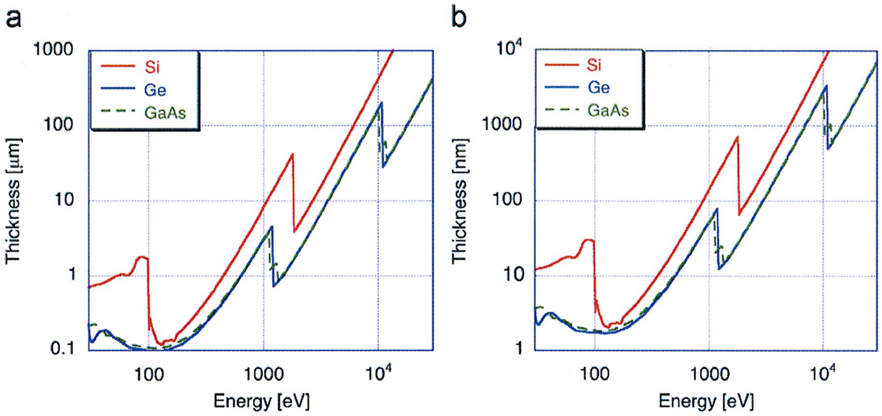

Fig. 11. (a) Thickness needed to absorb 95% flux and (b) window thickness to transmit 95% flux.

Fig. 11a shows the required detector thickness to absorb 95% of incident X-rays as a function of energy for three typical semiconductor detector materials: Si, Ge and GaAs. Typical silicon detector thicknesses are 200, 300 µm, showing that other materials are needed for harder X-rays. Conversely, Fig. 11b shows the maximum thickness of inert detector material allowable in order that 95% of incident X-rays are not absorbed, demonstrating that R&D on thin window implants is essential for soft X-ray detectors. Both of these areas are in need of significant R&D if the sophisticated detector systems being imagined by current instrument designers are ever to become a reality.

The issue of circuit complexity on the readout chips of pixelated detectors will require the use of deep submicron integration and even beyond, into the area of 3D stacking of circuitry to achieve optimal combinations of technologies and higher densities, and new approaches to thermal management, since all of this intelligence will consume significant power [26].

In addition to the primary data-collection devices, we should not neglect beam and beamline diagnostics. Devices to measure and control the photon beam position are significantly more challenging than the equivalent instruments for determining the electron beam position in an FEL or storage ring. The charged particle beam can interact directly with pickup electronics, whereas the photon beam must first be converted into an electrical signal; a process which inevitably introduces non-linearity to the problem. Measurements of photon bunch length below 1 ps (the current state of the streak-camera art [27]) is extremely challenging, and conventional streak-camera technology may not provide the final answer. Novel approaches, however speculative, should be tried.

4. Insertion devices

4.1. Present status

Well-established, high-performance undulator technologies include (a) planar permanent magnet (PM) undulators [28], (b) elliptically polarizing undulators (EPUs), e.g. the widespread Apple-IIs [29], and (c) in-vacuum undulators (IVIDs) [30], now standard in many synchrotrons. Under development are (a) new varieties of polarizing undulators, (b) quasi-periodic devices, (c) cryogenic PMs [30,31], and (d) superconducting undulators (SCUs), including planar designs and beyond [33]. Undulator designs specific for FELs and ERLs, but unsuitable for storage rings include (a) those with poles close to beam horizontally, e.g. vertically polarizing planar devices, some designs for variable polarization, e.g. Delta [34] and Apple-III [35] designs, and some superconducting designs, e.g., helical windings on a round beam tube [36,37], (b) ultra-small-gap, (< 4 mm) devices [38], and (c) specialty designs for small emittance, e.g. crossed undulators capable of fast polarization switching [39].

4.2. Undulator technology options for future light sources

An undulator technology's inherent strength and polarization capabilities impact both (a) nominally attainable FEL output capability, including spectral range, polarization, tuning range, and brightness and (b) overall [undulator + accelerator] system design footprint and cost. Furthermore, undulator technology choice also heavily impacts the practical design aspects of (a) field error control, e.g. where smaller undulator periods are problematic, (b) tunability ease and precision, (c) polarization flexibility, where added complexity provides added capability, and (d) reliable operability, e.g. avoidance of instabilities, device heating, radiation damage, and quenching.

Finally, undulator technology options present tradeoffs in performance risk vs. both enhanced performance and reduced cost. Planar permanent magnet undulators, PM EPUs and PM IVIDs are well-tested in storage rings, whereas Cryo-PMs and SCUs are still at or beyond state of the art, require further R&D, and are seen to entail greater risk.

Various SCU designs do in fact have the potential to vastly outperform all other undulator technologies (see Figs. 12, 13 and 14) [40]. Moreover, requirements for future light sources may also alter relative risks insofar as SCUs may prove less problematic in e.g. FEL facilities because of relative inherent ease of (a) field error control with device miniaturization and (b) spectral range and polarization control the macroscopic moving parts required by PM devices. Specifically, PM machining, assembly, shimming, and gap/polarization positional control become more problematic for smaller gaps and periods. Also, beam stay-clear requirements limit how small the gap can become, thus limiting the field strength achievable, e.g. from PM technology. Nb3Sn technology utilizes existing precision winding capabilities and offers variable strength operation with no moving parts. It also offers higher field strength, as compared with PM technologies, for the same beam stay-clear aperture. The high temperature superconductor (HTS) concept [40] utilizes accurate existing micromachining capability, and offers ease of assembly, and low device cost, all important for large-scale FEL applications.

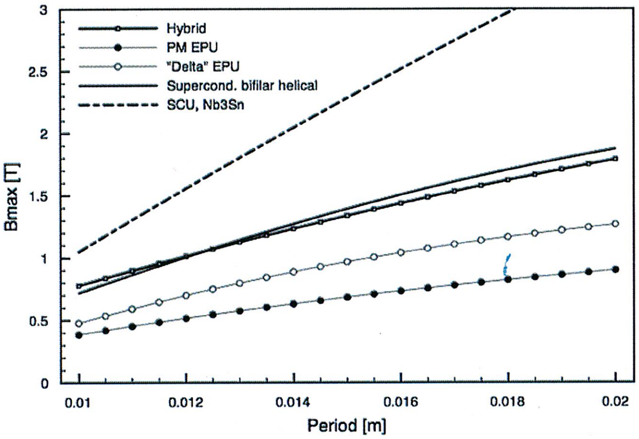

Fig. 12. Performance comparison between undulator technologies: PM-hybrid, APPLE EPU, Delta-EPU, and superconducting bifilar, for a vacuum aperture of 4 mm. Calculations of the bifilar helical SCU data assume an iron-free system with $JE = 1500\,\mathrm{A/mm^2}$, neglect $J_c(B)$ dependence, and are only reasonably valid for $B < 2\,\mathrm{T}$. PM-based devices assume $Br = 1.35\,\mathrm{T}$. SCU data assume Nb3Sn material. Fields are maximum on-axis values.

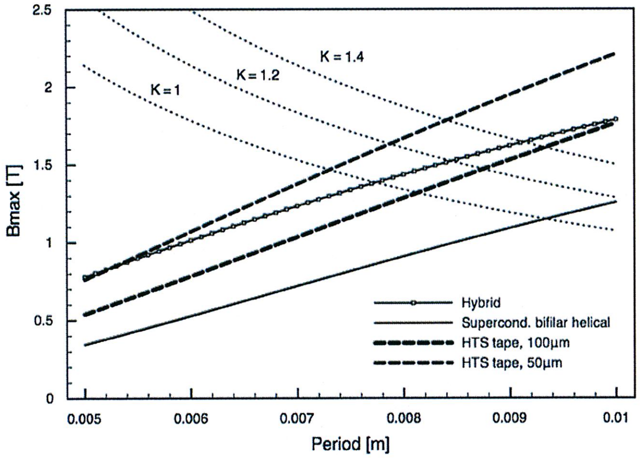

Fig. 13. Performance comparison between in-vacuum version of the PM-hybrid from Fig. 12, the HTS PM-hybrid, and the HTS tape concept. Calculations for two tape thicknesses (50 and 100 μm) are provided, both operating at 4.2 K.

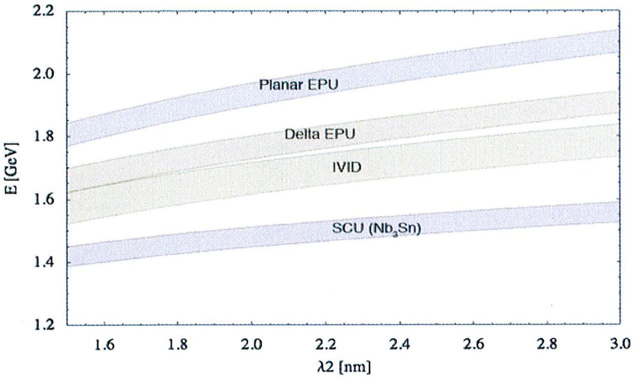

Fig. 14. Performance comparison: Machine electron energy (E) needed to produce radiation in the range $1.5\,\mathrm{nm} < \lambda < 3\,\mathrm{nm}$ for various undulator technologies. Planar modes assumed. Bands represent beam stay-clear apertures of 4–5 mm, illustrating gap-dependence. Band vertical position indicates required E for each undulator technology. For each technology, band width shows E sensitivity to vacuum gap. Band slope shows required E sensitivity to tunability capability.

R&D resources thus far invested in SCUs are an order of magnitude less than that devoted to IVIDs before their acceptance in third generation synchrotron facilities, and are significantly less than has been devoted recently to cryogenic permanent magnet systems in Europe, Japan and even the US [31,32,41–43]. Though the family of non-cryogenic PM devices is already poised to serve as baseline design options for future light sources, it would nonetheless be prudent to expedite SCU R&D to enable ultimate performance potential of future light sources.

4.3. Principal superconducting undulator (SCU) development challenges and readiness

Numerous groups are engaged in R&D aimed at overcoming practical limitations of other advanced undulator options, e.g. cryogenic-PMs [31,32]; issues for such devices include phase-shift/shake as a function of (a) gap variation, i.e. change in magnetic force state coupled with the mechanical structure (this is particularly true for EPUs), and (b) temperature, in particular for cryogenic devices. Another worthy goal is to ready the very highest performance capability devices, namely the SCU family of undulators, for implementation into future light source plans and designs.

Many key SCU developmental issues have already been addressed. Preliminary readiness has been demonstrated in various SCU prototypes [33,44–48], including specifically demonstration of (a) highest-performing strength capability of all candidate undulator technologies, (b) tuning strength capability technique for phase error correction, (c) in-situ cryogenic tuning control for maintaining phase, (d) attaining near (> 90%) short-sample fields in Nb3Sn undulators, (e) winding, fabrication, and assembly of Nb3Sn devices, and (f) development in industry of thin ceramic insulators with adequate coverage and insulator thickness quality control for long-length conductors [49].

Furthermore, conceptual and prototype designs have already been developed for (a) superconducting elliptically polarizing undulators (SC-EPUs) [50], (b) stacked HTS undulators [40], (c) micro-undulators [40], and (d) helical SCUs [36,37], all aimed to meet specific needs for ultimate performance capability at future light source applications.

Principal remaining R&D issues that should be addressed early so as to have the most favorable impact on future light source system design, cost, and ultimate performance capability include (a) fabrication method details, including coil winding and treatment, of various SCU design types, (b) vacuum and wakefield design accommodation and heating accommodation for various operating environments, (c) specifics of in-situ cryogenic field tuning and manipulation, and (d) cryogenic magnetic measurements.

4.4. Undulator R&D tasks

A listing of R&D tasks needed to be ready to incorporate the highest performance devices in a future light source facility is given in the following paragraph. Priority should be given to those that closely match the particular needs and result in optimal performance of a proposed future light source.

Reliable winding and potting processes have been demonstrated for NbTi [42] but they, along with reliable reaction processes, remain to be fully demonstrated for Nb3Sn-based planar and bifilar helical SCUs (Figs. 15 and 16). An in-situ trajectory correction method remains to be honed, and a cryogenic magnetic measurement system needs to be developed.

For stacked high temperature superconductor (HTS) undulators it remains to (a) demonstrate attainment of effective current density (*J*), (b) evaluate image-current issues, (c) determine field quality and trajectory drivers, (d) verify current path accuracy, i.e. the *J*(*x*,*y*) distribution, (d) qualify an accurate stacking technique, and (e) develop field correction methods, e.g. use of an outer layer devoted to field correction [46] (Figs. 17,18).

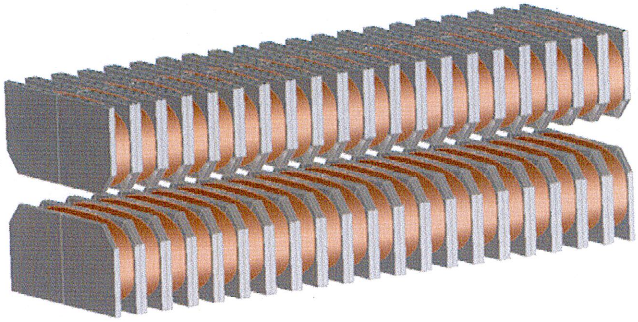

Fig. 15. Nb3Sn SCUs are thermally robust, and outperform all other technologies in the 10–20 mm period range, gap > 3 mm.

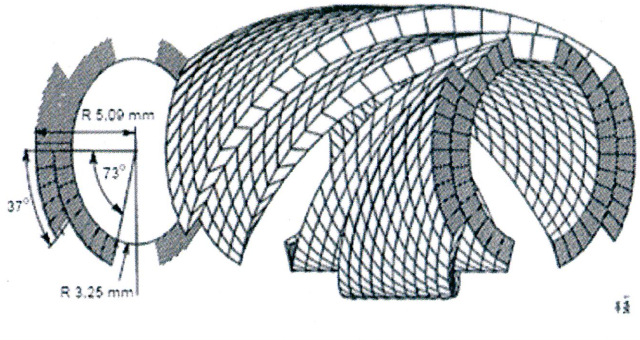

Fig. 16. A bifilar helical superconducting undulator would enable a shorter gain length and thus shorter FEL undulator length.

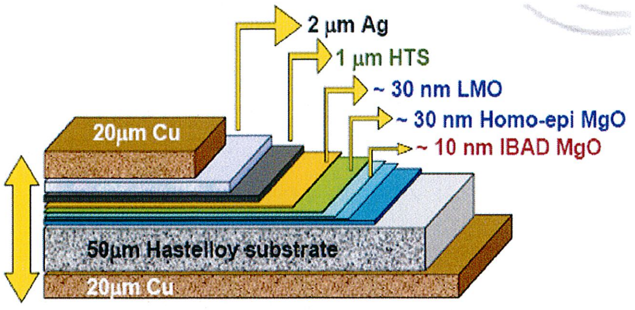

Fig. 17. Diagram (not to scale) of SuperPower Inc.'s YBCO tape. The material can be purchased with or without the Cu cladding. Similar conductors are available from other vendors.

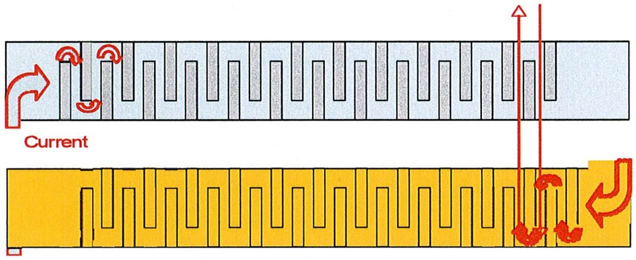

Fig. 18. HTS tape undulator concept. Laser cuts (in gray, not to scale) define the current path by destroying the YBCO superconducting layer in a thin strip of material, without impacting the underlying Hastelloy substrate. The current flows from left to right in the first layer (top); the current transitions to the next layer (bottom) on the right. The cuts are aligned to produce additive magnetic fields as the current flows back to the left.

For the Stacked HTS Micro-undulator it remains to (a) demonstrate ability to micro fabricate 5 μm stacked layers, (b) demonstrate attainment of effective current density (*J*), and (c) evaluate image-current issues.

For SC-EPU designs it remains to (a) develop an integrated switch network and (b) demonstrate performance in a prototype (Fig. 19).

For FEL/ERL long-undulators it remains to develop fast shifters/chicanes between FEL sections. Other candidate design types can also be considered including cryo-PM undulators and microwave undulators. The R&D issues associated with these devices are not treated here.

5. Summary and conclusions

5.1. Attosecond instrumentation

Developments in attosecond instrumentation will primarily benefit future FELs. For measurement of electron and photon bunch length, techniques that can vastly exceed the performance of current streak cameras is required. For some of the techniques under consideration, technical advances could be applied to both electron and photon diagnostics and therefore, it may be advantageous to embark on a coordinated research program. Measurements at FLASH indicate shot to shot variations in longitudinal profile that could impact certain experiments. Since future X-ray sources will probably exhibit similar behavior, an

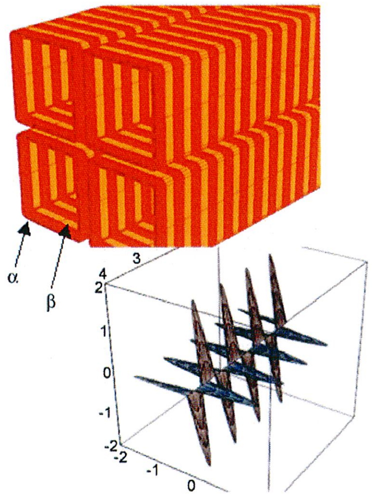

Fig. 19. Two interlaced sets (? and ?) of four-quadrant coil arrays (see top sketch), operated with four power supplies, can provide full variable linear and elliptic polarization control. As an example, the bottom figure maps the α and β fields for a case where the two planar fields are defined to be orthogonal, yielding variable elliptic polarization by varying the relative field strengths.

emphasis on single shot, nondestructive measurements would prove most beneficial.

Today, 10-fs jitter level synchronization over several hundreds of meters is possible using the techniques described above and has been demonstrated over several days of continued operation in the laboratory in operation. Prototype systems that can be deployed in facilities are in development and will be used over the next few years. Continued development over a time span of 5, 10 and 15 years is necessary to push the precision to the femtosecond and finally sub-femtosecond level over distances of up to 10 km and more and to go from laboratory systems to fully engineered systems deployable in accelerator and light source facilities. Such predictions would have been laughed at 10 and even 5 years ago. The progress in frequency metrology over the last 10 years shows clear pathways of how such precision might be achievable, and dedicated R&D programs could bring it to fruition.

In preparation for future experiments with intense, ultrashort pulses of soft and hard X-rays, optical components will require development on several fronts. From experiments at HHG sources and the FLASH facility, there is some experience in the EUV region, and this must be extended into the X-ray region. Theoretical and experimental studies of distortion and damage effects should be pursued for several types of optical components, include various types of zone plates and other diffractive structures such as uniformly redundant arrays. As photon pulses approach the attosecond regime, and photon energy increases, mirrors must support a very broad spectral pass band. Improvements in mirror technology would benefit virtually all experiments at future short pulse FELs.

5.2. *Detectors*

A coordinated R&D program in detector development could increase scientific output from all types of current and future light sources. To identify priorities for this broad program, a workshop similar to that summarized in Ref. [23] should be held. Some technical challenges cut across several light source types and may be more efficiently addressed by programs that are independent of particular facilities. Therefore, the synchrotron focus of the original workshop should be expanded to also include applications at FELs, ERLs, and additional novel sources. As discuss above, the detector community requires progress in several areas, including: improvements to US foundries, training of new talent, and developments in detector and window materials. Recent challenges that demanded sophisticated readout electronics have been addressed by piggy-backing on HEP developments. Ultimate detector performance may eventually require high performance integrated circuitry that is designed specifically for light source applications.

5.3. *Insertion devices*

Key performance metrics of candidate technologies show that various superconducting undulator (SCU) designs have the potential to vastly outperform all other undulator technologies. The unique requirements of future light sources may alter relative risks of candidate technologies, particularly to the advantage of SCU designs featuring no permanent magnets or macroscopic moving parts. Several SCU conductor technologies, including Nb3Sn-based and HTS-based designs have the potential to significantly enhance undulator performance. In addition, various superconducting designs incorporating special polarization features, including helical SCUs and SC-EPUs could play key roles in customization and optimization of future light sources.

Many key SCU R&D issues have already been addressed in completed SCU prototypes in-house at DOE laboratories and elsewhere. It would be prudent to address remaining development issues of these technologies, as discussed herein, so as to enable technology readiness for maximizing ultimate performance and low cost, with manageable risk for future light sources.

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