**Report of the BESAC Subcommittee on Future X-ray Light Sources**

**Approved by the Basic Energy Sciences Advisory Committee on July 25, 2013**

In a January 2, 2013 letter, then Director of the DOE Office of Science (SC), Dr. William Brinkman, asked the Basic Energy Sciences Advisory Committee (BESAC) to provide him with objective, independent advice in the following areas:

•Assessment of the grand science challenges that could best be explored with current and possible future SC light sources. The assessment should cover the disciplines supported by Basic Energy Sciences (BES) and other fields that benefit from intense light sources.

•Evaluation of the effectiveness of the present SC light source portfolio to meet these grand science challenges.

•Enumeration of future light source performance specifications that would maximize the impact on grand science challenges.

•Prioritized recommendations on which future light source concepts and the technology behind them are best suited to achieve these performance specifications.

•Identification of prioritized research and development initiatives to accelerate the realization of these future light source facilities in a cost effective manner.

It is important to note that the Future Light Source charge was provided to BESAC shortly after the Office of Science requested BESAC to provide a prioritization of the BES existing and planned major facilities. In the BESAC facilities prioritization report provided to the Office of Science on March 21, 2013, BESAC made the clear statement that "***the BESAC urges DOE to aggressively pursue a new future light source with unprecedented beam characteristics and thus unprecedented opportunities for world-leading science"***.

The BESAC facilities prioritization report, in concert with the outstanding success story of construction and early experiments of the Linac Coherent Light Source sets the stage for the present discussion and report.

## Executive Summary

The world leadership that the U.S. has provided in accelerator-based x-ray light source user facilities over the last 40 years has generated broad and far-reaching advances in diverse fields of science and technology. The unprecedented success of the U.S. x-ray light sources, under the stewardship of BES, has resulted in an extensive international activity in the development of innovative, and ever more advanced x-ray sources for discovery science and technological development. In spite of the present intensely competitive environment, an exciting window of opportunity exists for the U.S. to provide a revolutionary advance in x-ray science by developing and constructing an unprecedented x-ray light source. This new light source should provide high repetition rate, ultra-bright, transform limited, femtosecond x-ray pulses over a broad photon energy range with full spatial and temporal coherence. Stability and precision timing will be critical characteristics of the new light source.

We distinguish two classes of experiments which are not possible with any existing or planned facility: I) Diffraction/Scattering and II) Spectroscopy/Dynamics and both classes of experiments can utilize pump-probe schemes (either optical laser pump-x-ray probe or x-ray pump x-ray probe). Class I experiments requires high intensity and short pulse duration to "probe samples before destruction" while Class II experiments focus on multi-dimensional spectroscopy/dynamics that requires high rep rate and lower intensity pulses to study the structure and dynamics of gas-phase molecules, liquids and solids and bio-specimens. The conflicting demands on repetition rate and pulse energy from these different applications present a design challenge, which will require thoughtful tradeoffs.

Another new capability of a high repetition rate design, which mimics a CW beam, is that it will also allow most of the experiments currently undertaken at synchrotrons, which do not require time resolution, to be performed more efficiently on the new machine below the radiation damage threshold, while generating about 100 times more scattering per unit time. This reduction in data aquisition time will allow many experiments (eg 3D lensless imaging, photoemission spectroscopy) which currently require prohibitively long data acquisition time at synchrotrons to become practical.

Given the impressive advances in accelerator technologies during the last five years, it is likely that the best approach for a light source with the characteristics just enumerated would be a linac-based, seeded, free electron laser (FEL). To meet anticipated high demand for this linear device, the linac should feed multiple independently tunable undulators each of which could service multiple endstations. It is considered essential that the new light source have the pulse characteristics and high repetition rate necessary to carry out a broad range of coherent "pump-probe" experiments, in addition to a sufficiently broad photon energy range (at least ~0.2 keV to ~5.0 keV) and pulse energy necessary to carry out novel "diffract before destroy" structural determination experiments important to a myriad of molecular systems. A new light source that would meet the challenges of the future by delivering a capability that is beyond that of any existing or planned facility worldwide is now within reach. The highly successful experience with LCLS (and other facilities around the world) provides an understanding of the technical possibilities of sophisticated FELs. This window of opportunity is well established. Revolutionary new science would clearly arise from a facility with these photon characteristics. However, no proposal presented to the BESAC light source subcommittee met these criteria.

This revolutionary new x-ray user facility will complement the existing free electron laser facilities in the U.S., Europe and Asia, and will enable world-leading experiments in chemistry, physics, biology, and materials science – experiments that will expand the science frontiers and advance energy science resulting in broad economic and societal benefits. Anticipated experiments include time-resolved physics and chemistry studies to record movies of how bonds break and form, how energy flows at the molecular level, and how charge is transferred in nanoscale electronic devices. Photoemission with sub-micron spatial resolution is the key to understand complex solids with correlated electrons, such as high Tc superconductors in condensed matter physics. New approaches to ultrafast (magnetic) data storage devices can be explored. Pump-Probe imaging of biological and other soft material systems including viruses is critical to reveal mechanisms of energy (charge) transfer in biological molecules and biomimetic systems. With the capabilities of this new light source, each of these areas of science has the breakthrough potential worthy of Nobel Prizes.

At the same time, the Office of Basic Energy Sciences should ensure that U.S. storage ring x-ray sources reclaim their world leadership position. This will require a careful evaluation of present upgrade plans to determine paths forward that will guarantee that U.S. facilities remain at the cutting edge of x-ray storage ring science. The very large, diverse U.S. user population presently utilizing U.S. storage rings represents a major national resource for science and technology. It is essential that the facilities this science community relies on remain internationally competitive in the face of the innovative developments of storage rings in other countries. Such developments include diffraction-limited storage rings with beamlines, optics, and detectors compatible with the $10^2$-$10^3$ increase in brightness afforded by upgraded storage rings.

**Subcommittee Process**

In response to the request from the Office of Science, BESAC established the BESAC Future Light Sources Subcommittee, Chaired by the Chair of BESAC, Dr. John C. Hemminger. The full membership of the subcommittee is provided in Appendix I to this report. The subcommittee held two meetings. The first meeting was held on May 23, 2013 at the NAS Beckman facility in Irvine, California. The second meeting was held on July 9-12, 2013 at the North Bethesda Marriott Hotel and Conference center.

**May 23, 2013 meeting (NAS Beckman Facility, Irvine, CA)**

A one-day meeting of the subcommittee was held to have preliminary discussions, to decide on information the subcommittee should consider in its deliberations, and to set the agenda for the meeting to be held in July. The agenda for May 23, 2013 is provided in Appendix II. This first meeting of the subcommittee was attended by a large fraction of the subcommittee membership (members in attendance on May 23, are indicated by an asterisk next to their names on the membership list in Appendix I). Dr. Harriet Kung (Director of the Office of Basic Energy Sciences) and Dr. James B. Murphy (Director of Scientific User Facilities Division of BES) were also in attendance. Introductory presentations by Dr. John C. Hemminger and Dr. Harriet Kung were followed by two presentations that reviewed recent relevant BES/BESAC workshop reports. The first presentation by Dr. Wolfgang Eberhardt (*Review of the BESAC Report: "Next Generation Photon Sources for Grand Challenge Science and Energy Report"*), and the second by Dr. William Barletta (*BES Accelerator R&D for Future Light Sources*). These presentations were followed by a presentation by Dr. Persis Drell (*Status of International Light Sources*), and a presentation by Dr. Mikael Eriksson (*A Tutorial on Diffraction-limited Light Sources*). The remainder of the one-day meeting was taken up by preliminary discussions of how the U.S. light source facilities compare with present and near future international light source facilities, and discussions of the agenda for the July meeting of the subcommittee.

The subcommittee reached a number of consensus conclusions by the end of the one-day meeting. They are summarized here.

- The reports recommended as background material in the charge from the Office of Science to BESAC are compelling, and up to date, and do not need to be revised at this time. The titles of these reports are: "*Directing Matter and Energy: Five Challenges for Science and the Imagination*" (2007), *"Next-Generation Photon Sources for Grand Challenges in Science and Energy"*(2008), and the collection of reports from the BES Workshop *"Accelerator Physics for Future Light Sources"*(2009). In subsequent discussions the subcommittee relied heavily on the material in these reports. URL links to pdf files of these reports are provided in Appendix III.

- At the present time, the U.S. enjoys a significant leadership role in the x-ray light source community. This is a direct result of the successes of the major facilities managed by BES for the U.S. This leadership position is due to the science successes of the storage ring facilities and the particularly stunning success of the first hard x-ray free electron laser, the Linac Coherent Light Source

(LCLS). However, it is abundantly clear that the international activity in the construction of new diffraction limited storage rings, and new free electron laser facilities will seriously challenge U.S. leadership in the decades to come. Appendix IV of this report provides a tabular listing of the U.S. and international light source facilities and their specifications. A perusal of the information in Appendix IV makes it abundantly clear that the U.S. will no longer hold a leadership role in such facilities unless new unique facilities are developed as recommended by the BESAC facilities prioritization report.

•The subcommittee agreed that any recommendation for a new U.S. light source facility should not be based on capacity issues, but rather on **science-driven** needs for new and unavailable photon characteristics that would allow users to carry out previously impossible grand challenge experiments—similar to what has occurred with the highly successful LCLS

Based on these decisions, and the discussions that led to them, the subcommittee designed the agenda for the July 9-12, 2013 meeting. The first full day of the meeting (July 10) was assigned to fundamental grand challenge science presentations. The second day of the meeting (July 11) included invited presentations by proponents of several potential new light source facilities. A draft of the executive summary of the subcommittee report was to be generated and discussed in detail on the last day of the subcommittee meeting (July 12). The agenda for the July 9-12, 2013 meeting is provided in Appendix V of this report.

**July 9-12, 2013 Meeting of the BESAC Light Source Subcommittee**

On July 10 the subcommittee heard science presentations from Dr. Graham Fleming, UC Berkeley ("*Review of the BESAC 2008 Grand Challenges report--Directing Matter and Energy: Five Challenges for Science and the Imagination"*), Dr. Phil Bucksbaum, Stanford Univ. ("*Quantum Control and Electron Dynamics"*), Dr. Oleg Shpyrko, UC San Diego ("*Grand Challenges in Condensed matter physics, including emergent phenomena"*), Dr. Wei Yang, NIH ("*Observing Catalysis of a Chemical Bond Formation by X-ray Crystallography*"), and Dr. George Crabtree, Argonne National Lab ("*Fundamental Science Challenges in Energy Storage*")

On July 11, the subcommittee heard facility proposal presentations from Dr. Paul Alivisatos, LBNL ("*Next Generation Light Source"*), Dr. Chi-Chang Kao, SLAC ("*Future LCLS Upgrades including High Rep Rate concepts*"), Dr. Georg Hoffstaetter, and Dr. Joel Brock—both from Cornell Univ. ("*Energy Recovery Linac Sources*"), and Dr. Paul Evans, U. Wisconsin ("*Grand Challenge Science on Diffraction-Limited Storage Rings*").

**International Context**

The U.S. has been the world leader in accelerator based x-ray light source user facilities for over 40 years. The current suite of DOE Office of Science facilities includes four operating storage rings (ALS, APS, NSLS and SSRL), with the first optimized for soft x-ray science (below 1keV) and the next three optimized for hard x-ray science (above 1keV). The U.S. is also home to the world's first hard x-ray free electron laser, the LCLS, which operates from 280eV to over 10keV. Revitalizing upgrades for APS, LCLS and the construction of NSLS-II are either planned or underway to enhance both capability and capacity for these facilities by the end of this decade. This suite of facilities provides high intensity x-ray probes enabling pioneering research in chemical, material, physical and life sciences.

The success of the U.S. light source enterprise has inspired both Europe and Asia to emulate the U.S. resulting in tremendous light source developments in both regions. Presently there are operating storage rings and free electron lasers (FELs) in Europe and Asia that can rival the capability of the current suite of U.S. facilities and both regions have aggressive plans to upgrade and expand their light source portfolios. Next generation storage rings are under design or in construction in Brazil, France, Germany, Japan and Sweden that will optimize the average brilliance and spatial coherence of the x-ray beams in these machines. Soft x-ray FELs are already operating in Italy and Germany and a hard x-ray FEL recently turned on in Japan. Three other hard x-ray FELs are under construction in Germany, Korea and Switzerland. By 2020, Europe will have the most advanced suite of light source tools in the world in terms of both capability and capacity. Appendix IV summarizes the parameters of the key light source facilities worldwide.

While the current suite of U.S. light sources, together with their current and planned upgrades, will keep the U.S. competitive well into the next decade, it is imperative that the U.S. move forward to capitalize on the present opportunities to maintain its leadership position in this intensely competitive environment. The recommendations of this BESAC subpanel are focused to chart this path forward for the light source community.

**Grand Challenge Science Opportunities**

An exciting window of opportunity exists for the U.S. to provide a revolutionary advance in x-ray science by developing and constructing an unprecedented x-ray light source. **This new light source should provide high repetition rate, ultra-bright, transform limited, femtosecond x-ray pulses over a broad photon energy range with full spatial and temporal coherence. Stability and precision timing will be critical characteristics of the new light source.**

The most exciting scientific applications of such a new source can be grouped into two classes with opposite demands on the light source. One is destructive, the other non-destructive. The first (characterized as "diffract-before-destroy" and "spectroscopy-before-destruction"—taking advantage of the fact that femtosecond pulses can outrun radiation damage) – uses a single pulse per sample, which needs to be as energetic as possible to obtain the most information from each interaction. The second (characterized as "pump-probe") uses two or more pulses per sample to study dynamics and needs to be non-destructive, in order to allow repeated measurements by subsequent pulses of the same sample. Pump-probe experiments would permit, for example, multi-dimensional spectroscopy experiments in the x-ray spectra region similar to those that have revolutionized spectroscopy in other regions of the electromagnetic spectrum.

Given the impressive advances in accelerator technologies during the last five years, it is likely that the best approach for a light source with the characteristics just enumerated would be a linac-based, seeded, free electron laser (FEL). To meet the anticipated high demand for this linear device, the linac should feed multiple, independently tunable undulators each of which could service multiple endstations. It is considered essential that the new light source have the pulse characteristics and high repetition rate necessary to carry out a broad range of coherent "pump probe" experiments, in addition to a sufficiently broad photon energy range (at least ~0.2 keV to ~5.0 keV). It appears that such a new light source that would meet the challenges of the future by delivering a capability that is beyond that of any existing or planned facility worldwide is now within reach. However, no proposal presented to the BESAC light source subcommittee meets these criteria.

**Diffraction Limited Storage Rings and U.S. Storage Ring Upgrades**

As indicated in the tables in Appendix IV, there is a large and impressive international activity in the development of diffraction limited storage rings. Such "ultimate" storage rings will allow powerful new classes of experiments that take advantage of the full coherence and brightness of the diffraction limited radiation. At best the present plans for upgrades of U.S. storage rings will leave the U.S. behind the international community in this area of x-ray science. The Office of Basic Energy Sciences should ensure that U.S. storage ring x-ray sources reclaim their world leadership position. This will require a careful evaluation of present upgrade plans to determine paths forward that will guarantee that U.S. facilities remain at the cutting edge of x-ray storage ring science. The very large, diverse U.S. user population presently utilizing U.S. storage rings represents a major national resource for science and technology. It is essential that the facilities this science community relies on remain internationally competitive in the face of the innovative developments of storage rings in other countries. Such developments include diffraction limited storage rings with beamlines, optics, and detectors compatible with the $10^2$-$10^3$ increase in brightness afforded by upgraded storage rings.

**Energy Recovery Linacs**

One promising approach for a new light source, which the panel felt did not offer the full range of desired capabilities, is the Energy Recovery Linac (ERL). As the electron beam passes through the structure including several GeV of superconducting rf-linac once for acceleration and once for decelleration, the ERL offers the possibility of diffraction limited incoherent radiation at x-ray energies of 20 keV or more plus a line-width up to ten times shorter than diffraction limited storage rings. However, without one or more associated high-gain free electron laser lines, the ERL cannot deliver the high peak spectral brilliance required by a large class of grand challenge experiments. Moreover, despite many recent technical advances and many impressive attributes, the ERL is limited to providing temporally incoherent x-ray pulses the minimum duration of which is significantly longer than that achievable in the usual linac-driven FEL design. At present sub-femtosecond pulses with significant pulse energy seem out of reach. Likewise, no scheme for control of pulse synchronization and timing stability at levels of several femtoseconds has been advanced.

Nonetheless, the development of the ERL and its constituent technologies at Jefferson Lab and at Cornell has been impressive. Recirculation of very short electron bunches may be an eventual cost-effective **upgrade** path for a linac-based FEL to provide higher energy X-rays. In particular, the recent Cornell success in optimizing CW superconducting rf-structures and low emittance electron injectors is particularly valuable and would be directly applicable to a new linac-driven FEL.

**R&D in support of a future light source**

The BES sponsored workshops on Accelerator Physics for Future Light Sources (2009) identified several options for a new generation of capabilities for photon science. Since that time, advances in accelerator technology are making practical the opportunity for the transformative light source capability recommended in this report. In particular OBES has sponsored fruitful R&D efforts directly enabling the next light source: these include a novel approach to high repetition rate electron injectors, demonstrations of large dynamic range electron beam diagnostics, robust photocathodes, and innovative FEL seeding techniques. Combining these advances with the developments in superconducting rf-technology supported by other DOE and NSF programs, DOE's system of laboratories are poised to deliver a break-through capability in photon science. On the accelerator technology side further development and optimization will improve the cost-effectiveness of the facility design. Nonetheless, even at this point the underlying practicality is clear.

In the recommended source with transformative characteristics the areas of scientific investigation opened up will no longer be limited by the source, but instead by the x-ray detector. The BES Workshop on Neutron and X-ray Detectors (2012) has identified improvements in detector characteristics that would universally benefit photon science capabilities: increased x-ray detection efficiency, higher count-rate capability, larger dynamic range, improved energy resolution and lower noise. Many experiments would also benefit from geometric enhancement of detectors with respect to pixel and detector area.

A large class of experiments conducted at a new light source will involve maximum data rates exceeding $10^{10}$ x-rays/pixel/s; others will require recording an enormous dynamic range That varies by a factor of $10^6$ over the detector. X-ray detectors must be capable of capturing this span of data in each image while framing at kHz to MHz rates. Greatly increasing the framing and readout rates of imaging x-ray detectors would allow movies to be made for studies of nonreversible processes. Ideally the detectors would be efficient and highly sensitive capable of capturing wide-dynamic-range, high-spatial-resolution images. The workshop concluded that "given the broad range of science conducted at x-ray facilities, the catalog of unmet detector needs is quite large."

In conclusion the panel recommends that a decision to proceed toward a new light source with revolutionary capabilities be accompanied by a robust R&D effort in accelerator and detector technology that will maximize the cost-efficiency of the facility and fully utilize its unprecedented source characteristics.

**Appendix I**
**BESAC Subcommittee on Future X-ray Light Sources**

| | |
|---|---|
| John C. Hemminger* | University of California, Irvine |
| Simon Bare† | UOP a Honeywell Company |
| William Barletta* | MIT |
| Nora Berrah* | Western Michigan University |
| Gordon Brown* | Stanford University |
| Michelle Buchanan* | Oak Ridge National Lab |
| Sylvia Ceyer* | MIT |
| Yet-Ming Chiang | MIT |
| Helmut Dosch | DESY |
| Persis Drell* | Stanford University |
| Wolfgang Eberhardt* | Technical University, Berlin |
| Mikael Eriksson* | Max-Lab |
| Wayne Hendrickson | Columbia University |
| Franz Himpsel† | University of Wisconsin |
| Bruce Kay* | Pacific Northwest National Lab |
| Richard Osgood* | Columbia University |
| John Parise† | Stony Brook University |
| Maria Santore† | University of Massachusetts Amherst |
| Sunil Sinha* | UC San Diego |
| John Spence* | University of Arizona |
| Matthew Tirrell† | University of Chicago |
| John Tranquada* | Brookhaven National Lab |

* Attended the May 23 meeting in addition to the July meeting

† Video connected to the May 23 meeting and participated in the July meeting in person

## Appendix II

## Basic Energy Sciences Advisory Committee
## Future Light Source Subcommittee Meeting
## Agenda

NAS Beckman Center
Irvine, CA

| | Thursday, May 23, 2013 | |
|---|---|---|
| 7:30am - 8:30am | Continental Breakfast | |
| 8:30am - 9:30am | Welcome and Introduction: Goals for the day | John Hemminger, BESAC Chair<br>University of California, Irvine |
| 9:30am - 10:10am | Leone Report Summary/outcomes | Harriet Kung: All—General Discussion |
| 10:10am - 10:30am | Break | |
| 10:30am - 11:10am | Review of the BESAC Report: "Next Generation Photon Sources for Grand Challenge Science and Energy Report" | Wolfgang Eberhardt |
| 11:10am - 12 noon | BES Accelerator R&D for Future Light Sources | W. Barletta |
| 12:00 noon – 1:00 pm | Working Lunch – Discussion of Prior BESAC/BES Reports | All |
| 1:00pm - 1:40pm | Status of International Light Sources | Persis Drell |
| 1:40pm - 2:10 pm | Tutorial on Diffraction-limited Light Source | Mikael Eriksson |
| 2:10 pm - 2:30pm | Break | |
| 2:30---------3:00pm | Other options (ERLs, etc) | All --- General Discussion |
| 3:00pm - 4:00 pm | Discussion of Homework Assignments and July Meeting Agenda | All |
| 4:00 pm | Meeting Adjourn | |

Appendix III

url links to pdf files of important background material reports

"*Directing Matter and Energy: Five Challenges for Science and the Imagination"* (2007)
http://science.energy.gov/~/media/bes/pdf/reports/files/gc_rpt.pdf

*"Next-Generation Photon Sources for Grand Challenges in Science and Energy"*(2008),
http://science.energy.gov/~/media/bes/pdf/reports/files/ngps_rpt.pdf

The collection of reports from the BES Workshop *"Accelerator Physics for Future Light Sources"*(2009).
These reports were published in: Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 622, Issue 3, (2010).
The specific references for each report are:

1.) Free Electron Lasers: Present status and future challenges, W. A. Barletta, et al, NIM A618, p. 69 (2010).
2.) X-ray Sources by Energy Recovered Linacs and Their Needed R&D, S. Benson, et al, NIM A637, p. 1 (2011).
3.) The Potential of an Ultimate Storage Ring for Future Light Sources, M. Bei, et al, NIM A622, p. 518 (2010).
4.) New Source Technologies and Their Impact on Future Light Sources, B. E. Carlsten, et al, NIM A622, p.657 (2010).
5.) Enabling Instrumentation and Technology for 21$^{st}$ Century Light Sources, J.M. Byrd, et al, NIM A623, p. 910 (2010).
6.) Cathode R&D for Future Light Sources, D. H. Dowell, et al, NIM A622, p. 685 (2010).

## Appendix IV

International Comparison of the Characteristics of X-ray Light Sources

### FELs

| | BES FEL Light Sources | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **FEL Facility** | **LCLS/LUSI** | **LCLS-II** | **NGLS** | **FLASH** | **FLASH-II** | **XFEL** | **SACLA** | **SWISS FEL** | **PAL FEL** |
| **Laboratory, Country** | SLAC, USA | SLAC, USA | LBNL, USA | DESY, FRG | DESY, FRG | DESY, FRG | SPring8, JPN | PSI, CH | PAL, ROK |
| **First Operation** | Sep 2009 | ~2018 | ~2022 | Jun 2006 | ~2014 | ~2015 | Jun 2011 | ~2016 | ~2015 |
| **Construction Cost [M$]** | 474.3 | 405 | CD0 Range 900-1500 | | | ~1525 | | 294 | 400 |
| **FY12 Annual Ops Cost [M$]** | 123.9 | NA | NA | | NA | ~140 | | | ~60-80 |
| **Status** | Operating | Construction | Design | Operating | Construction | Construction | Operating | Construction | Construction |
| **E-Beam Energy [GeV]** | 2.2-15 | 7-13.5 | 2.4 | 0.5-1.25 | 0.5-1.25 | 17.5 | 8.5 | 2.1-5.8 | 3, 10 |
| **Peak Brightness** | 1.0E+33 | 1.9E+33 | 3.0E+32 | 2.0E+30 | 1.0E+31 | 8.7E+33 | | 2.0E+32 | 5.0E+31 |
| **Average Brightness** | 3.00E+21 | 5.80E+21 | 8.00E+24 | | | 3E+24 | | 2.00E+21 | |
| **Wavelength Range [Å]** | 1.3-50 | 0.7-50 | 10-120 | 41-450 | 40-800 | 0.5-10 | 0.63-2 | 7-70, 1-7 | 10-100, 0.6-7 |
| **Photon Energy Emphasis** | Hard X-Ray | Hard X-Ray | Soft X-Ray | Soft X-Ray | Soft X-Ray | Hard X-Ray | Hard X-Ray | Hard X-Ray | Hard X-Ray |
| **Peak Power [GW]** | 90 | 190 | 0.3-3 | 1-3 | 1-5 | 37 | 40 | 3 | |
| **Pulse Energy [mJ]** | 0.1-6 | 0.1-12 | 0.002-1 | 0.4 | 0.5 | 3.7 | 0.5 | 0.005-0.2 | |
| **Pulse Duration FWHM [fs]** | 1-500 | 1-500 | 1-300 | 50-200 | 10-200 | | <20 | 5-50 | |
| **Linac Type, Freq [GHz]** | NC, 2.856 | NC, 2.856 | SC, 1.3 | SC, 1.3 | SC, 1.3 | SC, 1.3 | NC, 5.7 | NC, 5.7 | NC, 2.856 |
| **Rep Rate [Hz]** | 120 | 120 | ≥1E6 | 10 | 10 | 10 | 10-60 | 100 | 60 |
| **Bunches per Cycle** | 1 now, 2 later | 1 now, 2 later | CW | 500 | 4000 | 2700 | | 2 | 1 or 2 |
| **Number of Undulators** | 1 | 2 | 3 now, 10 later | 1 | 1 | 3 | 1 now, 5 later | 2 | 2 |
| **Number of Instruments per Undulator** | 6 | 3 | ≥2 | 5 | 5 | 2 | | 3 | 1-2, 2-4 |

# Storage Ring Sources

| | BES Storage Ring Light Sources | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Storage Ring Facility | ALS | NSLS XRAY | NSLS-II w/ Damping Wiggler | SSRL | APS | APS-U | SLS | MAX IV | SIRIUS | ESRF | Spring-8 | PETRA-III | ESRF Phase I&II Upgrade | Spring-6 Upgrade |
| Laboratory, Country | LBNL, USA | BNL, USA | BNL, USA | SLAC, USA | ANL, USA | ANL, USA | PSI, CH | MAX, SWE | LNLS, FRB | ESRF, FRA | SPring8, JPN | DESY, FRG | ESRF, FRA | SPring8, JPN |
| First Operation | 1993 | 1984 | 2014 | 1974(2004) | 1996 | ~2018 | 2001 | 2015 | ~2016 | 1992 | 1997 | 2010 | ~2019 | ~2019 |
| Construction Cost [M$] | 146 | 24 | 912 | | 812 | 391 | 171 | | 320 | ~500 | 1240 | ~260 | 413 | ~450 |
| FY 12Annual Ops Cost [M$] | 60 | 36 | NA | 34.9 | 123.9 | NA | 38.7 | NA | NA | ~140 | ~95 | | NA | NA |
| Status | Operating | Operating | Construction | Operating | Operating | Construction | Operating | Construction | Construction | Operating | Operating | Operating | Design | Design |
| E-Beam Energy [GeV] | 1.9 | 2.8 | 3 | 3 | 7 | 7 | 2.4 | 3 | 3 | 6 | 8 | 6 | 6 | 6 |
| Emittance [nm] | 2.2 | 59 | 0.5 | 9.6 | 3.1 | 3.1 | 5.5 | 0.33 | 0.28 | 4 | 3.4 | 1 | 0.13 | 0.0675 |
| Average Brightness | 4E19@1 keV | 2E+17@3keV | 3E+21@3keV | 1.1E19@12keV | 1.4E20@8keV | 4E20@8keV | 4E19@1keV | 4E21@10keV | 2E21@10keV | 3E20@8keV | 8E20@10keV | 1E21@10keV | 1E22@8keV | 4E22@10keV |
| Circumference [m] | 197 | 170 | 792 | 234 | 1104 | 1104 | 288 | 528 | 518.2 | 844 | 1436 | 2304 | 844 | 1436 |
| Photon Energy Emphasis | Soft X-Ray | Hard X-Ray | Hard X-Ray | Hard X-Ray | Very Hard X-ray | Very Hard X-ray | Soft X-Ray | Hard X-Ray | Hard X-Ray | Very Hard X-ray | Very Hard X-ray | Very Hard X-ray | Very Hard X-ray | Very Hard X-ray |
| Beam Current [ma] | 500 | 300 | 500 | 450 | 100 | 150 | 400 | 500 | 500 | 200 | 100 | 100 | 200 | 100 |
| RMS Pulse Duration [ps] | 30 | 145 | 15 | 3-21 | 33 | 0.9 | 0.1-35 | | | | | | | |
| Number of Straights | 12 | 8 | 30 | 18 | 40 | 40 | 12 | 20 | 20 | 32 | 48 | | 32 | 48 |
| FY12 Annual Users | 1995 | 2453 | NA | 1597 | 4360 | ~5000 | 1793 | NA | NA | | | | NA | NA |

**Appendix V**
**Future Light Source Subcommittee Meeting**
**Agenda**

Bethesda North Hotel and Conference Center
Bethesda, MD

| | | |
|---|---|---|
| | Tuesday, July 9, 2013 Forest Glen | |
| 6:00pm - 9:00pm | Working Dinner (Dinner will arrive around 6:30) | Subcommittee Members Only with presentation by Pat Dehmer |
| | Wednesday, July 10, 2013 Salons G&H | |
| 8:30am - 8:45am | Welcome and Introduction: Goals for the day | John Hemminger, BESAC Chair<br>University of California, Irvine |
| 8:45am - 9:30am | Review of the BESAC 2008 Grand Challenges report-- Directing Matter and Energy: Five Challenges for Science and the Imagination | Graham Fleming, UC- Berkeley/LBNL |
| 9:30am - 10:15am | Quantum Control and Electron Dynamics | Phil Bucksbaum Stanford University/SLAC |
| 10:15am - 10:45am | Break | |
| 10:45am – 11:15am | Discussion | Subcommittee members only |
| 11:15am - noon | Grand Challenges in Condensed matter physics, including emergent phenomena | Oleg Shpyrko, UC- San Diego |
| Noon – 1:30 pm | Working Lunch | Subcommittee Members Only |
| 1:30pm – 2:15pm | Observing Catalysis of a Chemical Bond Formation by X-ray Crystallography | Wei Yang, National Institutes of Health |
| 2:15pm – 3:30pm | Fundamental Science Challenges in Energy Storage | George Crabtree, Argonne National Lab |
| 3:30pm – 4:00pm | Break | |
| 4:00pm - 5:30pm | Discussion | Subcommittee Members Only |
| 5:30 pm | Meeting Adjourn | |
| 6:30pm | Working Dinner (Dinner will arrive around 6:30) | |
| | Thursday, July 11, 2013 Salons G&H | |
| 8:15am – 8:30am | Welcome and Introduction | John Hemminger, BESAC Chair<br>University of California, Irvine |
| 8:30am – 9:30am | Next Generation Light Source | Paul Alivisatos, LBNL |
| 9:30am – 10:30am | Future LCLS Upgrades including High rep rate concepts | Chi-Chang Kao, SLAC |
| 10:30am – 11:00am | Break | |

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| 11:00am – Noon | Energy Recovery Linac Sources | Georg Hoffstaetter, Cornell |
| Noon – 1:30pm | Working Lunch | Subcommittee Members Only |
| 1:30pm – 2:30pm | Grand Challenge Science on Diffraction-Limited Storage Rings | Paul Evans, Wisconsin |
| 2:30pm – 4:00pm | Discussion | Subcommittee Members Only |
| 4:00pm – 4:30pm | Break | |
| 4:30pm – 5:30pm | Discussion | Subcommittee Members Only |
| 6:30pm | Working Dinner (Dinner to be delivered at 7:00) | Subcommittee Members Only |
| | Friday, July 12, 2013 Glen Echo | |
| 9:00am – 10:30am | Finalization of the Committee Recommendations | |
| 10:30am – 11:00pm | Break | |
| 11:00am – Noon | Discussion continued | |
| Noon – 1:30pm | Working Lunch | |
| 1:30pm – 3:00pm | Discussion continued | |