Workshop on Picosecond X-ray Sources at the Advanced Photon Source

May 9, 2008

Workshop Summary

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Executive Summary

On May 9, 2008, a group of current and future Advanced Photon Source (APS) users met to discuss the development of a picosecond-duration x-ray source at the APS. This meeting was motivated by significant technical progress in defining the cost, capabilities, and design of such a facility. Following ideas presented at the 2004 Lake Geneva workshop on time-resolved techniques,[1,2] the APS performed a detailed engineering design of crab cavities and a study of their performance and impact on the storage ring. ***The SPX significantly exceeds flux capabilities at current synchrotron-based slicing sources, and represents a completely different parameter space from that of the LCLS.*** The goal of this Workshop was to identify the many untapped areas for research and novel applications that would be enabled by the realization of an Argonne SPX.

The conclusions of the May 9, 2008 workshop are: ***1) There is a strong scientific case in atomic physics, chemical sciences, and condensed matter and materials science for a picosecond x-ray source at the Advanced Photon Source. 2) The energy tunability and high-repetition rate are unmatched by any present source and provide the basis for unique scientific capabilities.***

The result is that the community can now propose the short pulse x-ray (SPX) source as an imminent, medium-cost upgrade to the APS. Building on the workshop outcomes, the scientific case for a short-pulse x-ray source has been further elaborated, including the development of a nascent user community of ~40 users, as part of the proposal to significantly upgrade the Advanced Photon Source.[3]

Introduction

Goals of the May 9 APS SPX Workshop

The workshop had the following goals:

• Review, propose and brainstorm on future science that will become possible with the unique capabilities afforded by the APS short-pulse CW source. Enable leading edge research in AMO, Chemistry, Condensed Matter Physics, and Materials Science and Engineering.

• Formulate a comprehensive path leading to a proposal to the DOE Office of Basic Energy Sciences requesting funds to implement a short-pulse x-ray source at the APS, and to instrument facilities for short-pulse experiments which may include both hard and soft x-rays.

• Build and continue to grow the ultrafast science user community for cutting-edge time-resolved science to the APS.

Discussions among the 41 participants were based on the potential to make use of the unique source parameters of the SPX (Table 1). These parameters place the SPX in a unique range, in which the average flux is comparable to LCLS (Figure 1). The high-repetition rate experiments with ps-scale characteristic times identified at this workshop benefit tremendously from this high average flux.

pulse duration	1 - 2 ps (above 4 keV)
energy tunability	200 eV - 100 keV
repetition rate	6.5 MHz
photons/pulse	10^4 at 10^{-4} energy resolution 10^6 at 10^{-2} energy resolution
availability	all of the APS operating modes

Table 1 Projected characteristics of the future APS SPX source.

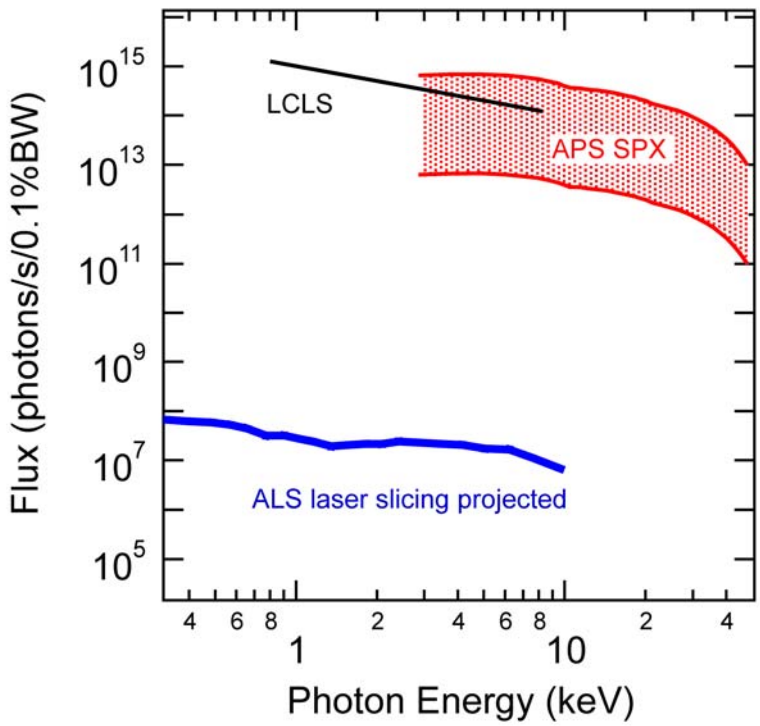

Figure 1 Photon flux for accelerator-based, short-pulse x-ray sources, after ref. 3. The flux for an SPX depends on the selected pulse duration and ranges from the current APS pulse-duration (top of shaded area) to the shortest pulses (bottom of shaded area).

Development of a Scientific Case for the Short-Pulse X-ray Facility

The development of the SPX has involved a long series of discussions and the development of a user community and broad scientific case. In addition to the Lake Geneva workshops in 2004,[1,2] and the present workshops, other important steps have included a 2008 workshop selecting the high-repetition rate variant of the SPX in preference to a low repetition rate variant,[4] and the development of a comprehensive scientific case as part of the proposal for the "APS Renewal" upgrade of the APS.[3]

The community of potential SPX users has begun the process of developing a letter of intent (LOI) to the APS, which would start the process of planning and fund-raising for the construction of an experimental facility based on the SPX source.[5]

Detailed Summary

The workshop was organized into four sessions focusing on the characteristics of the source and the development of specific applications. The notes below were taken by 4 recorders (Eric Landahl, Bernhard Adams, Xiaoyi Zhang, and Eric Dufresne) which were tasked to record the questions and answers from the attendees.

Session 1: Source Characteristics

Gabrielle Long (Advanced Photon Source) "Purpose of the workshop"

The goals for this workshop are:

1. Discussions between accelerator physics, beamline staff, and users
2. Nucleation of a real proposal

3. Discussion of capabilities of current source, especially with new detectors, choppers, and the current operating modes.

Ali Nassiri (Advanced Photon Source) "Overview of the CW picosecond source project at the APS."

Slides available at: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Nassiri.pdf

Work on the SPX project began immediately after the Lake Geneva meeting in 2004. The project now includes contributions from 20 people, as well as outside collaborators. The project has the following projected timeline: R&D 3 years, construction 2 years (dependent on funding). The earliest possible construction completion date is May, 2013. This timescale is consistent with the APS Renewal plan. The SPX lays foundation for the APS upgrade plan in 2020.

Discussion

Linda Young: How much do you think it is going to cost?

Ali Nassiri: We have looked at it. $20 - $25M up to $30M, including beamline

Linda Young: How much of this is just the accelerator?

Ali Nassiri: 2/3 of money for the accelerator ($20M), + $10M for the beamline. This includes contingencies.

Paul Fuoss: When you look at the 4 year timeline, is this on an optimistic to pessimistic scale?

Ali Nassiri: I will put it in the middle.

Paul Fuoss: Could you do it in 4 years, for instance?

Ali Nassiri: At the moment, our staff is only working on this part-time, our primary responsibility is to operate the machine as is. Direction of more staff onto this project could accelerate the pace. Regardless, we will have to hire new staff, such as someone for cryogenics.

Michael Borland (Advanced Photon Source) "Expected performance for the CW picosecond source"

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Borland.pdf

Michael Borland presented a detailed discussion of the performance of the proposed SPX source. Key details include calculations of the practical limitations on cavity voltages posed by the need not to increase the APS emittance and the potential for production of weak pre- and post-pulses in the sliced beam. At 3-4 MV cavity voltages, simulations predict a FWHM of 1-2 ps at hard x-ray energies. The FWHM depends on the photon energy, and is significantly longer at soft x-ray energies. Important design tolerances have been studied extensively.

Discussion

David Reis: Was the differential phase requirement shown in your talk on the harmonic or the fundamental RF?

Michael Borland: On the harmonic

David Reis: Is this a hard number to achieve?

Michael Borland: Yes

Ali Nassiri: 0.1 degrees is already pushing it. Getting to .07 is very hard.

Michael Borland: This is due to beam motion in part so maybe it can be done with slow feedback loops. This is also easier at lower voltages.

David Reis: Regarding the pre and post pulses, could these be diminished by not running at the zero crossing?

Michael Borland: Yes, you can trade pre-or post-pulse by running off zero crossing. There would be some emittance growth.

Phil Bucksbaum: Have beamline optics simulations been conducted for the pulse compression optics, as opposed to the slitting?

Sarvjit Shastri: The originally suggested optics compression scheme with asymmetric crystals has been studied by us in fair depth. First off, the crystal geometry does not work as originally drawn. In most cases, compression is obtained in glancing-incidence/steep-exit asymmetries, and not steep-incidence/glancing-exit asymmetries I've noticed in a lot of viewgraphs and figures. So the appropriate asymmetry vertically expands, say by a factor of three, a beam that is already large (25 mm) to begin with coming from the RF deflection. So one is dealing with a ~75 mm vertical beam that has to be focused to a useful spot size. A vertically reflecting, focusing mirror is out of the question - it would be tens of meters long. More reasonable is to use a horizontally reflecting mirror that focuses vertically. It would still be 1.5 - 2 m long and have a shape described as a paraboloid of revolution. This sounds daunting, but might be quite achievable because the specs on the mirror profile turn out to be not extremely stringent. In other words, there's no need to fight for a very precisely figured mirror because other effects in the overall scheme limit the focal spot size. In the vertical, the chromatic nature/aberration of asymmetric crystals prevents obtaining ideal source demagnification. And in the horizontal, the source size is quite large to begin with. So in the end, compression might very well be feasible, perhaps delivering a factor of ten over the approach of slitting-down.

Steve Southworth: Are there any low energy (200 eV) specifications?

Michael Borland: I do not have any simulations for 200 eV. At 1 keV, the pulsewidth is already ~3x the pulse width. What undulator would you use?

Steve Sourthworth: I don't know.

George Srajer: We use a 12.7 cm undulator in Sector 4 currently. But we are now thinking of a 9 cm period. It is almost like a wiggler.

Michael Borland: I can calculate that for SPX. [**Borland** later commented Final that for 200eV, the pulse duration would be 8 ps (FWHM).]

Linda Young: Since you can vary the pulsewidth by varying the deflection voltage, is this an option for users?

Michael Borland: It will probably be fine tuned for a particular configuration, so it would likely be difficult.

Kathy Harkay: You would have to change the lattice to change the pulsewidth, it would not be a good user knob.

Bernhard.Adams: The second harmonic peaks—could a different undulator be designed to eliminate them?

Michael Borland: Possibly. We have not looked at this yet.

Roger Falcone (Advanced Light Source): "Motivation for a range of ultrafast x-ray sources"

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Falcone.pdf

Emerging sources have a wide range of capabilities. Synchrotron slicing (e.g. using a fs laser) provide 10^2-10^4 photons/pulse at repetition rates of 1-10 kHz. Synchrotron crabbing sources (e.g. the SPX strategy) have 10^4-10^6 photons/pulse at rep. rates up to 6 MHz. Coherent sources such as the LCLS provide on the order of 10^{12} photons/pulse at 120 Hz. Laser-based higher-harmonic sources provide 10^{-6} conversion in peak and average power (MW peak / μW average).

Discussion

Kathy Harkay: What is the timescale for developing laser harmonic sources?

Roger Falcone: 5 years. The major issues are basically all thermal management in getting to 100 kW ultrafast lasers. Once CW lasers get to a new power level, it is usually translated quickly to short pulses, which are suitable for making x-rays with ~10^{-6} efficiency.

Paul Evans: What time distribution do we really want for the laser and x-rays? Given that we will have short bunches, will we want them all at once, or spread out at high repetition rates?

Roger Falcone: This is very experiment dependent and no generic statement can be made

John Bozek: If high harmonic sources are coming so soon, why should we be building accelerator based sources like the SPX?

Roger Falcone: There is a benefit to bringing these sources to a general community, which is not possible for very expensive lasers.

Gopal Shenoy: Can you comment on using degraded (spent) beam from LCLS to farm out to SPPS undulators to create short pulse incoherent x-rays?

Roger Falcone: The operational costs might be too high.

Phil Bucksbaum: The operational costs of SPPS were mostly borne by High Energy Physics.

Paul Fuoss: The electron charge per bunch for LCLS is far below that for SPPS. It would be difficulty to get the same performance out of the spent LCLS beam.

Linda Young: You need to rotate your parameter space graph by 90 degrees and look at the average power! We are only 10% different than LCLS. This sort of gentle, tunable x-ray probe will actually have a lot of advantages.

Linda Young: Our next speaker, Phil Bucksbaum, got the ball rolling on the SPX source at APS before the Lake Geneva meeting.

Phil Bucksbaum (Stanford Univ.): "Picosecond (not femto- or attosecond AMO X-ray Opportunities"

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Bucksbaum.pdf

The science case for a ps source includes rotational dynamics, cluster dynamics, spin dynamics, dipole-dipole interactions, interatomic Coulomb decay (ICD), and molecular dissociation. Diffraction studies can probe aligned molecules and clusters and dynamics in proteins. High repetition rates are important in molecular dynamics studies. Spectroscopy is an important tool – and requires continuously tunable photon energies. Nanomaterials have unique phonon modes that can be excited impulsively and probed using diffraction. Biological materials have benefitted from 100 ps-scale diffraction studies, but this is not fast enough for important processes. Potential multidimensional spectroscopies include two-dimensional X-ray correlation spectroscopy (2DXCS).

Discussion

Robin Santra: Regarding the ICD electron energy distribution. The spectroscopic results actually can not be used to give the lifetime—this is in fact an example of where time-resolved studies are needed.

Eric Landahl: What x-ray bandwidth is needed for multidimensional spectroscopy? Typically in the optical domain, transform limited pulses are necessary. (meV for ps)

Phil Bucksbaum: Not necessarily. Measuring the XANES spectrum while varying the delay between driving pulses would be sufficient to monitor coherencies, as long as the spectral sensitivity was enough to detect the small bond length changes.

Session 2: Condensed Matter and Materials Physics I

Philip Heimann (Advanced Light Source): Plasma physics with ultrafast x rays

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Heimann.pdf

Applications include planetary evolution, and a range of others. A list of nice experiments is available from FLASH. Creating plasmas is technically challenging, typically using laser heating. The 1 ps timescale is particularly relevant because this is the time over which the plasma remains spatially uniform. For example in an Al plasma, 1-2 ps is an appropriate time resolution. Warm dense matter phenomena, including shockwaves have ns time scales. EXAFS is an important probe, present studies of e.g. of melting in C are limited to 100 ps resolution, at which the EXAFS spectrum is already fully evolved.

Discussion:

The discussion focused on differences between the use of the high repetition rate SPX as currently proposed and the original room-temperature SPX with a proposed rate on the order of 100 Hz.

Paul Evans: To leverage the high rep. rate of SPX, use hi-rep-rate laser, and focus tightly to get power density.

Stuart Rice: Why is 3 hours data acquisition per point a problem, given the long setup times?

Phil Bucksbaum: We need to consider what the competition to SPX is to leverage our strengths. How do we make use of the high rep. Rate?

Eric Dufresne: Lasers with rep. rates to match the APS 6.5 MHz are available - long-cavity Ti:Sapphire.

Robert Schoenlein (Lawrence Berkeley National Laboratory): "Materials science with ultrafast x rays"

Examples of ultrafast phenomena in condensed matter include structural dynamics in transition-metal oxides, electron phonon coupling, and spin dynamics. There is a rich interplay of atomic and electronic structure (e.g. colossal magnetoresistance). Examples of ultrafast condensed matter science done at the ALS use the bunch structure and are limited to 65 ps now. Spin-crossover molecules in solution require x-ray absorption to probe the evolution of the molecular structure during reactions. Time resolved ARPES could be an important application of SPX because the high-repetition rate allows measurements at the appropriate time resolution to be made while minimizing space-charge effects.

Comments

Phil Bucksbaum: Is 100 meV resolution with hard x-rays feasible with photoemission?

Linda Young: Use 6.5 MHz long-cavity laser for high rep. rate experiments

Xiaoyi Zhang: Regarding the experiment with liquid-sample cell in Dr. Schoenlein's talk, does the flow replenish the sample from shot-to-shot?

Bob Schoenlein: No, no significant flow

Dave Tiede: In laser pump, x-ray probe spectroscopy on solvated molecules, the heat from the laser tends to displace the solvent within 100 ps

David Reis: To what extent is single-particle approximation, i.e., unchanged band structure in solid, valid under massive laser excitation? For example, coherent phonons might introduce changes.

Bob Schoenlein to Mike Borland: Is better time resolution possible with low-alpha mode?

Mike Borland: Not really, the emittance is too bad in that case.

Kathy Harkay: Perhaps with transient momentum compaction?

Phil Bucksbaum: They are planning to do that at SSRL

A more general discussion followed the morning sessions.

Paul Evans to David Reis: Expand on charge to workshop. Need to grow potential user community over next 5 years to be ready when source is available

Stuart Rice: After bad CARS experience, need to get word in time to DOE agencies to secure beamline operations money after construction

Phil Bucksbaum: Learn from high-energy-density working group, establish interagency working group.

Session 3: Chemical Applications

Professor Edward Castner (Rutgers University): "Rapid chemical and physical processes in solution"

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Castner.pdf

Short-pulse x-rays are useful for chemical and physical process in solution. Electron transfer is a quintessential process involved in enormous important process. One very important parameter in Marcus equation, used to describe the electron transfer reaction, is the reorganization energy which includes the contribution from the reorganization of the redox partners and the environment. Laser induced time resolved (LITR) x-rays probe method such as, LITR-XAS (X-ray absorption spectroscopy), LITR-XRD (X-ray diffraction), LITR-SAXS (small angle X-ray scattering) are all important and proven to be useful toward the structural understanding of photo-induced solvation and charge-transfer in solution. Many important processes happen in the ps time scale such as solvation and charge transfer, so having ps-short X-ray pulse is important to study structural dynamics in the ps time range. The time-dependent translational dynamics in ionic liquid using LITR-SAXS is one potential application of the SPX.

Comments

Dave Tiede: The thermal reaction of the solution to the laser pulses happen well within 100 ps, so we need to look at shorter times.

Roseanne Sension (University of Michigan): "Control of photoinitiated reactions"

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Sension.pdf

Present studies of photoinduced reaction are like sailing: "One has little control and must go with the wind." Reaction pathways can be controlled using several strategies: 1. pump-pump, pump-dump, 2. shaping of the photon spectrum, 3. control of excited state wave packets to direct reaction. Instead of just use light to trigger the reaction, ultrafast laser pulses, optical pulse shaping and feedback algorithms have been combined to control the reaction channel. The relevant timescales of this approach match the structural feedback that could be provided by the SPX.

Comments

Paul Evans: Can you use this approach to control solid samples? What will happen in X-ray scattering measurements? The outcome depends on couple of material on surface and laser.

Lin Chen: After the initial synchronization, may re-synchronize the reaction at one point. Use multipulse control.

Bernard Adams: Use two different well spaced band or interband to control the directions.

Session 4: Condensed Matter and Materials Science II

Hendrik Ohldag (Stanford Synchrotron Radiation Laboratory): "A quick look at magnetism using time-resolved soft-x-ray microscopy"

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Ohldag.pdf

Dynamics in magnetic systems include spin precession and coherent oscillations of the magnetic moment of large blocks. Systems include spin-transfer torque devices and other exchange-coupled multilayers. Experiments require full-field imaging with PEEM or scanning microscopy like STXM. Both benefit from improved time resolution with respect to present sources and profit from high repetition rates.

Discussion

Paul Evans: Initial conditions may affect the kinetic route in magnetism.

Hendrik Ohldag: Knowing the first few picosecond of initial conditions would greatly help to sort out the following kinetics.

Eric Dufresne: What is the contrast mechanism in the PEEM experiments shown here?

Hendrik Ohldag: Circular dichroism.

Steve Southworth: What problem would you solve with ps x-rays?

Hendrik Ohldag: Spin injection is not well understood, so they don't understand what determines the final magnetic state. The switching of nanomagnets interests him and is driven by technological applications.

Prof. Joel Brock "Scientific opportunities using a high-repetition rate, ultra-short pulse, hard x-ray source."

Slides: http://www.aps.anl.gov/Users/Meeting/2008/SPX_workshops/Brock.pdf

Collective modes have high *Q* and thus relatively long persistence times. Dynamics in charge density wave systems, for example, include fast THz-scale oscillation and a slower (10-100 GHz) overall relaxation. Probe with diffraction or diffuse scattering to get structurally resolved information. One proposed alternative source is the Cornell ERL, with GHz pulse rep. rates. Is this too fast for time-resolved experiments. ERL photon flux per electron bunch in Cornell "high flux" mode is not dramatically different from SPX (2-3 ps, 2.2 10^6 photons/bunch). Cornell's "short pulse" mode has 100 fs pulses, but only at 100 kHz.

Discussion

Eric Dufresne: Will coherent diffraction techniques would be interesting with SPX if the coherent flux is reduced by a factor 100?

Joel Brock: Coherent Diffraction Imaging in SAXS would be doable. Pink beam helps also in SAXS.

Concluding Discussion

Paul Evans: What is the status of SPX at the APS?

George Srajer: After the 2004 workshop, there was an intense R&D effort which resulted in a $10M initial estimate for a full CW source. The cost and lead time were long, so another approach emerged which could jump start the project more quickly and that could fit within the current APS budget. It consisted in developing a pulsed RF source working only during hybrid mode. After a full engineering design and quotes in November, 2007, the approach was found to be not cheap or quick, and the community decided to push instead for a full CW source that can be accessible for all the modes of the APS. External funding would be essential for this approach, and a concerted effort to approach our funding agencies from the facility and scientific side would be essential.

David Reis: What is on the table for SPX, i.e. what type of instruments and source will be available for SPX to define the scientific case?

George Srajer: Mid-term proposals are being developed by the user community and APS staff and that there is room for feedback on the process to include SPX. There remain three uncommitted sectors at the APS. The process to get a sector developed is to first submit a LOI to the SAC describing the scientific case. With a compelling case, several sectors might be assigned to SPX. Once the SAC has reviewed the LOI and accepts the project, one can submit proposals to funding agencies, and ultimately get assigned sectors once funding has been obtained. It is also possible that in the next 5 years that the geography of the floor may change.

Dennis Mills: A strong scientific case needs to be made. The community should be organized by the workshop organizers and should develop the science and source needs. From the needs of the community, it will be clearer what should be built, i.e. should one build a soft x-ray line? The steering group should develop an LOI and submit it to the SAC. A lot of effort will be required to fund SPX.

Bertold Kraessig: What would be the life of SPX when APS-II gets developed?

Dennis Mills: I gave a talk about the future of APS and its upgrade plan last Monday and the talk will be posted on the web soon. A midterm upgrade plan is being developed which will culminate in a strategic plan to be discussed in a workshop on October 20-21, 2008. The APS received 40 midterm proposals and many groups proposed compelling scientific cases that include for example long straight sections. Long straight sections will be necessary for SPX due to the length of the RF cavities. A longer term upgrade of the APS will be discussed within the ANL 2020 plan and his being called APS 2020. The senior management would make sure that SPX fits in the long-term future of APS.

References

[1] "*Workshop on Time Domain Science Using X-ray Techniques*," August 29 to September 1, 2004. Description available at: http://www.aps.anl.gov/Science/Future/Workshops/Time_Domain_Science_Using_Xray_Techniques/home.htm

[2] "*Time-Domain Workshop: Summary and Recommendations*," available at: http://www.aps.anl.gov/Upgrade/Time-domain_summary.pdf

[3] "*Fundamental Interactions in Chemical, Atomic, and Molecular Physics*," pp. 70-93 in Proceedings of the Advanced Photon Source Renewal Workshop October 20-21, 2008, published February 2009, publication ANL-09/4 Available at: http://www.aps.anl.gov/Renewal/Workshop/proceedings.pdf

[4] "*Mini-Workshop on Short X-Ray Pulses Generation and Applications at the Advanced Photon Source*," A. Nassiri and J. Wang, organizers Friday, February 15, 2008 http://www.aps.anl.gov/Upgrade/SPX%20Mini%20workshop2_08/

[5] "Short Pulse X-rays at the Advanced Photon Source," http://www.aps.anl.gov/Renewal/LOI/short_pulse.html

Appendix 1: Participants

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Appendix 2: Agenda

http://www.aps.anl.gov/Users/Meeting/2008/short-pulse.php

Session 1 Chair: Linda Young

8:45 - 8:55 Introduction and welcome to the workshop J. Murray Gibson, Argonne National Laboratory.

9:00 - 9:08 UU**Overview of the CW picosecond source project at the APS**, Ali Nassiri, Argonne National Laboratory.

9:10 - 9:25 **Expected performance for the CW picosecond source**, Michael Borland, Argonne National Laboratory.

9:30 - 9:55 **Motivation for a range of ultrafast X-ray sources**, Roger Falcone, Lawrence Berkeley National Laboratory.

10:00 - 10:25 **Ultrafast x-rays and applications in AMO science**, Philip Bucksbaum, Stanford University.

10:30 - 11:00 Discussion

11:00 - 11:10 Break

Session 2 Chair: David Reis

11:15 - 11:40 **Plasma physics with ultrafast x rays**, Philip Heimann, Lawrence Berkeley National Laboratory.

11:45 - 12:10 Materials science with ultrafast x rays, Robert Schoenlein, Lawrence Berkeley National Laboratory

12:15 - 12:45 Discussion

12:50 - 1:50 Lunch

Session 3 Chair: Lin Chen

2:00 - 2:25 **Rapid chemical and physical processes in solution**, Edward Castner, Rutgers University

2:30 - 2:55 **Control of photoinitiated reactions**, Roseanne Sension, University of Michigan

3:00 - 3:30 Discussion

3:30 - 3:40 Break

Session 4 Chair: George Srajer

3:45 - 4:10 **A quick look at magnetism using time-resolved soft-x-ray microscopy** Hendrik Ohldag SLAC

4:15 - 4:40 **Scientific opportunities using a high-repetition rate, ultra-short pulse, hard x-ray source**, Joel Brock, Cornell University

4:45 - 5:15 Discussion

5:30 Conclude