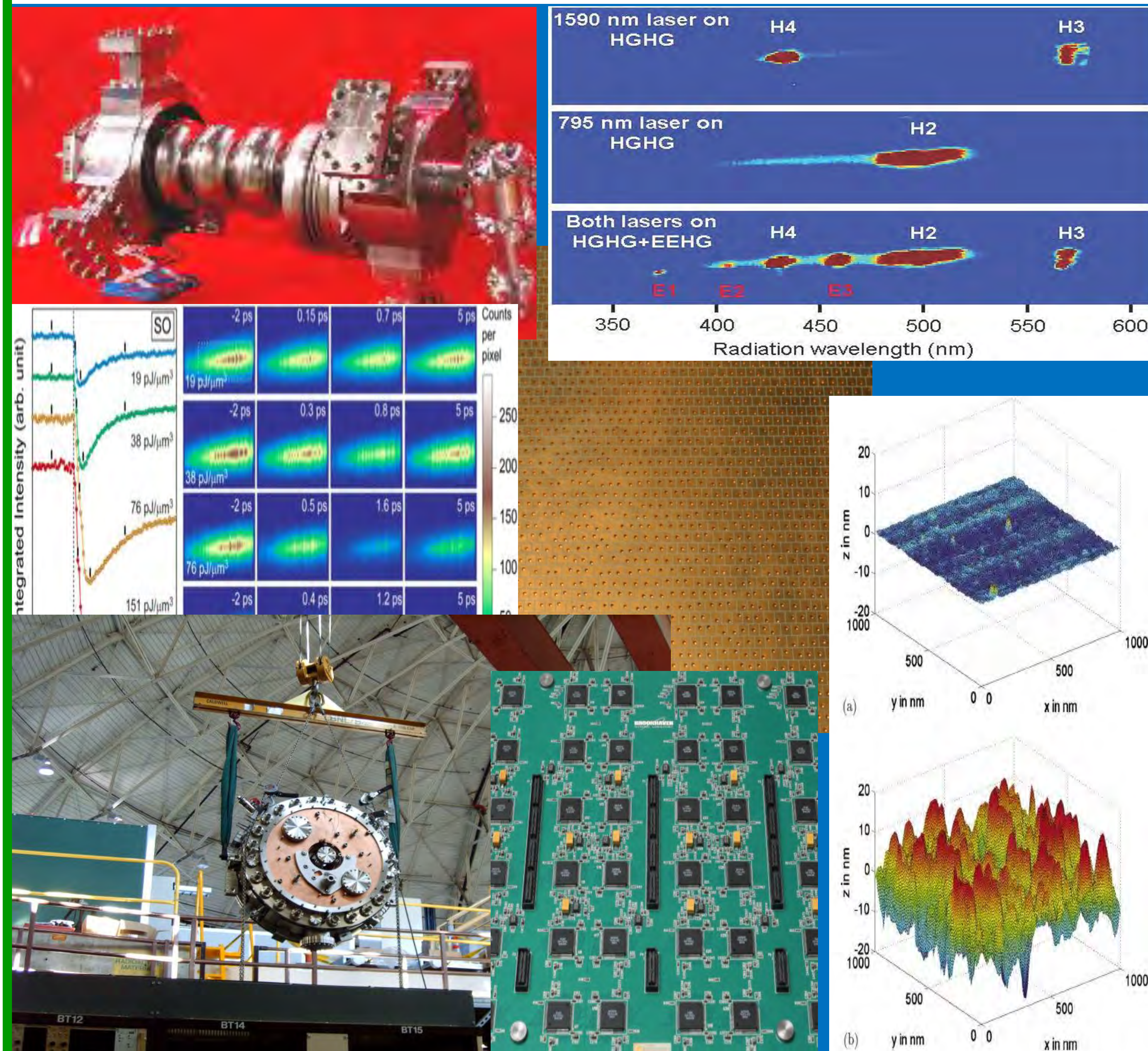
Accelerator and Detector Research and Development Program 2011 Principal Investigators' Meeting

Program and Abstracts



The Westin, Annapolis, MD, August 22-23, 2011

U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Basic Energy Sciences
Scientific User Facilities Division

NOTE: The printed version of this abstract book is provided in black-and-white; the accompanying CD contains full color versions of all the abstracts.

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between the U.S. Department of Energy and Oak Ridge Associated Universities.

ABOUT THE COVER

Upper left is a 1497 MHz superconducting cavity which has been optimized for high average current light sources by providing high acceleration gradients, large apertures, low losses, and substantial higher order mode (HOM) damping. The damping is provided through three HOM waveguides on each end of the cavity with an axial rotation to provide coupling to all modes. Fundamental power can be fed to the cavity through one or more of the same waveguides.

The initial demonstration of the Echo Enhanced Harmonic Generation (EEHG) seeding technique was made with a large energy chirp on the beam to shift the EEHG signals relative to the High Gain Harmonic Generation (HGHG) signals: PRL, 105: 114801 (2010). The top plot shows the measured radiation spectrum with just the laser at 1590-nm modulating the beam while the middle plot shows the spectrum with the 790-nm laser modulating the beam. The bunching measured in both these cases is due to the HGHG process. The bottom plot shows the result with both lasers modulating the beam. The additional EEHG signals can be seen (E1, E2, and E3). Further confirmation that these were due to the EEHG process was attained by comparing the frequency shifts of the different signals as a function of chirp amplitude.

Time evolution of the spin-ordered phase of a nickelate sample in a pump-probe experiment at the LCLS. The LBNL FastCCD detector was used to record shot-by-shot resonant soft X-ray diffraction patterns, allowing for the correction of intensity and timing fluctuations. Times shown are for the X-ray probe pulse relative to an optical laser pump pulse. From Y. D. Chuang, W. S. Lee, et al., in press.

The figure shows the LBNL CW photocathode gun being transported into place in the Beam Test Facility underneath the dome of the Advanced Light Source at LBNL. This electron gun operates in CW mode, the cavity is resonant in the VHF band (~200MHz), and is designed to produce high repetition rate and high-charge bunches with low emittance (nominally 1 MHz, up to 1 nC, and ≤1 mm-mrad). Advantages of the VHF cavity include low power density from RF currents in the cavity walls (readily cooled with conventional water channels), and excellent vacuum properties achieved through slots connecting to a pumping plenum around the azimuth of the cavity. The cathode is accessible via a vacuum load-lock, and various types of photocathodes are planned to be tested from LBNL and from collaborating institutions.

Nine-layer printed circuit board developed for the neutron pad detector, photographed from the top side, with the anode pads (gold plated copper). Each pad is 5mm by 5mm, and the complete array is 48 pads by 48 pads, providing an area coverage of 24 cm by 24 cm containing 2304 pads, or pixels.

The same nine-layer board shown above photographed from the bottom side, to which are soldered the Application Specific Integrated Circuits (ASICs), represented by the black square plastic packages. Each ASIC contains 64 channels, and the 36 ASICs therefore provide independent electronic channels to all 2304 pads. The transistor count in all those 36 ASICs is approximately 10 million !

Cornell University: the images show the surfaces of negative electron affinity GaAs photocathodes obtained with atomic force microscopy, that along with theoretical modeling explain anomalously large thermal emittance measured from these photocathodes. While the smooth crystalline surfaces as shown in (a) are expected to give sub-thermal transverse energy spread due to very low effective mass of the electrons inside GaAs, the rough surface as depicted in (b) after a typical preparation procedure leads to effective increase of the thermal emittance and can account for the discrepancy between theoretical predictions and experimental results as encountered in scientific literature. This work points out a way towards realization of sub-thermal transverse energy spread photocathodes, which will have immediate impact on high brightness electron sources.

Foreword

This volume summarizes the scientific content of the first Principal Investigators' meeting of the Accelerator and Detector Research and Development (ADRD) Program, sponsored by the Department of Energy Office of Basic Energy Sciences. The primary purpose of the meeting is to provide an opportunity for the exchange of information and ideas among DOE laboratory and university researchers, and to foster synergistic activities. The meeting also serves DOE/BES management to assess the state of the program, consider its future direction, and identify programmatic needs.

The ADRD Program supports a wide range of research and development activities in accelerator physics and x-ray and neutron detectors to develop new concepts in accelerator design for synchrotron radiation and spallation neutron sources. The Program has significantly expanded its funding for laboratory and university projects in the past two years. In addition, we are proud to sponsor five Early Career awardees. The Early Career Research Awards support the development of individual research programs of outstanding scientists early in their careers.

We organized the presentations in five sessions: three technical sessions, a brainstorming session to stimulate discussions on the potential applications for plasma accelerators and on the key characteristics of a test facility for future accelerators, and a final session where an overview of progress made on future light sources was designed to lead an open discussion on R&D needs for building the next generation light sources.

We gratefully acknowledge the contributions from all the participants, from the Program's principal investigators, to the coordinators of the discussion sessions, to the plenary speakers who gracefully accepted to cover wide and significant areas in their subject talks. We also thank Ms. Linda Cerrone, whose support was essential to the meeting's realization, and Ms. Connie Lansdon from the Oak Ridge Institute for Science and Education.

Eliane Schnirman Lessner
Program Manager,
Accelerator and Detector R&D Program
Scientific User Facilities Division
Office of Basic Energy Sciences
Department of Energy
August 2011

Accelerator and Detector Research and Development Program
2011 Principal Investigators' Meeting
Office of Basic Energy Sciences

The Westin Annapolis
100 Westgate Circle
Annapolis, MD 21401
Capitol Ballroom D

AGENDA

Monday, August 22, 2011

7:30 a.m.	Continental breakfast
8:00 a.m.	Registration and poster setup
8:30 - 9:30 a.m.	**BES Welcome** and Introductory Remarks, **"BES Perspectives"** *Harriet Kung, Associate Director* *Office of Basic Energy Sciences* *Eliane Lessner, Program Manager* *Accelerator and Detector Research and Development*
9:30 - 9:45 a.m.	Break
	Technical Session I: **Injectors, Accelerators, Cathodes, and Beam Dynamics-I**
9:45 - 10:00 a.m.	**A CW VHF Laser Photocathode Gun using a Room Temperature Copper Cavity** *John Corlett, Lawrence Berkeley National Laboratory*
10:00 - 10:15 a.m.	**The Wisconsin Superconducting RF Gun** *Joseph Bisognano, University of Wisconsin - Madison*
10:15 - 10:30 a.m.	**R&D Studies for Next Generation Light Sources** *Gwyn Williams, Thomas Jefferson National Accelerator Laboratory*
10:30 - 10:45 a.m.	**Photocathodes for High Repetition Rate Light Sources** *John Smedley, Brookhaven National Laboratory*
10:45 - 11:00 a.m.	**Extending Science and Technology behind High Brightness and Duty–Factor Photoinjectors** *Ivan Bazarov (Early Career Award), Cornell University*

11:00 - 11:15 a.m.	**Generation and Characterization of Ultrashort Electron-Beams for X-ray FELs** *Yuantao Ding (Early Career Award), SLAC National Accelerator Laboratory*
11:15 - 11:30 a.m.	**Towards Large Dynamic Range Beam Diagnostics and Beam Dynamics Studies** *Pavel Evtushenko (Early Career Award), Thomas Jefferson National Accelerator Laboratory*
11:30 - 12:30 p.m.	**Poster Session** *(Capitol Ballroom A/B)*
12:30 - 1:30 p.m.	**Lunch** (provided)
1:30 - 2:20 p.m.	**Plenary Session I: "Scientific Drivers and Required X-ray Capabilities"** *Fulvio Parmigiani, University of Trieste, Italy*
2:20 - 2:35 p.m.	Break
.	**Technical Session II**: **Detectors**
2:35 - 2:50 p.m.	**Advanced Neutron Detectors with Pad Readout** *Graham Smith, Brookhaven National Laboratory*
2:50 - 3:05 p.m.	**Advanced Detectors for Synchrotron Radiation** *Peter Siddons, Brookhaven National Laboratory*
3:05 - 3:20 p.m.	**Detector R&D at LBNL** *Peter Denes, Lawrence Berkeley National Laboratory*
3:20 - 3:35 p.m.	**Science "Inside" the Synchrotron Pulse Width: X-ray Pump/Optical Probe Cross-Correlation Study of GaAs** *Stephen Durbin, Purdue University*
3:35 - 3:50 p.m.	**Area X-ray Pixel Array Detectors for Time-Resolved Synchrotron Applications** *Sol Gruner, Cornell University*
3:50 - 4:05 p.m.	**Superconducting Sensors for X-ray Science** *Antonino Miceli (Early Career Award), Advanced Photon Source*
4:05 - 4:20 p.m.	**Simulation and Development of a Coded Source Neutron Imaging System** *Philip Bingham (Early Career Award), Oak Ridge National Laboratory*
4:20 - 5:00 p.m.	**Poster Session** (*Capitol A/B*) (light refreshments, cash bar)

5:00 - 7:00 p.m.	**Dinner** (on your own)
.	**Brainstorming Discussion**
7:00 - 8:00 p.m.	**Potential for Plasma Accelerators** Coordinator: *Wim Leemans, Lawrence Berkeley National Laboratory*
8:00 - 9:00 p.m.	**Characteristics of an Ideal Test Facility** Coordinators: *Claudio Pellegrini, University of California at Los Angeles* and *Tor Raubenheimer, SLAC National Accelerator Laboratory*

Tuesday, August 23, 2011

7:30 a.m.	Continental Breakfast
8:30 - 9:20 a.m.	**Plenary Session II: "Beam Dynamics at the Radiation Scale"** *James Rosenzweig (talk given by Pietro Musumeci), University of California at Los Angeles*
9:20 - 9:35 a.m.	Break
	Technical Session III: **Terawatt X-ray Radiation, Beam Dynamics-II, and Lasers**
9:35 - 9:50 a.m.	**Terawatt X-ray FELs for Biological Applications** *Claudio Pellegrini, University of California at Los Angeles*
9:50 – 10:05 a.m.	**The UCLA Program in Advanced Beam and Light Source Physics** *Pietro Musumeci, University of California – Los Angeles*
10:05 - 10:20 a.m.	**Toward Single e-Bunch Shape Diagnostics using THz Coherent Radiation** *Albert Sievers (talk given by Nikolay Agladze), Cornell University*
10:20 - 10:35 a.m.	**The Echo-7 Experiment at the NLC Test Accelerator** *Tor Raubenheimer, SLAC National Accelerator Laboratory*
10:35 - 10:50 a.m.	**Current Status of Modeling of Accelerators for Next Generation Light Sources** *John Corlett, Lawrence Berkeley National Laboratory*
10:50 - 11:05 a.m.	**Advanced Electromagnetic Modeling for BES Accelerators with ACE3P** *Cho Ng, SLAC National Accelerator Laboratory*

11:05 - 11:20 p.m.	**Coherent Light Source R&D at MIT** *William Graves, Massachusetts Institute of Technology*
11:20 - 11:35 p.m.	**Key Laser Technologies for X-Ray FELs: Pulsed Timing and Synchronization Systems** *Franz Kärtner, Massachusetts Institute of Technology and DESY, Hamburg*
11:35 - 12:15p.m.	**Poster Session** (*Capitol A/B*)
12:15 - 1:15 p.m.	**Lunch** (provided)
1:15 - 2:05 p.m.	**Plenary Session III: "Broad Update on the Progress towards Future Light Sources, Including R&D Progress"** *Ilan Ben-Zvi, Stony Brook University and Brookhaven National Laboratory*
2:05 - 3:30 p.m.	**Discussion** Coordinators: *Ilan Ben-Zvi, Stony Brook University* and *Michael Borland, Argonne National Laboratory*
3:30 – 3:45 p.m.	**Closing Remarks**
3:45 p.m.	**Adjourn**

Table of Contents

Poster-Only Contributors Abstracts

Technical Session I

Injectors, Accelerators, Cathodes, and Beam Dynamics–I

A CW VHF laser photocathode gun using a room temperature copper cavity

F. Sannibale, B. Bailey, K. Baptiste, J. Byrd, A. Catalano, D. Colomb, J. Corlett, C. Cork, S. De Santis, L. Doolittle, J. Feng, D. Filippetto, D. Garcia Quintas, G. Huang, S. Kwiatkoswski, M. Messerly*, W. E. Norum, H. Padmore, C. Papadopoulos, G. Penn, G. Portmann, M. Prantil*, S. Prestemon, J. Qiang, J. Staples, M. Stuart, T. Vecchione, M. Venturini, M. Vinco, W. Wan, R. Wells, M. Zolotorev, F. Zucca
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*Lawrence Livermore National Laboratory, Livermore, CA 94550

Proposal Title: Accelerator Research for a Next Generation Light Source

Scientific Challenge and Research Achievements:
We describe the development of a new concept high repetition rate high-brightness electron source for free electron laser (FEL) and energy recovery linac (ERL) applications. The successful development of such source will critically impact the performance of future 4th generation light sources when high-repetition rates (> 10 kHz) are required. The core of the system is a normal-conducting continuous wave (CW) RF cavity where the electrons are generated by laser-induced photo-emission on high quantum efficiency (QE) photo-cathodes and accelerated by the cavity fields up to about 750 keV energy. The cavity has been designed to resonate at about 200 MHz in the VHF frequency region. The low frequency choice makes the resonator size large enough to lower the power density on the structure walls at a level that conventional cooling techniques can be used when the cavity is run in CW mode. Another advantage of the low frequency is the relatively long wavelength that allows for large apertures on the cavity walls with negligible distortion of the field in the cavity. Such apertures are necessary for achieving high vacuum conductance allowing for the very low pressures required by the high QE semiconductor cathodes sensitive to contamination. An additional advantage of such a scheme is that it is based on mature and reliable RF and mechanical technology, a very important characteristic to achieve the reliability required to operate in a user facility.
Achievements include:

- Cavity, RF couplers, and tuner hardware are completed and integrated. Low power RF tests showed a frequency and quality factor in agreement with predictions. Tuner piezo actuators and controls are being finalized. Initial vacuum tests demonstrated the vacuum integrity and promising vacuum performance. The gun is installed and aligned in its final destination in the ALS Beam Test Facility (BTF), and final assembly of components and utilities is under way.
- The 120 kW VHF power supply is installed at the BTF and acceptance tests complete.
- The photocathode laser system developed in collaboration with LLNL has been delivered and re-commissioned at LBNL.
- Commissioning and debugging of the FPGA –based LLRF system is under way. Controls will use an EPICS system, and high level controls software is being developed in MathLab and will continue during the beam commissioning.
- Beamline components and diagnostics systems have been defined, designed, and are in advanced phase of fabrication.
- A collaboration with INFN Milano for the fabrication of Cs_2Te cathodes is in place. The cavity load-lock vacuum system is in the final phase of fabrication. The development of vacuum transport and installation systems for the K_2CsSb cathodes under development at

LBNL is under way. Systems for installing diamond cathodes in collaboration with a BNL group are under construction.

- Beam dynamics studies allowed definition of the beamline layout for the beam tests at the VHF gun energy. Work is under way to complete the layout for the proposed second phase of the project where the addition of a small linear accelerator will allow acceleration of the beam to an energy sufficient to measure the brightness of an injector based on the VHF gun.

Future Work:

- Complete the conditioning and commissioning of the VHF RF system.
- Complete the Control System development and commission it. Complete the control room.
- Continue beam dynamics studies for accelerator optimization.
- Commissioning and characterization of initial photo-cathode and of other possible cathodes.
- Characterize the electron beam at low energy and compare results with simulations.
- Develop the conceptual design of APEX Phase II that includes acceleration and characterization of the beam to a few tens of MeV for demonstrating the brightness of an injector based on the VHF gun.

Publications:

[1] *Low Energy 6D Beam Diagnostic for APEX, the LBNL VHF Photo-injector*. D. Filippetto, J.M. Byrd, M.J. Chin, C.W. Cork, S. De Santis, L.R. Doolittle, J. Feng, W.E. Norum, C. F. Papadopoulos, G.J. Portmann, D.G. Quintas, F. Sannibale, M.E. Stuart, R.P. Wells, M.S. Zolotorev. 2011 Particle Accelerator Conference, New York, NY USA, March 2011.

[2] *Photoinjector beam dynamics for a next generation x-ray FEL.* C.F. Papadopoulos, J. Corlett, D. Filippettso, G. Penn, J. Qiang, F. Sannibale, J. Staples, R. Wells, M. Venturini, M. Zolotorev. 2011 Particle Accelerator Conference, New York, NY USA, March 2011.

[3] *Drive Laser System for the Advanced Photo-Injector Project at the LBNL.* J. Feng, D. Filippetto, H.A. Padmore, F. Sannibale, R.P. Wells, M. J. Messerly, M.A. Prantil. 2011 Particle Accelerator Conference, New York, NY USA, March 2011.

[4] *Studies of a Linac Driver for a High Repetition Rate X-ray FEL*. M. Venturini, J.N. Corlett, L.R. Doolittle, D. Filippetto, C. F. Papadopoulos, G. Penn, D. Prosnitz, J. Qiang, M.W. Reinsch, R.D. Ryne, F. Sannibale, J.W. Staples, R.P. Wells, J.S. Wurtele, M.S. Zolotorev, A.A. Zholents. 2011 Particle Accelerator Conference, New York, NY USA, March 2011.

[6] *Status of the LBNL Normal-Conducting CW VHF Electron Photo-Gun.* F. Sannibale, B. Bailey, K. Baptiste, A. Catalano, D. Colomb, J. Corlett, S. De Santis, L. Doolittle, J. Feng, D. Filippetto, G. Huang, R. Kraft, D. Li, M. Messerly, H. Padmore, C. F. Papadopoulos, G. Portmann, M. Prantil, S. Prestemon, J. Qiang, J. Staples, M. Stuart, T. Vecchione, R. Wells, M. Yoon, M. Zolotorev. Proceedings of the 2010 Free Electron Laser Conference, Malmo, Sweden, August 2010.

[7] *Multiobjective Optimization for the Advanced Photo-injector EXperiment (APEX).* C.F. Papadopoulos, J. Corlett, D. Filippeto, J. Qiang, F. Sannibale, J. Staples, M. Venturini, M. Zolotorev. Proceedings of the 2010 Free Electron Laser Conference, Malmo, Sweden, August 2010.

THE WISCONSIN SUPERCONDUCTING RF GUN *

J. Bisognano, R. Bosch, D. Eisert, M. Fisher, M. Green, K. Jacobs, K. Kleman, J. Kulpin, G. Rogers (UW-Madison/SRC); J. Lawler, D. Yavuz (UW-Madison); R.Legg (JLAB); T. Miller (UIUC)

Proposal Title

Construction and Test of a Novel Superconducting RF Electron Gun

Research Achievement

The University of Wisconsin FEL team is moving forward with the development a 199.6 MHz superconducting RF gun that meets the required specifications for a CW FEL [1] in the soft X-ray region. A three year program is under way, with key procurements in place and installation of the hardware and commissioning in a year time frame. The principal parameters for the electron gun are shown in Table 1.

Parameter	Value
Beam kinetic energy	4.0 MeV
Bunch charge	10–200 pC
Norm. trans. emittance	0.2–0.9 mmmr
Max. average beam current	1.0 mA
Peak current (at 100 MeV)	50 A
Photocathode	varied
Driving laser wavelength	266 nm
Pulse duration (FWHM)	0.100 ps
Bunch repetition rate	5 MHz
Electric field at cathode	45 MV/m

Table 1: SRF Electron Gun Parameters

An SRF electron gun was chosen because it is well suited to the requirements of an accelerator based lightsource. It uses low charge bunches with a high peak current at the exit of the injector to minimize downstream magnetic compression and reduce collective effects. The electric fields on the cathode in an SRF gun are higher than other CW sources (>20 MV/m) resulting in greater ultimate brightness. Finally, the electron bunch pulse repetition rates for SRF guns are only limited by the RF power couplers and HOM suppression, meaning that user beamlines can be driven at megahertz repetition rates by a single accelerator. These features make the SRF gun very attractive at moderate currents compared to other devices proposed. The SRF electron gun design is shown in Figure 1. Further details of the design may be found in reference [2]. This approach complements programs in room temperature RF guns at LBNL, DC guns at Cornell, and L-band guns in Europe.

The electromagnetic design itself was optimized to produce maximum electric field at the cathode while minimizing the peak electric field in the cavity. This will reduce the possibility of field emission limiting the cavity gradient. Similarly, the peak surface magnetic field was minimized to reduce the possibility of magnetic quench of the cavity. The cavity was also optimized to produce a large integrated field between the cathode and anode gap in order that the gun should have a large exit energy. The overall design produces very bright bunches that have sufficient momentum to use the demonstrated LCLS emittance compensation scheme (gun / solenoid / linac section) as part of the injector for an FEL. The cathode is warm with respect to the cavity. Another feature of the design is a high T_c superconducting solenoid for emittance compensation.

To meet the stringent requirements on the longitudinal distribution of the bunch to avoid density modulations in the FEL, we plan to use self inflating (blow out mode) bunches for the FEL. Blow out mode is a scheme in which a laser pulse that is significantly shorter than the final bunch length is used to create a charge pancake on the surface of the cathode, which then expands under its own self space charge force to an ellipsoidal bunch with uniform charge density [3].

*The electron gun program is supported by DOE Award DE-SC0005264.

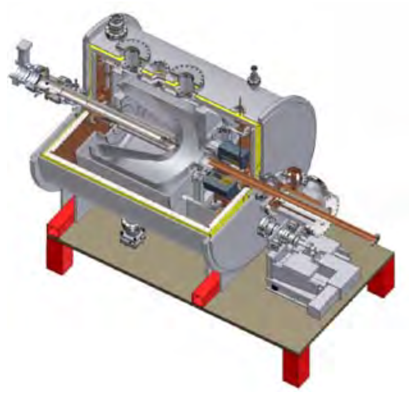

Figure 1: SRF Gun and Cryostat

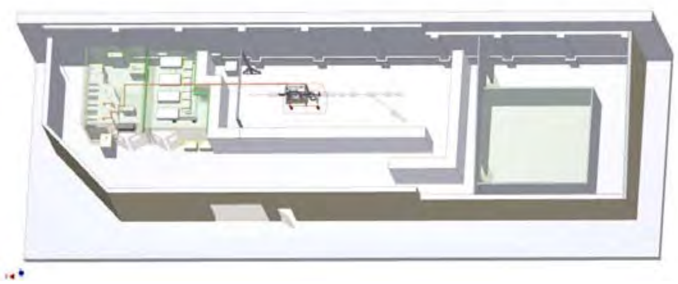

Figure 2: SRF Gun Vault

Future Work

Major procurements are now in place. Niowave is fabricating the cavity/helium vessel, and Danfysik is responsible for the High T_c emittance compensation solenoid. A variant of the Jefferson Lab 12-GeV low level RF control module will used to operate the 20 kW solid state RF system that has been delivered. The photocathode laser system has been selected and is scheduled for delivery at the end of the year. A vault area (Figure 2) adjacent to the Aladdin synchrotron is currently being refurbished as the home of the electron gun, and there is sufficient space to allow installation of a post-accelerator at a later date. Installation and system commissioning is scheduled for early 2012 with beam testing scheduled for fall 2012.

References

[1] J. Bisognano, et al., “The Wisconsin Free Electron Laser Initiative,” in: Proceedings of the 2009 Part. Accel. Conf. (2009).
[2] R. Legg, et al., “SRF Photoinjector R&D at University of Wisconsin,” in: Proceedings of ERL09, 45th ICFA Advanced Beam DynamicsWorkshop.
[3] O.J. Luiten, et al., “How to Realize Uniform Three-Dimensional Ellipsoidal Electron Bunches,” Phys. Rev. Lett. **93**, 094802 (2004).

Publications

J. Bisognano et al., “Progress toward the Wisconsin Free Electron Laser Facility,” 2011 Particle Accelerator Conference, 2011.

R. Legg, “Gun R&D at Wisconsin,” Mini-workshop on Compact X-ray FELs, LBNL, Berkeley, CA, August 5-6, 2010.

R. Legg, M. Fisher, K. Kleman, “Development of a Frequency Map for the WIFEL SRF Gun,” SRF 2011, Chicago, IL, July 25-29, 2011.

R&D Studies for Next Generation Light Sources

S. V. Benson, D. R. Douglas, P. Evtushenko, F. E. Hannon, C. Hernandez-Garcia, J. M. Klopf, R. A. Legg, G. R. Neil, R. A. Rimmer, M. D. Shinn, C. D. Tennant, S. Zhang and G.P. Williams.
Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA, 23606, USA

Proposal Title:
SRF Developments for Next Generation Light Sources

Scientific Challenges and Research Achievements:
Next generation light sources require high average and peak brightness low emittance electron beams [1]. At Jefferson Lab we operate the energy recovered superconducting linac [2] shown in Fig. 1 as a light source R&D test facility to study the generation and transport of such beams, as well as the physics of the Free Electron Laser (FEL) process using two optical oscillators [3].

Specifically under this contract we first designed and built the high current superconducting linac cavity pair shown schematically in Fig. 2. Second, we successfully installed and operated the world's highest gradient CW superconducting linac, with 8 × 7-cell cavities similar to the one shown in Fig. 3, and then tested it by driving an oscillator-based UV-FEL with harmonics up to 10 eV, at brightness levels 2 orders of magnitude higher than storage ring based sources. During these studies we studied the propagation of low emittance electron beams in our multi-pass, energy recovering machine and FEL gain mechanisms.

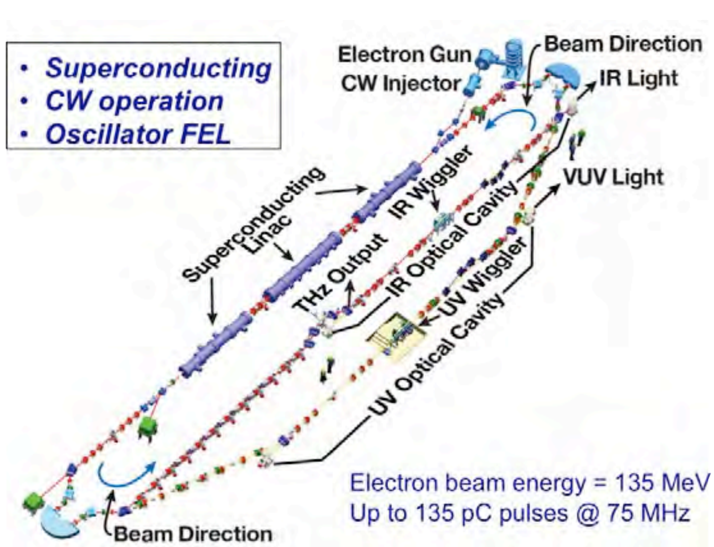

Fig. 1. Layout of the JLab FEL used for this R&D study.

The present activities are guided by developments in refining user needs for 4th generation light sources, and in particular the road-map defined by the BES sponsored Barletta-Corlett report [1]. Thus priority for high gradient became apparent early in CY 2010. In addition, recent calculations relating the peak beam current required to deliver the GW peak power levels required by the users, imply a reduction in peak current demands in the accelerator [4].

The electron beam quality has been evaluated since June 2010 with reference to gain in an optical oscillator operating as a light source. To do so requires repetition rates of 4.7 MHz and higher, which correspond to the round-trip time of the cavity. First lasing was obtained from this system in August 2010, and in March 2011 the third harmonic output of this oscillator was delivered into a user lab. Measurements indicate 5 nanoJoules (3×10^9 photons) of fully coherent light being produced at the output of the FEL in each 10eV micropulse. This represents approximately 0.1% of the energy in the fundamental, as expected. These numbers allow us to anticipate being able to deliver 25 - 100 mW by operating CW at up to 4.687 MHz with more optimized water-cooled optics, and several 100's of mW with cryogenically-cooled optics.

Notice: Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

In addition to the above activities we are involved with materials studies aimed at higher gradients, lower loss (higher Q) linacs, and with injector design including collaborations primarily with Berkeley and Wisconsin regarding low emittance injectors.

Future activities: To our studies of low emittance electron beams in re-circulating, energy recovering machines and FEL gain mechanisms, we plan to add designs and tests of low-emittance injectors. This would involve collaborations with other R&D programs. We also plan theoretical and experimental tests of CSR emittance growth in bends, a study critical to the preservation of high brightness in multipass linacs. We plan to install and test a second higher gradient cryomodule, which would allow us to study propagation of higher energy beams, and FEL gain mechanisms at higher beam energies [5]. And finally, we plan to install a new undulator A on loan from Argonne. We have returned the one on loan from Cornell that was used for the initial testing.

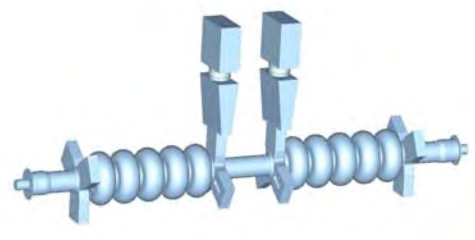

Fig. 2. High current cavity showing the rf coupling and harmonic damping.

These plans are supported by 3 reports. First we have studied re-circulation of low-emittance beams up to 600 MeV [6], second, connected the peak electric field in the user's experimental sample chamber with the peak current in the FEL [3], and third, studied a VUV/soft X-ray oscillator [5].

Publications:

1. W. Barletta et al., "Free electron lasers: Present status and future challenges," Nuclear Instruments & Methods in Physics Research, **A618** 69 (2010).
2. G.R. Neil et al., "The JLab High Power ERL Light Source", Nucl. Instr. & Methods **A557** 9 (2006).
3. S. V. Benson et al., "The VUV/IR/THz Free Electron Laser Program at Jefferson Lab", Nucl. Instr. and Meth. A doi:10.1016/j.nima.2010.12.093 (2010).
4. S.L. Hulbert and G. P. Williams, "Calculations of Synchrotron Radiation Emission in the Transverse Coherent Limit", Rev. Sci. Instr. **80**, 106103 2009.
5. S. V. Benson et al. "A Proposed VUV Oscillator-based FEL Upgrade at Jefferson Lab", submitted to Journal of Modern Optics (2011).
6. C. Tennant and D. Douglas, "Design Concept for a Compact ERL to Drive a VUV/Soft X-Ray FEL", to appear in Proc. PAC2011 (New York, March 2011); www.jacow.org.

Fig. 3. High gradient superconducting linac cavity strings under assembly at Jefferson Lab.

Acknowledgements: Work funded by DOE Basic Energy Sciences, the Office of Naval Research, the Air Force Research Laboratory, the Joint Technology Office, and the Commonwealth of Virginia.

Photocathodes for High Repetition Rate Light Sources

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Proposal Title: Photocathodes for High Repetition Rate Light Sources

Scientific Challenge

Fourth generation light sources, such as Energy Recovery Linacs (ERL) and Free-Electron Lasers (FEL), represent the future of x-ray science, with higher brightness, better time resolution, and greater coherence than current synchrotron-based light sources. However, the electron sources to make high repetition FELs and high current ERLs are beyond the current state of the art [1]. The goal of this project is to develop high average current electron sources, including photocathodes and amplifiers, for modern light source applications. The research objectives of this work are:

- To use the tools of modern materials science to understand the growth of alkali antimonide cathodes. This includes understanding the crystalline properties of the cathode (texture, grain size, strain) and how they are influenced by substrate and growth parameters.
- To characterize the emission process, including spectral response and momentum distribution, thus allowing the properties of the emitted beam to be understood.
- To understand and optimize the diamond amplifier for light source applications.
- To test the performance of both the diamond amplifier and alkali antimonide cathodes in a range of practical injector environments, including both NCRF and SRF injectors.
- To understand failure modes and factors limiting performance by post-operation analysis of the cathodes.

This project brings together the accelerator physics and materials science programs at three institutions (LBNL, BNL and SUNY Stonybrook), and leverages the capabilities of several major user facilities (NSLS, APS, ALS, CFN, CNM). This project is in its first year, but has already made significant progress on both diamond amplifiers and alkali antimonide cathodes.

Research Achievements

High quantum efficiency **alkali antimonide** cathodes have been grown at both BNL and LBNL. The momentum distribution of the emitted electrons has been characterized from a K_2CsSb cathode. In-situ analysis of cathode growth has begun at NSLS beamline X21. Ex-situ analysis of the substrate dependence of the antimony layers has been done at NSLS beamline X20C and APS beamline ID11D.

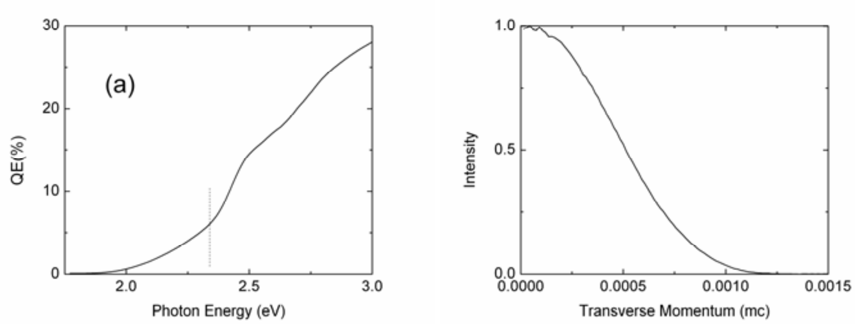

Figure 1 QE and normalized transverse momentum of alkali antimonide cathodes

We have developed techniques to grow high QE films and established a new technique to measure transverse momentum measurements at low energy, directly after deposition. Initial results have shown QE up to 6% at 532 nm, and we have measured normalized rms transverse momentum down to 0.36 microns / mm rms at 543 nm. We have also demonstrated tuning of the transverse momentum distribution through stoichiometric influence on the electron affinity.

One of the major aspects of this program is analysis of cathode formation during growth, using in-situ X-ray diagnostics (fluorescence, diffraction and reflectivity). This work has yielded a wealth of information on the growth of Sb films – fig. 2 shows a textured Sb film sputtered onto polished Mo. A system to do in-situ cathode growth at NSLS beamline X21 has been designed and is under construction.

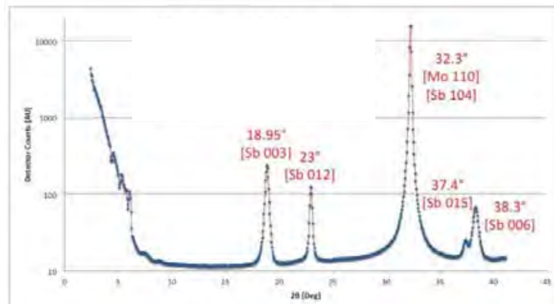

Figure 2 Theta-2heta scan of Sb film sputtered on a Mo substrate. The film exhibits a clear [003] texture.

The **Diamond amplifier** is a promising technique to increase the effective quantum efficiency by orders of magnitude with a good lifetime and low thermal emittance [2]. Hydrogenation of the diamond amplifier endows it with the negative electron affinity property, fundamental to emission of electrons into vacuum. A systematic study of hydrogenation in a diamond amplifier was carried out, leading to a recipe that delivers consistently high emission gain amplifiers.

Electron emission from diamond is critical to the function of the diamond amplifier. Electrons which reach the diamond surface in the conduction band minimum are constrained by momentum from direct emission. However, strong electron-phonon coupling enables emission through a multi-body process, resulting in an energy spectrum of the emitted electrons showing clear phonon peaks [3]. This was observed (fig 3) using a 6 eV laser with angle-resolved photoemission spectroscopy at NSLS beamline U13.

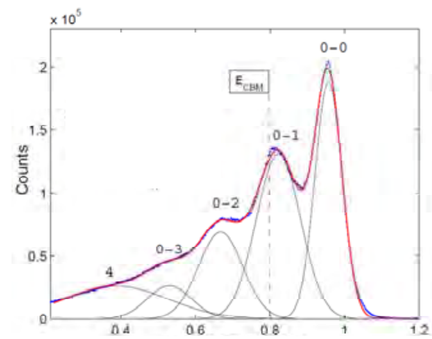

Figure 3 Energy Distribution Curve of diamond, using 6 eV laser ARPES

Future Work

The materials science studies described above are ongoing. In addition, the deposition system for the 704 MHz RF gun is in the final stages of commissioning. Preparations are already underway to introduce a diamond amplifier into the LBNL normal conducting gun.

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Extending science and technology behind high brightness and duty-factor photoinjectors

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Proposal Title

Investigation of Fundamental Limits to Beam Brightness Available From Photoinjectors

Scientific Challenge and Research Achievement

Modern and future electron accelerators that employ linear accelerators rely on photoelectron sources that can deliver high brightness and high current beams. Improvements in photoinjectors will have a dramatic effect for various applications such as coherent X-ray light sources, electron-ion colliders, and electron cooling. This proposal is to extend the state-of-the-art of high brightness photoelectron sources through theoretical and experimental understanding of fundamental physics limits to the maximum achievable beam brightness.

The brightness limit formulated for photoinjectors [1] states that the maximum brightness is proportional to the electric fields at the cathode and inversely proportional to the mean transverse energy of photoelectrons leaving the photocathode, which is an intrinsic property of the photoemissive material and its surface conditions. In addition, the intense space charge forces in the photoelectron gun vicinity need to be harnessed and controlled to avoid dilution of the phase space or make it reversible. This is usually achieved via 3D shaping of the laser pulse and appropriate electron beam optics. To this end, investigations are being carried out to 1) measure and model the intrinsic mean transverse energy of high quantum efficiency photocathodes; 2) explore novel photocathode materials and preparation techniques in real-life accelerator conditions of a high current photoinjector; 3) perform laser shaping to minimize the beam emittance after a high-voltage photoemission gun; 4) explore, both experimentally and via simulations, the implications of a virtual cathode instability on short electron bunches for transverse phase space dilution. To ensure the practical value of the advances made to the field of high brightness photoinjectors, the ultimate tests will be carried out at the world's highest average current photoinjector presently in operation, the Cornell ERL injector prototype (funded by the National Science Foundation).

Achievements to date include the development of a new stand-alone energy analyzer for the photocathode characterizations, investigation and modeling of surface conditions of negative electron affinity photocathodes and their effect on intrinsic cathode emittance, demonstration of > 1000 Coulomb charge lifetime from a multialkali photocathode and measurement of its mean transverse energy (for the first time) and the response time, the parameters of relevance for accelerator physics.

Future Work

The photocathode research lab has been established and new capabilities are being added consistent with the requirements for investigations of the photocathode material properties: the energy analyzer (being commissioned), LEED/Auger capabilities, two new growth chambers for positive and negative electron affinity photocathode growth and characterization. Much of this work is being supported by this DOE Career grant. The use of facilities available on Cornell campus such as Cornell High Energy Synchrotron Source X-ray facility, Cornell Center for Material Research and Cornell Nanofabrication Facility for the photocathode characterization has begun and will increase in future. Collaborations on modeling of electron transport inside photocathodes have been formed and are being pursued.

A new experimental beamline with improved diagnostics capabilities is being constructed for detailed investigation of space charge dominated beam dynamics after a new high-voltage photoemission gun. Detailed calculations and optimizations of the laser pulse shape and its effect on achieving the smallest beam emittance out of photoinjectors are being carried out.

Successful new photocathodes and laser shaping methods will be evaluated in the Cornell high current photoinjector.

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Generation and characterization of ultrashort electron-beams for x-ray FELs

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Proposal Tile: Early Career - Generation and characterization of ultrashort electron-beams for x-ray free-electron lasers. (4/15/2010--4/14/2015)

Main Collaborators: Z. Huang, P. Krejcik, A. Lutman, H. Merdji, L. Wang.

Scientific Challenge and Research Achievement:

The successful operation of the Linac Coherent Light Source (LCLS) [1], with its capability of generating x-ray pulses from a few femtoseconds (fs) up to a few hundred fs, opens up vast opportunities for studying atoms and molecules on an unprecedented time scale. Generation of even shorter x-ray pulses in fs to sub-fs regime is a challenging topic requiring theoretical and experimental breakthroughs to develop new concepts. At the same time, tremendous challenges remain in the mesurement and control of these ultrashort pulses with femtosecond precision, for both electron-beam (e-beam) and x-ray pulses. The objective of this project is to investigate new methods for generation and characterization of ultra-short e-beams and x-ray pulses.

1) Generation of ultrashort e-beam and x-rays.

Experimental studies for generating short x-ray pulses with a slotted-foil putting at the middle of the second bunch compressor (BC2) have been first carried out at LCLS. With a bunch charge of 250 pC, the unspoiled section of the e-beams has been clearly observed on the dump screen in the energy dimension, where a chirped beam was used in the over-compression mode. At 20 pC operating charge, we measured the single-shot FEL spectra at soft x-ray wavelengths. By properly setting up the slot width of the foil, single-spike spectrum has been observed (Fig. 1 (a)). This means in the time domain, the x-ray pulse only has a single temporal spike.

Start-to-end simulations also have been carried out for the short pulse optimization studies. In the soft x-ray regime, simulations verified that single spike x-ray pulses can be achieved by combining low charge operation with the slotted-foil at the over-compression mode (Fig. 1 (b)). In addition, because of the big chirp at the over-compression mode, it is also possible to use the undulator taper to select the core part of the electron bunch for lasing and hence get a shorter x-ray pulse. At hard x-ray regime, by tuning the linac-1 rf phase and operating at full compression in BC2, sub-fs x-ray pulses can also be achieved, without using the slotted-foil.

A two-bunch self-seeding scheme for generation of fully-coherent short x-ray pulses, with a pulse length as short as 10 fs at a few GW level, also has been studied [2].

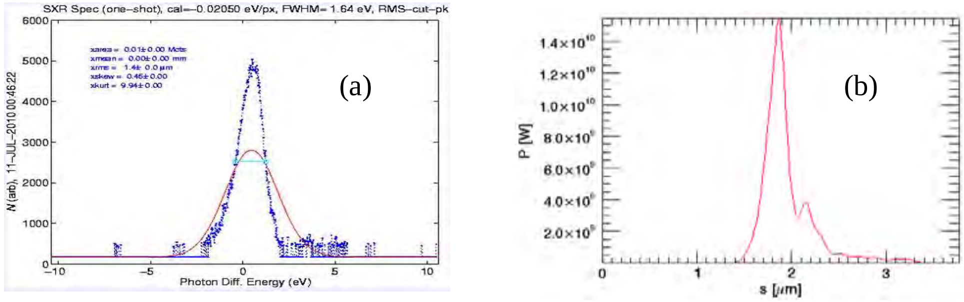

Fig. 1: (a) A snapshot of the measured single-shot FEL spectrum shows single-spike profile; (b) A simulation example of the temporal x-ray profile. Both measurements and simulations are using 20 pC charges with slotted-foil.

2) Characterization of ultrashort e-beam and x-rays.

A simple, single-shot method for measuring the longitudinal e-beam profile, which uses a chicane followed by an rf linac has been proposed and studied [3,4]. By slightly adjusting the final bunch compressor strength and running the beam on the zero-crossing phase in the linac that follows, the longitudinal z dimension is fully mapped to the energy dimension, and we only have to measure the energy distribution with an energy spectrometer to get the bunch length profile. This method has been applied to the LCLS machine using SLAC A-line as a high resolution spectrometer. We benchmarked this method with a transverse cavity at a relative longer bunch length. Experimental data shows a resolution down to 1 fs rms can be achieved at LCLS (Fig. 2).

We proposed another method to characterize the temporal duration and shape of both e-beam and x-ray pulses by measuring the time-resolved electron-beam energy loss or energy spread, with an X-band RF transverse deflecting cavity located after the undulator [5]. Its merits are simplicity, high-resolution, wide diagnostic range, and non-invasion of user operation. When the system is applied to the LCLS, simulation shows it can reach a resolution on the order of 1-2 fs rms. Conceptual design and engineering evaluation have been started for this project. Since we measure the e-beam and x-ray pulses at the same time, it will also provide an effective tool for FEL physics studies.

There are some other methods being proposed and still ongoing, such as the longitudinal-to-transverse mapping [6], laser-based modulation [7], and statistical analysis on the spectrum [8].

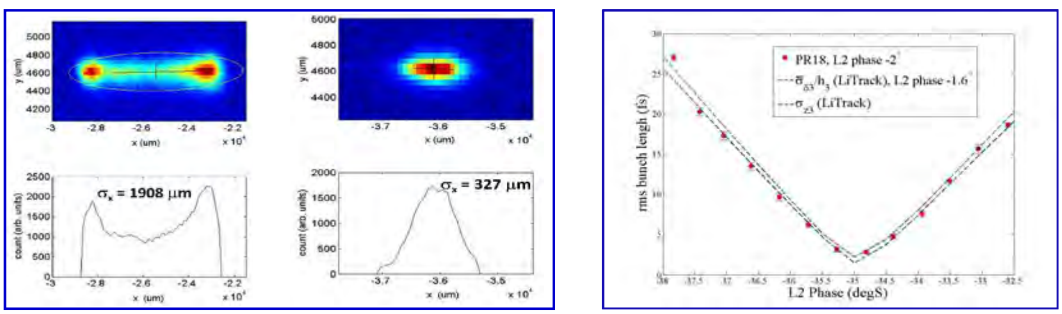

Fig. 2: Experimental measurements on the low-charge e-beam temporal profiles (left) and comparison with simulations (right). The measured resolution reaches 1 fs rms.

Future Work:

We will focus on the X-band transverse cavity project, from design, installation to experimental measurements. With this new diagnostic tool, we will have the capability to fully characterize the FEL lasing process, benchmark simulations with measurements, and optimize the machine setup for ultrashort x-ray generation. Laser based techniques and spectral domain diagnostics are also very promising in reaching a better temporal resolution, and we will continue investigations in this direction.

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Towards large dynamic range beam diagnostics and beam dynamics studies

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Proposal Title

Large dynamic range beam diagnostics and beam dynamics studies for high current electron LINACs

Scientific Challenges and Research Achievements

It is envisioned that superconducting radio frequency (SRF) linacs running average current of 1 mA or higher and a beam energy in the range of 0.6 - 1.2 GeV can be used to provide beams for next generation light sources in a seeded free electron laser (FEL) configuration. It would be beneficial to increase the average current even more to increase the number of FELs it can supply with beam simultaneously. FELs now operating in the soft and hard X-ray wavelength ranges (FLASH and LCLS) utilize average currents of up to 24 μA and 15 nA respectively, which is orders of magnitude less than the above mentioned mA. In contrast, operation of the IR-Upgrade at Jefferson Lab with average current of up to 9 mA has provided an experience base with high-current linac operation [1]. The primary operational difference between such high current linacs and storage rings, even with a few hundred mA of average current, is that linac beams have neither the time nor the mechanism to come to equilibrium, in contrast to storage ring beams – in which are essentially Gaussian. This has significant operational impact: when linac setup is made (the longitudinal and transverse matching), a tune-up beam with small average current is used. This accelerator setup is based most frequently on measured mean and RMS parameters such as beam size, bunch length, and energy spread. When going from tune up mode to higher duty cycle and CW operation, it is frequently found that the "best" RMS-data-based setup must be changed to allow for high current operation so as to eliminate beam losses. Even when this modification is successful, it is time-consuming process involving some trial and error. It is frequently unclear what the sources of problem are, and which adjustments to the low-density parts of the phase space distribution were effective in improving performance. This is highly undesirable for any user facility where high availability is required. Also of significance is that the resulting setup does not necessarily provide the best beam brightness and is a compromise between acceptable brightness and acceptably low beam losses.

Contributing to this problem is the fact that the measurements used for machine setup are typically based on methods with a dynamic range (DR) of 10^3 or even less. It is not surprising that the relevant (from the high current operation and beam loss point of view) low-intensity and large-amplitude parts of the phase space are simply not visible during machine tuning.

The figures below show an example of measurements of a low intensity fraction of the beam in the JLab FEL injector and results of a corresponding PARMELA simulation. This is an example of the measurements and simulations we intend to conduct in this study. In this example both the measurements and the simulations are reviling details of the distribution function at the level of 10^{-3}. Figure 1a (on the left) shown the transverse profile of the beam measured downstream of the injector booster unit at the beam energy of 9 MeV. The "halo" with local intensity of about 10^{-3} relative to the well-defined beam core is clearly seen surrounding the core. PARMELA simulations with $3{\cdot}10^5$ macro particles were made to imitate the experimental conditions. Results of the simulations are shown in Fig. 1b (on the right). Here the transverse beam profile, its projections to one of the axis and transverse phase space distribution are shows. Beam halo with about the same intensity relative to the core of the beam is reviled in the simulations. The goal of the proposed program is to extend the dynamic range of both the measurements and the simulations by three orders of magnitude. While we realize that it will be very challenging enterprise in our opinion it is necessary for the design and operation of future light sources.

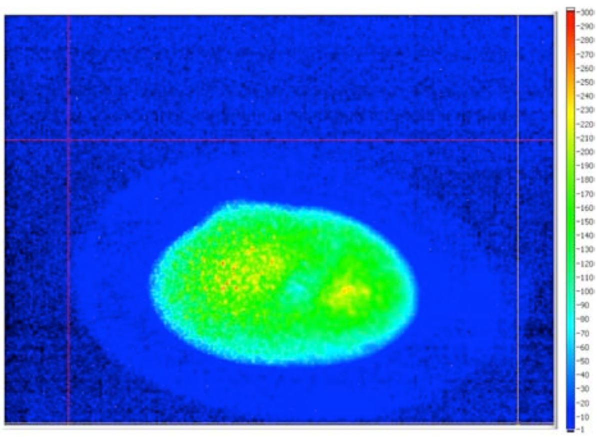

Fig. 1a: Transverse beam profile measured in JLab FEL injector with halo of relative intensity of 10^{-3}

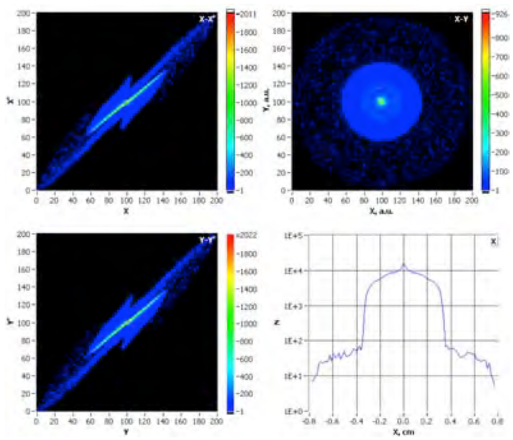

Fig. 1b: Results of PARMELA simulation with 300,000 particles – an attempt to reproduce measurements shown in Fig. 1a

Future Work

Solution to the above described problem is to base the determination of beam parameters on measurements with much larger DR. The goals of this program are following:

1. develop electron beam diagnostics to allow measurements of the transverse and longitudinal phase spaces with a significantly larger dynamic range than presently available,
2. use these diagnostics to study beam dynamics – the evolution of the phase space distribution – in an SRF linear accelerator with a high average CW current (1 mA or more),
3. develop and test electron beam optics solutions to diagnose and control the parts of the phase space distributions with very small intensity and large amplitude – i.e., halo,
4. apply, benchmark, and extend existing machine models to explain the results of the measurements and test the ability of the models to predict the generation and evolution of the low intensity tails in phase space distributions.

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Plenary Session I

Scientific Drivers and Required X-ray Capabilities

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Addressing the important and urgent needs of the present day society while doing fundamental science is one of the most challenging problems that the human kind is facing nowadays. After more than thirty years it is now evident that the science describing the interactions between electromagnetic radiation and matter plays a fundamental role for addressing the research relevant to renewable energy sources, climate change, information technology, biological complexity, and biomedicine. To translate these problems into a scientific language this requires an extraordinary intellectual effort that can be summarized as the control of complex materials and chemical processes, real time evolution of chemical reactions, motion of charges and spin, imaging and spectroscopies of object down to the nano-scale statistical laws of complex systems. Success in this endeavor requires realizing advanced radiation sources with a very high brilliance, high degree of coherence, variable polarization and complete control of the photon flux, together with very innovative detection devices and spectroscopic tools[1]. However, the insights, so far obtained, are largely relevant to systems at equilibrium. Therefore, the actual understanding of the structure of matter is mostly based upon time-independent theories and experiments in the energy (frequency) domain; by contrast, our knowledge of system out of equilibrium or under extreme conditions is very limited. Nonetheless, the access to the physics and structure of states evolving from one equilibrium state to another is of paramount importance to expanding our understanding to mechanisms that play fundamental roles in critical technologies requiring photo-chemical and bio-chemical reactions, collective excitations, phase transition, imaging of ultrafast processes of nanosystems (10^{-9} m) and matter under extreme conditions.

In these last years a significant effort has been focused to produce femtosecond (fs, 10^{15} s) duration X-ray pulses by slicing the synchrotron electron bunch with an ultrashort laser beam and setting the path for low photon flux experiments, i.e. up to 10^4-10^5 photons/s, on the dynamics of systems out of equilibrium.

Unfortunately, the technology of the synchrotron-based radiation sources cannot meet the general needs for fs-time resolution experiments, mostly because of the time structure of the electron bunches (several tens of picosecond) in the storage-rings. In addition, the nanometer (10^{-9} m) spatial resolution requested by nano-science experiments is out the range for current synchrotron sources because of their limited output coherence. Conversely, the relatively low intensity, coherence and time structure of the X-ray sources available today, along with the well known limit of generating coherent light in the X-ray region using conventional laser sources, has compelled the necessity of considering new sources such as the free electron laser (FEL) or insertion devices powered by electron beams from recirculating LINACs (linear accelerators) or energy recovery linac (ERL's). These new radiation sources, also known as fourth generation light sources, can produce X-ray pulses with an unprecedented peak brilliance (photons/second mm^2 $mrad^2$ 0.1% BW), orders of magnitude higher than those of the third generation synchrotron radiation sources, pulse durations from few fs to tens of fs with high transversal and longitudinal coherence, approaching values associated with conventional lasers but in the soft and hard X-rays spectral regions, variable (linear and circular) polarization, and significant photon energy tunability. Very interesting maps of such a photon beam parameters, related to the radiations sources are give in Fig. 1 (a-d) taken from Ref. 2

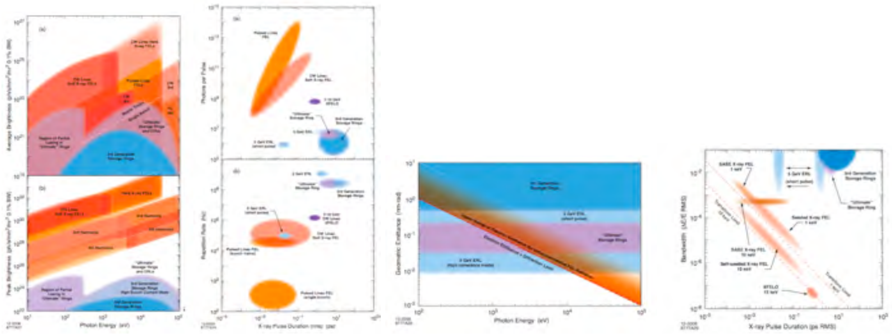

Fig.1- (a) Photon energy versus peak brightness and average brightness versus photon energy for different operating and future light sources. (b) X-ray pulse duration versus photon/pulse and repetition rate for the same light sources as reported in (a). (c) Photon energy versus geometric emittance. (d) X-ray pulse duration versus pulse bandwidth for operating and future light sources.

FEL's, both operating currently or in the near future, and ERL-based light sources will permit extending our experimental investigations to dynamic phenomena through ultrafast stroboscopic (pump-probe) experiments, single pulse coherent diffraction imaging with a spatial resolution in the nm domain, or matter under extreme thermodynamic conditions (warm and dense matter phases). This will lead, for example, to the control of several degrees of freedom such as spin and charge, opening the possibility of gaining new insights into the physics of superconductivity, magnetisms and complex materials, allowing entrance into the future of the information science, energy production, energy storage and energy saving.
Moreover, by taking advantage of the ultrabright and ultrashort pulses, single photon pulse experiments will collect images at time scales faster than radiation damage, therefore opening the possibility of studying the morphology and the structure of bio-systems unstable under Xray radiation exposure. For these reasons, this new generation of light sources will have a broad and deep impact in experiments involving the temporal evolution in the fs time-domain of chemical bonds formation and breaking, dynamics of magnetic moments, spin, and phase transition processes and imaging of objects down to nano-scale sizes with an ultimate resolution of the order of the nanometer.
Here I am reporting an overview on future light sources, such as FEL, super storage ring and ERL, aimed describing their strengths and weaknesses.
In particular, by starting from state-of-art experiments a new scenario for advanced frontiers experiments and advanced analytical tools is presented. By considering the photon beam behavior requested for such experiments a critical comparison among the different sources is presented and discussed. Finally, a strategy for the future, representing the complexity and the grand challenges offered by these facilities, is conferred.

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Technical Session II

Detectors

Advanced Neutron Detectors with Pad Readout

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Instrumentation Division, Brookhaven National Laboratory

C.L. Britton, W.L. Bryan, L.G. Clonts and S.S. Frank
Engineering, Science and Technology Division, Oak Ridge National Laboratory

Proposal Title

High Rate, High Resolution, ^{3}He-based Pad Detectors for the SNS.

Research Achievement

Existing gas-filled detectors at neutron user facilities remain popular because of their high efficiency, insensitivity to background, and relative ease in covering large areas, but they exhibit increasing dead-time losses above about 10^5 counts s^{-1}, a critical limitation for new high flux facilities. As part of a general effort to significantly improve the performance of thermal neutron detector instrumentation [1], we have developed a solution to the rate problem based upon a highly segmented anode plane and operation of the chamber with unity gain. In this technique, first evaluated by our group in one dimension [2], the primary ionization from the neutron-^{3}He interaction drifts to an anode plane composed of many "pads", each one implemented with a electronic counting channel. This can only practically be accomplished by using an Application Specific Integrated Circuit (ASIC), and a 64 channel version with electronic noise on the order of 130 electrons rms has been developed specifically for this project. These ASICs have been implemented in a prototype detector with a 48 × 48 array of pads (2304 channels) and a pad pitch of 5mm, representing a sensitive area of 24cm × 24cm. The approximately 30,000 electrons from the neutron-^{3}He interaction can be easily sensed by the ASIC using the ionization mode, making this device remarkably stable (no electron multiplication), very reliable, and capable of very high rates. Use of an appropriate "stopping" gas, mixed with the ^{3}He, to limit the range of the reaction products, a proton and triton, can lead to the primary charge sharing between two or three adjacent pads, with a consequent improvement in position resolution by a factor two over the pad pitch.

An indication of the technique's significant power is shown in the two diagrams: fig 1 shows the pulse height distribution from one pad when the device is under uniform illumination with thermal neutrons. The primary electrons from each event are collected either by one pad, or by two to three adjacent pads. The main peak corresponds to events confined to one pad; the FWHM, 1.6%, is one of the best ever recorded by a gas detector. The pulser response to an injection of charge of 5pC shows the noise at ~1% FWHM. Figure 2 illustrates the imaging capability from uniform illumination of the whole detector, with letters made from cadmium sheet placed on the entrance window.

Some key achievements from this work are:

- a prototype detector, with 24cm × 24cm sensitive area and 2304 channels, has been developed and successfully evaluated in a user facility environment at ORNL.
- the detector system has high throughput: 5kHz per channel, equivalent to 10^8 s^{-1} over $1m^2$, and 2.5mm position resolution.
- the device operates in ionization mode; there is no Frisch grid, no wire array and no plasma in the gas, so "ageing" is not a concern. The device behaves extremely stably.
- it has high efficiency for thermal neutrons, >50% for 2-10Å.

• electronics resides inside the gas enclosure (only power supplies/computer on outside).
• this development would not have been possible without the use of ASICs

Future Work

• Explore the limits of pad and ASIC density, thereby improving both rate and resolution.
• Explore the possibility of using BF_3 in place of ^{3}He.
• Investigate more sophisticated center-of-gravity algorithms for finer position resolution.
• Examine curved pad planes to allow location of detector closer to sample under study.

References

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2. B. Yu, G. J. Mahler, N. A. Schaknowski, and G. C. Smith; A Position Sensitive Ionization Chamber for Thermal Neutrons; IEEE Trans. Nucl. Sci. 48, (2001) 336-340 (2001).

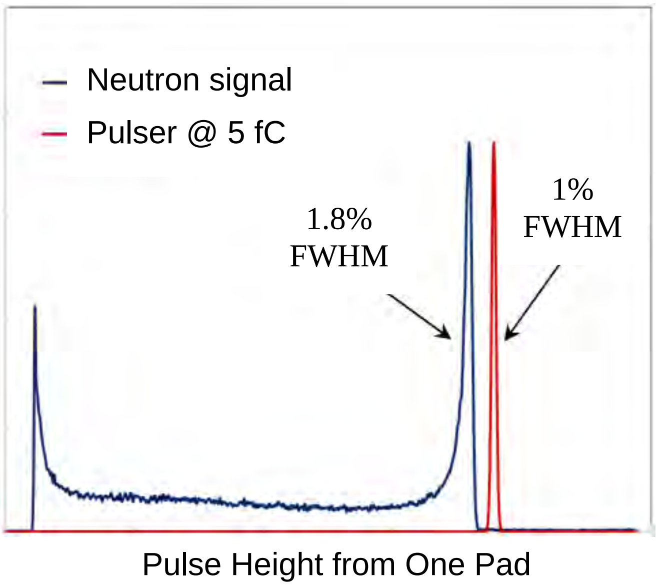

Fig. 1 Pulse height distribution from one pad when detector is uniformly irradiated with thermal neutrons. 1.8% FWHM is one of the best resolutions ever measured with a gas-based detector – also, note the very small electronic noise.

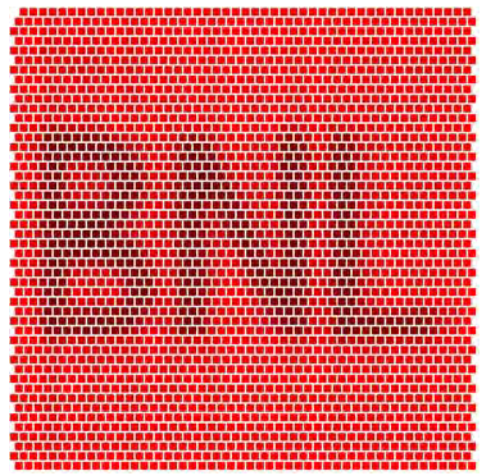

Fig. 2. Position response of detector from uniform irradiation with neutrons, with letters made from Cd placed on entrance window of the detector.

Publications from this Work

N.A. Schaknowski, G.C. Smith, B. Yu, and A. Doumas; Two-dimensional, ^{3}He Neutron Detectors with Pad Readout for High Rates; 2005 Nucl. Sci. Symp. Conf. Record (2005) 1201-1204.

G. De Geronimo, J. Fried, G.C. Smith, B. Yu, E. Vernon, C.L. Britton, W.L. Bryan, L.G. Clonts, and S.S. Frank; ASIC for Small Angle Neutron Scattering Experiments at the SNS; IEEE Trans. Nucl. Sci. NS-54 (2007) 541-548.

B. Yu, N.A. Schaknowski, G.C. Smith, G. De Geronimo, E.O. Vernon, L.G. Clonts, C.L. Britton and S.S. Frank; Thermal Neutron Detectors with Discrete Anode Pad Readout; 2008 IEEE Nuclear Science Symposium Record 1878 – 1881.

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Advanced Detectors for Synchrotron Radiation

D. Peter Siddons, Paul O'Connor
Brookhaven National Laboratory

Proposal title

Advanced Detectors for Synchrotron Radiation

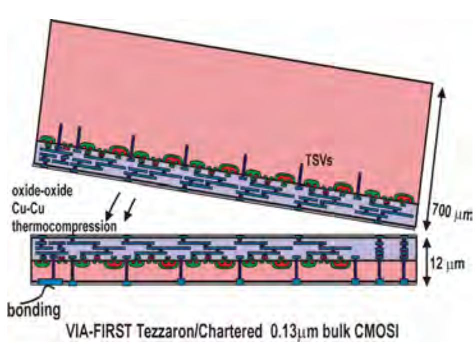
Scientific Challenge and Research achievement

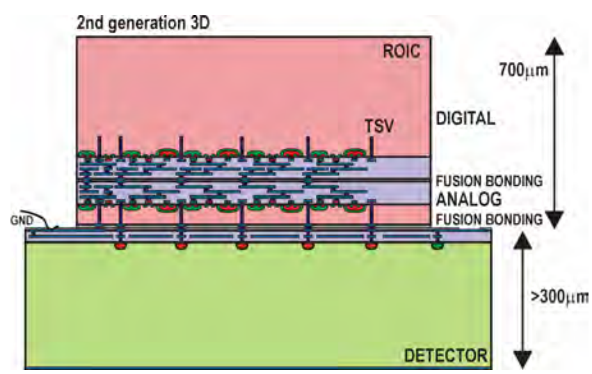
The project has two primary directions:

(a) To explore the feasibility of using 3D integration techniques as a means to enhance the signal processing capabilities in each pixel, i.e. towards making 'smart detectors'.

(b) To develop a planar process for the fabrication of hyper-pure germanium detectors, thereby allowing the production of similar devices to those routinely made in silicon such as microstrip detectors and drift detectors.

3D integration is a new technology aimed at increasing the density of microcircuits by expanding in the third dimension, by stacking CMOS chips one atop the other and providing high-density interconnections between the layers. The two figures below summarise the process. First, two wafers are prepared with CMOS circuits on one face. The difference between these circuits and conventional ones is the presence of so-called Through-Silicon Vias (TSVs). These are the small projections protruding into the bulk silicon wafer. After the two wafers are bonded together (also connected together electrically in the process), then one of them is ground down to expose these TSVs (the bottom wafer in the figure). We now have the possibility to connect to the circuits by electrically contacting these vias. The right-hand diagram shows how we can connect a third layer, the x-ray sensor to this 2-layer CMOS stack.





In this process, we are currently somewhere between these two diagrams.

- We have designed the two CMOS circuits to be bonded. Together they implement a detector for X-ray Correlation Spectroscopy, a new technique for studying material kinematics, e.g. the motion of atoms in condensed matter such as liquids. The detector provides sparsified readout and a time resolution of 10 microseconds.
- The CMOS wafers have been fabricated by a commercial vendor, Chartered Semiconductor, to our designs.
- They have been bonded together by another vendor, Tezzaron.
- We have fabricated the x-ray sensors in-house at BNL and prepared them for bonding to the 3D ASICs.

As mentioned above, the first of the straw-man detectors we chose to illustrate the potential of the 3D technology is X-ray Photon Correlation Spectroscopy (XPCS). In anticipation of receipt of the 3D devices, we have focused on the processing of the data which it will generate. The technique requires

that a time autocorrelation be performed on the photon stream from each pixel. Since the prototype chip has 64 x 64 pixels, we therefore need 4096 multiple-Tau autocorrelators. The structure of the 3D chip suggests a partition of this into blocks of 256. We have therefore designed an FPGA-based circuit capable of performing this analysis in real time, on 256 photon streams simultaneously.
The second straw-man detector we have worked on is an energy-resolving imaging detector. To this end we have:

- Made a design study of achievable noise level and thermal dissipation constraints
- Made transistor-level design and modeling of a circuit which can achieve a noise level of 10 electrons RMS.
- Made a detailed layout of an integrated circuit embodying this design.
- Designed a low-power ADC capable of digitizing the signals.
- Made sensor arrays which can be attached to existing amplifiers to allow us to study charge-sharing effects and methods to overcome them.

A second theme was added to the project in its second year. It aims to develop a planar technology which would allow us to produce segmented monolithic (i.e. pixelated) sensors from germanium, providing enhanced sensitivity for photons of energies higher than the 15keV or so which planar silicon detectors are optimal for.
Our proposal was to provide a way to fabricate microstructured detectors similar to those made routinely in silicon, such as microstrip detectors, drift detectors etc.
We have:

- Developed a new low-defect high-resistance coating to serve as a passivation layer.
- Developed an ion-implantation recipe to form P-N junctions in germanium.
- Developed a range of etching recipes for forming the microstructures in the various process layers.
- Designed a lithography mask set to make microstrip and pad detectors.
- Almost completed the first fabrication of devices using all of these process elements.

Future Work

We will pursue the XCS detector design, while working on an enhanced version which will provide ~1000 x better time resolution, i.e. around 10ns. We will also continue with our hyperspectral imaging design and fabricate a prototype. The germanium project will produce a microstrip detector for high-energy X-ray diffraction, in particular pair - correlation function experiments.

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3D design activities at Fermilab: Opportunities for physics" Raymond Yarema, et al.. NIM A: **617** (2009), Pages 375-377.

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Current and Future Detector Research & Development at BNL/NSLS", D. P. Siddons, Synchrotron Radiation Instrumentation conference, Melbourne, Australia, September 2009. Invited talk.

High k oxides on Germanium: High energy x-ray detector R&D. Rumaiz, Abdul; Carini, Gabriella; Siddons, Peter; Rehak, Pavel. American Physical Society, APS March Meeting 2010, March 15-19,2010, abstract #K1.048

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Band alignment of atomic layer deposited HfO2 on clean and N passivated germanium surfaces. Abdul K. Rumaiz et al. Appl. Phys. Lett. **97**, 242108 (2010); doi:10.1063/1.3524262

Detector R&D at LBNL

P. Denes, N. Andresen, D. Contarato, D. Doering, D. Gnani, C. Grace, B. Krieger, J. Joseph, H. von der Lippe, P. McVittie, H. Padmore, C. Tindall, JP Walder, B. Zheng

Lawrence Berkeley National Laboratory

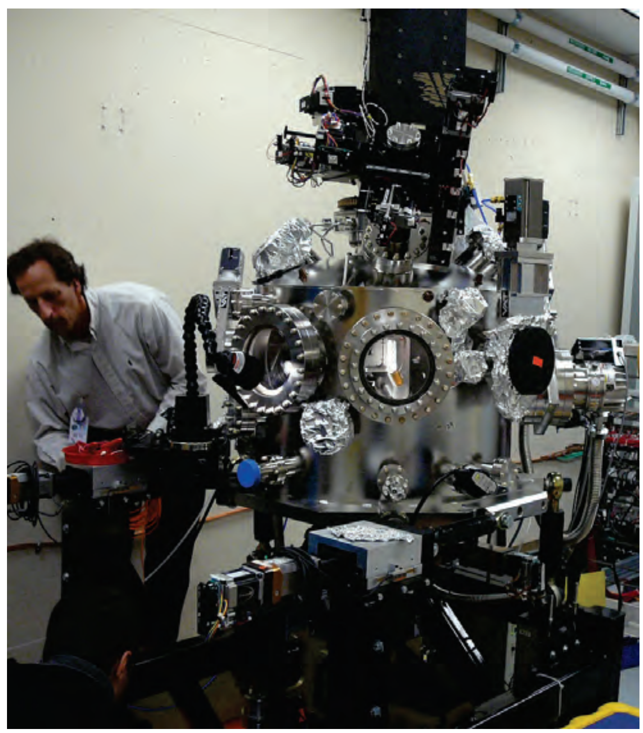
Proposal Title: "Detector R&D"

Research Achievement

The ALS is the largest of the three BES User Facilities (ALS, NCEM, TMF) at LBNL. The goal of this detector R&D effort is to innovate soft X-ray detection solutions that maximize the scientific reach of the ALS, and to collaboratively improve the state of the art in X-ray detection at other light sources. Techniques at light sources are quite varied, but a well-chosen selection of detector technology advances can improve a large number of experiments. Speed, sensitivity and accessibility are perennial overarching user requests.

We continue to concentrate on direct detection in silicon, since conventional microelectronic silicon wafer thicknesses, up to several hundred microns, are ~100% efficient up to ~8 keV.

Under this R&D program we have developed compact packaging for our 200 frame/second FastCCD[1] in order to support beamlines at ALS, APS and initial and on-going experiments at the soft X-ray beamline at LCLS. We have also designed larger devices (a 1k frame-store CCD) as well as a 5 µm pitch CCD for spectroscopy. With the design of an 80 MHz, 12-bit, 200 µm pitch digitizer in 65 nm CMOS (used as four 20 MHz, 12-bit ADCs), the foundation is being prepared for a 10,000 Megapixel/second direct-detector CCD.



Resonant Soft X-ray Scattering chamber - used at ALS and LCLS

Continuing our investigation of silicon-on-insulator technology[2], a customized high-speed gated detector will be deployed this fall on ALS ultrafast Beamline 6.0

Future Work

The prototype 10,000 MPix/s CCD system will be evaluated and developed into a larger, useable format. A considerable amount of readout development is required, together with an exploration of data compression and reduction techniques. These studies, performed initially in software, will move rapidly to firmware and eventually into hardware.

For ultimate soft X-ray performance, we will continue investigations of techniques for thin contacts, in particular those which can be applied at low temperature (so that they can be applied to processed die). We will also continue work on detector thinning: starting a new attempt to reliably thin CMOS to the epitaxial layer.

As part of the 65 nm CMOS development, we have included a prototype 400 x 400 pixel array. We intend to thin this device to the (~10 μm) thick epitaxial layer, apply a thin contact, and characterize this device as a soft X-ray imager. Such a very deep sub-micron CMOS active pixel sensor, combined with on-chip processing, offers an attractive path to 100,000+ frame/second detectors for future high-rate soft X-ray FELs.

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Y. D. Chuang et al., "*A Rich Hierarchy of Time Scales in Stripe Phase Nickelates*" Submitted to *Nature*.

D. Doering et al., "*Development of a Compact Fast CCD Camera and Resonant Soft X-ray Scattering Endstation for time-resolved Pump-Probe experiments*", Rev. Sci. Instrum., in press.

Science "inside" the synchrotron pulse width:
x-ray pump/optical probe cross-correlation study of GaAs

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Physics Department,
Purdue University

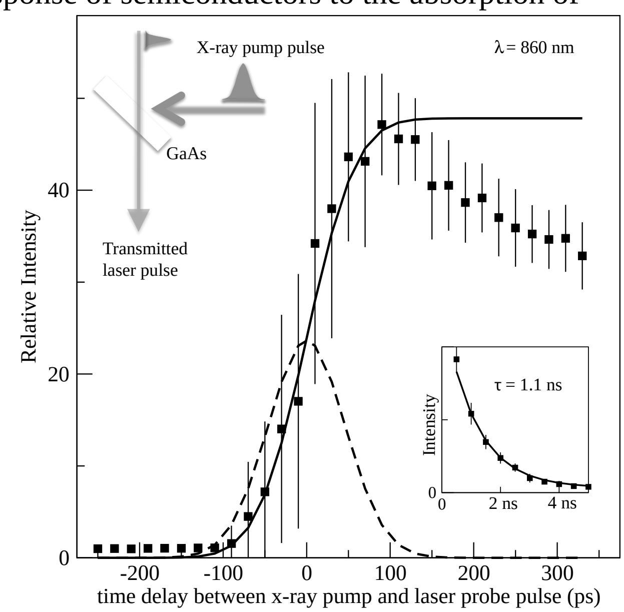
Proposal Title: Picosecond X-ray Detector for Synchrotrons

Research Achievement

A picosecond (ps) is the order of magnitude governing the transfer of energy from a photo-excited electronic system to the underlying lattice, and hence is of fundamental importance in many energy-related systems. The goal of this program is to develop a semiconductor-based x-ray detector that will provide ps time resolution for standard laser pump/x-ray probe experiments at x-ray synchrotron sources. This is important because the synchrotron pulse width of nearly 100 picoseconds prevents reaching the highly desirable 1 ps range, using standard detectors. Progress has been made in two related areas, 1) fundamental studies of ultrafast semiconductor response to x-ray pulses observed by band-gap laser transmission spectroscopy, and 2) development of a coplanar stripline (CPS) circuit on GaAs with ps optical sampling. These are described separately below.

1. X-ray pump/optical probe cross-correlation study of GaAs

We discovered how an intense x-ray pump beam transforms a thin GaAs specimen from a strong absorber into a nearly transparent window in less than 100 picoseconds, for laser photon energies just above the bandgap. We find the opposite effect, x-ray induced opacity, for photon energies just below the band gap. These observations raise interesting questions about the ultrafast many-body response of semiconductors to the absorption of hard x-rays, and provide a new and simple approach for constructing an x-ray/optical cross-correlator for both synchrotron and XFEL applications.



In our experiments at the APS (Sector 14) a thin GaAs specimen absorbs an intense, 100 ps synchrotron x-ray pump pulse and the transmission of a picosecond laser probe pulse is measured as a function of the pump/probe delay time. The intensity of transmitted beams for λ=860 nm, normalized to the signal without x-rays, is shown in Fig. 1 as a function of the time delay between the x-ray pump and the laser probe. Also shown is the time profile of the x-ray pulse (convoluted with laser jitter), and its integral which matches the initial data range quite well. The specimen switched from optically opaque to transparent in about 100 ps, the duration of the x-ray pulse, a 40-fold increase in intensity. An 860 nm photon has just enough energy to excite a valence electron across the gap into the conduction band. So many electrons end up in the conduction band in response to x-ray absorption that states at the bottom of the band are filled, causing x-ray induced transparency that decays with a 1.1 ns exponential lifetime (Fig 1, inset), a measure of the electron-hole recombination time. This enormous increase in sensitivity suggests new opportunities for both ultrafast semiconductor investigations and as timing sensors for free electron laser and synchrotron pulsed x-ray sources. For laser wavelengths just below the bandgap, the opposite effect is seen: the normally transparent material becomes relatively opaque, an effect that is not yet fully understood.

2. Coplanar stripline GaAs detector with picosecond optical sampling

A standard approach for generating THz radiation is to illuminate the gap of a biased coplanar stripline on a semiconductor substrate with a 100 fs laser pulse. The induced electrical pulse shape is then measured by optical sampling via a "pick-up" electrode. Our detector concept is the same, except x-ray synchrotron pulses replace the 100 fs laser pulses to excite the electrical pulse on the coplanar stripline. A synchronized laser still provides the optical sampling in exactly the same manner. We have tested prototype Si and GaAs detectors (fabricated at Purdue) and have investigated reduced carrier lifetimes controlled by 8 MeV proton implantation (at Purdue's Prime Lab). The first round of measurements at the APS Sector 7 found that the monochromatic x-ray pulses produced very strong and easily measured currents in these devices. We also found strong evidence that the ion implantation was successful in reducing the carrier lifetimes, as desired. Additional measurements conducted in late July 2011 will also be reported on.

Future Work

1. The x-ray pump/optical probe studies are being extended to other semiconductors, and especially to determine if the response from a diffracted monochromatic beam is sufficient to provide ps detection capabilities. If so, this could be used to measure the ps response of optically-induced melting, phase transitions, or near edge absorption changes in various materials.
2. The coplanar stripline (CPS) detectors will be refined to determine optical configurations with maximum sensitivity to serve as a useful detector for optical pump/x-ray probe measurements. This will be tested on a semiconductor such as InSb to measure laser-induced melting and associated vibrational excitations.

Publications: Manuscript submitted (July 2011) – "X-ray pump, optical probe cross-correlation study of GaAs," S. M. Durbin, T. Clevenger, T. Graber, & R. Henning (Nature Photonics)

Area x-ray pixel array detectors for time-resolved synchrotron applications

Sol M. Gruner, Mark W. Tate, Hugh T. Philipp, Department of Physics, Cornell University, Ithaca, NY 14853 and Marianne Hromalik, Electrical and Computer Engineering Dept. SUNY Oswego, Oswego, NY 13126

Proposal Title
Versatile, reprogrammable area pixel array detector for time-resolved synchrotron x-ray applications

Scientific Challenge and Research Achievement
It is widely acknowledged that many, if not most, experiments at modern synchrotron radiation (SR) sources are limited more by detector capabilities than by the source. This is especially true for time-resolved studies. Examples span many disciplines and include, but are not limited to, material processing; understanding how materials fail; time-resolved protein interactions (e.g. enzymes, membrane proteins, gene regulation); depositions and growth of technologically significant complex films; turbulence in liquids; etc. The goal of this grant is to develop a programmable, silicon-based area detector that can directly address the needs of the scientific community by providing customized, programmable, real-time analysis of data. The front-end detector hardware comprises a pixelated, high-resistivity, direct-detection, silicon diode that is connected at the pixel-level to a CMOS Application Specific Integrated Circuit (ASIC). The CMOS is fabricated by taking advantage of highly-refined, commercialized manufacturing processes. Each pixel of the detector being developed has circuitry for detecting single x-rays and signal conditioning. The pixels use a high-speed, low-level, semi-synchronous data interface to communicate with field programmable gate arrays (FPGAs). This low-level interface to programmable logic will make a hugely powerful and flexible tool available to the synchrotron radiation community.

Maximizing the scientific potential of this new kind of 'smart' detector requires designing a high-speed CMOS front-end and examining each point along the communication chain (from x-ray detection to signal collection and conditioning to FPGA processing to data acquisition and storage) to avoid bottlenecks. Since the design and fabrication of custom, large-format ASICs suitable for area detectors, is inherently expensive it is imperative that each PAD design build on the lessons of earlier work and, in so far as possible, utilize integrated circuit parts that have already been proven to work. Utilizing the past experiences of the detector development group and elements of previous high-speed pixel designs, we have been able to (1) adapt pixel circuits developed in the past to new FPGA controller hardware to realize usable detectors as rapidly as possible, and (2) perform R&D on novel FPGA-reliant pixel designs.

With respect to the first part of the approach, a pixel previously developed under Keck Foundation support was modified, simulated, and adapted for incorporation into a large-scale array [1]. This PAD has demonstrated the capability of capturing up to 8 successive images every 150 ns, which is sufficiently fast to allow single-bunch imaging at SR sources. The pixel has sufficient sensitivity for greater than unity signal-to-noise for 8 keV x-rays over a dynamic range span of several thousand x-rays. The time interval between exposures may be programmed at will to, for example, capture data in logarithmic time. The pixel may also be used in a “lock-in” mode whereby x-ray images from a cyclic process is divided into up to 8 phases that are coherently readdressed and integrated over many cycles. This mode is useful for very weak x-ray signals. This large scale array, which will consist of 128x128 pixels, has been laid out and committed to fabrication.

With respect to the second part of the approach, several novel FPGA-reliant pixel architectures have been explored. These include semi-synchronous, high-speed approaches to interface the pixel array detector to the FPGA. We have converged on a test architecture that is now ready for small-scale layout and fabrication. There are several critical and unique features of the ASIC design. The first is that the pixels of the array are divided into small (nominally 30 pixels), independent groups that have a dedicated interface to the FPGA. Second, the read-out from each group is event-driven. This means the group is only passing data to the FPGA when x-rays are detected. Third, the pixels use time-division multiplexing on a high-speed serial bus to pass data to the FPGA. Fourth, the front-end is fast and configurable with dark-current compensation so that sparse and infrequent readout is possible in areas of the array that are not active. This has huge benefits because it reduces the data bandwidth which is becoming an ever increasingly difficult issue as detectors increase their temporal and spatial resolutions.

Future Work

PAD development is an iterative process consisting of cycles of design, fabrication and testing of successively larger arrays of pixels. Typically, several cycles of small and large-scale ASICs are required. The small-scale ASICs for the Keck PAD have been tested and we are now engaged in large-scale fabrication. This will be followed by testing, assembly of FPGA-based control electronics, detector tiling and full-scale detector assembly. Testing by application to time-resolved research problems of significance will be an inherent part of this process.

The second part of the approach, namely R&D on novel FPGA-reliant pixels, is at the much earlier stage of small-scale ASIC design.

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Publications

None to date.

Superconducting Sensors for X-ray Science

PI: Antonino Miceli (Argonne National Laboratory, Advanced Photon Source)

Proposal Title: High-Resolution Spectroscopic X-ray Detectors using Superconducting Sensors

Research Achievement

This proposal will focus on the research and development of Microwave Kinetic Inductance Detectors (MKIDs) [1]. While semiconductor spectroscopic detectors use the creation of electron-hole pairs, MKIDs utilize the breaking of Cooper pairs in superconductors as the physical mechanism to measure the energy of the incoming photons. The number of broken Cooper pairs (i.e., quasiparticles) is proportional to the incident photon energy. These quasiparticles result in a change in the kinetic inductance of the superconductor. The superconducting X-ray absorbers in MKIDs are coupled to superconducting microwave resonators, which enables incoming photons to induce a temporal change in the phase and amplitude of microwave probe signals sent at the resonant frequency of the MKID resonator. The beauty of MKIDs lies in the ability to multiplex the readout of arrays of MKIDs to build detectors capable of high count rates. Each individual MKID is set to a slightly different resonant frequency, which allows thousands of MKIDs to be read out with only two coaxial cables and one cryogenic amplifier. All other readout electronics are at room temperature.

This year has been mostly focused on planning, acquiring, and building the infrastructure necessary for detector testing. One of major pieces of equipment that we have acquired this year has been a cryogen-free adiabatic demagnetization refrigerator from HPD Inc. This cryostat reaches a base temperature of ~ 50mK. We installed the cryogenic cabling, low noise amplifier, and a sample box. With the heat load from the full cabling set, we are able to regulate the temperature at 100mK for about 4 days. (Figure 1)

We continue to work on the device fabrication. In particular, we have been working on optimizing parameters for the photolithography and reactive ion etching process of the aluminum resonator layers. We have converged on the etching parameters which result in vertical sidewalls (anisotropic etch). We have fabricated several devices which have been sent to our collaborator Ben Mazin at UCSB. These devices performed quite well. The internal quality factors are over 2 Million, which are some of the best every measured in thick aluminum resonators (Figure 2). These results validate the first stages of our fabrication process. In addition, we have started to investigate tungsten silicide has a new material for x-ray lump-element kinetic inductance detectors (LEKID) [2]; this variant of an MKID uses the resonator as x-ray absorbers as well as the sensing circuit. We have successfully fabricated tungsten silicide resonators and have begun the electromagnetic simulations to design arrays of LEKID.

We have started to investigate materials and the fabrication process for the x-ray absorber layer. The interface between the aluminum resonator and the x-ray absorber layer must be void of any interface. We have fabricated several devices with niobium absorbers with different schemes to achieve a clean interface. The niobium deposition was performed in the Lesker sputtering chamber at a base pressure of $<10^{-9}$ Torr. Prior to niobium deposition, the native aluminum oxide needs to be removed in-situ. This oxide was removed using back-sputtering in the Lesker. However, the back sputtering conditions were first measured since back-sputtering had never been done in the Lesker chamber prior this. Two niobium/aluminum devices were sent to UCSB for testing with x-rays. Most resonators showed pulse spectra consistent with a combination of substrate hits and rarer hits in the aluminum center strip. There was evidence of a proximity effect that near aluminum/niobium which indicates that electrical contact between the aluminum and niobium. However, the connection was not good enough for the quasiparticles to be trapped from the absorber (Nb) into the resonator (Al). The back-sputtering needs to be optimized improve the interface. We will need to study the effects of the back-sputtering parameters (e.g., power and time) on the roughness of the aluminum interface.

We have order and received most of the microwave electronics test equipment, including vector network analyzer, microwave synthesizers, cryogenic amplifiers, and coaxial cabling. We are currently able to measure quality factors of resonators at Argonne and have confirmed those measurements taken by our collaborators at UCSB.

Figure 1 -- ADR refrigerator setup and microwave test equipment.

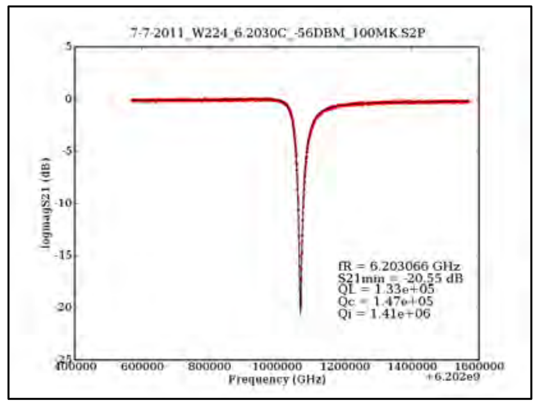

Figure 2 -- Resonance measurement of aluminum superconducting MKID resonator. This device was fabricated and measured at Argonne.

Future Work

During the next year, we plan to focus on the building the device testing system at Argonne, in particular IQ mixing to detect individual x-ray events. We expected to be able to fully test devices in-house by the end of 2011. In addition, we will focus the device fabrication efforts on testing various absorbers (including optimizing the interface) and exploring techniques for thick absorber deposition. Finally, we will explore LEKID using tungsten silicide.

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[2] S. Doyle, P. Mauskopf, J. Naylon, A. Porch and C. Duncombe, *Lumped Element Kinetic Inductance Detectors,* Journal of Low Temperature Physics, 151:530-536, 2008

Publications

Miceli, A. et al, Microwave Kinetic Inductance Detectors for Synchrotron Hard X-ray Science, Journal of Low Temperature Physics, (submitted), 2011

Cecil T. et al, Kinetic Inductance Detectors for X-ray Science, Technology and Instrumentation in Particle Physics 2011 Conference (poster).

Simulation and development of a coded source neutron imaging system

Philip R. Bingham (PI) and Hector Santos-Villalobos
Imaging, Signals, and Machine Learning Group
Measurement Science and Systems Engineering Division
Oak Ridge National Laboratory

Proposal Title: Early Career: Research and Development of Neutron Imaging Systems and Analysis Algorithms for Applications in Materials and Engineering

Research Achievement

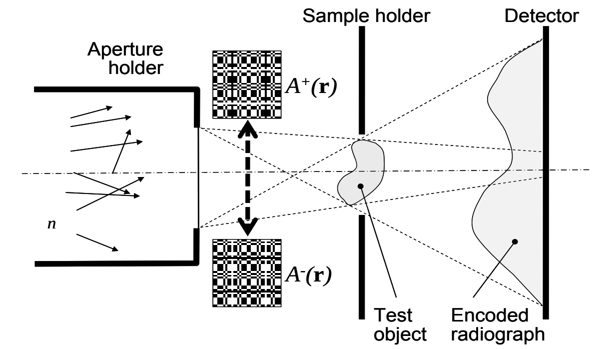

Figure 1. CSNI design

Neutron radiography was first introduced in the 1930s and has seen use for non-destructive testing in aerospace, nuclear, and other industries where the need to inspect for cavities or light materials within a much heavier object [1]. Developments in digital imaging systems and scintillation screens have improved resolution to the 50-100μm range for scintillator based detectors. Micro-channel plate (MCP) detectors have been developed with 6-10μm channels that provide resolution of 10-15μm mark [2] and capture individual neutrons for time resolution. This research effort is focused on development of a neutron imaging system using magnification to improve resolution without the loss of neutrons associated with a pinhole source. This system development is building on previous research in coded aperture imaging of sources [3] to develop a coded source neutron imaging (CSNI) system as depicted in Figure 1. Previous research by other groups on CSNI has shown resolution improvements through more efficient use of the extended source [4] and that low divergence of most neutron imaging beam lines severely limits potential for 3-dimensional reconstruction from a single coded image [5]. As a result, this project is developing a system to perform CSNI radiography and 3-dimensional measurements will be performed with multiple projections as in traditional computed tomography. Progress to date has been made in design calculations, simulation, initial CSNI testing, and masks development.

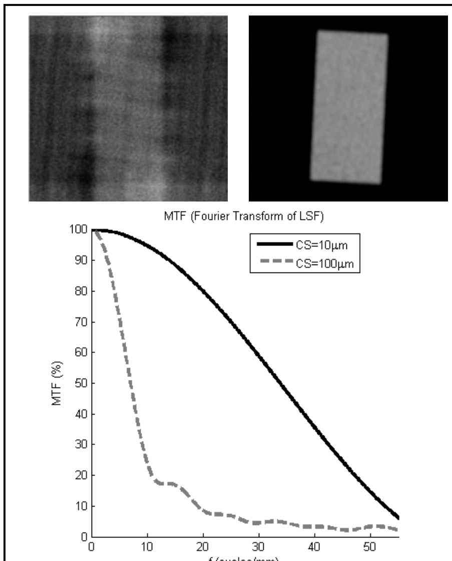

Figure 2. (Top left) raw simulated line edge image (Top right) reconstructed image (Bottom) calculated MTF

Analysis of the system shown in Figure 1 has resulted in a set of equations to determine relationships between key design parameters and performance. Field-of-view and resolution of the final system are determined by beam characteristics (size and divergence), mask properties (size, resolution), detector specifications (resolution and size), and the distances between the source, mask, object, and detector. Using these parameters, a set of initial CSNI designs have been developed for resolutions ranging from 100µm down to 1µm. Simulations of the 100 µm and 10 µm designs over a tilted edge object have been performed with McStas to calculate resolution in a modulation transfer function (MTF) curve for the systems. Results of these simulations are shown in Figure 2. From these curves, we see that the resolution in the reconstructed object provide contrast above 10% at the design resolutions. For initial CSNI testing, a simple coded aperture mask set was manufactured by drilling a hole pattern into a 1mm thick borated aluminum sheet. Two experiments have been performed at HFIR's CG1 development beam line with these mask sets imaging a pinhole to identify system development issues that are not included in the current simulations (beam uniformity, mask/anti-mask positioning, etc.). Initial tests were very low resolution (300µm) due to limitations in drilling the mask. Manufacturing masks for higher resolution systems is a challenge for this project. The plan is to use semiconductor manufacturing processes to pattern masks out of Gadolinium on a Silicon wafer. Tests on deposit and etch of Gd on Si are underway to determine limitations of the method. A wafer design is shown in Figure 3 to include aperture and anti-aperture masks at 12 different design resolutions between 1 and 100 µm along with support features for resolution measurements at the beam.

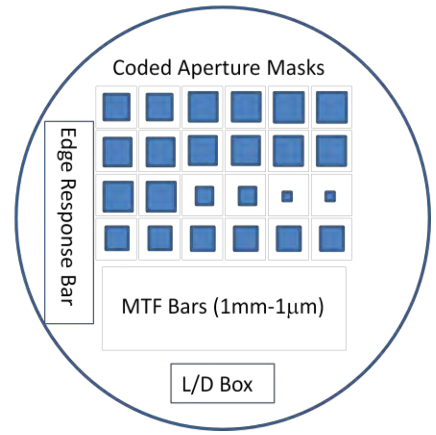

Figure 3. Coded mask wafer design

Future Work

Next steps in this effort include development of iterative reconstruction capabilities, development of mask handling and shielding, simulation of three-dimensional objects, testing of high resolution mask, and development of x-ray imaging system. Longer term efforts will push resolution toward 1µm resolution and investigate reconstruction with multiple wavelength neutrons and x-ray images together.

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Plenary Session II

Beam Dynamics at the Radiation Scale

James Rosenzweig *(talk given by Pietro Musumeci)*
University of California at Los Angeles

Technical Session III

Terawatt X-ray Radiation, Beam Dynamics–II, and Lasers

Terawatt X-ray FELs for biological applications

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Research achievements

High resolution coherent diffraction imaging of complex molecules, like proteins, and other biological applications require a large number of hard X-ray photons, ~10^{13}/pulse, within a time of about10fs or less. This is equivalent to a peak power of about one TW, much larger than that currently generated by LCLS or other X-ray FELs now under construction.

We show the feasibility of producing such pulses from LCLS and/or LCLS-II, employing a configuration beginning with a SASE amplifier, followed by a "self-seeding" crystal monochromator, and finishing with a long tapered undulator. Our results show that TW-level output power at 8 to 10 keV is possible, with a total undulator length below 200 m. The calculations use a 40 pC electron bunch charge, normalized transverse emittance of 0.2-0.4 mm-mrad, 4kA peak current, and electron energy of 14 GeV. The beam peak power is about 56 TW. Thus a 1 TW X-ray pulse requires an energy extraction fraction of a few %, well below the theoretical limit.

The main schematic of the system and some results are shown in Figure 1. The tapering strategy extends the original KMR “resonant particle” formulation [1] by optimizing the transport lattice to maximize optical guiding and enhance energy extraction. We also discuss the transverse and longitudinal coherence properties of the output radiation pulse as predicted by multiple simulations codes.

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Future Work

Having established the feasibility of short pulse, TW X-ray FELs, the future work has the goal of optimizing the system by reaching the maximum output power in the shortest possible undulator length. The work will include considering the case of helical undulators, and the study of the feasibility of a tapered superconducting helical undulator magnets. Additional work will be done to study the tolerances of the tapered undulator and the sensitivity of output power, line-width and pulse duration to beam parameters like transverse emittance, peak current, energy spread.

Publications

Work submitted to the proceedings of the 33th International Free-electron laser conference, Shanghai, China, August 2011.

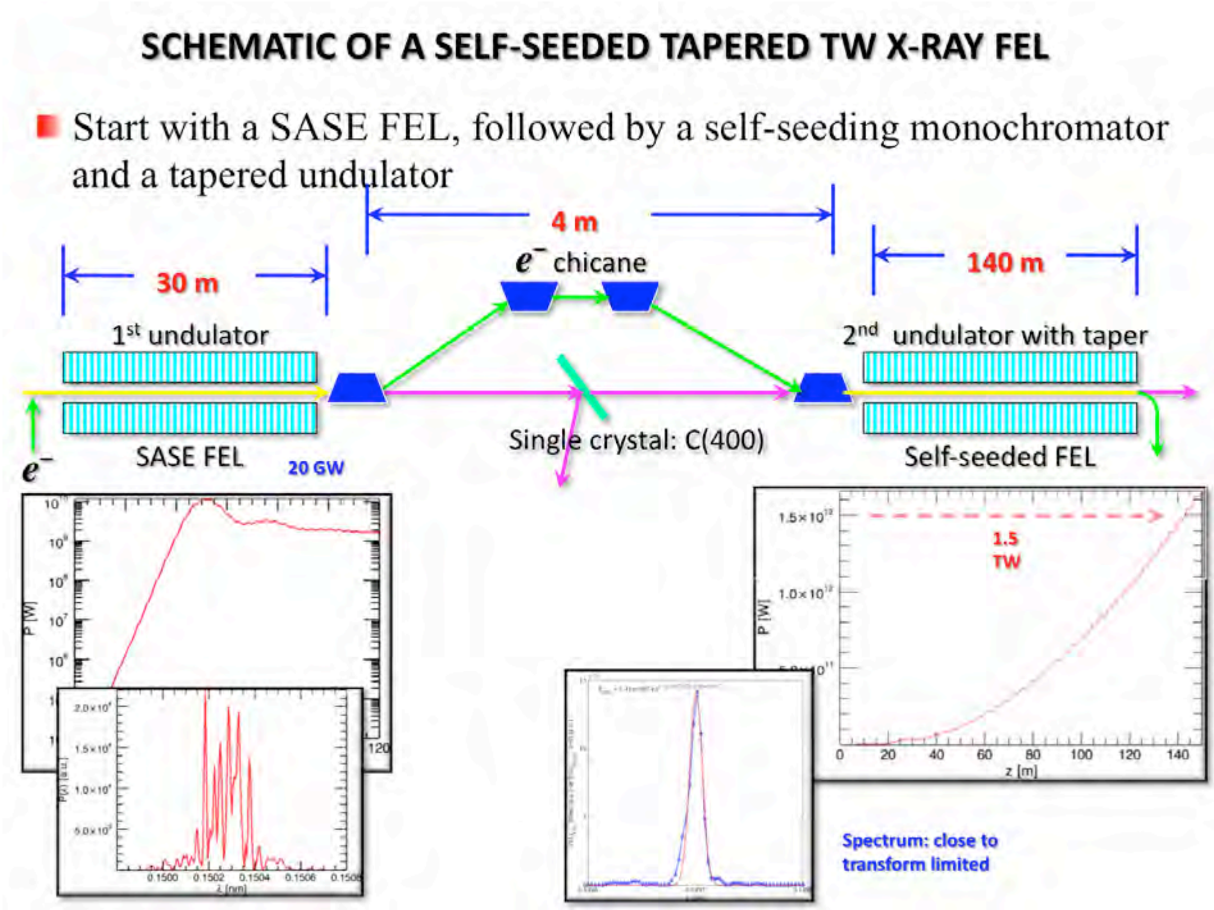

Figure 1. TW undulator schematic, showing the self seeding system and the tapered undulator. The FEL peak power and spectrum results from simulations are shown at the exit of the first, seeding SASE undulator, and at the exit of the tapered undulator, where the peak power exceeds 1TW.

The UCLA Program in Advanced Beam and Light Source Physics

Proposal Title: The Physics of Gain Mechanisms in Self-Amplified Spontaneous Emission Free Electron Lasers (BES contract no. DE-FG-98ER45693)

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Scientific Challenge

We present here the recent results from the above-titled grant, covering the period since the most recent renewal of the corresponding. The accomplishments achieved under this grant have been broad-based, covering experimental, theoretical, and computational work. The work under this grant has expanded in the recent years, beyond the original mission as stated in the now-dated grant title, which was formulated during proof-of-principle experiments of the self-amplified, spontaneous emission free-electron laser (SASE FEL) per se. We have in recent work emphasized fundamental beam physics as it underpins phenomena in FELs, and looked increasingly at advanced concepts that impact the next two generations of FEL. These fundamental beam physics topics are increasingly of novel flavor, as we look at time scales of beam and FEL pulses in the *attosecond* regime. In this new regime, the challenge of creating, manipulating, transporting and diagnosing ultra-high brightness electron beams to drive SASE FELs and other advanced light sources becomes a compelling and intricate enterprise. At we UCLA have been central in the conception and investigation of this new frontier, which now embraces the other main activity here, that of advanced acceleration techniques, now that we have begun to work on the light sources based on plasma and dielectric accelerators, driven by both beams and by lasers. Finally, we note that in developing new light sources, we have pushed towards proof-of-principle experiments showing the *use* of new tools such as inverse Compton scattering (ICS), and ultra-relativistic electron diffraction (UED). These activities take place in the context of a coherent educationally-driven program known as Particle Beam Physics Laboratory (PBPL) at UCLA. This program produces a notable fraction of the PhDs granted in the US in the physics of accelerators, beams, and FELs.

Research Achievements

The current areas of active emphasis are listed below, with select associated journal articles published by the UCLA PBPL listed as references.

- First characterization of a phase transition using sub-ps time-resolved UED [1]
- First demonstration of single shot diffraction in an ICS hard X-ray source [2]
- Detailed experimental explorations of longitudinal phase space in the photoinjector blowout regime [3]
- Experimental development of dielectric wakefield accelerators as novel FEL injectors and as coherent, narrow-band sources of THz Cerenkov radiation [4]
- Theoretical and experimental investigations of the role of orbital angular momentum modes in FELs and inverse FELs. [5]
- Theoretical and experimental studies of novel coherent radiation processes [6]
- Demonstration of multi-photon-excited emission of photoinjector cathodes [7]
- Development of advanced undulators and investigation of their use in 4th and 5th generation FELs [8]

— Exploration of creation and use of high-brightness electron beam pulses in FELs and advanced accelerators [9]
— Fundamental experimental and computational FEL studies [10]
— Theoretical and experimental investigations of linear and nonlinear space-charge effects on beam bunching from the THz to the optical scale [11]
— Advanced fs-to-as electron beam diagnostic development [12]

Future plans

The PBPL program in beam physics and FELs will profit from the momentum built up in recent years. In electron sources, we are building a new generation of hybrid standing-traveling wave photoinjectors that will produce unprecedented short beams for coherent radiation and UED applications. The program in developing advanced accelerators for 5th generation FEL will be fully engaged at FACET and the BNL ATF. We will advance in ICS studies by examining the deep nonlinear regime and novel harmonics production. Advanced undulators will be employed in both FEL and IFEL studies. Novel FEL configurations involving OAM light will be investigated. Deeper studies of longitudinal space-charge effects will be performed to permit noise suppression or enhanced gain.

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Toward single e-bunch shape diagnostics using THz coherent radiation

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Proposal title: Holographic Spectroscopy for Rapid Electron Bunch Analysis

Scientific Challenge

One of the most pressing issues in accelerator science today is the production of sub-picosecond duration electron bunches. Such bunches are required for a broad spectrum of applications, from achieving high luminosity in a linear collider to generating short duration X-ray pulses[1,2]. Means to measure the temporal distribution of charge within a single bunch on a bunch-by-bunch basis are required to make progress in this direction. The main thrust of our project is to develop and use methods of holographic spectroscopy to measure the coherent THz spectrum from a single e-bunch.

Research Achievements

The main thrust of our project is to apply the concepts of holographic spectroscopy, developed earlier in the visible and near IR[3] to the THz region for the measurement of coherent radiation from e-bunches. Two main components are required for realization of this method. The first is the development of a new kind of static THz interferometer to sample the coherent radiation autocorrelation function in the spatial domain, and the second is the integration of a detection system capable of rapid and accurate sampling of the pattern and transforming the digital signal into the computer. In the course of this groundbreaking work the following major milestones were achieved.

(1) THz interferometer. The first static interferometer for the THz region was realized making full use of the holographic spectroscopy concepts. The main features of this instrument are optimized throughput, aberration compensation, and a compact and versatile design. It is capable of operating over the full THz region, from mm waves to mid IR. This permits the construction of instruments for single bunch shape characterization down to bunch lengths of ~ 3 microns.

(2) THz holographic Fourier transform spectrometer. In the first realization of the THz HFTS the static interference pattern was sampled using a commercial THz array Pyrocam III. Experimental tests and analysis of the observed results were compared with those obtained using standard FTS providing the necessary foundation for future development of the THz detector arrays optimized for spectroscopic applications.

(3) THz HFTS with EO detection and optical Fourier transform. Due to the absence of the spectroscopy grade THz arrays at the present time we have explored the electro-optic (EO) detection of the THz pulse using the short pulse of a visible diode laser synchronized to the bunch. The main hurdle was found to be the parasitic scattering of the optical radiation in the EO crystal medium. By using the optical Fourier transform of the THz interference pattern in the crystal the effects of this background were sufficiently suppressed to obtain the spectrum using a sensitive optical array detector. During our experiments at the FLASH facility at DESY we determined that for single bunch measurement capability the diode laser has to be able to produce sub 100 ps pulses with

peak power of at least 1 W. Since these parameters are quite feasible at the current stage of diode laser science this combination of techniques can be used for single shot measurement of a short electron bunch.

(4) EO sampling with the incoherent radiation of the same bunch. An important alternative to the diode laser EO approach is to use the visible/near IR incoherent radiation produced by the same bunch for sampling the THz interference pattern. In this case the background is expected to be essentially absent. The first proof-of-principle experiment using this method was conducted in April 2011 at Jefferson Lab. Results confirmed the feasibility of this approach and points to the possibility to use the frequency resolved optical gating (FROG) method[4] for the bunch asymmetry retrieval. The static THz interference pattern obtained with the variable delay of the incoherent readout pulse would provide a 2D matrix of the coherent THz data permitting retrieval of both amplitude and phase information and thus completely characterize the longitudinal profile of the e-bunch.

(5) Coherent/incoherent pulse EO overlapping for bunch length measurement. In the course of these studies we found that a simplified, less precise bunch diagnostic method can be realized even without the THz interferometer or any external laser. The procedure is to overlap at oblique incidence the coherent THz and the incoherent visible pulse wavefronts inside the EO crystal. In this way the degree of overlap between the THz pulse and the incoherent pulse varies across the EO crystal and the observed signal on the array detector gives a direct measurement of the “symmetrized” bunch shape. This procedure has been confirmed in proof-of-principle experiment at Jefferson Lab.

Future work

(1) Single shot THz HFTS with diode laser readout and optical FT. Experimental results obtained at DESY have provided the necessary information for future optimization of the optics and required characteristics of the ultra-short pulsed diode laser in order to realize single shot measurement capability.

(2) Asymmetry capable THz HFTS with the incoherent pulse readout. The e-bunch longitudinal asymmetry measurement capability using the FROG technique will be developed based on the success of the proof-of-principle experiments at Jefferson Lab. Experiments are planned at the LCLS with much shorter electron bunches.

(3) Bunch shape characterization using the coherent/incoherent pulse overlapping. This investigation will focus on exploring the effects of dispersion on the performance of a simple self-contained instrument based on the overlapping of the coherent THz and the incoherent pulses in the EO medium.

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The Echo-7 Experiment at the NLC Test Accelerator*

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Proposal Title: Accelerator R&D for a Soft X-ray Free Electron Laser: Echo Enabled Harmonic Generation (Echo-7) [award # 2009-SLAC-1032]

Research Achievement:
The Echo-7 experiment is aimed at demonstrating the Echo Enabled Harmonic Generation (EEHG) FEL seeding technique [1]. EEHG is believed to be one of the most promising approaches to seeding a soft x-ray FEL at nm wavelengths with GeV energy beams. The Echo-7 experiment aims to demonstrate the technique at wavelengths of a few hundred nm with 120 MeV beams and perform detailed benchmarking of the simulations against the experimental results to provide confidence in extrapolating to shorter wavelengths.

The Echo-7 experiment is installed at the NLC Test Accelerator (NLCTA) facility. The NLCTA is an X-band linac that was built in the early 2000's and since then has supported the E-163 laser acceleration program, high gradient X-band structure testing and testing of ILC rf components.

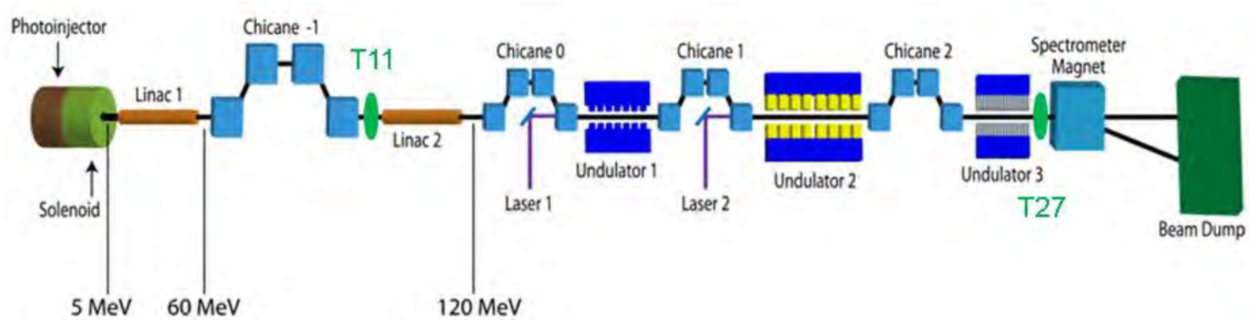

Figure 1. The NLCTA beamline with the Echo-7 components indicated.

To implement the Echo-7 experiment, we rebuilt the last 25 meters of beamline. The beamline components of the NLCTA are illustrated in Figure 1. We installed an additional X-band accelerator structure and rf power system (X2) to double the beam energy from 60 MeV to 120 MeV, two undulators (U1 and U2) where the beam would interact with lasers to modulate the beam energy, three chicanes, and additional diagnostics to characterize the performance including 8 new OTR screens. The 1st chicane (C0) allows one laser to be brought onto the beamline, the two following chicanes (C1 and C2) provide the dispersive paths necessary to rotate the longitudinal phase space. In addition, we installed a new beam energy spectrometer with a resolution of $<10^{-4}$, a UV vacuum spectrometer for characterizing the radiation spectrum, and two X-band transverse deflecting cavities (T11 and T27), one to characterize the longitudinal phase space and the other to increase the beam slice energy spread which is needed to illustrate the potential of the EEHG technique.

* Work was supported by the U.S. DOE Office of Basic Energy Sciences using the NLCTA facility, which is partly supported by U.S. DOE Office of High Energy Physics under Contract No. DE-AC02-76SF00515.

We have developed techniques to cleanly separate the EEHG and the HGHG signals and have systematically benchmarked the EEHG physics by varying the beam optics, beam energy, energy spread and beam emittance to compare against simulation predictions allowing one to extrapolate to much higher harmonic numbers as needed for a soft x-ray source. The experiments have shown the viability of the EEHG concept and the ability to use beam energy modulations that are small compared to the beam energy spread to generate high harmonic seeding which is not possible with HGHG or similar techniques.

Future Work:

The NLCTA and the Echo-7 beam line is an excellent facility to continue studies of beam dynamics critical for future FELs. We plan to continue to test the EEHG seeding concept at higher harmonic numbers where the beam optics and collective effects may become more important. To do this, we will upgrade the existing NLCTA injector to provide higher brightness beams which will allow us to study limitations of the EEHG technique with greater sensitivity as well as study a number of other beam physics topics important for future FELs.

First, we will upgrade the NLCTA bunching system to improve the beam longitudinal phase space allowing us to attempt to extend the EEHG demonstration to the 14^{th} and 21^{st} harmonics. We would also use the existing hardware to demonstrate narrow-band and broad-band THz generation and perform detailed studies of the micro-bunching instability, which is a limitation in the LCLS and likely will be in other FEL facilities.

Next, we propose to further upgrade the injector of the NLCTA to increase the bunch charge and improve the beam emittance by a factor of 10 to the sub-micron level. This upgrade would enable higher harmonic generation with EEHG, studies of alternate advanced seeding concepts, higher resolution on the micro-bunching instabilities and studies of CSR emittance growth, and study of emittance exchange. We would also use the facility to test undulator technology such as mm-wavelength undulators being developed at UCLA and rf undulators being developed at SLAC as well as other diagnostics techniques that have the potential to provide detailed resolution of the longitudinal phase space which will be critical to optimize operating parameters at future FELs.

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Current Status of Modeling of Accelerators for Next Generation Light Sources

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Proposal Title: Advanced Modeling of Accelerators for Next Generation Light Sources

Scientific Challenge and Research Achievement

Large-scale simulation, used in concert with theory and experiment, is essential for understanding the dynamics of particle beams in accelerators and for designing future accelerators. Light source modeling is especially challenging due to the extreme range of spatial and temporal scales, and the multi-physics nature of the phenomena involved. We have developed the IMPACT (Integrated Map and Particle Accelerator Tracking) code framework for modeling high intensity, high brightness beams in accelerators [1-11]. It consists of two parallel particle-in-cell tracking codes IMPACT-Z and IMPACT-T (the former uses longitudinal position as the independent variable and allows for efficient particle advance over large distances as in an RF linac, the latter uses time as the independent variable and is needed to accurately model systems with strong space charge as in photoinjectors), an rf linac lattice design code, an envelope matching and analysis code, and a number of pre- and post-processing codes. Both parallel particle tracking codes assume a quasi-electrostatic model of the beam (i.e. electrostatic self-fields in the beam frame, possibly with energy binning for a beam with large energy spread) and compute 3D space-charge effects self-consistently at each time step together with the external acceleration and focusing fields. Besides the fully 3D space-charge capability, the IMPACT suite also includes detailed modeling of beam dynamics in rf cavities (via field maps or z-dependent transfer maps including rf focusing/defocusing), various magnetic focusing elements (solenoid, dipole, quadrupole, etc), allowance of arbitrary overlap of external fields (3D and 2D), structure and CSR wake fields, tracking multiple charge states, tracking multiple bin/bunches, Monte-Carlo simulation of gas ionization, an analytical model for laser-electron interactions inside an undulator, and capabilities for machine error studies and correction.

A notable milestone in the development of the IMPACT suite was the first-ever multi-billion particle simulations of beam dynamics though electron linacs for future x-ray light sources [10], ushering in a new phase of large-scale electron linac modeling, in which high brightness beams are modeled with a real-world or near-real-world number of simulation particles. The development of this capability was motivated by the need to faithfully model the microbunching instability, a key phenomenon affecting future light sources, which can grow out of small beam density fluctuations, for example due to shot noise, as a result of collective effects. Figure 1 provides an example of how models using a number of macroparticles significantly smaller than the number in a physical bunch population can lead to overestimating the effect of the instability by introducing an artificially high numerical shot noise. While these effects may be addressed using analytical and numerical smoothing techniques, the use of a real-world number of macroparticles provides a highly robust method for modeling collective phenomena in high brightness electron beams for future light sources.

Future Work

In the next three years, we will focus on three main areas of activities: (1) Advancing the state-of-the-art in start-to-end, 3D, multi-physics modeling for BES applications, (2) development of new parallel, multi-scale methods for modeling phenomena in future light sources that cannot currently be modeled adequately; and (3) development of a simulation-based parallel optimization capability so that BES researchers can not only perform high-resolution simulations with accelerator parameters varied "by hand," but also use parallel, computer-aided optimization for accelerator system design itself for performance optimization, fault analysis, and other design studies.

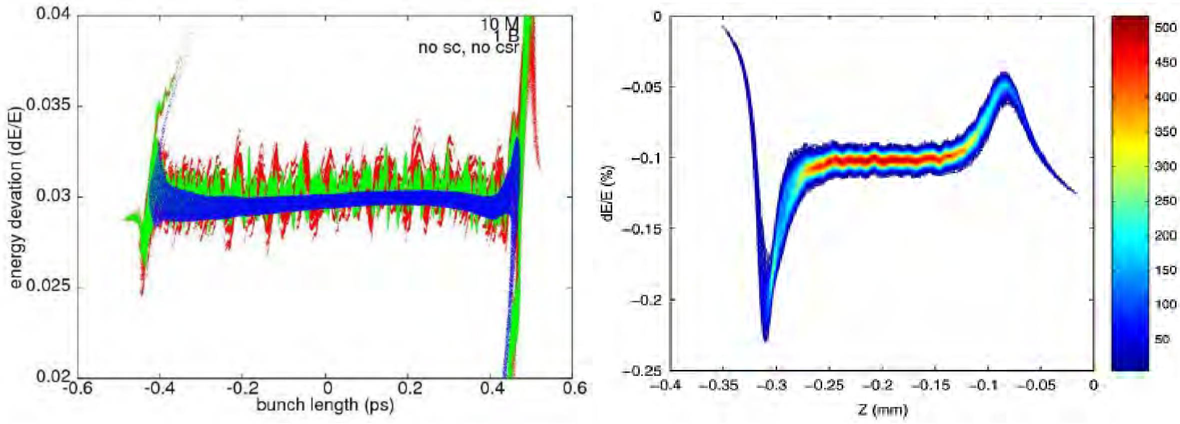

Figure 1. Left: the longitudinal phase space of an ideal beam at the exit of a linac shows a highly desirable smooth density when collective effects are neglected (blue). Unfortunately when collective effects are included in the simulations (green, red) an instability appears, manifesting itself in phase space density fluctuations along the bunch length. These fluctuations can have a deleterious effect on the performance of the x-ray radiators. Simulations done with one billion macroelectrons (green) are more accurate and show a lesser degree of instability than simulations done with only 10 million macroelectrons (red) because of reduced spurious numerical noise. Right: the density plot for a beam distribution obtained with a number of macroelectrons equal to the physical bunch population (5 billion). This simulation included all the relevant collective effects. These simulations then allowed careful design and specification of beam and lattice parameters to control the instability [10].

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Advanced Electromagnetic Modeling for BES Accelerators with ACE3P

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Advanced Computations Department, SLAC National Accelerator Laboratory

Research Achievement

Under the support of the SciDAC program, SLAC has developed a comprehensive set of parallel electromagnetic codes for accelerator modeling. The simulation suite, **ACE3P** [1], employs the high-order finite-element method on unstructured grids for high-accuracy and high-fidelity modeling of complex accelerator structures, and its parallel implementation allows large problems to be solved with high resolution through increased memory and linear speedup. **ACE3P**'s simulation capabilities include cavity design and optimization, wakefield computation, dark current and multipacting simulation, particle-in-cell rf gun modeling, and multiphysics analysis comprising rf, thermal and mechanical effects. The simulation modules of **ACE3P** have been applied to several BES accelerator projects.

LCLS rf gun design. The eigensolver **Omega3P** in **ACE3P** was used to provide the dimensions of the rf gun cavity to meet design requirements [2]. The cavity design reduces pulse heating by rounding of the z-coupling iris and minimizes dipole and quadrupole fields via a racetrack dual-feed coupler design. The simulation results of the rf parameters of the cavity agree excellently with measurements (Fig. 1). Using the particle-in-cell module **Pic3P**, the first-ever calculation of the rf gun from first principles provided unprecedented accuracy for the beam emittance.

RF parameter	Design	Measured
f_π (GHz)	2.855987	2.855999
Qo	13960	14062
β	2.1	2.03
Mode Sep. Δf (MHz)	15	15.17
Field balance	1	1

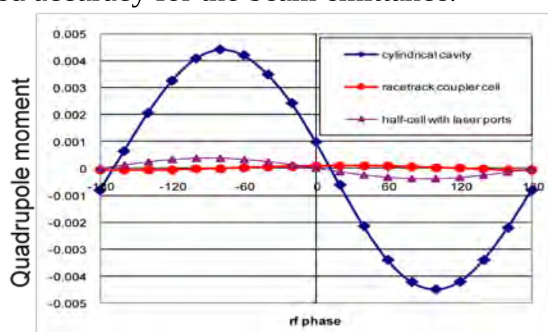

Figure 1. (Left) Model of LCLS rf gun; (Middle) Comparison of Omega3P calculation with measurements; (Right) Quadrupole moment as a function of rf phase for different cavity shape.

Multipacting in SNS SRF cavity. During the operation of the SNS superconducting linac, abnormal field signals were observed at the HOM coupler of the β=0.81 superconducting rf (SRF) cavity. Multipacting (MP) was suspected to be the cause of the anomaly and **Track3P** was used to analyze the problem [1]. A scan for the mutipacting activity shows two MP bands in the gradient range up to 20 MV/m which are in good agreement with experimental observations (Fig. 2).

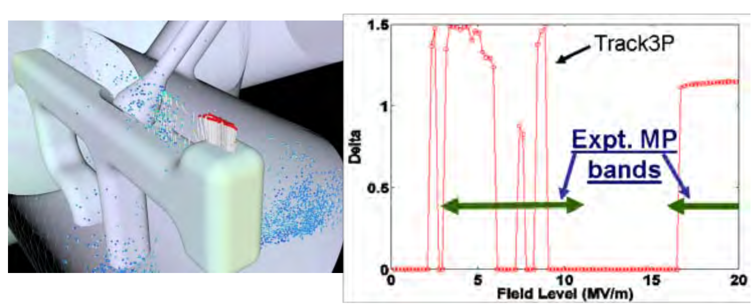

Figure 2. (Left) Multipacting activities in the SNS HOM coupler; (Right) Comparison of MP bands with measurements.

<u>*Short-range wakefields in PEP-X*</u>. For the storage ring as a next generation synchrotron light source, PEP-X requires the calculation of wakefields at ultra-short bunch length in long 3D beamline components which is a computational challenge. Such a case is the undulator structure for PEP-X which consists of a long smooth taper that connects vacuum chambers with different cross sections on either side (Fig. 3). The structure length is 0.3 m, which is much longer than the RMS bunch length of 0.0005 m. Because of the disparate length scales the moving window technique in **T3P** is used to significantly reduce the computational resources required for the simulation [3, 4]. Fig. 3 shows the wakefield for 0.5 mm bunch and the comparison of a 3 mm bunch with that reconstructed from 0.5 mm. The excellent agreement confirms the calculation with the short bunch. This computation took 15 CPU hours using 6000 cores on Jaguar to obtain the results with the desired accuracy.

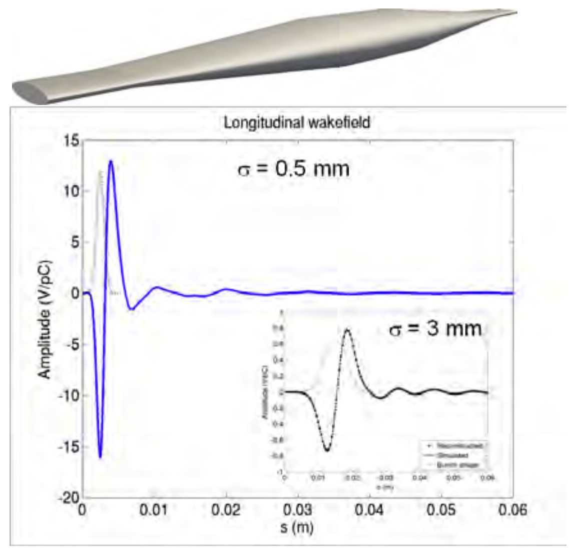

Figure 3. (Top) Model of PEP-X undulator chamber; (Bottom) Longitudinal wakefield.

Future Work

The advanced simulation capabilities of ACE3P will enable better design, optimization and analysis of existing and future BES accelerator projects that include

SPX deflecting cavity for APS upgrade. Multipacting studies will be carried out for the SPX (short-pulse x-ray) deflecting cavity to characterize its rf performance at designed voltages. The impedances of the higher-order-modes (HOMs) and lower-order-modes (LOMs) will be evaluated and provided as input for beam dynamics studies. The spatial separation between two SPX cavities will be optimized for beam dynamics considerations. Thermal effects in the cold-warm cavity waveguide transition and in the beampipe transition will be determined.

NSLS-II. Planned efforts are multipacting simulation for the SRF cavity and impedance calculations of the beamline components.

ERL & NGLS. These light sources will use SRF linacs for acceleration. Simulations will be carried out to determine wakefield effects of the SRF cavity on beam breakup. Thermal analysis will be performed to determine the thermal loads in the cavity coupler and in HOM absorbers if needed by the design.

Publications

[1] K. Ko et al., Advances in Parallel Electromagnetic Codes for Accelerator Science and Development, Proc. of Linac 2010, Tsukuba, Japan, September 12-17, 2010.
[2] D.H. Dowell et al., The Development of the Linac Coherent Light Source RF Gun, SLAC-PUB-13401, in ICFA Beam Dyn.Newslett.46:162-192, 2008.
[3] L.-Q. Lee et al., On Using Moving Windows in Finite Element Time Domain Simulation for Long Accelerator Structures, J. Comput. Phys., Vol. 229, Issue 24, Dec 2010.
[4] C.-K. Ng et al., High Fidelity Calculation of Wakefields for Short Bunches, Proc. of PAC11, New York, March 28 – April 1, 2011.

COHERENT LIGHT SOURCE R&D AT MIT

W.S. Graves, F.X. Kaertner, D.E. Moncton - Massachusetts Institute of Technology
P. Piot - Northern Illinois University

Proposal Title: Key Laser Technologies for X-ray FELs

MIT is engaged in a wide-ranging program to develop future light sources with an emphasis on a compact light source based on inverse Compton scattering (ICS). This report focuses on recent work toward generation of coherent ICS x-ray beams and ultrashort electron pulses using a novel approach that employs electron emission from a nanocathode array and subsequent transformation of the periodic electron beamlets from the transverse to longitudinal dimensions.

Research Achievements: An attractive approach to building a more powerful ICS source is to seek a method of coherent emission. The present studies investigate emission of electrons from a nanotip array, and transformation of the array of beamlets into a longitudinally bunched beam. While individual nanotips can have emittance near the quantum limit, the total emittance of a group of beamlets emitted by an array necessarily includes the dead space between tips comprising an area much greater than that of tip emission. While this deadspace is generally not useful, a new method is studied that transfers the spatial density modulation from the transverse into the longitudinal dimension, where the array of beamlets looks much like the desired longitudinal bunching of an FEL-like electron beam. The advent of emittance exchange beamlines that completely transpose transverse to longitudinal electron beam distributions makes this possible. The steps to achieve the desired beam are (1) emission of a group of beamlets from a nanocathode array, (2) focusing of the individual beamlets by microlenses that are part of the cathode structure, (3) acceleration to relativistic energy, (4) focusing and rotation of the entire group of beamlets in preparation for emittance exchange, (5) emittance exchange, and finally (6) inverse Compton scattering of laser photons by the coherently bunched electrons. The sections below describe progress and plans for each step.

Modeling of Nanotip Electric Fields: Figure 1 shows the geometry of a double-gated nanotip and equipotential field lines generated with the electromagnetic modeling program Poisson/Superfish. A variety of configurations is under investigation, including single-gated tips, gates with a thin graphene layer covering the aperture and providing a field boundary that is essentially transparent to the low energy emitted electrons, nanolens arrangements including Einzel configuration with 3 focusing elements, and a range of gate diameters, array pitches, needle geometries, and material thicknesses. The Microsystems Technology Laboratories (MTL) at MIT have produced numerous nanotip arrays with the desired properties, and can fabricate feature sizes of a few nm. Such tips have been used in plasma display technology [1] and have begun to be considered for high energy electron beam applications [2,3,4].

Modeling of Electron Emission and Low Energy Transport: The generated nanotip field maps are exported for use in the tracking program PARMELA. A model of the initial electron distribution has been developed that takes into account local current emission following Fowler-Nordheim theory, the map of surface electric fields from the Poisson model, and measured data on the spread in momenta from nanotip field emission.. It is assumed that field emission is gated on by a 300 fs laser pulse using photo-field emission. This model produces an initial 6D distribution that is read by PARMELA. Due to the small tip radius of 3 nm, the emission area is only about 5 square nm. The maximum current density is 10^8 A/cm^2 at 10 GV/m applied field (gate = 40V for geometry of Fig. 1) with an initial emittance of 6×10^{-13} m-rad estimated for field emitted electrons from that area. Each tip is limited to a peak current of ~10 uA, therefore 10^5 tips are required to generate a peak current near 1 A (0.3 pC bunch charge), which can be accomplished by e.g. a 300x300 tip array. Although this is a low charge level relative to conventional cathodes, coherent x-ray emission and repetition rate of 100 MHz planned in the MIT ICS source results in a bright photon beam with high flux. The circular electrostatic lenses used as focusing gates are known to have high aberration [5] but can focus to ~3 angstroms in the absence of correctors.

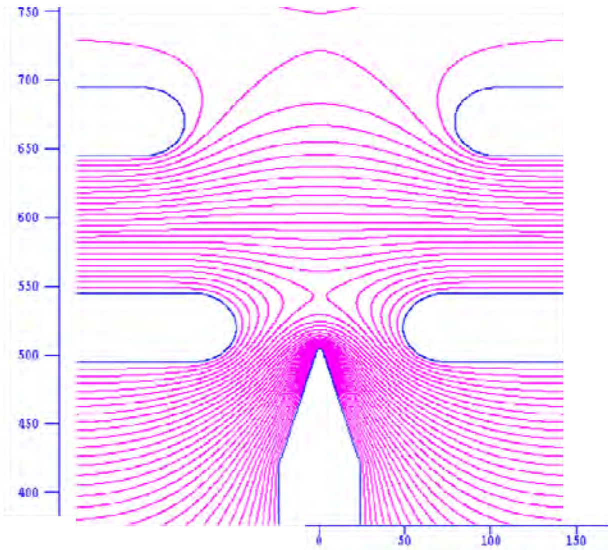

Figure 1. Poisson/Superfish model of double-gated nanotip. Dimensions are nm.

Modeling of Emittance Exchange: Models of an emittance exchange line consisting of 4 dipole magnets in a dogleg configuration with an RF cavity at the center of the line have been created in both MATLAB and the tracking program ELEGANT. The MATLAB routines quickly establish desired input parameters and allow rapid studies. The ELEGANT model includes higher order effects and a thick-lens model of the RF cavity. An iterative process of tracking particles both forwards through the line, beginning with an assumed distribution, and backwards through the line starting from an ideal output distribution, converged on both an achievable initial distribution and the desired bunching properties at the beamline exit.

Future Work: Extend and combine the existing simulation efforts to generate start-to-end (S2E) models from electron emission at the nanocathode through emission of coherent x-rays via ICS. The S2E model will be used to investigate parameter tolerances and jitter specifications. After the numerical studies are complete, it is straightforward and inexpensive to implement initial experiments at EUV photon energy using the output of a copper gun with nanocathode and photocathode drive laser. Work continues on development of an ICS source based on a superconducting RF injector and linac, and high average power lasers.

Publications:

"Compact Source of Coherent X-rays and Attosecond Electron Pulses", W.S. Graves, F.X. Kaertner, D.E. Moncton, P. Piot, submitted to IPAC 2011

US Patent Application No. 13105114, "Compact Coherent Current and Radiation Source"

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Key Laser Technologies for X-Ray FELs: Pulsed Timing and Synchronization Systems

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Summary: We demonstrate reliable timing transfer between remote (340 m) lasers within sub-10 fs precision over hours of operation. The overall jitter is currently limited by the jitter in the lasers used, i.e. fiber lasers. We identified the limitations in long term stability of the link, which are PMD and fiber nonlinearities. Most importantly, we showed for the first time, that jitter in mode-locked lasers can be as low as about 10as, when properly constructed. In fact, it may reach zepto-second levels, if only fundamentally limited by spontaneous emission noise. This result shows that the current timing distribution systems can in principle be scaled to 100 and maybe even 10 attosecond precision by continuous development over the coming years.

Research Achievements: Characterization of sub-10fs timing distribution system and its limitations: Femtosecond performance timing distribution and synchronization of lasers and RF-sources is critical for development and use of next-generation X-ray free electron lasers (X-FEL) to its full potential. Today, these short-pulse X-ray sources require tight synchronization across 300 m-3 km distances with less than 10 fs precision. Due to the rapid progress in X-FEL technology, femtosecond level and even sub-femtosecond level timing distribution will be demanded over the next years to come. In this project, we have studied an ultrafast, fiber-optic, timing distribution system based on balanced optical cross-correlation (BOC). A BOC allows, with typical pulse parameters, attosecond resolution timing measurements. Analytical analysis of the BOC has been carried out and suggests a thermal noise limited resolution of about 20 as rms for typical fiber link operating parameters[1].

The performance of the current timing distribution system was investigated at a prototype system consisting of a link of 300 m of telecommunications (Corning SMF-28e) fiber and 40 m of dispersion compensating fiber (DCF) was implemented, as shown in Fig. 1. The link is stabilized by measurement of pulse timing between a pulse returning from the end of the fiber link, and a new pulse from the master laser. The timing between these pulses is measured in the BOC, and the error signal corrects fiber fluctuations by adjusting a free space delay. The stabilized fiber link has demonstrated 5 fs rms precision timing distribution over 7 days of continuous operation, with polarization maintaining output. Ultimately, here we demonstrate actual timing transfer from master laser to remote laser through the 340 m long, stabilized timing link. This is accomplished by synchronizing the remote laser to the output of the stabilized link with a second BOC. The out-of-loop performance is then assessed by comparison of timing stability between the master and remote lasers in a third BOC. The results of a 3.5 hour timing transfer test are shown in Fig. 2, demonstrating 2.3 fs rms precision, which is

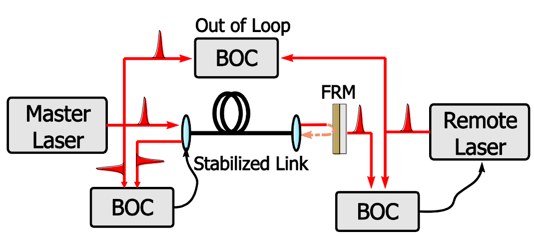

Fig. 1. Schematic of timing transfer system from master to remote laser through a stabilized link.

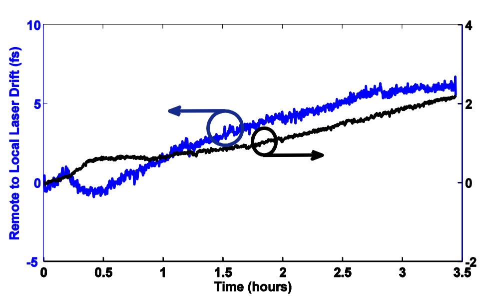

Fig. 1. Timing transfer performance from laser to laser through the stabilized fiber link. Blue line: out-of-loop drift, black line shows corrected fiber fluctuations.

currently only limited by the out of loop timing jitter of the free running lasers.

With an eye toward attosecond pulse X-FELs, we investigated the potential for sub-femtosecond timing distribution through experimental study and computer simulations. For instance, it was found that polarization mode dispersion (PMD) in the fiber can be a significant contributor to timing drift. For instance a fiber stretcher was found to have as much as 83 fs of differential group delay (DGD). Proper installation of the fiber is necessary to minimize mechanical stress and, therefore, PMD. Still a timing system based on the demonstrated links can deliver stable timing distribution over hundreds of meters and over a week at the 10 fs level, if properly selected low PMD fiber links are used and sudden shocks, both thermal and acoustic, to the fibers are avoided. More robust and even, sub-femtosecond timing distribution, will require migration to an all-polarization maintaining (PM) fiber scheme to eliminate PMD. Finally, we also investigated the impact of fiber non-linearity on timing distribution by simulating pulse propagation in a fiber link. For a typical link, a threshold energy of about 40 pJ was identified, where pulse reshaping due to fiber nonlinearities lead to strong distortion of the BOC signal, leading to timing shifts.

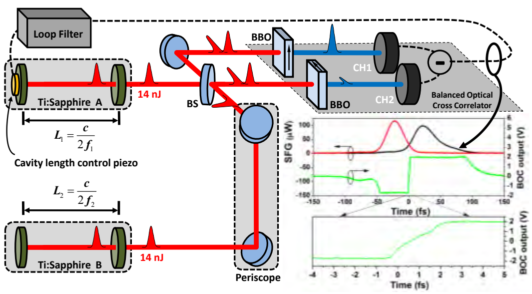

Fig. 3. BOC setup for jitter measurement between two Ti:sapphire lasers.

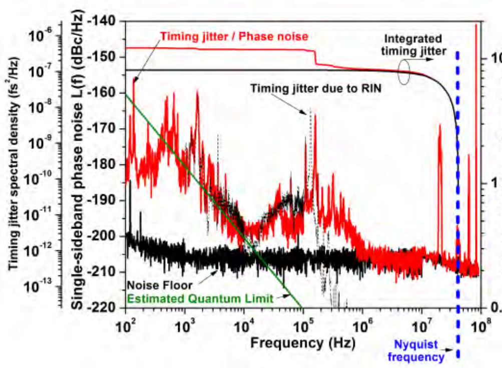

Fig. 4. Timing jitter spectral density and rescaled single sideband phase noise between the phase locked optical pulse trains from the Ti:Sapphire lasers, scaled for a 10 GHz carrier. BOC trace in red, BOC noise floor in black, estimated contribution due to pump laser RIN is dotted black**.**

Complete Characterization of Mode-locked Laser Timing Jitter: Fiber-optic timing between independent laser sources is limited by the out of loop jitter of the free running lasers involved. Therefore, it is of key importance to understand the origin and scaling of timing jitter in modelocked lasers. Within this program we have for the first time fully characterized the timing jitter from fiber lasers over the full Nyquist bandwidth and verified its quantum mechanical origin, i.e. spontaneous emission noise. Second, we verified the scaling of timing jitter with cavity loss, pulsewidth and pulse energy $\frac{\mathrm{d}}{\mathrm{dt}}\langle \Delta t^2 \rangle = \frac{\pi^2}{6}\tau^2 \frac{h\nu}{E_P \tau_c}$, where Δt is the offset of the pulses from their nominal time locations, τ is the full width at half maximum pulse width divided by 1.76, E_P the intracavity pulse energy, τ_c the cavity decay time and $h\nu$ the quantum energy of the laser photons. This formula indicates that 10-fs Ti:sapphire lasers may show zepto-second level jitter. Therefore, we did setup the system shown in Fig. 3 able to verify timing jitter at such a low levels. The residual timing/phase jitter spectrum from the phase locked pulse train is plotted in Fig. 4, indicating a high frequency jitter between the two lasers as low as 12.3 +/-0.6 as with a noise floor contribution of 8.1 +/-0.4 as^2. This result shows that mode-locked lasers can be engineered to enable few 10’s of attosecond timing and synchronization systems.

Future Work: Demonstrate PM fiber links and 100as level jitter lasers suitable for timing distribution.

Publications:

1. J. A. Cox and F. X. Kärtner, “A femtosecond-precision, fiber-optic timing transfer system with long-term stable, polarization maintaining output,” submitted to Review of Scientific Instrumentation.
2. A. J. Benedick, J. G. Fujimoto, F. X. Kärtner, “Ultrashort laser pulses: Optical flywheels with attosecond jitter,” submitted to Nature Photonics.

Plenary Session III

Broad Update on the Progress towards Future Light Sources, Including R&D Progress

Ilan Ben-Zvi, Stony Brook University and Brookhaven National Laboratory

Abstract

Over the past ~50 years, synchrotron light sources advanced in performance and applications at a breathtaking pace. X-ray Free-Electron Lasers are presently a reality. We arrived at this juncture through R&D aimed at improving the performance of previous generation light sources. This impressive progress continues, spurred by past successes and well placed R&D funding aimed at future light sources. I will provide an update on preparations and progress towards future light sources; highlight key R&D, which is being done and that is needed to make future light sources a reality.

What are the future light sources depends on the person providing the answer. It also depends on the application. However, we can expect some general trends. Higher average brightness, shorter pulses, longitudinal coherence, harder X-rays, multiple beam lines, lower-cost / compact sources have been mentioned in the community. There is a large variety in the accelerators employed – linacs (normal conducting, superconducting, dielectric, plasma), and energy recovery linacs. We encounter various ways of achieving coherence by various methods of seeding FELs, operating an FEL oscillator. The electron sources and photocathodes play an important role in whatever is the future light source.

This presentation will not cover synchrotron light sources. That is not meant to signify that they are not part of the future. Given improvements made continuously, and the advantage of dozens of simultaneous beam lines, we can expect synchrotron light sources to continue to be an important part of our future.

This update will address science and technology issues that are being pursued to advance future light sources. These include seeding schemes, short period undulators, generation of short X-ray pulses, compact sources, high repetition rate X-ray FELs, X-ray FEL oscillators, accelerators and high-brightness electron guns and photocathodes for CW X-ray sources. The resources used for this review are based on material provided by request, mostly from participants in this meeting, proceedings of recent workshops and the general literature.

This review aims at a presentation of the main R&D being carried in various laboratories towards future light sources and the progress made. It is hoped that the presentation will serve as a starting point for a discussion. This will serve DOE/BES management with information to assess the state of the program, consider its future direction, and identify programmatic needs. As a famous person said, “The future belongs to those who prepare for it today”.

Poster-Only Abstracts

Multi-objective optimization of storage ring dynamic acceptance and lifetime [1]

M. Borland, V. Sajaev, L. Emery, A. Xiao, ANL, Argonne, IL 60439, USA

1 Proposal Title

Multi-objective optimization of storage ring dynamic acceptance and lifetime

2 Research Achievement

As storage ring light sources are pushed to smaller emittances and otherwise modified to meet user requirements, the difficulty of achieving workable injection efficiency and Touschek lifetime increases. Workable injection efficiency requires sufficient dynamic acceptance (DA), while workable Touschek lifetime requires sufficient local momentum acceptance (LMA). We recently developed direct (i.e., tracking-based) single- and multi-objective techniques for tuning linear optics and sextupoles in order to maximize DA and lifetime [1].

The Advanced Photon Source (APS) has 40 double-bend sectors in an essentially symmetric configuration with independently-powered quadrupoles (400) and sextupoles (280). We plan to provide long straight sections (LSSs) to several sectors [2] by removing the long Q2 quadrupoles and other nearby components. The most natural configuration is to make every tenth or fifth straight section a long one. However, this requires expensive and disruptive relocation of existing beam lines. Also, for implementation of the deflecting-cavity-based short-pulse x-ray (SPX) scheme [3], we need two LSSs (to accommodate the SPX cryostats) separated by a single short straight. Hence, we favor a non-symmetric arrangement of LSSs.

Modern light sources incorporate a large number of independent sextupole families in order to provide the flexibility to optimize both the DA and LMA. The difficulty of optimization is increased in that APS operates with high chromaticity $\xi = \partial\nu_{x,y}/\partial\delta$ in order to stabilize the beam for timing mode operation. Even with bunch-by-bunch feedback [4], we will require $\xi \approx 8$ for 150-mA, 24-bunch operation and $\xi \approx 9$ for 16 mA hybrid mode. We use a multi-objective genetic algorithm[5], set to maximize the DA area and the Touschek lifetime, while minimizing the chromaticity error $(\xi_x - \xi_{x,desired})^2 + (\xi_y - \xi_{y,desired})^2$. Tracking is performed with the program `elegant` [6, 7].

For DA computation, line scans from the origin are used to find the stability boundary. To prevent pathological results, a clipping algorithm [8] is used to eliminate parts of the DA that are not deemed useful, prior to computing the area. We also limit the search region in the vertical plane to avoid increasing the area by enlarging the vertical acceptance to an unnecessary degree.

The Touschek lifetime is determined by first tracking to determine the local momentum aperture by searching from $\delta = 0$ outward in the positive and negative directions until the stability boundary is reached. Having this data, which is representative of the entire ring, we then compute the Touschek lifetime using Piwinski's method [9] as embodied in the program `touschekLifetime` [10].

The optimizer varies not only sextupole strengths, but also the tunes. (Tune variation is implemented using interpolation of a set of pre-calculated lattices with fractional tunes covering a grid.) Depending on the quality of the starting point, optimization typically requires evaluation of 1000 or more configurations before adequate convergence is obtained. Figures 1 through 2 show results for long straight sections in sectors 1, 5, 7, and 11. The desired DA is -15 mm (injection is on the inboard side) while the required lifetime is about 4 hours.

3 Future Work

Future work will concentrate on continued application of these techniques to the APS upgrade. We are optimizing mock-up configurations that will allow testing lattices with four long straight sections

[1] Work supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

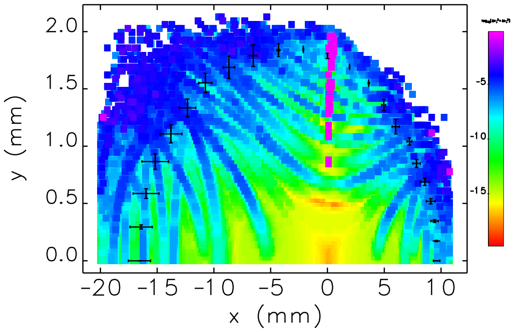

Figure 1: Dynamic acceptance for 50 ensembles for $\xi = 8$, superimposed on frequency map.

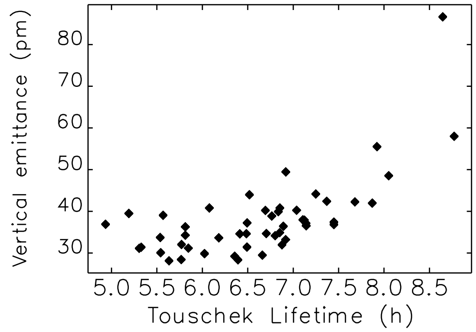

Figure 2: Lifetime and vertical emittance for 50 ensembles for $\xi = 8$.

and other features prior to making hardware changes.

4 Publications

V. Sajaev *et al.*, Multi-objective optimization of a lattice for potential upgrade of the Advanced Photon Source, Proc. PAC11, to be published.

M. Borland *et al.*, Multi-objective direct optimization of dynamic acceptance and lifetime for potential upgrades of the Advanced Photon Source, APS LS-319, August 2010.

M. Borland *et al.*, Application of direct methods of optimizing storage ring dynamic and momentum aperture, Proc. ICAP09, 255-258 (2010).

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XDL-2011: Workshops on Science at the Hard X-ray Diffraction Limit

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Cornell University, Ithaca, NY 14850

Proposal Title: Workshops on Science Enabled by a Coherent, CW, Synchrotron X-ray Source

Research Achievement

A series of six (6) workshops exploring the scientific potential of a continuous-duty, coherent (fully diffraction-limited), hard ($\lambda \leq 1.5$ Å) synchrotron x-ray source were held on the Cornell University Campus in June 2011. A continuous-duty source (also known as a continuous wave or "CW" source) is one that delivers x-rays in a continuous train of pulses at rates exceeding a million per second.

CW, diffraction-limited, hard x-ray sources will be especially advantageous for a variety of coherent and nanobeam experiments including: (i) cases where the sample must be repetitively probed; (ii) cases where the samples are unique and the requisite scattering information cannot be obtained with a single pulse; and, (iii) cases such as spectroscopy where incident beam stability is paramount. Potential future synchrotron x-ray source technologies meeting these constraints include ultimate storage rings (USRs), energy recovery LINACs (ERLs), high-repetition-rate, x-ray free-electron lasers (X-FELs), and x-ray free-electron laser oscillators (X-FELOs).

The modest coherent x-ray flux currently available at partially-coherent 3rd generation synchrotron sources has enabled the development of exciting new experimental techniques such as X-ray Photon Correlation Spectroscopy (XPCS) and Coherent Diffraction Imaging (CDI). However, full utilization of these and other novel techniques awaits the deployment of more advanced hard x-ray sources with orders of magnitude more coherent flux. Fully coherent hard x-ray sources promise to enable revolutionary new techniques for examining non-crystalline and time evolving systems on atomic length scales.

The dates, titles, and organizers of the six workshops were:

June 6,7: ***Diffraction microscopy, holography and ptychography using coherent beams.*** Janos Kirz (Lawrence Berkeley National Lab), Qun Shen (Brookhaven National Lab), Darren Dale (Cornell University)

June 13,14: ***Biomolecular structure from nanocrystals and diffuse scattering.*** Ed Lattman (Hauptmann-Woodward Medical Research Inst.), Mavis Abandje-McKenna (Univ. Florida), Keith Moffat (Univ. Chicago), Sol M. Gruner (Cornell Univ.)

June 20,21: ***Ultra-fast science with "tickle and probe".*** Robert Schoenlein (Lawrence Berkeley National Laboratory), Brian Stephenson (Argonne National Laboratory), Eric Dufresne (APS), Joel Brock (Cornell University)

June 23,24: ***High-pressure science at the edge of feasibility.*** Russell J. Hemley (Carnegie Institution of Washington), Neil Ashcroft (Cornell University), Roald Hoffmann (Cornell University), John Parise (SUNY Stony Brook), Zhongwu Wang (Cornell University)

June 27,28: ***Materials science with coherent nanobeams at the edge of feasibility.*** Christian Reikel (ESRF), Simon Billinge (Columbia University), Kenneth Evans-Ludderodt (Brookhaven National Laboratory), Don Bilderback (Cornell University)

June 29,30: ***Frontier science with x-ray Correlation spectroscopies using continuous sources.*** Mark Sutton (McGill University), Simon Mochrie (Yale), Arthur Woll, (Cornell University)

Future Work:

1. Prepare a series of workshop reports for publication in Synchrotron Radiation News.
2. In collaboration with SSRL, prepare a detailed science case document for a CW, diffraction-limited, hard x-ray source.

These workshops were jointly sponsored by SSRL, DESY, KEK, and Cornell University. The DOE provided travel support for the invited speakers. The NSF provided support for the conference center and travel support for 21 students and post-docs.

References:

Publications: none yet.

Status of the MAX IV Storage Rings

Multibend achromats for ultralow emittance (0.3 nm rad)

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Abstract. A synchrotron light facility is currently being built in Lund, Sweden. The accelerator part of this facility consists of two storage rings, operated at 3 and 1.5 GeV respectively. These rings are injected from a S-band warm linac operated at 3 GeV. The 1.5 GeV ring is injected half-way down the linac.

Apart from acting as an injector, the linac will also be used as an electron source for a Short Pulse Facility (SPF) for the generation of short X-ray pulses from a spontaneously emitting undulator. In a longer time perspective, the linac energy could be extended to 6 GeV to serve as the electron source for an X-FEL.

The 3 Gev ring has an ultra-low emittance of 0.3 nm rad for the naked lattice and 0.2 nm rad for a ring fully ID equipped. This low emittance is achieved by using 7-Bend Achromats (7BA). 20 achomats forms the ring with a total of 140 elementary cells.

The 7BA offers a high degree of stability since the Hamiltinonian driving terms can be cancelled within an achromat and betatron shifts induced by varying undulator gaps thus have little impact on this cancelation.

The large number of elementary cells calls for a special magnet technology to limit the total circumference of the ring. This technology will in its turn call for a linearly pumping vacuum system.

The 1.5 GeV ring is using a similar technology. This ring will be built in two copies, one will be placed at the MAX IV Laboratory, the other one will be placed at the Solaris facility in Krakow, Poland.

The MAX IV project was funded in September 2010 and is supposed to be commissioned in late 2015. The first phase funding covers the accelerators, buildings and operation (Swedish research Council, University of Lund, the county of Skåne and VINOVA (Swedish Technical research Council) and the first set of 7 beam-lines are funded by the Wallenberg Foundation who also funds an educational program for young scientists.

The poster will describe the machine parameters and also present some of the technologies chosen. A more detailed description of the facility is found at MAX IV Detailed Design Report, http://www.maxlab.lu.se/maxlab/max4/index.html.

High Intensity Proton Beam Studies at the Spallation Neutron Source (SNS) *

J. Galambos, A. Aleksandrov, V. Danilov, M. Plum, A. Shishlo, Spallation Neutron Source, Oak Ridge National Laboratory

Motivation

Next generation high power hadron accelerators face ever-more stringent beam loss considerations and high intensity effects become more critical with increasing power demands (e.g. neutron sources, muon collider, neutrino factory, radio-active ion beams, accelerator driven systems). The Spallation Neutron Source (SNS) is the world's highest power pulsed proton accelerator and is an ideal test bed to investigate high intensity effects. Areas of proposed study include identifying beam loss mechanisms, benchmarking simulation tools with large dynamic range profile measurements and demonstrating H^- foil stripping alternatives for accumulation in rings. In particular improved profile measurement with beam distribution reconstruction is being pursued as well as a laser-stripping alternative to foil injection for ring injection [1].

Research Achievement

The SNS linac offers an ideal platform for the study of high intensity proton beams. It is a MW class linac, and already includes some provisions for beam studies. The SNS Medium Energy Beam Transport (MEBT) section between the RFQ and initial Drift Tube Linac (DTL) accelerating structure offers means to characterize the input beam: 5 transverse profile measurements, and a transverse emittance station, presently being commissioned. Beyond the MEBT in the warm accelerating structure area there are 14 transverse profile measurement stations and 4 longitudinal profile measurements (~ 90 m, 186 MeV). In the beam simulation area the ORBIT multi-particle beam transport code, a standard for high intensity proton beam ring simulations [2-3], is being readied for linac beam simulations. It includes the usual space charge, collective effects, has parallel-processing capability, uses modern software languages and incorporates an extremely flexible scripting user interface. In the ring injection area we have demonstrated the first proof of principle laser stripping example of the full energy (~ 1 GeV) SNS H^- beam [4]. We also have built up a laser expertise [5] that is useful for profile measurement and follow-on laser stripping development.

Future Work

To delineate possible loss mechanisms specific to H^- beams we are installing a retractable thin stripper foil at the start of the SNS acceleration chain to produce a

* Work performed at (or work supported by) Oak Ridge National Laboratory, which is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

proton beam. This will offer a direct comparisons of measured beam loss distributions from a single linac that accelerates both high intensity protons and H^- linac beams, each being tunable.

The first step in the simulation benchmark area will be to quantify the initial beam distributions (taken here as the exit of the RFQ). In the MEBT section following the RFQ we propose to 1) increase the dynamic range of the transverse profile measurements with a goal of 10^4 - 10^5, 2) provide slit and collector transverse emittance measurements with a 10^4 dynamic range goal, and 3) install and commission a laser based longitudinal bunch profile measurement. This concentration of profile measurements will be used in conjunction with the ORBIT simulation tool to reconstruct the initial beam phase space distribution with tomographic techniques [6]. Throughout the rest of the linac we propose to improve profile measurement dynamic range and use this to benchmark with the simulated data under a variety of conditions. There is already considerable flexibility in the lattice configuration of the CCL and SCL sections, in both the longitudinal and transverse focusing. The SNS linac could then be used to study effects such as transverse / longitudinal emittiance exchange, halo formation, and mismatch effects. There has not been a significant proton linac machine / simulation benchmark since the LEDA work at low energy over 10 years ago.

For the laser stripping follow-on effort we propose an intermediate 10 μs demonstration. This step will require more efficient use of the laser light, including improved laser and optics as well as incorporation of an innovative H- beam optics with derivative dispersion tailoring to minimize the detrimental effect of the beam energy spread [7].

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Superconducting Accelerator R&D for Coherent Light Sources

Authors: J. Mammosser, A. Hutton, R. Rimmer (Jefferson Laboratory)

Proposal Title: Superconducting Accelerator R&D for Coherent Light Sources

Jefferson Lab proposes to perform the necessary research for the development of compact SRF electron accelerators, optimized for the needs of the light source community. This research will be based on development of SRF cavity structures that are compact, demonstrate excellent beam dynamics performance, operate continuous wave (CW) and can operate in the temperature range of 4.2-4.5 K with good stability. Operating at 4 K temperatures significantly reduces the initial and operational cost of a small accelerator therefore making it more feasible for small research facilities. The surface resistivity of SRF materials scales as the square of the RF frequency and exponentially with temperature below the critical point. SRF cavities operating at temperatures of 4 K have high surface resistance and thus generate high cryogenic heat loads. Therefore it is necessary to develop cavity structures at lower frequencies where cryogenic heat loads are manageable. Successful cavity designs will be demonstrated in a test cryostat to validate cavity performance under accelerator operational conditions at the design temperature.

Scientific Challenge and Research Achievement:

This proposal is aimed at performing the necessary accelerator R&D for the development of a cost effective, compact electron accelerating module for use in small X-ray facilities such as proposed by MIT [1]. MIT has developed the concepts of an Inverse Compton Scattering (ICS) X-Ray machine based on a low emittance and short bunch electron beam. The MIT ICS design requires a short linear accelerator that takes a 4MeV beam and accelerates it to 25MeV with very low emittance growth of less than 10%. In collaboration with MIT, Jefferson Lab will perform the necessary accelerator R&D to develop a compact linear accelerator that suits the needs of affordable X-ray sources of relatively high brightness. X-Ray machines such as the ICS fill the need for small accelerator applications such as university scale or medical research size facilities. To achieve this goal a focused SRF R&D effort is needed for the very different needs of coherent light source facilities. These needs include reduced complexity and reduced costs of the cryogenic infrastructure, particularly for small facilities, ultrahigh stability, CW operation and ability to preserve very low emittance.

The scope of this R&D will be focused in following areas of accelerator technology: RF cavity development, cavity process development and cryostat development.

RF cavity Development:

RF cavity development effort will be focused on design and qualification of novel SRF cavity structures that are optimized for coherent light source applications. The basis of this development will be beam dynamics simulations of low frequency cavity designs that have small size, low wake fields and excellent emittance preservation. One such cavity that has these properties is the TEM mode spoke cavity. The spoke cavity has many desirable properties including: preservation of beam quality, low wake fields, higher voltage gain, low nonlinearity of fields, highly symmetric fields, excellent energy stability, resistance to microphonics and Lorentz detuning [2,3,4]. Spoke cavity designs will be developed for the light source application (β=1) as well as other novel cavity designs. Selected designs will be prototyped, qualified in vertical test, and dressed and qualified in a test cryostat.

Cavity Process Development:

An important parameter of the compact light source accelerator is operation at 4 K temperature where significant energy savings are possible. Therefore the operating Q-value of the SRF cavity is extremely important. The higher the Q-value the lower the dynamic cryogenic heat load. Typically, cavity Q-values operating at 4K are dominated by BCS losses and by field emission (surface contamination). Field emission adds additional surface heating due to electron bombardment from emitter sites. The more complicated the SRF cavity structure the more difficult it is to clean and reduce field emission. Spoke cavities fall into this category. Plasma cleaning, a standard semiconductor cleaning process, will be developed for the spoke cavities. R&D on plasma cleaning for these cavity structures will be focused on developing a reliable procedure for routinely cleaning cavity surfaces at any stage of their qualification.

Cryostat Development:

Cryostat development R&D will be focused on fabrication of a small test cryostat designed for 4K operation and rapid qualification of the chosen SRF cavity structures. Some existing Jefferson lab cryostat hardware will be utilized in the design and a test cryostat will be fabricated for testing successful cavity designs that are fully dressed with helium vessels and associated testing hardware and instrumentation. The cryostat testing of cavities is necessary to demonstrate cavity performance mounted in a vacuum vessel where standard operating conditions must address issues of microphonics and thermal instabilities. The cavity testing will also demonstrate the installed accelerating gradients and achievable Q-values. Outcome of this R&D will be cryostat subcomponent designs suitable for production style cryomodules for light source applications.

Future Work:

If Jefferson Lab is successful with the development of SRF cavities for a compact, cost effective light source application, a proposal will be submitted to build a demonstration light source accelerating linac for 4K operation consisting of a single cryomodule that produces 25MeV acceleration with low beam emittance and stable operation. Additionally a cost effective 4 K refrigerator design for the accelerator linac will be developed.

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Performance of Multi Alkali Cathode in JLab DC Gun

PIs: Triveni Rao (BNL), John Smedley (BNL), Mat Poelker (JLab)

Goals:
Two photocathodes are frequently considered for generating high average current electron beams and/or beams with high brightness: GaAs:Cs and CsK_2Sb. Evaluation of the performance of these cathodes in the operating conditions of the gun is critical to the selection of appropriate cathode for the ERL and FEL applications. Until recently, the GaAs:Cs cathode has been tested extensively in DC field[i] and CsK_2Sb in RF field[ii]. The performance of both cathodes should be measured under identical conditions in order to make a well-informed choice for new accelerators,. The goal of this project is to characterize the performance of CsK_2Sb before, during and after installation and while in use in a DC gun. We plan to

- Fabricate and characterize the photocathode at BNL in a UHV vacuum.
- Transport it in a UHV load-lock system compatible with the JLab DC gun and evaluate the changes in the photocathode properties during transit.
- Install it in DC gun and measure the QE, it change, and uniformity under different conditions using multiple wavelengths.
- Measure the changes in the cathode after use using modern surface science techniques.

This project brings together the expertise at JLab in operating DC high voltage photoguns and the experience at BNL in cathode fabrication and characterization. It leverages the capabilities of several major facilities (NSLS, and CFN at BNL, Injector test Stand at JLab).

Research Achievements:
A high quantum efficiency **alkali antimonide** photocathode was grown at BNL and transported to JLab. Early results on the cathode preparation, characterization, and transport in Load-lock are presented in PAC 11[iii]. The cathode was inserted in the test gun at JLab and the QE and life time were measured using 532 and 440 nm radiation. Results with 440 nm radiation at 3 mA current from 850 µm diameter spot and gun voltage of 200 kV are shown in Figure 1 a. The maximum charge accumulated during this run was 850 C from a single spot and QE was not observed to decrease. It is worth noting that this charge was extracted from the electrostatic center (EC) of the gun where beam emittance is expected to be the smallest - an important consideration for high brightness applications, but the effect due to the ion bombardment is the most severe. In a GaAs:Cs cathode, illuminating this site is typically avoided to extend the life time of the cathode. During this run, inadvertent events increased significantly the base pressure, and thereby the ion current, back bombarding the cathode. Such an event would have completely halted beam delivery from a GaAs:Cs photocathode. The QE of the CsK_2Sb, on the other hand, decreased only in the center but remained high around the edge. Interestingly, after this event the performance of the photocathode improved significantly for green laser light at 532 nm. Figure 1 b shows the cathode performance away from EC for a beam current of 20 mA, after the impairment at the EC. The cathode uniformity appears to improve upon storage and upon heating it in the presence of 440 nm radiation, indicating changes in the surface morphology during these processes. Comparison of performance at 532 nm and 440 nm radiation indicates that it is more robust with 440 nm, implying an absorption depth dependent behavior. Furthermore, the QE at this shorter wavelength increases with time, the magnitude of which depends on the laser power.

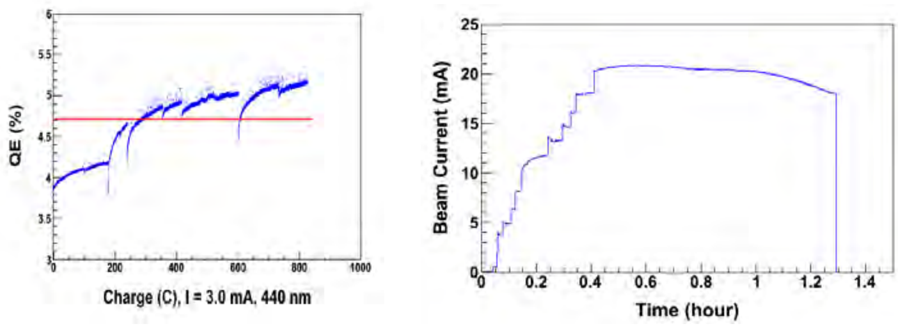

Figure 1 Time (and Charge) dependence of the cathode with 3 mA (a) and 20 mA (b) current

Numerous runs at currents between 1 and 10 mA were performed, the cathode irradiated by 440 and 532 nm laser wavelengths, and with the laser positioned at many different photocathode locations. Each run exhibited exceptional photocathode performance, with photocathode QE continuing to increase throughout the run. The total charge extracted during these runs is 5000 C. QE remained unchanged during the 10 mA operation. The corresponding current density is 100 mA/mm^2, value significantly higher than the requirement for FEL operation. The laser power was increased further to boost the current to 16 mA and 20 mA respectively, from 350 µm diameter spot. When the current approached 16 mA, the QE started declining, and further investigation suggests QE decay is related to heating of the photocathode. This assertion is supported by the observation that the charge lifetime at 20 mA improved from 14 to 617 C when the laser spot was increased from 350 um to 800 um In summary, the multi alkali cathode has proven to be a robust cathode that is relatively insensitive to back bombardment, capable of delivering current densities of 100 mA/mm^2, and adaptable to vacuum transport.

Future Plans:

Further measurements include investigating

- sensitivity of the cathode to typical vacuum chamber contaminants
- possible rejuvenation techniques
- spent cathode using surface science techniques
- the performance of the cathode with higher QE

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Femto-second X-ray Pulse Generation by Electron Beam Slicing

F. Willeke, L.H. Yu

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Research Achievement:

We propose to investigate femto-second x-ray pulse generation by electron beam slicing of a storage ring beam. When a short electron bunch from linac (5MeV, 100pC, 100fs) passes above a storage ring bunch (30 ps), it kicks a slice (150fs) vertically (Figure 1). The radiation from short slice is separated from the core bunch [1]. The new method may be used to create Ultra-short x-ray pulse in storage rings. There is strong user interest in ultra-short x-ray pulses (see APS upgrade [2]).

The new method has many advantages when compared to other schemes. It needs much smaller space in storage ring for interaction point, compared with crab cavity, as used in APS upgrade. The pulse length (150fs) is much shorter than crab cavity method (1-2ps). The flux per pulse may be increased significantly compared with laser slicing (by a factor of 6-10). The repetition rate can be many orders of magnitude higher than laser slicing (about 10 MHz, compared with 1-10 kHz). Compare with LCLS, there is 10^4~10^5 of magnitude higher repetition rate. And the output is much more stable.

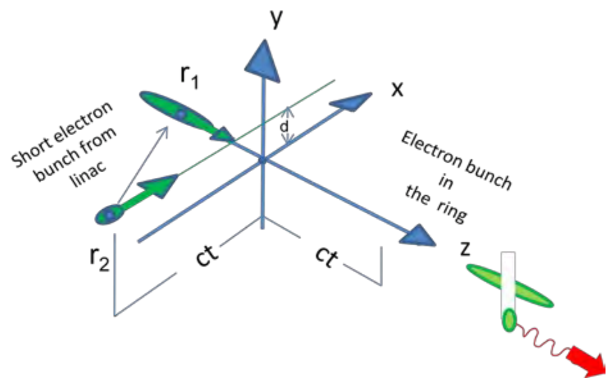

Fig.1 Illustration of e-beam slicing

We had already derived a formula for the deflection of the electrons in the storage ring. The result shows that to achieve sufficient deflection angle and sufficient short slice we need tightly focused and short electron bunch to perpendicularly cross the electron bunch in the storage ring. To achieve high repetition rate and lower the cost of the system, we need to lower the energy of the linac beam, preferably as low as 5 MeV and coming directly from RF photo-electron gun.

A typical set of parameters as our calculation shows is as follows. A bunch of 100 pC charge is focused to a beam waist size of 35 micron with bunch length of 100 fs. The linac beam is oriented perpendicularly to the storage ring beam and at a distance of 50 micron from it. With the passage of the short linac bunch, when the force exerted by the electrons in the linac bunch on an electron in the storage ring is integrated over the passage time and the profile of the linac electron bunch, it gives a deflection angle of 7 micro-radian. The deflected electrons in the bunch in the storage ring form a slice with profile width of 150 fs. Calculation shows that the required deflection for this slice to be separate from the rest electrons in the stored beam (core) by 5 RMS beam size is 3.5 micron, if we set the deflection point near the center of a straight section of NSLSII ring. A 5 σ separation has been shown to be sufficient to separate a hard x-ray beam from the core [3]. Thus the 7 micron deflection will provide ample separation from the core. A second linac electron bunch is needed at a 180 degree vertical betatron phase advance point (for storage ring beam) to deflect the slice back to join the core again, thus forming a local bump. This will allow for high repetition rate operation of the system and produce minimum perturbation to the rest part of the storage ring.

Future Work:

Our estimate on space charge effect at the focal point shows that the space charge effect dominates the dynamics at the focal point. The bunch length will vary significantly when it passes through the focal point. Hence not only we need to focus the linac bunch to 35 micron, we also need to prepare the electron bunch before it enters the focal point in such a way that its bunch length is compressed to minimum just as it reaches the focal point.

In addition to this, because the electron bunch coming out of the RF-gun will have significant phase-correlated energy spread of about 1-2% showing up as an energy chirp along the bunch length. This is useful for bunch compression. But on the other hand it also generates chromatic errors at the focal point. That is, electrons with different energy will have different focal length, and hence will increase the beam size at the focal point.

To overcome this chromatic error, we need to develop a magnetic system with dispersion so that two sextupoles and a set of quads and a dipole can be used to correct this error and minimize the focal point size. Another way to reduced chromatic error is to remove or partially remove the energy chirp in the electron bunch by a section of linac. Clearly, this will increase the cost of the whole system. Hence we need to find a balance between energy chirp removing, chromatic correction and space charge effect in strong focusing to see if it is possible to avoid the need to remove the energy chirp.

Based on this, our future work will be a more extensive detailed simulation including the space charge effect and followed by a principle experiment using existing electron gun and a low energy beam line to test focusing.

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"Experimental R&D program at Brookhaven Accelerator Test Facility"

Vitaly Yakimenko, Brookhaven National Laboratory

ATF operations: June 2010 - May 2011 highlights

The ongoing program of user experiments capitalizes on the unique ATF infrastructure comprising a high-brightness 80-MeV linac and a Terawatt picosecond CO_2 laser employed separately or in combination. Nineteen current experimental activities were presented and evaluated by the ATF Program Advisory Committee at the User's Meeting in October 2010. The Program Advisory Committee was chaired by Wim Leemans of LBNL and included well-known researchers from universities and national laboratories.

ATF systems were operated for a total of 206 run-days during last twelve months. This included 119 days of experiments that require electron beam only, 67 days of accelerator development and training, 30 days for experiments that exclusively use the CO_2 laser beam, 50 days of CO_2 laser development and training and 18 days for experiments that require the interaction of electron and CO_2 laser beams. Over the past year, 34 users from 13 institutions have been setting up and conducting their experiments at the ATF. Experimental results for 3 PhDs were collected. Below are highlights on the last-year milestone research.

The most Important results:

Linac only experiment:
First Observation of Coherent Synchrotron radiation suppression with shielding plates - a very important result for future Energy Recovery Linacs. It is listed as one of the R&D goals defined at the BES planning workshop. The experiment was carried out in collaboration with the Collider Accelerator Division R&D group and the ATF. It was supported with eRHIC funding.

CO_2 laser only experiment
Ion acceleration researched by a broad international collaboration including RAL, Imperial College, Strathclide Univ., Ecole Polytechnique, and SUNYSB. The experiment provided the first demonstration of a new radiation pressure regime of proton acceleration advantageous due to the extremely good beam quality and fast energy scaling in linear proportion to the laser intensity. Recent ATF CO_2 laser development has offered unique capability to deliver designed and well characterized beam time profiles from a single pulse to multiple pulses with variable spacing and power. This is believed to be crucial in future understanding and advancing the radiation pressure regime.

Linac/CO_2 combined experiment
The Inverse Compton scattering study conducted in collaboration with INF and UCLA capitalized on the high efficiency of an x-ray source created by counter-propagating electron and CO_2 laser beams, a technique pioneered by the ATF. The experiments allowed the demonstration of single-shot femtosecond phase-contrast radiography of biological objects and single-shot Bragg spectroscopy never achieved previously with Compton sources.

Facility upgrades

- The X band klystron was successfully tested at SLAC and is in transit to Brookhaven. This new capability will allow unprecedented characterization and control of the longitudinal phase space. It will open access for users to use X band powered high gradient accelerator structures with high brightness electron beam.
- Partial replacing of regular CO_2 gas with isotopes allowed for the first time single-pulse laser amplification improving the ATF's CO_2 laser system utility for users' experiments.
- The drive laser system currently generating the facility's electron bunches and providing synchronization between electron bunches and CO_2 laser pulses is approximately 20 years old and at its ultimate performance limits. A replacement process is underway to provide enhanced performance and increased reliability, while maintaining the high availability current users rely on. Higher brightness electron bunches will be made possible by this upgrade through the use of ultrafast laser technology, allowing shaping of the laser pulse on the sub-picosecond time scale. Furthermore, the highly stable synchronization and femtosecond pulse durations promised by the new laser will expand the range of experiments possible as well as bring the facility to the state-of-the-art in beam diagnostic capabilities.
- Ongoing project – replacing the conventional 5-ps seed pulse generator with all solid-state femtosecond OPO shall allow improvement of the ATF's CO_2 laser performance by an order of magnitude.
- A host of further innovations, including chirped pulse amplification that has been never attempted for this class of lasers, have been put into a proposal submitted to the BNL directorate. This upgrade shall bring the ATF laser to sub-petawatt power range to support super-strong field experiments and applications, including debris-free sources of high-fidelity ion beams for cancer therapy.

Long-term prospects

Recent milestone research prompted new lab-wide and higher-level initiatives, such as development of the BNL-SUNY research center on proton cancer therapy based on a prospective sub-PW CO_2 laser.

Moving to a more spacious building being investigated. The move would provide a shielded experimental hall for experiments with laser generated ion beams, higher final beam energy and considerably higher density.

There are ongoing discussions to join different accelerator R&D activities under R&D division umbrella as part of Collider Accelerator Division.

Proposal Title: High Stability LINAC by Electron Beam Regeneration

L.H. Yu, T. Shaftan

NSLSII, BNL

Research Achievement:

We propose to develop a new feedback mechanism in LINAC to achieve unprecedented energy stability. In a LINAC the energy stability is determined by the stability of the RF system, i.e., the RF voltage across the accelerator cavity and the phase stability of the electron bunches. Since there is no correlation between the electron bunch and the bunch following it, there is no feedback mechanism to use the information obtained from the first bunch to influence the second bunch. Hence it is difficult to achieve very high stability. We studied the possibility of developing just such kind of feedback mechanism using free electron laser operating in high gain harmonic generation (HGHG) mode[1].

We consider that the first electron bunch interacts with seed and generates HGHG radiation in an undulator, then the output of HGHG is sent back to cathode of the RF electron gun to generate second electron bunch (see Figure 1). If first electron bunch energy is higher than design value, its path length in the compressor is shorter, so the output HGHG pulse when returns back to the RF gun, strikes the cathode earlier. Because the second electron bunch is earlier, and photo-cathode RF gun is always operating on a slope such that when laser pulse strikes earlier, the electron bunch energy is lower. The result is that the energy of the second electron bunch is lower than first because the first electron bunch energy is higher than design value. Thus the energy is stabilized.

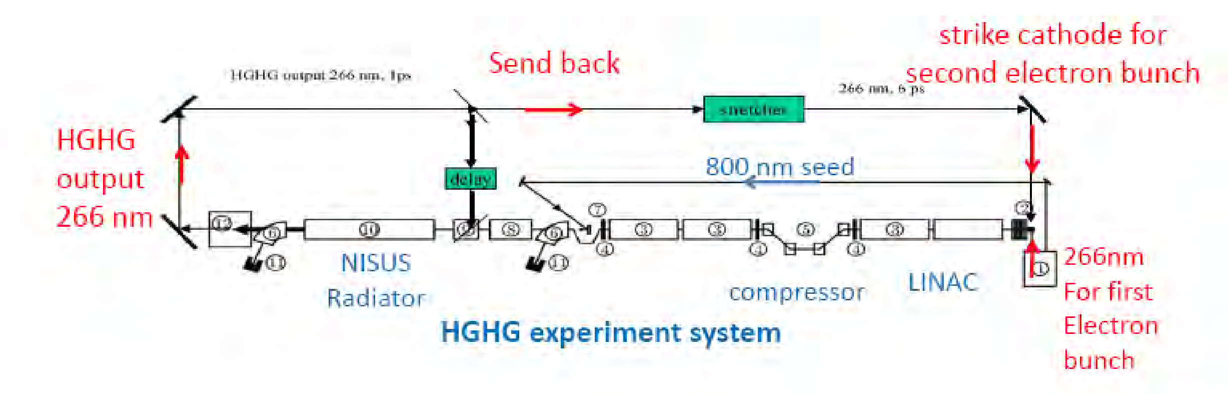

Figure 1. Illustration of basic principle of LINAC feedback by e-beam regeneration

Our quantitative analysis shows that the energy jitter of the second bunch is reduced by compression ratio (for SDL at BNL, it is a factor 6-10). Similarly analysis is valid for arrival time, thus both energy and phase are stabilized.

If the HGHG output is split into two parts, one part is sent back to the cathode, as before mentioned, while the other part is delayed sufficiently to seed the second bunch, with the HGHG output from the second bunch sent back to cathode again, then the third electron bunch is more stable than the second one. Clearly this is a feedback mechanism.

For CW operation, the system behaves like an engine with the first external laser pulse as the ignition pulse. We only need one pulse to start the self sustaining operation. The stability will be determined by other noise sources such as mirror vibration (0.2μm).

Once the feedback mechanism is introduced into the system, the feedback will not be limited to energy and phase. We can design the system to introduce charge and laser intensity feedback into the process. For example, the HGHG system can be designed such that when the seed laser intensity is higher, the output will be lower. Similarly, pointing stability of the laser can also be stabilized so that the laser spot position on cathode can also be stabilized when we design the steering mechanism for the laser such that the steering feedback is negative.

Future Work:

Future X-ray FELs and possibly other next generation linac-based machines require unprecedented timing and energy stability. The stability in existing x-ray FEL is a crucial issue. The HGHG experiment has generated 180 μJ stable operation while the cathode only need 60 μJ for 400 pC electron bunch. High energy machine, need only very short wiggler and hence only small cost increase, and the output will be more than 1 mJ, much more than enough to be used to generate several electron bunches. In a CW system, with new feedback mechanism implemented, a single laser pulse can trigger start the whole linac system operation—an ideal system for ERL.In system requiring very high average power laser as photo-cathode driver, the new method will provide a high stability laser source.

Recent development of IR laser driver for RF gun photo-cathode will make it possible for a high average power IR source with a conventional single shot trigger laser[2]. For current high average power cavity oscillator FEL system ,high power on mirror is a limitation. single pass FEL will solve the problem, hence possibility for higher average power.

Since the HGHG experiment has already achieved the desired value for its output, we only need to implement a mirror system to send the output back to the cathode to carry out a first proof of principle experiment. We propose to carry out this test experiment in near future.

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