Final Report

DOE Award Number DE-FG02-07ER46272

Recipient: University of California, Los Angeles

The Physics of Gain Mechanisms in a Self-Amplified Spontaneous Emission Free-Electron Laser

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Report date: January 26, 2015

Overview and previous to final year efforts

This grant began under a title that gives its history in a few words: *The Physics of Gain Mechanisms in a Self-Amplified Spontaneous Emission Free-Electron Laser*. At the time of adopting this name, the UCLA Particle Beam Physics Laboratory (PBPL) was at the forefront of the first demonstrations of SASE FEL, giving the experimental basis for the 4th generation X-ray light source now exemplified by the LCLS, a remarkable generation of machines that have revolutionize nanoscale and ultrafast science. The grant title indicates that physical aspects of the FEL are of interest, and implies that progress requires comprehensive investigations. These aspects include: the physics and technology of high brightness electron beam generation, phase space manipulations, advanced beam diagnostics, state-of-the-art undulators, studies of FEL mode characteristics, as well as the introduction of new theoretical models and start-to-end simulations, all yielding a deep understanding of the SASE FEL.

This work is synergistic with another research thrust at UCLA PBPL, the study of advanced acceleration (AA) techniques, based on use of plasmas, wakefields, and lasers (including the inverse of the FEL process, IFEL acceleration). Many of the same themes occur in light sources and AA, such as production of low emittance, ultrafast (now <fs) beams, new magnetic devices, high field acceleration, and advanced computation. This synergy yields two immediate benefits for BES research: first, the development of high brightness beams is *the* essential technique underpinning ultrafast imaging based on photons (FEL and inverse Compton scattering, ICS), and directly on electrons (ultra-relativistic electron diffraction, UED). Also, AA techniques for HEP will be applied in colliders after much development; however, they may be used in the present/near-future to light sources. Basing of a new class of light source on AA is a compelling new concept, that of the 5th generation light source. The UCLA program is thus increasingly characterized by three themes: frontiers of high brightness beam physics and technology, initial application of advanced electron-beam based imaging (ICS, UED), and the 5th generation light source.

FEL-related experimental and theoretical work has been funded by this grant nearly continuously since 1998, with a <1 year pause in a difficult budget year. While the UCLA PBPL is, as indicated, broad-based in its accelerator and beam physics programs, the existence of this grant has permitted us to vigorously engage 4th — and now 5th — generation light source issues of direct relevance to the BES mission. The distinction between BES-sponsored work and that sponsored by other agencies is important to appreciate, and is made using the following principles: BES supports all advanced radiation production experimental and theoretical work and the technologies that *directly* contribute to light source research; in addition, all applications for imaging using light sources or electron diffraction are supported by BES. BES is our principal support in these areas, with minor contributions from ONR and DARPA (both these contracts, along with a DTRA grant, are in sequester-driven no-cost extensions at present). In the area of 5th generation light source, the research supported by BES is that dedicated to new light sources, and not acceleration *per se*. As an example, DARPA supports a dedicated project in dielectric laser acceleration based X-ray FEL; the results obtained in this project are nearly self-contained in the DARPA program and are not directly discussed here. However, the DARPA program has spun off several ideas that are outside of its scope, but have seeded our main FEL research supported by BES. For example, MEMS-realized μm-scale undulators and beam optics have been generated first in the DARPA program, but now represent a serious path for the UCLA group to develop an ultra-compact soft x-ray FEL. This possibility conceptually drives a significant portion of the research we propose, and indeed opens up an entirely new, potentially advantageous physical scenario in FEL: a Raman regime, short wavelength FEL.

The latest period (2010-13) of BES grant support has been the most productive yet for the UCLA PBPL, and the extensive list of accomplishments is illustrative of our central contributions to advanced FEL research. We give a concise overview here and review our research results in further detail below. In FEL and ultrafast beam physics, we have experimentally investigated: production of helical beams and FEL modes with orbital angular momentum; chirp-taper single-spike FEL gain; new FROG techniques

optimized for FEL, introduced coherent imaging of beam profiles using transition radiation; and demonstrated a next generation cryoundulator. We have performed deep theoretical studies of these phenomena and other advanced FEL physics concepts, such as the space-charge amplifier. In high brightness beams, we have: introduced a new class of hybrid photoinjector for <100 fs beam production; developed new approaches to self-shaped ellipsoidal beams; used nonlinear plasma oscillations to create beam pulse trains; tested new plasmonic, high quantum efficiency cathodes, and developed new methods of beam measurement with um spatial/sub-fs temporal resolution. In ultrafast imaging, we have: developed advanced electro-optic timing systems, performed the 1st pump-probe study using single shot UED, demonstrated continuously time-resolved UED with RF deflection; made initial use of inverse Compton scattering (ICS) X-ray sources in application through single-shot inline phase contrast imaging, established single-shot X-ray diffraction, and observed ICS high harmonic generation and redshifting due to nonlinear effects. In 5th generation light source research, we have developed the techniques of narrow-band, very high power coherent Cerenkov radiation sources based on dielectric wakefield devices. This work is represented by numerous publications in leading journals: *e.g. Nature Physics, Physical Review Letters, Applied Physics Letters*. The PBPL program's influence on the field also extends to organization of the electron beam applications community; we have organized the first international UED workshops and the initial two meetings dedicated to 5th generation light source.

This ambitious program requires considerable infrastructure. The PBPL maintains two on-campus laboratories: Neptune and Pegasus. Pegasus, led by co-PI Musumeci, is already heavily engaged in BES-related research through its emphasis on high brightness beams. Neptune is now transitioning to a different on-campus site, and this change will permit its use for eventually staging the microundulator-based compact soft X-ray FEL. Further, UCLA PBPL is perhaps the leading external user group at both the BNL ATF and the SLAC NLCTA, with the majority of the work there focused on advanced light sources. Further 5th generation light source work occurs at SLAC FACET. This research has laid the groundwork of fundamental progress in FEL and high brightness beam physics as the age of the SASE FEL and related devices. Most importantly, the students trained by the Rosenzweig (previously also with the Pellegrini before his retirement) group have become leaders in the accelerator-based light source field. In the latest grant period, UCLA PBPL graduates M. Dunning (NLCTA/FACET), E. Hemsing (LCLS/NLCTA), Agostino Marinelli (LCLS/NLCTA), and Joel England (NLCTA/FACET, now a Panofsky Fellow) have gone to SLAC, while Gabe Marcus has joined the LBNL FEL effort, and F. O'Shea has moved to RadiaBeam Technologies to develop FEL-related concepts in an industrial setting.

One of the great advantages of the PBPL graduates staying in the field, from the viewpoint of continuing work in the field, is that these alumni are available for continuing collaboration. Indeed, the majority of PBPL graduates have either been or continue currently as active collaborators. UCLA graduates are well habituated One of the reasons that they are well established in the field is that they are involved intensively in collaborations external to UCLA as graduate students. These collaborations include some of the most active practitioners of FEL science today. There is a strong collaboration with the University of Rome and INFN-LNF (Massimo Ferrario, Luigi Palumbo, Bruno Spataro) on single spike FEL experiments, novel FEL diagnostics, and advanced RF photoinjectors. Also in Italy, there is an ongoing collaboration with Sincrotrone Trieste (Luca Giannessi and Gerardo D'Auria), on similar themes in novel FEL physics and state-of-the-art photoinjector development. With the University of Tel Aviv, an extensive collaboration with Avi Gover on a variety of cutting edge topics in beam and FEL physics. At SLAC, there are numerous collaborations with the recent graduates listed above as well as others (Mark Hogan, Sami Tantawi, Valery Dolgashev, and Vitaly Yakimenko), on new FEL physics, coherent beam diagnostics, plasma-based high brightness beams for FEL, and THz sources. At BNL, there is a very productive collaboration with Yakimenko and Igor Pogorelsky on coherent Cerenkov production of THz radiation, as well as on the physics and application of inverse Compton scattering sources. It should be noted that UCLA PBPL is, in large part due to its BES work, the leading university user group of the national user facilities BNL ATF, SLAC NLCTA and SLAC FACET. At UCLA, we note that there are

also extremely productive collaborations associated with our FEL physics program: inside our department vigorous work continues with Claudio Pellegrini (professor emeritus) who retired during the most recent grant period; in Electrical Engineering, the Neptune Lab is a joint effort with Chan Joshi, and an extremely active collaboration with Rob Candler on micro-undulator/optics and photonic structures.

Before recounting, broken down by PI, the accomplishments produced by this grant in the recent performance period we quote from the project summary of 2010 UCLA PBPL proposal to DoE BES the list of topics to be addressed in this unique program to give an idea of the initial conditions:

"The proposed work, discussed in detail in the project narrative, embraces: ultra-fast high brightness beam production at UCLA and Frascati; single-spike fs FEL experiments; first fs resolution pump-probe experiments using ICS and UED; novel THz production using advanced photo-injectors; ultra-short wavelength, high K undulators for high gain, compact FELs; laser wakefield-based (table-top) FEL, development of fs resolution beam diagnostics; experiments in dielectric wakefields for compact light source; fs high brightness beams for TV/m plasma wakes and ionization studies."

This program was followed well, but as grants are expected to evolve when the results of curiosity-driven research are known and new opportunities become apparent, what was written at the end of 2009 deserves updating. As such, we reproduce the following list, taken from the last progress report submitted (March 31, 2012), informing DoE BES of the succeeding year's plans (2013). Comparison with the overview given above and the more detail discussion below shows that *every task* communicated to DoE BES in this update was initiated and *nearly all* completed:

In the next year, we plan a vigorous continuation and extension of the activities described in the achievement section above. We summarize them point-by-point below:

- *The HZB-UCLA cryo-undulator will be installed at the NLCTA and initial experimental testing in an IFEL configuration performed, using advanced aerogel diagnostics. COTR will be used to develop an ORS system.*
- *The helical-phase IFEL proof-of-principle experiment performed at UCLA Neptune Lab, will be followed by an experiment that will show FEL gain using a helically bunched beams at the SLAC NLCTA, using a UCLA modulator-undulator and an existing undulator at SLAC.*
- *The Univ. Florida permanent magnet microundulator and a UCLA-developed electromagnetic version of the microundulator will be tested at the BNL ATF, producing 1E5 soft X-rays with 4 cm structures.*
- *An X-band RF standing wave undulator developed by S. Tantawi will be tested with UCLA collaboration at SLAC. This experiment will be followed by a TW 10 μm-laser driven EM undulator at BNL.*
- *The UCLA-Univ. Rome hybrid standing wave-traveling wave photoinjector will be installed and high-power/beam tested at the UCLA Pegasus Laboratory. The X-band version of this device that uses a permanent magnet solenoid proceed to the design and cold-testing stage. Fabrication in Rome will proceed later in 2012.*
- *Advanced, very high quantum efficient surface-plasmon-enhanced photocathodes developed at UCLA will be tested at Pegasus.*
- *Time-resolved reversible and irreversible phase transition experiments utilizing FRED will be performed at Pegasus using an upgraded TW laser pump.*
- *The UCLA-BNL ICS source will be used to demonstrate for the first time single-shot diffraction from a crystal, opening the way to ICS use in pump-probe experiments.*
- *First tests of the UCLA high-energy-gain IFEL, suitable for an IFEL-driven FEL, will be performed at BNL, with the goal of observing over 100 MeV energy gain.*

— *First experiments at FACET performing GV/m breakdown tests using cylindrical dielectric wake tubes (SiO_2, diamond) will be performed.*
— *Net 1 GeV acceleration will be demonstrated at FACET in a DWA.*
— *~100 MW coherent Cerenkov radiation production will be demonstrated at in FACET.*
— *High gradient dielectric wakefields and CCR production will be demonstrated using slab-symmetric dielectric wake structures at FACET. These studies will be extended to examine THz photonic bandgap structures based on the logpile architecture.*
— *Atomic physics-based optimization of Trojan horse injection in a PWFA at FACET will be studied in preparation for experiment. Laser transport system will be designed and implemented for this expt.*
— *A second volume of the textbook "Fundamentals of Beam Physics" will be initiated, covering collective effects: space-charge, coherent and incoherent radiation (FELs, ICS, etc.), beam-plasma and other wakefield interactions.*

PI J.B. Rosenzweig: Accomplishments under this grant

The research accomplished in this latest grant period has been by any standard, impressive. We recount here the major results obtained with support of this grant, particularly in regards to research that is proposed to continue under this renewal. We indicate personnel (particularly PhD students) involved, and the refereed publications resulting from the research. We do not segregate the work by classifying it as on-campus or off-, instead we indicate in which lab (UCLA Neptune or Pegasus, SLAC NLCTA or FACET, BNL ATF, and INFN-LNF) the main efforts took place. As some research thrusts had on-campus and off-campus components, this organization permits a conceptually smooth discussion. Lists of participating personnel, PhD's produced, and publications from 2010-2013 are also included separately for easy reference. We proceed now with a discussion, by conceptual category as indicated above, the main results obtained under support of this grant in the latest performance period.

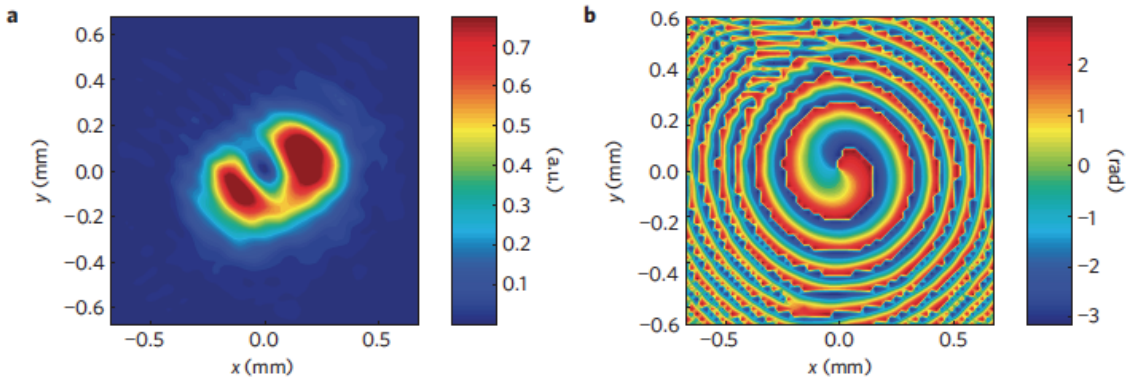

Figure 1. (a) Observed intensity of FEL light in UCLA/SLAC OAM emission experiment at NLCTA; (b) reconstructed phase from oversampling analysis, showing helical characteristics (from [6]).

Novel FEL and IFEL operation modes

This grant has funded a wide variety of initiatives in FEL and related inverse research. For several years now, we have investigated the creation of beams with helical microbunching, and the associated problem of creating FEL or other coherent electron-beam derived radiation having helical phase. Such photon beams having *orbital angular momentum* [1,2], which are uniquely accessed at short wavelength through FELs [3], are a very active topic in the laser and imaging community. They are finding novel applications ranging from mechanical rotations of nanosystems, to fundamental probing of inner shell electronic structure in atoms, and novel imaging that profits from the unique phase structure of these modes.

UCLA PBPL work in this area initiated with a series of groundbreaking efforts in the theoretical understanding the production of beams having *helical microbunching* through a higher harmonic interaction inside specially designed undulators. In 2011, we have published the first demonstration of helical microbunching [4] at Neptune, which was the thesis experiment of Erik Hemsing. In this experiment, the main diagnostic method used was the signature of the coherent transition radiation emitted by the helical beam distribution [5], but the angular distribution. We have also performed an experiment in which FEL gain was demonstrated in a helical phase mode (see Figure 1), at the NLCTA (the thesis experiment of A. Knyazik, also published in *Nature Physics* [6]).

In addition to exploration of the novel FEL physics of definite orbital angular momentum modes, we have performed a number of advanced FEL experiments aimed at production of ultra-short, broadband radiation pulses, emphasizing novel collective effects. In a recent experiment at the NLCTA, we have produced coherent broadband photon pulses in the visible with a cascaded (multi-chicane) longitudinal space-charge amplifier, a result published in *PRL* [7]. In conceptually related work, we have proposed (also published in *PRL* [8]) to use the strong relativistic two-stream instability to amplify microbunching

at very short wavelengths, a scheme that should enable *attosecond* coherent soft X-ray pulses only a few cycles long. The two-stream instability work is also connected in physics scenario to two-energy FEL operation at SPARC [9] discussed in the context of co-PI Musumeci's program (below).

This ultra-short pulse work has proceeded in parallel with a concerted effort to achieve single spike operation. We have performed proof-of principle experiments on the chirped-beam, tapered-undulator scheme at SPARC, showing enhanced gain through use of the majority of the beam charge in the amplification process [10]. This initiative is an outgrowth of our original proposal for single spike operation of SASE FELs based on very small charge, ultra-short beams, as well as the application of such beams to advanced PWFA and atomic physics experiments [11].

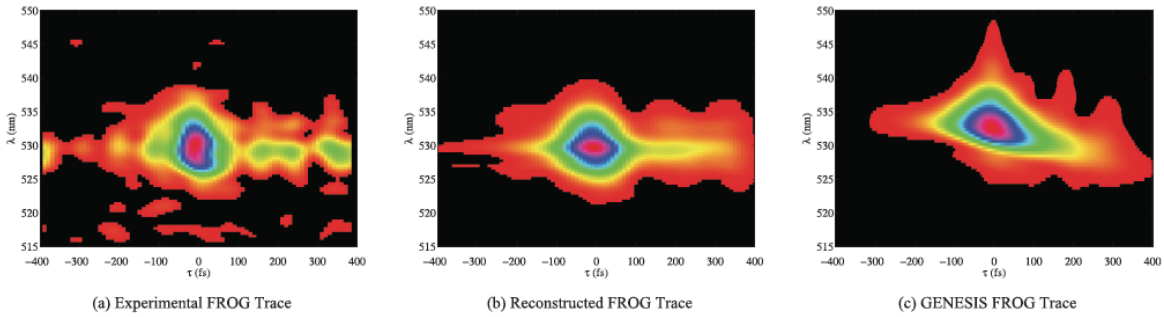

Figure 2. **Comparison of the (a) experimental, (b) reconstructed, and (c) simulated FROG traces (from [12]).**

Advanced FEL and Beam Diagnostics

The chirp-taper FEL experiment at SPARC was followed by an extremely challenging measurement of the radiation pulse characteristics with the first use of transient-grating, frequency-resolved optical gating (TG-FROG) techniques in an FEL. As the technique allows use of arbitrary wavelength radiation down to near 200 nm, it is ideal for use in FELs due to their tunability. This work, published in *Applied Physics Letters* [12], formed the basis of the PhD thesis of G. Marcus. It illustrated the nearly ideal application of this TG-FROG (illustrated in Figure 2) to FELs, and also showed that single-spike, <100 fsec pulse operation was achieved with compact Wigner space properties.

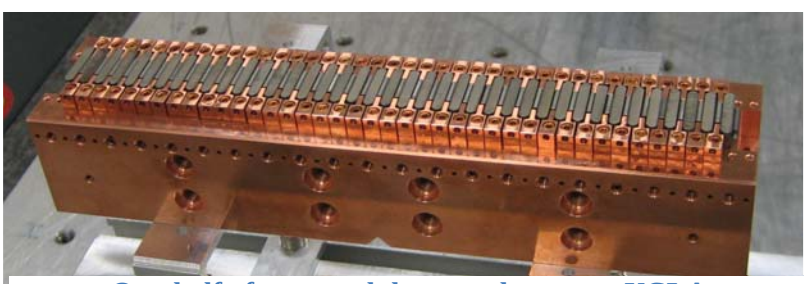

Figure 3. **One-half of cryo-undulator under test at UCLA.**

The extension of diagnostic methods in our program extended also to intense, ultra-short electron beams. We showed the first use of an extremely innovative method for determining the transverse profile of high brightness beams typical of FEL injectors, a measurement often afflicted by coherent transition radiation, where the coherence arises due to longitudinal space-charge instability [13]. This method, termed *coherent imaging*, borrowed a modern, burgeoning approach from the world of the X-ray FEL itself [14]; it also opens the way to use of coherent imaging in advanced "optical replica" beam diagnostics.

High Field, Short Period Undulators

We have developed, for application in both 4th and 5th generation light sources, high field undulators. One device, that has been specifically designed and fabricated by UCLA and HZB (Berlin) for use as an undulator that permits X-rays to be produced from <GeV laser wakefield accelerators (LWFA), has 9 mm period and peak field in excess of 2 T. This praseodymium-based, cryogenic undulator (Figure 3) was

recently tested in spontaneous radiation and IFEL mode at the SLAC NLCTA. This work [15] has formed a significant part of the PhD thesis of Finn O'Shea.

Work at PBPL has been extended through collaboration, first established in the context of a UCLA-led DARPA program (GALAXIE, a table-top X-ray FEL), on micro-undulators [16]. One collaboration, with Univ. Florida, has produced 400 um period, 0.3 T peak field laser-cut PM undulators, while the other is based on microfabrication of electromagnets (Candler group, UCLA EE). Both of these devices are currently undergoing testing at PBPL, and will be soon used by PBPL for e-beam based radiation production at both UCLA Pegasus and the NLCTA. The existence of microundulators (as well as the electromagnetic undulators discussed immediately below), points the way to future experiments in a novel and promising operational mode of the FEL: the soft X-ray Raman regime.

Electromagnetic Undulators

In the context of GALAXIE, PBPL has collaborated on the first ever testing of an electromagnetic undulator at SLAC, using the >100 MW X-band source available at the NLCTA. This work was led by collaborator Sami Tantawi, with participation of UCLA students Ivan Gadjev and Andrey Knayzik. The collaboration with Tantawi on the X-band undulator has been notably augmented by the GALAXIE effort at both UCLA and SLAC. The strength of the undulator has been demonstrated to be K=0.7 at an effective period of 1.4 cm; this has been used as a radiator in UCLA microbunching experiments (described below). We are now working with Tantawi on extension of this scheme to high field photonic designs inspired by the GALAXIE accelerator, as discussed below.

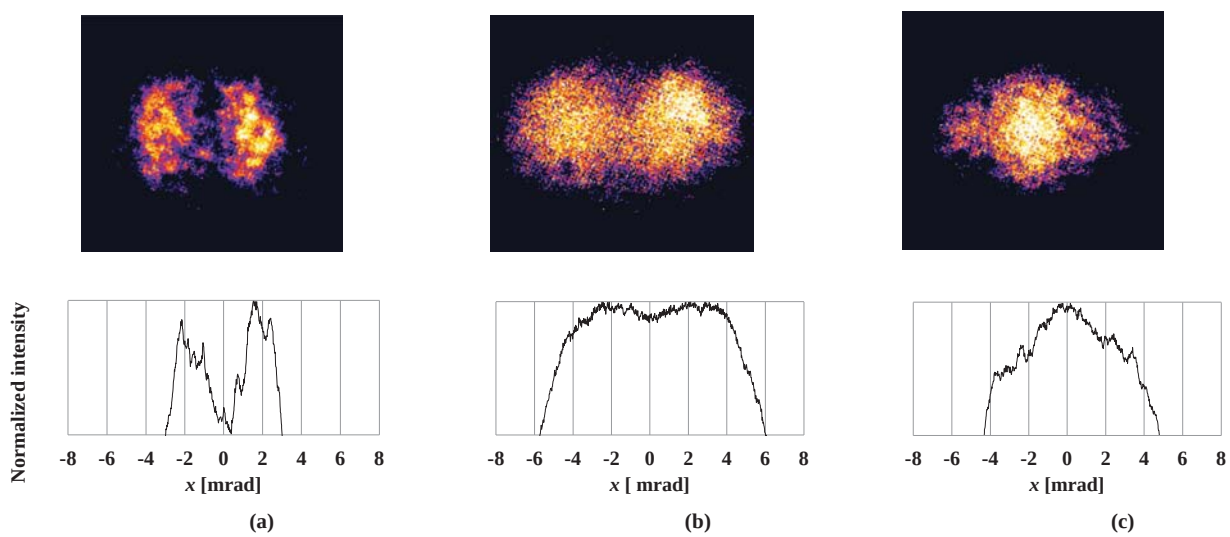

Figure 4. Observed ICS 2nd and 3rd harmonics with the laser parameter a_0>0.6; (a) narrow-band transmission through 20 μm Au foil gives the characteristic shape of the 2nd harmonic; (b) transmission through 250μm Al foil shows superposition of 2nd and 3rd harmonics; and, (c) 1000 μm Al foil transmits only 3rd and higher harmonics.

Inverse Compton Scattering

The UCLA effort in ICS at the BNL ATF has met with considerable success in the past few years, with notable milestones on the road to application reached. These include the first ever demonstration of single-shot Bragg diffraction [17], which leads the way to use of ICS in pump-probe experiments. This investigation formed another part of the PhD work of Finn O'Shea. Recently, we have begun exploration of the ICS nonlinear regime [18], showing for the first time the redshifting of the fundamental ICS radiation, and production of both the second and third ICS harmonics. This comprehensive measurement enables key insights into the nonlinear electrodynamic emission process, in that only through the simultaneous observation of redshifiting and 3rd harmonic (Figure 4) have allowed the first unequivocal determination of the effects of the relativistic figure-eight oscillation of the electrons in the intense laser

field. The nonlinear regime is of key interest in ICS physics, as the changes in the spectral characteristics when one attempts to increase scattered photon production can limit applications requiring narrow bandwidth; we have also proposed harnessing nonlinear effects to produce a side-bands of ICS harmonics in a two-laser-frequency scheme [19]. This work has since been extended to studies of nonlinearity in the circularly polarized case. The ICS program has shared infrastructure with the IFEL program at the BNL ATF, and will also be connected in the future, to explore the possibility of an all-optical x-and-γ-ray source. Indeed, while the production of narrow-band X-rays is of inherent interest to BES in context of this contract, this work was partially supported by DTRA, which is interested in high flux, directed, narrow band, 10 MeV-class photons for photo-fission-enabled detection of nuclear materials.

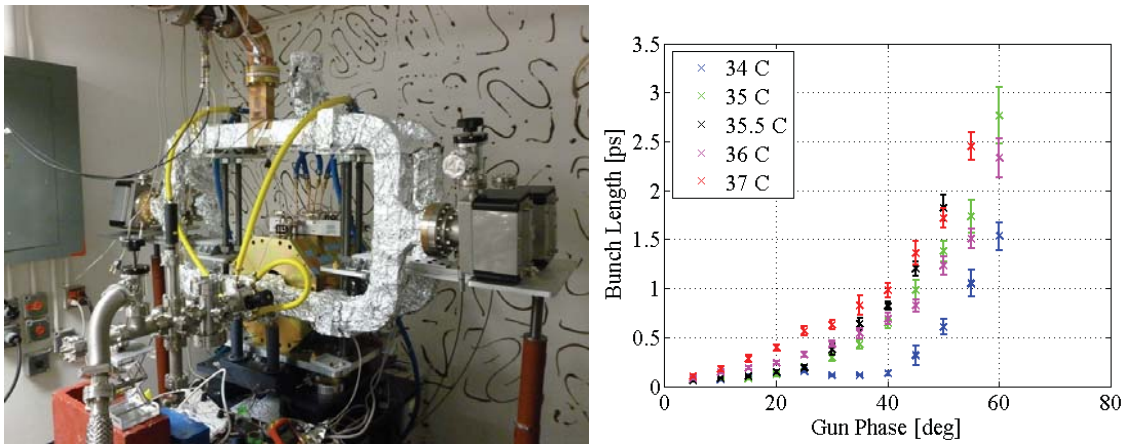

Figure 5. (left) Hybrid SW-TW photoinjector, during installation at UCLA Pegasus Lab; (right) measured electron be pulse compression due to velocity bunching in device.

New RF Photoinjectors

We have reached the culmination of a multi-year effort to develop a new photoinjector, a *hybrid traveling-standing wave* RF gun, a design which suppresses RF reflections, and thus permits extension of photoinjectors to very high field X-band operation [20]. This novel next-generation device produces, through inherent velocity bunching, highly compressed beams, down to the 10 fsec level. We have performed an exhaustive study [21] of applications enabled by this new technology, that include THz production, ICS, PWFA, and ultra-relativistic electron diffraction. The device has undergone commissioning at the Pegasus Laboratory, in a joint effort with co-PI Musumeci. The photoinjector was thoroughly characterized in cold-test and high power experiments, confirming its novel hybrid SW-TW features. It was subjected to an extensive round of beam tests, leading to emittance <1 mm-mrad, and demonstrated beam compression to the 100 fs level (Figure 5). This work, led by UCLA researcher A. Fukusawa, is continuing in beam and application tests (e.g. electron diffraction) and has paved the way for next generation device development in S- and X-band.

High brightness beam and FEL theory

The UCLA program in FEL and high brightness beam physics is ultimately experimental in its outlook, but also has a strong theoretical theme, as new ideas are developed that require theoretical underpinning. In the past three years, much has been accomplished in this regard

- We have, in support of the experiments in helical beam bunching at Neptune and later on optical orbital angular momentum coherent emission from an undulator at the NLCTA, performed a series of high impact theoretical studies. The most recent of these concerned the generation of OAM radiation in a high-gain FEL at the 1st harmonic [22].

- Very high brightness electron beams have permitted the use of the next generation of extremely short period undulators, as indicated above. This in turn implies that the energy needed to reach X-rays in FELs may be lowered. Such as scenario introduces a previously unexamined effect: space-charge in short wavelength FELs. In this context, we have based on theoretical and computational studies, extended the M. Xie FEL gain length fitting formulae to include strong space-charge effects [23]. This study has led to an explicit appreciation of the characteristics Raman regime X-ray FEL.
- As conceptual background for the coherent imaging experiment, the development of space-charge instability-induced microbunching in 3D, due to self-consistent plasma motion is of high interest. We have investigated a fully three-dimensional analysis of longitudinal plasma oscillations in thermal electron beams for this application [24].
- The analysis of beam longitudinal space charge dynamics has led to the proposal to utilize the relativistic two-stream instability, with its remarkably large bandwidth, for the generation of coherent *attosecond* soft-X-ray pulses [25].

Light Sources Based on Advanced Accelerators

The theme of the 5th generation light source, defined as an ultra-compact X-ray FEL based on an advanced accelerator schemes, has gained much traction in the field recently, and now represents a significant theme in UCLA PBPL research. There are two strands of this theme: wakefield accelerators and laser-based accelerators. We are the leading group in GV/m dielectric wakefield acceleration (DWA), with a series of high profile publications arising from work at the BNL ATF [26,27]. This work has recently been successfully extended to very high field wakes at FACET in UCLA-led experiment E-201. UCLA also leads E-210, the so-called Trojan Horse PWFA injection scheme [28]. This scheme is aimed at producing beams with excellent phase space characteristics (see Figure 6), that can enable an X-ray FEL with unprecedented performance [29], due to extreme small emittances.

The GALAXIE program has attacked vigorously a number of compelling issues in 5th generation light source, including electromagnetic undulators, quantum FEL gain, very high field RF photoinjectors with magnetized cathodes, and, above all, a sophisticated new approach to laser-driven dielectric structure accelerations. This structure has been optimized to solve a fundamental problem in transverse stability in high field optical accelerators that is identifiable from Earnshaw's theorem [30], through acceleration on a higher spatial harmonic of the structure. In addition, in the process of examining the longitudinal stability during acceleration, a new phenomenon was discovered, termed adiabatic compression, that enhances the beam current by strong bunching (a factor of >1000) during acceleration.

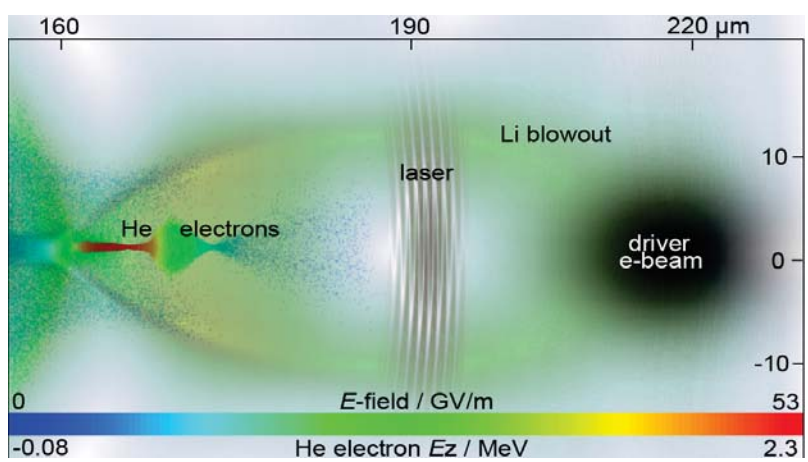

Figure 6. Schematic of Trojan horse laser-based injection scheme now being developed by UCLA-led collaboration in FACET E-210 experiment.

Despite the success of GALAXIE and its sibling programs [see, *e.g.*, "Demonstration of electron acceleration in a laser-driven dielectric microstructure", E.A. Peralta, *et al.*, *Nature* **503**, 91–94 (Nov. 7, 2013)] inside of the DARPA AXiS initiative, DARPA has lost *all* funding for such research, due to sequester effects. We are thus attempting now to transition out the significant research programs to other agencies. Our BES research is the beneficiary, above all, of the new and transformative undulator techniques.

Co-PI P. Musumeci: Accomplishments under this grant and previous work

We begin this discussion with results obtained in on-campus work at the Pegasus High Brightness Beam Laboratory. In the course of the last three years, the Pegasus Laboratory has seen a significant increase in research productivity. We summarize here recent highlights funded, in part or completely, through this BES program:

Low charge high brightness electron beams

As noted above, a recent trend in FEL research calls for lower beam charges and higher beam brightness as the pathway to shorter X-ray pulses and more compact FEL designs. Using the Pegasus RF photocathode gun we have explored the issues in beam generation, control and diagnostics associated with decreasing the beam charge below 1 pC. Thanks to the development of a high sensitivity electron detector we were able to routinely tune the beam and measure all beam parameters with charges and as low as few fC [31]. We developed a new technique to measure with a good accuracy the emittance of extremely low charge beams using the information embedded in a transmission electron microscope grid shadow image, adapting to MeV beams a common technique in electron microscopy [31]. This method was instrumental in measuring the very small beam emittances (25 nm) obtained when focusing the laser on the cathode to ultrasmall transverse spot. The beam charge in these measurements was 0.1 pC.

Ellipsoidal beam generation (cigar and pancake regimes)

We demonstrated a novel regime of operation of the RF photoinjector based on illuminating the cathode with a properly shaped laser pulse. When a relatively long laser pulse with a parabolic temporal profile is focused to a small transverse spot on the cathode (cigar aspect-ratio), the strong space charge dominated transverse expansion leads to the creation of a uniformly filled ellipsoidal beam distribution, characterized by linear and well-behaved space charge forces. This dynamics can be thought as the transverse counterpart of the blowout regime which occurs for pancake-like initial distributions [**Error! Bookmark not defined.**]. It should be noted that a surface charge density field larger than 40 MV/m is generated when 2 pC of charge are emitted by sub-25 um rms laser spot size at the cathode. The cigar beam regime is characterized by very low charge to avoid reaching the space-charge limits set by the extraction field. At Pegasus proper longitudinal laser pulse shaping was obtained using a prism-based UV stretcher. The final beam distribution was measured using the RF deflector; it approximated by a uniformly filled ellipsoid and normalized emittances have been found to be smaller than 100 nm, close to the thermal emittance levels.

We investigated in more detail the space charge dominated limit in photoemission to understand the effect of the elongated aspect ratio of the laser in the cigar regime. With the help of a simple disk-like particle model corroborated by three-dimensional simulations we obtained new scaling laws for the space-charge limited emission. In collaboration with LBNL scientists we showed that, when a long laser pulse is focused to a small transverse spot, the simple limit obtained comparing the extraction field and the surface-charge density at the cathode is no longer valid and larger beam charges can be extracted. These results suggest new optimization paths for RF photoinjectors enabling the generation of ultrahigh brightness beams [32]. The implications for this scheme on proposed work is discussed further below.

Advanced cathode research

Following up our results on multiphoton photoemission for RF photoinjectors, we have pioneered the use of nano-engineered cathodes in an RF photoinjector [33,34,35]. Applying nanoplasmonics concepts and using nanofabrication techniques to pattern a square array of nanoholes on the surface of a copper cathode we demonstrated how it is possible to control and shape the optical response of a metal surface and significantly improve its photoemission properties. The dimensions of the nanohole pattern were tuned to

enhance the surface plasmon coupling for 800 nm laser pulses. The increased absorption and the optical field enhancement were observed to generate an increase in the electron yield by more than two orders of magnitudes. The intrinsic emittance of the beam was measured and found about a factor of two larger than the one from a flat surface. Damage properties of the patterned surface were also characterized. Due to the very favorable scaling of the charge yield, these cathodes are very promising for high average power electron sources and future light sources applications. The paper describing these results [33] was selected as Editor Suggestion for PRL and is the topic of one of the Viewpoint articles in Physics.

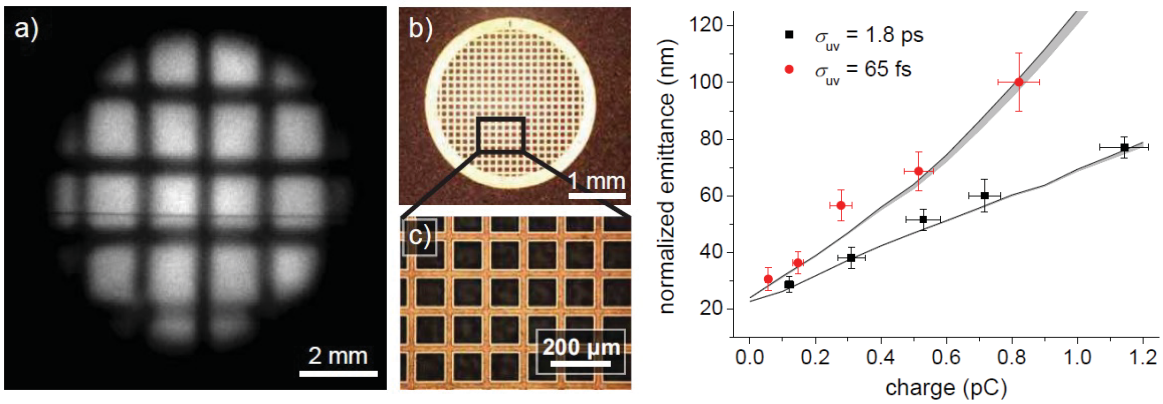

Figure 7. Left a) Shadow image of the electron beam through a TEM grid. b) and c) Optical microscope images of the TEM grids used in the measurement. Right) Emittance measurement as a function of beam charge for short and long laser pulse on the cathode.

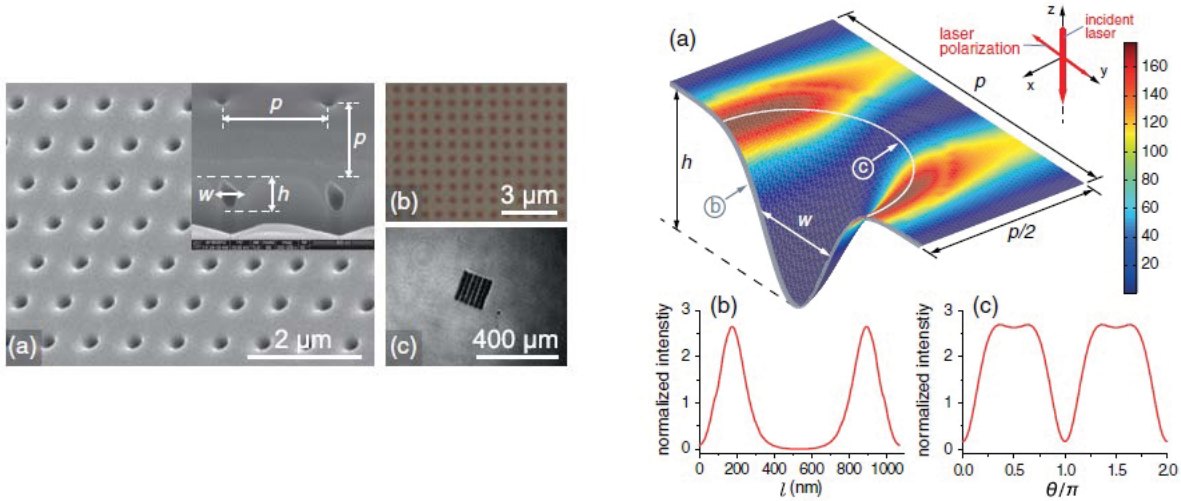

Figure 8. Left: (a) Scanning electron microscopy images of the nanohole array. Inset: Zoomed-in cut view of the nanoholes. (b) Nanohole array under an optical microscopy with off-resonance visible light. (c) A nanopattern consisting of 6-by-6 25 um square.

This research was originally partially funded by ONR (optical tests and advanced designs of nanopatterned cathodes) and more recently was also supported through an STTR with Radiabeam (nanofabrication of nanopatterned cathodes). BES funds are mainly used for the electron beam characterization and the measurements of these cathodes in the high peak field S-band 1.6 cell RF gun.

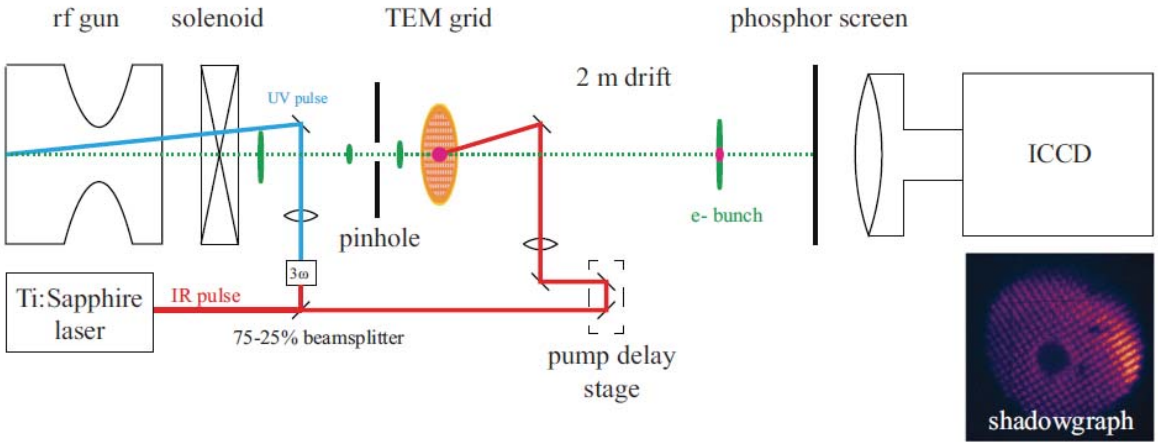

Figure 9. Schematics of shadowgraphy experiment. The ultrashort electron beam from the Pegasus RF gun goes through the TEM copper grid and samples the electromagnetic fields generated when the high intensity laser illuminates it. From an analysis of the shadowgraph recorded by the ICCD it is possible to reconstruct the dynamics of the electromagnetic field with 50 fs temporal resolution.

Ultrafast electron sources for diffraction and microscopy

The Pegasus laboratory is a world-leader in the field of application of high brightness relativistic electron beam to the study of matter at the fundamental spatial and time scales. The first international workshop on *Ultrafast Electron Sources for Diffraction and Microscopy Applications* was organized December 12-14th 2012 by UCLA in collaboration with X.J. Wang from Brookhaven National Laboratory. All the workshop presentations are available from the workshop website [36]. The workshop objectives included informing the broad scientific communities – accelerator, electron scattering and ultrafast science, on the latest development in ultrafast electron sources, and to identify critical technologies and high impact scientific opportunities. Incidentally, it was noted that an RF photoinjector based diffraction and microscopy beamline can ideally complement X-ray beamlines at 4th generation light sources and provide a well matched probe to investigate the ultrafast response to intense X-ray illumination [37].

In the context of MeV diffraction we developed an electro-optic sampling based single shot nondestructive time-stamping diagnostics which was used to acquire time-of-arrival information from mildly relativistic beams with < 3 pC charge [38]. In a recent experiment (published in *Applied Physics Letters* [39]), we demonstrated the capability of single shot relativistic electron probing and imaging of intense electromagnetic field with sub-50 fs resolution. Using an RF deflecting cavity as an ultrafast streak-camera, we studied the evolution of the electromagnetic field in the first few hundred fs after the laser-induced plasma formation at a copper grid surface. The scattering of the beam electrons can be used to reconstruct the field configuration at the target. These results give insight on the ultrafast dynamics of electromagnetic fields in high intensity ultrafast laser-plasma interactions and constitute the first step towards a new ultrafast diagnostic tool with the capability to take transmission images with sub-ps temporal resolution and moderate (sub-um) spatial resolution.

Accomplishments under this grant and previous work: Off campus & simulations

Advanced light sources

Building on our recent work on non-linear space charge oscillations we optimized the design for a THz source based on illuminating the cathode in an RF photoinjector with a modulated laser pulse[10]. The unique feature of this design would be to generate high power narrowband radiation using a compact source. The limits in the current enhancement factor found after ½ space charge oscillations are explored

as well as the possibility of using an accelerating section in order to freeze the longitudinal phase space dynamics and accelerate the beam to higher final energies. This work has been presented at the Puerto Rico ICFA *Physics and Applications of High Brightness Beam Workshop* and a paper with the results of this optimization appearing in PRSTAB [11].

In the development of future generation light sources, an important element is to be able to control and shape the beam distribution in longitudinal phase space and design FEL schemes that can take advantage of the beam characteristics. In our program, this has been explored in a variety of configurations. As an example, in collaboration with the SPARC team we analyzed the possibility of increasing the gain bandwidth of FELs by using an electron energy distribution characterized by multiple peaks. When a single electron beam is used, the shortest temporal structures of a SASE FEL radiation pulse are set by the amplifier gain bandwidth which proportional to the Pierce parameter rho. In a recent experiment performed at SPARC the amplifier gain bandwidth had been increased injecting in the undulator two different electron beamlets temporally superimposed but with relative energy difference of the order of few percent. The two beamlets are generated at the cathode using two properly spaced UV pulses and then transported through the linac using the velocity bunching technique. By analyzing the radiation output pulse with spatiotemporal FROG diagnostics it is possible to distinguish time-structures much shorter than those possible considering the FEL gain bandwidth [12]. Simulations are in good agreement with the experimental results and indicate a possible way to further shorten the duration of FEL pulse.

Similarly, in close connection with our high energy physics funded program on laser based acceleration and its relevance for future light sources, we explored the possibilities entailed by laser accelerator driven FEL-based light sources[13]. The bunched output of laser-based accelerators characterized by high peak current spikes is well-suited for a modelocked FEL. We studied a scheme were by introducing proper spatio-temporal shifts in between undulator sections it is possible to obtain femtosecond spaced attosecond trains and frequency combs from a current-modulated electron beam as usually obtained from laser-based accelerator [14].

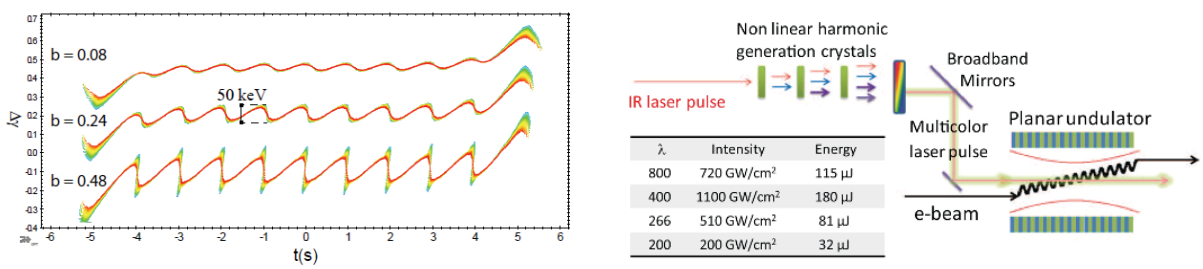

Figure 10. (left) Longitudinal phase spaces for different initial modulation amplitudes. For largest initial modulation (b=0.48) the nonlinearity of the oscillations is evident in the sawtooth shape associated with higher harmonic content. (right) IFEL harmonic bunching scheme. Using four phase-locked laser harmonics it is possible to linearize.

We also studied the possibility of using the interaction of a relativistic electron beam with multiple harmonics of a same fundamental resonant frequency in a single bunching undulator to linearize the ponderomotive FEL/IFEL potential and obtain very large bunching factors and higher quality longitudinal phase spaces. This scheme is useful in improving the performances of laser-based bunchers and will allow increased harmonic numbers in ECHO-FEL schemes [13].

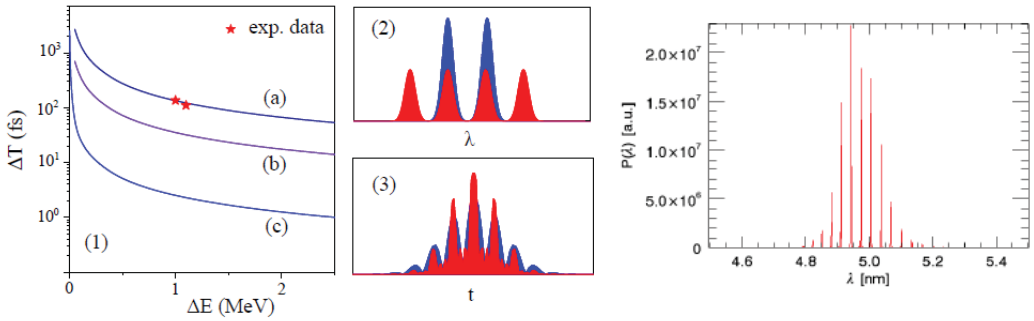

Figure 11. Left) Multi energy level FEL results. Right) Comb spectral output for modelocked FEL. The spectrum is the result of a Genesis simulation where proper chicane delays have been introduced to optimize the gain from an IFEL accelerated and microbunched beams.

Personnel supported

J. Rosenzweig (PI), 1 month summer

P. Musumeci (co-PI), 1 month summer

G. Andonian, 50% Associate researcher

R. K. Li, 20 % Assistant researcher

A. Fukusawa, 50% Assistant researcher

Y. Sakai, 33% post-doctoral researcher

O. Williams, 33%, engineer

S. Barber, 0.5 graduate student

G. Marcus, 0.5 graduate student

P. Huang, 0.5 graduate student

P. O'Shea, 0.25 graduate student

A. Knayzik, 0.25 graduate student

A. Marinelli, 0.25 graduate student

Y. Xi, 0.5 graduate student

J. Moody 0.5 graduate student

J. Duris 0.5 graduate student

D. Cesar 0.25 graduate student

N. Sudar 0.25 graduate student

A. Valloni 0.1 visiting graduate studnet

Numerous undergraduate student helpers

Transitions:

PhDs granted: E. Hemsing (SLAC), G. Marcus (SLAC), A. Marinelli (SLAC), F. O'Shea (RadiaBeam), A. Knayzik (Newport).

Promotions: G. Andonian, to Associate Researcher

Unexpended funds at end of budget period

$0.00

Final Report on expenditures

See attached

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The first section covers remaining publications from previous years.

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