Final Technical Report

Theoretical and Experimental Studies in Accelerator Physics

DOE Office of HEP Grant DE-FG02-92ER40693

This grant covers a wide range of research activities in accelerator and beam science carried out by the UCLA Particle Beam Physics Laboratory (PBPL). As such, it is split into two components, Task A and Task J. The activities carried out in Task A are performed under the direction of Prof. James Rosenzweig, PBPL Director and current Chair of the UCLA Dept. of Physics and Astronomy. His co-PI on this task until recently was Prof. Claudio Pellegrini, who has attained emeritus status and has adopted a role of theoretical collaborator. Additional senior personnel on Task A include Dr. Gerard Andonian, who helps lead numerous off-campus wakefield and coherent radiation experiments at SLAC and the ATF, Dr. Atsushi Fukusawa, an expert in high field radio-frequency systems. As we have need of significant computer modeling, we include in Task A activities significant on-going consultation and collaboration of Prof. Bernard Hidding of Univ. Hamburg, and Dr. David Bruhwiler of Univ. Colorado, who while are not directly supported by this proposed grant, contribute directly to its success through their efforts. Task J has been created to administer the Outstanding Junior Investigator grant awarded to Prof. Pietro Musumeci.

A non-exhaustive list of other collaborators on the proposed work (described here includes: Chan Joshi (UCLA Neptune Lab), Seth Putterman (UCLA GALAXIE laser acceleration lab), Sami Tantawi of SLAC (laser acceleration, advanced undulators), Vitaly Yakimenko and Igor Pogorelsky of the BNL ATF (dielectric wakefield acceleration, inverse Compton scattering, laser acceleration, quasi-nonlinear plasma wakefield acceleration), Mark Hogan of SLAC (FACET DWA and Trojan horse PWFA); Patric Muggli of MPI/USC (FACET DWA, Trojan horse and quasi-nonlinear PWFA); Erik Hemsing, Mike Dunning, Agostino Marinelli of the SLAC NLCTA (coherent radiation); Bruno Spataro, David Alesini, Luigi Palumbo, Massimo Ferrario and Luca Giannessi of SPARCLab at INFN-LNF (beam dynamics, coherent radiation, RF devices); Avi Gover of Tel Aviv Univ. (RF devices, coherent radiation, beam dynamics). There is notable cooperation between UCLA PBPL and industrial partners RadiaBeam Technologies, and Euclid Technologies in a variety of topics.

In order to place the proposed work in correct intellectual and historic context, we organize the topics under investigation in two parts: the background and importance of the concept, and recent accomplishments at UCLA PBPL as performed under this grant.

Dielectric wakefield acceleration (DWA)

The subject of dielectric wakefield Acceleration (DWA, see Figure 1) has been the subject of investigation, notably by the ANL AWA group [1], for several decades. This work, concentrated previously in the RF regime, seeks to invent a new type of power source for high gradient accelerators. After the UCLA proposal in 2006 [2] to use ultra-short beams at the SLAC FFTB to excite GV/m-class wakefields, the field has been

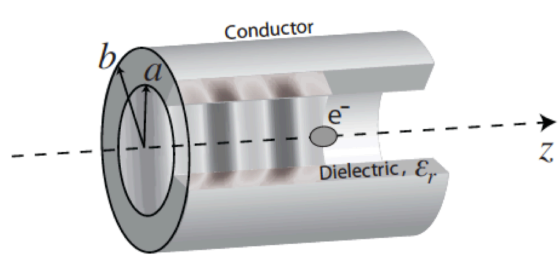

Figure 1. Cutaway of cylindrically symmetric DWA structure, wake-excited by passing intense relativistic electron beam.

reinvigorated, extending to the THz regime at fields well over an order of magnitude higher than previously achieved. The tolerance of high fields before breakdown, the extension of accelerators to high frequency, the enabling of novel geometries, synergy with more mainstream wakefield accelerator schemes (e.g. CLIC) all make the DWA a compelling, and newly competitive field.

UCLA's recent record in this field in this area is by now extensive. At the FFTB we showed, in T-481, that THz DWA structures may function at up to 9 GV/m accelerating field amplitude before breakdown [3]. After this pioneering experiment, and with the loss of the FFTB, we turned our attention to experiments at Neptune, in which we measured the coherent Cerenkov radiation emitted from DWA sections, showing that CCR can be used to produce high levels of very narrow-band EM radiation in a highly compact scheme [4]. This work was extended under this grant in recent work using the capability of producing tunable pulse trains at the BNL ATF, to show resonant excitation of the DWA, in both fundamental and higher harmonic modes [5]. The pulse-train response of the DWA is a key problem, as applications to linear colliders or FELs may demand high efficiency obtained most straightforwardly through use of pulse trains. Finally, in the past year, we have explored the use of slab-symmetric DWA structures [6]. With ribbon-beams that are wide in the large transverse structure direction (Figure 2, top), one may store significantly more energy per unit length in the structure, permitting much higher beam loading. At the same time, transverse wakes are mitigated by fundamental EM coupling effects in this geometry [7]. As these attributes serve to enable shorter wavelength accelerators, there are significant synergies between slab-DWA work and laser accelerators [8], as discussed below.

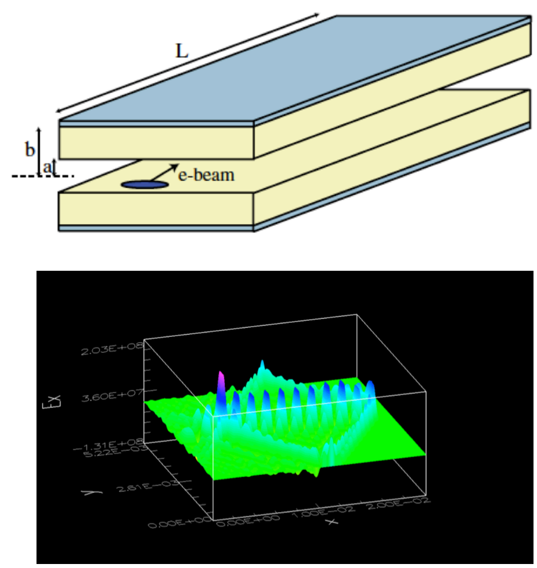

Figure 2. Slab symmetric DWA (top); Bragg-confined slab-structure (SiO2,ZTA) for ATF and FACET (bottom)

We are presently carrying on further research into high-field THz DWAs at FACET, in the context of the commissioned E-201 high gradient DWA experiment, as well as at the BNL ATF. The ATF option provides a flexible, lower charge environment in which precision energy spectra and CCR measurements can be made, with pulse trains as well as shaped (*i.e.* ramps for high transformer ratio) beams. Continuing work at the ATF concerns extending the slab-symmetric structure to an all-dielectric, Bragg-confined scheme (Fig. 2, bottom). This move to an all-dielectric approach is needed for DWAs, as at high field we have found experimentally (T-481) and that the dissipation in the THz does not easily permit use of metal boundaries (as displayed in Figs. 1 and 2-top).

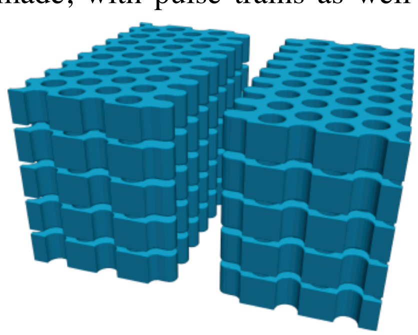
Figure 3. GALAXIE-like 3D photonic structure, scaled for THz DWA experiments.

The Bragg scheme is an example of a photonic structure, in which confinement of a defect mode is introduced in 1D. We have also been examining a fully 3D photonic structure in the context of the GALAXIE laser acceleration project. 3D mode control is demanded in order to ensure confinement, field flatness of the accelerating mode, and HOM damping. The scaled (to THz) structure shown in Figure 3 is presently under construction at using advanced laser cutting techniques. Both Bragg and 3D photonic measurements are scheduled for the 2013 experiments at the ATF.

There is now a vigorous program in DWA measurements at the FACET E-201 experiment, that has been commissioned and has undergone initial runs at SLAC. A full system for positioning numerous samples, provided by the E-201 collaboration (UCLA-Munich-SLAC) and by E-205 (Euclid Techlabs), has been setup, along with associated THz launching, quasi-optical transport and detection apparatus based on the Neptune, ATF and T-481 experience. Initial running yielded the first measurements of CCR and coherent transition radiation, but with poor performance. This is because the beam conditions for these runs were not yet ideal — the bunch transverse size was notably larger than expected, leading to use of larger aperture (lower gradient) tubes. Additionally one cannot yet change the bunch length or charge quickly enough to scan peak fields or breakdown. In addition, there was notable halo that gave a first data point on direct electron beam irradiation-induced damage. Nonetheless, the UCLA team and its collaborators are learning and reacting quickly to the new but changing situation at FACET, and E-201 will proceed again in January.

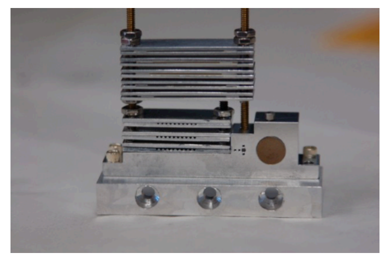

Figure 4. The E-201 DWA sample assembly with slab-structures, cylindrical holders and CTR target.

The E-201 program includes the following: measurement of breakdown thresholds in cylindrical and slab-symmetric structures. These structures are already in hand (with many installed, per Figure 4) at FACET, in a variety of materials, such as SiO_2, diamond, alumina, ZTA, that are known to have low THz losses. There are Bragg structures constructed of such elements, as well as downstream tests of 3D (GALAXIE-like) photonic structures. Parametric studies of beam shape (pulse length, ribbon beam, etc.) parameter system response, including CCR have been performed, as well as deceleration and acceleration experiments in longer (>10 cm, as opposed to 1 cm currently used) structures. Indeed, after beam improvements, >GeV/m acceleration (200 MeV in 15 cm) has been demonstrated and published in *Nature Communications* [9]. Finally, FACET promises to deliver positron beams, permitting an exploration of charge asymmetry in breakdown processes. These results are critical inputs to our understanding of the promising applicability of DWAs to linear colliders and light sources.

Plasma Wakefield Acceleration (PWFA)

UCLA PBPL has played a key role in another type of wakefield accelerator, the PWFA, in which the scale of the fields may extend from GV/m to TV/m. The dominant interest in PWFA excitation is found in the “blowout regime” [10], where the beam is much denser than the plasma, and plasma electrons are rarefied in response. This highly nonlinear plasma response produces excellent wake characteristics, however — linear, time independent focusing due to uniform ion density in the blown-out cavity behind the driving beam, and electromagnetic acceleration fields that do not notably depend (as in an RF linac) on transverse position. These characteristics have been shown at PBPL to give excellent beam propagation characteristics [11], and the initial explorations of the PWFA in the blowout regime were performed by the PBPL [12]. Afterwards, the FFTB-based E-167 collaboration showed dramatic results in blowout regime experiments, with energy doubling of a 42 GeV injected beam demonstrated in a meter-long plasma [13].

During this recent grant period, the PBPL program in PWFA has concentrated on building up of experimental tools, such as the ramped beam production and measurement experiment at Neptune [14], and theoretical and computational work to explore new directions in the PWFA (e.g. TV/m PWFA using LCLS very small charge beams [15]). This effort has produced a number of ideas that are now turning into experimental efforts. These include: use of pulse trains with very small charge and ultra-low emittance bunches, in the so-termed quasi-nonlinear regime [16], ionization injection (Trojan horse scheme) in the PWFA [17], and creation of exponential energy spectra beams for simulating the space radiation environment with the PWFA [18].

These experiments are have taken place in three different venues. The quasi-nonlinear (QNL) PWFA regime experiment is located at the BNL ATF, and is a collaboration with P. Muggli (MPI/USC), and BNL. In the QNL regime it is, in principal, possible to combine the benefits of both nonlinear and linear PWFA. That is, beams of high quality can be maintained through acceleration due to the complete ejection of plasma electrons from beam occupied region, while large energy gains can be achieved through use of transformer ratio increasing schemes, such as ramped bunch trains. In addition, resonant excitation, a linear characteristic, is possible when the beam charge is much smaller that inside a cubic plasma skin-depth k_p^{-3}, quantity designated $\tilde{Q}$ [19,20]. With an ultra-short focal length (>500 T/m gradient [16]) PMQ triplet developed at UCLA capable of focusing the ATF low-emitttance tunable-period [21] pulse train beams to the few μm scale (and thus needed density), the ATF offers the unique capabilities to probe these characteristics of the QNL regime. This experiment has now being installed, with initial running taking place in Fall 2012. In it, we seek to simultaneously show resonant response through measurement of the beam energy spectrum, and blowout regime guiding by sub-μm resolution beam profile measurements (using a BNL/USC-developed optics and detection system). Follow-on experiments in the multi-GV/m regime are planned at the SPARC lab in Frascati. This work, currently being prepared for publication in *PRL,* has led to the PhD of PBPL student Sam Barber, who has joined the BELLA team at LBNL as a post-doc.

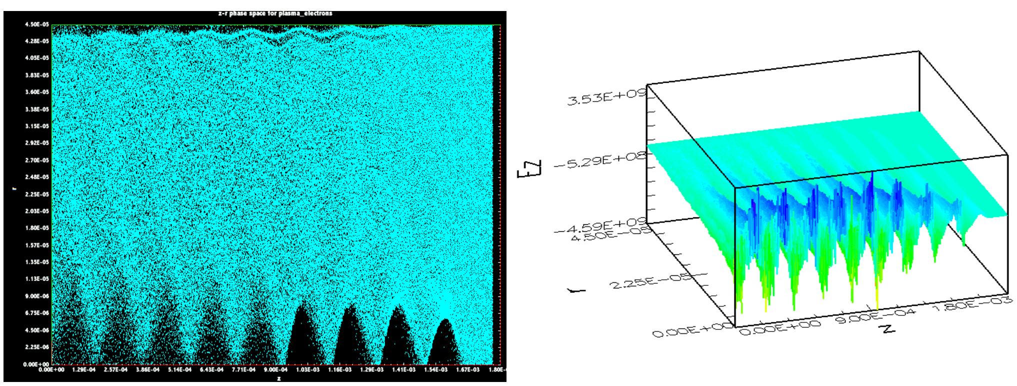

Figure 5. (left) Plasma electron spatial (*r,z*) response to a 4-beam pulse train with each beam having $\tilde{Q}$ =0.11, separated by $\lambda_p = 190$ *m*m, and (right) the associated longitudinal electric fields.

The new concept termed "Trojan horse" injection was, recently proposed [14], relying on particle-in-cell simulation predictions, utilizes a high-ionization threshold gas (e.g. He) component added to a low ionization threshold species such as Li, in order to produce ultra-short electron bunches with unprecedented emittance. Such bunches are extremely promising for XFEL applications in the low-charge regime, and for direct light emission (betatron radiation) via offset electron release. The central idea is to use a synchronized, focused laser pulse to

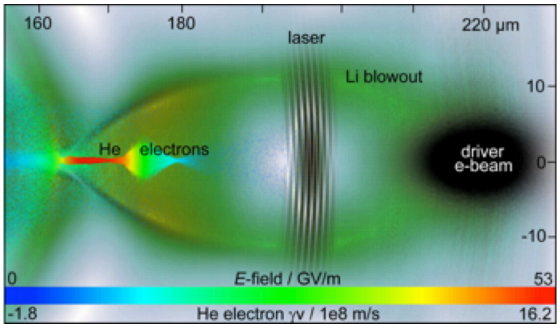

Figure 6. Simulation of Trojan horse injection scheme in PIC code (VORPAL).

release electrons at chosen, narrow range of positions within the blowout by ionizing the high-ionization threshold gas component, which is left in the neutral state as it is not ionized by the intense fields electron bunch driver.

This conceptual proposal was formalized into a FACET proposal (UCLA-SLAC-Hamburg-MPI collaboration), accepted by the SAREC committee with an "excellent" rating, and given the designation E-210. In this past year, we have studied with computation and analytical modes, the atomic-plasma-beam physics needed to understand the limits of emittance and beam brightness in this scheme [22]. Initial plans for exploiting the plasma source to yield the needed region of He gas for injection have been formulated, and the laser transport optics are being studied by a UCLA student and post-doc. The advantages of using 400 nm light [20], as opposed to 800 nm, has been examined in both theoretical and experimental design studies. The first runs of E-210 should have taken place in 2013, after arrival of the laser system. The observables in this experiment are congruent with those of E-200 — we must measure narrow energy spectra of the trapped beam, and determine the emittance. This final point is under study, as the emittance resolution is orders of magnitude smaller than the drive beam emittances at FACET. The initial experiments demonstrating Trojan horse injection, as well as a related concept, the plasma torch, have shown emittances of <5 mm-mrad, with the resolution limited by methodology used thus far.

The final thrust in PWFA under way at UCLA PBPL has begun with the use of low energy beams at Neptune and/or Pegasus to drive high transformer ratio PWFA using a ramped pulse, an activity that has been under development for several years. From the viewpoint of the drive beam, this experiment, carried to nearly complete exhaustion of drive beam energy, produces an energy spectrum that is strongly decaying from low-to-high energy. In fact, with the proper pulse shape and plasma density chosen, one may approximate an exponentially decaying distribution. This distribution is of high interest to the space-radiation community as a compelling application, as it provides a way of simulating an typical radiation belt-spectrum. The advantages of this scheme for the critical testing of space-craft electronics [23,24] have attracted interest from JPL and ESA.

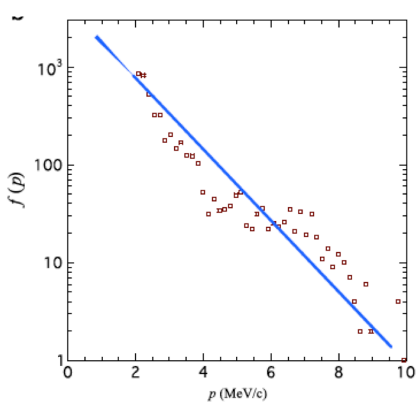

Figure 7. Exponential energy spectrum from initial 4 MeV beam in PWFA.

The ramped beam experiment at Neptune has required that we develop a hollow cathode arc plasma source with the capabilitye of mid-10^{14} cm^{-3} density. This source may be used in an even simpler scenario that does not require beam shaping with the relatively complex beamline at Neptune, to produce an exponential beam spectrum. Instead, a very short, yet high-charge pulse is obtained with the new hybrid photo-injector (described below), in which a 4 MeV, velocity-bunched beam is injected into the plasma, and through a blowout PWFA interaction, the beam core is decelerated, and few tail particles accelerated, producing a nearly exponential spectrum [21], as shown in Fig. 7. This experiment is scheduled to be performed after commissioning of the hybrid photoinjector at the UCLA Pegasus Lab.

Hybrid photoinjector

It has been appreciated for some time that it is not always straightforward to take advantage of high fields in photoinjectors, which should give very high brightness, because the peak fields do not scale as strongly with frequency (linearly) as they need to do to create a simple two-cell device. In addition, long standing wave devices present problems with RF reflections and related issues. In response to this an INFN-LNF/UCLA/Univ. Rome I collaboration has developed *hybrid photoinjectors* in S- and X-band [25,26]. These devices are integrated structures consisting of initial standing wave gun cells linked on-axis to the input coupler, which is coupled to a traveling wave section. This design nearly eliminates the RF reflections from the SW section; further, a 90° phase shift in the accelerating field at the coupling cell yields strong velocity bunching in the TW section. This initiative has, after nearly a decade of study, produced an S-band hybrid realized at INFN-LNF (Frascati, Italy), that is has proceeded to high power testing and photo-electron beam production measurements at the UCLA Pegasus lab. This hybrid has 1.5 cell SW and 9 cell TW sections, and can produce strongly compressed (to > 1 kA current in the high charge case) 3.5-4 MeV beam. It is planned to be used for novel applications such as inverse Compton scattering, or directly at low energy for the previously discussed production of an exponential energy spectrum extending from 1-12 MeV to simulate space-craft radiation environments. At lower charges, the beam may be used for DWA/CCR applications, and is also an ideal candidate for a next generation ultra-fast electron diffraction, which is of high interest to Prof. Musumeci [27]. It can be optionally used with a 3 m TW linac fed from the RF output of the hybrid, to boost the energy to 22 MeV for application to e.g. FEL and wakefield generation.

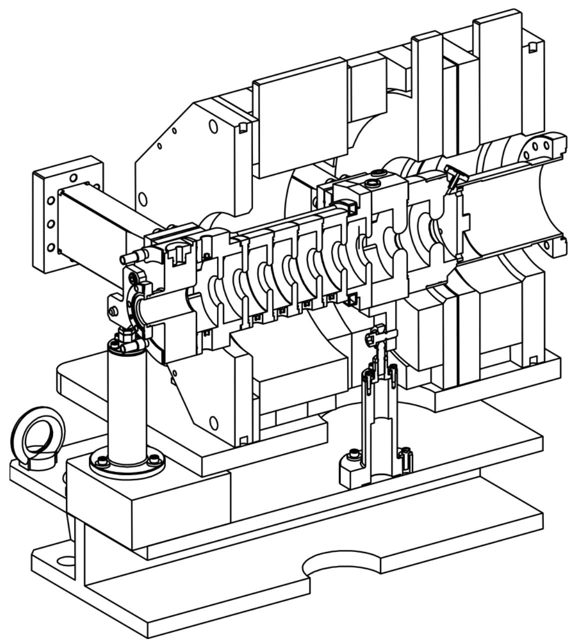

Figure 8. Cutaway of hybrid photoinjector per installation at UCLA Pegasus lab.

After RF commissioning studies, initial beam measurements at Pegasus have concentrated on the measurement of the pulse compression, using an X-band RF deflector built originally for Neptune ramped beam experiments, and on determination of emittance compensation efficacy in the presence of large compression at ~4 MeV energy [28]. These are planned to take six months, after which applications of the S-band hybrid will be explored, at Pegasus or another site. We note that the S-band photoinjector forms a template for a newly funded collaboration between UCLA, INFN-LNF and Tel Aviv Univ. to develop a new source for THz creation at Tel Aviv.

Scaling this now mature hybrid photoinjector design from S-band to X-band is limited by technological limits, that require changes in both RF and magnetostatic designs. As the field is limited by RF breakdown to 200MV/m peak field, the SW section must be expanded to 2.5 cells to reach 3.5 MeV; this permits added flexibility in the solenoid design, which we are developing to utilize permanent magnet components. On the RF side, we are currently building an RF cold-test X-band structure, and will proceed to construction of the device (at LNF) in 2013. Looking to future injector performance, beam dynamics simulations show what we term 6D phase space compensation [29] at 7 pC; sub-0.1 mm-mrad at the emittance minimum that is predicted to occurs simultaneously with a longitudinal focus of of 20 fs rms. Applications of this source to radiation production, wakefield acceleration and electron diffraction are being studied as its characteristics become clearer.

Novel Inverse Free-Electron Lasers (IFELs)

The advancement of IFEL techniques is a priority of both Task A and Task J on this grant. In both Neptune IFEL [30] and ATF FEL [31] experiments in the recent past, PBPL investigations have uncovered aspects of higher harmonic laser-electron-undulator interactions. We have engaged in extensive theoretical studies of such interactions to excite, through electromagnetic modes having *orbital angular momentum* [32] (OAM, having helical phase, and indicated by quantum number *l*), helical bunching, a new and novel state of accelerating beams. The light that is produced from the interactions of a helically bunched beam may be used to manipulate physical systems at the level of angular momentum quantum numbers, e.g. selective interactions of inner shell electrons. We have recently published a *PRL* [33] that discusses the use of such a beam in an FEL to give X-rays with defined OAM. In pursuit of this fascinating scenario, we have performed the first measurements at Neptune showing helical bunching, utilizing coherent transition radiation [34] to unfold the *l*-dependence of the bunching, as shown in Fig. 9. This result has been published in *Applied Physics Letters* [35], paving the way for further studies.

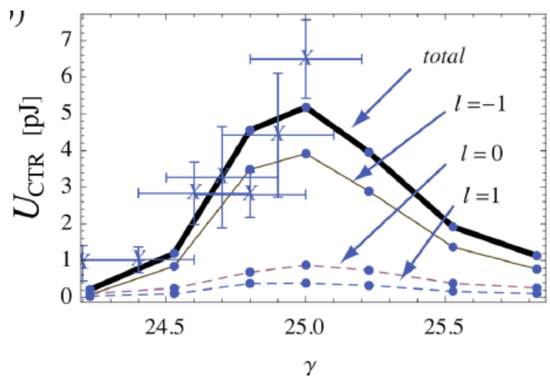

Figure 9. Comparison of measured CTR signals with CTR energies calculated from corresponding bunching factors from simulations. Thick black line is sum of the CTR energies from all the modes.

The major challenge of the OAM IFEL bunching experiment at Neptune was that we utilized 10 um light in the interaction, and thus all diagnostics were in the far-IR. The next experiments were performed at the SLAC NLCTA, using an 800 nm laser and concomitant higher beam energy. The helical-bunching undulator for this experiment has been constructed at UCLA. The helical bunching in this new case has been used in a downstream undulator to produce a very high power pulse of OAM light [36].

Figure 10. Radiograph of wasp made by narrow-band ICS X-rays, showing phase contrast effect at boundaries.

Inverse Compton Scattering (ICS)

The subject of ICS is of compelling interest to the advanced beam physics field, due to its fundamental electrodynamics, its manifold applications, its technical challenges. The electrodynamics are of interest particularly in the hard to access nonlinear regime, where the radiation may be red-shifted, but also develop harmonics. On the applications side, ICS is a strong candidate to be a compact X-to-γ–ray sources in the range from 10 keV to MeV-class photons. From the HEP viewpoint, ICS photons may play a central role in polarized positron production. Additionally quantum aspects of the ICS interaction dominate in the application of photon conversion in possible future γ–γ colliders. Technically the emerging use of short, intense lasers has led to the productions of sub-ps pulses of up-to $10^{7\text{-}8}$ X-rays or γ-rays, but only at the cost of very strong focusing (few um laser spots), thus giving technical difficulties (ICS is a type of e-γ collider in its own right. Other potential users of ICS include medicine, where the tunable quasi-monochromatic photons are useful for X-ray phase-contrast and two-color imaging as well as therapy, and national security, in the remote sensing of nuclear materials. Indeed, UCLA PBPL performs some of our ICS research under the support of the agency DTRA on this subject.

A UCLA-led team a the BNL ATF ICS source, created by the collision of the ATF CO_2 laser with a high brightness electron beam, has in the last few years produced a string of fundamental and applied experimental results. The initial commissioning of the source led to development of foil-filtering techniques that permit characterization of the single-shot spectrum of the hard X-rays produced [37]. Successive experiments explored novel single-shot applications, the first of which demonstrated the phase contrast effect from the production quasi-monochromatic X-rays [38]. The second application produced single shot diffraction images with ICS x-rays, paving the way to ultrafast pump-probe experiments using ps ICS X-rays [39]. Finally, in recent months, we have taken first data on the nonlinear ICS interaction in which red-shifting and (for the first time) 1[st] and 2[nd] harmonics, as shown in Fig. 10, are observed. These results are of particular interest in applications such as polarized e+ production, as the spectral characteristics revealed diminish the γ-polarization.

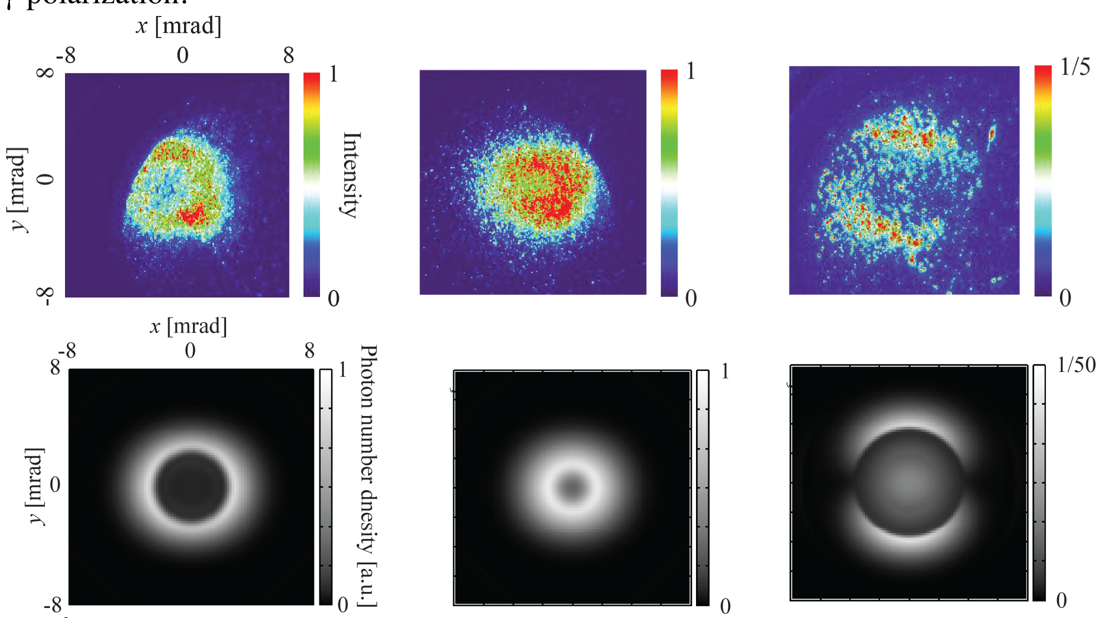

Figure 10. (top) Experimentally observed intensity distribution with K-edge foils, (a) 50 μm Fe foil, 68 MeV beam, (b) 50 μm Fe foil, 65 MeV beam, (c) 20 μm Au foil, 65 MeV beam. (Bottom) Numerically calculated (field amplitude of $a_L = 0.5$) intensity distribution for experimental scenarios at top.

These exciting results are preliminary, as there are experimental uncertainties left to sort out, including laser pulse characterization and improved x-ray detection using a new micro-channel plate detector. These experiments lead to a new investigation, in which two different laser wavelengths are employed in the ICS interaction, thus producing a picket-fence spectral signature in the photons radiated [40]. After this study, in following years will utilize the high energy electrons produced by the Rubicon IFEL discussed in the Task J proposal to create a compact, all optical X-to-γ ray source.

The GALAXIE All-optical XFEL Project

The GALAXIE (*G*igavolt-per-meter *A*cce*L*eration *A*nd *X*-ray-source *I*ntegrated *E*xperiment) project is a comprehensive effort by a consortium led by UCLA PBPL, to develop an ultra-compact all-optical, monochromatic X-ray source based on relativistic electron beams. This project is a DARPA AXiS-funded effort, an ambitious scenario based on the XFEL principle that meets the requirements on X-ray brightness, energy efficiency, electron energy and acceleration gradient set by applications within DARPA, including efficient phase contrast imaging. The FEL performance in turn dictates the description of the electron beam accelerator and electron source. This integrated project, involving UCLA, SLAC, Penn State and RadiaBeam, is funded externally, but has exerted considerable positive influence on the HEP-directed progam here.

Thus we should review this project's synergies with the HEP program. There are number of new components in GALAXIE [41], including: a brightness X-band photoinjector e-beam source, and having unprecedented low asymmetric emittances. This high field source uses manipulations in 4D transverse phase space that exploit the angular momentum in a beam magnetized at the cathode. This source is injected into a fully dielectric laser accelerator (DLA), driven by a unique, high power 5 μm OPA/OPG laser source under development in the GALAXIE collaboration at Penn State [42]. This is accompanied a dedicated program in materials optical and breakdown properties at 5 μm. Acceleration of the electron beam to >700 MeV is to be accomplished in photonically-confined, bi-periodic defect modes in the traveling wave DLA. The monolithic structure design, which is the first of its type capable of simultaneous focusing and acceleration at low energies (Fig. 11), is used to reach multi-GV/m fields. The unique photonics and particle dynamics associated with this structure are discussed in detail in a new *PRL* [43]. A SASE FEL then uses a high field undulator based for the first time on electromagnetic rather than static fields.

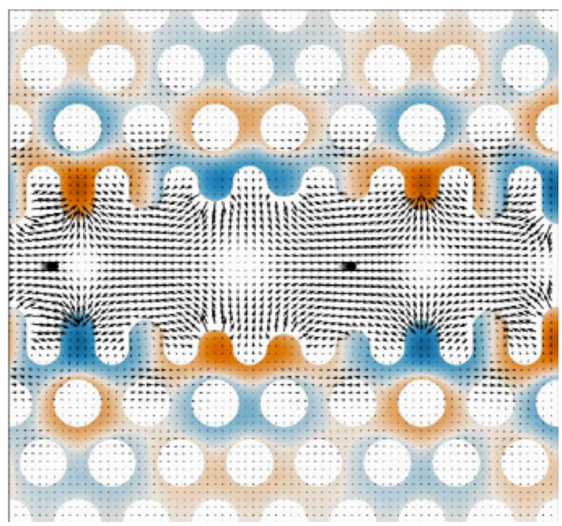

Figure 11. Side-view of the GALAXIE accelerator structure, with dielectric photonic confinement, bi-periodic accelerating/focusing and resonant mode fields shown. For scale, the periodicity in the photonic structure is 1.3 mm,

This combination of efforts has caused the main PBPL effort in DLAs to change radically, with previous work on the standing wave MAP structure continuing independently (with DTRA funding) under the direction of Gil Travish at UCLA. It has also caused us to significantly redirect our DWA program to embrace photonic concepts [44], and to introduce longitudinally periodic accelerating "tooth" structures in the DWA, mitigating the peak fields in the dielectric considerably. Both innovations are great conceptual leaps forward. Also, we note that design work on the GALAXIE gun [40] is obviously synergistic with the X-band hybrid work. Finally, and not of least importance, the funding for GALAXIE is enabling the construction of an expanded lab that will permit an upgrade to the aging Neptune facility. This new lab is discussed in the Facilities section.

Other related NLCTA work

UCLA has a vigorous program in FEL and beam physics at the SLAC NLCTA (as well as at INFN-LNF) that augments the topics discussed above. These are also synergistic with our overall program. We recap these activities here. First, there have been a series of theoretical works aimed at microbunching studies [45], in which the plasma nature of the beam longitudinal oscillations are investigated. Recently, this thrust has allowed demonstration of the powerful new tool of coherent imaging of transverse beam profiles [46]. These studies will continue with an experiment on two-stream instability at the NLCTA [47]. A longitudinal coherent diagnostic, THG FROG, has produced a conceptually similar result in characterizing the phase and amplitude of a single-spike FEL pulse [48].

Task J Technical Report

Nonlinear longitudinal space charge oscillations.

In a recent *PRL* publication, we reported on the theoretical and experimental study of the evolution of an initial periodic modulation in the temporal profile of a relativistic electron beam under the effect of longitudinal space-charge forces. Linear theory predicts a periodic exchange of the modulation between the density and the energy profiles at the beam plasma frequency. For large enough initial modulations, wave breaking occurs after one-half period of plasma oscillation leading to the formation of short current spikes. We confirm this effect by direct measurements on a ps-modulated electron beam from the Pegasus RF photoinjector. These results are useful for the generation of intense electron pulse trains for production of coherent high power THz radiation and for driving large amplitude wakefields in plasma or dielectric structures. Various methods so far have been employed to generate pulse trains, but when the peak current is increased they all suffer from the longitudinal space charge effects. This study turns the issue around and exploits the nonlinearity of the longitudinal space charge forces to enhance the peak current from the initial modulation. A complete study of 3D and energy spread effects and the full design of a high peak current ps-bunch train source is still underway.

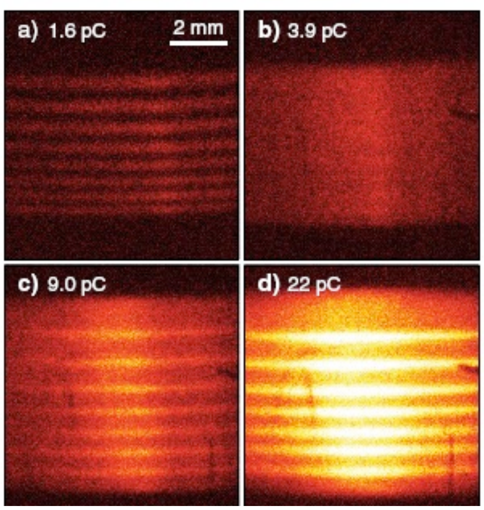

Figure 1. Bunch train streak-images for four different charges. The initial modulation disappears at 3.9 pC and then reappears with increased harmonic content

Detection of ultralow charge beams

Measurements of pC and sub-pC beams have been made possible at the Pegasus laboratory by the development of a new detector for imaging MeV electron beam distribution. With a careful choice of scintillator screen (P43 phosphor), lens coupling system and intensified camera we were able to demonstrate a new detector with a record sensitivity down to the single electron detection level.

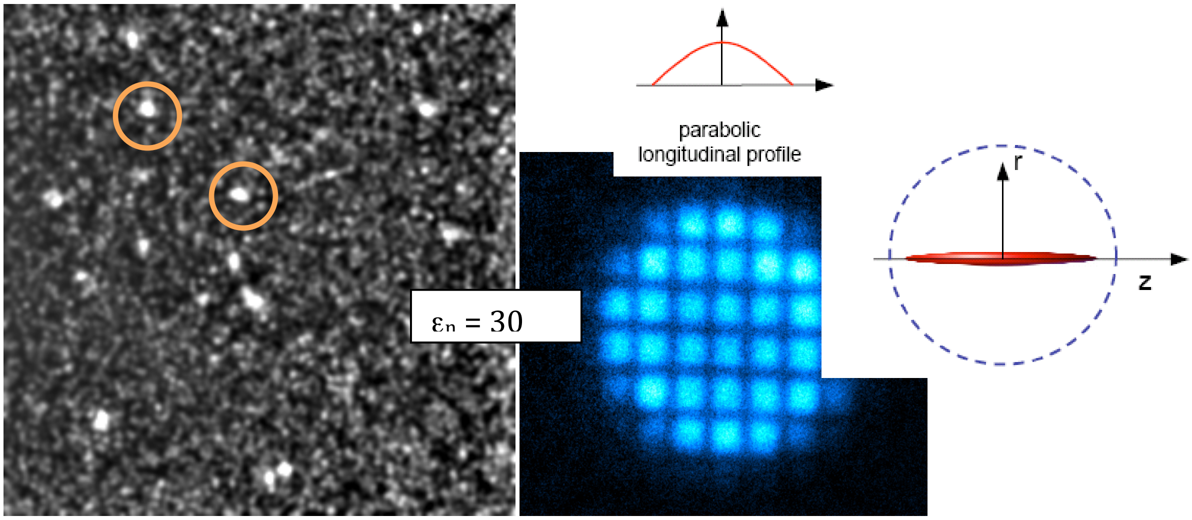

Figure 2. a) Single electrons detected by ICCD camera. b) pepper-pot image obtained with TEM grid. The reconstruction algorithm gives 30 nm normalized emittance. c) Cigar beam geometry.

Using a fast fluorescent screen (for example YaG screen) and a 10 ns pulse to gate the intensified CCD it is also possible to remove the dark current noise from the background improving by many times the signal to noise ratio in ultralow charge beam measurements.

Ultralow emittance beams.

Full characterization of ultralow charge beams allowed the experimental demonstration of sub-pC 30 fs beams out of RF photoinjector and normalized emittances as low as 30 nm. In particular at Pegasus we are exploring a new regime where the laser is focused on the cathode to a very small spot size (< 50 um RMS). The laser fluence is maintained very low (0.1-1 pC) for damage threshold consideration and to avoid virtual cathode formation effects. By shaping parabolically the longitudinal profile of the laser, the pencil beam will undergo a strong space charge driven transverse expansion creating a nearly ideal uniformly filled ellipsoidal distribution. Simulations predict that the normalized emittance can be preserved to its thermal levels. A new emittance measurement technique based on the pepper-pot scheme is used to measure < 30 nm emittances for these low charge beams. It uses commercial transmission electron microscope grids and allows a single shot measurement of the 4D transverse phase space. Fine-tuning of the correction of the skew-quadrupole components in the gun/solenoid system becomes immediate when looking at the image of the grid on a downstream screen.

Cathode research

We have investigated the effect of polarization in multiphoton photoemission using oblique incidence on the cathode of the RF photoinjector. For coated cathodes, all the differences in charge yield can be explained by the different absorption due to Fresnel laws. For uncoated cathodes (bare copper), the increase in the yield for p-polarization is the signature of surface photoelectric effect.

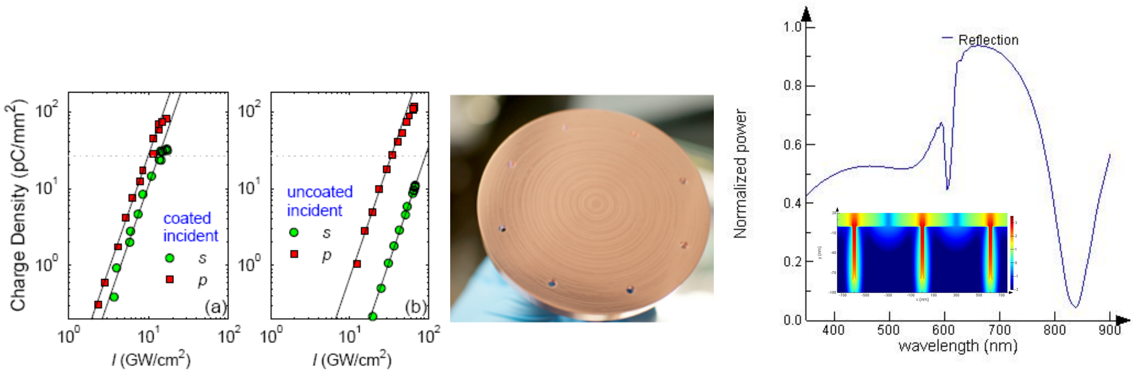

Figure 3. Charge yield for oblique incidence on coated and uncoated cathodes (s and p polarization). b) free-form fabricated cathode installed on Pegasus phootoinjector. c) FDTD simulation of grating pattern on Cu cathode.

A new idea we have started working on in collaboration with LBNL Padmore group consists in taking advantage of the cubic dependence on the laser intensity of multiphoton photoemission. By properly machining the surface of a cathode it could be possible to couple the laser to a surface bound charge oscillation (plasmon mode). The advantages in photoemission come from the possibility of reducing to nearly zero the reflection from the metal surface and from the large field enhancement factor associated with plasmons. Using the nanofabrication facilities of the UCLA CNSI, we are working to imprint on the cathode the proper sub-wavelength structures to allow plasmon-assisted photoemission. Also, in collaboration with Radiabeam Technologies at Pegasus we tested for the first time a solid free-form fabricated cathode. The results are very promising. The free-form fabricated cathode shows no difference in the tuning, vacuum performances and quantum efficiency yield than a conventional solid copper one.

LLNL-IFEL experiment

The UCLA participation to the LLNL experiment has increased significantly in the last few months. A UCLA graduate student, Josh Moody, has been attached to the experimental program, and fully participates in the experimental activities at the LLNL Pleiades beamline. The first section of the beamline has been recommissioned, with photoelectrons obtained in April this year. The rest of the linac is currently being commissioned for the IFEL experiment. The 5 TW high power laser system needed to drive the IFEL acceleration will be installed in September. Meanwhile, we are taking advantage of the facility to conduct interesting high brightness beam experiments. The photoinjector operates in blow-out regime and should generate very linear longitudinal phase space beams. We plan to compare the performances of chicane magnetic compression and the RF velocity bunching compression in this regime.

Rubicon IFEL undulator construction

A strongly tapered helical undulator has been built for the Rubicon project. This IFEL experiment will demonstrate for the first time high gradient acceleration in the helical geometry. The design allows for a relatively large gap (15 mm) between the magnet poles to allow nearly 99 % transmission of the driving CO2 laser pulses. The low transport losses are required for the future foreseen installation of a recirculating laser cavity to demonstrate a high efficiency IFEL accelerator. First measurements on the magnet are in very good agreement with the simulations.

Final tuning and vacuum testing are expected to take place in the next month prior shipping to BNL.

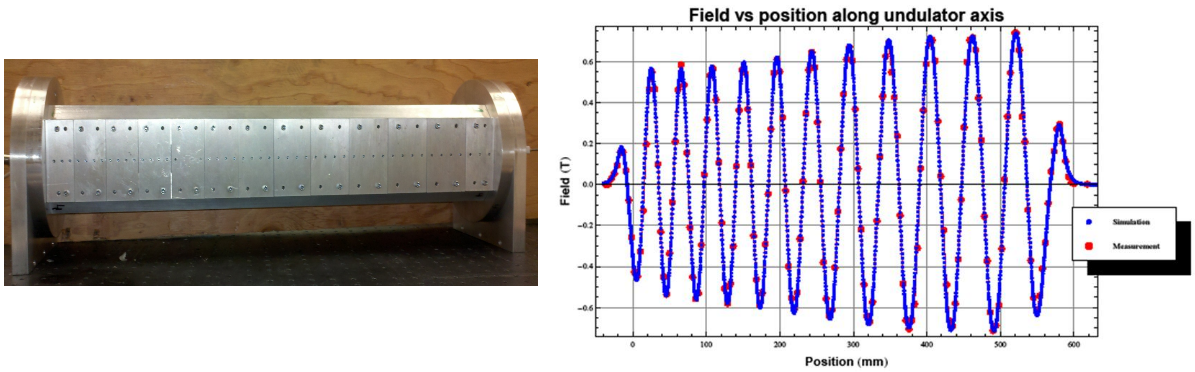

Figure 4. a) Rubicon helical strongly tapered undulator. b) On axis mangetic field. Hall probe data and simulation.

Self consistent IFEL simulations (GENESIS)

The widely used Genesis FEL code has been modified to be able to simulate strongly tapered IFEL undulators to have a self consistent model of the loading of the laser wave due to the accelerating particles. The results led to the design of a highly efficient IFEL accelerator where most of the laser power (> 60 %) can be transferred to the electron beam. The limit in efficiency comes from the non uniform transverse distribution of the laser mode and from the coherent radiation emission at the harmonics of the fundamental undulator wavelength.

Planned upgrades to Pegasus Laboratory

A new pump laser (1 J @ 1064 nm, 300 mJ @ 532 nm) has been purchased second hand from a used laser company (Anderson lasers). This system will pump a bow-tie postamplification stage for the present Ti:Sa laser system which will boost the energy of the 50 fs laser system to 100 mJ and a peak power in excess of 2 TW. Applications of this upgraded laser include the production of higher power of THz radiation by optical rectification (up to 50 mJ and 50 MW peak power), inverse Compton scattering, external injection into a laser plasma based structure. Funding from the laser comes from the residual startup seed grant from UCLA.

An RF hybrid gun built in collaboration with INFN and University of Rome La Sapienza will be tested in the Pegasus Laboratory. The new RF structure combines a standing wave section with a traveling wave bunching section. The beam dynamics is characterized by a simultaneous transverse as well as longitudinal focus. The beam will be characterized using the extensive set of diagnostics already installed on the Pegasus beamline.

In collaboration with FarTech we will test a high shunt impedance dual-slot resonance linac. This device only uses 2 MW of RF power and will allow to boost the Pegasus beam energy to 13-14 MeV. By running it at the zero-cross phase point, another interesting application is the compression of the ellipsoidal beam to sub-10 fs bunch length. The required high power waveguide modifications (power splitter, phase shifter) will be provided from the FarTech SBIR phase II grant.

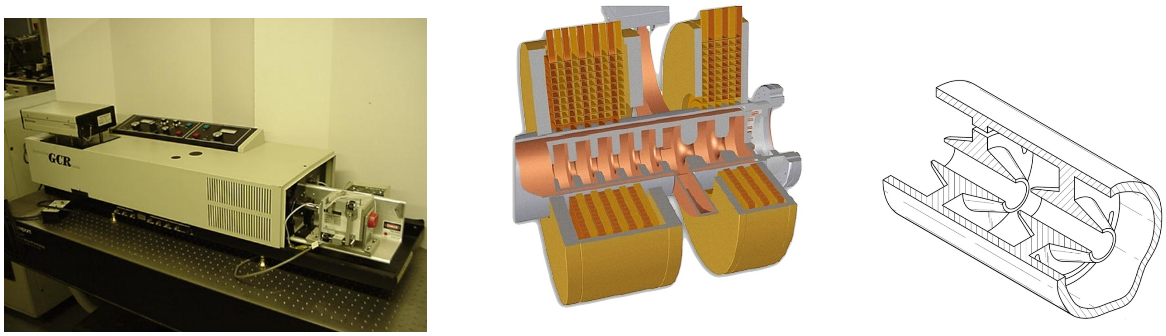

Figure 5. a) GCR pump laser. b) Hybrid gun. c) Dual-slot resonant coupled linac.

Task A Publications

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