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Experimental Study of Electron Dynamics in Strongly Relativistic Laser Fields

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Final Report

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14. ABSTRACT This multi-PI project focused on understanding the trajectories and energetics of individual charged particles ultra-relativistic strong laser fields under conditions ranging from single particles in vacuum to collective electron dynamics in over-dense plasmas. The importance of the studies in the program lies in the fact that understanding single electron dynamics underly more complex phenomena. Under this grant we have undertaken three linked studies, spanning particle densities from single particles to overdense plasmas and intensities from weakly relativistic (~1018 W/cm ²) to the ultra-relativistic (>1022 W/cm ²), the very highest intensities that can be technologically accessed.					
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Final Report FA-9550-14-1-0045

“Experimental study of electron dynamics in strongly relativistic laser fields”

B. Manuel Hegelich, M. Downer

Overview

This multi-PI project focuses on understanding the trajectories and energetics of individual charged particles ultra-relativistic strong laser fields under conditions ranging from single particles in vacuum to collective electron dynamics in over-dense plasmas. The importance of the studies in the program lies in the fact that understanding single electron dynamics underly more complex phenomena.

Under this grant we have undertaken three linked studies, spanning particle densities from single particles to overdense plasmas and intensities from weakly relativistic ($\sim 10^{18}$ W/cm²) to the ultra-relativistic ($> 10^{22}$ W/cm²), the very highest intensities that can be technologically accessed.

These three topical thrusts, managed by the three PIs, consisted of:

1. ***Study of ionization dynamics and ejection of electrons from isolated single ions at ultra-relativistic intensities (Ditmire).***
 - a. Development of an ion time-of-flight spectrometer to study ultrarelativistic ionization.
2. ***Dynamics of relativistic electron beams in strongly relativistic laser fields (Downer).***
 - a. Development of an integrated plasma-mirror setup to enable electron beam interaction with a Lorentz-boosted field.
 - b. Simulation studies of relativistic plasma-mirrors to support 2a).
3. ***Electron dynamics and classical and quantum radiation effects at ultra-relativistic intensities in relativistically transparent plasmas (Hegelich).***
 - a. Intensity upgrade of the Texas Petawatt laser, implementation of closed-loop adaptive optics and F/1 focusing to support 1), and 3).
 - b. Development of novel gamma-ray diagnostics to support 2) and 3).
 - c. Theory and simulation program to support experimental design and analysis for 2), and 3).

In this first three year phase of the project, we successfully upgraded the TPW laser, developed and tested the required diagnostics, the ion time-of-flight-spectrometer and two different gamma spectrometers, demonstrated focused intensities $I > 10^{22}$ W/cm², performed an initial experiment in area 1), performed two experiments on nonlinear Compton scattering in a Lorentz-boosted field in area 2), performed a commissioning high field, relativistic transparency experiment in area 3) and constructed an effective field theory (EFT) based on quantum electrodynamics (QED) with a strong classical laser potential, used the PSC PIC code to systematically investigating photon emission under TPW conditions scanning target densities and thicknesses, winning a grant of 3.5 million computing hours to proceed to 3D simulations.

The detailed contributions and achievements in the individual project areas are described below.

1) Ionization Dynamics at Ultrahigh Intensities (PI Ditmire)

In research area 1 we developed a five channel ion time-of-flight spectrometer (iTOFS), based on high sensitivity Microchannel plates (MCP). The In July 2017 we fielded a joined experiment (Ditmire & Hegelich groups) in *research area 1) ionization in ultra-relativistic fields*. The iTOFS was tested in experiments on the J2 Ghost laser system in preparation for experiments at TPW. Also developed was a low density gas jet target and nozzle, capable of creating a low density ($\sim 10^{16}$ /cc) Argon gas plume as a target. Development lasted from the project start until summer 2017. In July 2017 the gas target and the iTOFS were fielded in a TPW experiment. In the experiment, the TPW pulse, focused to $> 10^{22}$ W/cm² using the F/1 off-axis parabola and closed-loop AO corrections, interacted with an underdense Argon gas jet at electron densities $n_e \sim 10^{16}$ cm⁻³.

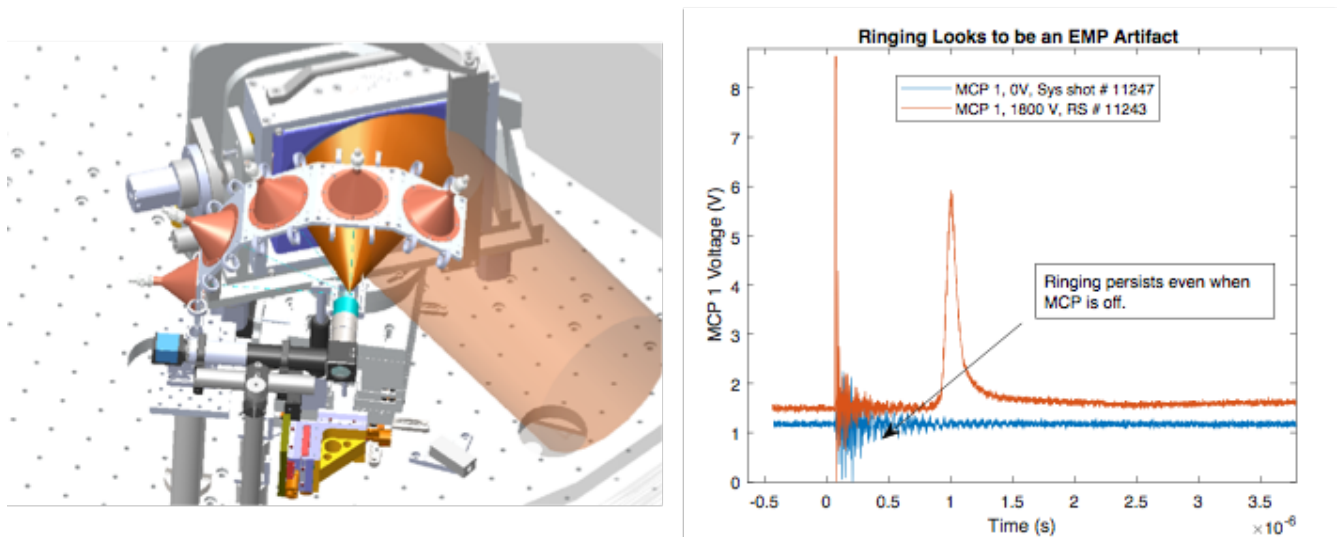


Fig. 0: General Setup of the 5-channel ion time-of-flight spectrometer (left) and signal obtained on TPW experiment showing excessive ringing from strong induced Electromagnetic Pulse (EMP).

Strong ringing was observed in the iTOFS diagnostic that had not been present in the Ghost tests and that precluded getting ionization data. The ringing was identified as a strong Electromagnetic Pulse induced by the Texas Petawatt lasers much more powerful pulse. Analytics is ongoing to determine the future prospects of this experimental approach to measuring the ionization dynamic.

2) Dynamics of relativistic Electron beams in relativistic Laser Fields (PI Downer)

The relativistic electron beams originated from laser wakefield accelerators (LWFAs) driven by laser pulses from one of two facilities: (1) The University of Texas Tabletop Terawatt (UT³) facility: 1 J, 30 fs, 0.8 μ m laser pulses; (2) Texas Petawatt (TPW): 150 J, 150 fs, 1 μ m laser pulses. The LWFAs produced quasi-mono-energetic electron bunches of \sim 100 pC charge, with electron energy ranging from \sim 100 MeV (UT³) to over 2 GeV (TPW). The interaction of these electron bunches with strongly relativistic laser fields was brought about by inserting a plasma mirror (PM) near the exit of the LWFA. The PM retro-reflected the LWFA drive pulse back onto trailing LWFA-accelerated electrons, generating Compton backscatter (CBS) x-rays (100-200 keV, UT³) and gamma-rays (5-80 MeV, TPW). We characterized the photon spectrum, total energy, and angular distribution of the CBS radiation, while simultaneously characterizing energy spectrum, charge, and emittance of LWFA-accelerated electrons, and the focusing properties of the PM-retro-reflected laser light. PIC simulations supported all experimental results. The major scientific accomplishment was detailed experimental-theoretical explication of the PM + LWFA method of generating directional, ultrafast x-/gamma-rays, and the optimization of its performance. Two PhD and one MS student completed their degrees based on their contributions to this part of the project, publishing several journal articles and presenting numerous conference talks, as detailed below.

Below is a summary of the main accomplishments of Downer's group under FA-9550-14-1-0045 during each of its three years. Further details are given in the preceding annual reports.

1st year: Downer's group, supported by theory and simulations from Shvets and Arefiev, reported an experimental study of relativistic (50-100 MeV) electrons from a terawatt laser-driven LWFA interacting with a relativistically intense, counter-propagating laser field created by retro-reflecting the LWFA drive pulse with a plasma mirror (PM). After optimizing laser-plasma conditions, they generated quasi-monoenergetic (50% FWHM energy spread), tunable (75-200 keV) Compton backscatter x-rays [Tsai15], characteristics previously achieved only on more powerful laser systems by CBS of a split-off, counter-propagating pulse. Laser to x-ray photon conversion efficiency (6e-12) exceeded that of previous LWFA-based Compton sources. PhD student H.

E. Tsai reported the findings at the APS-DPP meeting [TsaiAPS15].

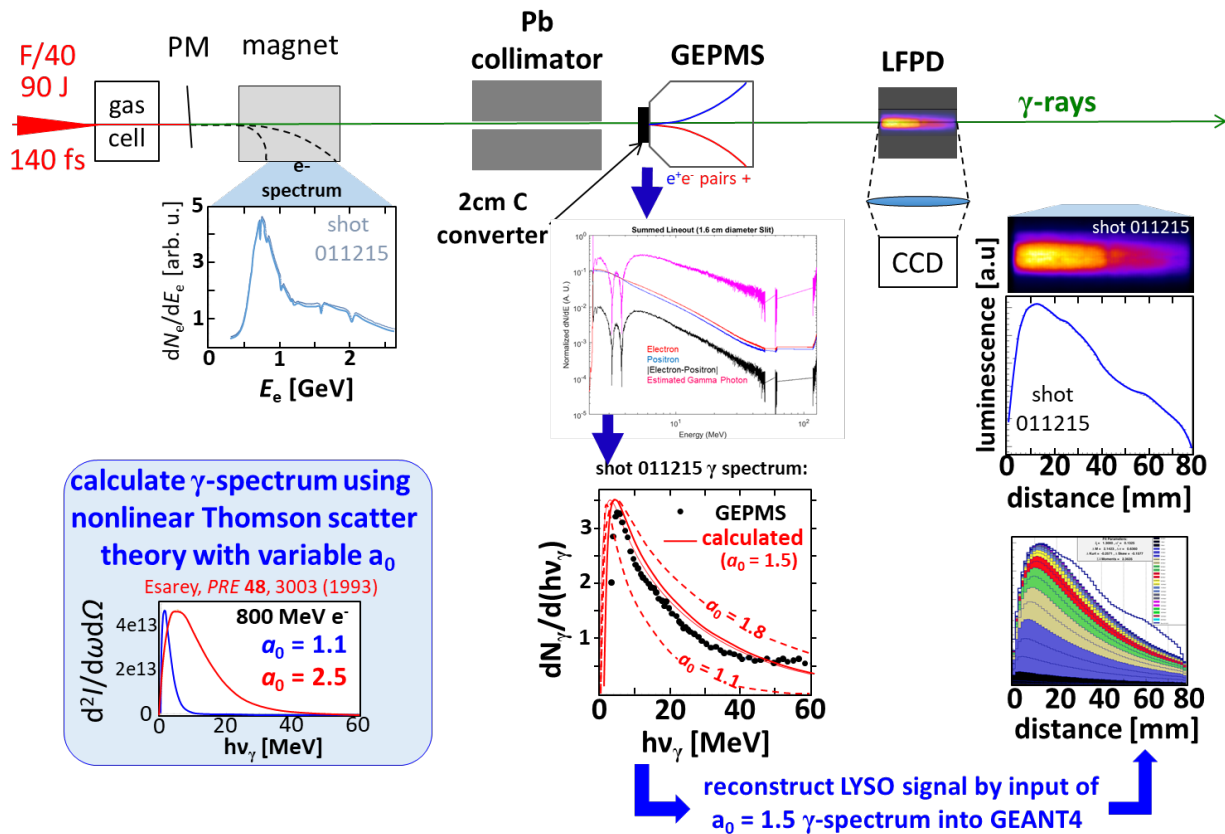


Fig. 1: General Setup of LWFA 7.0 with typical spectrums of LWFA electrons and CBS photons. LWFA 6.0 did not have LFPD.

2nd year: During this year, they followed up on indications in the earlier study that light pressure of the retro-reflecting LPA drive pulse relativistically dented the PM, causing it to focus onto trailing electrons. They carried out a quantitative laboratory study of the focusing properties of PMs excited by high-contrast 30fs, 800nm laser pulses at intensities up to $I_0 \sim 5e18$ W/cm². The results showed that relativistically excited PMs can act as self-aligning concave mirrors with ultrafast adjustable foci. When pre-pulses satisfied specified criteria, results showed that the relativistic PMs could be highly reflective (0.6 to 0.8), and could focus reflected light to intensity as large as $10I_0$ at distance f as small as 25 μ m from the PM. Particle-in-cell simulations supported the experimental findings. The importance of the findings was that it demonstrated the possibility of achieving focused intensities relevant to vacuum quantum electrodynamics (QED) in the reference frame of trailing GeV electrons. This motivated an attempt to replicate these results at the Texas PW facility. The group reported the new results at the Advanced Accelerator Concepts Workshop [DownAAC16] and H.-E. Tsai’s PhD dissertation [TsaiPhD15], and published the results in [Tsai17].

3rd year: The group transferred the Compton backscatter (CBS) experiment to the Texas Petawatt (PW) laser-driven plasma accelerator, which produces quasi-monoenergetic 2 GeV electrons. They observed that PM retro-reflection of the PW LPA drive pulse generated CBS gamma rays that readily penetrated several centimeters of lead, indicating a photon energy of tens of MeV. Analysis showed that the CBS pulse contained $\sim 1e8$ gamma-ray photons with sub-mrad divergence, and estimated peak brilliance $1e21$ photons/s/mm²/mrad²/0.1% bandwidth and negligible bremsstrahlung background. The tunable photon energy range (5 to 85 MeV) spans a range otherwise available with comparable brilliance only from large-scale GeV-linac-based high-intensity gamma-ray sources. The group submitted papers reporting the findings to the 2016 Conference on Lasers and Electro-Optics (CLEO 2016) [ShawCLEO16] and the 2016 Advanced Accelerator Concepts Workshop [ShawAAC16], the latter earning MS student Joseph Shaw a “best student presentation” prize. The PI gave

several invited talks on these results [NatPhot16, HZDR17, CHILI17]. The group is preparing an archival publication [Shaw18]. Recently a new PhD student has demonstrated efficient generation of 1-3 MeV Compton backscatter x-rays using the PM + LWFA method at the Draco laser facility at Helmholtz-Zentrum Dresden Rossendorf (HZDR) in Dresden, Germany, and reported initial results at the European Advanced Accelerator Concepts workshop [HanEAAC17]. We plan to continue study of the relativistic laser-beam interaction there.

3) Electron dynamics and classical and quantum radiation effects at ultra-relativistic intensities in relativistically transparent plasmas (Hegelich).

3a) Diagnostic Development and Experiments

The project contained a multi-year campaign to perform radiation reaction (RR) experiments at the TPW Facility. Since measurable RR effects require $>10^{22}$ W/cm² on-target intensity, TPW went through two upgrades, contrast and intensity, in order to achieve this ultra-relativistic intensity. With active theory and simulation support from Dr. Labun, a postdoc in the Hegelich group financed by this project, high field experiments were designed and executed alongside the design and fabrication of multi-MeV charged particle and photon detectors by graduate students. Here we recall the major achievements of the past three years and ongoing progress of our experimental group.

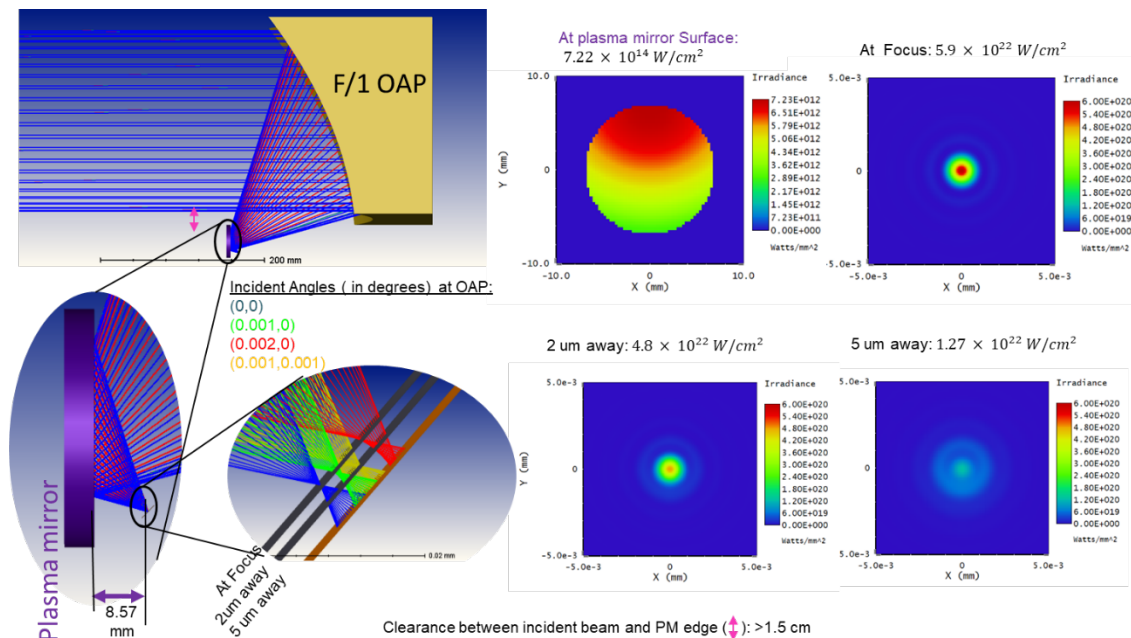


Fig. 2: Setup of F/1 OAP and plasma mirror in Zemax OpticStudio with ideal Top-Hat TPW beam of 0.8 PW

First Year: A major contrast upgrade was performed with the development and installation of a full beam closed-loop adaptive optics system (AO) in the compressor chain of TPW. The details of this upgrade have been published in [Gaul16]. Our team designed, selected and procured a custom build F/1 Off-axis parabola (OAP) to reach the ultra-relativistic intensities for Radiation Reaction (RR) type experiments. The technical details of the upgrade plan were reported in more depth in the annual report from 2015. We also completed the design of a multi-MeV photon detector based on Compton Scattering and Pair Production, which was also reported in detail in the annual report of 2015; a manuscript is in preparation for submission to “Review of Scientific Instruments [GEPMS18].

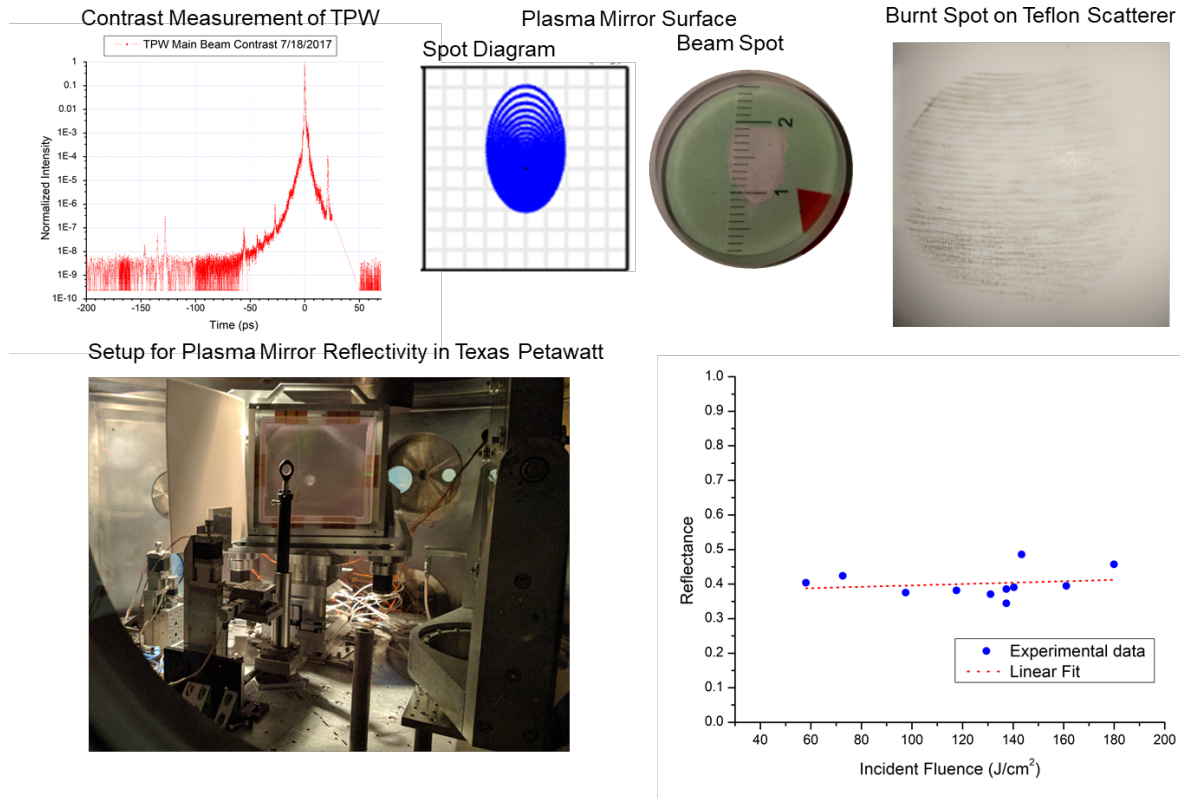
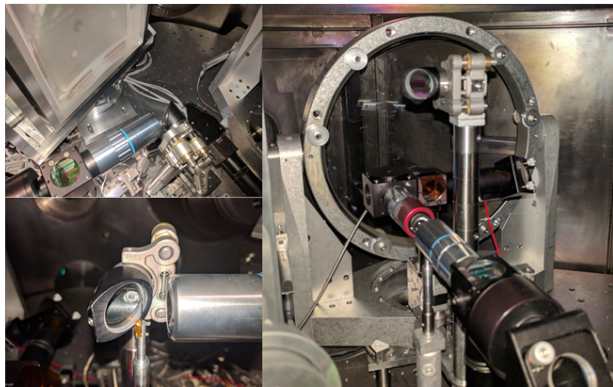


Fig. 3: Contrast Measurement of TPW Beam and Plasma Mirror Reflectivity Measurement during HFE 2.

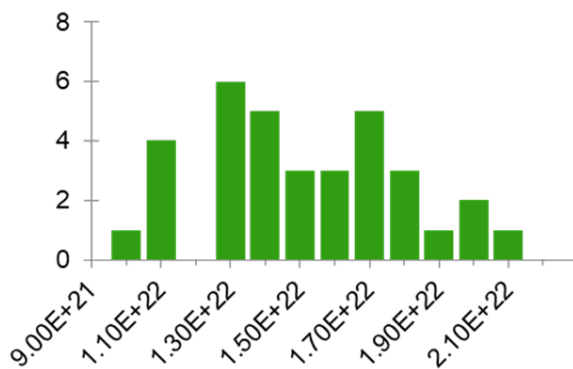
Second Year: We completed the fabrication of the Gamma-to-Electron-Positron Magnetic Spectrometer (GEPMS) and conducted the first RR type experiment (annual report 2016). In the first RR experimental campaign (July-August 2016), we implemented a newly developed modified Confocal High Intensity Positioner (mCHIP) for accurate positioning of the solid target in the focus plane of F/1 OAP and executed closed loop wave-front correction setup between the target chamber and newly installed AO in the compressor chain for the first time in TPW. With these diagnostics, we measured a confirmed on-target intensities exceeding 10^{22} W/cm², but observed no measurable RR effects, as outlined in the annual report of 2016. To supplement the GEPMS in the detection of low flux photons, we designed a novel gamma-photon detector consisting of compact pixelated LYSO (Cerium doped-Lutetium Yttrium Orthosilicate) scintillators and an imaging system with a high dynamic range CCD camera. We are a research paper based on this low flux photon detector (LFPD) in for submission in Rev. Sci. Instr. [Lisi18]. Additional details regarding the LFPD are available in the annual report of 2016. Collaborating with PI Downer and his group, we conducted a joined experiment addressing in research area 2) *dynamics of relativistic electron beams in strongly relativistic laser-fields*, successfully deploying the developed GEPMS gamma-ray and measuring Compton Backscattering (CBS). The results of this experiment with GEPMS data is are in preparation for publication and are expected to appear in multiple articles, including [TiwCBS18]. **Third Year:** We conducted another joined experiment with Downer's team in research area 2) at TPW with a focus on CBS where we fielded both GEPMS and LFPD. Figure 1 demonstrates the preliminary analysis a typical energy spectrum observed in GEPMS and an image of scintillation captured by LFPD. We are working with Downer's group to report overall results from LWFA 6.0 and LWFA 7.0 in high impact journals.

We performed two ultrahigh intensity experiment, interacting the strongly focused TPW pulse at $I > 10^{22}$ W/cm², with various overdense foam and foil plasma targets, as suggested by PIC simulations. A first experiment in April 2017 did not observe any gamma signal from radiation reactions, in spite of a verified high focus intensity.

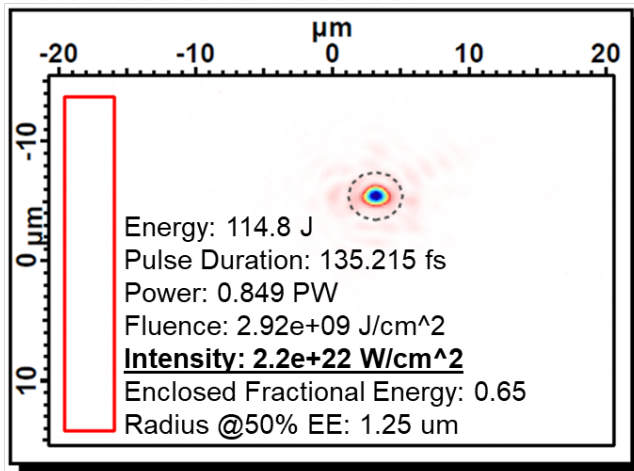
mcHIP, Plasma Mirror and THRU focus setup (HFE 2)



Frequency of Peak Intensities during HFE 2



11345 Measured Far-Field at OSP



11345 Predicted Aberration Phase Map at TC 1

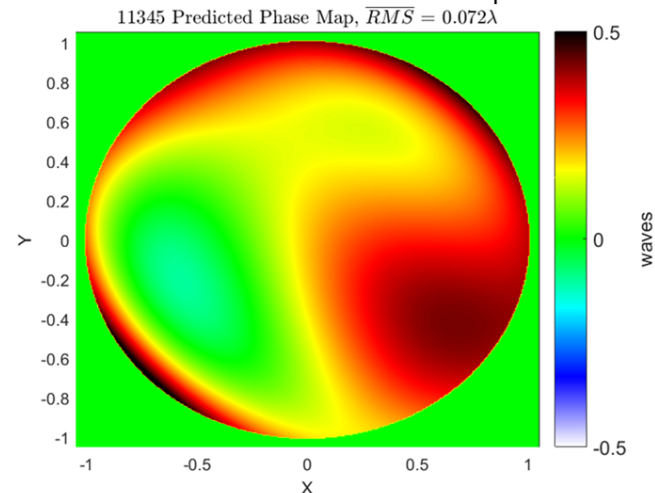
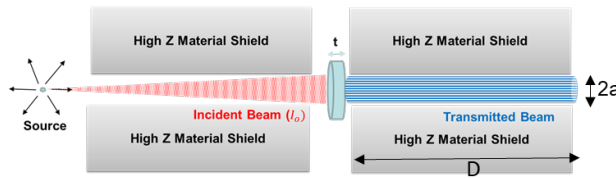


Fig. 4: Setup of HFE 2, measured Far-field data at OSP and Predicted Aberration Phase map at Target Chamber of the highest intensity recorded far-field.

The second experiment was aimed at understanding this lack of signal, by performing a detailed laser pulse characterization. We measured the third order autocorrelation of TPW laser intensity in mid-July as shown in Fig. 2; a significant pre-pulse with contrast of $\sim 5 \times 10^{-7}$ is observed about 135 picosecond (ps) following two smaller pre-pulses starting at 150 ps before the arrival of the main pulse. Mitigating the effects of pre-pulse and pre-plasma with a plasma mirror before the focus was made challenging by the tight focal geometry and tight spatial tolerances of the F/1 OAP. We conducted a careful analysis of the setup of the plasma mirror in Zemax OpticStudio (figure 2); this setup was applied in our second High Field Experiment (HFE) that occurred from late July to Mid-August of 2017 as shown in figure 4. Figure 4 also shows the frequencies of peak intensities reached during HFE 2. We broke our record of measured peak intensity of $\sim 1.65 \times 10^{22}$ W/cm² in HFE 1 with a new record of 2.2×10^{22} W/cm². We also observed $> 10^{22}$ W/cm² more frequently and consistently in HFE 2 than in HFE 1. We are working on a manuscript featuring the highest intensity obtained with F/1 OAP at TPW to be submitted to one of the Optical Society of America journals [F1OAP18]. Although we were able to reach higher intensities, again no clear indication of RR effects were observed. Preliminary analysis of Plasma mirror reflectivity suggests that the laser energy reaching target dropped by about 50% (figure 3) suggesting negligible triggering of RR effects in the solid targets used. Further analysis of electrons and ion energy spectrum are ongoing. We hope to unravel the physics involved in a consistent fashion. This work will ultimately lead to a PhD dissertation at UT Austin in 2018 [Tiw18].

- Narrow Beam Attenuation Approximation $I = I_0 \exp(-\mu t)$.



- Collimation
Half-Cone Angle: $\phi \approx (C = \frac{a}{D})$ (rad) or $\phi \sim \frac{180}{\pi} * \frac{a}{D}$ (degrees).

- Energy of Recoil Electron versus Incident Photon Energy at different Recoil Angles

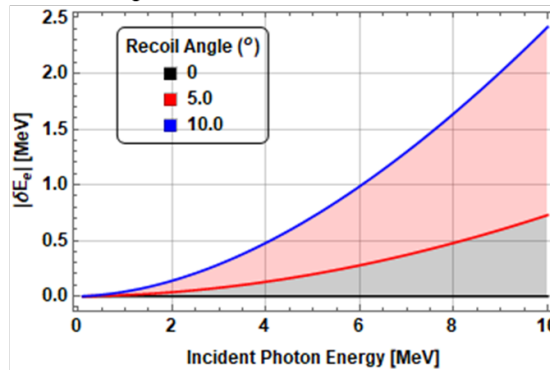
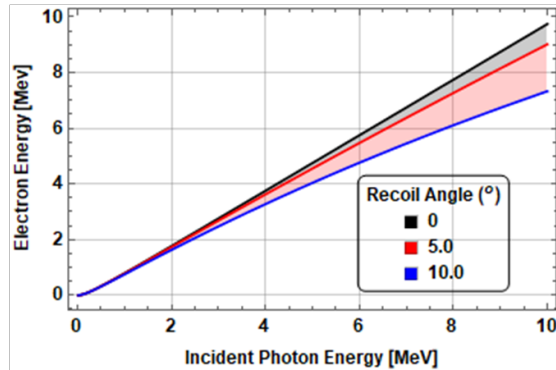
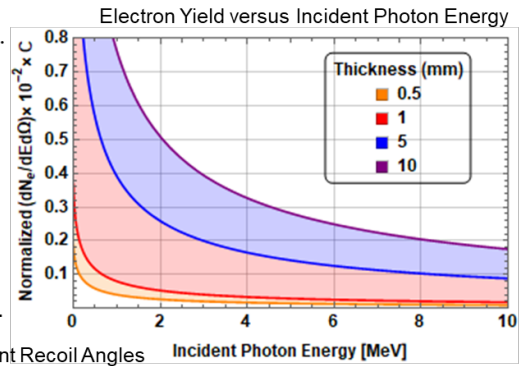


Fig. 5: Working Principle of CCMS: Narrow Beam Attenuation, energy distribution of Compton scattered electrons for different recoil angles, electron yield versus incident photon energy for different thickness of carbon converter, error in energy distribution of Compton scattered electrons versus incident photon energy for various recoil angles. Cross-section data were extracted from NIST Photon Cross-Section Database.

In addition, we started work on the design of a compact Compton Magnetic Spectrometer (CCMS) with the energy range of 1 to 10 MeV (figure 6) but very high spectral resolution of better than 1%. The working principle of CCMS involves narrow beam attenuation, Compton scattering (CS) and magnetic deflection (see figures 5 and 6). In the primitive design, we have achieved desired precision of focusing Compton scattered electrons in the horizontal (x) direction as shown in figure 5. Our ultimate goal is to achieve stigmatic focusing (i.e. focusing of the electrons in vertical direction as well as horizontal focusing) [CCMS18]. CCMS will be one of a kind spectrometer upon completion and will be used in experiments at two off-site facilities, as necessitated by the shutdown of the TPW facility by DOE. The CCMS will be used in experiments at the BELLA laboratory at Lawrence Berkeley National Laboratory in collaboration with C. Geddes, for the detection of the Thomson scattered photons from LWFA electrons, as well as on radiation reaction experiments at the 4PW laser at the Center for Relativistic Laser Science, Institute of Basic Sciences at the Gwangju Institute of Science and Technology.

We will be actively participating in high field experiments and CBS based experiments scheduled at Center for Relativistic Laser Science, Institute for Basic Science, South Korea in the summer and fall of 2018. We plan to field several ion detectors in the HFE and gamma spectrometers, particularly GEPMS and LFPD in the CBS experiments.

3b) Theory and Simulations

Overview

To support experimental design and analysis, our group carried out both theoretical and numerical investigation of quantum radiation dynamics in laser-plasma interactions. We began with ab initio study of quantum electrodynamics (QED) in strong classical potentials and proved “factorization theorems,” which separate high-energy, quantized single-particle dynamics from low-energy classical collective plasma dynamics. Factorization theorems are necessary to ensure control of accuracy and precision of predictions given the many length, time and momentum scales in the laser-plasma experiments [HegJPP17]. We used two complementary methods, both

deriving an effective field theory similar to advanced examples in quantum chromodynamics [ZhangPhd16] and working in the full theory to connect more explicitly to previous work in strong-field QED [Lab18].

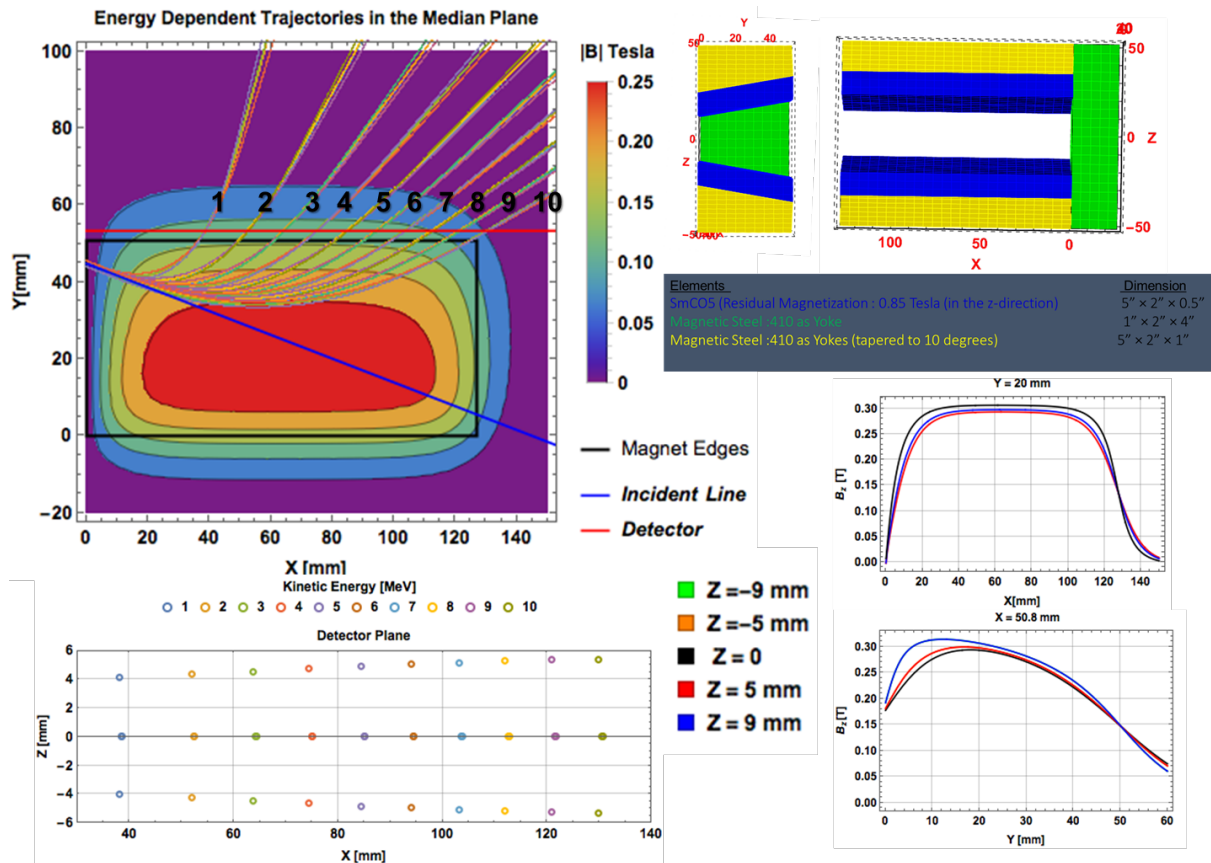


Fig. 6: CCMS Design, Energy Dependent Trajectories in horizontal and vertical directions and field maps.

Concurrently, we explored characteristics of photon emission in numerical simulations of experiments anticipated to be performed on the Texas Petawatt Laser (see High-Field Experiments). For these intensities, many groups' simulations predict large numbers of high-energy photons can be produced, provided the right target conditions. Our group studied the photon energy and directionality in several ways, studying target structure-dependence, quantifying the strength of the directionality with a “jet” observable, and ensuring statistical significance of our results.

Both theory and simulation progress was described in invited and conference presentations, offering discussion and feedback. Complimentary work included: identifying generic experimental signatures of critical phenomena in particle-producing systems, which was first motivated by the search for the critical point of nuclear matter in heavy ion collisions, but may also become relevant as we approach the pair-creation threshold in strong-field QED [Chen16,Chen17]; and establishing an effective field theory for waves on non-trivial background fields [Lin16].

Below we recall the first and second year accomplishments, for which more detail can be found in previous annual reports, and briefly describe additional progress in the third year.

First year: We worked with Dr. Zhang and her adviser Prof. Sean Fleming at the University of Arizona to develop an effective field theory description of high-energy photon emission and pair-creation processes in high-intensity laser fields. We proved that both the photon and positron angular distributions, as would be measured in experiment, are factorized into three typical pieces: an initial-state function containing classical dynamics determining the momentum of the initial emitting electron, a final-state function containing final-state radiation and quantum corrections, and a soft-radiation function containing quantized but more isotropic (away from both

initial and final state) radiation. The derivation of the effective theory and preliminary results for one-loop corrections to each factor are published in the dissertation of Dr. Zhang [ZhangPhd16]. In addition, we applied similar systematic methods to investigate the Unruh effect, and show that this effect is incompatible with neutrino mixing, opening new questions and in-principle experiments to explore the relationship between quantum theory and general relativity [Ahl16].

During this year, Dr. Labun visited the group of Prof. Dr. H. Ruhl and learned to use the PIC code known as the PSC, and trained other members of the group in its use for the remaining years.

Second year: We began repeating derivations of the factorization theorems in the “full theory” of strong-field QED, which helps both to clarify why the effective theory previously derived makes sense and to connect to previous work in strong-field QED. We described our approach and its necessity to strengthen connections between theory and experiment in a special issue article [HegJPP17]. In addition, we continued a study of the Green's functions of strong-field QED, which is part of a long-term foundation for constructing a quantum kinetic theory including radiation and spontaneous pair production, in collaboration with Dr. Emil Mottola of Los Alamos National Lab. Unfortunately, we ultimately found that analogies between QED and gravity used by Dr. Mottola were not valid, which has delayed publication of our study.

Our group also studied photon emission from solid-density plasma targets. Dr. Arefiev and collaborators demonstrated control of photon emission direction using micro-structured targets [Are16]. Mr. Luedtke and Dr. Labun conducted a systematic study of the directional photon emission, showing that total energy converted to photons is maximized for a moderate density (60-100 times critical density) and moderate thickness (10 micron) target, and that the directionality survived realistic variations in target conditions such as pre-plasma and non-normal laser incidence. We won and utilized a 3.5 million hour grant of computation time from XSEDE to support and continue this project.

Third year:

We calculated a complete 1-loop correction to the photon angular distribution using the full-theory factorization framework, and checked our results by calculating with two different regulators. The results are close to being released [Lab18].

We ran additional simulations building on the previous year's insights, and developed a new observable, jet energy, to quantify the directionality of photon emission under varying target conditions. With additional simulations from the XSEDE grant, we have filled in parameter scans in density and increased the statistics on the jet energy. These results are also in the final stages of preparation [Lue18]. We initiated collaboration with Dr. L. Yin and B. Albright of Los Alamos National Lab, where Mr. Luedtke learned to run a third PIC code, VPIC, which has the advantage of running efficiently in 3-d. We are preparing to add QED emission to VPIC, which will allow us to utilize our theory framework to develop a more systematic model of the QED emission and compare results across three different codes.

Publications and Conference Contributions

Refereed Journal Articles citing support of FA-9550-14-1-0045:

[Tsai15] H.E. Tsai *et al.*, “Compact tunable Compton x-ray source from laser-plasma accelerator & plasma mirror,” *Phys. Plasmas* **22**, 023106 (2015).

[Chen16] J.-W. Chen, J. Deng, H. Kohyama, and L. Labun, “Robust characteristics of nongaussian fluctuations from the NJL model,” *Phys. Rev. D* **93**, 034037 (2016).

[Lin16] C. Lin and L. Labun, “Effective field theory for broken spatial diffeomorphisms,” *J. High Energy Phys.* **1603**, 128 (2016).

- [**Sta16**] D. J. Stark, T. Toncian, and A. V. Arefiev, “Enhanced Multi-MeV Photon Emission by a Laser-Driven Electron Beam in a Self-Generated Magnetic Field,” *Phys. Rev. Lett.* 116, 185003 (2016).
- [**Ahl16**] D. v. Ahluwalia, G. Torrieri and L. Labun, “Neutrino mixing in accelerated proton decays,” *Eur. J. Phys. A* 52, 189 (2016).
- [**Tsai17**] Hai-En Tsai, A. V. Arefiev, J. M. Shaw, D. J. Stark, X. W. Wang, R. Zgadzaj, and M. C. DOWNER, “Self-aligning concave relativistic plasma mirror with adjustable focus,” *Phys. Plasmas* **24**, 013106 (2017).
- [**HegJPP17**] B. M. Hegelich, L. Labun and O. Z. Labun, “Finding quantum effects in strong classical potentials,” *J. Plasma Phys.* 83, 595830301 (2017).
- [**Chen17**] J.-W. Chen, J. Deng, H. Kohyama, and L. Labun, “Universal relations between nongaussian fluctuations in heavy-ion collisions,” *Phys. Rev. D* 95, 014038 (2017).
- [**Shaw18**] J. M. Shaw, A. C. Bernstein, R. Zgadzaj, A. Hannasch, M. LaBerge, Y. Y. Chang, K. Weichman, J. Welch, W. Henderson, H.-E. Tsai, N. Fazel, X. Wang, T. Ditmire, M. Donovan, G. Dyer, E. Gaul, J. Gordon, M. Martinez, M. Spinks, T. Toncian, C. Wagner and M. C. DOWNER, “Bright 5-85 MeV Compton gamma-ray pulses from GeV laser-plasma electron accelerator and plasma mirror,” arXiv 1705.08637.

Refereed Journal Articles in Preparation citing support of FA-9550-14-1-0045:

- [**GEPMS18**] G. Tiwari, X. Jiao, R. Kupfer, E. Gaul and B. M. Hegelich. “Multi-MeV Gamma to Electron Positron Magnetic Spectrometer”. (Preparing for *Rev. Sci. Instr.* (2018)).
- [**Lisi18**] L. Lisi, G. Tiwari, O. Z. Labun, L. Labun and B. M. Hegelich, “Low flux Multi-MeV Gamma Photon Detector based on Pixelated LYSO array”. (Preparing for *Rev. Sci. Instr.* (2018)).
- [**F1OAP18**] G. Tiwari et. al. “Greater than 10^{22} W/cm² on-target laser intensities at the Texas Petawatt Laser”, in preparation for *Optics Letters* (2018).
- [**TiwCBS18**] G. Tiwari et. al. “On the analysis of linear and nonlinear CBS photon spectrums from 2 GeV Wakefield Electrons at TPW.” (in preparation (2018)).
- [**CCMS18**] G. Tiwari et. al. “On the design of a Stigmatic Focusing High Precision Compton Spectrometer from 1 to 10 MeV.” (in preparation (2018)).
- [**Lue18**] S. V. Luedtke, L. Labun, O. Z. Labun and B. M. Hegelich, “Jet observable for photon emission in high-intensity laser experiments”, prepared for submission to *Physical Review Letters*
- [**Lab18**] L. Labun, O. Z. Labun and B. M. Hegelich, “Factorization of high-energy photon emission in high-intensity laser-plasma interactions”, prepared for submission to *Physical Review D/X*

Invited talks reporting work done under FA9550-14-1-0045:

- [**ExHiLP15**] L. Labun, “Texas Petawatt: Status and future”, *Extremely High-Intensity Laser Physics*, Max Planck Institute for Nuclear Physics, Heidelberg, Germany, 21 July 2015
- [**Camp16**] L. Labun, “Quantum effects in strong classical fields: high intensity frontier”, *Campinas State University, Campinas, Brazil*, 3 March 2016 [**BellaI16**] B. M. Hegelich, “Why does a Quantum Field Theory for Intense Laser Matter Interactions matter?”, *High Energy Density Plasma Physics with BELLA-I*, Berkeley, CA,

January 2016,

[HPLSE16] B. M. Hegelich, “Extreme Fields and Relativistic Plasmas at the Texas Center for High Energy Density Physics”, 2nd International Symposium on High Power Laser Science and Engineering, Suzhou, China, March 2016

[Fisch16] B. M. Hegelich, “Unsolved Problems in Plasma Physics: Relativistic Plasmas in Extreme Fields”, Fisch-fest, Princeton Plasma Physics Laboratory, Princeton, Mach 2016

[LLE16] B. M. Hegelich, “What to do with a 100 Petawatt laser”, Laboratory for Laser Energetics, Rochester, NY, April 2016

[ICMRE16] B. M. Hegelich, “Nonlinear Quantum Electrodynamics and other Quantum Physics with Ultrahigh Intensity Lasers”, International Conference on Matter and Radiation at Extremes, Chengdu, China, May 2016,

[CAEP16] B. M. Hegelich, “Relativistic Plasmas and Extreme Field Physics”, CAEP, Mianyang, China, May 2016.

[NUDT16] B. M. Hegelich, “Relativistic Plasmas and Extreme Field Physics”, National University of Defense Technology, Changsha, China, June 2016.

[CLEO16] Shaw, J. M., A. C. Bernstein, Y. Y. Chang, R. Zgadzaj, A. Hannasch, K. Weichmann, J. Welch, et al. “Production of Tens-of-MeV Compton Gamma-Rays from a 2 GeV Laser-Plasma Electron Accelerator.” In *Lasers and Electro-Optics (CLEO), 2016 Conference on*, 1–2. IEEE, 2016. <http://ieeexplore.ieee.org/abstract/document/7787734/>.

[Xian16] B. M. Hegelich, “High Energy Density Physics with Ultrahigh Intensity Lasers”, Xian Jiaotong University, Xian, China, May 2016

[Berk16] L. Labun, “Quantum Corrections to Laser Acceleration of Electrons,” Lawrence Berkeley National Laboratory, Berkeley, CA, 1 July 2016

[LMU16] B. M. Hegelich, “Relativistic Plasmas and High Energy Density Physics”, Ludwig-Maximilian University Munich, August 2016

[ICONO16] B. M. Hegelich, “Beyond relativistic laser matter interactions – Quantum Processes in Strong Classical Potentials”, International Conference on Nonlinear Optics”, Minsk, Belarus, September 2016

[NuclPhot16] M. C. Downer, “Generation of collimated tunable 10-75 MeV gamma rays at the Texas PW facility,” Nuclear Photonics, Monterey, CA, 16-21 October 2016.

[Chic16] L. Labun, “Quantum dynamics in high intensity electromagnetic fields,” University of Illinois, Chicago, 11 October 2016

[IBS16] B. M. Hegelich, “Vacuum birefringence, advanced imaging, cancer therapy - Science and applications of ultrahigh intensity lasers”, 2016 IBS Symposium: Frontiers in Light-Matter Interaction, Gwangju Institute of Science and Technology, Gwangju, Korea, November 2016

[Morelia17] B. M. Hegelich, “Extreme Photon Science”, Universidad Michoacana, Morelia, Mexico, February 2017

[SLAC17] B. M. Hegelich, “A new multi-beam, multi-PW Extreme Field Laser at UT Austin – Science and

Prospects”, SLAC, Stanford, CA, February 2017,

[**ICFPS17**] B. M. Hegelich, “Science and applications of extreme field Laser – matter interactions.”, 8th International Conference on the Frontiers of Plasma Science, Vina del Mar, Chile, April 2017

[**HZDR17**] M. C. Downer, “Texas tabletop source of GeV electron and tens-of-MeV Compton gamma-ray beams,” *Strahlenphysik Institute Seminar*, Helmholtz-Zentrum Dresden-Rossendorf, Germany, 08 March 2017.

[**IAOCM17**] L. Labun, “Theory and simulation of quantum processes in plasmas with strong fields,” Institute for Applied Optics and Computational Mechanics, Beijing, China, 16 March 2017

[**AST17**] L. Labun, “Effective Field Theory and Quantum Dynamics in Strong Fields,” Academia Sinica seminar, Taipei, Taiwan, 23 November 2017

[**CHILI17**] M. C. Downer, "Inverse Thomson scattered x-rays from a laser-plasma accelerator and plasma mirror," Conference on High-Intensity Laser Interactions (CHILI 2017), Tel-Aviv, 11 December 2017.

[**FUN18**] O. Zhang, “Effective Field Theory for High-intensity laser experiments”, Fudan University, Nuclear Theory group seminar, Shanghai, China, 3 January, 2018

Conference Papers reporting progress under FA9550-14-1-0045:

[**TsaiAPS15**] Hai-En Tsai, Alexey V. Arefiev, Joseph M. Shaw, David J. Stark, Xiaoming Wang, Rafal Zgad Zaj and M. C. Downer, “Self-aligning concave relativistic plasma mirror with ultrafast adjustable focus,” oral paper G07.00009, American Physical Society Division of Plasma Physics Annual Meeting, Savannah, Georgia, 17 November 2015.

[**ShawAPS15**] Joseph M. Shaw, Hai-En Tsai, Rafal Zgad Zaj, Xiaoming Wang, Vincent Chang, Neil Fazel, Watson Henderson and M. C. Downer, “Compton MeV gamma-ray source on Texas Petawatt laser-driven GeV electron accelerator,” oral paper C08.00001, American Physical Society, Division of Plasma Physics Annual Meeting, Savannah, Georgia, 16 November 2015.

[**ShawCLEO16**] J. M. Shaw, A. C. Bernstein, Y. Y. Chang, R. Zgad Zaj, A. Hannasch, K. Weichmann, J. Welch, M. LaBerge, W. Henderson, H.E. Tsai, N. Fazel, X. Wang, T. Ditmire, M. Donovan, G. Dyer, E. Gaul, J. Gordon, M. Martinez, M. Spinks, T. Toncian, M. C. Downer, “Production of tens-of-MeV Compton gamma-rays from a 2 GeV laser-plasma electron accelerator,” submitted to Conference on Lasers and Electro-Optics (CLEO 2016), San Jose, CA, 5-10 June 2016.

[**DownAAC16**] M. C. DOWNER, H. E. Tsai, D. Stark, J. M. Shaw, R. Zgad Zaj, and A. Arefiev, “Concave relativistic plasma mirrors for advanced accelerator applications,” oral presentation, Working Group 7 (Radiation Generation and Advanced Concepts), *Advanced Accelerator Concepts Workshop* (AAC 2016), National Harbor, MD, 4 August 2016.

[**ShawAAC16**] J. M. Shaw, A. C. Bernstein, A. Hannasch, M. LaBerge, Y. Y. Chang, K. W. Weichmann, J. Welch, R. Zgad Zaj, W. Henderson, H.-E. Tsai, N. Fazel, X. Wang, C. Wagner, M. Donovan, G. Dyer, E. Gaul, J. Gordon, M. Martinez, M. Spinks, T. Toncian, T. Ditmire and M. C. DOWNER, “Generation of tens-of-MeV photons by Compton backscatter from laser-plasma-accelerated GeV electrons,” *AIP Conf. Proc.* **1812**, 100012 (2017). ISBN: 978-0-7354-1480-8; <http://dx.doi.org/10.1063/1.4975910>

[**HanEAAC17**] A. Hannasch, R. Zgad Zaj, M. LaBerge, M. C. DOWNER; A. Laso-Garcia, A. Irman, M. Molodtsova, U. Schramm, O. Zarini, J. Couperus, “Inverse Thomson scattered x-rays from a laser-plasma

accelerator and plasma mirror,” European Advanced Accelerator Concepts (E-AAC) Workshop, Isola d’Elba, Italy, 19 September 2017.

S. V. Luedtke, "Comparing Particle-in-Cell QED models for High-intensity Laser-Plasma interactions", APS DPP Annual Meeting, San Jose, CA, 31 October 2016

L. Labun, "Improved theory and simulation of quantum radiation in high-intensity laser experiments," NNSA High Energy Density Summer School, UC San Diego, 7 August 2017

O. Zhang, "Effective Field Theory for Quantum Radiation in a strong electromagnetic field," NNSA High Energy Density Summer School, UC San Diego, 7 August 2017

S. V. Luedtke, "Exploring Laser-Plasma Interaction Physics with QED Particle-in-Cell Simulations", Los Alamos Student Symposium, U. New Mexico/Los Alamos, 9 August 2017

O. Zhang, Stanford Workshop on High-intensity lasers

S. V. Luedtke, "Exploring High-Intensity Laser-Plasma Interaction Physics with QED Particle-in-Cell Simulations", APS DPP, Portland, OR, 5-9 November, 2017

L. Labun, "Predicting radiation in the high-acceleration regime," 3rd LeCosPA symposium, National Taiwan University, Taipei, Taiwan, 28 November, 2017

Dissertation supported by FA9550-14-1-0045:

[TsaiPhD15] Hai-En Tsai, “Tunable quasi-monoenergetic Compton x-ray source from laser-plasma accelerator,” PhD dissertation, The University of Texas at Austin (May 2015).

[FazelPhD15] Neil Fazel, “Quasi-monoenergetic laser-plasma acceleration of electrons beyond 1 GeV at the Texas Petwatt Laser,” PhD dissertation, The University of Texas at Austin (May 2015).

[ZhangPhD16] O. Zhang, “Effective field theories for quantum chromo- and electrodynamics,” Ph.D. dissertation, University of Arizona (December, 2016).

[ShawMS18] Joseph M. Shaw, “Compton gamma-rays from a GeV laser-plasma accelerator and plasma mirror,” MS dissertation, The University of Texas at Austin (May 2018).

[Tiw18] Ganesh Tiwari, “Experimental Test of Radiation Reaction Theories with Petawatt Class Lasers”, PhD dissertation, The University of Texas at Austin (December 2018).

[LuedtkePhD19] Scott Luedtke, “The treatment of Quantum Effects in strong classical Potentials in Particle-in-Cell simulations”, PhD dissertation, The University of Texas at Austin (July 2019).

[YandowPhD20] Andrew Yandow, “Ionization Dynamics in Ultrastrong Laser Fields”, PhD dissertation, The University of Texas at Austin (July 2020).

[LisiPhD21] Luc A. Lisi, “Experimental validation of quantum effects in strong laser fields”, PhD dissertation, The University of Texas at Austin (July 2021).

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[Gaul16] E. Gaul et. al. “Improved pulse contrast on the Texas Petawatt Laser.” J. Phys.:Conf. Ser. 717, 012092

(2016).

[Stark16] D. J. Stark, T. Toncian, and A. V. Arefiev, “Enhanced Multi-MeV Photon Emission by a Laser-Driven Electron Beam in a Self-Generated Magnetic Field,” *Phys. Rev. Lett.* 116, 185003 (2016).

Hosted Talks and Colloquia

1. UT Physics Colloquium, October 2016, E. Motola, Los Alamos National Laboratory, “Dark Energy and Condensate Stars: A Massless Scalar in Low Energy Gravity”
1. UT Physics Colloquium, May 2017, T. Ma, Lawrence Livermore National Laboratory, “Creating a Star on Earth: Status of Ignition Experiments at the NIF”