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14. ABSTRACT
With an interest in designing a Thomson scattering experiment based on laser interactions with solid-density materials, we have explored the effects of prepulses on preplasma conditions and the effects of preplasma conditions on harmonic generation and absorption. We have established that the necessary contrast exists in the HERCULES laser to conduct solid density experiments with samples as tin as 20 μm. We have correlated electron acceleration from solid targets with HHG and analyzed the electron and photon spectra. We have developed new targets for solid density work using liquid targets. As a result of considering these efforts we conclude that the

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ABSTRACT

With an interest in designing a Thomson scattering experiment based on laser interactions with solid-density materials, we have explored the effects of prepulses on preplasma conditions and the effects of preplasma conditions on harmonic generation and absorption. We have established that the necessary contrast exists in the HERCULES laser to conduct solid density experiments with samples as tin as 20 μm. We have correlated electron acceleration from solid targets with HHG and analyzed the electron and photon spectra. We have developed new targets for solid density work using liquid targets. As a result of considering these efforts we conclude that the mechanism for driving electrons from solids is not presently as reliable as laser wakefield acceleration in gases and that further exploration of laser liquid interaction has the potential to provide sources of energetic ions and fission products such as neutrons. The development of strong Thomson scattering sources from solid density targets needs some other invention to make it competitive.
Finally, we have demonstrated scintillator and knock-on diagnostics for laser generated gamma rays.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
06/02/2015	4.00	Z.-H. He, B. Hou, V. Lebailly, J.A. Nees, K. Krushelnick, A.G.R. Thomas. Coherent control of plasma dynamics, Nature Communications, (05 2015): 0. doi: 10.1038/ncomms8156
06/02/2015	7.00	Z.-H. He, J.?A. Nees, B. Hou, K. Krushelnick, A.?G.?R. Thomas. Ionization-Induced Self-Compression of Tightly Focused Femtosecond Laser Pulses, Physical Review Letters, (12 2014): 0. doi: 10.1103/PhysRevLett.113.263904
06/02/2015	6.00	Tong Zhou, John Ruppe, Cheng Zhu, I-Ning Hu, John Nees, Almantas Galvanauskas. Coherent pulse stacking amplification using low-finesse Gires-Tournois interferometers, Optics Express, (03 2015): 0. doi: 10.1364/OE.23.007442
06/02/2015	5.00	Z.-H. He, B. Hou, G. Gao, V. Lebailly, J. A. Nees, R. Clarke, K. Krushelnick, A. G. R. Thomas. Coherent control of plasma dynamics by feedback-optimized wavefront manipulationa), Physics of Plasmas, (05 2015): 0. doi: 10.1063/1.4921159
08/28/2014	3.00	S. Feister, J. A. Nees, J. T. Morrison, K. D. Frische, C. Orban, E. A. Chowdhury, W. M. Roquemore. A novel femtosecond-gated, high-resolution, frequency-shifted shearing interferometry technique for probing pre-plasma expansion in ultra-intense laser experimentsa), Review of Scientific Instruments, (11 2014): 1. doi: 10.1063/1.4886955

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Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

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Received Paper

06/02/2015 8.00 Tong Zhou, John Ruppe, Cheng Zhu, I-Ning Hu, John Nees, Almantas Galvanauskas. Coherent Pulse Stacking Amplification of Nanosecond and Femtosecond Pulses,
Advanced Solid State Lasers. 16-NOV-14, Shanghai. : ,

06/02/2015 9.00 John A. Nees, Alexander Thomas, Bixue Hou, Anatoly Maksimchuk, Victor Yanovsky, Karl Krushelnick. Solid-Density Experiments for Laser-Based Thomson Scattering: Approaching the Radiation Dominated Regime,
Frontiers in Optics. 19-OCT-14, Tucson, Arizona. : ,

TOTAL: **2**

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(d) Manuscripts

Received		Paper
09/07/2011	2.00	Bixue hou, John Nees, Zhaohan He, George Petrov, Jack Davis, James Easter, Alexander Thomas, Karl Krushelnick. Laser-ion acceleration through controlled surface contamination, Physics of Plasmas (04 2011)
09/07/2011	1.00	Igor Sokolov, Natalia Naumova, John Nees. Numerical Modeling of Radiation-Dominated and QED-Strong Regimes of Laser-Plasma Interaction, Physics of Plasmas (02 2011)

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Books

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Patents Awarded

Awards

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NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John Nees	0.10	
Anatoly Maksimchuk	0.05	
Victor Yanovsky	0.05	
FTE Equivalent:	**0.20**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

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Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Zhao-Han He

Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
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Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Technical Report 2015 –Final Report

Statement of the problem studied

This program was funded to study the design of experiments for using accelerated electrons to scattering radiation in the relativistic regime. Depending on the frequency of the incident light entering into the interaction light scattered from electrons may be referred to as Thomson or Compton scattered. When the incident light carries a frequency corresponding to energies greater than the rest mass energy of the electron, light scattering is labeled Compton scattering, otherwise it is Thomson scattering. This determination is generally made in the frame of reference where the electron is initially at rest. Using the intense high-contrast HERCULES and λ^3 lasers at University of Michigan we are able to deliver light with frequencies corresponding a little more than 1 eV in the laboratory frame. However, by scattering light from electrons in strongly driven plasma, we can observe light scattered from relativistic electrons. This work concentrates primarily on scattering of light from solid density targets where electrons can be driven to MeV energies in an interaction lasting a few tens of femtoseconds.

In this type of experiment evidence of the electron dynamics is impressed on the scattered radiation through processes of absorption, and High-order Harmonic Generation (HHG). In addition, electrons and ions are accelerated away from the focal zone of incident intense laser pulses and can be measured by several means. Finally, we addressed the need for targets that can be used as a base for accelerating electrons and ions for the purpose of generating scattered radiation and other secondary emission.

Summary of the most important results

The key element of this effort is the development of an experimental framework for exploring light scattering from electrons in the relativistic domain. This effort is associated with a wide variety of experiments that are now or have been conducted in the Center for Ultrafast Optical Science. Data from these experiments is presented to show the key design considerations for the design of scattering experiments. The in those various experiments the laser characteristics play a central role. In the Section I Laser pulse contrast, pulse energy limits and pulse shortening are discussed to establish the parameters available for modern laser systems and some of the limits imposed by their design. Section II contains an account of high harmonic generation and a discussion of its role in understanding the coherent scattering of laser-driven electrons in over-critical-density plasma and the role of scale length in determining electron acceleration. Section III reviews data from absorption measurements and addresses the role of electron and preplasma behavior in exposing the interaction of the fundamental driving wave with the target. The results of focusing relativistically intense light on low Z and High Z targets is discussed in Section IV. Gamma ray production was found to arise from the collisions of electrons with the chamber rather than from interaction with the target, indicating the acceleration of electrons back toward the laser to be much more significant than into the target. Section V discusses results of an electro-positron spectrometer that can be used to measure the spectrum of gamma rays such as those that might be generated in strongly driven laser matter interactions. In section VI a new liquid target is discussed which can deliver liquid droplets on approximately single μm radius. Such minuscule targets have the potential to provide substantial numbers of particles at strongly relativistic velocities for relativistic Thomson and Compton scattering experiments. They also have the potential to drive efficient ion acceleration; a matter that has been verified by the production of heavy water d-d fusion and the production of neutrons. Finally, in section VII the tight focusing of light by a 2π mirror is discussed as a means of obtaining extremely high intensity by using dipole-like focusing.

Section I

Laser contrast and amplification limits and pulse shortening

Laser contrast is critical to nearly all experiments involving very intense laser pulse interaction with solid density target because it determines the state of the preplasma at the time when the intense pulse arrives. In high power laser systems nanosecond-duration Amplified Spontaneous Emission (ASE) light is emitted by the laser gain material toward the experimental optics. Also, prepulses may be introduced to the target if they leak through optical gates or if they are transferred from the post-pulse domain to the prepulse domain during chirped pulse amplification (CPA). Experiments targeting the acceleration of ions from thin foils were successful with SiN foils down to 20 nm thick. At 8-nm thickness the ion acceleration was reduced, suggesting the disassembly of the target due to prepulse energy. Intensity contrast on the ns timescale for the HERCULES laser system is estimated to be 10^{-15}, using cross-polarization modulation and two plasma mirrors. These parameters allow prepulse expansion to be reduced in the 100 TW range to the point where high harmonic generation is suppressed due to plasma stiffness.

In an auxiliary study on amplification in Ti:sapphire, the possibility of suppressing the effects of ASE and parasitic lasing were analyzed and a scheme of amplification during pumping was developed to enable the next generation of lasers to be operated well into the PW peak power regime.

Further development of laser plasma interaction at low pulse energies has revealed a scheme for intensifying laser pulses through ionization blueshift. In this scheme laser pulses are passed through an f/2 focus near a 100-µm nozzle that flows argon gas into a vacuum chamber. The ionization and phase re-ordering of the pulse allows the compression of 35 fs pulses to 16 fs with an increase of intensity [He]. Such post CPA compression may play a key role in providing enhanced high fields in the future.

Section II

High harmonic generation

HHG from solid target at intensities of ~10^{21} W/cm^2 was studied as a function of the plasma scale length using the extremely high contrast of the HERCULES laser system. It was determined that scale lengths of $L<\lambda/10$ are too short for relativistic HHG to be efficient while, $L>\lambda/2$ are too long. $\lambda/5$ produced clean HHG spectra that were measured up to the 52nd harmonic. Radiation between harmonics carries signatures of the electron dynamics during the HHG process.

Section III

Absorption

S- and *p*-polarized fundamental wavelength light has also been used to probe the reflectivity of targets to indicate the quality of the surface. In these experiments the absorption of the driving pulse in the target was mapped as a function of angle by simple projection onto a screen. The result is that the reflectivity is known to be nearly independent of angle in an f/1 focus and that polarization plays its usual role in determining the degree of absorption even as relativistic nonlinearity id driving HHG.

Section IV

Electron acceleration

During solid-density experiments electron spectra were collected and analyzed, yielding few MeV energies and indicating that the GeV/µm fields present in the laser focus were not converted into GeV electron beams within the range of preplasma conditions explored in our experiments. Work on optimizing interactions between lower energy pulses and water that was done in the lab of Mel Roquemore and Wright Patter AFB took advantage of an unusually large prepulse many nanoseconds before the main laser pulse to generate high x-ray flux and MeV electrons. This also employed a preplasma scale length of more than λ. Thus there appears to be some uncertainty in the changes in dynamics between the threshold of the relativistic nonlinearity and the dtrongly relativistic range accessed in the HERCULES experiments.

Section V

Gamma ray measurement schemes

Two schemes were tested for measurements of gamma rays that would be associated with highly relativistic electrons interacting with relativistic intensity light. In one test the bremsstrahlung radiation from a high-Z target excited by a few-hundred MeV electron beam was used to irradiate a pixelated BGO scintillator array. Filtering of the signal by a disc of depleted uranium indicated a small degree of discrimination among gamma ray energies. More interesting was the implementation of a knock-on spectrometer that converted gammas into knock-on electrons and positrons in a high Z target and then successfully analyzed these particles in magnetic spectrometers. These tools are needed to monitor the gammas produced in Thomson scattering experiments.

Note on numerical simulation of scattering from a wakefield accelerated electron beam

A number of theoretical calculations have studied the effect of radiation reaction forces on radiation distributions in strong field counter-propagating electron beam-laser interactions, and the question of whether these effects – including quantum corrections – could be observed in interactions with realistic electron bunches and focusing fields. We performed numerical calculations of the angularly resolved radiation spectrum from an electron bunch with parameters similar to those produced in laser wakefield acceleration experiments, interacting with an intense, ultrashort laser pulse. For our parameters, the effect of radiation damping on the angular distribution and energy distribution of photons is not easily discernible for a “realistic” moderate emittance electron beam. However, experiments using such counter-propagating beam-laser geometry should be able to measure these effects using current laser systems through measurement of the electron beam properties. In addition, the brilliance of this source is very high, with peak spectral brilliance exceeding 10^{29} photons /(s•mm^2•mrad^2•[0.1% bandwidth]) with ~2% conversion efficiency and with a peak energy of 10 MeV.

Section VI
Water target
Using a high-pressure syringe pump to drive water through a 10-μm nozzle and a piezo transducer to instill synchronization, 3 μm droplets can be controlled to below a single μm in the laser focus. We added tot his mechanism a needle to 'prick' a water droplet periodically and draw off a microdroplet 1-μm to 1.5-μm radius. Such a droplet is ideally suited to absorb a tightly focused laser pulse and to convert the energy in the pulse to energetic electrons and ions. Indeed, preliminary results with specially tailored laser pulses impinging on a heavy water column indicate that a strong d-d fusion source is produced in the focal zone.

Section VII
2π focusing
A literature search exploring means of obtaining more intense light by extremely high numerical aperture focusing has returned us to the regime where atoms emit light: the dipole emission regime. As we analyzed focusing from aperture comprising much more of the available 4π sr, we found that the effective intensity of focused light might be enhanced by as many as 10 to 30 times that obtained in focusing HERCULES to $>10^{22}$ W/cm^2 [Yanovsky]. With 2π sr focusing the numerical aperture of the optic is one order of magnitude greater than that reported in that publication. In addition, advancing to more nearly 4π sr focusing and single cycle pulses could render another factor of 3. To this end we obtained a 2π mirror and have begun characterization and focusing experiments.

Conclusion
With an interest in designing a Thomson scattering experiment based on laser interactions with solid-density materials, we have explored the effects of prepulses on preplasma conditions and the effects of preplasma conditions on harmonic generation and absorption. We have established that the necessary contrast exists in the HERCULES laser to conduct solid density experiments with samples as tin as 20 μm. We have correlated electron acceleration from solid targets with HHG and analyzed the electron and photon spectra. We have developed new targets for solid density work using liquid targets. As a result of considering these efforts we conclude that the mechanism for driving electrons from solids is not presently as reliable as laser wakefield acceleration in gases and that further exploration of laser liquid interaction has the potential to provide sources of energetic ions and fission products such as neutrons. The development of strong Thomson scattering sources from solid density targets needs some other invention to make it competitive.
Finally, we have demonstrated scintillator and knock-on diagnostics for laser generated gamma rays.

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