REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE:	3. REPORT TYPE AND DATES COVERED Final Report 18-Aug-2003 - 17-Feb-2007

4. TITLE AND SUBTITLE
Development of an electron-positron source for positron annihilation lifetime spectroscopy

5. FUNDING NUMBERS
DAAD19-03-1-0287

6. AUTHORS
John A. Nees

8. PERFORMING ORGANIZATION REPORT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Michigan - Ann Arbor
Office of Sponsored Programs
Room 1058 Wolverine Tower
Ann Arbor, MI 48109 -1274

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
44917-PH.1

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)
The abstract is below since many authors do not follow the 200 word limit

14. SUBJECT TERMS
Relativistic, plasma, electron, kinetics, femtosecond, attosecond

15. NUMBER OF PAGES
Unknown due to possible attachments

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Report Title

Development of an electron-positron source for positron annihilation lifetime spectroscopy
Final Report

ABSTRACT

Laser intensities capable driving relativistic phenomena are delivered in a single-wavelength spot size on solid targets producing energetic electrons for positron production. This program has accomplished the production of >1 MeV electron energies with laser pulse energy of ~ 1mJ at 500Hz repetition rate. The properties of the laser, diagnostics and the energetic electron emission are discussed. Application of the laser-produced plasma phenomena to positron generation is discussed and future directions are briefly stated.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

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

1) "Distinctive physical effects and applications approaching the relativistic lambda-cubed regime," J. Nees, Bixue Hou, B. Bowes, N. Naumova, A. Mordovanakis, E. Power, M. Downer, and G. Mourou, J. Sel. Topics in Quant. Electronics, 12, 2, 223 (2006).
2) "Relativistic generation of isolated attosecond pulses: a different route to extreme intensity," J. Nees, N. Naumova, E. Power, V. Yanovsky, I. Sokolov, A. Maksimchuk, S. Bahk, V. Chvykov, G. Kalintchenko, B. Hou, and G. Mourou, J. Mod. Optics 52, 305 (2005).
3) "Attosecond electron bunches," N. M. Naumova, , I. V. Sokolov, J. A. Nees, A. Maksimchuk, V. Yanovsky and G. A. Mourou, Phys. Rev. Lett. 93, 195003 (2004).
4) "Hard x-ray generation from solids driven by relativistic intensity in the lambda-cubed regime," Bixue Hou, J. Nees, W. Theobald, G. A. Mourou, L-M Chen, J-C Kieffer, A. Krol, C. C. Chamberlain, Appl. Phys. B, 83, 81-85(2006).
5) "Dependence of hard x-ray yield on laser pulse parameters in the ?3 regime," B. Hou, J. Nees, W. Theobald, G. A. Mourou, L-M Chen, J-C Kieffer, A. Krol, C. C. Chamberlain, Appl. Phys. Lett. 84, 13 2259-61,(29 March 2004).
6) "Carrier-envelope phase stabilization of high-contrast femtosecond laser pulses with a relativistic intensity," Kyung-Han Hong, Jongmin Lee, Bixue Hou, John A. Nees, Erik Power, and Gerard A. Mourou, Appl. Phys. Lett., 89 (3): Art. No. 031113, JUL 17 2006.
7) "Femtosecond microscopy of radial energy transport in a micro-scale aluminum plasma excited at relativistic intensity," B. T. Bowes, H. Langhoff, M. C. Downer, M. Wilcox, B. Hou, J. Nees, and G. Mourou, Optics letters, Vol. 31 (2006), No. 1, pp116-118.
8) "Spatial coherence properties of a compact and ultrafast laser-produced plasma keV x-ray source," D. Boschetto, G. Mourou, A. Rousse, A. Mordovanakis, Bixue Hou, J. Nees, D. Kumah and R. Clarke, Appl. Phys. Lett., 90 (3): Art. No. 011106, 2007.
9) "Relativistic Attosecond Physics", N. M. Naumova, J. A. Nees, and G. A. Mourou
Physics of Plasmas 12, 056707 (2005).
10) "Isolated Attosecond Pulse Generation in the Relativistic ?3 Regime by Reflection/Deflection/Compression," G. A. Mourou, N. M. Naumova, I. V. Sokolov, B. Hou, and J. A. Nees Ultrafast Optics IV Vol. 95 of Springer Series in Optical Sciences, F. Krausz, G. Korn, P. Corkum, and I. A. Walmsley, eds. (Springer-Verlag, Berlin, 2004), p.303.
11) "Relativistic Generation of Isolated Attosecond Pulses in a ?3 Focal Volume,"
N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou
Phys. Rev. Lett. 92, 063902 (2004).
12) "Isolated attosecond pulses generated by relativistic effects in a wavelength-cubed focal volume," N. M. Naumova, J. A. Nees, B. Hou, G. A. Mourou, and I. V. Sokolov
Opt. Lett. 29, 778 (2004).

Number of Papers published in peer-reviewed journals: 12.00

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

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

"Experimental observations of the relativistic deflection of light,"
Power, E.P.; Nees, J.A.; Naumova, N.M.; Hong, K.-H.; Matsuoka, T.; Yanovsky, V.P.; Hou, B.; Mourou, G.A.; Sokolov, I.V.;Quantum Electronics and Laser Science Conference, 2005. QELS '05, Volume 3, 22-27 May 2005 Page(s):1509 - 1511 vol. 3.

"Attosecond optoelectronics in the relativistic /spl lambda//sup 3/ regime,"
Naumova, N.M.; Nees, J.A.; Mourou, G.A.; Quantum Electronics and Laser Science Conference, 2005. QELS '05, Volume 3, 22-27 May 2005 Page(s):1506 - 1508 vol. 3.

"Relativistic optics in the lambda-cubed regime and applications to attosecond physics,"
Mourou, G.A.; Naumova, N.M.; Power, E.P.; Yanovsky, V.; Nees, J.A.; Conference on Lasers and Electro-Optics Europe, 2005. CLEO/Europe. 2005, 12-17 June 2005 Page(s):691 - 691.

"Chirped-pulse cascaded quadratic compression of millijoule-energy, 35-fs pulses,"
Moses, J.A.; Wise, F.W.; Vuong, L.; Grow, T.; Gaeta, A.; Nees, J.; Hong, K.-H.; Hou, B.; Mourou, G.; Conference on Lasers and Electro-Optics, 2005. (CLEO).
Volume 2, 22-27 May 2005 Page(s):962 - 964 Vol. 2.

"Fiber laser driven EUV generation," Yu-Chung Chang; Mordovanakis, A.; Kai-Chung Hou; Nees, J.; Hou, B.; Maksimchuk, A.; Mourou, G.; Galvanauskas, A.;, Conference on Lasers and Electro-Optics, 2005. (CLEO). Volume 3, 22-27 May 2005 Page(s):2200 - 2202 Vol. 3.

"Relativistic kHz chirped-pulse amplified laser with >10/sup 8/ intensity contrast ratio and carrier-envelope phase stabilization," Hong, K.-H.; Hou, B.; Nees, J.A.; Power, E.; Mourou, G.A.; Quantum Electronics and Laser Science, 2005 Conference
Volume 3, 22-27 May 2005 Page(s):2006 - 2008 vol. 3.

"The measurement of sub-Brownian lever deflections," Hammig, M.D.; Wehe, D.K.; Nees, J.A.; Nuclear Science Symposium Conference Record, 2004 IEEE, Volume 2, 16-22 Oct. 2004 Page(s):707 - 711 Vol. 2.

"Enhancement of high-harmonic soft X-rays by adaptive wave-front control with genetic algorithm," Yoshitomi, D.; Miyamoto, N.; Kanai, T.; Sekikawa, T.; Watanabe, S.; Nees, J.; Mourou, G.; Conference on Lasers and Electro-Optics, 2003. CLEO '03.
1-6 June 2003 Page(s):2 pp.

"Efficient generation of isolated attosecond pulses through relativistic effects," Power, E.; Naumova, N.; Nees, J.; Hou, B.; Bahk, S-W.; Vanovsky, V.; Maksimchuk, A.; Mourou, G.; Sokolov, I.; Quantum Electronics Conference, 2004. (IQEC). International
2004 Page(s):966 - 967.

"Relativistic electron acceleration in the wavelength-cubed regime," Mordovanaki, A.G.; Nelson, N.; Hou, B.; Nees, J.; Naumova, N.M.; Mourou, G.; (CLEO). Conference on Lasers and Electro-Optics, 2004. Volume 1, 2004 Page(s):2 pp. vol.1.

"Efficient generation of isolated attosecond pulses through relativistic effects," Power, E.; Naumova, N.; Nees, J.; Hou, B.; Bahk, S.-W.; Yanovsky, V.; Maksimchuk, A.; Mourou, G.; Sokolov, I.; Lasers and Electro-Optics, 2004. (CLEO). Conference on Volume 1, 2004 Page(s):2 pp. vol.1.

"Development of novel ultrafast-laser-based micro-CT system for small-animal imaging,"
Krol, A.; Kieffer, J.-C.; Nees, J.A.; Liming Chen; Toth, R.; Bixhue Hou; Kincaid, R.E.; Coman, I.L.; Chamberlain, C.C.; Lipson, E.D.; Mourou, G.A.; Nuclear Science Symposium Conference Record, 2003 IEEE, Volume 3, 19-25 Oct. 2003 Page(s):1993 - 1996 Vol.3.

"Polarization and power scaling of harmonics from solid and targets in the /spl lambda//sup 3/-regime," Wilcox, M.; Nees, J.; Hou, B.; Theobald, W.; Mourou, G.; Quantum Electronics and Laser Science, 2003. QELS. Postconference Digest, 1-6 June 2003 Page(s):2 pp.

"Laser-matter interaction in the "relativistic 3" regime,"Bixue Hou; Nees, J.A.; Wilcox, M.I.; Mourou, G.A.; Conference on Lasers and Electro-Optics, 2003. CLEO '03, 1-6 June 2003 Page(s):381 - 382.

"Relativistic /spl lambda/' regime: from relativistic electrons to relativistic ion,"Naumova, N.; Mourou, G.; Nees, J.; Yanovsky, V.; Conference onLasers and Electro-Optics, 2003. CLEO '03, 1-6 June 2003 Page(s):1036 - 1038 .

"Relativistic Microelectronics'" J. Nees, Bixue Hou, A. Mordovanakis, G. Mourou, International Conference on Ultrahigh Intensity Lasers

Tahoe City CA October 3-7, 2004.

"Attosecond phenomena in the relativistic lambda cubed regime," N. Naumova, J. Nees, JG. Mourou, International Conference on Coherent and Nonlinear Optics, St. Petersburg, Russia, May 11-15, 2005.

"Efficient Attosecond Phenomena Arising in the Relativistic Lambda Cubd Regime," J. Nees, International Conference on Multiphoton Processes 9-14 October 2005.

Number of Presentations: 18.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
James Easter	0.10
Erik Power	0.30
Aghapi Mordovanakis	0.10
FTE Equivalent:	**0.50**
Total Number:	**3**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John Nees	0.05	No
FTE Equivalent:	**0.05**	
Total Number:	**1**	

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: ......

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

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ......

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......

Names of Personnel receiving masters degrees

NAME

James Easter

Erik Power

Aghapi Mordovanakis

Total Number: 3

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME PERCENT_SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Development of an Electron-Positron Source for Position Annihilation Lifetime Spectroscopy

DAAD19-03-1-0287

Final Report
2/17/2007

Submitted to Richard Hammond
US Army research Office
May 2007

Principal Investigator
John A. Nees

Center for Ultrafast Optical Science
EECS Department, University of Michigan
2200 Bonisteel Blvd, Ann Arbor, MI 48109-2099
(734) 764-9271

Table of contents

Summary	**3**
Statement of the problem studied	**3**
Summary of the important results	**3**
Publications	**9**
Participating personnel	**11**
Report of inventions	**12**

Summary
Laser intensities capable driving relativistic phenomena are delivered in a single-wavelength spot size on solid targets producing energetic electrons for positron production. This program has accomplished the production of >1 MeV electron energies with laser pulse energy of ~ 1mJ at 500Hz repetition rate. The properties of the laser, diagnostics and the energetic electron emission are discussed. Application of the laser-produced plasma phenomena to positron generation is discussed and future directions are briefly stated.

Statement of the Problem
Among the many material systems needed to reduce power consumption and to increase the clock rate of modern microprocessor are low dielectric constant materials such as porous silicon. A key means of measuring the properties of porous materials incorporates positron annihilation lifetime spectroscopy. Presently this technique utilizes radioactive ^{22}Na as a source of positrons. This program is developing the science of relativistically driven microscopic plasmas as possible alternatives to radioactive material in such applications.
The problem addressed in this work is how to control the irradiation of target materials to produce the desired MeV particle energy levels and how to identify optimal schemes for converting these energetic particles to useful diagnostics.

Summary of important results
Progress in ultrafast laser science has opened the way for studies of high-filed science at a variety of levels. Beginning with nonlinear optics utilizing electrons bound by eV-scale potentials in optical materials and progressing to the acceleration of electrons to the GeV range, the study of physics related to short pulse lasers has produced a wealth of knowledge and practical applications.
In this work we have directed our efforts to developing a laser driven positron source based on the excitation of a microscopic plasma volume with light focused to relativistic intensity. In the following report we discuss our accomplishments toward this goal. The report is divided into sections dealing with:

1) The Relativistic λ^3 concept and its relation to efficient pulse use.
2) Elements related to the physics of laser plasma interaction.
3) Significant improvement in the laser's ability to interact with a solid-density material.
4) X-rays and g-rays as probes of electron activity.
5) Electron spectroscopy.
6) Femtosecond microscopy of plasma evolution.

1) The Relativistic λ^3 concept
Concentrating light to its optimal intensity requires management of both temporal and spatial aspects of light pulses. Both are subject to the Maxwell Equations and when interacting with matter, the relativistic equations of motion. Nevertheless, in a simple view the temporal and spatial behavior of a light pulse can be treated independently using scalar wave theory. This view is sufficient to enable the understanding, from Fourier analysis, that a broad optical bandwidth is necessary to form a short pulse, and a broad range of spatial frequencies (i.e. a high numerical aperture) is needed to form a small focal spot.
Thus, it is clear that the intensity, I, in the focus of a short pulse is the pulse energy, E, divided by the pulse duration, τ, and the focal area, A. It also follows that, for a given central wavelength, λ, the minimal pulse duration is near $\tau = \lambda / c$, and the minimal focal area is near $A = \lambda^2$. Hence, for a given pulse energy, the maximal focal intensity is approximated by $I \approx Ec / \lambda^3$. At the moment when a pulse meeting the above condition passes through focus its isointensity contour takes on an ellipsoidal shape enclosing a λ^3 volume.

The term 'relativistic' is applied to an optical field when it is capable of producing free electron velocities, v_{osc}, approaching the speed of light, c. In the case of a plane wave interacting with an electron the quiver motion is approximated in the form:

$$\left(\frac{\gamma v_{osc}}{c}\right)^2 = \frac{p_{osc}}{m_e c} = \frac{I\lambda_\mu^2}{1.3\times10^{18}}. \qquad (1)$$

Here, γ is the relativistic factor, $\sqrt{1+p_{osc}^2}$, m_e is the electron rest mass, c is the speed of light in vacuum, p_{osc} is the quiver momentum, I is in units of W/cm^2, and λ_μ is the wavelength of the driving light in microns. The threshold of relativistic intensity for 0.8μm light is where $I\lambda^2 = 1.3\times10^{18}\,W/cm^2$, or $I = 2\times10^{18}\,W/cm^2$. Here we note the ubiquitous scaling factor, $I\lambda^2$ which can be found throughout the physics of light-plasma interactions, can be considered in the λ^3 regime as $I\lambda^2 \xrightarrow{I\to Ec/\lambda^3} Ec/\lambda$, taking into account that the pulse duration and focal area are wavelength dependent. In the true limit of a single cycle pulse with a single wavelength focus this condition can be met with a pulse-energy of only 34μJ! In a single cycle pulse is not yet available at near optical frequencies. But, with pulses of about 10 cycles focused to 0.8mm intensities of $10^{22}\,W/cm^2$ have been obtained.

In our research we have emphasized a laser platform that can be found in more than one hundred labs worldwide, the milijoule-level Ti:sapphire laser. With its 30fs pulse duration and few milijoule energy level we focus pulses to approximately $5\times10^{18}\,W/cm^2$.

2) Laser plasma interaction

With the short focal zone (or Rayliegh range) of tightly focused light one may expect interactions to be determined over only a few cycles of propagation. It is therefore expected that the most efficient interactions will be found in materials producing a plasma density near or above the critcal density, $n_c = \omega^2 m_e / 4\pi e^2$, where w is the radial frequency of the light, m_e is the electron mass and e, its charge. The reaction strength of the plasma at such densities limits the interaction to a volume not much exceeding the λ^3 volume of the pulse at focus. Because of the effects of relativistic motion of electrons in the plasma a relativistic critical density may be used for higher intensities where $n_{cr} = \gamma n_c$. Indeed, we found by simulation that material densities ranging from ½n_{cr} to roughly 4n_{cr} to be most effective for interaction in the λ^3 regime.

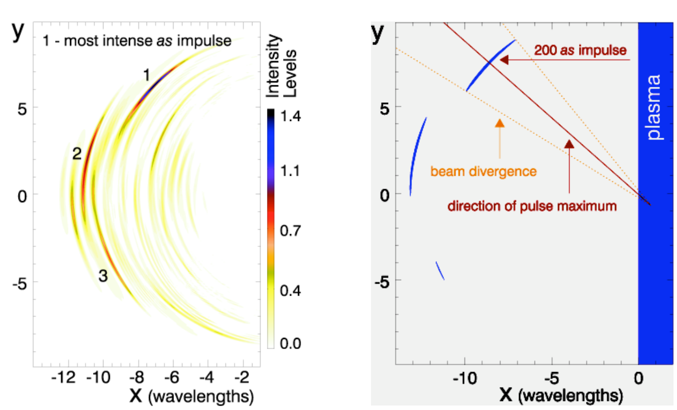

Fig. 1 Attosecond pulse formation by reflection with deflection and compression. Portion I contains 10% of the incident pulse energy within its isointensity contour.

In conjunction with work sponsored by NSF two main effects were found in the relativistic λ^3 regime that were notable with respect to the generation of electrons of sufficient energy to produce electron positron pars: the efficient formation of isolated attosecond pulses; and the generation of attosecond electron bunches. In reflection from a plasma having a layer of density ~n_{cr}, Particle In Cell (PIC) simulations indicate that attosecond pulses can be formed with efficiency of the order of 10%

with respect to the main pulse energy, shown as item 1 in Fig. 1. The mechanism for the pulse formation is understood to be reflection with concurrent deflection into new directions and compression from relativistic effects. The process is efficient and indicative of the relativistic motion of the electrons near the plasma vacuum boundary. The second discovery made in this line of investigation was the possibility of forming attosecond electron bunches with energies well into the MeV range, though this scheme involves substantially higher intensity. Under a more restrictive set of conditions, most notably at high incidence angles, electrons undergo a reactive effect in the bulk of a plasma with the resurgent electrons jetting into vacuum to be collected by the propagation electromagnetic structure and accelerated to 10s of MeV over a distance of only several wavelengths. As seen in Fig. 2 the mechanism for electron ejection, together with the potential structure of the fields, preserves a very short bunching length and a small phase-space volume for the accelerated electrons, making a favorable source for applications based on energetic electrons.

The efficiency of both of these processes and the coherent behavior of the electrons in the simulations provides evidence that the λ^3 regime can be used to generate energetic electrons and thereby, positrons. This is a framework for micron scale *relativistic optoelectronics*.

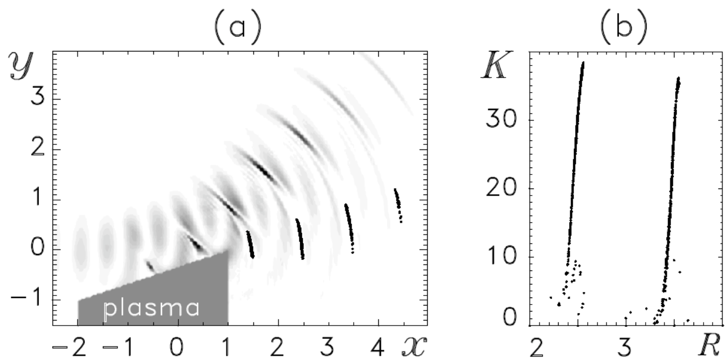

Fig. 2 Attosecond electron bunches (25-40MeV shown separating near the horizontal) formed at high angles of incidence (left), and their spatial energy distribution in MeV (right). Incident pulse entering from left has initial normalized amplitude of $a_0 = 10$ and a single wavelength focal spot.

3) Laser improvements needed to conduct experiments on efficient processes in micro-plasmas

As mentioned in the previous section, the use of efficient processes at n_{cr} is important. Consequently, it is necessary to accurately control the expansion of the target material as it is ionized and driven by the laser. However, the pulses from typical milijoule laser systems are littered with energy that arrives before the main femtosecond pulse. It is not uncommon to have femtosecond-duration prepulses or nanosecond duration Amplified Spontaneous Emission (ASE) incident on targets with sufficient fluence to produce plasma well before the main laser pulse. If such a plasma expands beyond the scale-length require in our micro-plasma source, it will distort the incoming laser beam before it can efficiently interact at the relativistic critical density. To control these prepulse effects we converted our laser to operation at a level of 4mJ and 32 fs with a prepulse ASE contrast (as shown in Fig. 3) on the order of $\sim 10^{-11}$ and with no measurable prepulse inside of a 4 ns window (This was actually achieved in by two laser modifications: the addition of a saturable absorber in the amplifier chain, to $\sim 10^{-9}$, then by reconfiguration of the power amplifier, to $\sim 10^{-11}$). In conjunction with the deformable mirror that we have used for the duration of this work the temporal pulse contrast ensures that the energy we use in these experiments not only arrives at a 'clean' target, but that the pulse energy is properly contained within the dimensions of the experiment. Thus we minimize collateral sources of noise and background signal. In addition we have applied modern carrier-envelope phase locking techniques to control the pulse from the laser system so that access to the attosecond domain is not hampered by a lack of correlation between the electric field phase and its envelope when we few cycle pulses as described in the previous section.

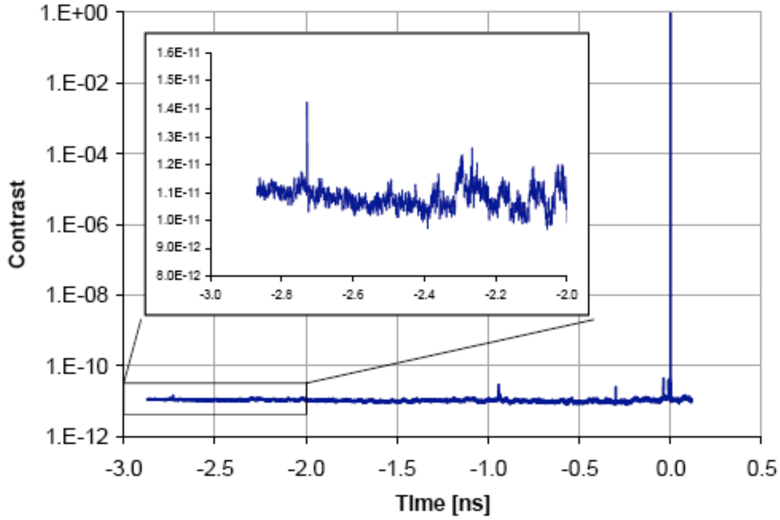

Fig. 3 ASE contrast measurement made by third-order correlation. All of the short-pulse spikes seen in the near time scan are accounted for as correlator artifacts generated by the third-order correlator directly of by artificial conversion of real post pulses.

4) X-rays and γ-rays as probes of electron activity

The activity of electrons in a high-density target produces a few measurable effects that convey both qualitative and quantitative information about their energy distribution. In this section a brief summary is given of the instrumentation used to interrogate the electron activity, the measurements we made and the significance of the results.

We may distinguish the x-ray regime from the γ-ray regime by drawing a dividing line at 1 MeV. This is also near the threshold energy for pair production from γ-rays. In material laden with nuclei electrons undergo many collisions and produce bremsstrahlung radiation. The distribution of this radiation may be used as a measure of the electron energy distribution, particularly if the radiation exhibits an exponential distribution in energy, i.e. the spectral power density is an exponential function of the photon energy. The radiation from a laser excited plasma being measured with such a distribution is then presumed to be generated by thermalized electrons with a characteristic temperature according to the functional form $N \approx N_0 e^{-E/k_B T_e}$, where N is the number of electrons per energy slice, N_0 is some reference number of electrons at a specific energy, E is the electron energy, k_B is the Boltzmann constant, and T is an effective electron temperature. The true electron distribution does not exactly follow the x-ray distribution due to re-absorption and other minor factors, but the effective temperature assigned by this means is an adequate gauge of the electron activity for use in comparing experiments done in vastly different environments.

We use targets of various types with high contrast laser pulses to generate x-rays and to determine effective electron temperatures. With statistics accumulated from more than half a million shots on a solid Mo target we scale the effective electron temperature and determined its pulse-energy and pulse-duration dependencies. Analysis of voltages produced by an amplified CdTe x-ray detector when exposed to single x-ray photons from the source yields spectral measurements. Temperature scaling with pulse energy was found to follow a $T \propto E^{0.5}$ dependence, and with pulse duration, $T \propto e^{-\tau/0.95}$. For Mo irradiated with 22 fs pulses and 1 mJ energy the temperature was roughly 20 keV. These results for 45° angle of incidence indicate that the vast portion of the Bremmstrahlung generated is coming from thermalized electrons and that the temperatures to be expected in those electrons is far below the MeV level. There is, however a class of electrons that is not expected to generate x-rays within the target plasma: these electrons escape the plasma and may be accelerated by the reflecting laser pulse as indicated in the PIC simulations. Spatial characteristics of the source are alsop determined by analysis of knife-edge diffraction of the generated x-rays.

5) Electron spectroscopy
Detection of electrons that have escaped the target is performed using a permanent-magnet-based electron spectrometer with a sub-millimeter entrance aperture. Spectrometer design details and calibration are given in the year one report. Unlike the x-ray measurement, this spectrometer directly measures the electron distribution in a smal solid angle. In addition to spectra taken at discrete viewing angles, image plates calibrated for electron exposure are used to determine some aspects of electron spatio-spectral distribution. The spectrometer provides absolute electron numbers for electrons passing its aperture while image plates detecting electrons through filters provide a degree of spectral information.
Exciting the plasma at a 65° angle of incidence (+/-20° full angle) with *p*-polarized light, as indicated by the PIC simulation, and collecting spectra along the central angle of the specular reflection a spectrum of electrons can be detected with a 250keV temperature, however, a second distribution can also be seen emerging at 1MeV with a temperature of 550keV.

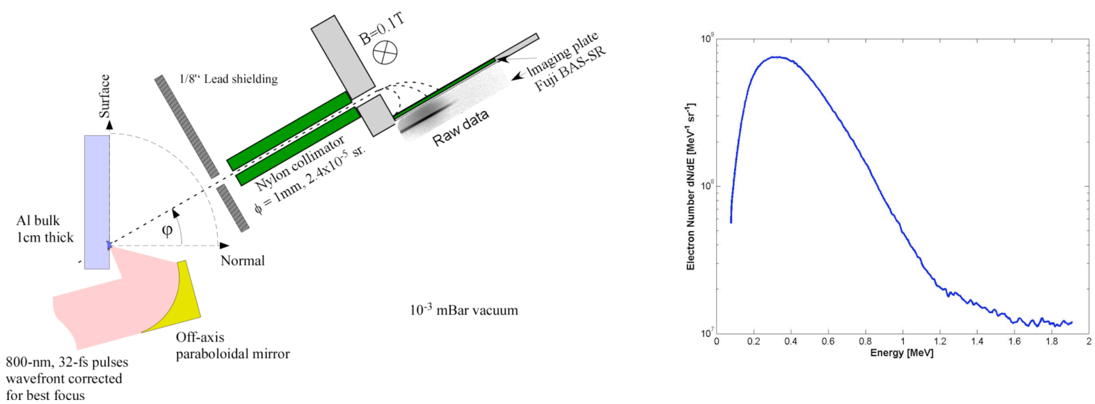

Fig. 4 Schematic of the apparatus for acquiring electron spectra at the central specular angle (diagram on the left) with electron spectrum (shown on the right). The location of image plates for spatial resolution is also indicated by the arc in the left-hand figure.

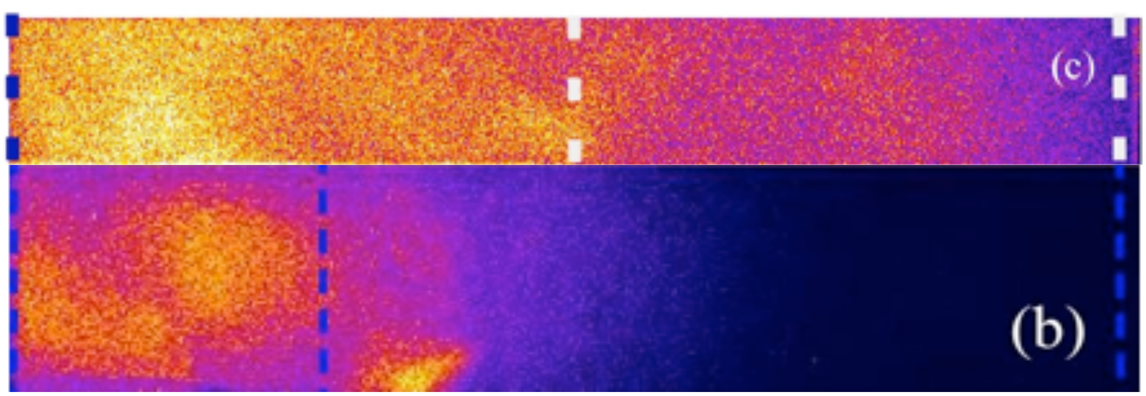

Fig. **5** Image plate readouts taken at the location indicated in Fig. 4 filtered a) by a 50μm Cu foil and one image plate with a 45° central incidence angle and b) by a 25 μm Al filter and on image plate with a 65° central incidence angle. Electrons above 300 keV are indicated with unmatched color scales.

Preliminary analysis of absolute electron numbers is obtained by integrating the exposure of image plates directly exposed to the electron flux in front of the target. Two such exposures were taken over angles from target normal (left-hand dashed marker) to the target surface direction in the plane of incidence and in the quadrant opposite to the incoming laser pulse (right-hand dashed marker). In these images the central specular angle is represented by a dashed maker at 45° in the top image, and at 65° in the lower image. These exposures represent electrons that have penetrated a 25 or 50 micron thick metallic filter and another image plate place in contact with the image plate. These filters limit the exposure to electrons exceeding 300keV and provide both minimal number densities and beam formation characteristics. Plate (b) shows the effect of high angle of incidence in the formation of three beamlet structures for high-energy electrons. These beamlets represent $3\times10^{6}\, e^{-}/shot$ or $1.5\times10^{9}\, e^{-}/s$. Based on the spectrum found at the specular angle we may expect that one electron in 60 is at an energy greater than 1 MeV and that we have $\sim 2.5\times10^{7}\, e^{-}/s$ with $\gamma>3$. Based on estimates for positron production from $\gamma=3$ electrons we would not expect to see positrons in a measurable quantity in these experiments. However, with a modest increase in electron energy such that the relativistic factor becomes 5 or higher we should begin to have conversion on the order of 10^{-3}, giving both more electrons and a clearly measurable yield of positrons in a converter material.

6) Femtosecond microscopy (a related project carried out with Prof. Micheal Downer at University of Texas, Austin—funded by NSF Frontiers of Physics Center, FOCUS)

The activity of the plasma discussed so far has been modeled by PIC simulation and it x-rays and emitted electrons probed externally. But, to experimentally determine the activity of the plasma it is necessary to probe it with temporal and spatial resolution. This work is being carried out in the relativistic λ^3 lab at The University of Michigan under the Frontiers of Physics Center, FOCUS, under the direction of Michael Downer. The chief result is related to here to emphasize both the very small dimension of the source and the rate at which it develops from a clean target to a source of x-rays and energetic electrons.

In this work a pump-probe experiment is configured to acquire the reflectivity of a metallic target, with submicron resolution, the time frame surrounding the incident laser pulse energy. The probe wavelength is the second harmonic of the pump wavelength so that it may be more readily distinguished and to enable better spatial resolution. At times shortly after the irradiation of the target, the pump light is lost due to resonance absorption. This effect subsequently expands in the radial direction owing to the transport of energy outward from the irradiated region of the target. By considering models of energy transport involving the diffusion energy by electron-electron collisions and by radiative energy diffusion in the plasma, solely diffusive means of energy transport can be eliminated, leaving ballistic transport by electrons as the primary candidate for energy transport. This finding has a bearing on the scheme used to generate positrons in that the localization of the more energetic electrons within the plasma, at the plama-vacuum boundary, or external to the plasma will determine both the choice of target material for positron generation and the need for an external positron converter.

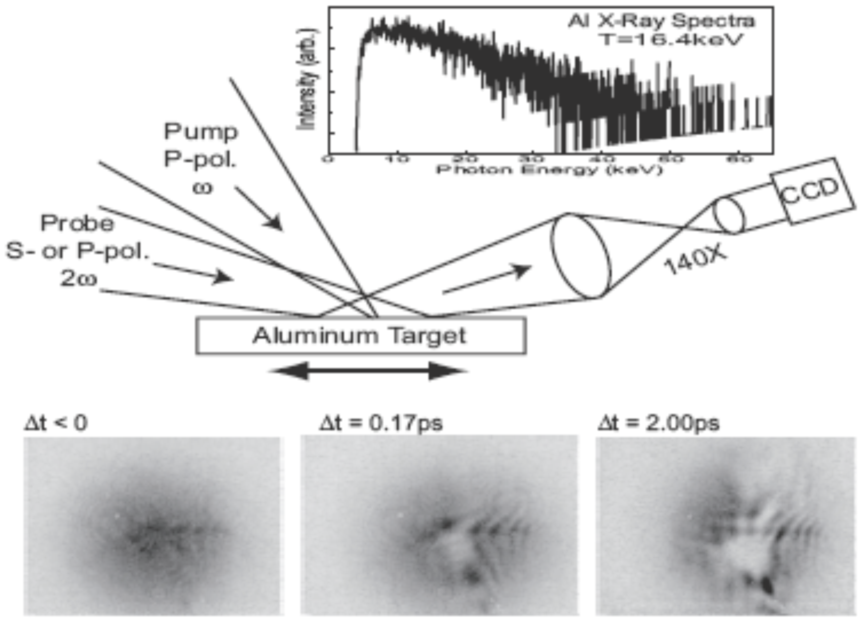

Fig. 6 Time resolved optical micrographs of plasma reflectivity at indicated delays following target irradiation. *P*-polarization reflected signal is shown with an inverted greyscale. Each frame is 20 μm wide and is shown with its original aspect ratio.

References

1) "Distinctive physical effects and applications approaching the relativistic lambda-cubed regime," J. Nees, Bixue Hou, B. Bowes, N. Naumova, A. Mordovanakis, E. Power, M. Downer, and G. Mourou, *J. Sel. Topics in Quant. Electronics*, **12**, 2, 223 (2006).
2) "Relativistic generation of isolated attosecond pulses: a different route to extreme intensity," J. Nees, N. Naumova, E. Power, V. Yanovsky, I. Sokolov, A. Maksimchuk, S. Bahk, V. Chvykov, G. Kalintchenko, B. Hou, and G. Mourou, *J. Mod. Optics* **52**, 305 (2005).
3) "Attosecond electron bunches," N. M. Naumova, , I. V. Sokolov, J. A. Nees, A. Maksimchuk, V. Yanovsky and G. A. Mourou, *Phys. Rev. Lett.* **93**, 195003 (2004).
4) "Hard x-ray generation from solids driven by relativistic intensity in the lambda-cubed regime," Bixue Hou, J. Nees, W. Theobald, G. A. Mourou, L-M Chen, J-C Kieffer, A. Krol, C. C. Chamberlain*, Appl. Phys. B*, **83**, 81-85(2006).
5) "Dependence of hard x-ray yield on laser pulse parameters in the λ^3 regime," B. Hou, J. Nees, W. Theobald, G. A. Mourou, L-M Chen, J-C Kieffer, A. Krol, C. C. Chamberlain, *Appl. Phys. Lett*. **84**, 13 2259-61,(29 March 2004).
6) "Carrier-envelope phase stabilization of high-contrast femtosecond laser pulses with a relativistic intensity," Kyung-Han Hong, Jongmin Lee, Bixue Hou**,** John A. Nees, Erik Power, and Gerard A. Mourou, *Appl. Phys. Lett*., **89** (3): Art. No. 031113, JUL 17 2006.

7) “Femtosecond microscopy of radial energy transport in a micro-scale aluminum plasma excited at relativistic intensity,” B. T. Bowes, H. Langhoff, M. C. Downer, M. Wilcox, B. Hou, J. Nees, and G. Mourou, *Optics letters*, Vol. **31** (2006), No. 1, pp116-118.
8) “Spatial coherence properties of a compact and ultrafast laser-produced plasma keV x-ray source,” D. Boschetto, G. Mourou, A. Rousse, A. Mordovanakis, Bixue Hou, J. Nees, D. Kumah and R. Clarke, Appl. Phys. Lett., **90** (3): Art. No. 011106, 2007.

Conference presentations

1) "Experimental observations of the relativistic deflection of light," Power, E.P.; Nees, J.A.; Naumova, N.M.; Hong, K.-H.; Matsuoka, T.; Yanovsky, V.P.; Hou, B.; Mourou, G.A.; Sokolov, I.V.;Quantum Electronics and Laser Science Conference, 2005. QELS '05, Volume 3, 22-27 May 2005 Page(s):1509 - 1511 vol. 3.
2) "Attosecond optoelectronics in the relativistic /spl lambda//sup 3/ regime," Naumova, N.M.; Nees, J.A.; Mourou, G.A.; Quantum Electronics and Laser Science Conference, 2005. QELS '05, Volume 3, 22-27 May 2005 Page(s):1506 - 1508 vol. 3.
3) "Relativistic optics in the lambda-cubed regime and applications to attosecond physics," Mourou, G.A.; Naumova, N.M.; Power, E.P.; Yanovsky, V.; Nees, J.A.; Conference on Lasers and Electro-Optics Europe, 2005. CLEO/Europe. 2005, 12-17 June 2005 Page(s):691 - 691.
4) "Chirped-pulse cascaded quadratic compression of millijoule-energy, 35-fs pulses," Moses, J.A.; Wise, F.W.; Vuong, L.; Grow, T.; Gaeta, A.; Nees, J.; Hong, K.-H.; Hou, B.; Mourou, G.; Conference on Lasers and Electro-Optics, 2005. (CLEO). Volume 2, 22-27 May 2005 Page(s):962 - 964 Vol. 2.
5) "Fiber laser driven EUV generation," Yu-Chung Chang; Mordovanakis, A.; Kai-Chung Hou; Nees, J.; Hou, B.; Maksimchuk, A.; Mourou, G.; Galvanauskas, A.;, Conference on Lasers and Electro-Optics, 2005. (CLEO). Volume 3, 22-27 May 2005 Page(s):2200 - 2202 Vol. 3.
6) "Relativistic kHz chirped-pulse amplified laser with >10/sup 8/ intensity contrast ratio and carrier-envelope phase stabilization," Hong, K.-H.; Hou, B.; Nees, J.A.; Power, E.; Mourou, G.A.; Quantum Electronics and Laser Science, 2005 Conference Volume 3, 22-27 May 2005 Page(s):2006 - 2008 vol. 3.
7) "The measurement of sub-Brownian lever deflections," Hammig, M.D.; Wehe, D.K.; Nees, J.A.; Nuclear Science Symposium Conference Record, 2004 IEEE, Volume 2, 16-22 Oct. 2004 Page(s):707 - 711 Vol. 2.
8) "Enhancement of high-harmonic soft X-rays by adaptive wave-front control with genetic algorithm," Yoshitomi, D.; Miyamoto, N.; Kanai, T.; Sekikawa, T.; Watanabe, S.; Nees, J.; Mourou, G.; Conference on Lasers and Electro-Optics, 2003. CLEO '03. 1-6 June 2003 Page(s):2 pp.

9) "Efficient generation of isolated attosecond pulses through relativistic effects," Power, E.; Naumova, N.; Nees, J.; Hou, B.; Bahk, S-W.; Vanovsky, V.; Maksimchuk, A.; Mourou, G.; Sokolov, I.; Quantum Electronics Conference, 2004. (IQEC). International 2004 Page(s):966 - 967.
10) "Relativistic electron acceleration in the wavelength-cubed regime," Mordovanaki, A.G.; Nelson, N.; Hou, B.; Nees, J.; Naumova, N.M.; Mourou, G.; (CLEO). Conference on Lasers and Electro-Optics, 2004. Volume 1, 2004 Page(s):2 pp. vol.1.
11) "Efficient generation of isolated attosecond pulses through relativistic effects," Power, E.; Naumova, N.; Nees, J.; Hou, B.; Bahk, S.-W.; Yanovsky, V.; Maksimchuk, A.; Mourou, G.; Sokolov, I.; Lasers and Electro-Optics, 2004. (CLEO). Conference on Volume 1, 2004 Page(s):2 pp. vol.1.
12) "Development of novel ultrafast-laser-based micro-CT system for small-animal imaging," Krol, A.; Kieffer, J.-C.; Nees, J.A.; Liming Chen; Toth, R.; Bixhue Hou; Kincaid, R.E.; Coman, I.L.; Chamberlain, C.C.; Lipson, E.D.; Mourou, G.A.; Nuclear Science Symposium Conference Record, 2003 IEEE, Volume 3, 19-25 Oct. 2003 Page(s):1993 - 1996 Vol.3.
13) "Polarization and power scaling of harmonics from solid and targets in the /spl lambda//sup 3/-regime," Wilcox, M.; Nees, J.; Hou, B.; Theobald, W.; Mourou, G.; Quantum Electronics and Laser Science, 2003. QELS. Postconference Digest, 1-6 June 2003 Page(s):2 pp.
14) "Laser-matter interaction in the "relativistic 3" regime,"Bixue Hou; Nees, J.A.; Wilcox, M.I.; Mourou, G.A.; Conference on Lasers and Electro-Optics, 2003. CLEO '03, 1-6 June 2003 Page(s):381 - 382.
15) "Relativistic /spl lambda/' regime: from relativistic electrons to relativistic ion,"Naumova, N.; Mourou, G.; Nees, J.; Yanovsky, V.; Conference onLasers and Electro-Optics, 2003. CLEO '03, 1-6 June 2003 Page(s):1036 - 1038 .
16) "Relativistic Microelectronics"' J. Nees, Bixue Hou, A. Mordovanakis, G. Mourou, International Conference on Ultrahigh Intensity Lasers Tahoe City CA October 3-7, 2004.
17) "Attosecond phenomena in the relativistic lambda cubed regime," N. Naumova, J. Nees, JG. Mourou, International Conference on Coherent and Nonlinear Optics, St. Petersburg, Russia, May 11-15, 2005.
18) "Efficient Attosecond Phenomena Arising in the Relativistic Lambda Cubd Regime," J. Nees, International Conference on Multiphoton Processes 9-14 October 2005.

University of Michigan Personnel

John A. Nees—Principle Investigator, Associate Research Scientist
Bixue Hou—Assistant Research Scientist
Aghapi Mordovanakis—graduate student
James Easter—graduate student

Erik Power—graduate student

Patents

A provisional patent was filed August 24th 2004, entitled "System and Method for Generation of High-Density Electron Bunches of Ultrashort Duration." This provisional patent was NOT pursued to full patent.