

REPORT DOCUMENTATION PAGE			Form Approved OMB NO. 0704-0188		
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1. REPORT DATE (DD-MM-YYYY) 31-03-2010		2. REPORT TYPE Final Report		3. DATES COVERED (From - To) 20-Dec-2006 - 19-Dec-2009	
4. TITLE AND SUBTITLE Development of an electron-positron source for positron annihilation lifetime spectroscopy: FINAL REPORT			5a. CONTRACT NUMBER W911NF-07-1-0056		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER 611102		
6. AUTHORS John Nees, Bixue Hou, Aghapi Modovanakis, James Easter, Igor Sokolov, Stepan Bulanov, Michael Downer			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Michigan - Ann Arbor Room 1058 Wolverine Tower 3003 South State Street Ann Arbor, MI 48109 -1274			8. PERFORMING ORGANIZATION REPORT NUMBER		
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. SPONSOR/MONITOR'S ACRONYM(S) ARO		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) 50617-PH.2		
12. DISTRIBUTION AVAILABILITY STATEMENT Approved for Public Release; Distribution Unlimited					
13. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.					
14. ABSTRACT The extremely strong fields produced by focusing powerful laser pulses into minute volumes of material enable relativistic effects to be used to generate radiation, to accelerate particles, and to produce electrons and positrons from vacuum. From applications using existing high-repetition-rate lasers to those projected for super intense systems, the individual and collective behavior of electrons is the hub of both practical and theoretical directions. This report reviews work directed toward the application of positron generation from laser interaction with matter					
15. SUBJECT TERMS Relativistic, plasma, electron, kinetics, femtosecond, attosecond, quantum electrodynamic, high order harmonics, accelerators					
16. SECURITY CLASSIFICATION OF:		17. LIMITATION OF ABSTRACT		15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	UU		John Nees
					19b. TELEPHONE NUMBER 734-764-9271

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

Contract Number
W911NF0710056

Final Report
20 December 2006- 19 December 2009

Submitted to Richard Hammond
US Army research Office
Tuesday, March 30th, 2010

Report Abstract

The extremely strong fields produced by focusing powerful laser pulses into minute volumes of material enable relativistic effects to be used to generate radiation, to accelerate particles, and to produce electrons and positrons from vacuum. From applications using existing high-repetition-rate lasers to those projected for super intense systems, the individual and collective behavior of electrons is the hub of both practical and theoretical directions. This report reviews work directed toward the application of positron generation from laser interaction with matter and vacuum. It spans funded original experimental research in laser-plasma interaction, where electrons dominate energy transport and MeV/ μm fields are revealed, to theoretical collaborations exploring the connection between present and foreseeable lasers to the quantum electrodynamics of radiating electrons and electron-positron pair production from vacuum.

Statement of the problem studied

Means of converting the extreme intensities available in modern and foreseeable lasers into new sources of particles and radiation for materials studies are studied. Particular interest is given to the generation of electrons or gamma rays from which positrons may be produced from interactions with heavy nuclei. An additional study related to direct electron-positron generation from vacuum is brought in by way of collaboration.

Statement of key results

Experimental work with tightly focused millijoule-level pulses produces MeV-level electron and proton beams from distinct microscopic TeV/m (MeV/ μm) accelerating structures. Similar experiments now link high-order harmonic generation to the plasma dynamics, showing the potential for better interrogation of the dynamics of the laser matter interaction.

Collaboration with U. Texas Austin has yielded a clear analysis of energy transport in the aftermath of the driving pulse interaction in the same configuration above-stated experiments. Further collaborations have begun to address theoretical and computational aspects of extreme light interactions where QED strong fields effects can give rise to electron-positron pair production in the absence of heavy ion mechanisms.

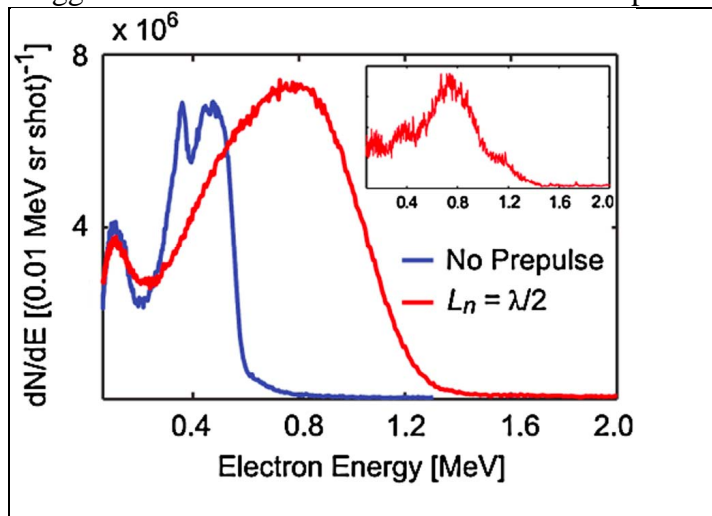
Laser matter interaction in the relativistic regime

Energy transport in strongly driven plasmas (funded U. Texas collaboration Mike Downer with Benjamin Bowes - PhD U. Texas Austin Winter 2007, further analyzed by Hans Langhoff, Universität Würzburg, Germany)

The immediate and dominating interaction of strongly focused, relativistically intense laser pulses as they impinge upon a material and following the ionization of the material by the fields leading the pulses is the exchange of energy from the light field to electrons in the newly formed plasma. Allowing that energy is transferred from the incident light to electrons by various mechanisms and tracking the expected transport of that energy through electron motion and radiative coupling mechanisms, the results of femtosecond pump-probe microscopy studies were analyzed. A summary of this work is included below and labeled as the U. Texas contribution to this program. NSF sponsored aspects of this work that were directed coherent processes.

Electron acceleration (Aghapi Mordovanakis - PhD U. Michigan Winter 2007, with assistance of James Easter)

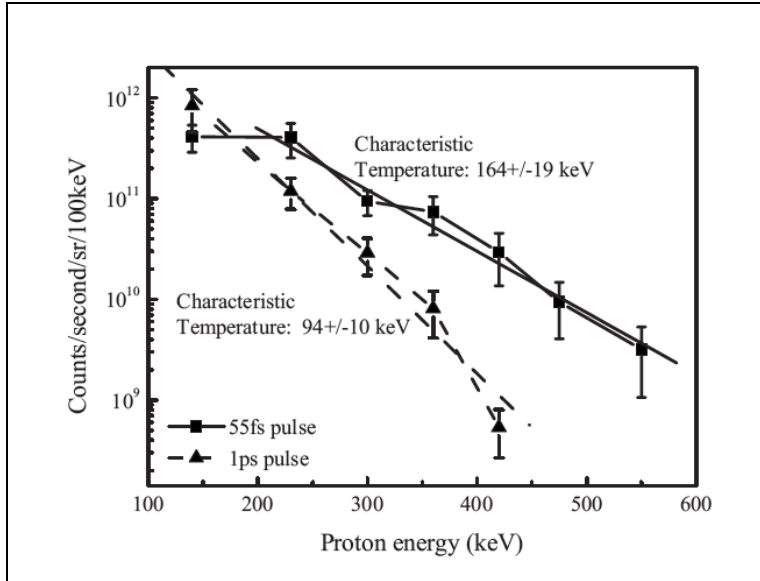
As we state in our *Physical Review Letter* of 4 December 2009: “We investigated the production of electron beams from the interaction of relativistically-intense laser pulses with a solid-density SiO_2 target in a regime where the laser pulse energy is $\sim\text{mJ}$ and the repetition rate $\sim\text{kHz}$. The electron beam spatial distribution and spectrum were investigated as a function of the plasma scale length, which was varied by deliberately introducing a moderate-intensity prepulse. At the optimum scale length of $\lambda/2$, the electrons are emitted in a collimated beam having a quasimonoenergetic distribution that peaked at 0.8 MeV. A highly reproducible structure in the spatial distribution exhibits an evacuation of electrons along the laser specular direction and suggests that the electron beam duration is comparable to that of the laser pulse.



Quasi-monoenergetic MeV electron spectra emitted by an SiO_2 plasma with (red) and without (blue) a 16.8 ps prepulse.

Particle-in-cell simulations, which are in good agreement with the experimental results, offer insights on the acceleration mechanism by the laser field.” While these electron beams exceed the strict threshold of electron-positron pair production by interaction with heavy nuclei, the expected efficiency is still too low to form a practical source. Nevertheless the process of electron acceleration reveals a mechanism that can be driven by stronger laser fields to produce significantly more energetic electron beams from microscopic, laser-induced accelerator structures. Aspects of this work that were directed toward coherent processes were sponsored by the NSF

Ion acceleration (Bixue Hou, U. Michigan partially funded Associate Research Scientist)



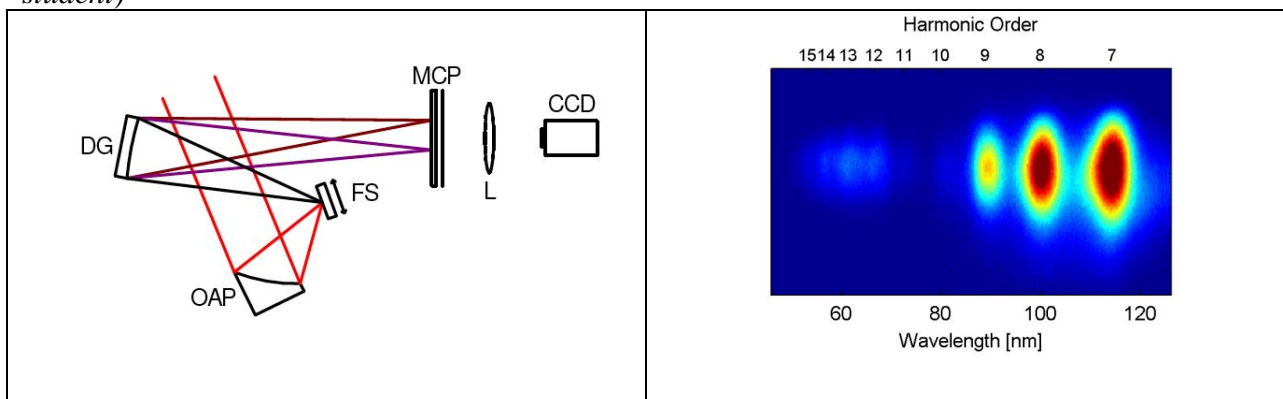
Proton spectra arising from irradiation of a glass target with 55fs and 1 ps pulses. Water and oil adhering to the target surface are the likely sources of protons driven by TeV/m electric fields.

Following the report made in *Applied Physics Letters* on 10 September 2009 we found that: “Well-collimated proton beams are generated from bulk glass along the target normal direction by tightly focused 55 fs, 3 mJ pulses from a laser operating at 0.5 kHz repetition rate. Proton beams with energies of >265 keV have an emission angle of about 16° full width at half maximum. Spectral measurements indicate proton energies exceeding 0.5 MeV with a flux of $3.2 \times 10^9 \text{ s}^{-1} \text{ sr}^{-1}$ and the flux of measured protons with energies of greater than 90 keV is $8.5 \times 10^{11} \text{ s}^{-1} \text{ sr}^{-1}$ on center.”

This related work also exploits a solid glass target to produce TeV/m accelerating gradients and to launch nearly MeV particles. However this

work also indicates that the ionized material gathered into a beam and accelerated along the target normal direction is composed of foreign matter such as water and pump oil that had been adhering to the target surface. Aspects of this work that were directed toward neutron production were sponsored by the NRL.

High-order harmonic generation (James Easter-PhD U. Michigan Spring 2010 *partially funded student*)



High-order harmonic generation experimental geometry.

Preliminary spectra showing up to 15th order harmonics.

Present experiments on the generation of harmonics from SiO₂ targets are directly related to both of the preceding sections as they involve nearly the same target and irradiation conditions

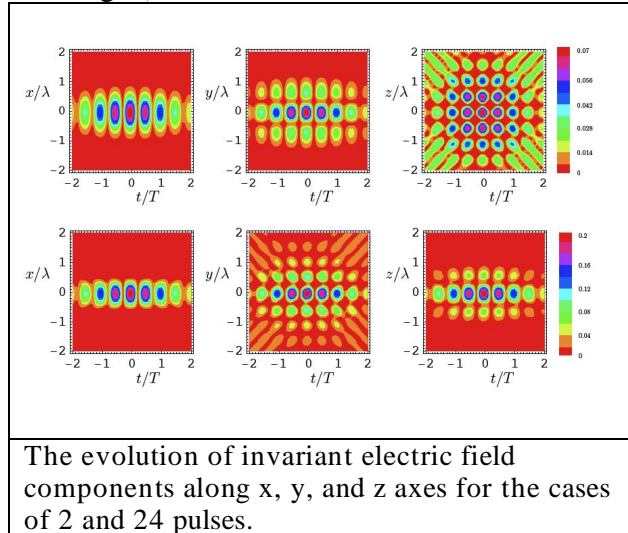
and represent the integrated effect of radiation from those electrons involved in the most dynamic motion. We note in our summary for *The 2010 Conference on Lasers and Electro-Optics* that: “Harmonics up to the 15th order are produced from solid targets using 3 mJ, 30 fs pulses focused to a spot size of 1.7 μm and $3 \times 10^{18} \text{ W/cm}^2$. Combined conversion efficiency to the highest harmonics is $>10^{-5}$.” This work begins to draw on the measurement of the radiation field collected from the driven electrons to determine the collective motion of those particles during the laser interaction. A clear advantage of this approach is that the electromagnetic signals have the capability to remain unperturbed over a longer range than do electrons which are highly reactive to fields and charges. Harmonics can therefore port information about collective electron behavior where and electron beam could not. This is exemplified in that the acceleration mechanism viewed in 2- and 3-D PIC simulations indicates violent acceleration in very short structures with electric field strength of several $\text{MeV}/\mu\text{m}$ along with weaker acceleration in more extended fields. The former dynamic structures will radiate strongly due to the strength of their acceleration, while the latter will continue to modify the electron distribution, but with insignificant radiation. Thus the earlier phase of acceleration can be viewed by its radiation, while the combined effect of the two phases is quantified by the integrated effect on the electron beam. The NSF sponsored aspects of this work directed toward coherent processes.

Electromagnetic radiation in the QED regime

Emission and its back-reaction accompanying electron motion in relativistically strong and QED-strong pulsed laser fields, (Igor Sokolov, U. Michigan and Natalia Naumova, LOA, France)

On the strength of Igor Sokolov’s theoretical development of radiating electrons in strong laser fields a simulation was implemented by Natalia Maumova. In combination, these accomplishments lead to the understanding stated in *Physical Review E* of 25 March 2010 that: “The emission from an electron in the field of a relativistically strong laser pulse is analyzed. At pulse intensities of $J \geq 2 \times 10^{22} \text{ W/cm}^2$ the emission from counterpropagating electrons is modified by the effects of quantum electrodynamics (QED), as long as the electron energy is sufficiently high: $E \geq 1 \text{ GeV}$. The radiation force experienced by an electron is for the first time derived from the QED principles and its applicability range is extended toward the QED-strong fields.” Most significant aspect of this work is the capability to compute and accumulate radiation produced under conditions of violent acceleration in regimes where present-day lasers can drive electrons into their own radiation, producing a boosted frame where electric field reaches the Schwinger limit for production of electron-positron pairs from vacuum. The theoretical framework developed here allows one to obtain valuable results at much deeper into the domain of quantum electrodynamics. DOE sponsored aspects of this work that were directed toward radiative shock hydrodynamics.

Lowering the threshold for Schwinger electron-positron pair production (Stepan Bulanov, U. Michigan)



Following the view that even stronger lasers will be constructed in the next several years the potential for generating electron-positron pairs directly from vacuum was investigated by Stepan Bulanov. In a paper submitted for publication and available on ArXiv it is noted that: “The scheme of simultaneous multiple pulse focusing on one spot naturally arises from the structural features of projected new laser systems, such as ELI and HiPER. It is shown that the multiple pulse configuration is beneficial for observing e^+e^- pair production from vacuum under the action of sufficiently strong electromagnetic fields. The field of the focused

pulses is described using a realistic three-dimensional model based on an exact solution of the Maxwell equations. The e^+e^- pair production threshold in terms of electromagnetic field energy can be substantially lowered if, instead of one or even two colliding pulses, multiple pulses focused on one spot are used. The multiple pulse interaction geometry gives rise to subwavelength field features in the focal region. These features result in the production of extremely short e^+e^- bunches.” NSF sponsored aspects of this work that were directed coherent processes.

1. “Surface energy transport following relativistic laser-solid interaction,” H. Langhoff, B. T. Bowes, M. C. Downer, Bixue Hou, and J. A. Nees *Physics of Plasmas* **16** 072702 (2009).
2. “Quasimonoeenergetic Electron Beams with Relativistic Energies and Ultrashort Duration from Laser-Solid Interactions at 0.5 kHz,” Aghapi G. Mordovanakis, James Easter, Natalia Naumova, Konstantin Popov, Paul-Edouard Masson-Laborde, Bixue Hou, Igor Sokolov, Gérard Mourou, Igor V. Glazyrin, Wojciech Rozmus, Valery Bychenkov, John Nees, and Karl Krushelnick, *Physical Review Letters* **103**, 235001 (2009).
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5. “Emission and its back-reaction accompanying electron motion in relativistically strong and QED-strong pulsed laser fields,” Igor V. Sokolov, John A. Nees, Victor P. Yanovsky, Natalia M. Naumova, and Gérard A. Mourou, *Phys. Rev. E* **81**, 036412 (2010).
6. “Multiple colliding electromagnetic pulses: a way to lower the threshold of e^+e^- pair production from vacuum,” S. S. Bulanov, V. D. Mur, N. B. Narozhny, J. Nees, V. S. Popov, <http://arxiv.org/abs/1003.2623v1>. *Submitted for publication.*

Report on U. Texas contribution to ARO contract “Further development of an electron-positron source”

Abstract: The U. Texas group led by Mike Downer performed and analyzed a series of experiments investigating energy transport along the surface of an Al target following excitation at relativistic intensity. After a ~ 1 -micron Al target spot is excited at $3e18 \text{ W/cm}^2$, a delayed probe detects isotropic surface heating out to $12 \mu\text{m}$ radius. Analysis shows runaway electrons and strong magnetic fields govern fs surface heating. The results demonstrate how close interplay among fs-time-resolved, μm -space-resolved measurements, theory and PIC simulations can lead to improved physical understanding of complex laser-target interactions that underlie production of relativistic charged particle beams.

U. Texas personnel: Prof. Mike Downer, project leader; Benjamin Bowes (Ph.D. 2007) performed experiments at U. Michigan’s λ^3 facility; Prof. Hans Langhoff (visiting U. Texas from U. Würzburg, Germany) developed theoretical model of the experimental results.

Other collaborator: Prof. Y. Sentoku (U. Nevada, Reno) performed PIC simulations of the experiments.

1. Introduction. Relativistically intense ultrashort laser pulses can deposit as much as half their energy collisionlessly into a solid target in the form of suprathermal electrons. Such fast electrons have been extensively studied by observing them in the forward direction [1], because of their importance for fast ignition of laser fusion and generation of charged particle beams. However, strong electric and magnetic fields in the interaction region can also redirect hot electrons along the target surface, particularly with obliquely incident laser pulses. This lateral energy spread is less extensively characterized. In 2006, we performed and reported results of a fs microscopy experiment [2] in which a planar Al target was excited by a 24 fs pump focused to intensity up to $1e18 \text{ W/cm}^2$ in a ~ 1 micron radius spot. Time-resolved images of the surface obtained with a p-polarized, 400 nm ultrashort probe pulse showed sharply reduced reflectivity within the directly heated area, which expanded to $\sim 2.5 \mu\text{m}$ radius within ~ 500 fs (Fig. 1a). At the outer boundary of the reduced reflectivity region, probe reflectivity drops mainly because of increased collisional absorption, and is sensitive to surface temperatures $kT_{\text{surf}} \sim 40$ eV, much lower than x-ray diagnostics. No model of the lateral heat transport physics was presented in that work.

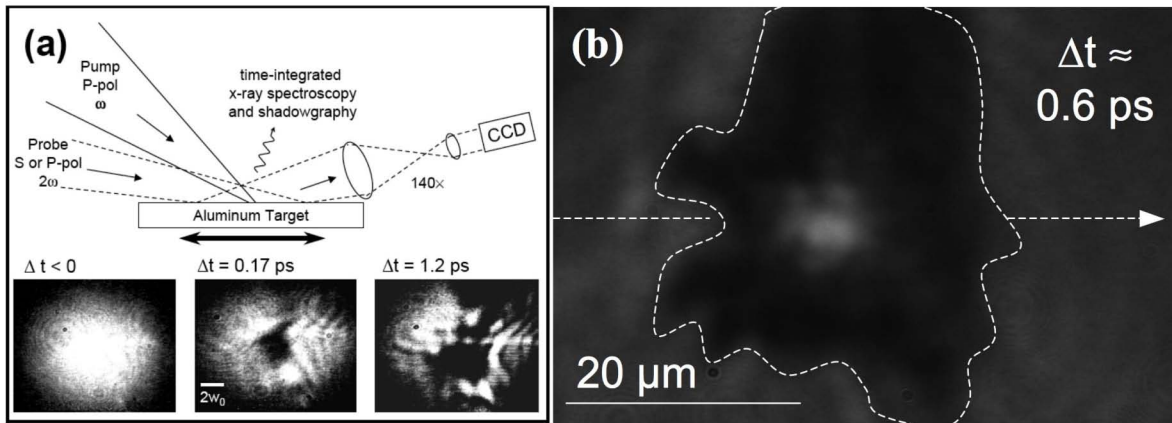


Fig. 1. Summary of measurements of surface heat transport for Al target excited at relativistic intensity. (a) Experimental setup for femtosecond microscopy with selected images from [2] of the heated plasma using p-polarized probe at the indicated time delays Δt and focused pump intensity $I_{\text{pump}} \approx 1e18 \text{ W/cm}^2$ (bottom). (b) New probe image as in (a), but for $\Delta t = 0.6 \text{ ps}$ and $I_{\text{pump}} \approx 3e18 \text{ W/cm}^2$. The bright central spot is second-harmonic radiation generated by the focused pump that was scattered into the probe imaging system. Reduced reflectivity region, outlined by dashed curve, is $\sim 25 \mu\text{m}$ in diameter..

2. Follow-up experiments, theory and simulation results. We then obtained new experimental results, enabled by a laser upgrade, in which the Al target was excited at $3e18 \text{ W/cm}^2$ in the same spot size. We observed the dark hot region grew to more than four times larger ($12 \mu\text{m}$ radius) than observed at $1e18 \text{ W/cm}^2$ on a similar time scale, but remained approximately isotropic, as shown in Fig. 1b. In addition we developed a semi-empirical model [3] to explain the lateral heat transport and its apparent isotropy in three steps. First, the pump drives hot electrons into the

target via collisionless interactions according to the empirical rule $kT_e^{(hot)} \propto (I_{pump}\lambda^2)^{1/3}$ of Beg [4]. These hot electrons are slowed by their space charge electric field, which we calculate reaches ~ 20 GV/m over a depth of ~ 3 μm for $I_{pump} = 3e18$ W/cm². Second, the space charge field drives a return current that ohmically heats the target and, as I_{pump} increases, includes more and more runaway electrons that reach the surface without colliding. We calculate that ~ 1 keV runaway electrons comprising $\ll 1\%$ absorbed energy first appear at $I_{pump} = 0.5e18$ W/cm², then increase nonlinearly in energy to 70 keV and 10% of absorbed energy at $I_{pump} = 3e18$ W/cm². Third, returning runaway electrons diffuse laterally, while oscillating across the target surface confined by space charge and heating it collisionally. The solid curve in Fig. 2a shows our calculated diffusion diameter (achieved in ~ 500 fs) inside which surface temperature exceeds 40 eV detectable by probe reflectivity. The sharp increase in diameter for $I_{pump} > 1e18$ W/cm² reflects the nonlinear increase in runaway electron population and energy, and agrees reasonably well with measurements. Isotropy of the observed expansion is consistent with dominance of resonance absorption over $j \times B$ heating, indicating pre-pulse heating was important.

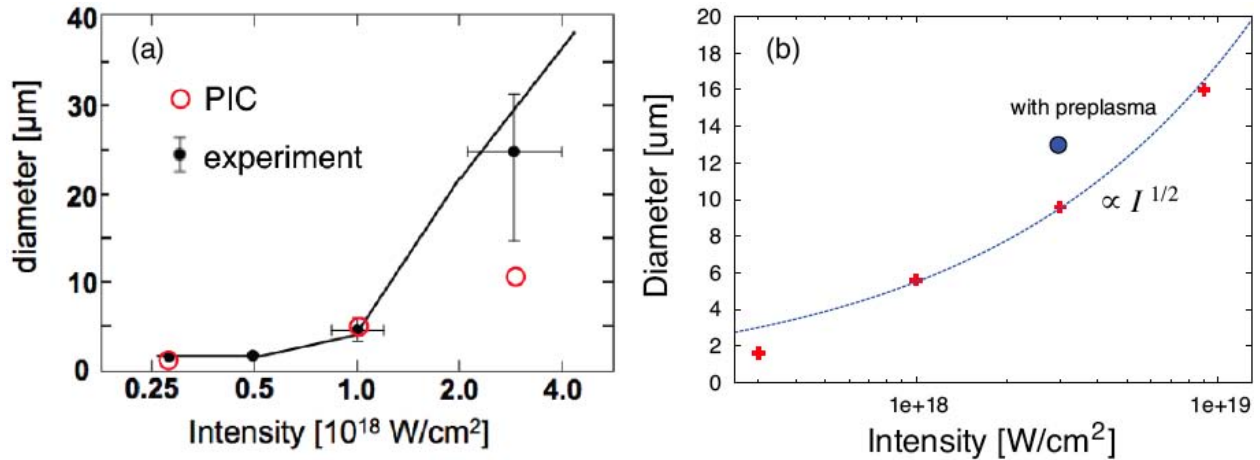


Fig. 2. Comparison of measurement, theoretical model and PIC simulation of intensity scaling of diameter of heated region. **(a)** Data points: measured diameter of region of reduced probe reflectivity. Solid curve: estimated diameter after stoppage of runaway electrons from model calculations [3]. Red circles: PIC simulations with no pre-plasma. **(b)** Red crosses: intensity scaling of PIC-simulated diameter of surface region heated to $kT_{surf} > 40$ eV, compared to $I_{pump}^{1/2}$ curve. Solid circle: simulated diameter of $kT_{surf} > 40$ eV area with a thin preformed plasma.

Two-dimensional particle-in-cell simulations using the code PICLES2d, which includes ionization and binary collisions among charged particles, confirm the important role of pre-plasma in the experiment for $I_{pump} > 1e18$ W/cm² [5]. When pre-plasma was neglected, the simulations predicted the diameter of the surface region with $kT_{surf} > 40$ eV increased as $\sim I_{pump}^{1/2}$ (Fig. 2b, red crosses and curve) and agreed reasonably well with measured diameter up to $I_{pump} \sim 1e18$ W/cm² (Fig. 2a, left two red circles). However, at $I_{pump} = 3e18$ W/cm², they predicted strongly *anisotropic* surface heating with major diameter (Fig. 2a, right-most red circle) $\sim 2.5\times$ smaller than observed. On the hand, with a thin pre-plasma in front of the target, simulated pump absorption and heated diameter increased by $\sim 50\%$ (Fig. 2b, solid circle) and surface heating became nearly isotropic. An important factor in creating isotropy was a strong (~ 10 MG) magnetic field in the pre-plasma, about 10% of the laser magnetic field, strong enough to rotate sub-MeV electrons on a micron scale and thus spoil expansion anisotropy of surface-propagating electrons.

The results demonstrate how close interplay among fs-time-resolved, μm -space-resolved measurements, theory and PIC simulations can lead to improved physical understanding of complex laser-target interactions that underlie production of ultrashort x-rays, fast ignition of laser fusion and production of relativistic protons.

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- [2] B. T. Bowes *et al.*, "Femtosecond microscopy of radial energy transport in a micrometer-scale aluminum plasma excited at relativistic intensity," *Opt. Lett.* **31**, 116 (2006).
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- [4] F. N. Beg and A. R. Bell, "A study of picosecond laser-solid interactions up to 10^{19} W cm⁻²," *Phys. Plasmas* **4**, 447 (1997).
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