Relativistic short-pulse high harmonic generation at 1.3 and 2.1 μm wavelengths

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Abstract

While nearly all investigations of high order harmonic generation with relativistically intense laser pulses have taken place at 800 or 1053 nm, very few experimental studies have been done at other wavelengths. In this study, we investigate the scaling of relativistic high harmonic generation towards longer wavelengths at intensities of \( a_0 \sim 1 \). Longer driver wavelengths enable enhanced diagnostics of the harmonic emission, as multiple orders lie in the optical regime. We measure the conversion efficiency by collecting the entire harmonic emission as well as the divergence through direct imaging. We compare the emission with 2D particle-in-cell simulations to determine the experimental target conditions. This new regime of high order harmonic generation also enables relativistic scaling as well as improved discrimination of harmonic generation mechanisms.

1. Introduction

The interaction of short-pulse, high-intensity lasers with solid-density plasmas can yield great insight into the complex interplay between high electric fields and over-dense plasmas on ultrafast timescales. With the rapid increase of laser intensities to beyond \( 10^{22} \) W cm\(^{-2}\) [1], the generation of higher order harmonics (HHG) from such interactions has become an exciting avenue for numerous applications, stemming from their ability to produce coherent attosecond-duration light in the extreme ultraviolet and soft x-ray regimes [2–4]. Two distinct mechanisms of short-pulse laser-solid HHG in reflection geometries have been investigated: the relativistic oscillating mirror (ROM) and coherent wake emission (CWE). ROM HHG occurs when the critical density surface electrons are driven to relativistic speeds by the intense laser field. The resulting nonlinear motion gives rise to the re-radiation of the laser field containing harmonics of the fundamental frequency [5–8]. CWE occurs through the excitation of plasma-wakes at the critical density surface by laser-driven electron bunches. These wakes, which are locked to the optical cycle of the laser, emit bursts of radiation resulting in harmonic structure in the reflected light [9].

High-intensity laser-plasma interactions are described via the normalized vector potential written in the convenient form: \( a_0 = 0.85 \times 10^{-3} \sqrt{I_0 (\text{W cm}^{-2})} \lambda_0^2 (\text{μm}^2) \), where \( I_0 \) is the peak laser intensity and \( \lambda_0 \) is the driving laser wavelength. \( a_0 \) succinctly describes the change in momentum of an electron in a high-intensity laser field. The value of \( a_0 = 1 \) occurs when the electron momentum equals its rest momentum \( \gamma m_e c = m_e c \) at an intensity \( I_0 \lambda_0^2 \approx 1.4 \times 10^{18} \) W cm\(^{-2}\) μm\(^2\) and signals the transition to the relativistic regime of laser-matter interactions. This transition coincides with the change from CWE dominated harmonic generation to one that is predominantly from the ROM mechanism. However, it should be noted that both mechanisms can be present during laser-solid interactions near the relativistic threshold [10].

The two key parameters in the normalized vector potential are the laser intensity and the driving laser wavelength or frequency, \( \omega_0 \). With the use of near-infrared (NIR) lasers and variable intensities, interactions have been studied from under-relativistic, \( a_0 \ll 1 \) [9, 10] to the ultra-relativistic limit, \( a_0 \gg 1 \) [11, 12]. While much work has been devoted to studying laser-solid relativistic HHG in the NIR regime [13–15], very few recent experiments have been performed with longer wavelengths [16]. The advent of new laser technologies such as...
optical parametric chirped-pulse amplification and fiber laser systems has enabled high intensity laser-plasma experiments at longer wavelengths than traditional laser systems. Therefore, being able to validate the predictions of relativistic HHG theory will be critical for implementation in those new systems.

Moving to longer wavelengths provides a secondary benefit. For NIR lasers the second and third harmonics are the only emissions which lie in the visible spectrum. These lowest order harmonics can be produced by multiple mechanisms, which can be more dominant than the HHG mechanisms [17–19]. Harmonics due to purely relativistic interactions, i.e. the fourth harmonic and above, are in the ultraviolet or deep ultraviolet wavelength region, making their manipulation and detection practically very difficult. Therefore, in order to study the high harmonic generation mechanism it has been necessary for NIR HHG experiments to measure the higher-order harmonic emission at much higher orders that lie within the extreme ultraviolet region. Conversely, MIR lasers have multiple harmonic orders in the visible wavelength region enabling direct measurements and testing of relativistic HHG properties such as the polarization and divergence of individual harmonics.

In this Article, we investigate the high harmonic generation from mechanism laser-solid interactions at the threshold of the relativistic regime with 1.3 and 2 μm wavelengths. We present polarization-dependent intensity and divergence measurements of individual optical-order harmonics. We find that the measured polarization selection rules of the optical harmonics are in agreement with ROM model [6, 7]. Particle-in-cell simulations are conducted to determine the experimental plasma conditions present during the OPA-driven laser-plasma interactions.

2. Experimental setup

Experiments were performed at two facilities using an optical parametric amplification (OPA) with Ti:Sapphire (λ₀ = 800 nm) driving lasers: the University of California, Irvine (UCI) and the Relativistic Lambda Cubed Laser at the Center for Ultrafast Optical Science (CUOS), University of Michigan. The experimental conditions are as follows.

2.1. Lambda cubed, University of Michigan

Lambda Cubed produces 16 mJ laser pulses with 30 fs FWHM duration at a 500 Hz repetition rate. The 800 nm light is then down-converted via a two stage homedbuilt OPA to 1.6 mJ of λ₀ = 2 μm [20]. The pulse duration of the CUOS laser after OPA was measured via autocorrelation to be τ₀ = 67 fs temporal FWHM. The output polarization from the OPA was controlled with a half waveplate to select between s- and p-polarized driving of the HHG interaction. A 1.65 μm longpass filter (Andover 1.65ILP-25) was used to remove residual lower wavelength light from the OPA process. After filtering, the pulse duration of the CUOS laser increased to τ₀ = 100 fs temporal FWHM due to dispersion. The MIR beam was then directed through a reflective telescope to up-collimate to a 50 mm beam diameter and prior to entering the experimental chamber had its wavefront corrected by a 47 mm diameter deformable mirror (Xinetics) with 37 actuators. The beam was sent into a vacuum chamber through an uncoated fused silica window at normal incidence. A gold-coated, fast-focusing, off-axis parabolic (OAP) mirror (f/1.3) focused the beam onto the target at angle of incidence near 45° producing a maximum focal intensity of 8.7 × 10¹⁶ W cm⁻², a₀ = 0.5. The 2 μm focal spot was optimized through a genetic algorithm measuring the second harmonic produced from plasma formation in low level atmosphere, ~1 Torr [21]. Silicon wafers and fused silica glass targets were mounted on an automated spindle to keep the target within the Rayleigh range of the laser focus and to continually refresh the target during the experiment. A dial indicator with ±2 μm accuracy was used during target alignment to ensure target flatness within the Rayleigh range. The accuracy of the dial indicator is smaller than the Rayleigh range of the experiment which is ~10 μm. The different targets were selected due to their difference in work function: silicon is 4.8 eV whereas fused silica is 5.0 eV [22]. The difference in the work function will cause the two materials to have different damage thresholds and resulting plasma scale lengths. The thickness of the targets was much greater than the skin depth of the laser: the silicon wafer and fused silica were 500 μm and 5 mm thick, respectively. The vacuum chambers were evacuated to below 10 mTorr levels to avoid plasma formation before the target surface. In situ control of the target focal positioning was performed to maximize harmonic intensities.

Two separate diagnostics were used to measure the harmonic polarization and divergence at CUOS. For polarization measurements, the harmonics generated from the interaction were collected using an aluminum OAP (f/1.5), directed out of the chamber, and focused with a UV fused silica lens (f = 1000 mm) into an optical spectrometer (Thorlabs CCS200). The harmonics passed through a Zinc Calcite polarizer to control polarization-dependent throughput. For divergence measurements, a diffusing screen was placed 2 cm in the specular direction from the target to intercept the harmonics. Two fused silica lenses (f = 1000 mm and f = 150 mm) imaged the screen onto a charge-coupled device camera (Mightex CGE-B013-U). Bandpass filters
(Edmund Optics S/N 65-694, 65-717, and 65-741) were used to isolate each harmonic separately. Each bandpass filter was selected to center on the harmonic of choice for 2 μm with a FWHM window of 10 nm, e.g. the 4th harmonic was imaged using a bandpass filter at 500 ± 5 nm. The 5th harmonic bandpass filter had a 50 nm FWHM; however, only broadband plasma recombination emission was detected during the divergence measurements at that harmonic. Divergence measurements are integrated from 5 to 500 shots. Shot to shot fluctuations of ~15% intensity were present in the divergence measurements due to stage instability.

2.2. University of California, Irvine
The experiments at UCI were similar to those performed at CUOS; therefore, only the differences will be noted as follows. UCI has a commercial Ti:Sapphire laser system (SpectraPhysics Solstice ACE) that produces 7 mJ laser pulses with 35 fs temporal FWHM at central wavelength 800 nm, which is then down-converted through OPA to 1.1 mJ of λ₀ = 1.3 μm at 1 kHz. The output polarization from the OPA was controlled with a periscope system and passed through a 1.0 μm longpass filter (Thorlabs FGL1000). After filtering, the laser pulse remained near the transform limit of τ₀ = 35 fs measured via second harmonic generation frequency resolved optical gating. A deformable mirror was not used to correct the wavefront prior to entering the vacuum chamber through an anti-reflection coated fused silica window. An OAP (f/1) focused the beam onto the target at angle of incidence near 45° producing a maximum focal intensity of 5 \times 10^{17} \text{ W cm}^{-2}, \theta₀ = 0.78. Silicon wafers and silica glass targets were mounted on an automated translation stage for high repetition rates and in situ control of target positioning. For experiments at UCI, the laser repetition rate was reduced to 250 Hz to prevent focal spot overlap from consecutive shots.

Similar to the experiment at CUOS, the harmonics generated from the interaction at UCI were collected using an aluminum OAP (f/4), directed out of the chamber, and focused with a UV grade fused silica lens (f = 350 mm) into an optical spectrometer (Ocean Optics Flame-S). The signal was integrated over five shots to produce the measured spectrum. Harmonic polarization was measured by inserting a linear polarizer in front of the spectrometer. The polarizer was on a BK-7 substrate which removed all signal beyond the 4th harmonic due to its poor transmission of UV light. No divergence measurements were taken at UCI. This is because the harmonics of interest, namely 4ω₀ and above, that are exclusively generated through the high-intensity interaction lie within the near ultraviolet. Unfortunately, we did not have access to bandpass filters which transmit in this spectral region.

3. Results
The measured optical order harmonics generated from glass targets using 1.3 and 2 μm lasers can be seen in figure 1. Between five and ten shots are integrated on the spectrometer. This is performed at high repetition rates by continuously collecting spectra while translating the target, enabling each successive laser pulse to interact with fresh target. The spectra are then corrected for the optical response of the metallic-coated mirrors, lenses, vacuum windows, and spectrometer for signal collection. Relative harmonic intensities are calculated by integrating over their full width at half maximum (FWHM) energy bandwidths. Figure 1(a) shows the efficiency-corrected harmonic spectra from a p-polarized interaction of a 1.3 μm wavelength laser incident on soda lime glass with (dark red) and without (red) a BK-7 linear polarizer inserted to remove all s-polarized light. The apparent lack of polarized harmonics beyond 4ω₀ (325 nm) is due to the poor transmission of ultraviolet light through BK-7 glass. No detectable s-polarized harmonic signal was measured from a p-polarized incident significantly above the noise. Harmonics from an s-polarized interaction were never observed at UCI. The correspondence of the harmonic intensity values are shown in figure 1(b) and are normalized to the intensity of the second harmonic. Overlaid is a power law fit (dashed green line) showing a relative intensity scaling of \( I_n \propto n^{-4.8} \) where \( I_n \) is the intensity of the nth harmonic. The choice of a power law fit is due to the well-known power law scaling of ROM HHG [2]. Figure 1(c) shows spectra from s- and p-polarized 2 μm wavelength interactions with a fused silica target normalized to the peak of the p-polarized signal. Note the significant structural differences between the 1.3 and 2 μm wavelength harmonics as well as the much larger energy FWHM than the transform limit of the incident 2 μm wavelength laser (shown in gray). This is not the case with the 1.3 μm wavelength harmonics which have much narrower bandwidths. Figure 1(d) shows the integrated intensity values for the 2 μm wavelength interaction with a power law fit of \( I_n \propto n^{-6.9} \). No detectable fifth harmonic or above were measured with silica targets at CUOS.

Figure 2 displays the polarization dependence of optical order harmonics generated with two separate target materials using a 2 μm driving laser. Figure 2(a) shows p- and s-polarized harmonics from a silicon wafer and figure 2(b) shows the corresponding harmonics from a fused silica target. The harmonic structure is significantly different between the two targets. In both cases, there is significant bandwidth beyond the initial energy bandwidth (shown in gray). The strong modulations from the silica targets, as noted above, were less apparent in
Figure 1. 1.3 and 2 μm harmonics from a silica target. Note the logarithmic scale of the y-axis. (a) Unpolarized (dark red) and p-polarized (red) emission spectra from p-polarized 1.3 μm wavelength interaction. Initial pulse energy bandwidths centered on the peak of each harmonic shown in gray. (b) Corresponding harmonic intensity values: (circles) experiment, (green dashed line) best fit line. (c) Emission spectra of p-polarized (red) and s-polarized (blue) harmonics from 2 μm wavelength interaction. (d) Corresponding harmonic intensity values: (triangles) experiment, (green dashed line) best fit line.

Figure 2. Comparison of harmonic spectra generated by 2 μm wavelength light. Note the logarithmic scale of the y-axis. (a) P-driven (red) and S-driven (blue) harmonics from silicon wafer targets. (b) P-driven (red) and S-driven (blue) harmonics from fused silica targets. Significant structure seen outside of initial energy bandwidth (gray). (c) Harmonic intensity values for silicon (circle) and glass (triangle) targets.
the harmonics from the silicon wafers targets, but there exists notable secondary peaks for both $4\omega_0$ and $5\omega_0$ in the silicon target spectra. Figure 2(c) compares the integrated intensity measurements of the two targets. The silicon target has a shallower power law decay compared with the glass target. In addition, the fifth harmonic can be resolved for a silicon wafer target but not a fused silica target.

Figure 3 shows the measured divergence of harmonics from silicon and silica targets from $p$-polarized interactions at CUOS. The red dashed circle corresponds to the divergence angle of the fundamental defined by the $f/1.3$ focusing geometry. The light transmitted through the bandpass filters contains structure for lower order harmonics. As seen in figures 3(a)–(c), it appears as though the low order harmonics are generated in beamlets, which are not collinear with the specular direction. The image of glass 5th harmonic, figure 3(d), is most likely diffuse plasma discharge from the target, which is consistent with $5\omega_0$ never being observed from glass targets interactions.

4. Discussion and simulations

From the ROM HHG selection rules [7], we expect $p$-polarized odd and even harmonics from $p$-polarized interactions, whereas we expect $s$-polarized odd and $p$-polarized even harmonics from $s$-polarized interactions. Figures 1 and 2 show that up to the fifth order both odd and even harmonics from $p$-polarized interactions are also $p$-polarized. $S$-polarized light from the $p$-polarized interactions was at the noise level. It can be assumed that the observed 5th and 6th harmonic in figure 1(a) would also follow this trend and could be confirmed using a UV polarizer. The weaker signal of the $S$-polarized harmonics in figures 2(a) and (b) is due to the inherently weaker interaction of $s$-polarized light. It was possible to resolve the 3rd harmonic from the $s$-polarized interaction, and we can confirm that it is also $s$-polarized. The theoretical ultra-relativistic harmonic intensity scaling is given by $p = 8/3$ [23]. However, our measured $p$-values ($4.33 < p < 6.9$) lie between this limiting case and other experimental values of $5.2 < p < 10$ [12, 15, 24, 25]. Because the experiments were carried out near the threshold of the relativistic regime and not in the ultra-relativistic limit, it is unsurprising that the measured relative intensity decay is faster than the theoretical value.

The strong spectral modulations in the $2\mu m$ fused silica target data as seen in figure 2(a) coupled with evidence of two separate beamlets in the 3rd harmonic, figure 3(b), suggests multiple harmonic sources. This suggests a secondary harmonic generation mechanism from fused silica targets but not from the silicon wafer target. The strong modulations in the $p$-polarized data have a frequency spacing of 8THz which would correspond to a secondary harmonic pulse separated by a 125 fs delay or by a source spatially separated by $\sim 40 \mu m$. A pulse delay of 125 fs is too short to be from either the next laser pulse (2 ms) or any type of double pulsing of the oscillator which runs at MHz repetition rates, and $40 \mu m$ is much larger than the laser focal spot, $\sim 5 \mu m$. The source of these modulations is not immediately obvious.
There are three main distinguishing features between CWE and ROM HHG. First, CWE has only been detected in $p$-polarized geometries, therefore detection of the 4th and higher harmonics from an $s$-polarized interaction would be a strong indicator for ROM HHG [9]. Unfortunately, the interaction intensity was not such that the 4th harmonic could be resolved from $s$-polarized interactions. The second distinguishing feature between ROM and CWE in $p$-polarized interactions is the sharp cutoff for CWE HHG occurring at the plasma frequency, $\omega_p$ [9]. The cutoff contrasts with the universal ROM harmonic spectrum defined by a power law decay, $I_n = I_0 \mu^{-n}$, up to some maximal cutoff frequency $\omega_0 = 4\gamma^2$, where $\gamma = \sqrt{1 + a_0^2}$ is the maximum electron relativistic factor at the critical surface [23, 26]. For solid density targets the plasma frequency is tens of times greater than the laser frequency which is well outside the visible spectrum in the extreme ultraviolet regime. However, it is possible to use the strong dependence of the ROM on $a_0$ to determine the driving mechanism of the interaction. This method requires the complete capture of harmonic spectra which is not necessarily possible with traditional experiments at 800 nm, because x-ray spectrometers typically capture only portions of the harmonic beam in question. The measurement of the optical harmonics from midinfrared laser systems allows for the discrimination of ROM and CWE harmonics using traditional optical techniques.

The dependence of ROM HHG production on $a_0$, where slight variations in $a_0$ can dramatically alter the spectrum, is significantly stronger than for CWE. Notably, CWE has been detected down to intensities as low as $I\lambda^2 = 4 \times 10^{15}$ W cm$^{-2}$ $\mu m^2$ or $a_0 \ll 1$ and has been shown to have harmonic conversion efficiencies that vary weakly with the incident laser intensity ($I_0 \propto \mu^4$) [9]. In the experiment performed at CUOS, the intensity dependence of the generated harmonics was measured by moving the automated target stages by less than two Rayleigh lengths from optimal focus. The resulting harmonic spectrum can be seen in figure 4(a) as the blue curve with a direct comparison of optimal focal position shown in red. The corresponding relative harmonic intensities are shown in figure 4(b). It should be noted that the relative intensity of the 3rd harmonic decreases by a factor of ten. If we assume that the interaction is CWE dominated then relative harmonic intensity scales according to $I_{\omega_0}$ [4]. The measured relative $3\omega_0$ intensity values would require the initial laser intensity to drop by a factor of 300. This corresponds to a motion of 18 Rayleigh lengths away from best focus, which is well outside of the measured range of the stage instability as measured by a dial indicator to be within a Rayleigh length during the experiment as described above. Coupling this with the consistent harmonic polarization selection rules suggests that the dominate mechanism in these interactions is from the ROM model.

Two-dimensional numerical simulations were performed using the the PIC code OSIRIS [27]. Simulations were run using a 133.7 $\times$ 133.7 $\mu m^2$ square box with 128 particles per cell, using a grid size of 5000 $\times$ 5000. This results in a spatial resolution in both dimensions of $\lambda/87$, enabling lower-order harmonic frequencies to be resolved in the simulation. The plasma was a slab with density 100$n_i$, and thickness 534 nm angled at 45$^\circ$ with respect to the input laser. A variable scale length exponential density ramp of the form $\exp(-x/L_x)$ was placed before the front surface of the target to represent the preplasma formed by the laser prepulse. The plasma scale length, $L_x$, was varied over a range $\lambda/10 \leq L_x \leq 10\lambda$ to determine effects of the preplasma on harmonic generation. The laser pulse had a central wavelength $\lambda_0 = 2.1 \mu m$, temporal FWHM duration $\tau_0 = 100$ fs, and

![Figure 4](image-url)
was $p$-polarized. The pulse duration of the laser was chosen to match the temporal duration of the 2.1 $\mu$m laser after dispersing through the longpass filter before the laser-plasma interaction. The pulse was focused to a 2.5 $\mu$m FWHM Gaussian focal spot on the front surface of the target producing a normalized vector potential $a_0 = 1$. After the interaction, the light reflected away from the target into free space; there, the reflected light was analyzed using two-dimensional fast Fourier transforms (FFTs) to determine the harmonic spectra and divergence.

Example harmonic spectra produced from various scale lengths are shown in figure 5(a) with harmonics resolved up to the 9th order, 233 nm. The spectra are extracted from the 2D FFT through radially summing along constant $k = \sqrt{k_0^2 + k^2}$ values to capture the full spectral content. Integrated intensity curves calculated using the energy FWHM bandwidths are shown in figure 5(b) with associated power law fits shown as dashed lines. The experimental harmonic intensity values are plotted in black for comparison. Figure 5(c) shows how the scale length of the solid density plasma dramatically alters the harmonic production. With varying scale length, the simulated harmonic intensity efficiency ($I_n = I_0 n^{-p}$) varies from 4.1 < $p$ < 6.0 with a peak in harmonic efficiency occurring around $L_s = \lambda/2\pi = c/\omega_0$. This optimal scale length is consistent with previous length scale studies using an ultra-relativistic 800 nm laser [12].

The measured divergence angles (black) of the optical harmonics falls within the range of angles from the simulation seen in figure 5(d). Under ideal circumstances, i.e. spatially constant intensity and a plane wave source, the harmonic angular divergence should follow the diffraction-limited divergence for a given order, $\theta_n = \theta_0/n$, where $\theta_0$ is the divergence of the incident laser [28, 29]. In practice, the laser-plasma interaction is not constant in intensity with the focal spot intensity approximately Gaussian in distribution. The 3rd harmonic looks to fall closer to the diffraction limited case, which is not consistent with simulated divergences of any length scale (colored lines). The discrepancy of the 3rd harmonic divergence is likely due to a non-relativistic harmonic generation mechanism. The 4th harmonic falls almost identically along the trend lines of the simulated harmonics, which would indicate it is most likely due to the high-intensity laser-plasma interaction.

The experimental harmonic intensity measurements from figures 2(a) and (b) suggests that the laser-plasma interactions are occurring with very short plasma scale lengths. This can be inferred from the difference in the harmonic intensity power law decay for the silica target compared to the silicon wafer and through comparison with the simulated length scale study. Silica has a higher ionization potential than silicon, so silica must have a shorter plasma scale length. In order for silica to have a harsher power law decay than silicon, the interactions must be occurring for length scales shorter than the ideal $L_s = c/\omega_0$. Therefore, the OPA-driven laser-plasma

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**Figure 5.** Simulation results. Note the logarithmic scale of (a) and (b). (a) Example spectra for $L_s < c/\omega_0$ (yellow), $L_s \approx c/\omega_0$ (blue), and $L_s > c/\omega_0$ (pink). (b) Example integrated intensity measurements comparing simulation (color) versus experiment (black) harmonic emission. Dashed lines are power law fits ($I_n = I_0 n^{-p}$) to simulated results. (c) Power law fit coefficient as a function of length scale. Increase in efficiency near $L_s = c/\omega_0$. (d) Example divergence measurements for simulated (color) versus experimental (black) harmonic emission.
interactions most likely occur with near perfect step-function-like density profiles due to improved pulse contrast inherent in the OPA process. However, due to the lack of detectable CWE harmonics, the scale length cannot be much shorter than $L_s < \lambda/15$, which is the requirement for the generation of CWE harmonics [9]. The pre-pulse contrast of the CUOS Lambda Cubed laser has been shown to achieve $\lambda/10$ scale lengths in previous experiments with comparable contrasts expected after the OPA process used during this experiment [30]. This can be confirmed by pre-ionizing the target with a heater beam to determine if the ROM harmonic efficiency increases with additional plasma scale length.

5. Conclusion

In conclusion, we have demonstrated the generation of optical order harmonics up to the 6th order of 1.3 $\mu$m wavelength (217 nm) and 5th order of 2 $\mu$m wavelength (400 nm) with accompanying divergence measurements for $3\omega_0$ and $4\omega_0$ of the 2 $\mu$m wavelength interaction. We have shown that the measured harmonics follow selection rules in agreement with the ROM model of laser-solid high harmonic generation. We determined the plasma scale length from 2D PIC simulation validation of experimental results. The inherently shorter scale lengths produced via OPA laser-plasma interactions and the comparison of the measured harmonic emission with simulations both suggest that the interaction is taking place with an extremely sharp plasma density profile.

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