Second Harmonic Light Generation From Plasma Apertures Modelled in Particle-in-cell Simulations

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INTRODUCTION AND MOTIVATION

- Interest in generating higher-order structured light at high intensities (>10^{18} Wcm^{-2}) has been developing in recent years [1,2]. The predominant motivation of this comes from the ability to exercise control over the spatio-temporal profile of the resultant light which has the potential to be applied to laser-driven particle acceleration medical science, imaging, optical communication and inertial confinement fusion .
- Here we have investigated second harmonic ($2\omega_L$) light generation from an intense laser-pulse interacting with a micron-scale planar target with a preformed aperture on the order of the laser focal spot. This builds on previous work [3,4], exploring the effect of the initial target electron density on the $2\omega_L$ conversion efficiency and laser propagation.

STRUCTRURED SECOND HARMONIC LIGHT GENERATION

- Relativistically intense laser pulse (I >10^{18} Wcm^{-2}) interacts with a relativistically self-induced transparent aperture (RSIT) or a pre-formed aperture target.
- Intense light at fundamental, ω_L, and higher harmonic frequencies of the laser are produced with distinct spatial structure.

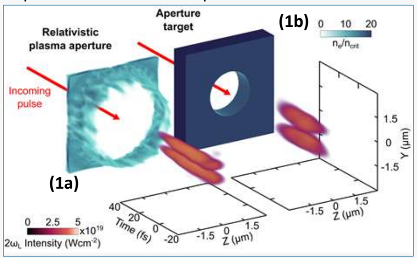

Fig 1a - Laser pulse interacts with nm-thick solid target forming plasma aperture via RSIT, $2\omega_L$ light is generated at the aperture in laser propagation direction [3].

Fig 1b - Laser pulse interacts with pre-formed aperture μm-thick targets show increased conversion efficiency to $2\omega_L$ light [4].

- Driver interacts with electron population around aperture and accelerates them in bunches along the laser axis through the aperture.
- Acceleration and deceleration of the electron bunches at the surfaces and the oscillating aperture generate harmonics with higher order spatial modes.

SIMULATIONS AND SECOND HARMONIC CONVERSION EFFICIENCY

- Laser-pre-formed aperture interaction was simulated using the fully relativistic PIC code EPOCH in 2D [2] to investigate the generation frequency doubled light specifically.
- A $2\omega_L$ bandpass filter was applied to the spatial transverse electric field.
- The $2\omega_L$ signal at each output timestep (δt = 10 fs) was calculated by spatially integrating a 3 μm spatial region 5 μm after the rear of the target.
- This was then temporally integrated over the whole simulation to give the $2\omega_L$ conversion efficiency:

$$\eta_{2\omega L} = \frac{\int_{t_0}^{t_1}\int_{x_0}^{x_1} E_{y,\,2\omega_L}\,dx\,dt}{\int_{t_0}^{t_1}\int_{x_0}^{x_1} E_{y,\,1\omega_0}\,dx\,dt} \text{ x } 100$$

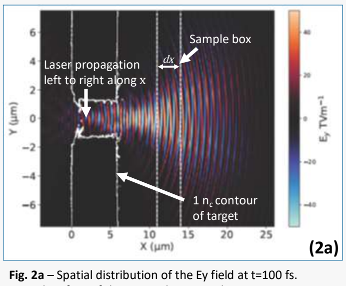

Fig. 2a – Spatial distribution of the Ey field at t=100 fs. Critical surface of the target shown in white

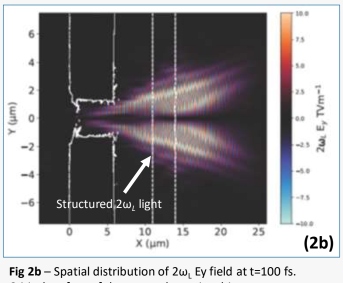

Fig 2b – Spatial distribution of $2\omega_L$ Ey field at t=100 fs. Critical surface of the target shown in white

APERTURE-DENSITY SCAN

- Previous work [4] has shown $\phi_L \approx$ aperture diameter is optimal for improving $\eta_{2\omega L}$.
- The efficiency is also dependent on quantity of laser light entering aperture, strength of the longitudinal field of the focused laser and laser absorption into the plasma

$$\eta_{2\omega L} \propto |E_X(d/2)|Abs_L(l)\,K_{in}(d)$$

- Performed a 2D parameter scan of the aperture diameter and density, n_e for I_L = 10^{21} Wcm^{-2} , λ_L = 800 nm , ϕ_L = 2.1 μm , τ_L = 40 fs and 6 μm – thick targets
- $2\omega_L$ yield improved to 3.9 % with the optimal aperture diameter 1.9 μm and n_e = 16 n_{crit}

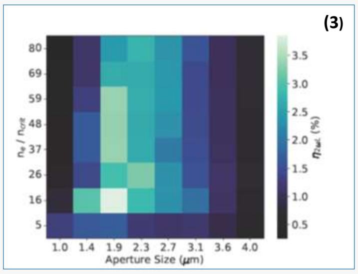

Fig 3 – $2\omega_L$ conversion efficiency as a function of aperture diameter and initial target density

LASER AND PLASMA EVOLUTION WITH DENSITY

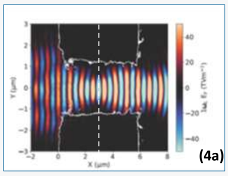

Fig. 4a $1\omega_L$ Ey field at t=100 fs for a 6 μm target with initial density 16 n_{crit}

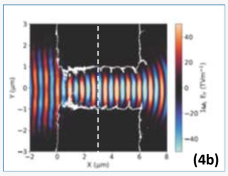

Fig. 4b $1\omega_L$ Ey field at t=100 fs for a 6 μm target with initial density 80 n_{crit}

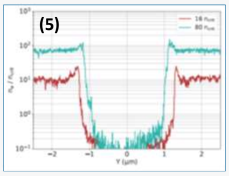

Fig. 5 Relativistically corrected density at X=3 μm and t=100 fs

- For lower density targets, the aperture radius can temporally evolve to become significantly wider due to the spatial pondermotive force of the laser pulse.
- The front surface can become tapered to the laser field leading to a variation in the focal position of the propagating laser pulse.
- The tapered channel guides and focuses the laser into the central region of the aperture allowing higher intensities to be reached and reinteraction with aperture edges.
- Conversely at higher densities the laser pulse remains collimated through the aperture.
- $2\omega_L$ light generated is more divergent but higher in energy with a low-density target.
- For a high-density target, the $2\omega_L$ generated light is lower in energy and more collimated.

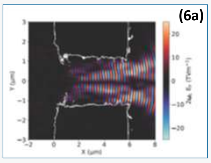

Fig 6a $2\omega_L$ Ey field at t=100 fs for a 6 μm target with initial density 16 n_{crit}

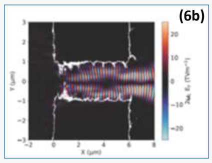

Fig 6b $2\omega_L$ Ey field at t=100 fs for a 6 μm target with initial density 80 n_{crit}

- By reducing the target thickness the reinteraction of the laser at lower densities is reduced.
- This leads to a variation in the efficiency trends for target thickness for targets of different initial densities.

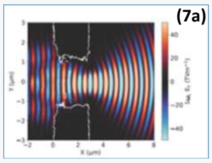

Fig. 7a $1\omega_L$ Ey field at t=100 fs with a 3 μm target with density 16 n_{crit}

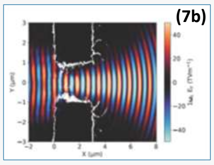

Fig. 7b $1\omega_L$ Ey field at t=100 fs with a 3 μm target with density 80 n_{crit}

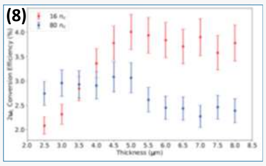

Fig. 8 Variation in $2\omega_L$ efficiency for target thickness for 16 n_{crit} and 80 n_{crit} targets

DISCUSSION AND FUTURE WORK

- Combined effects of the formation of the evolution of aperture diameter, the tapering of the front surface, the subsequent laser self-focusing and re-interaction with the aperture leads to improved efficiency of the generation of $2\omega_L$ light for lower density targets.
- For experiments, lower density targets are not practical but the effect may be reproduced by introducing a pre-plasma scale length on a solid density target.
- Initial testing with defined scale-lengths have demonstrated this.
- As efficiency varies with a large number of parameters, machine learning techniques are being investigated to optimize this behaviour.

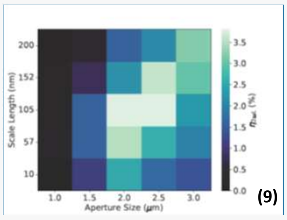

Fig 9– $2\omega_L$ conversion efficiency as a function of aperture diameter and scale-length

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