Temporal Characterization of Low-Order Harmonics from a Relativistic Plasma Mirror

V. Dewan,[1] X. Xu,[1] V. Leshchenko,[2] Z. Li,[1] A.Das,[1] and J. M. Mikhailova[1]

[1]*Princeton University, Princeton, New Jersey, 08544*
[2] *LCLS, SLAC, Menlo Park, California, 94025*

MIKHAILOVALAB
ETOILES

1. Introduction

A plasma mirror forms when an intense laser pulse ionizes a solid target, creating a dense plasma layer that reflects the incident light. In the relativistic regime ($I > 10^{18} Wcm^{-2}, \lambda = 800nm$), plasma mirrors generate harmonics [1–5] extending into the EUV/soft X-ray range.
Unlike gas-phase HHG, which is limited to $\sim 10^{15} Wcm^{-2}$ by ionization, relativistic surface high-harmonic generation (RSHG) has no fundamental intensity limit.
Low-order harmonics can be generated with efficiencies exceeding 20% [6], making RSHG a promising source of intense few-cycle pulses, with the potential to produce PW-class UV sources (200–400 nm) and enable multi-color waveform synthesis at next-generation laser facilities.

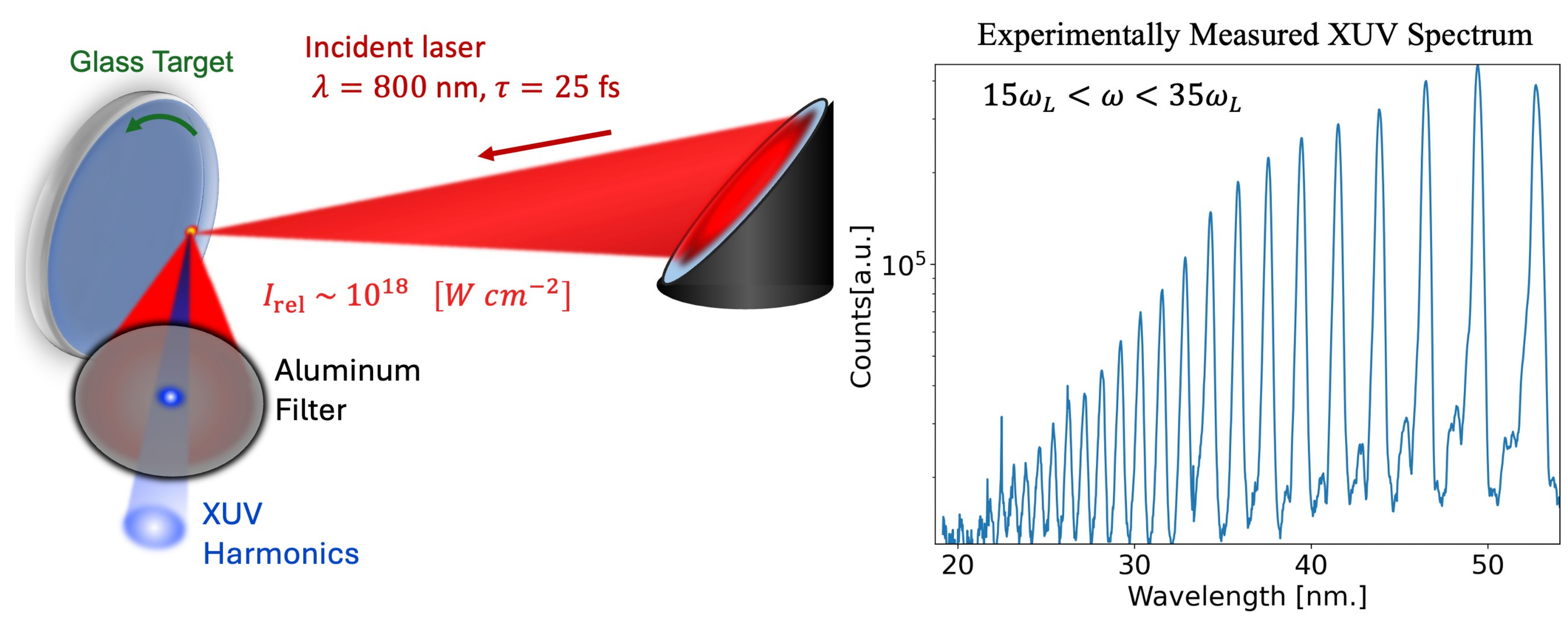


Figure. 1. Schematic of relativistic harmonic generation from a solid target (left). Experimentally measured XUV spectrum from a plasma mirror in our laboratory (right).

2. Coherent Synchrotron Emission (CSE)

The Coherent Synchrotron Emission (CSE) [4, 5] model shows that for a single-cycle of a laser pulse at relativistic intensities, electron bunches in the plasma perform synchrotron-like trajectories and emit intense bursts of coherent and broad-bandwidth radiation with pulse widths as short as attoseconds

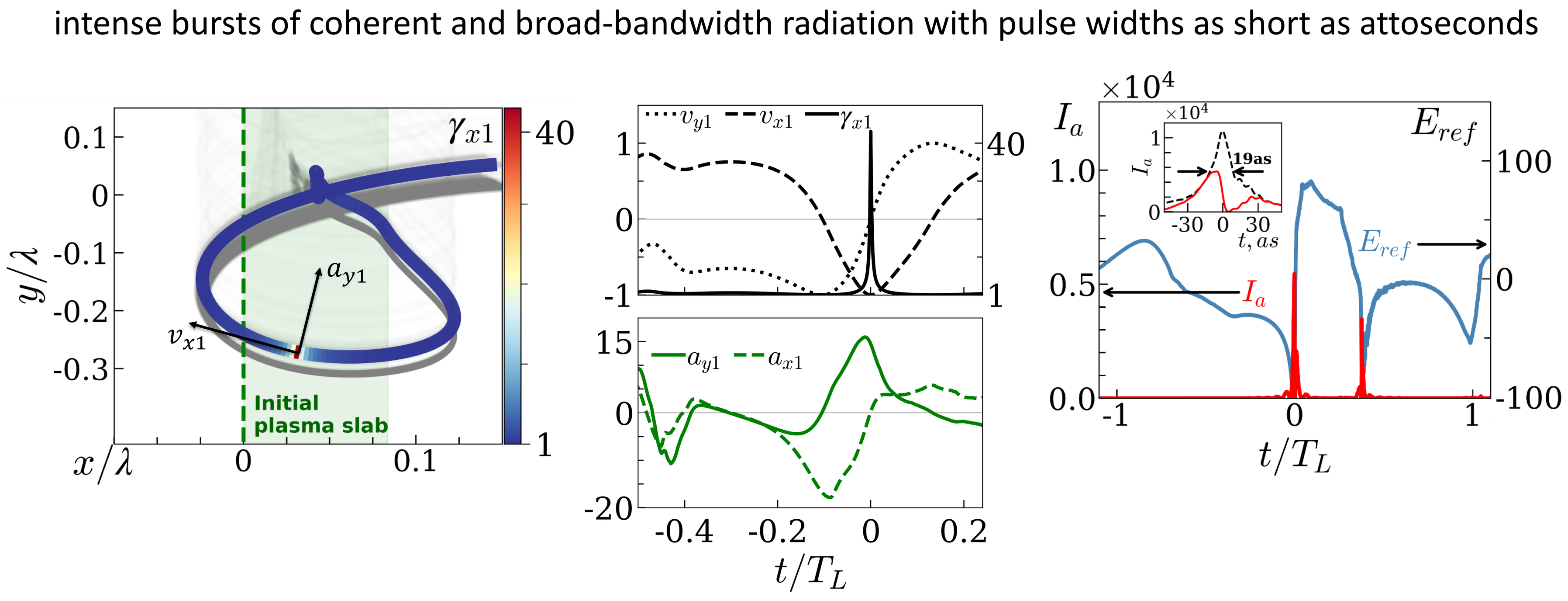
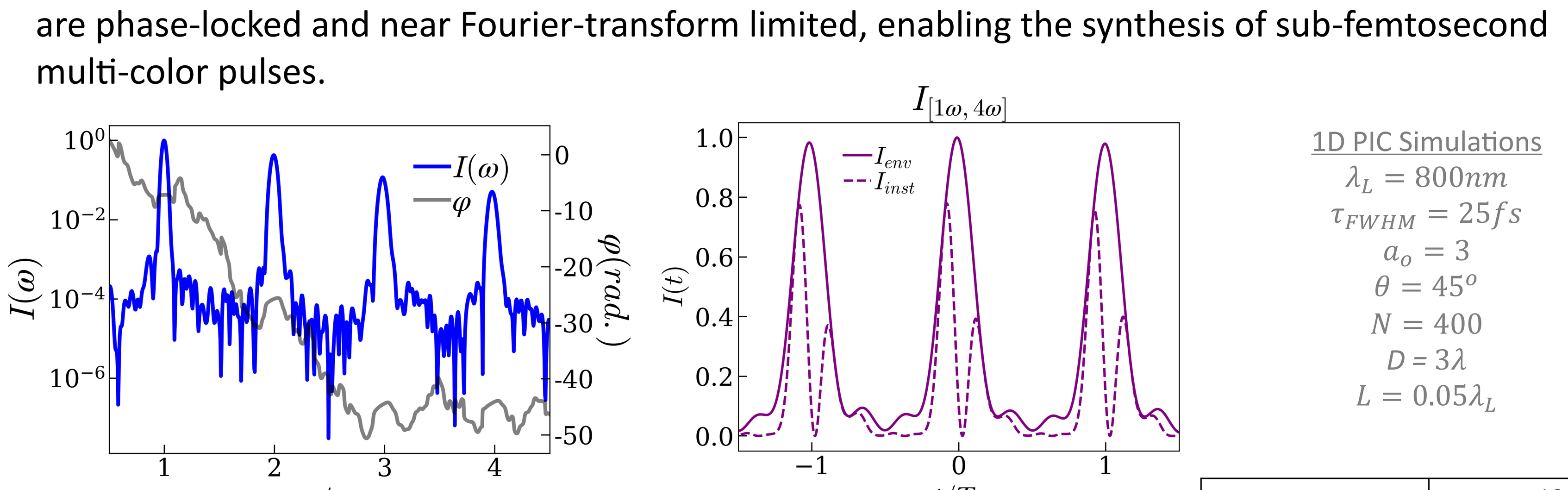


Figure. 2. 1D EPOCH particle-in-cell (PIC) simulations: Synchrotron-like trajectories for leading electron bunches (left). Velocities, acceleration and Lorentz factor in the specular direction for leading electron bunches (center). Total reflected electric field and attosecond pulse intensity after spectral filtering in the range $10 < \frac{\omega}{\omega_o} < 400$ (right) [7].

3. Multi-color Waveforms

Low-order harmonics generated from plasma mirrors offer a promising route to multi-color waveform synthesis at terawatt- and petawatt-scale laser facilities. Simulations indicate that these harmonics are phase-locked and near Fourier-transform limited, enabling the synthesis of sub-femtosecond multi-color pulses.



Harmonic Range	$\tau_{FWHM}(fs)$
1ω	4.3
$[1\omega, 2\omega]$	1.4
$[1\omega, 3\omega]$	0.9
$[1\omega, 4\omega]$	0.7

Figure. 3. 1D EPOCH PIC simulations: The spectral phase and amplitude of the first four harmonics from a plasma mirror for our experimental conditions. The simulated spectral phase of the low-order harmonics is smooth and flat over all regions above the noise floor (left). Pulse train of sub-femtosecond pulses after spectral filtering in the range $1 < \frac{\omega}{\omega_o} < 4$ (right).

4. Experimental Setup

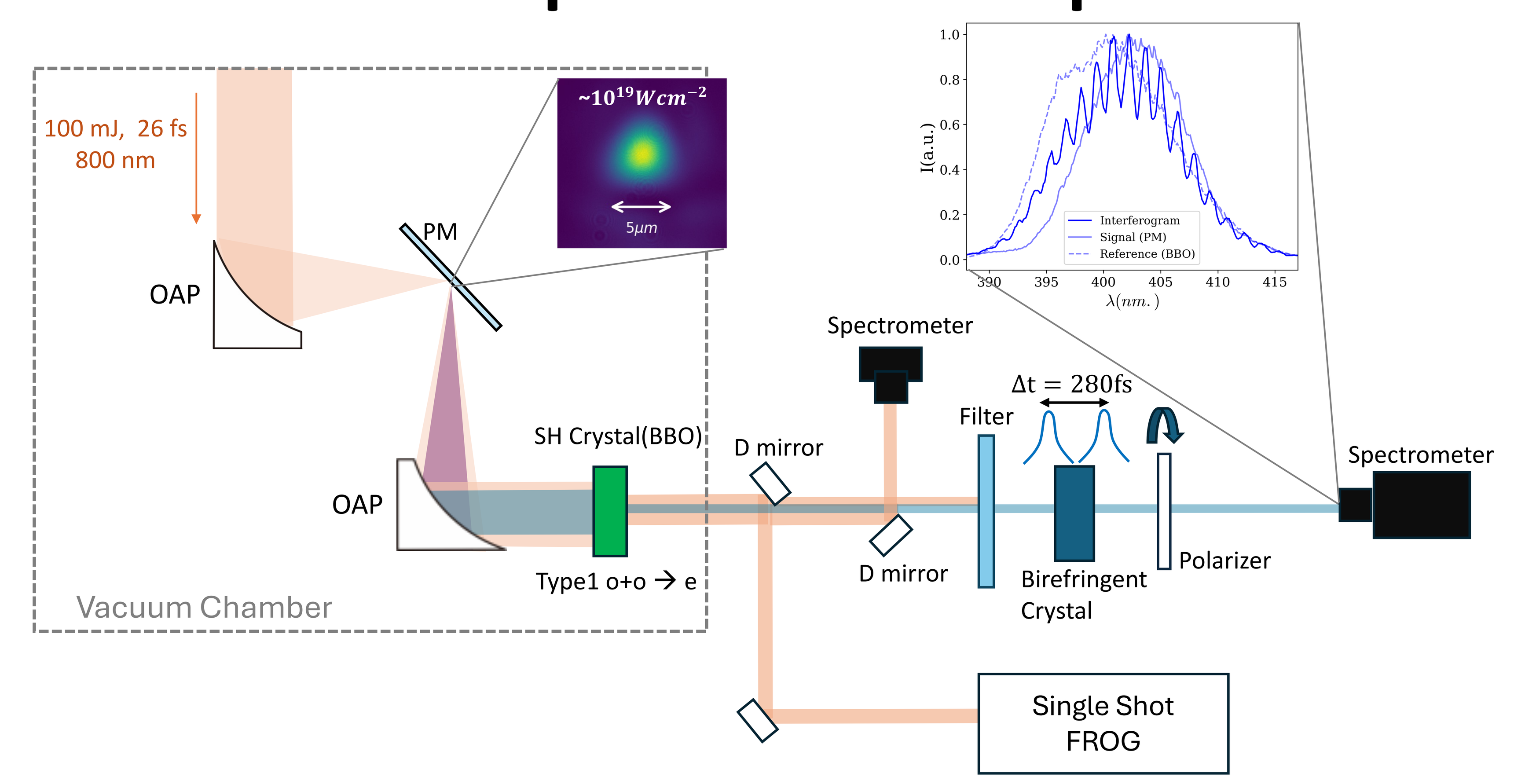


Figure. 4. Experimental setup at the ETOILES laboratory using a 20TW Ti:Sapphire laser. The beam was focused onto a plasma mirror at a 45^o angle of incidence with an f/2.5 OAP, reaching $10^{19} Wcm^{-2}$. The reflected fundamental and plasma-mirror second harmonic (SH) were recollimated, and a $100\mu m$ BBO crystal generated a reference SH from the fundamental. A split-off beam was characterized using single-shot FROG. After removing the residual fundamental, the orthogonally polarized signal and reference SH pulses were delayed in a calcite wafer and selected with a polarizer for spectral interferometry.

5. Temporal Measurement of the Second Harmonic (SH)

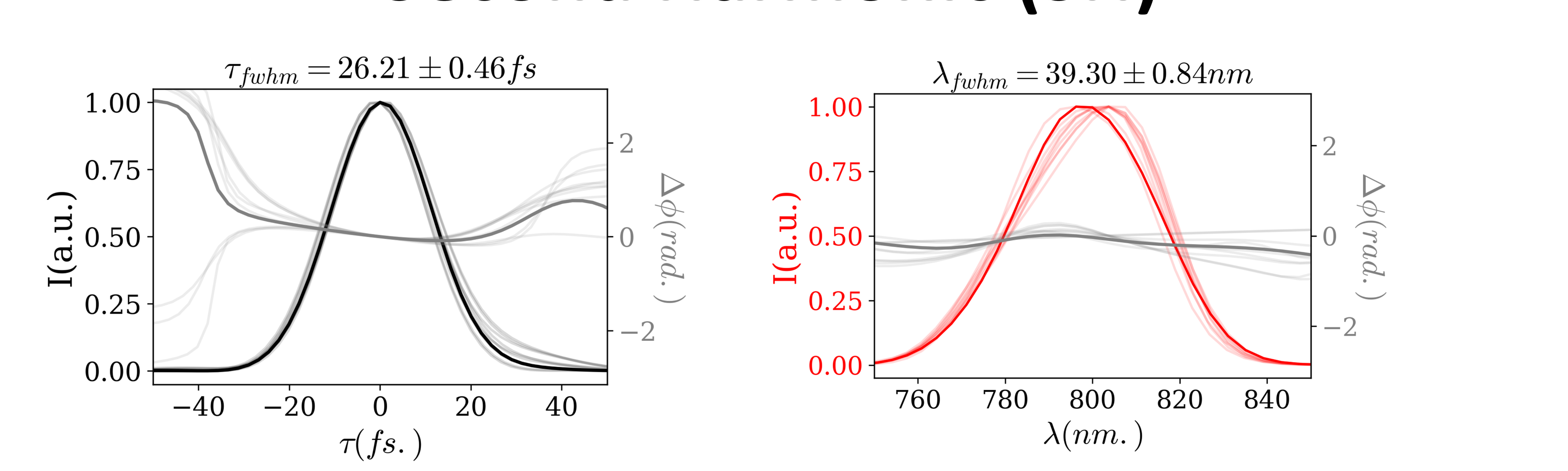


Figure .5. Temporal and spectral measurement of the fundamental reflected from the plasma mirror.

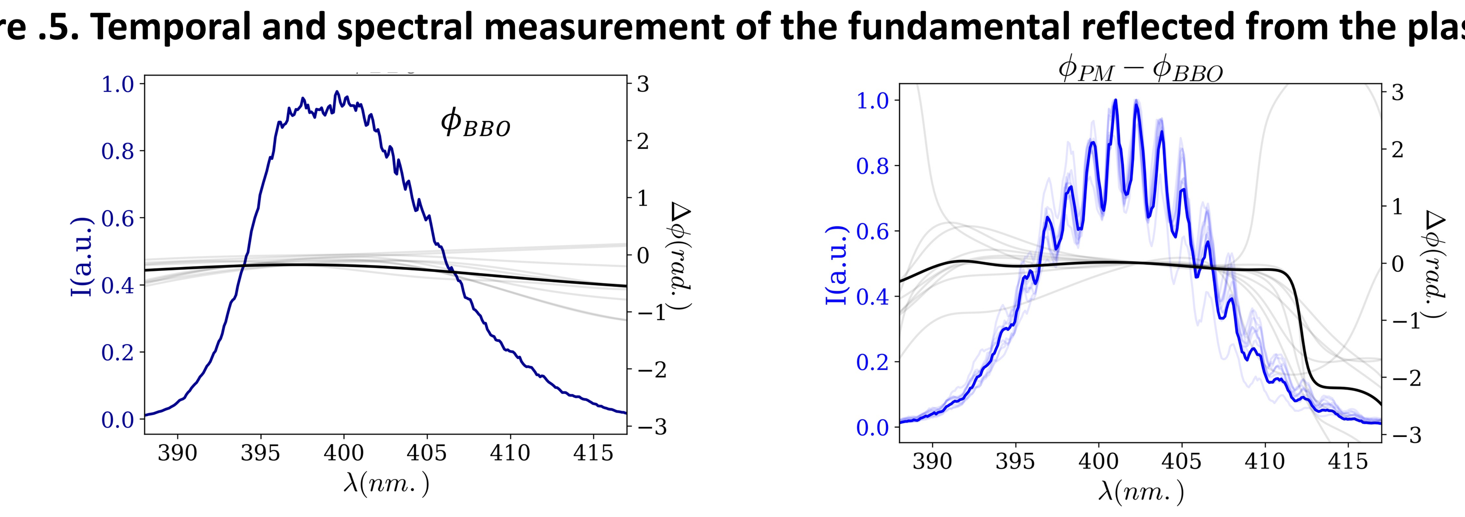


Figure .6. Phase and amplitude of the reference (BBO) SH calculated from the SSFROG measurements (left). Phase difference between the signal (PM) and reference (BBO) SH calculated from the interferogram (right).

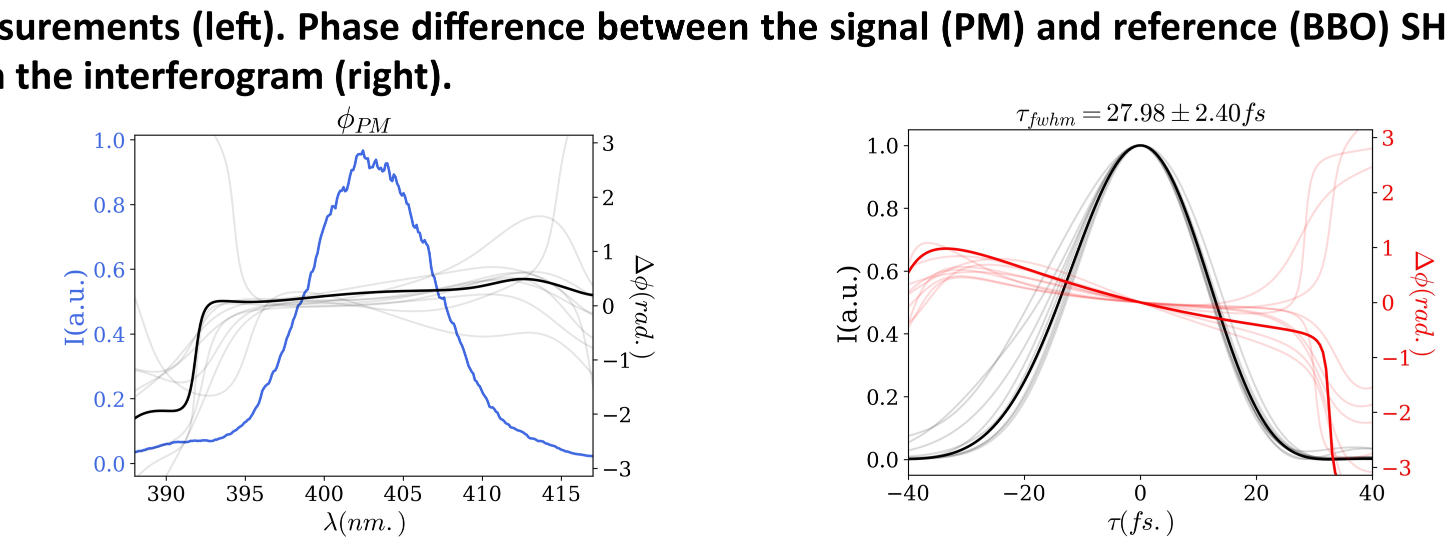


Figure .7. Temporal and spectral phase and amplitude of the SH from the plasma mirror.

6. Conclusion

Together, our measurements and simulations demonstrate that plasma mirrors can generate near FTL low-order harmonics with high mutual coherence, preserving the phase characteristics of the driving field.

This capability is promising for PW-scale multi-color synthesized pulses and sub-femtosecond pulses.

As a next step, we will then extend our spectral-interferometry approach to the third harmonic, using the SH+fundamental from the plasma mirror to generate the reference third harmonic pulse in a thin BBO crystal.

We will also use spectral shearing interferometry to measure the temporal characteristics of the XUV harmonics [8,9]

References

1. M. J. Streeter, et al., New Journal of Physics 13, 023041 (2011).
2. F. Quer ́e, et al., Physical Review Letters 96, 125004 (2006).
3. P. Heissler, et al., Applied Physics B: Lasers and Optics 118, 195 (2015).
4. J. M. Mikhailova, et al., Physical Review Letters 109, 245005 (2012).
5. M. R. Edwards, J. M. Mikhailova, Scientific Reports 2020 10:1 10, 1 (2020).
6. M. R. Edwards, et al., Optics Letters, Vol. 45, Issue 23, 6542 (2020)
7. V. Dewan, et al, https://arxiv.org/abs/2604.20672 (2026)
8. Y. Mairesse, et. al., *Phys. Rev. Lett*. **94**, 173903 (2005)
9. C. Wu, et. al., *Opt. Express* **30,** 389-402 (2022)

Acknowledgments

This work was supported by the NSF Grants No. PHY 2206711, PHY 2512131, DOE Grant DE-SC0025497, and by the Gordon and Betty Moore Foundation, grant DOI 10.37807/GBMF12255. V.D. gratefully acknowledges support from the Program in Plasma Science and Technology of Princeton University.

The EPOCH code was developed as part of the UK EPSRC 300 360 funded project EP/G054940/1.

vd7785@princeton.edu j.mikhailova@princeton.edu