U.S. NAVAL RESEARCH LABORATORY

AE128: Ionization Currents and Secondary Radiation from Two-Color Pulses at Long Laser Wavelengths

Proposal # 312798

Funding Status: NRL Base Program, Received

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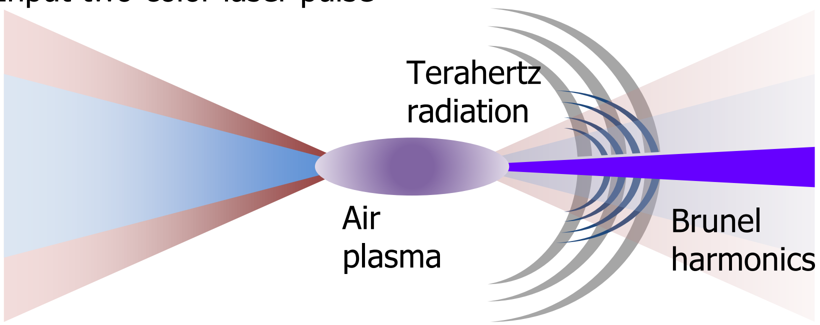
Proposed Objectives for AE128

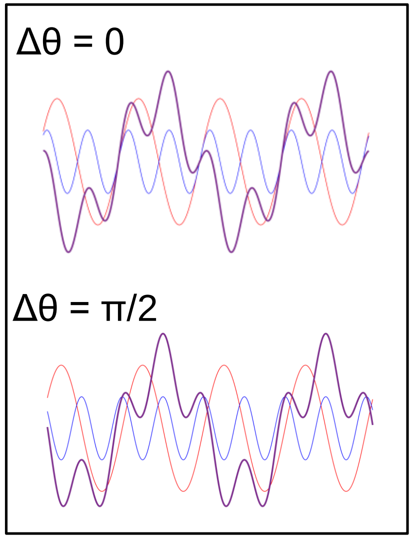
- **Map wavelength dependence of air ionization**
- Use a two-color pulse to coherently control ionization currents – make it easier to interpret diagnostics based on secondary radiation
- Secondary radiation = microwaves, THz, and Brunel harmonics
- Link early and late plasma characteristics with concurrent measurements of the plasma size, density, and optical emission spectrum
- Integrate LWIR results in comparison study with NIR, SWIR, MWIR wavelengths with different lasers (Ti:S and OPA)

Input two-color laser pulse

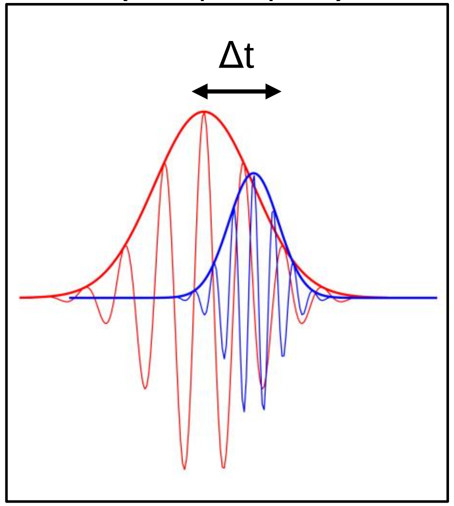


Microwave radiation

Relative phase (intra-cycle)

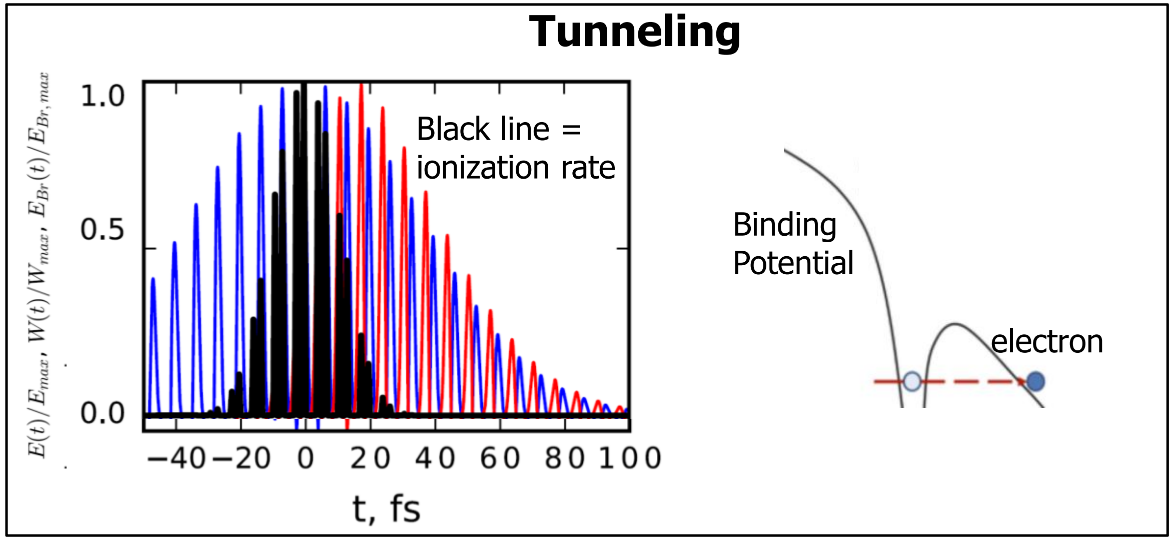


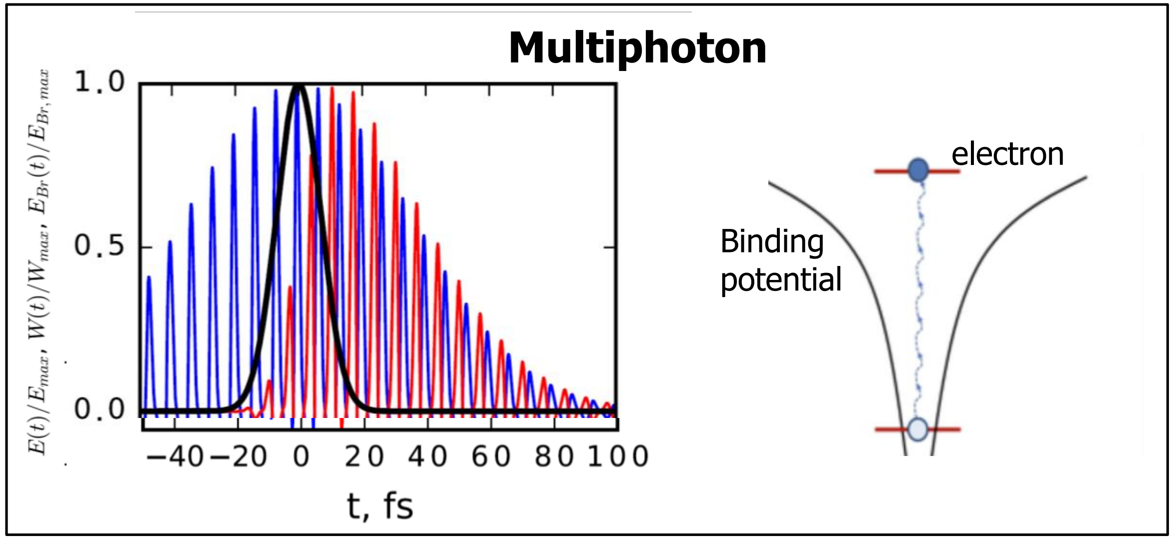
Envelope overlap (multiple cycles)



Ionization Currents Determine Secondary Radiation

- Optical field ionization by intense laser pulses occurs in the tunneling or multiphoton regime – Keldysh theory
- For ionization of atmospheric air, traditional NIR sources ionize via multiphoton
- Long wavelengths are needed to drive tunneling ionization in air
- The liberation of electrons constitutes an ionization current, whose time dependence can be step-like (tunneling) with each laser field maximum, or vary slowly with the laser envelope (multiphoton)
- The relative phase of a two-color pulse changes the shape of the laser electric field waveform, and thus the ionization currents





I. Babushkin, *J. Mod. Opt.* 64(10), 1078 (2017).

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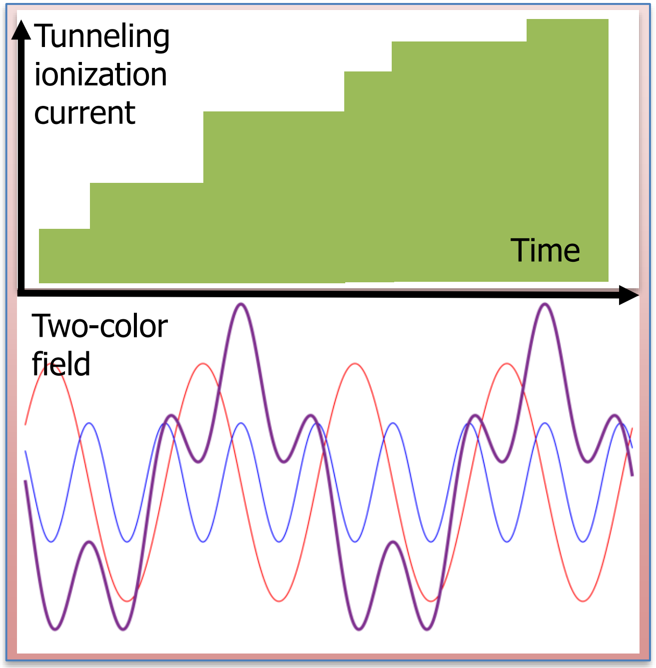
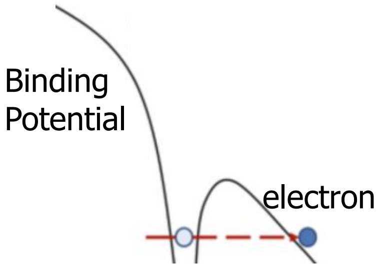
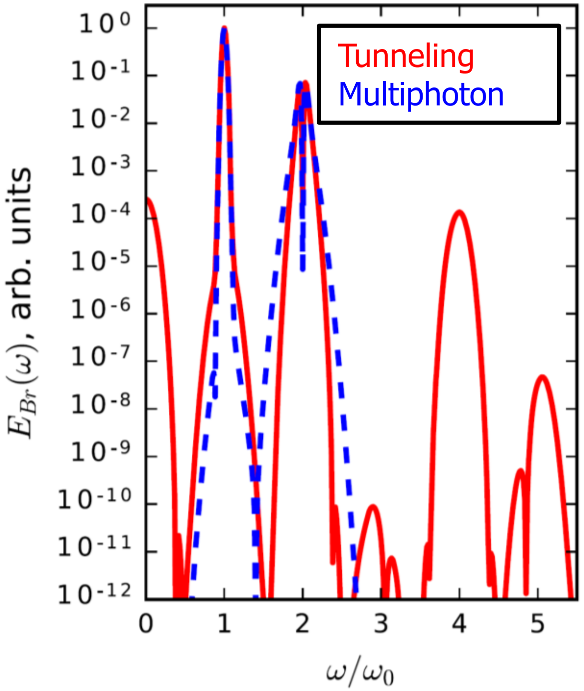


Tunneling





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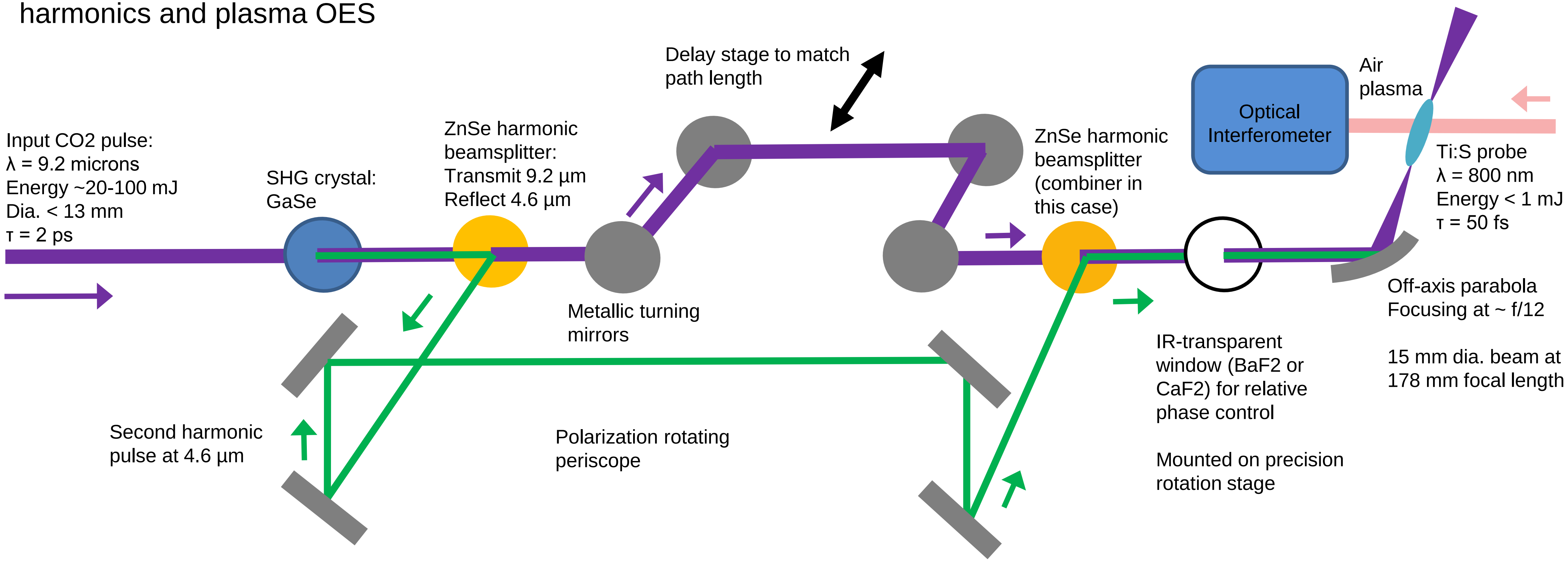
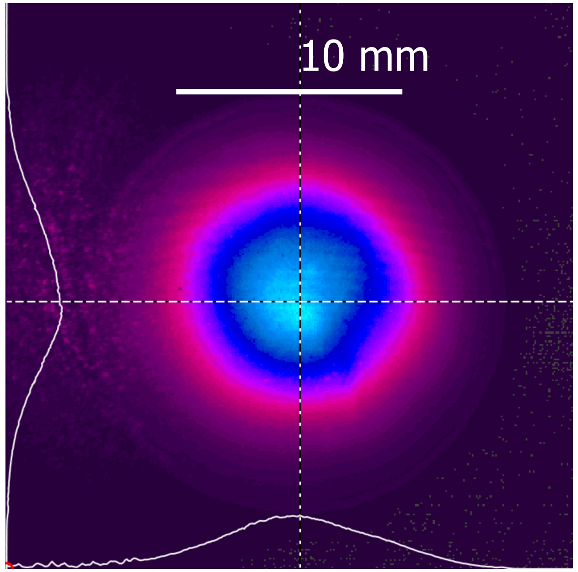
First BNL Experiments Feb-March 2024

- Second harmonic generation by type-1 phase matching in GaSe
- Optical setup co-polarizes 1ω and 2ω fields by rotating 2ω polarization by 90 degrees
- Other diagnostics viewing the air plasma: d-dot probe, visible camera, spectrometers for laser harmonics and plasma OES

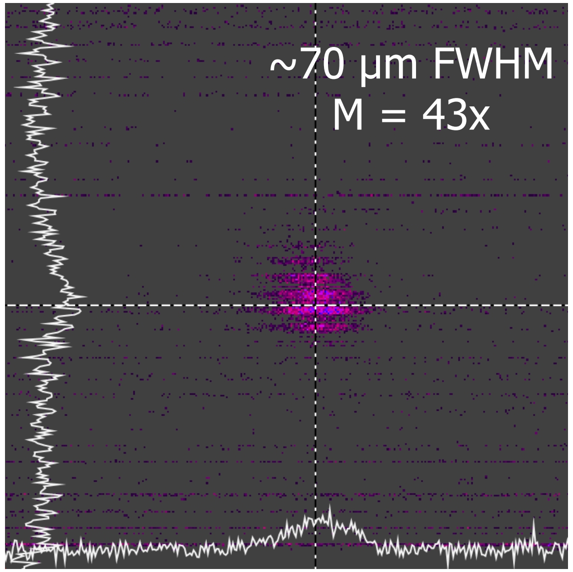


Generated Two-Color LWIR pulses GaSe for SHG

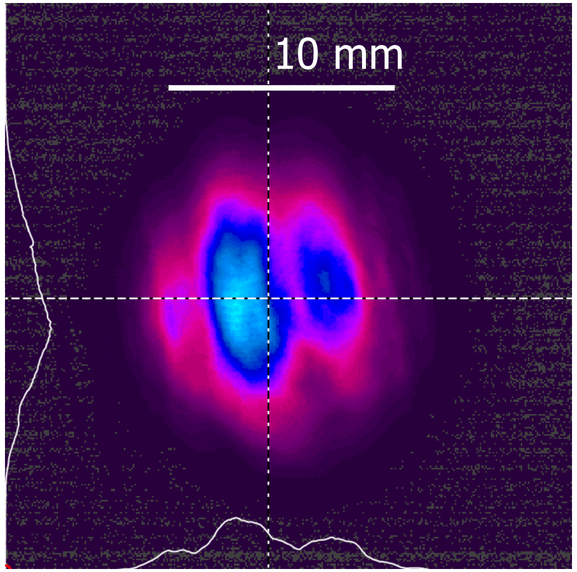
Input 9.2 μm Profile



OAP Focal Spot



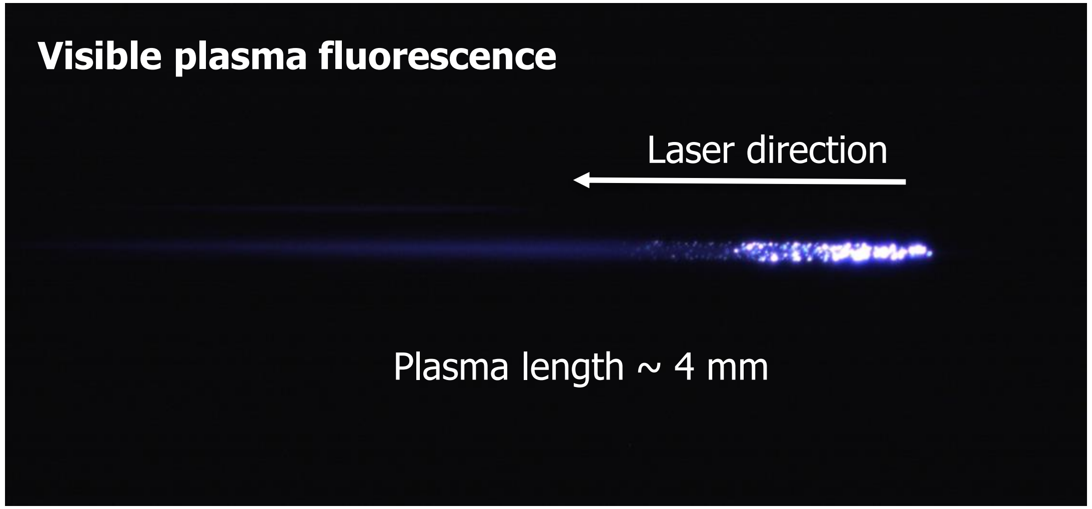
Input 4.6 μm Profile

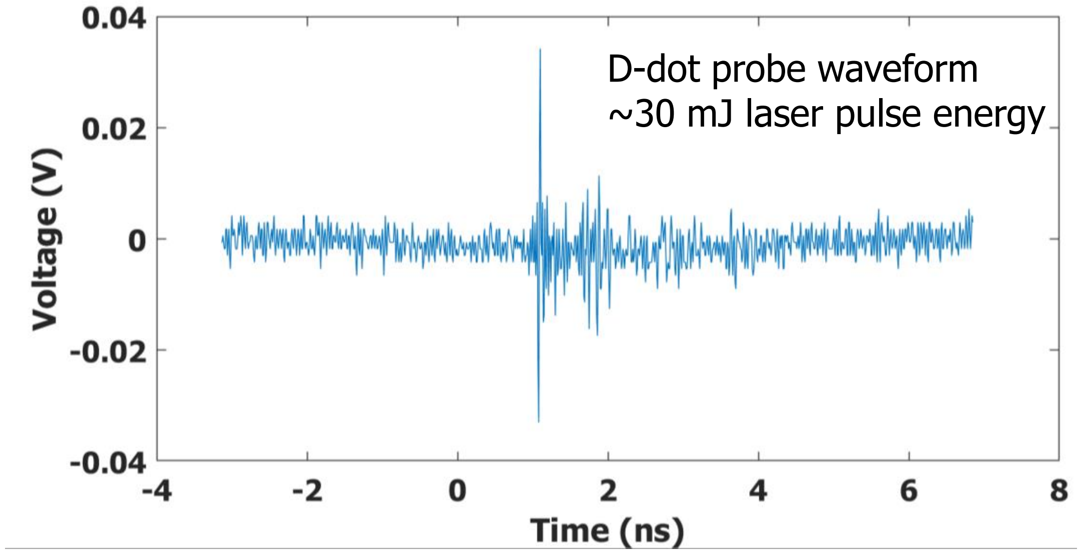


- Good input beam quality led to ~70 μm FHWM focal spot
- Keldysh parameter ~ 0.04, focal intensity ~ 10^{14} W/cm^2
- Achieved sufficient SHG conversion efficiency (~7%) for two-color pulse
- GaSe crystal quality is not great - note structure in 2ω profile
- ~50% energy throughput due to reflections – lose ~30% pulse energy on each crystal surface

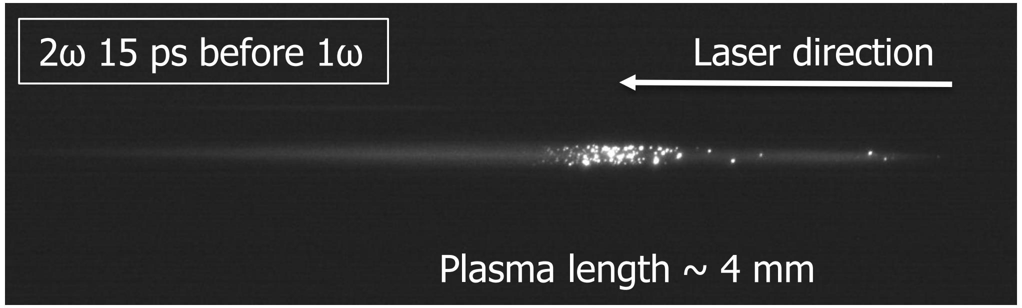
Summary of Preliminary Results

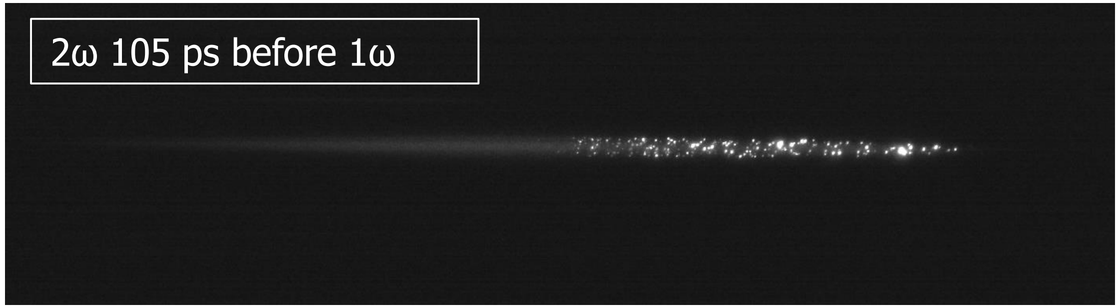
- Collisional ionization by second harmonic
- Microwave radiation amplitude likely upholds ponderomotive scaling
- No evidence of coherent superposition of laser harmonics
- Did not observe Brunel harmonics or nonlinear harmonic generation. 2.2 μm was the longest wavelength we could measure
- Spectrometers, interferometer will benefit from new alignment procedures

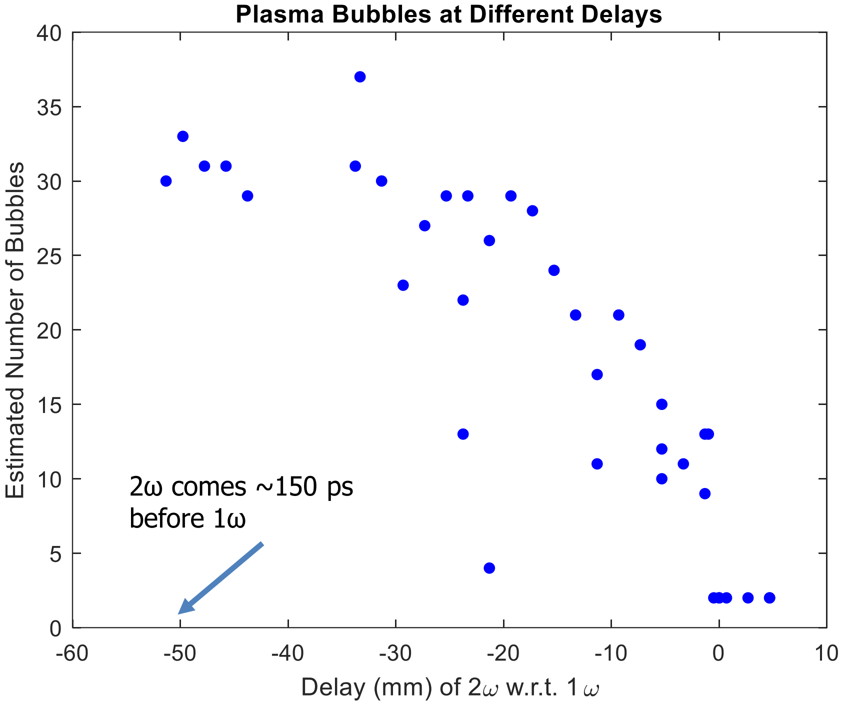


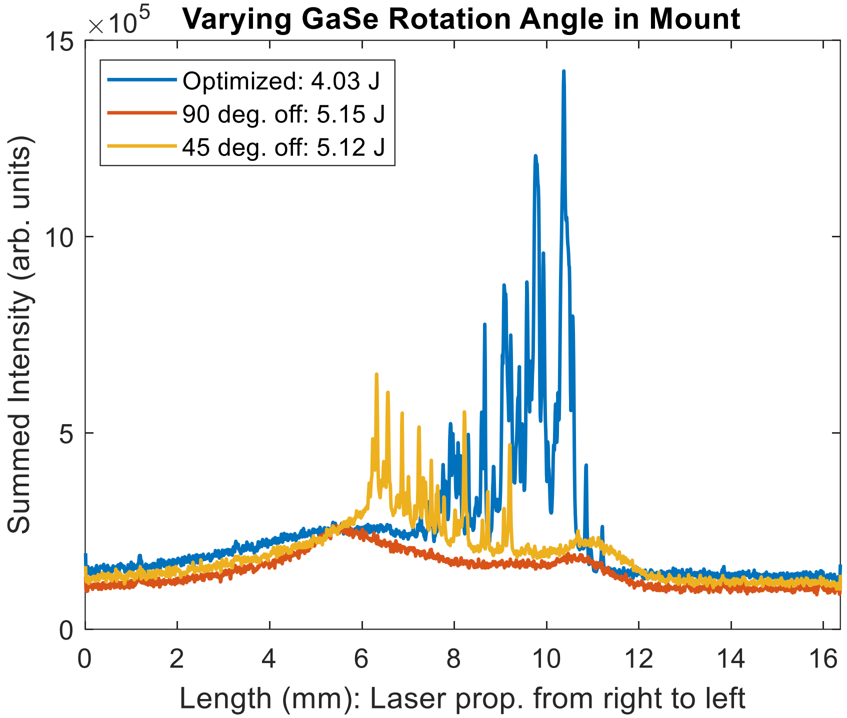


Second Harmonic Field Mediates Collisional Ionization





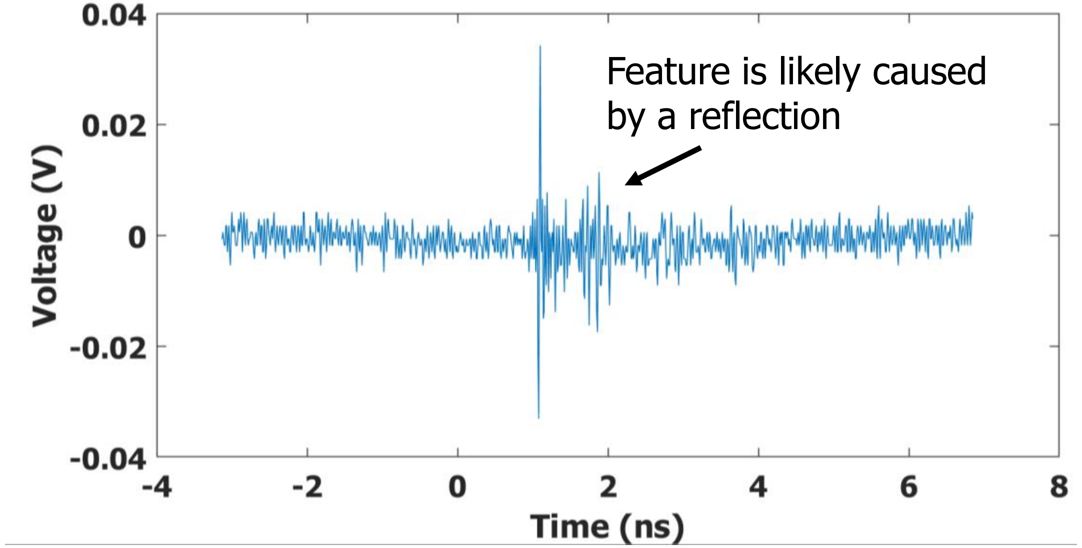




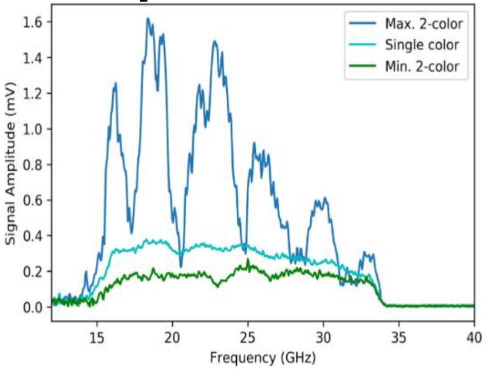
Two-Color Enhancement Absent for Microwave Radiation

NRL PPD

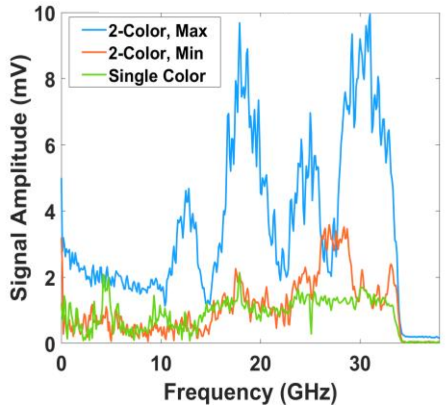
- Microwave amplitude is large considering 15 GW peak power (~30 mJ going into focusing optic in 2 ps pulse) – expected from ponderomotive scaling
- With a NIR laser pulse peak power of 15 GW in similar focusing geometry microwave peak power would probably not exceed noise floor without amplification
- When two-color pulse is properly phased, observe amplitude enhancement and spectral modulations (see NIR, SWIR examples)
- We did not see amplitude enhancement or change in spectrum during delay stage scans
- Careful analysis required



SWIR, picosecond



NIR, femtosecond



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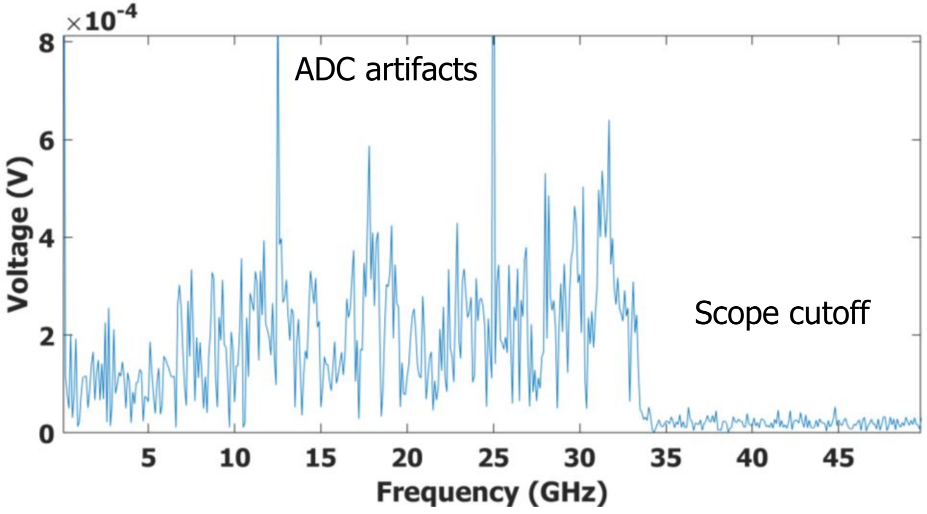
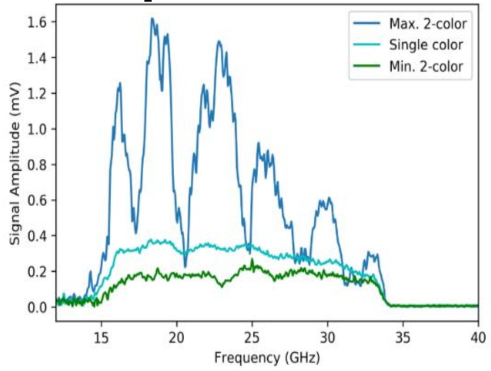
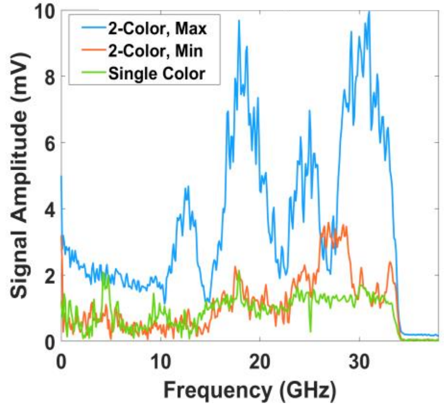


SWIR, picosecond



NIR, femtosecond



Future Plans

- Need to work on theory and simulation to explain collisional ionization
  - HITRAN – species identification
  - CHMAIR+SPARC – simulate air chemistry in time (and space)

- Expand scope of experiments:
  - Continue working on original idea – relative phase control of a two-color pulse
  - Explore physics of collisional ionization – existing diagnostics might cover this

- Each of the above will likely require distinct but similar setups
  - Relative phase control – eliminate harmonic beamsplitters, acquire dual-wavelength waveplate
  - Collisional ionization – keep current Mach-Zehnder-like setup

- Increase focal intensity or lengthen confocal parameter = add ability to vary f-number – reflective beam expanders

- Vary pressure and gas species to enhance/diminish collisional ionization

Future Plans

- CO_2 laser operating point from first experiments is good
  - Keep 13 mm Teflon limiting aperture
  - ~70-150 mJ pulse energy delivered to experiment worked well
- Will use AR-coated ZGP instead of uncoated GaSe for second harmonic generation – increase energy throughput
- Test THz detector at NRL

Products Delivered

Conference Presentations:

- “Ionization of Air by Intense Long Wave Infrared Two-Color Laser Pulses”, Directed Energy Professional Society Science and Technology Symposium, May 2024

Electron Beam Requirements – Not Applicable

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Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	

CO_2 Laser Requirements

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Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	
	Peak Power	GW	~3		
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	M^2	---	~1.5		
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	
CO_2 CPA Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2 microns*
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	5	*~5 TW operation will become available shortly into this year's experimental run period. A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	*< 100 GW*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2 ps*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	*~ 100-150 mJ*
	M^2	---	~2		
	Repetition Rate	Hz	0.05		*0.05*
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*	*Linear*

Other Experimental Laser Requirements

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Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments	Requested Values
Central Wavelength	nm	800	800	*Stage I parameters are presently available and setup to deliver Stage II parameters should be complete during FY22*	*800 nm*
FWHM Bandwidth	nm	20	13		
Compressed FWHM Pulse Width	fs	<50	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.*	*~ 50 fs*
Chirped FWHM Pulse Width	ps	≥50	≥50		
Chirped Energy	mJ	10	200		
Compressed Energy	mJ	7	~20	*20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.*	*< 7 mJ*
Energy to Experiments	mJ	>4.9	>80		*< 4 mJ*
Power to Experiments	GW	>98	>1067		*<< 100 GW*

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	
Energy	mJ	5		
Pulse Width	ps	14		
Wavelength	nm	532	*Frequency doubled*	
Energy	mJ	0.5		
Pulse Width	ps	10		

Special Equipment Requirements and Hazards

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- CO_2 laser
  - Keep 13 mm Teflon limiting aperture in place

- Ti:S laser

- **New: Small vacuum/pressure vessel, gas cylinders**

- Microwave scattering diagnostic: already on ESR, but we may need to increase the power transmitted in free space

Experimental Time Request

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CY2024 Time Request

Capability	Setup Hours	Running Hours
Electron Beam		
NIR Laser	0	0
LWIR Laser	0	0

Total Time Request for the 3-year Experiment (including CY2024-26)

Capability	Setup Hours	Running Hours
Electron Beam		
NIR Laser	120	120
LWIR Laser	120	120