AE119 Radiofrequency Emission from 10 Micron Short Pulse Laser Ionized Gases and Solids

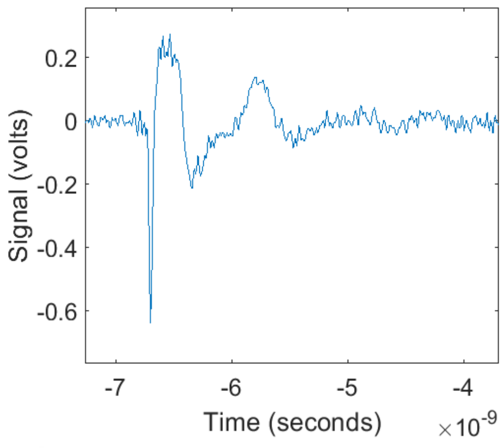
Dr. Jennifer Elle AFRL/RDH

BNL ATF Users Meeting 2025

Dr. Erin Thornton AFRL/RDH, Oli Sale Leidos, Dr. Andy Goers, JHUAPL, Dr. Brian Gibbons, JHUAPL

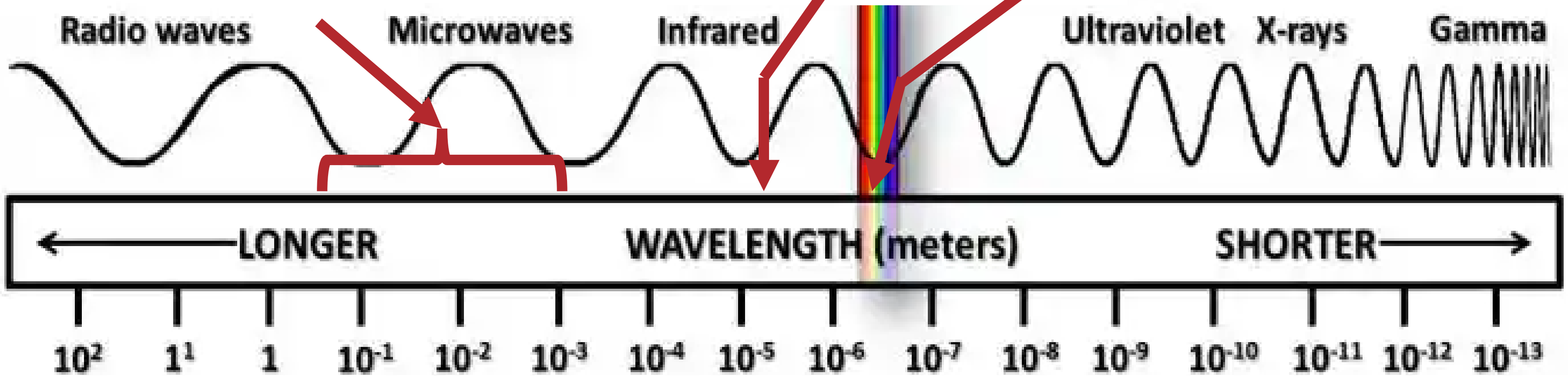
Dr. Eric Rosenthal NRL, Dr. Trenton Ensley ARL, Dr. Zachary Quine, ARL

Over multiple experimental campaigns, we observed and measured secondary down (microwaves) and up (mid IR - UV) frequency conversion generated by plasma filaments.



BNL CO_2

λ = 9.2 microns



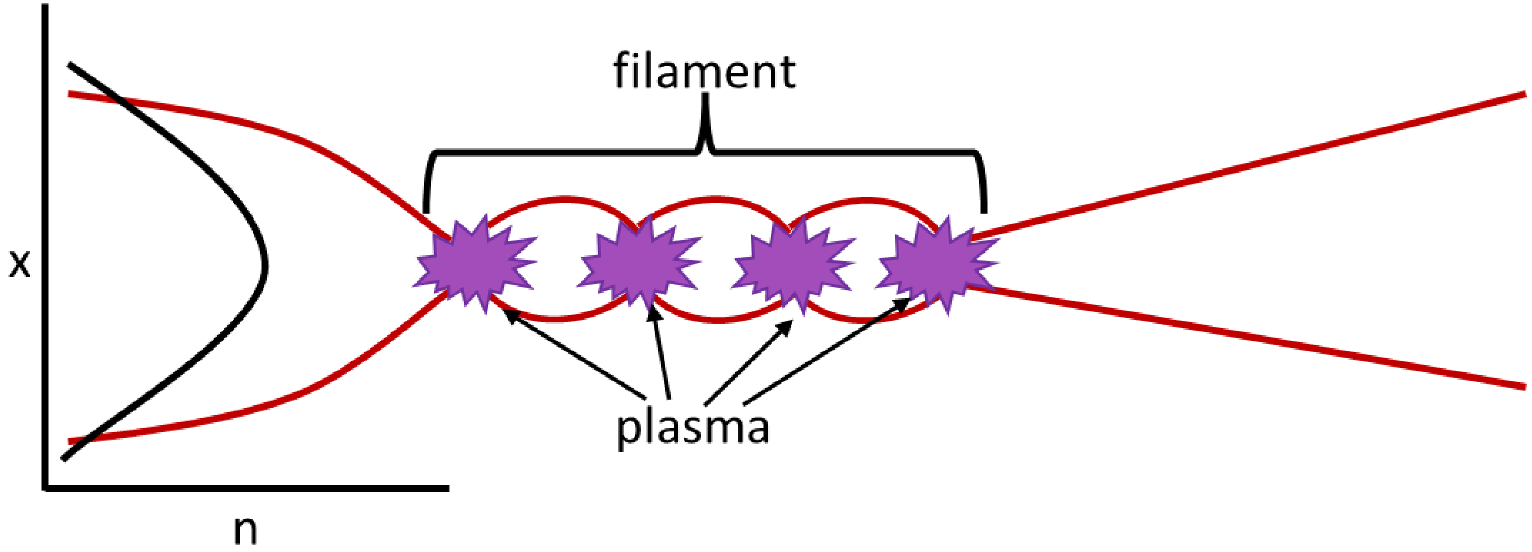
Broadband Microwave Generation

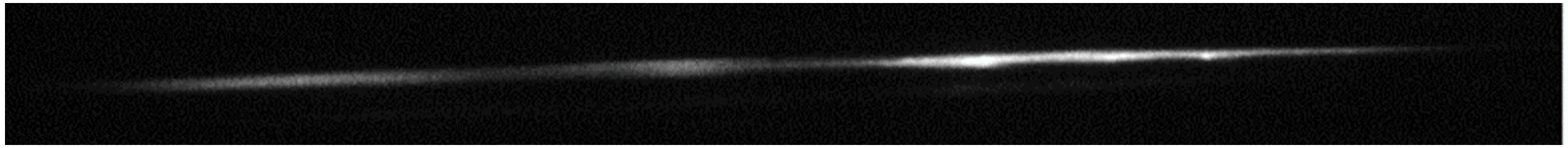
CO2 laser parameters for the microwave generation experiment

Credit: https://www.bnl.gov/atf/capabilities/co2laser.php

Wavelength:	9.2 microns
Pulse length:	2 ps
Energy:	~ 3 J
Repetition rate:	0.05 Hz
Initial spot size:	50 mm
Focusing:	2 m focus

USPLs focused in air can generate plasma filaments. Plasma filaments occur when the laser power is above critical power allowing for a balance between plasma defocusing and nonlinear self focusing.



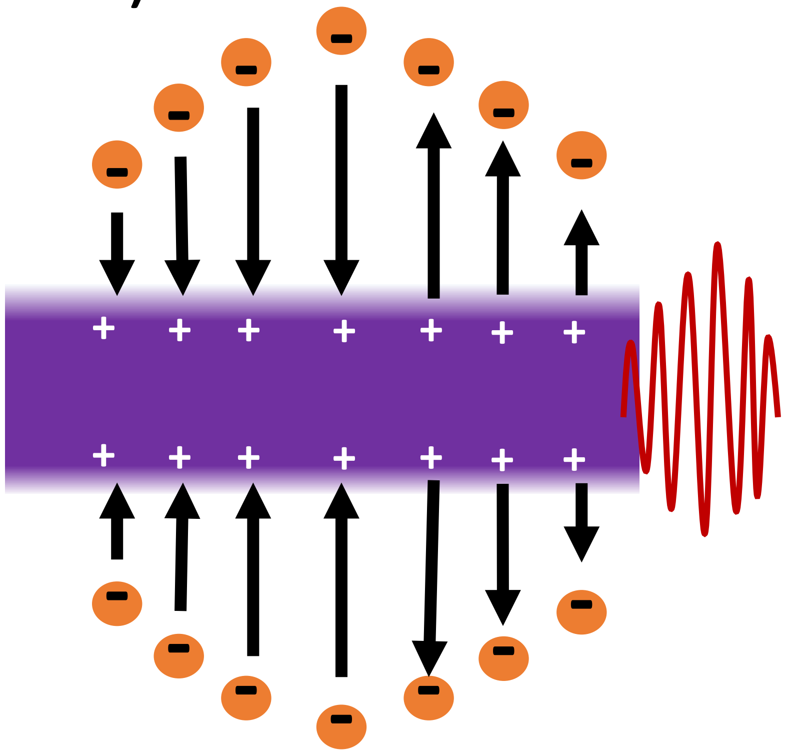


Laser direction

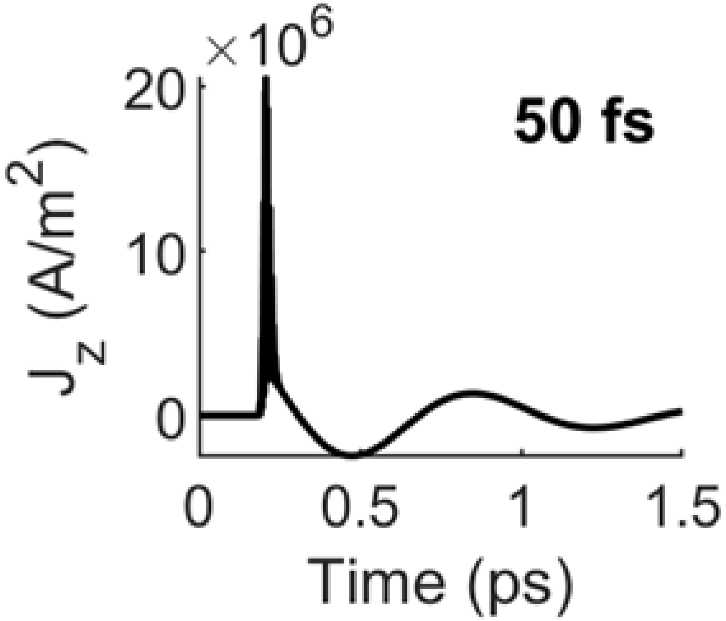
$$P_{cr} = \frac{a\lambda_0^2}{n_0 n_2}$$

Currents within the filament excite and drive the broadband microwave radiation.

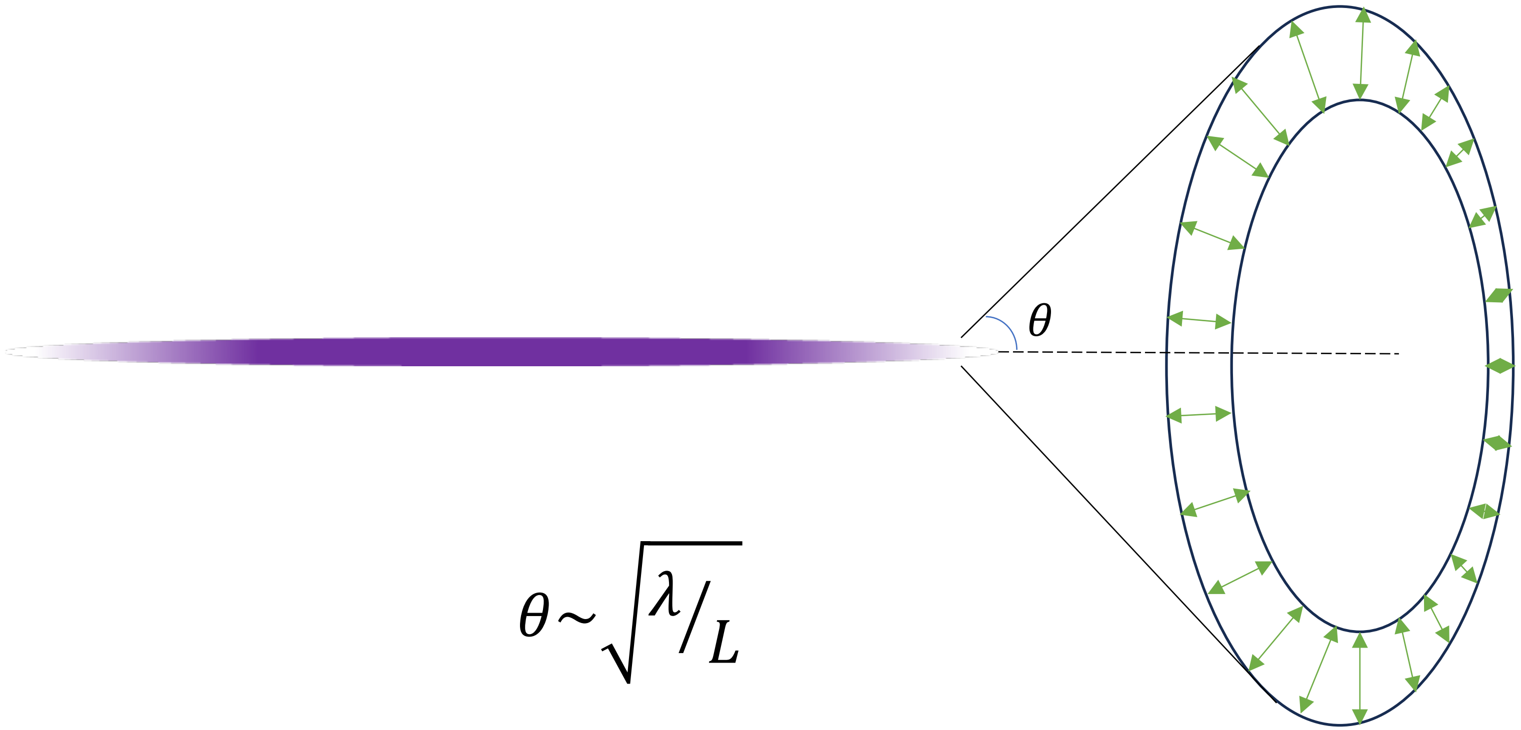
Plasma wake surface wave (PWSW)



Ponderomotive

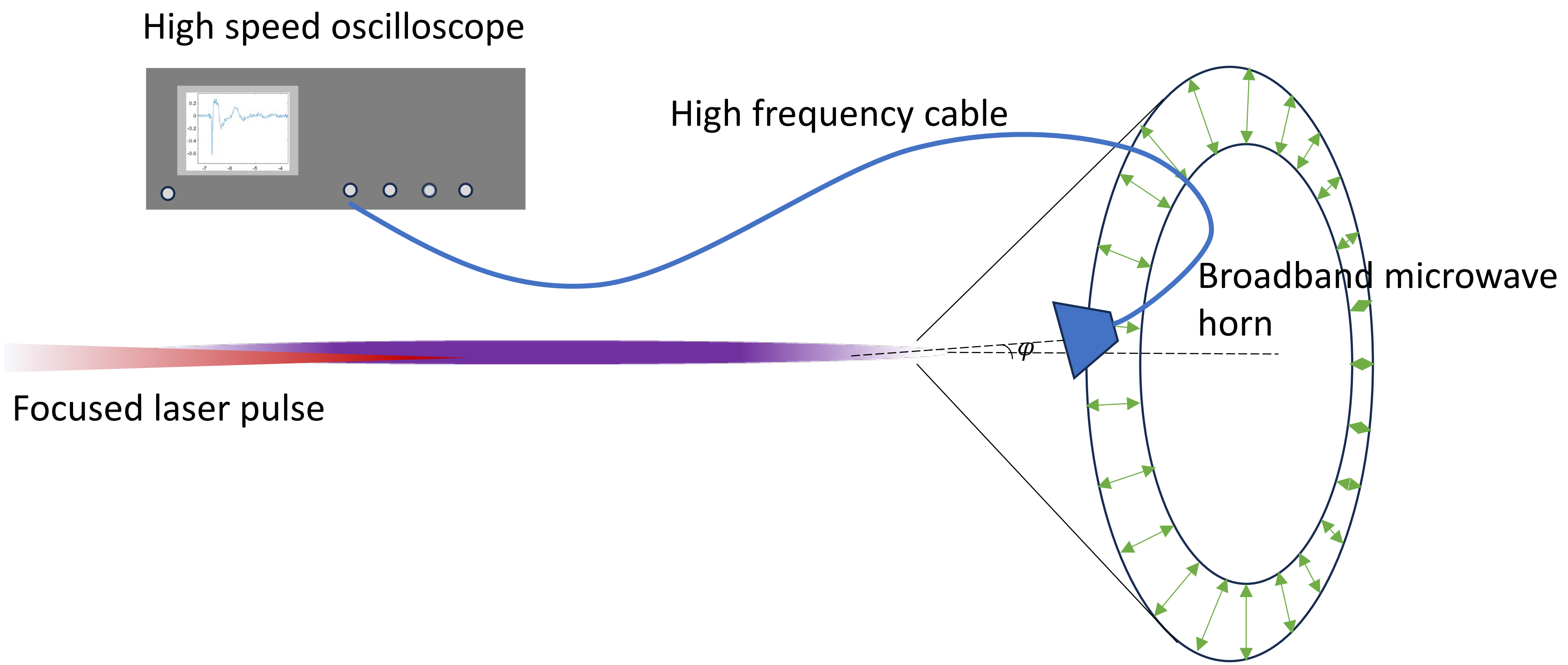


Both currents are emitted off the end of the filament via a transition-Cherenkov radiation mechanism resulting in a radially polarized, forward conical emission pattern.

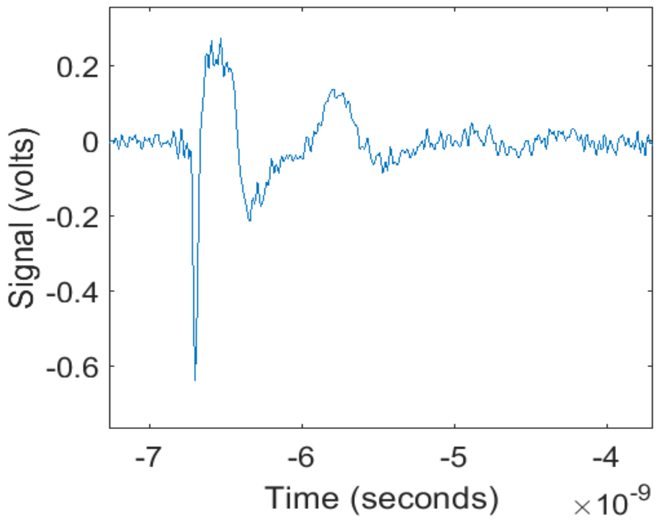


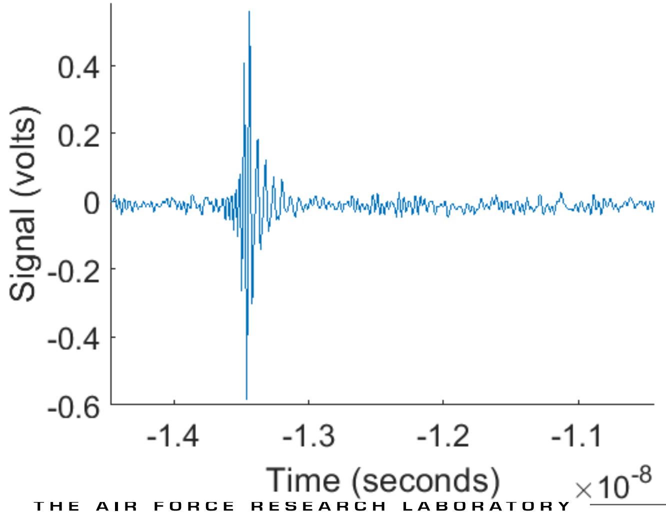
$$\theta \sim \sqrt{\lambda / L}$$

Due to the frequency content and amplitude sensitivity to angle of emission, it is necessary to take an angular scan of the signal.

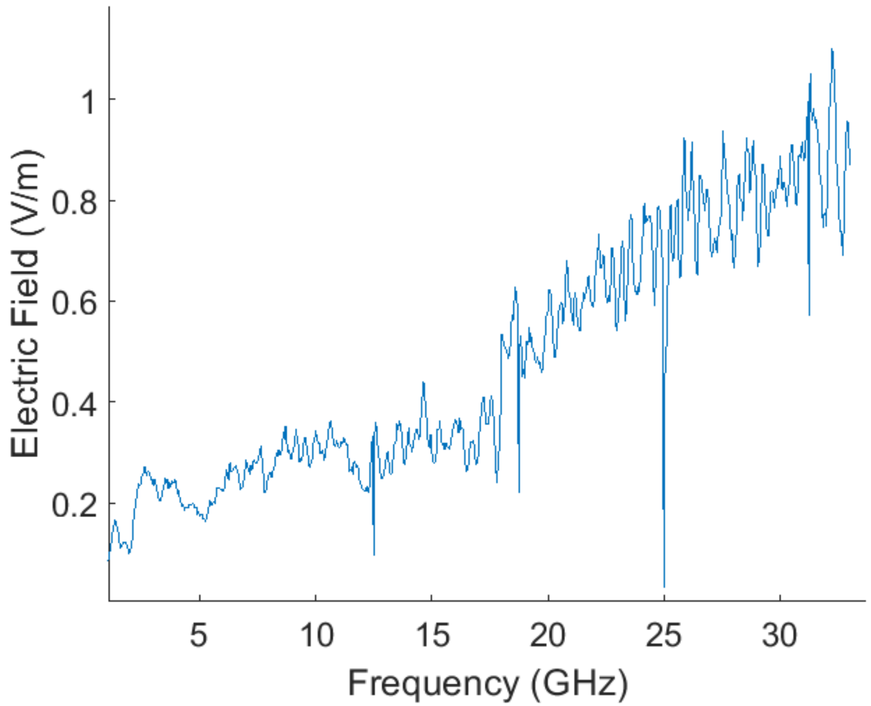


Time domain signals from difference horns can be Fourier transformed, calibrated and combined into one spectrum.





1. Fourier transform
2. Horn and cable response calibration
3. Stitch together



Electron energy scales with the square of the laser wavelength benefiting both the ponderomotive and PWSW currents within the laser.

Ponderomotive current

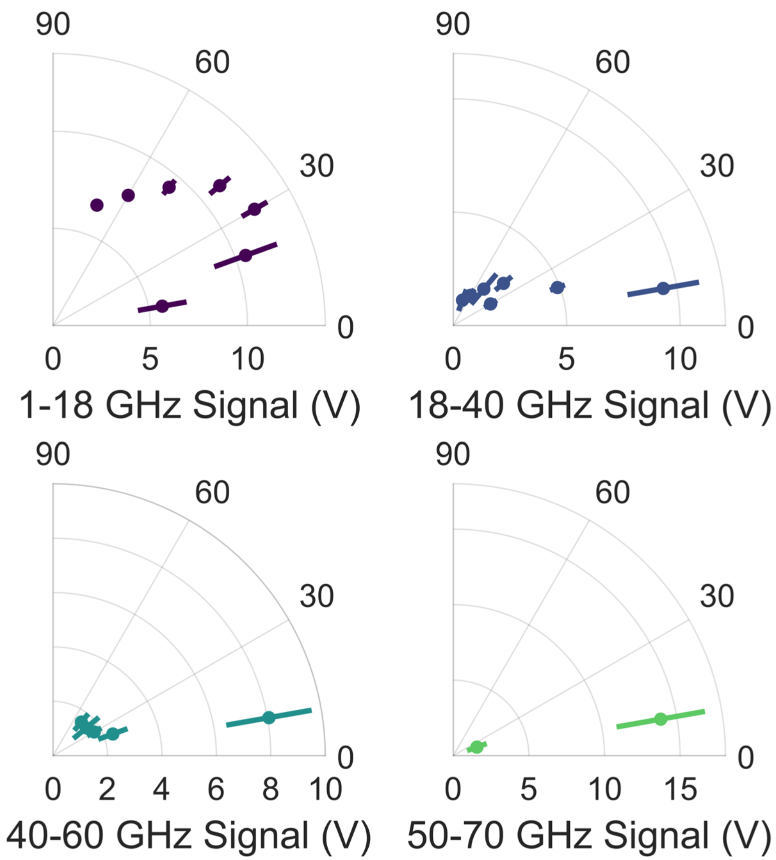
$$S_z(r,z,t) \sim \frac{e\omega_{pl}^2}{2\varepsilon_0 m_e \omega_0^2 c}\left(\frac{2\nu_e}{c} + \frac{2}{c\omega_{pl}^2}\frac{\partial \omega_{pl}^2}{\partial t} - \frac{\partial}{\partial z}\right) I_L$$

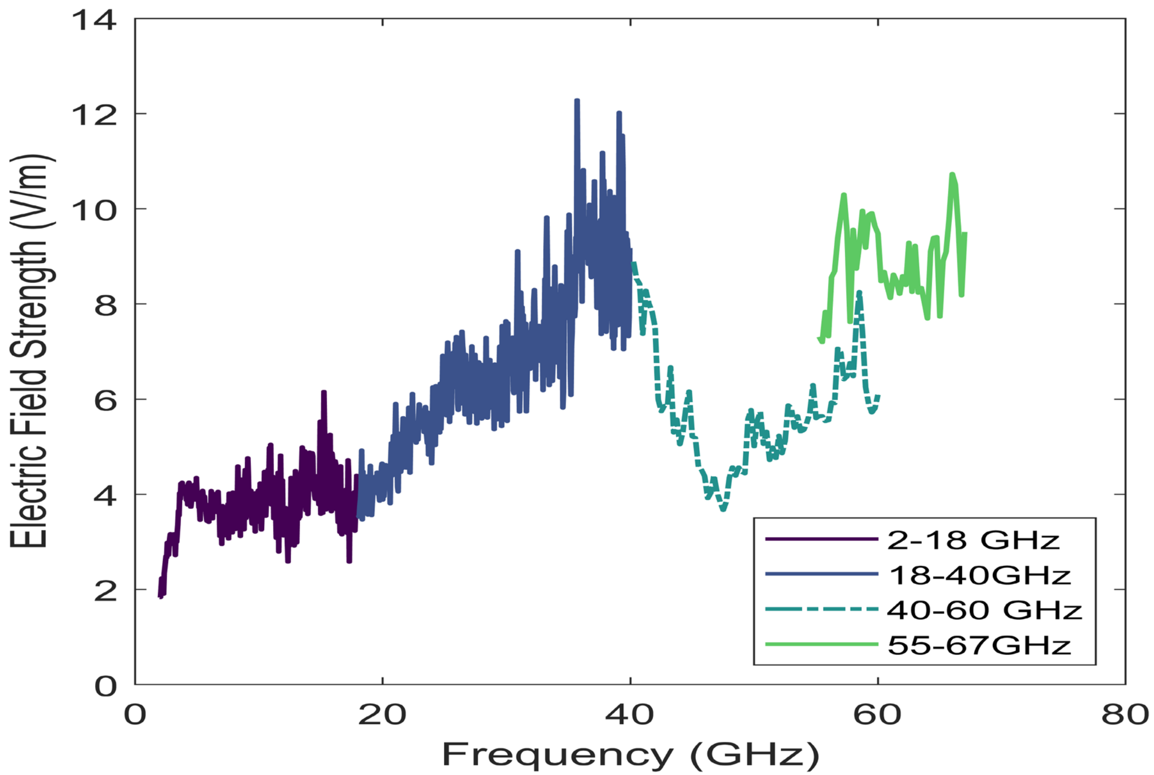
$$S_z \propto \lambda^2$$

PWSW current

$$I_z \propto \lambda^2$$

Significant RF signal detected out to 67 GHz from LWIR driven filament in air.



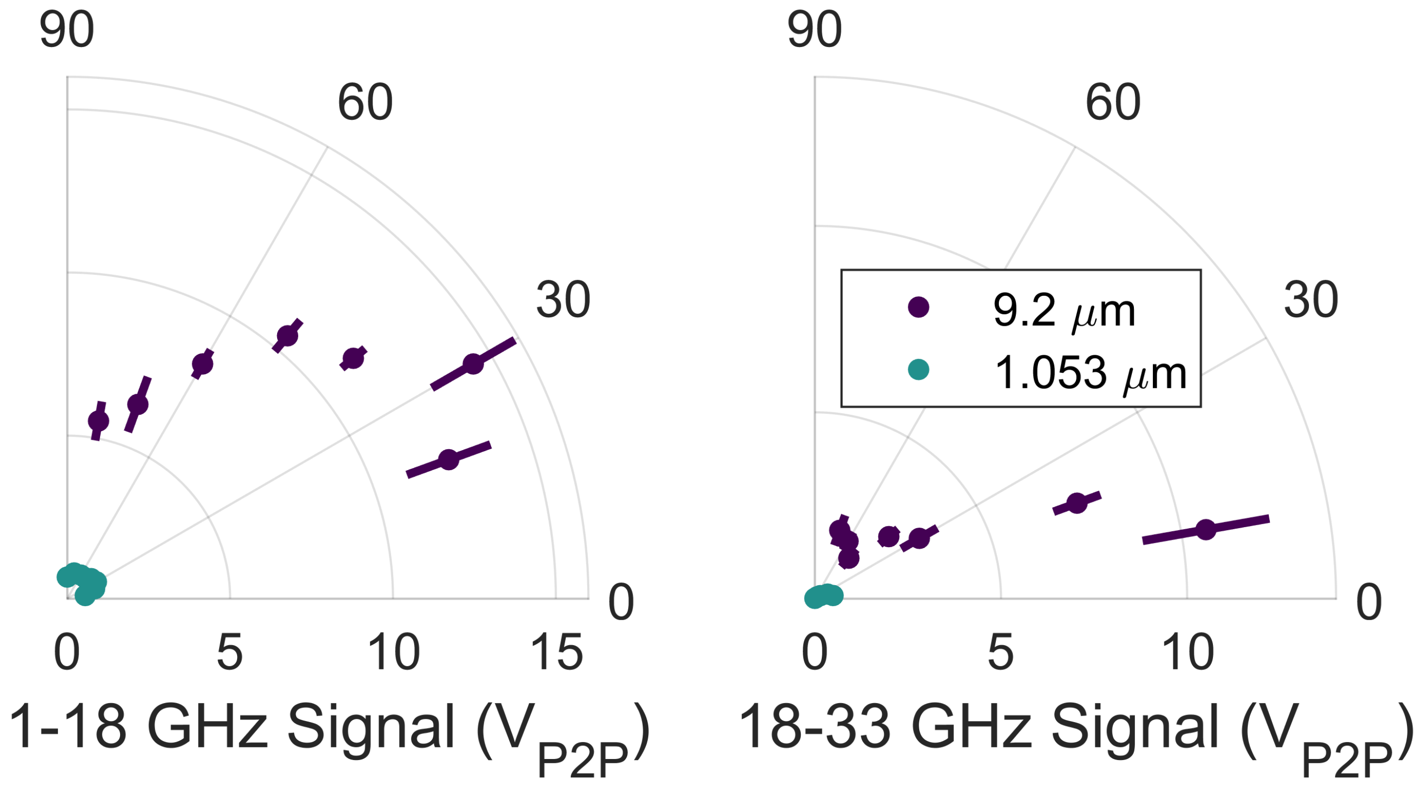


10° off laser axis

Increasing the wavelength by a factor of 9 results in over an order of magnitude increase in resulting RF amplitude.

COMET laser system parameters

Wavelength:	1053 nm
Pulse length:	~3.6 ps
Energy:	2.5 J
Initial spot size:	60 mm
Focusing optic:	3 m focusing lens



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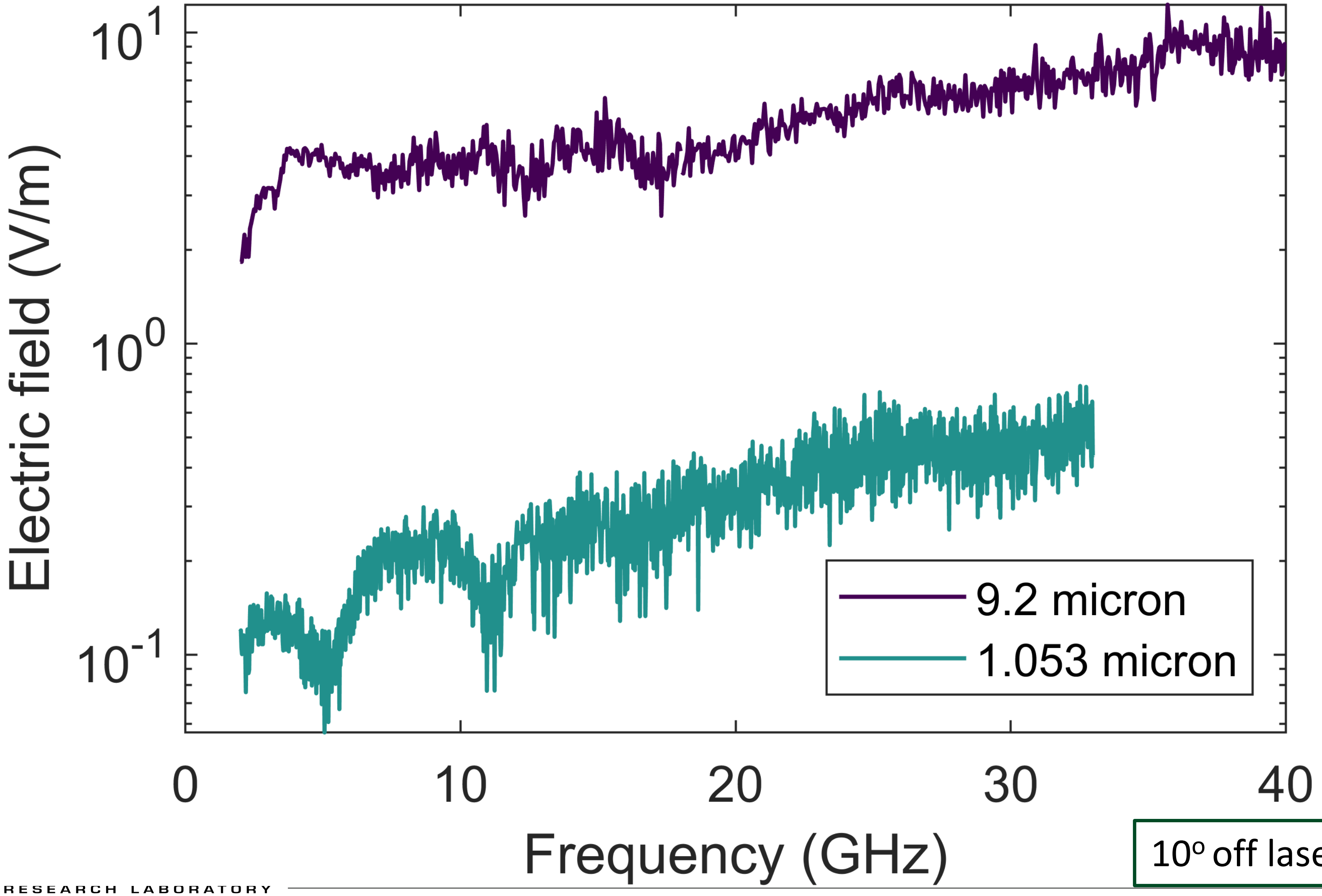
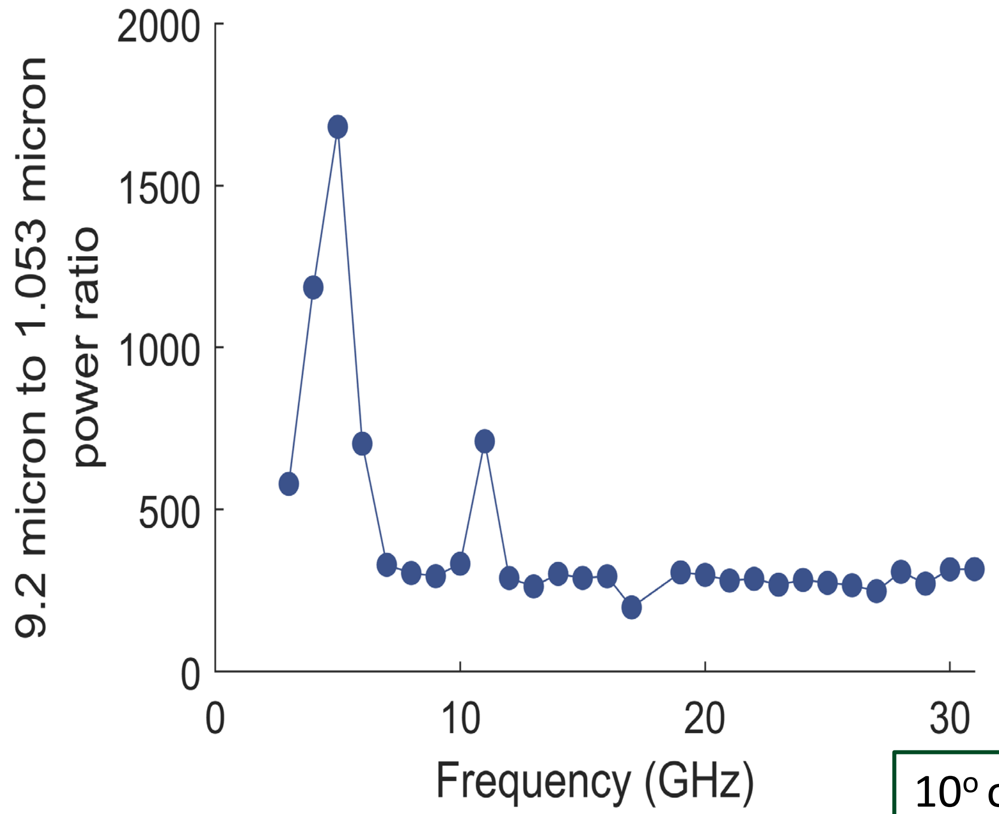


10° off laser axis

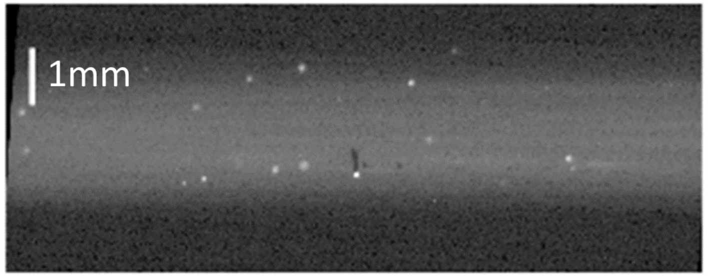
Comparing the ratios of emitted microwave power, a 300 time increase in the total emitted power is observed with greater increases in the lower frequencies.



10° off laser axis

LWIR laser driven filaments become opaque to the laser because the plasma density is greater than the critical density for the laser.

1.053-microns

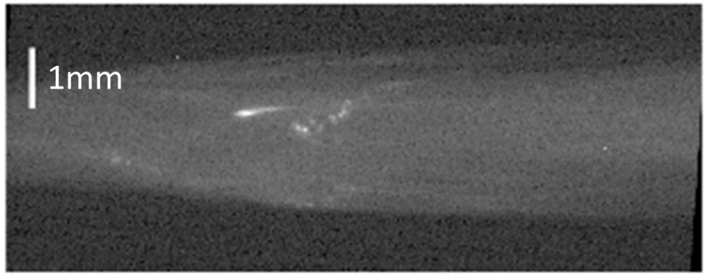


$n_{e,1.053} \sim 10^{25} m^{-3}$

$n_{cr,1.053} \sim 10^{27} m^{-3}$

$$n_{cr} = \frac{q_e^2}{\varepsilon_0 m \omega_0^2} \propto \lambda^2$$

9.2-microns

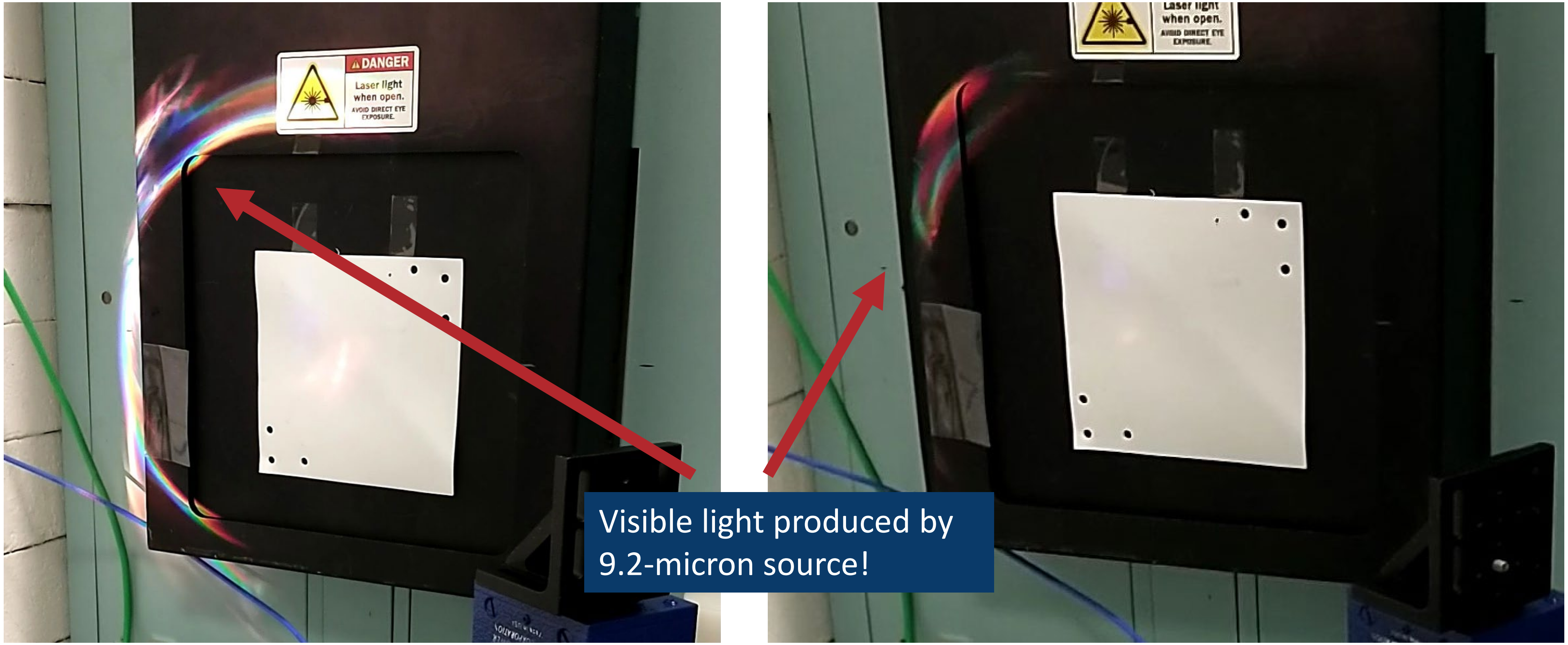


$n_{e,9.2} \sim 10^{25} m^{-3}$

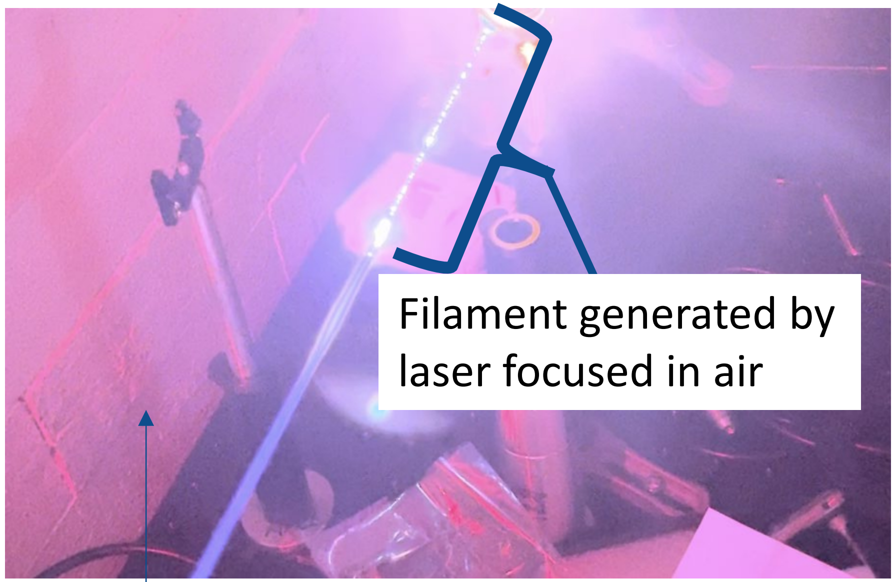
$n_{cr,9.2} \sim 10^{25} m^{-3}$

Supercontinuum Generation

During broadband microwave experiment, visible light was observed prompting follow up experiment into long wave IR supercontinuum generation



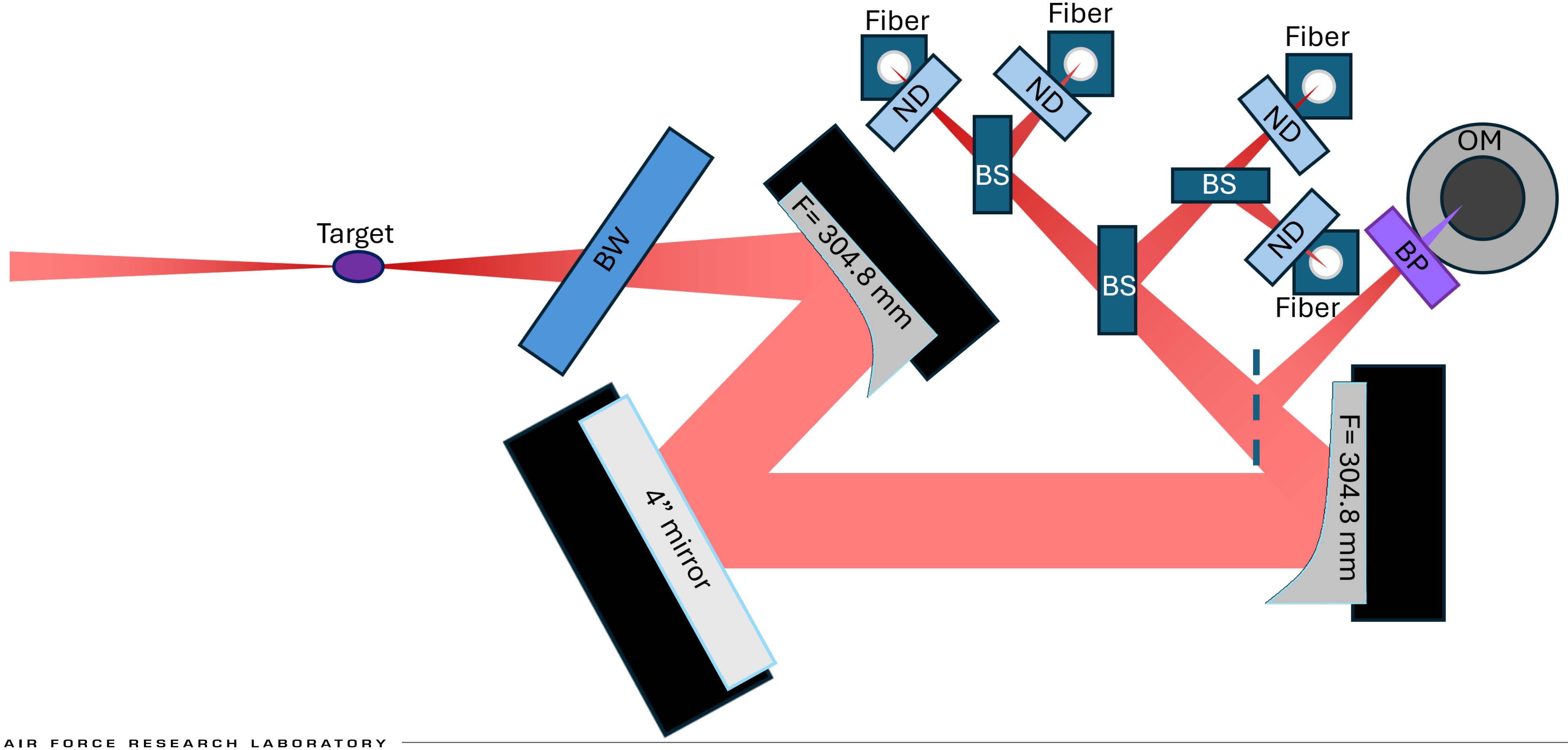
CO2 laser parameters for the supercontinuum generation experiment



Background scattering from supercontinuum on beam stop

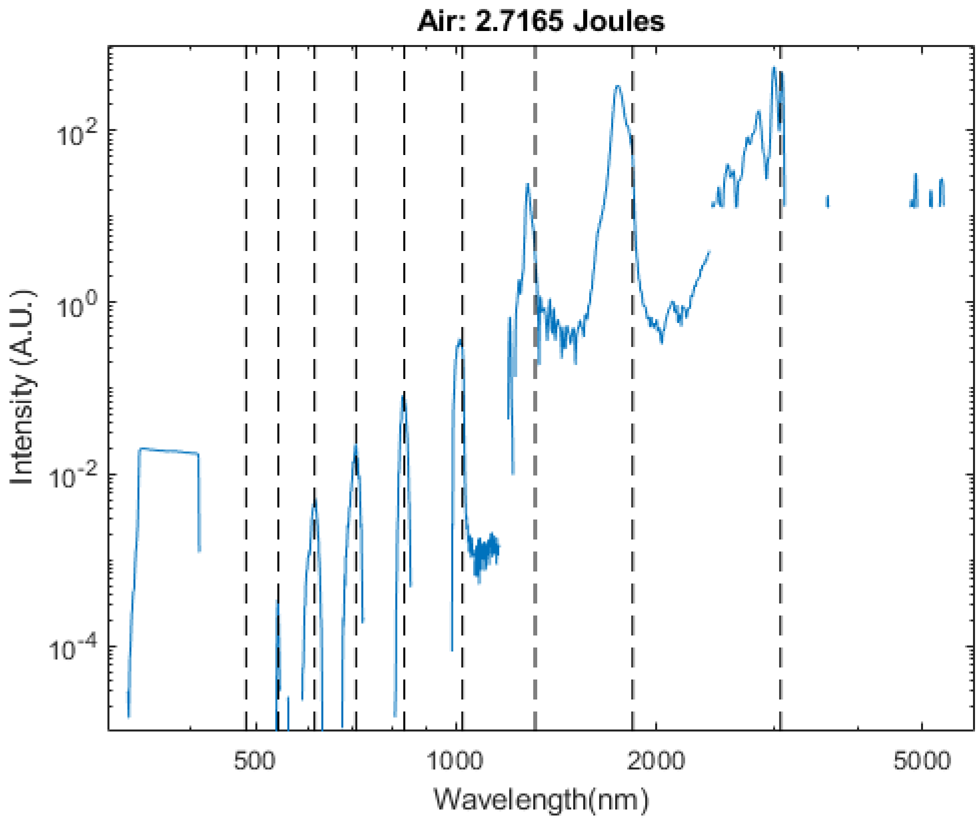
Wavelength:	9.2 microns
Pulse length:	2 ps
Energy:	~ 3 J
Repetition rate:	0.05 Hz
Initial spot size:	50 mm
Focusing:	2 m focus

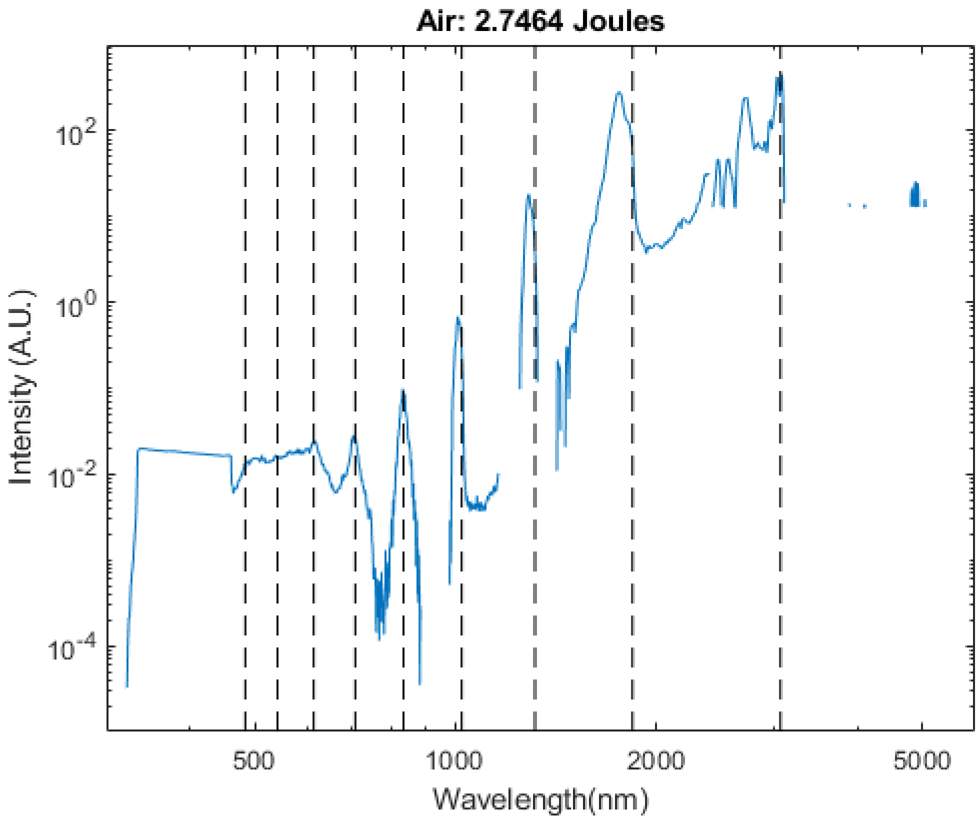
SCG experimental set-up feed designed by Army DEVCOM supercontinuum into multiple spectrometers calibrated to capture the spectrum from 0.3 to 6 microns in one shot.



Due to chaotic nature of plasma filamentation, even small variations in drive laser energy can shift spectrum from odd harmonics to supercontinuum for shortwave edge.

$n_2 = 3.3E\text{-}23\ m^2/W$

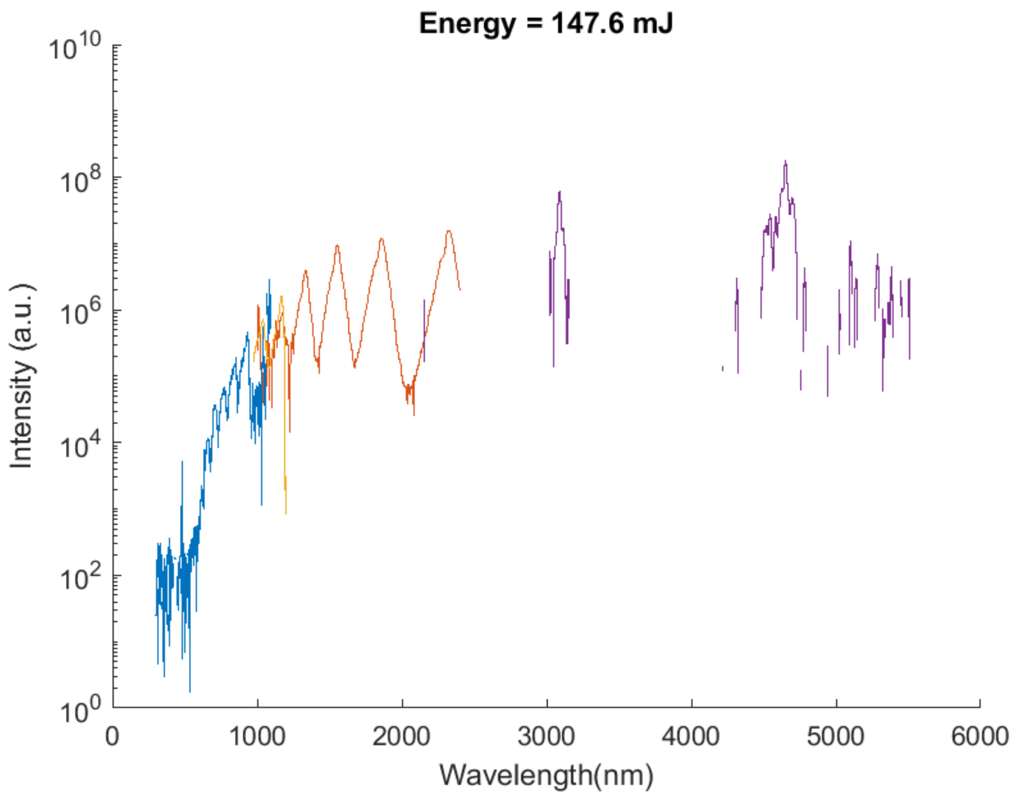


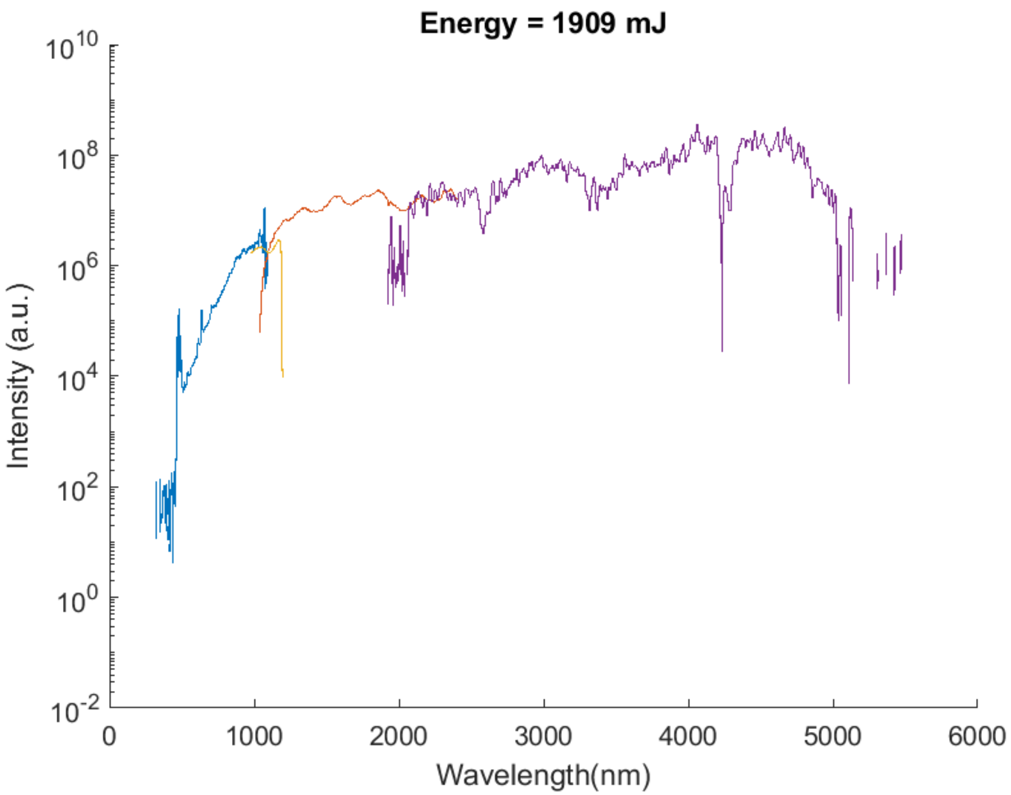


Dashed lines indicate odd harmonics

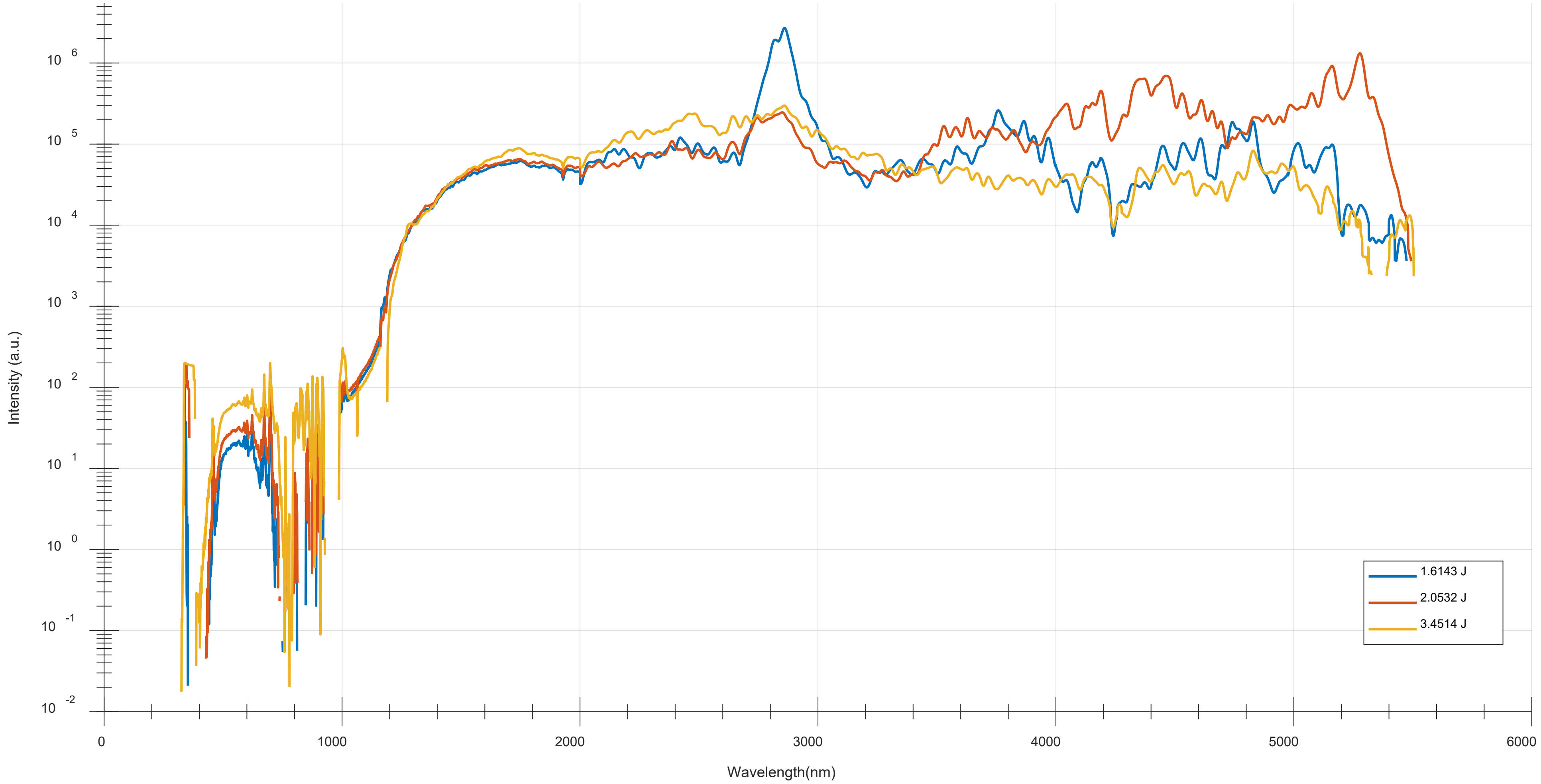
ZnS exhibits both even and odd harmonics at low energies but show SGC at high laser energies.

$n_2 = 4.00E\text{-}19\ m^2/W$



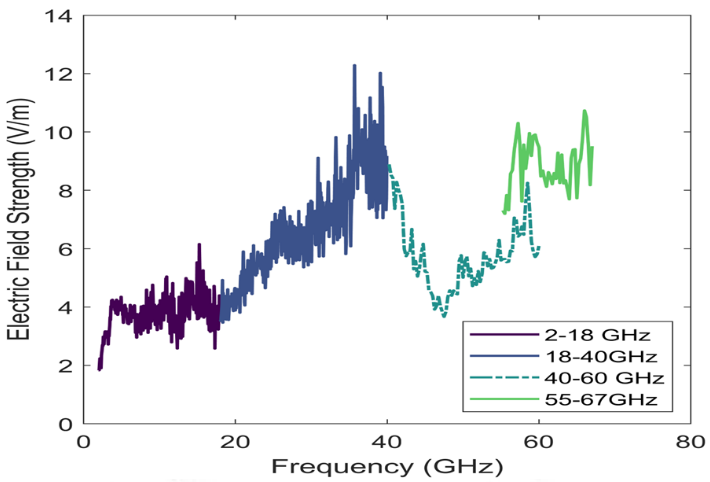


Cesium iodide(50 mm thick) demonstrates consistent strong SCG.



$n_2 = 1.20E\text{-}19\ m^2/W$

Long wave IR ultrashort pulse laser sources are powerful tools in generating broad spectral coverage both above and below the center wavelength of the laser.



BNL CO_2
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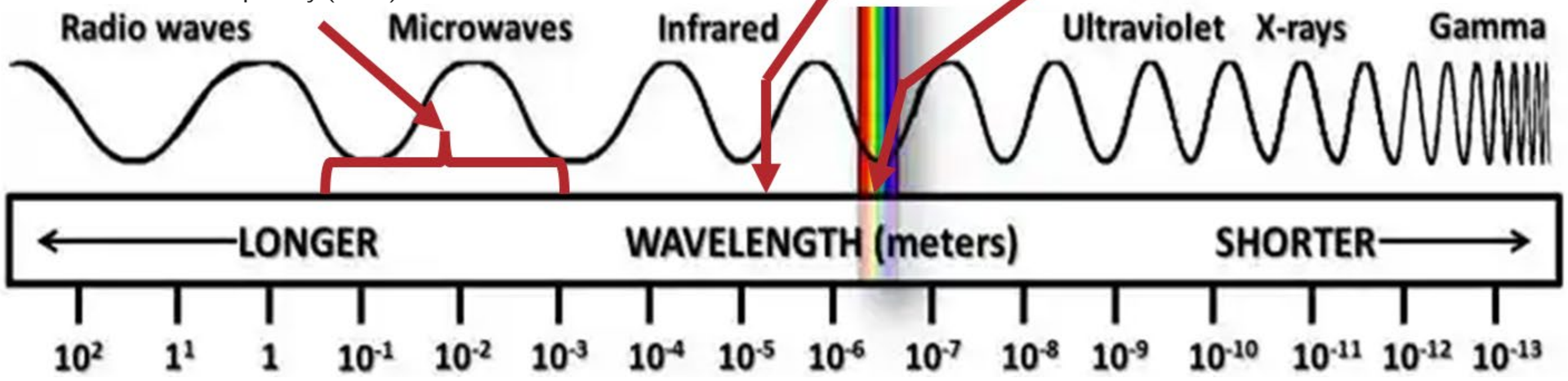


Activities and Impacts

PhD Thesis Dr. Erin Thornton, "OPTIMIZING ULTRA-BROADBAND MICROWAVE RADIATION THROUGH PLASMA DYNAMICS OF USPL FILAMENTS" June 2024

Conference presentations:
"Radiofrequency emission from 9.2-micron short pulse laser in gases" DEPS San Antonio, Texas April 5, 2023
Directed Energy Professional Society Systems Symposium Fall 2023
Directed Energy Professional Society Science and Technology Symposium Spring 2024

Papers:
In Preparation. E. Thornton et al. "Increasing broadband microwave radiation generation of picosecond filamentation in air via wavelength scaling"

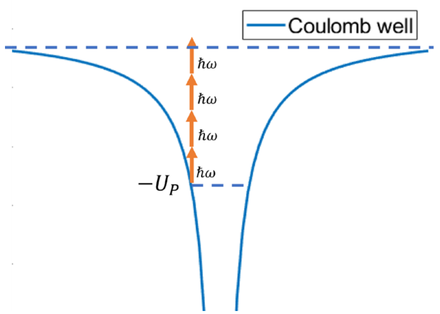
Covid Impacts

Minimal impacts five years later, delayed Dr. Thornthon’s thesis.

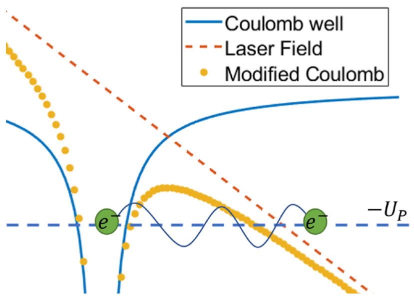
Back up

- Plasma wake surface wave current is the mechanism understood to drive the low frequency microwave pulse.

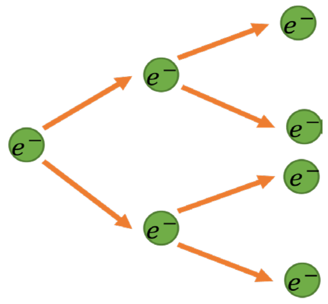
1. Laser ionizes the gas as it passes through via



Multiphoton



Tunneling



Collisional

- Plasma wake surface wave current is the mechanism understood to drive the low frequency microwave pulse.

1. Laser ionizes the gas as it passes through via multiphoton, tunneling, or collisional ionization.
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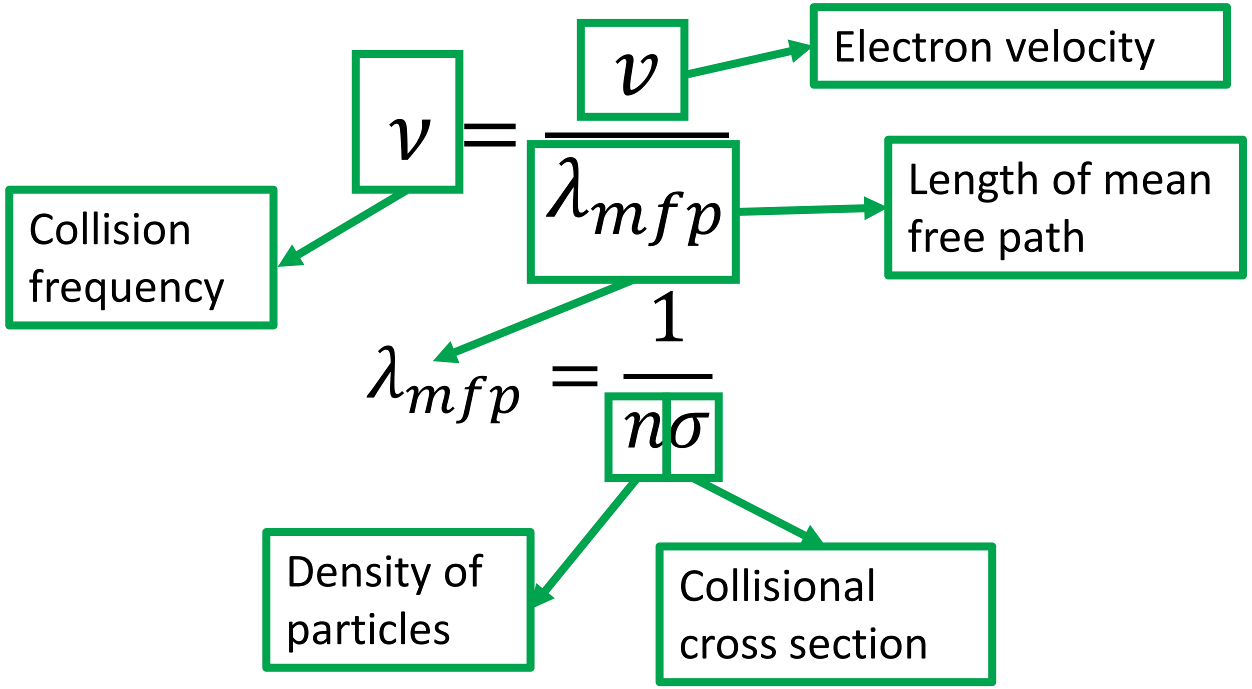
1. Laser ionizes the gas as it passes through via multiphoton, tunneling, or collisional ionization.
2. Hot electrons near the edge of the plasma:
   - escape outwards ($n_L \propto K_{tail}$),
   - lose energy via collisions with neutral gas,



$$\nu = \frac{v}{\lambda_{mfp}}$$

$$\lambda_{mfp} = \frac{1}{n\sigma}$$

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2. Hot electrons near the edge of the plasma:
   - escape outwards ($n_L \propto K_{tail}$),
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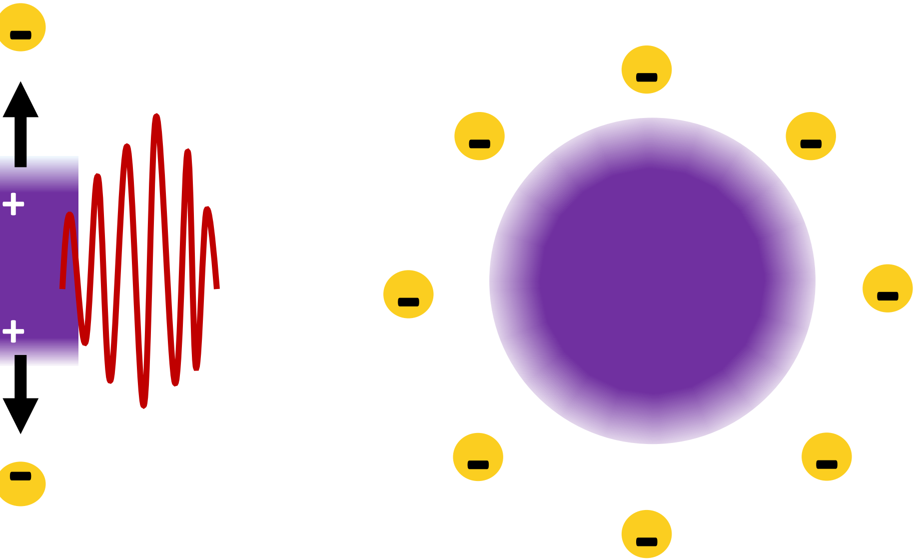
   - and return to the plasma channel via restorative force of positive ions.

Plasma wake surface wave current is the mechanism understood to drive the low frequency microwave pulse.



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3. The electron excursion drives symmetrical radial current behind the laser pulse.

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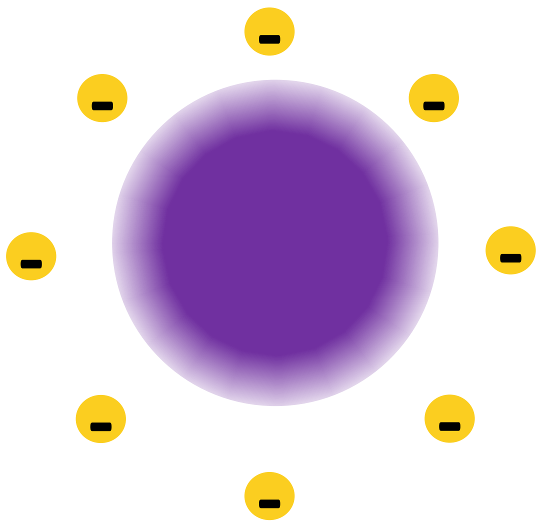

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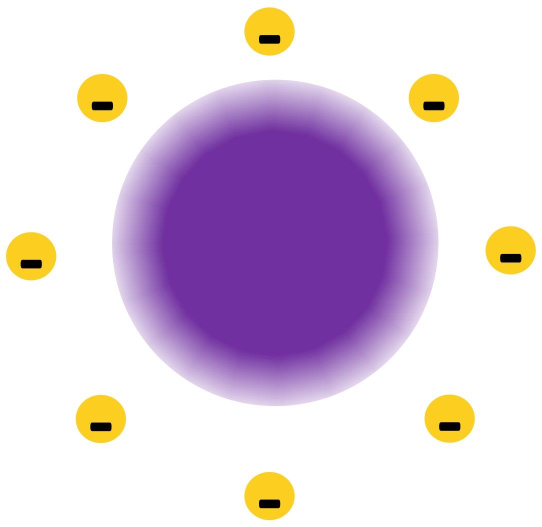

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3. The electron excursion drives symmetrical radial current behind the laser pulse.

$$J_r \propto \; n_L \; and \; v_{eff}$$

$$v_{eff} = min \begin{cases} v_{tail} \\ v_{diff} \end{cases}$$

$$v_{diff} \propto {}^{1}\!/_{\sqrt{\nu}}$$

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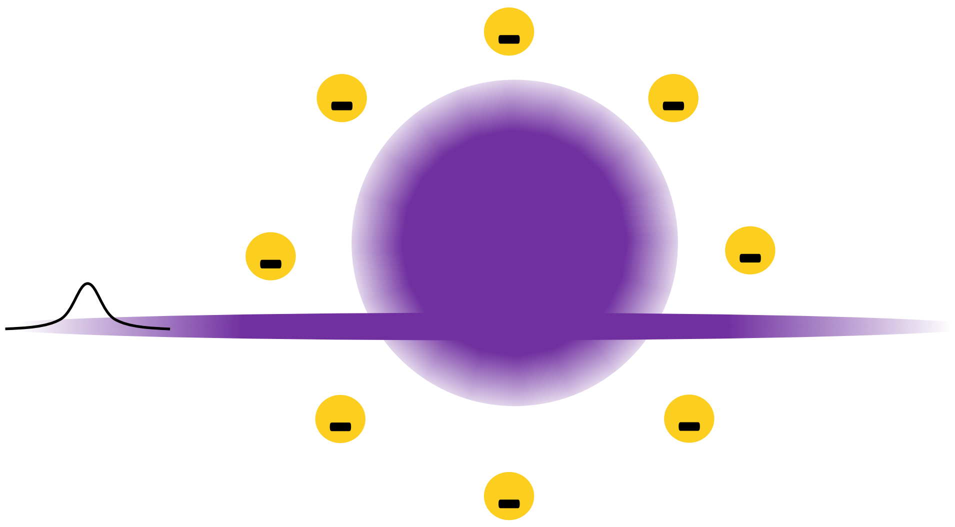

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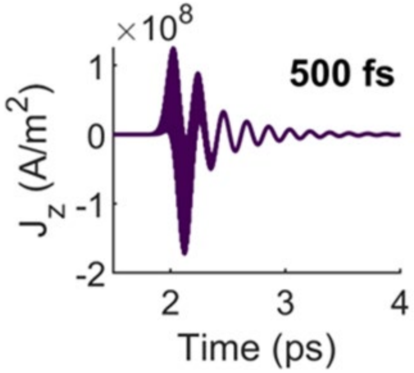
   - and return to the plasma channel via restorative force of positive ions.
3. The electron excursion drives symmetrical radial current behind the laser pulse.
4. The radial current excite a surface wave on the plasma that constructively builds along the plasma column resulting in a longitudinal current.

$$I_z \propto J_r$$

- Ponderomotive bulk currents drive the high frequency THz pulse but would have a tail of the low frequency GHz.

$$\frac{\partial \boldsymbol{J}}{\partial t} = -\nu_e \boldsymbol{J} + \frac{\omega_{pl}^2}{4\pi}\boldsymbol{E} + \boldsymbol{S}$$

- $\frac{\partial \boldsymbol{J}}{\partial t}$: Change in current density over time
- $-\nu_e \boldsymbol{J}$: Collisions dissipating energy into heat
- $\frac{\omega_{pl}^2}{4\pi}\boldsymbol{E}$: Collective plasma effects on current
- $\boldsymbol{S}$: Laser source term acting on the plasma



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$$S_z(r,z,t) \sim \frac{e\omega_{pl}^2}{2\varepsilon_0 m_e \omega_0^2 c}\left(\frac{2\nu_e}{c} + \frac{2}{c\omega_{pl}^2}\frac{\partial \omega_{pl}^2}{\partial t} - \frac{\partial}{\partial z}\right) I_L$$

Longitudinal source term

Radiation pressure from the laser pulse

Changes in electron density due to ionization

The spatial gradient of the laser envelop

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$S_z \propto n_e^2$

$S_z \propto \lambda^2$

$S_z \propto laser\ intensity$