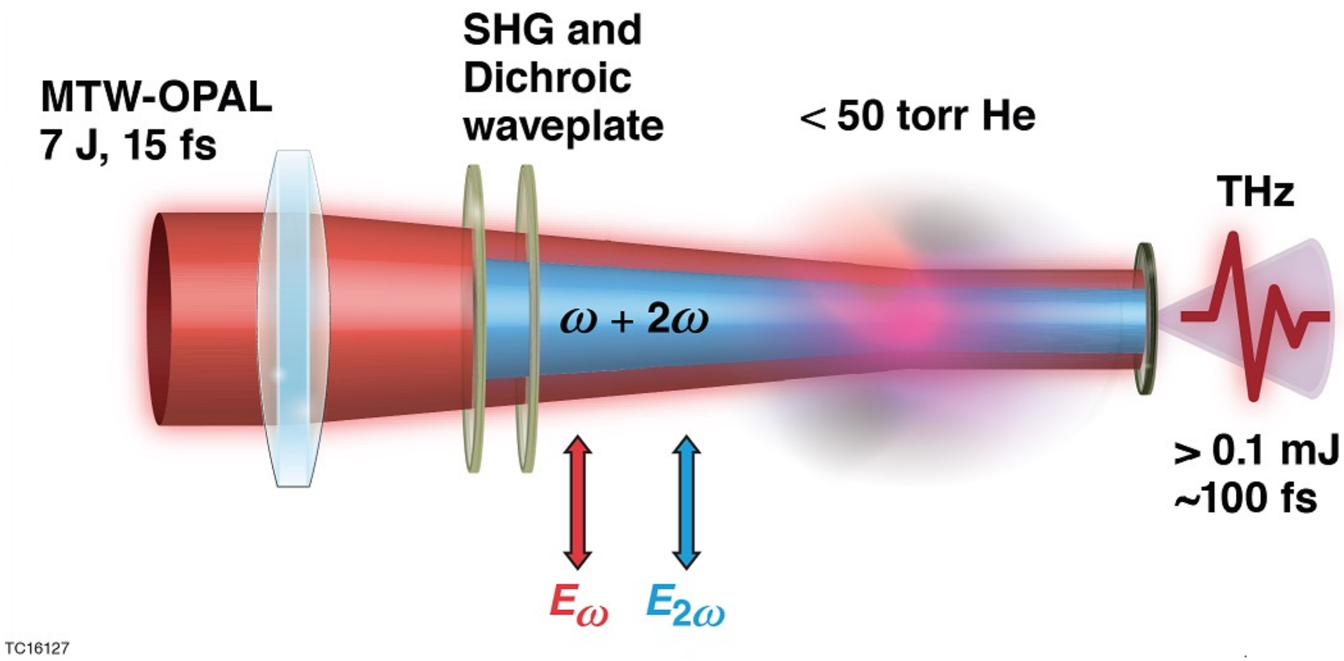
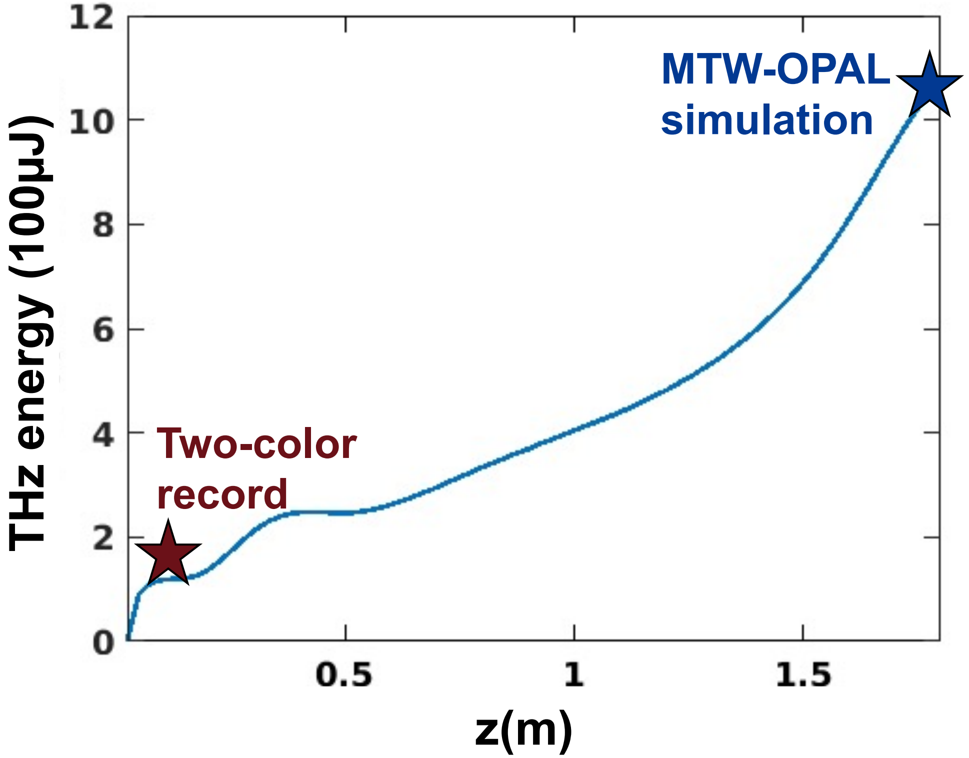
High-energy, two-color terahertz generation





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Skytop, Pennsylvania
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The ‘two-color’ filamentation technique provides a path to high-energy, near-single-cycle terahertz pulses

UR LLE

- A laser pulse composed of a first and second harmonic can drive a time-dependent current of photoionized electrons which generates broadband terahertz (THz) radiation
- A high-ionization potential, low-density background gas can enhance the THz radiation properties for 100 TW class drive lasers by enabling a greater transient electron current and mitigating beam breakup
- Early simulation results suggest a THz source with an energy greater than 1mJ is achievable with the 100 TW class MTW-OPAL laser at the LLE

A high-energy terahertz source could enable access to a novel regime where bound electron nonlinear optics and relativistic plasma physics overlap

Collaborators

J. Pigeon, R. Boni, M. Lim Pac Chong, D. Ramsey,
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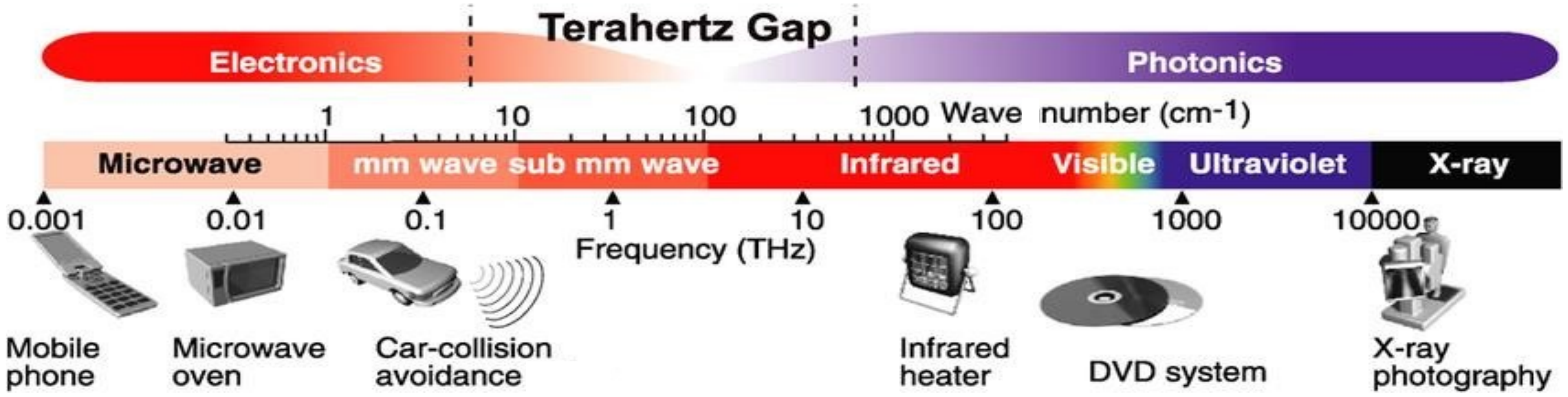
National Nuclear Security Administration

U.S. DEPARTMENT OF ENERGY | Office of Science

Terahertz radiation lies in the ‘gap’ between electronic and photonic sources

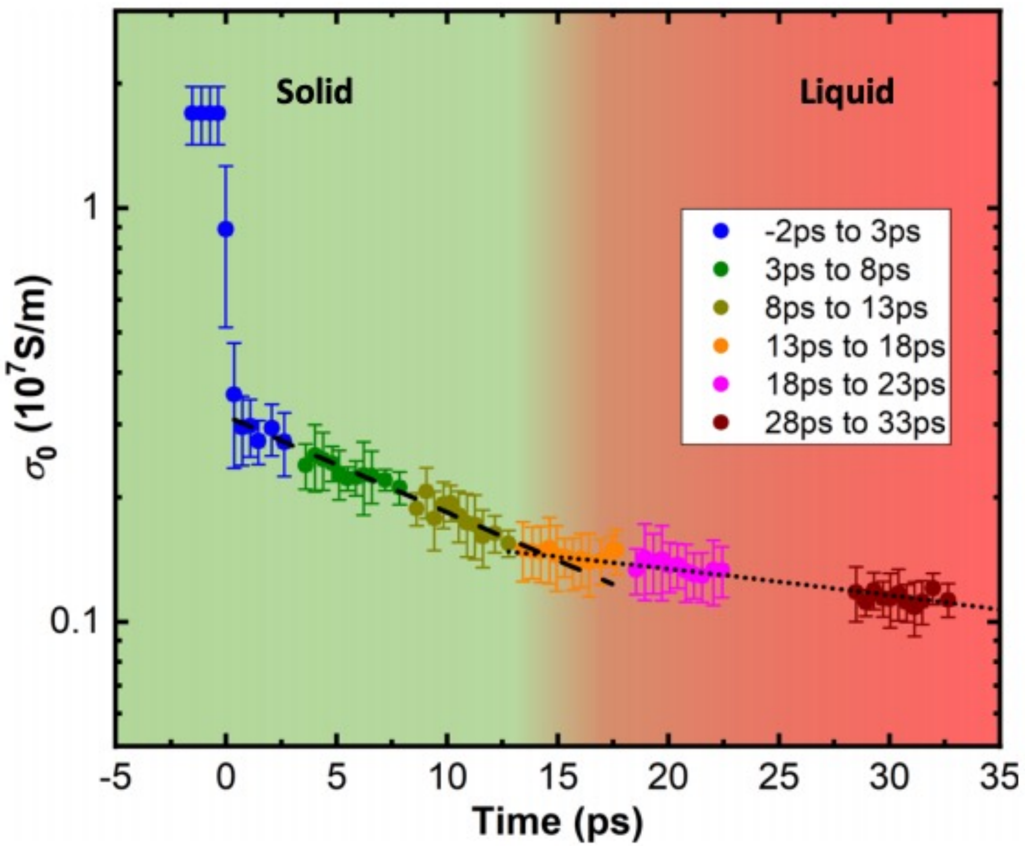


THz radiation has many applications, such as

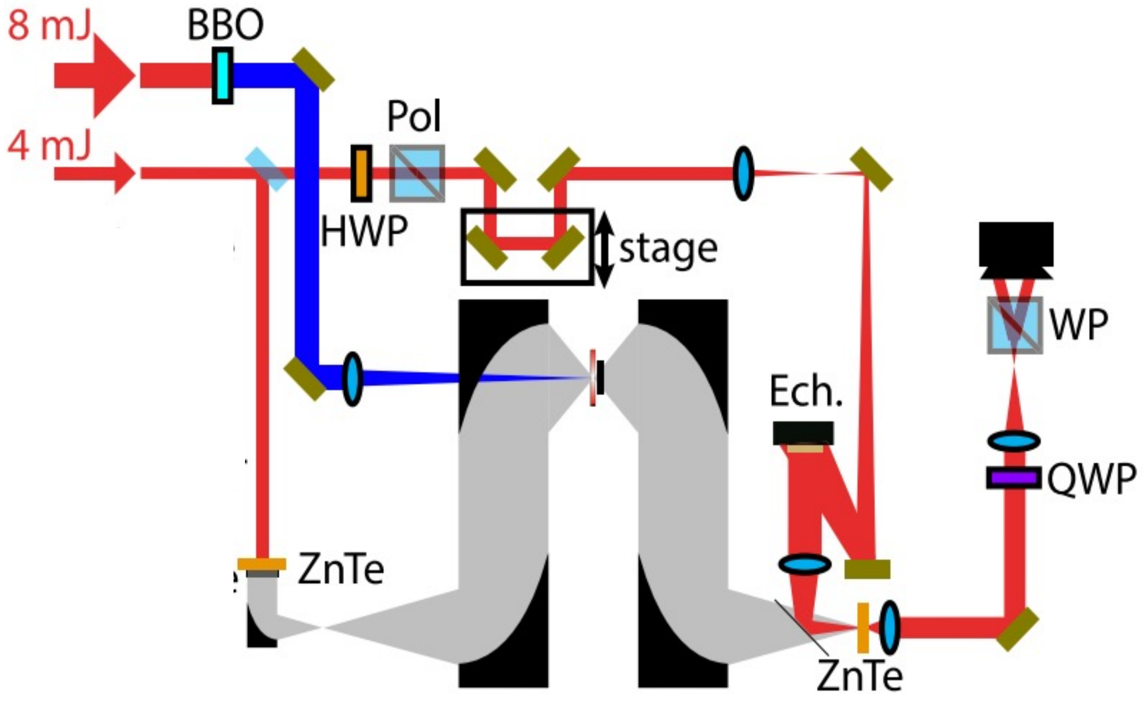
- Ultrafast optical switches
- Driving extreme nonlinear optics
- Non-invasive spectroscopy

THz pulses can act as powerful, quasi-DC probes for HED experiments

Au conductivity, THz FEL*

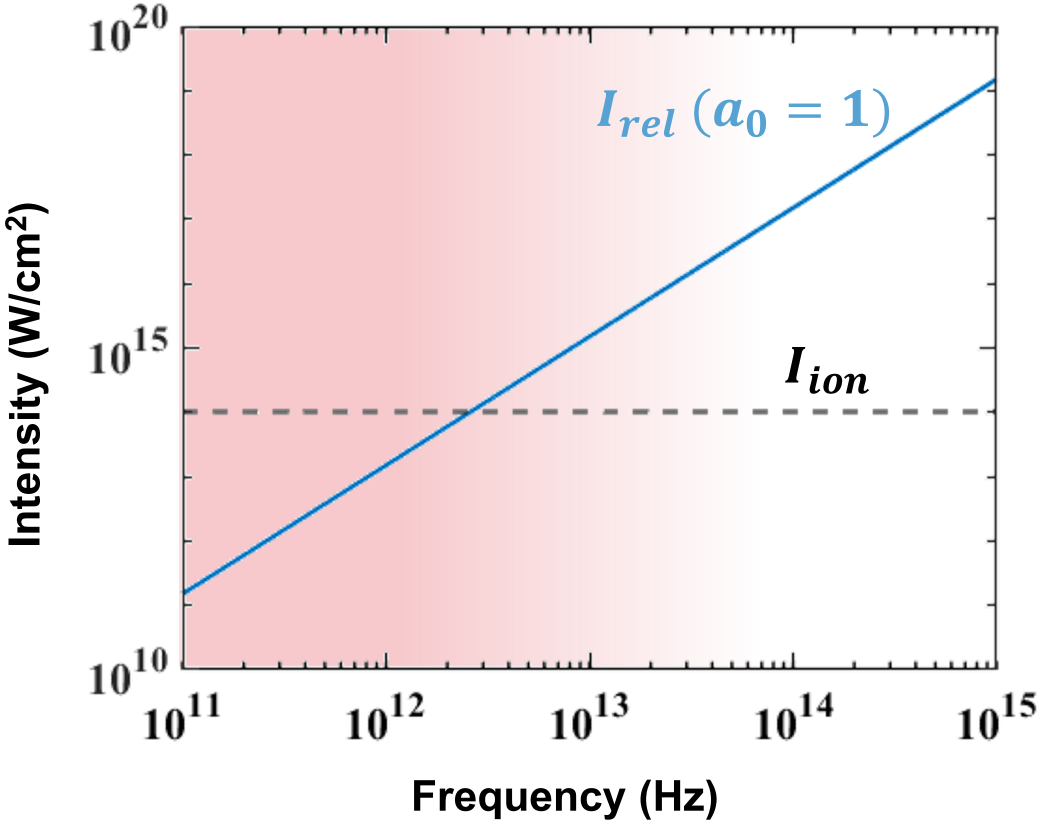


SLAC proposed setup for optically driven THz probe**



*Chen et al., Nat. Comm. (2021) **Oforo-Okai et al., Rev. Sci. Inst. (2018)

A high-energy terahertz source could enable access to a ‘wavelength frontier’ where bound electron nonlinear optics and relativistic plasma physics overlap



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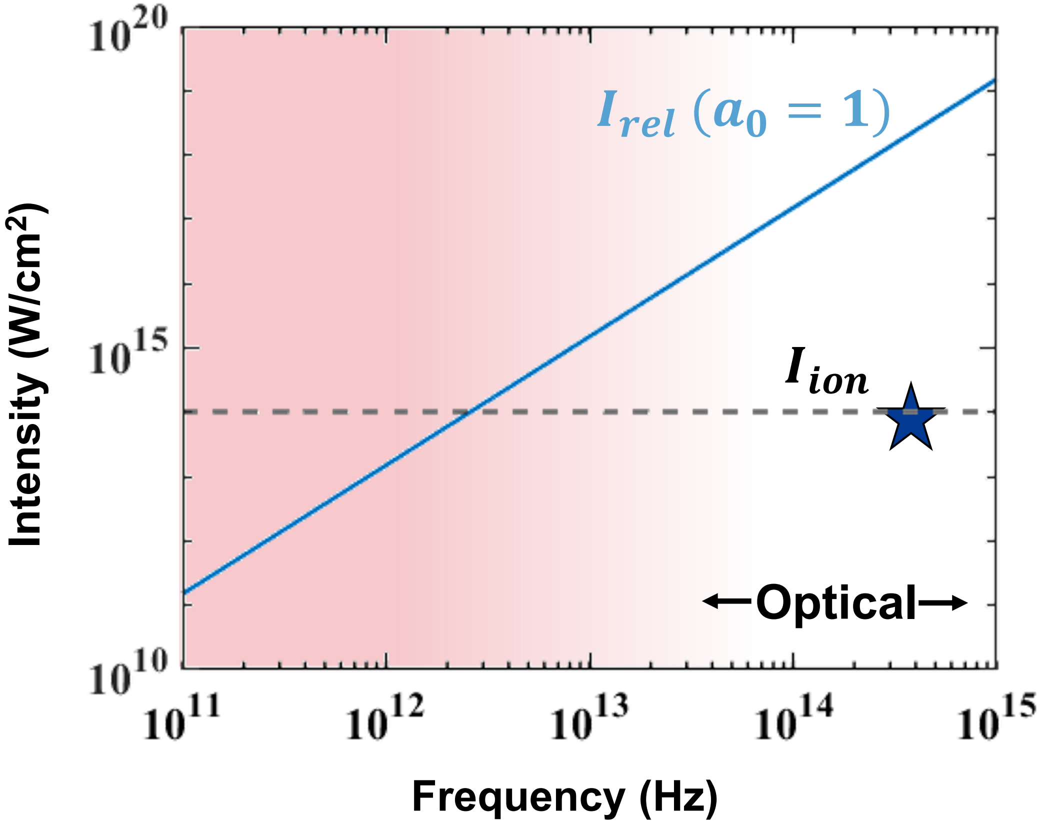
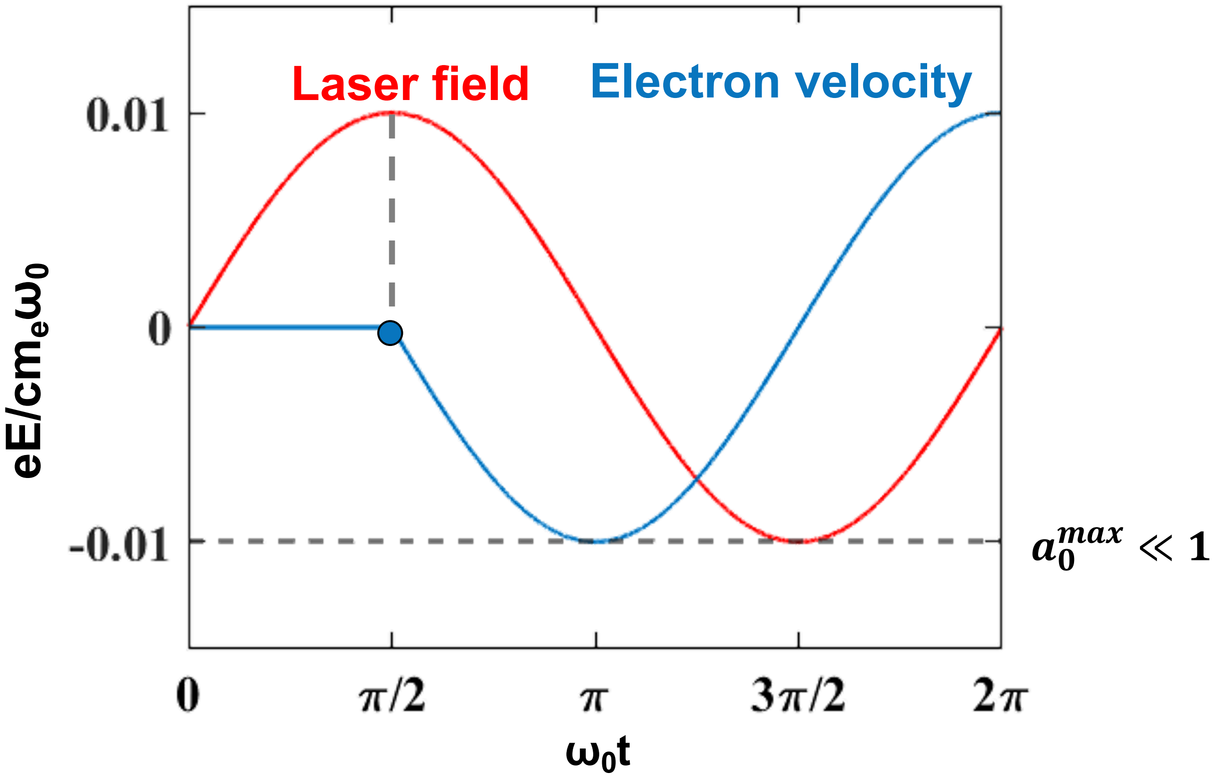
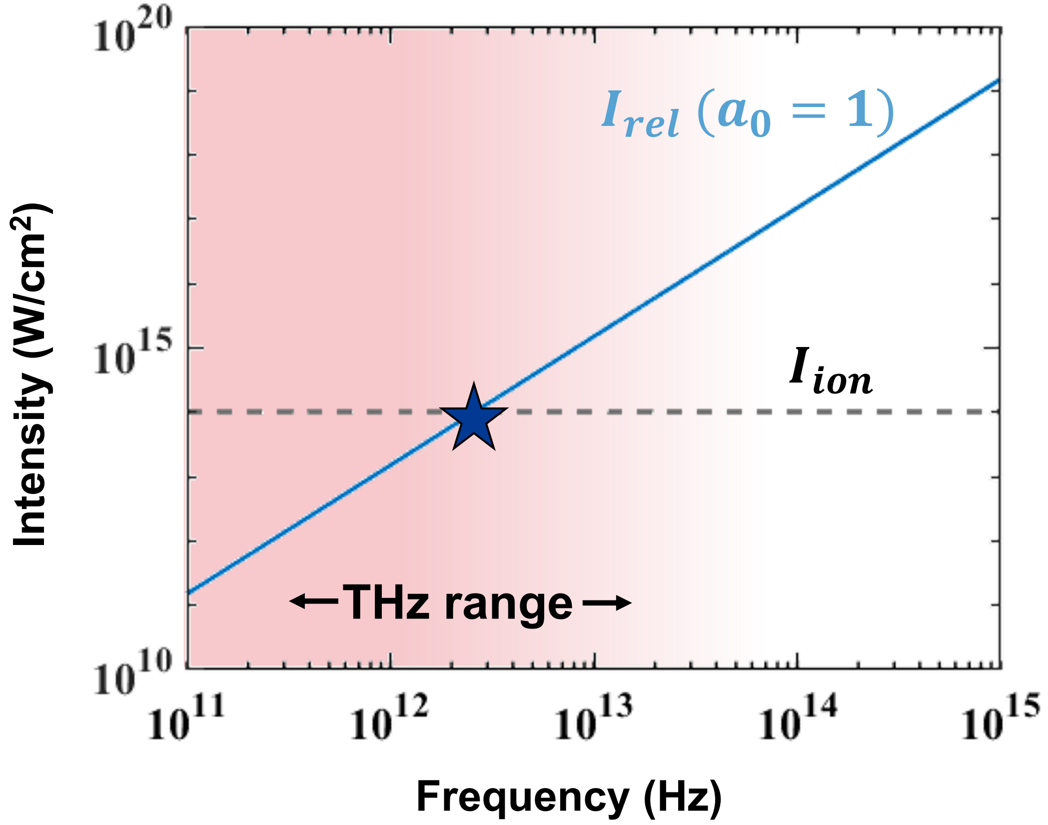
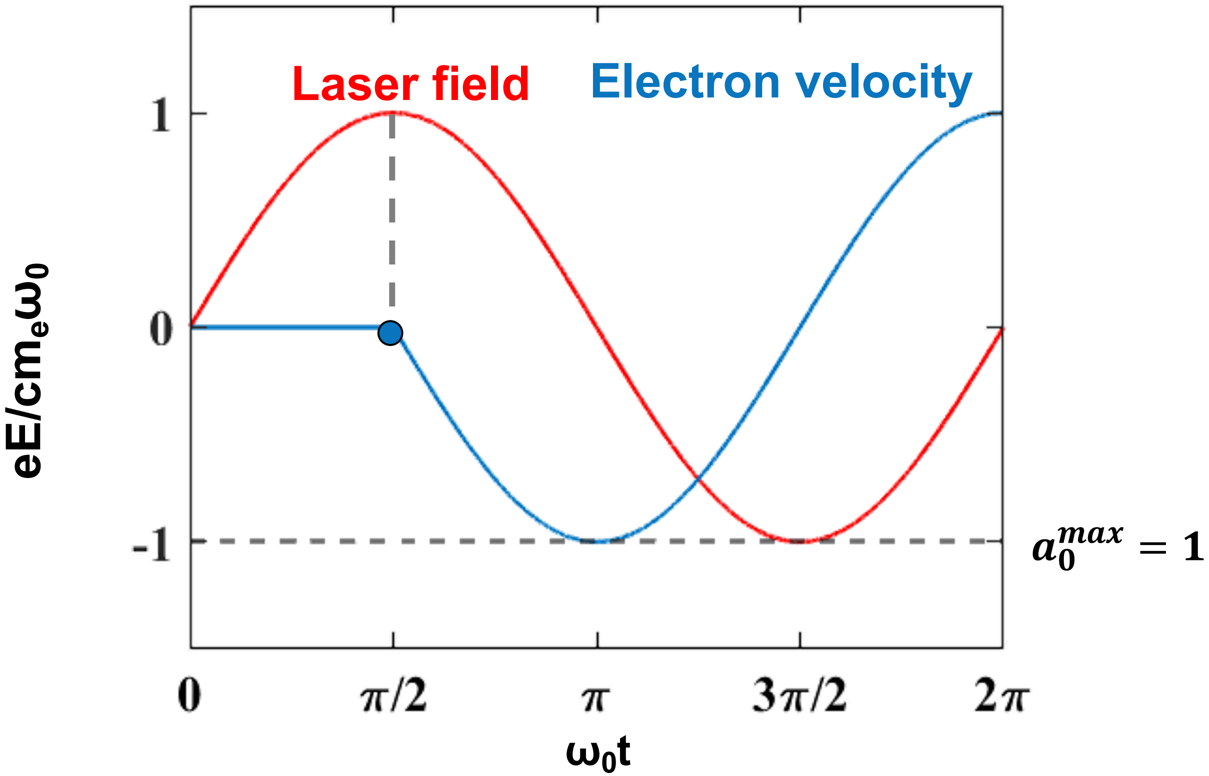




In the optical range, the intensity for relativistic electron motion is much greater than the intensity required for ionization

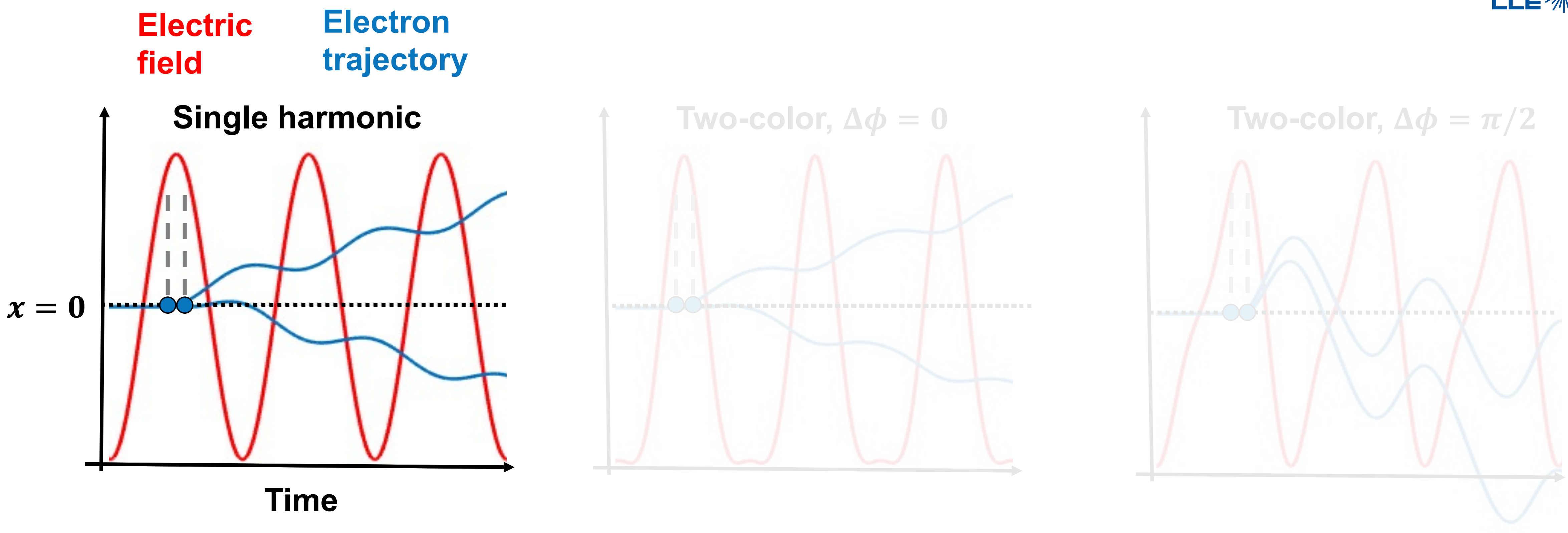
A high-energy terahertz source could enable access to a ‘wavelength frontier’ where bound electron nonlinear optics and relativistic plasma physics overlap





In the THz range, the intensity for relativistic electron motion is comparable to the intensity required for ionization

Photoionization by a monochromatic pulse produces no net current, precluding terahertz generation

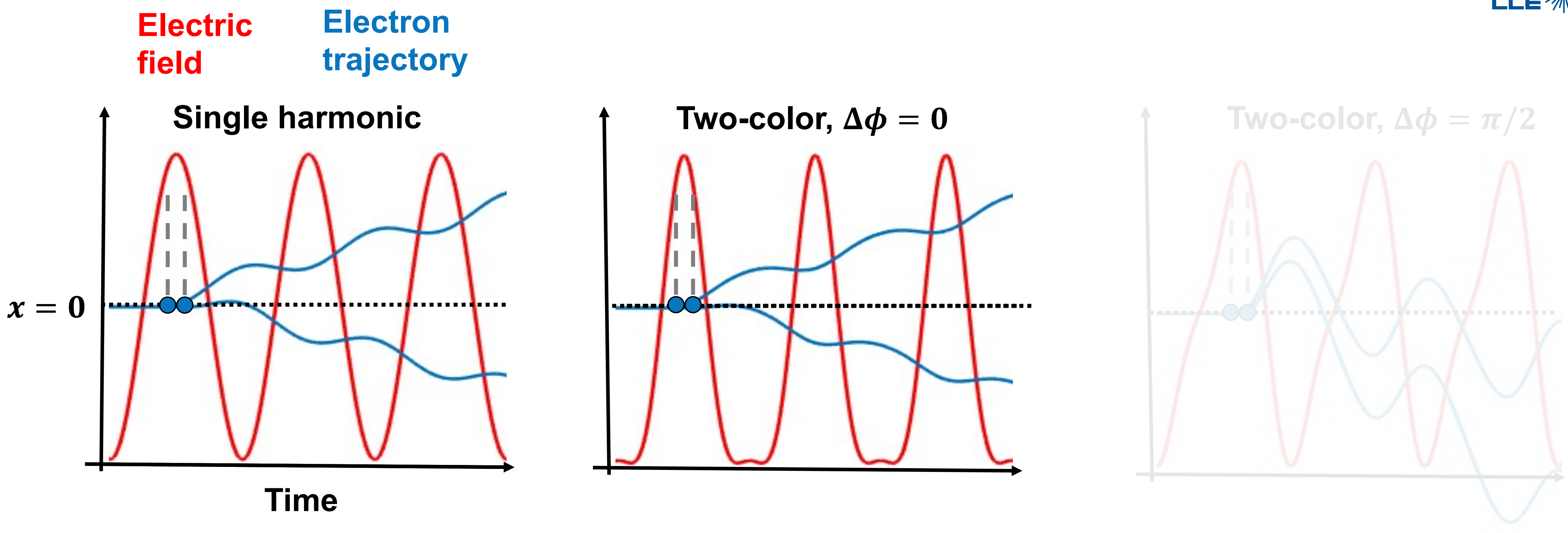


Symmetric peaks
No drift current

Symmetric peaks
No drift current

Asymmetric peaks
Net drift current

Photoionization by an in-phase two-color pulse also produces no net current, precluding terahertz generation

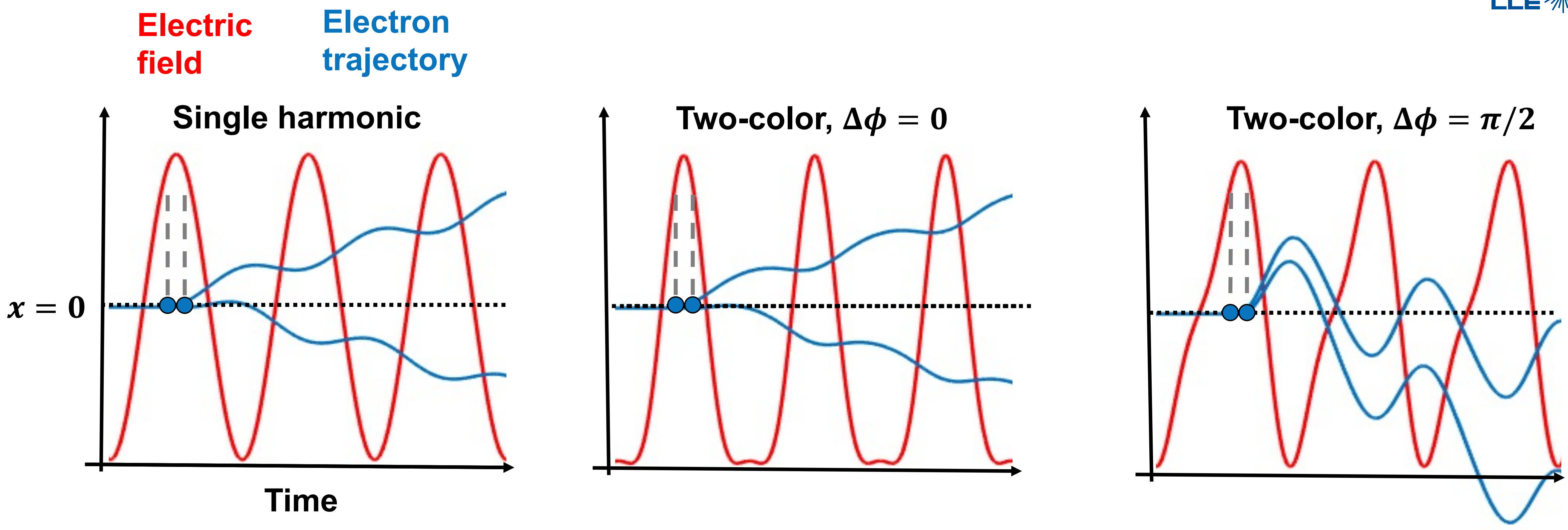


Symmetric peaks
No drift current

Symmetric peaks
No drift current

Asymmetric peaks
Net drift current

The addition of an out-of-phase second harmonic breaks the field symmetry and produces a net current of photoionized electrons



Symmetric peaks
No drift current

Symmetric peaks
No drift current

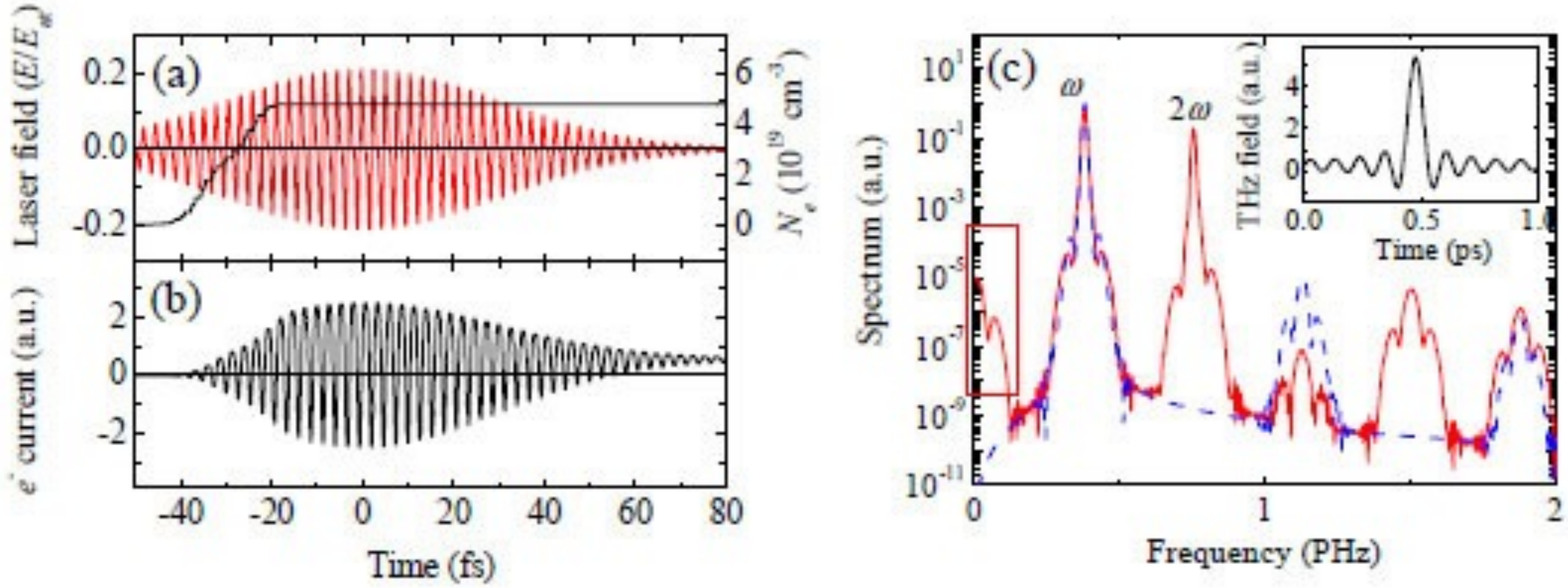
Asymmetric peaks
Net drift current

Over the duration of a pulse, the time-dependence of the ionization produces a time-dependent current

$$E_{THz} \propto \frac{\partial J}{\partial t} = e\frac{\partial N_e}{\partial t}\, v_d$$

Ionization

Drift velocity



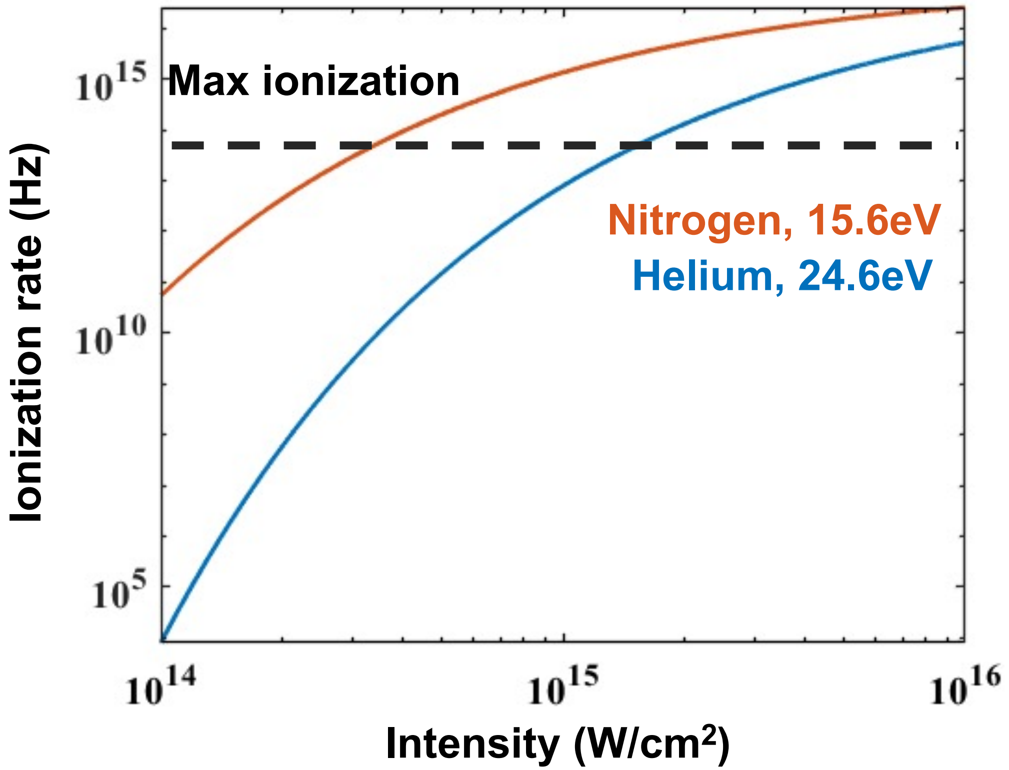
The combination of ionization and the net drift velocity induced by the asymmetric two-color field generates THz radiation

Kim et al., *Optics Express* (2007)

How do we optimize the THz generation for 100 TW class laser pulses?

The terahertz production for a high-power laser pulse can be improved by using a high ionization potential gas

The field at electron birth scales with the gas ionization potential



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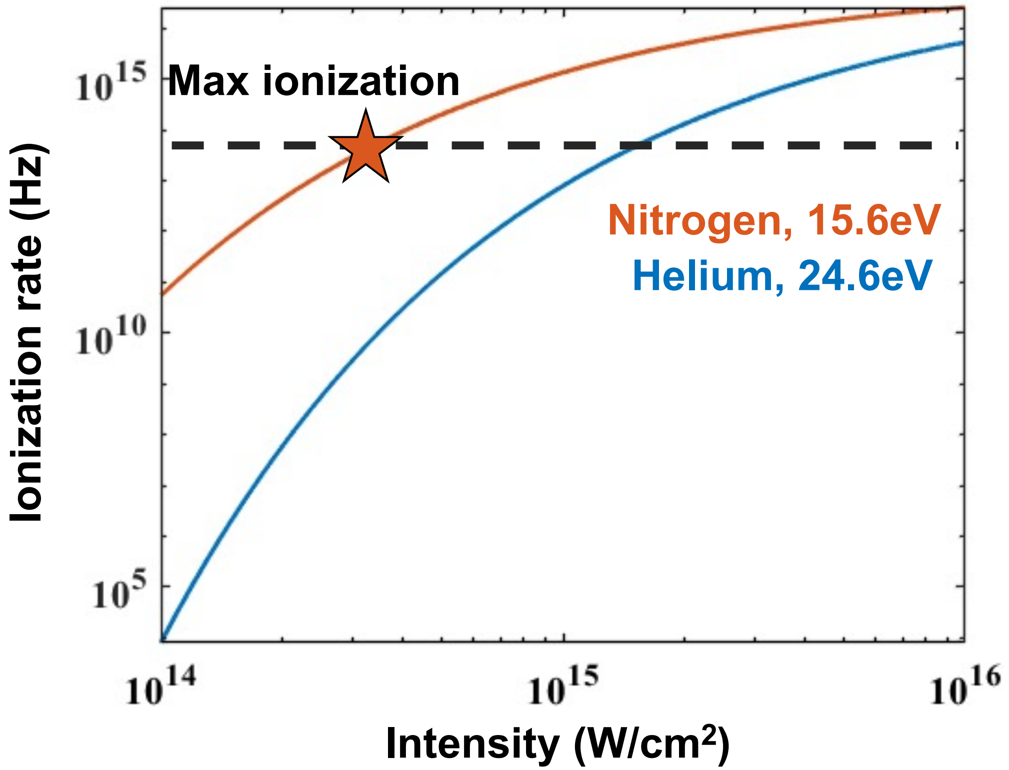

For a 15fs drive pulse in 10^{17}/cc density gas,

$$v_d^N \approx 1.8\times10^6 m/s$$

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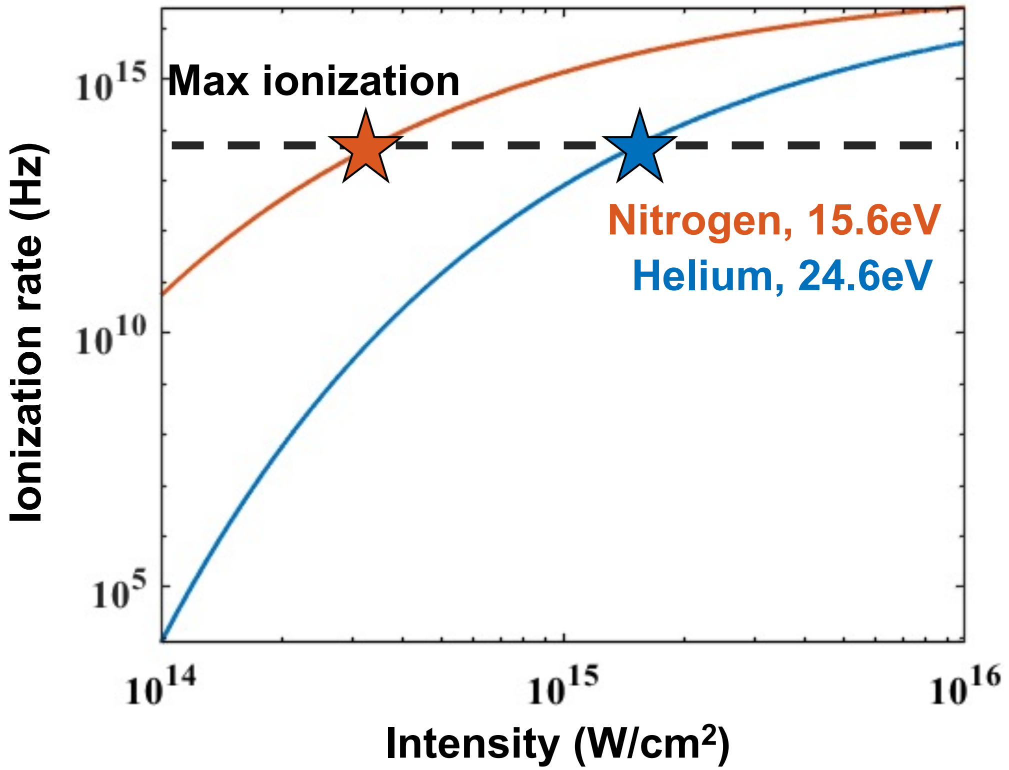


For a 15fs drive pulse in 10^{17}/cc density gas,

$$v_d^N \approx 1.8\times10^6 m/s$$

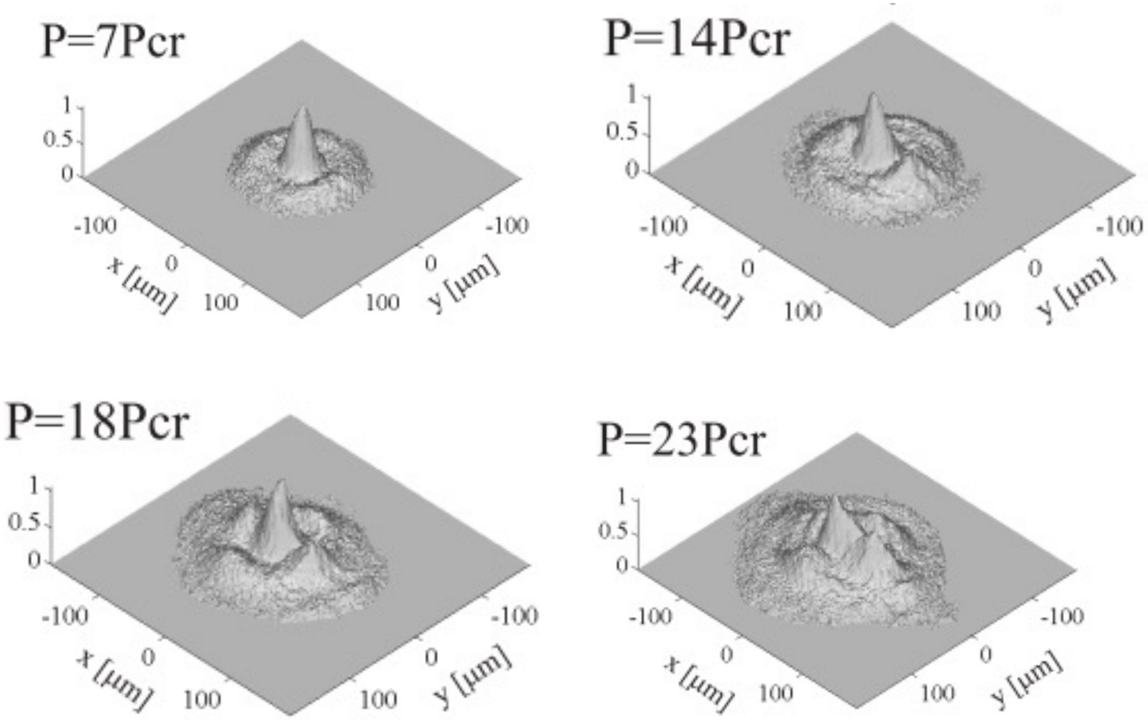
$$v_d^{He} \approx 3.6\times10^6 m/s$$

Increasing the intensity without increasing the ionization potential does not result in a larger drift velocity

A higher ionization potential gas increases the electron drift velocity and corresponding terahertz yield

A low-density gas can maximize the stability of the drive laser pulse, in addition to promoting other favorable properties

Lower gas densities increase the critical power, which allow for more linear propagation and less beam break up



$$P_c \propto 1/n_g$$

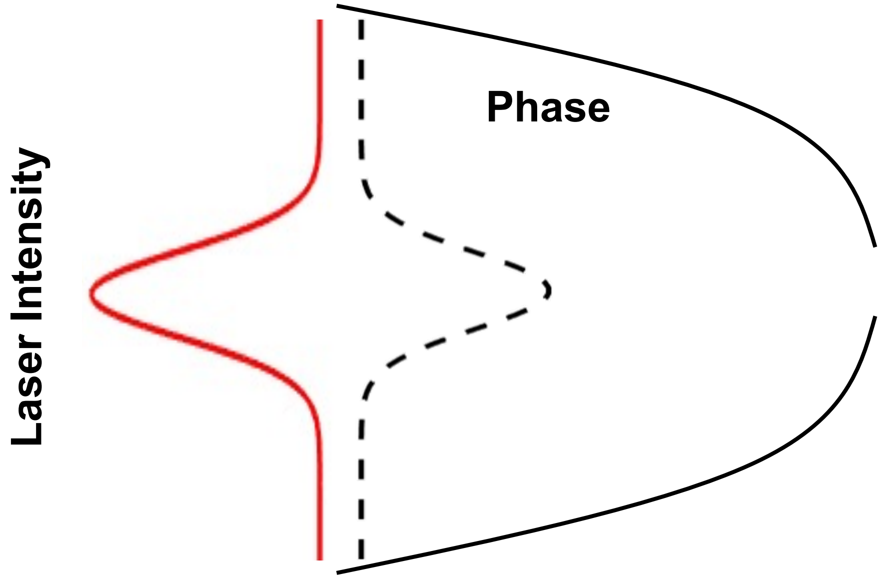
$$P_c^{He,3\,Torr} \approx 80TW$$

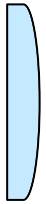
A low gas density is required for mitigating beam breakup of 100 TW class laser pulses

Fibich et al., *Optics Express* (2005)

Filamentary propagation can increase the THz yield by extending the range of high intensity beyond a Rayleigh length

A laser pulse propagating in a medium with an intensity-dependent refractive index will self-focus

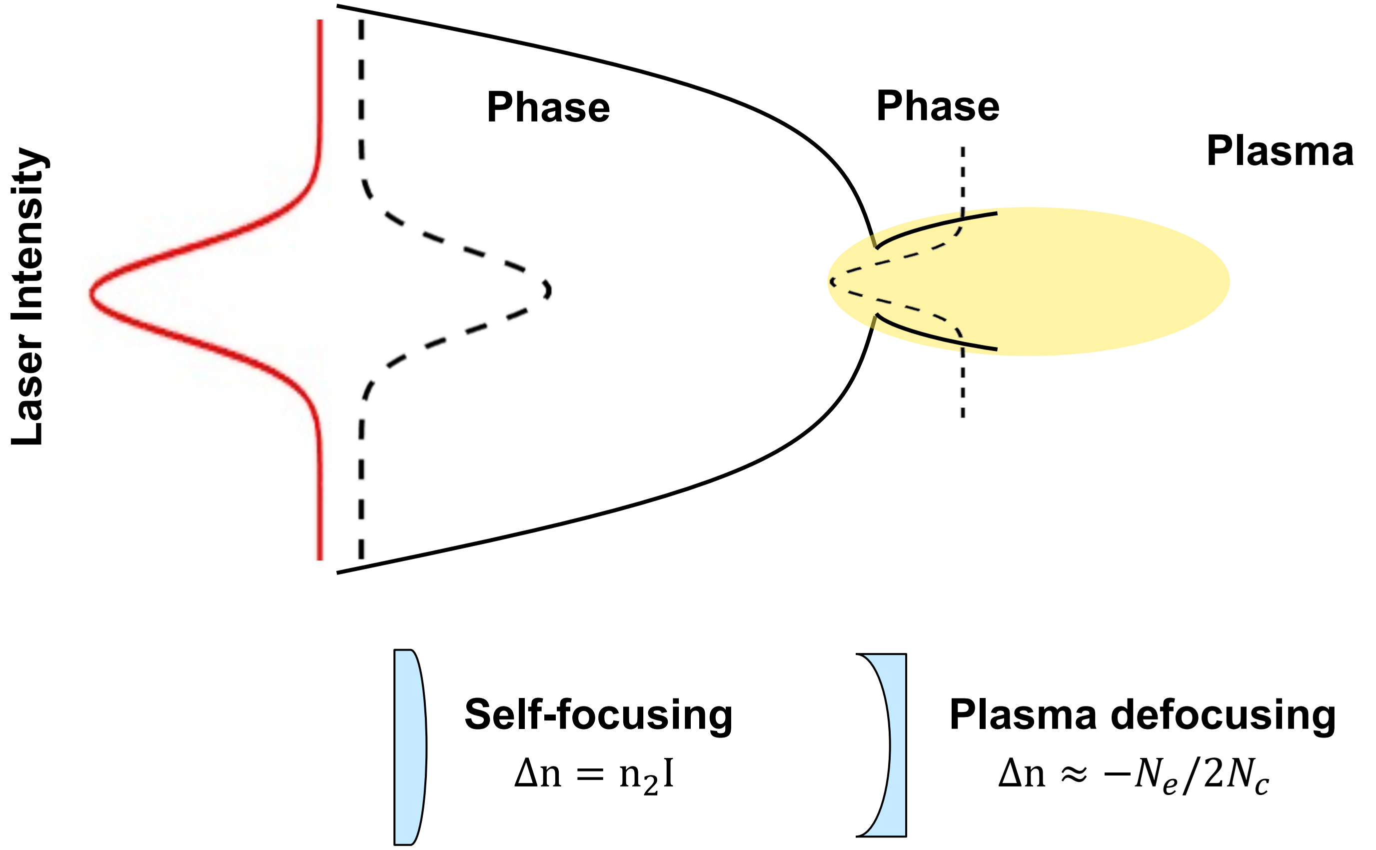




$\Delta n = n_2 I$

Filamentary propagation can increase the THz yield by extending the range of high intensity beyond a Rayleigh length

The laser intensity will rise enough to ionize the background gas, which defocuses the pulse



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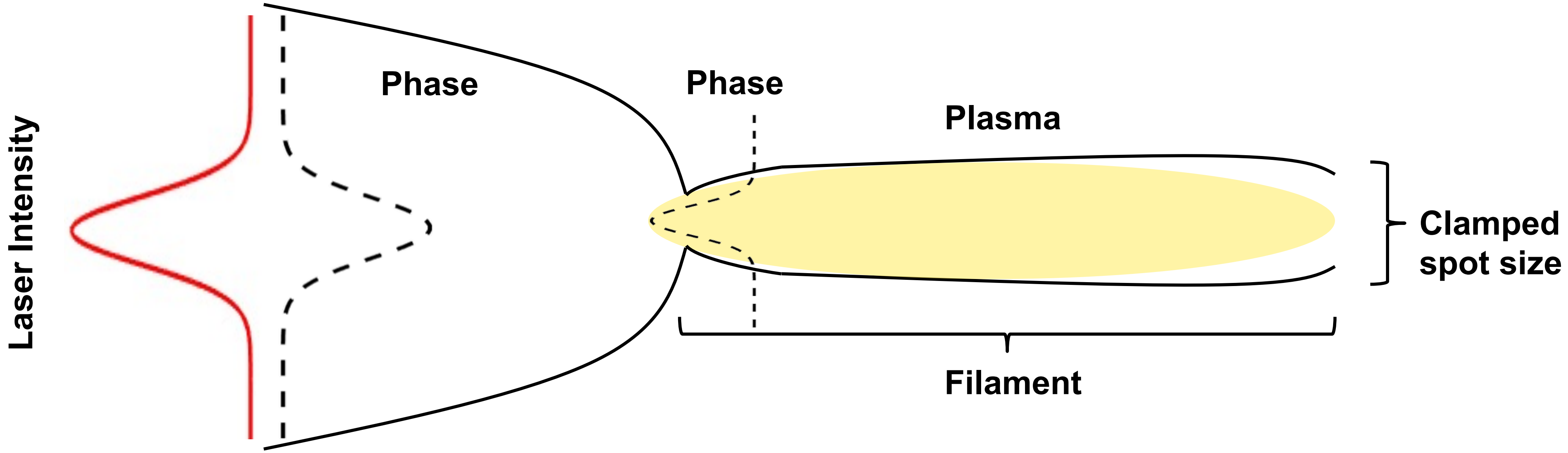
Filamentation occurs when self-focusing is balanced by plasma defocusing, resulting in a clamped intensity and spot size



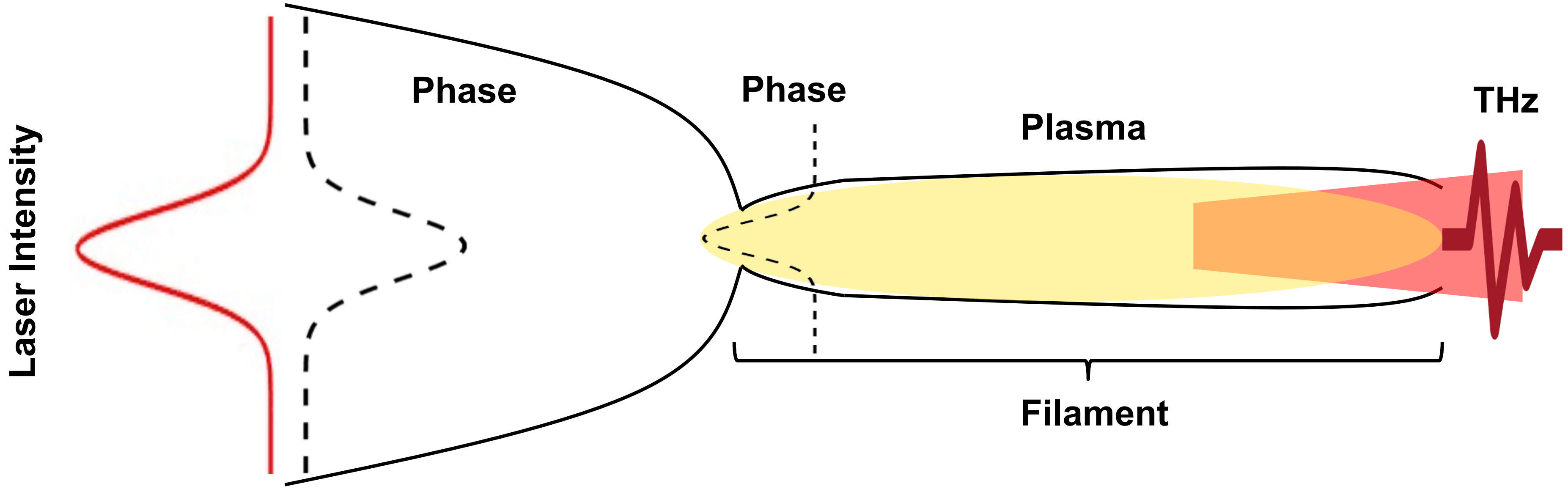
Self-focusing
$\Delta n = n_2 I$

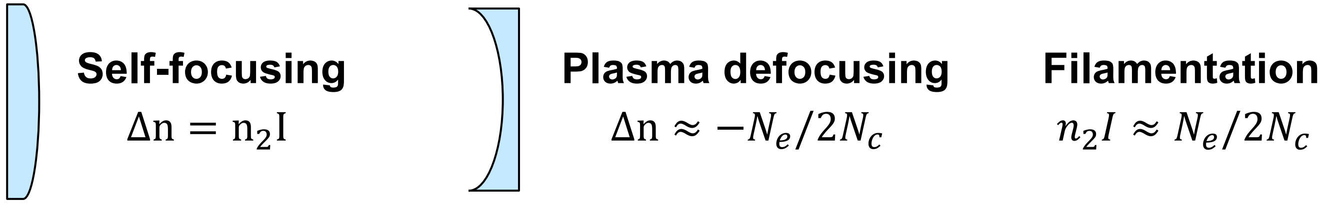
Plasma defocusing
$\Delta n \approx -N_e/2N_c$

Filamentation
$n_2 I \approx N_e/2N_c$

Filamentary propagation can increase the THz yield by extending the range of high intensity beyond a Rayleigh length

Terahertz radiation is emitted from each point within the filament and constructively interferes





Simple scalings suggest the number of freed electrons (and resulting terahertz current) within a filament is independent of gas density

- The filament area scales with the critical power, so the filament area is inversely proportional to the gas density

$A \sim P_c / I_s$ $P_c \sim 1/n_g$ so, $A \sim 1/n_g$

- The density of free electrons is proportional to the gas density

$$n_e \sim n_g$$

- The number of free electrons per unit length is determined by multiplying the free electron density by the filament area

$$\frac{N_f}{\delta z} = n_e A \sim \frac{n_g}{n_g} \sim const$$

Ionization simulations reproduce the simple scalings: freed electrons are not lost by going to low density

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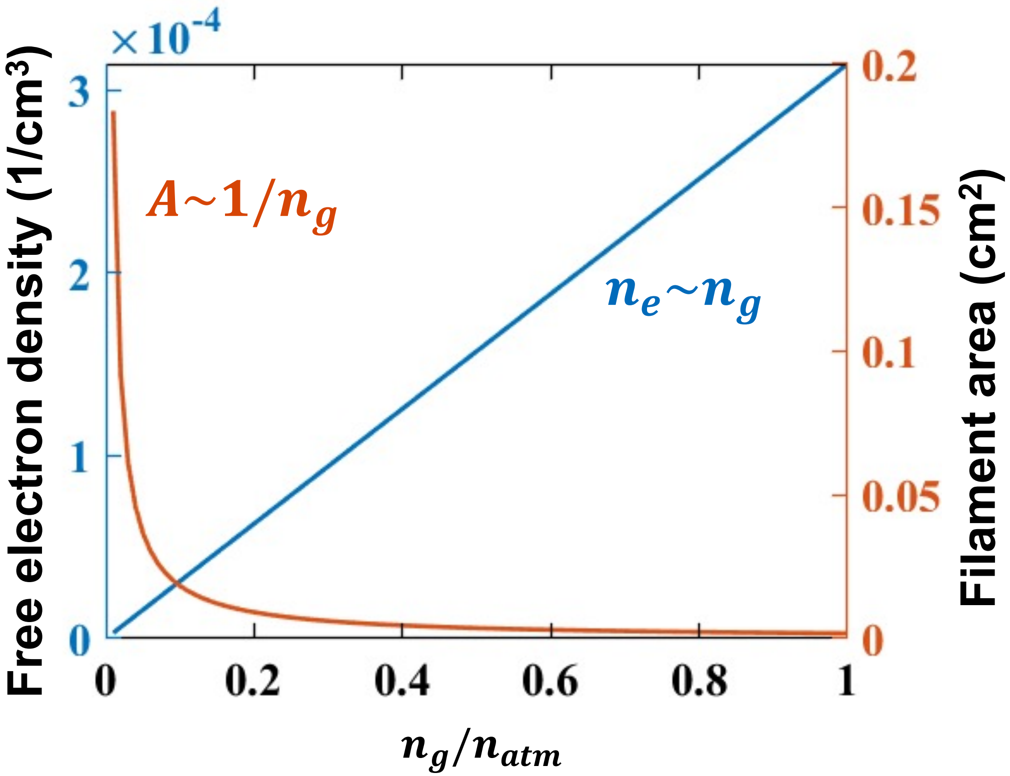

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Propagation and THz generation were modelled using the unidirectional pulse propagation equation (UPPE)

The UPPE evolves the electric field of an arbitrarily large frequency domain, necessary to resolve both the drive laser harmonics and terahertz

Linear **Nonlinear**

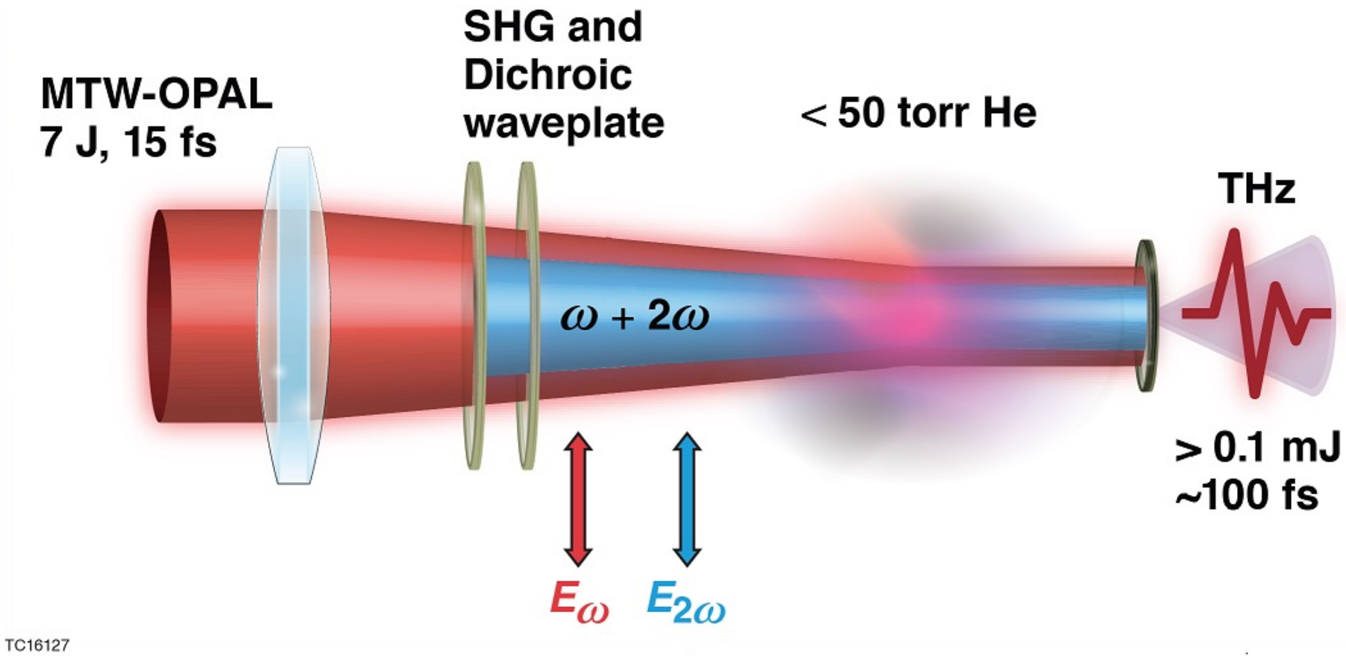
$$\frac{\partial \tilde{E}}{\partial z} = i\left(K - \frac{\omega}{v}\right)\tilde{E} - \frac{1}{2iK}\frac{\omega^2}{\epsilon_0 c^2}\left(\tilde{P}_{NL} - \frac{i}{\omega}\tilde{J}_{loss} + \frac{1}{\omega^2}\widetilde{\frac{\partial J_{plas}}{\partial t}}\right)$$

Linear propagation | **Third order polarization** | **Pump depletion** | **Plasma current**

The terahertz is primarily produced via the transient plasma current

$$\frac{\partial J}{\partial t} = \frac{e^2}{m_e} N_e E + \mathrm{v}_{\mathrm{EN}} \mathrm{J}$$

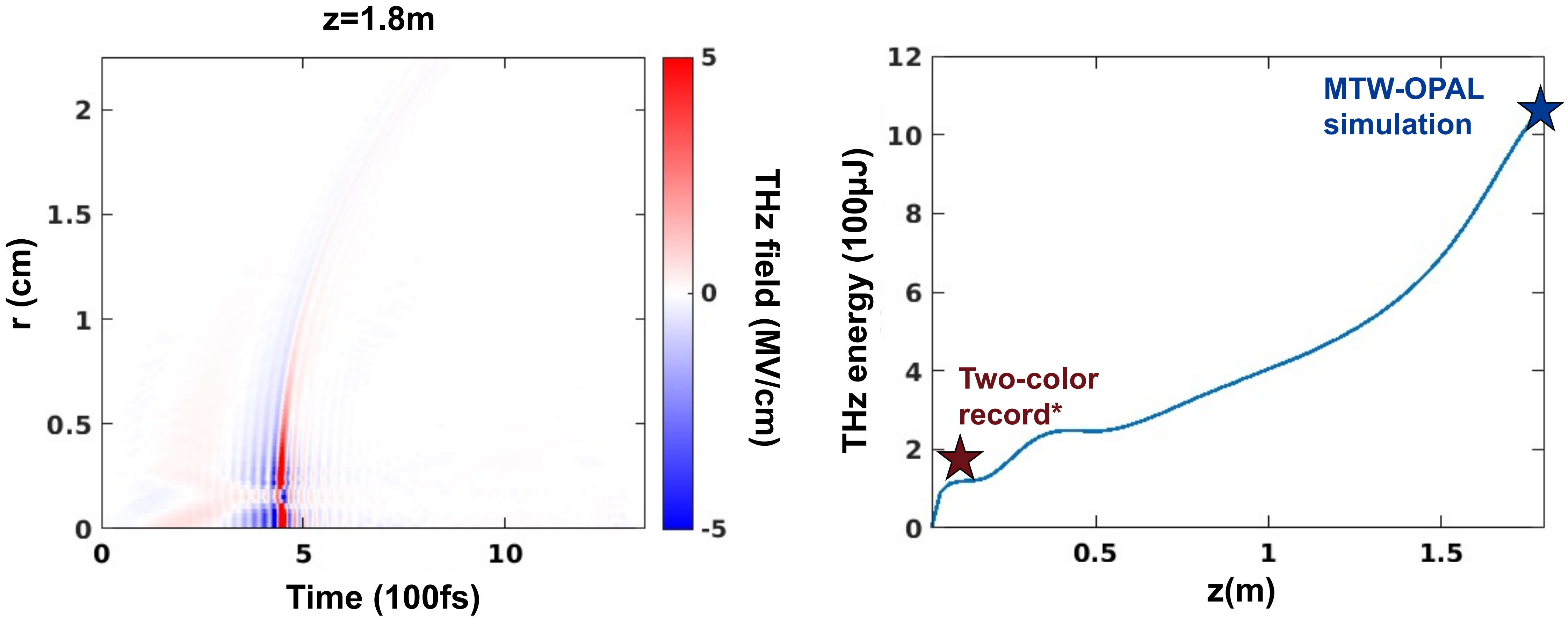
Simulation parameters are chosen to study the terahertz yield for an upcoming campaign on LLE's MTW-OPAL laser



Laser parameters	Value
$P_{1\omega}$ (TW)	400
$P_{2\omega}$ (TW)	80
$\lambda_{1\omega}$ (nm)	920
τ (fs)	15
$f/\#$	500

Gas parameters	Value
Species	Helium
U_I (eV)	24.6
n_g (10^{17}/cc)	1
P_c (TW)	85

Preliminary simulations suggest that >1mJ of THz energy can be produced by two-color filamentation for MTW-OPAL parameters



*Koulouklidis et al., *Nat. Photon.* (2020)

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