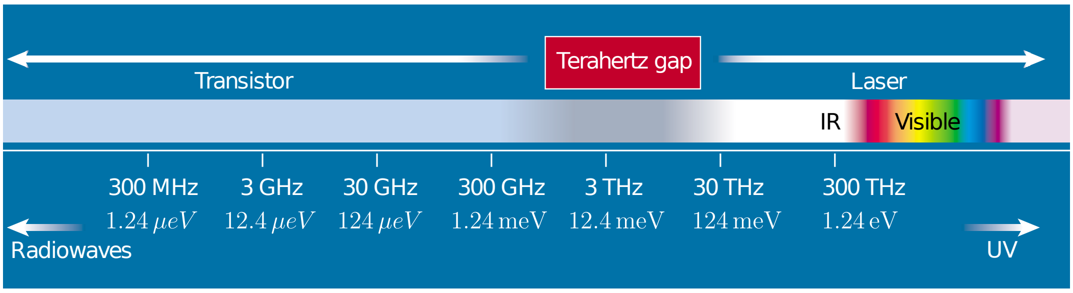
THz to Far-Infrared Supercontinua from Laser-Driven Gas-Plasmas

I. Thiele, B. Zhou, A. Nguyen, E. Smetanina, R. Nuter, P. González de Alaiza Martínez, K. J. Kaltenecker, J. Déchard, L. Bergé, P. U. Jepsen, and S. Skupin

[1] CELIA, Univ. Bordeaux – CNRS – CEA, France
[2] DTU Fotonik, Technical University of Denmark
[3] CEA/DAM Île-de-France, Arpajon, France
[4] ILM, Univ. Claude Bernard Lyon 1 and CNRS, France

9ème Forum Lasers et Plasmas, 15 juin 2018

The Terahertz (THz) Spectral Range



spectral range of THz frequencies is difficult to access [C. Sirtori, Nature 417, 132 (2002)]

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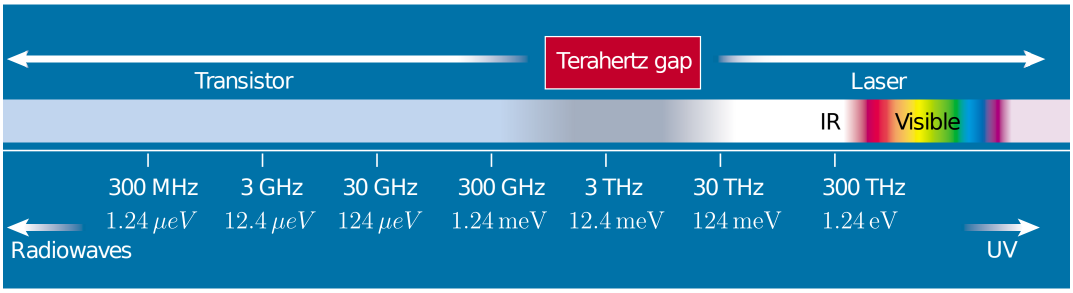

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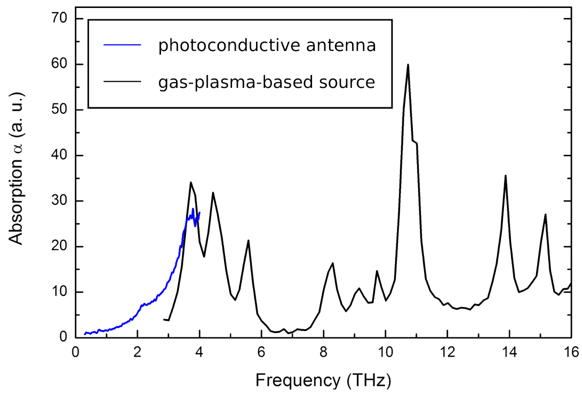
- ➜ identification of organic molecules
- ➜ THz time-domain spectroscopy



Absorbtion spectra of TNT

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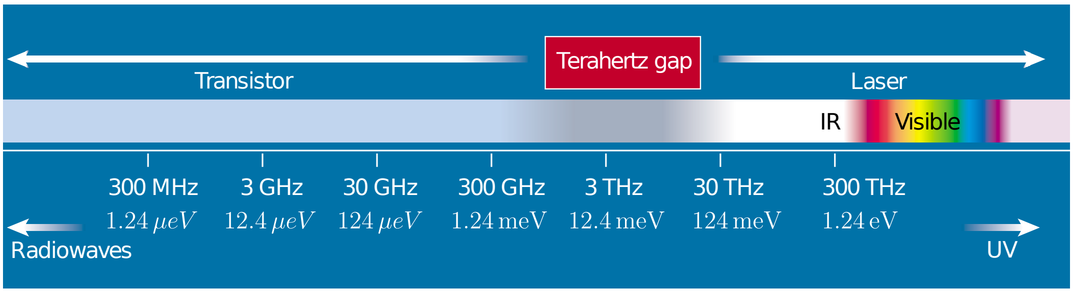
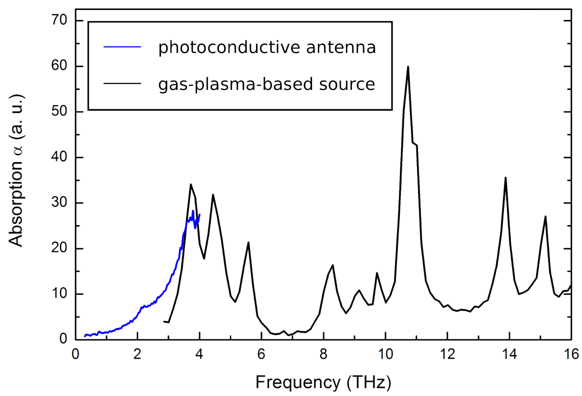


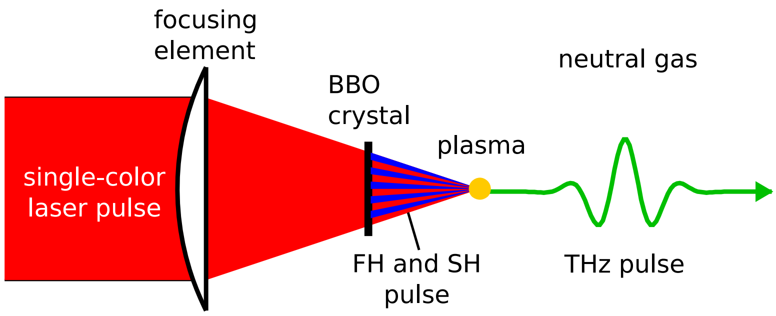
spectral range of THz frequencies is difficult to access [C. Sirtori, Nature 417, 132 (2002)]

- ➜ identification of organic molecules
- ➜ THz time-domain spectroscopy
- ➜ the broader the spectrum the better
- ➜ compact, cheap, remote ... sources



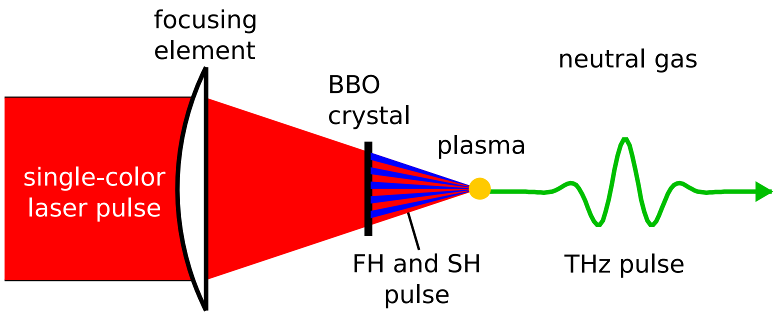
Absorbtion spectra of TNT

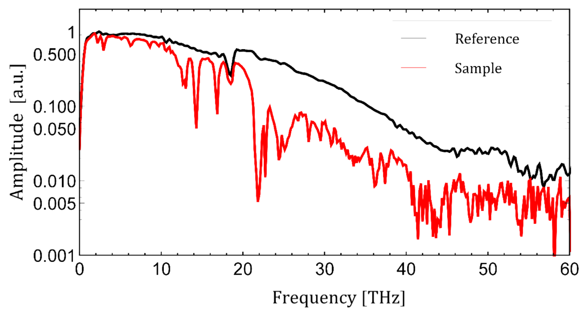
THz Emission from Plasmas



➜ standard two-color scheme [K. Reimann, Rep. Prog. Phys. 70, 1597 (2007)]

THz Emission from Plasmas





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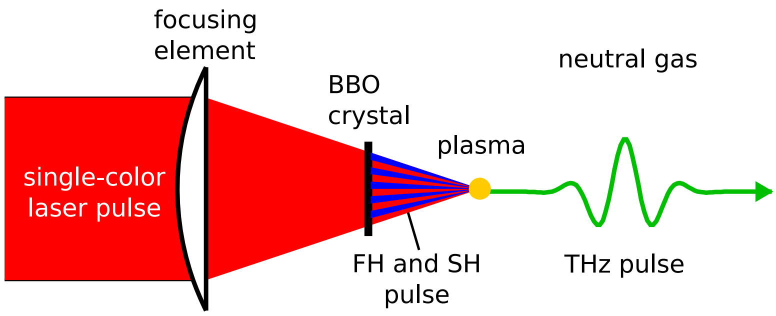
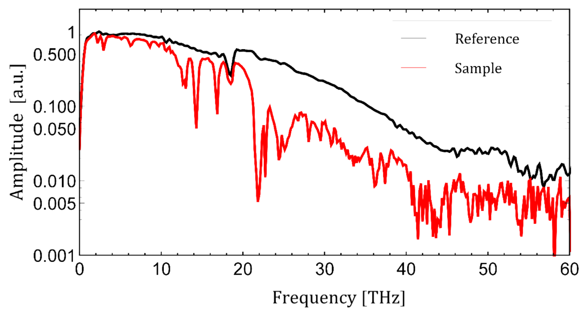
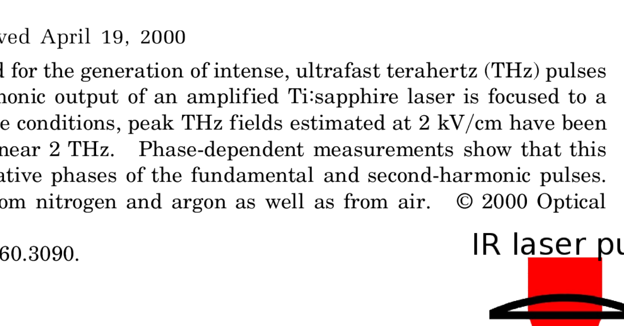
➜ broadband THz to FIR emission up to 50 THz and beyond

THz Emission from Plasmas





- ➜ standard two-color scheme [K. Reimann, Rep. Prog. Phys. 70, 1597 (2007)]
- ➜ broadband THz to FIR emission up to 50 THz and beyond
- ➜ remote sources are possible [J.-F. Daigle, Opt. Express 20, 6825 (2012)]
- ➜ gas plasmas are cheap (if you have the fs laser already ...)
- ➜ compact sources → use microplasmas [F. Buccheri, Optica 2, 366 (2015)]



1210 OPTICS LETTERS / Vol. 25, No. 16 / August 15, 2000

Intense terahertz pulses by four-wave rectification in air

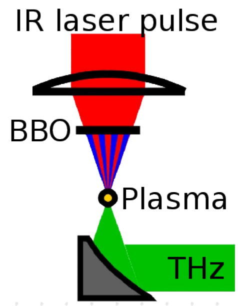
D. J. Cook and R. M. Hochstrasser

Department of Chemistry, University of Pennsylvania, 231 S. 34th Street, Philadelphia, Pennsylvania 19104-6323

Received April 19, 2000

We describe a new four-wave rectification method for the generation of intense, ultrafast terahertz (THz) pulses from gases. The fundamental and second-harmonic output of an amplified Ti:sapphire laser is focused to a peak intensity of ~5×10^{14} W/cm^2. Under these conditions, peak THz fields estimated at 2 kV/cm have been observed; the measured power spectrum peaks near 2 THz. Phase-dependent measurements show that this is a coherent process and is sensitive to the relative phases of the fundamental and second-harmonic pulses. Comparable THz signals have been observed from nitrogen and argon as well as from air. © 2000 Optical Society of America

OCIS codes: 320.7110, 320.7160, 190.4380, 260.3090.



➜ $E(t) \propto e^{-t^2/t_p^2}\left[\cos(\omega_0 t) + \xi \cos(2\omega_0 t + \phi)\right]$

➜ $P(t) \propto E(t)^3 \quad \Longrightarrow \quad 2\omega_0 - \omega_0 - \omega_0 = \mathrm{THz}$

Two-Color Pulses: Plasma Current

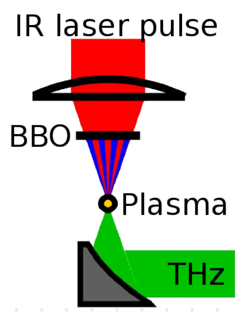
LETTERS

Coherent control of terahertz supercontinuum generation in ultrafast laser–gas interactions

K. Y. KIM*, A. J. TAYLOR, J. H. GLOWNIA AND G. RODRIGUEZ

Material Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
*e-mail: kykim@lanl.gov; alex.kiyong.kim@gmail.com

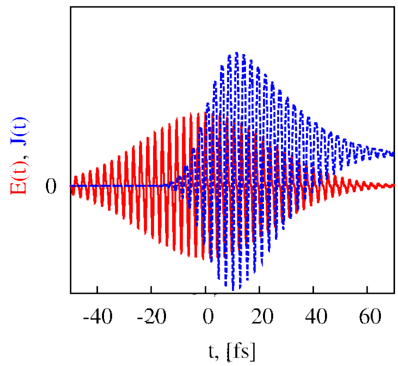
Published online: 27 July 2008; doi:10.1038/nphoton.2008.153

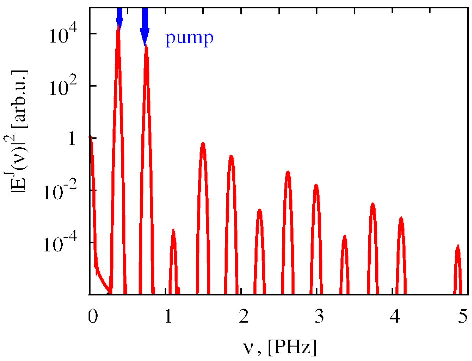


- ➜ two-color pulse generates asymmetric plasma resp. ionization current J_e
- ➜ radiation $E^{J_e} \propto \partial_t J_e$ emitted in THz range

Two-Color Pulses: Plasma Current

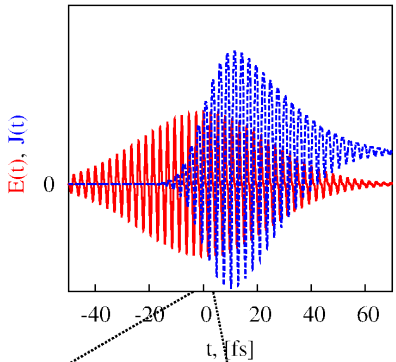
➜ radiation
$E^{J_e} \propto \partial_t J_e \propto n_e E$

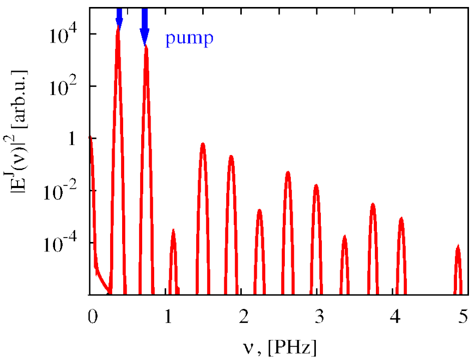


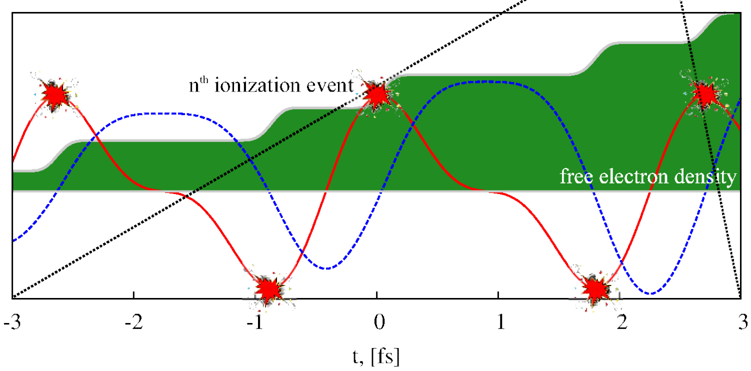


Two-Color Pulses: Plasma Current

- ➜ radiation
  $E^{J_e} \propto \partial_t J_e \propto n_e E$
- ➜ tunnel ionization:
  electrons get "injected"
  at extrema of *E* field
  $\rightarrow$,,DC"-conponent







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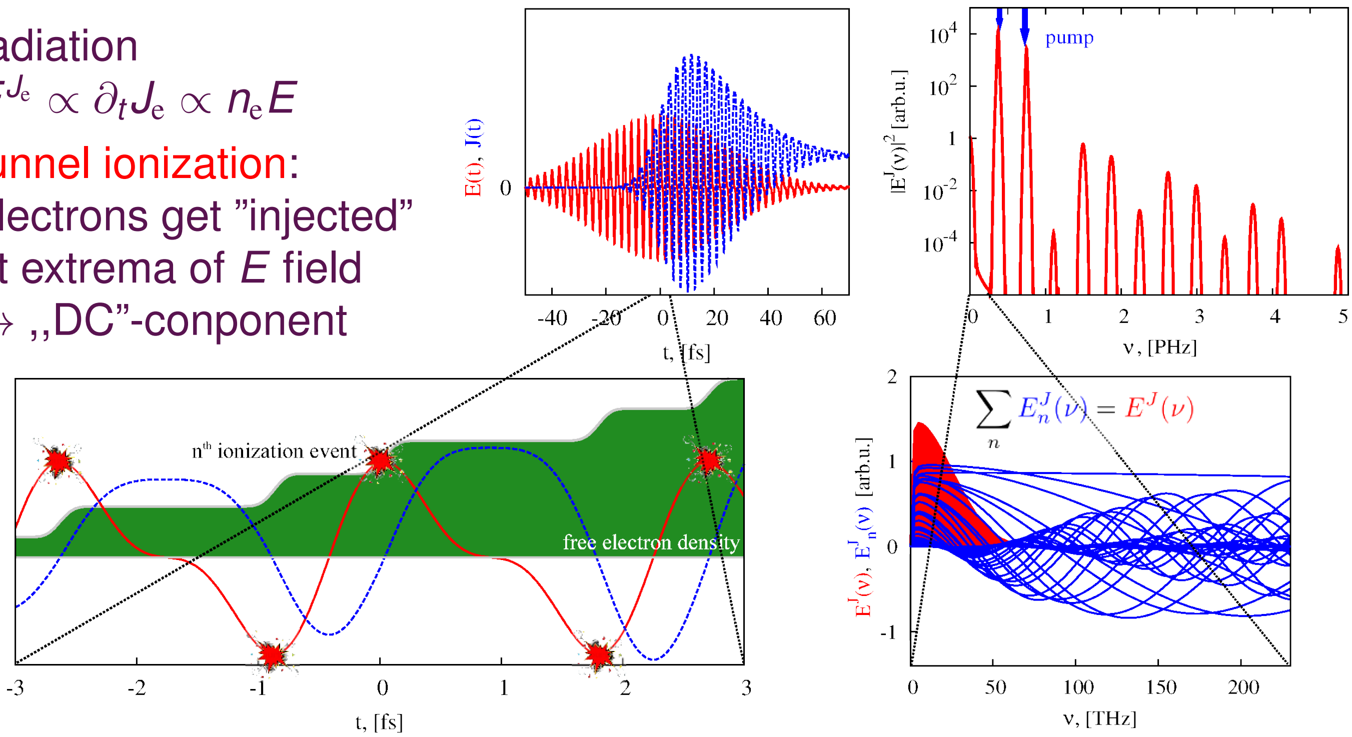
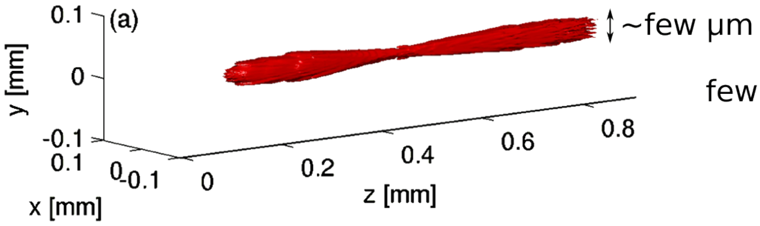


- ➜ extreme sensitivity of THz spectra with respect to pump-pulse!

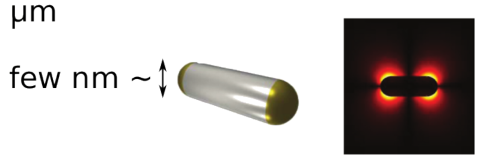
Plasma as Plasmonic Particle

gas plasma



[I. Babushkin et al., PRL 105, 053903 (2010)]

plasmonic nanoparticle

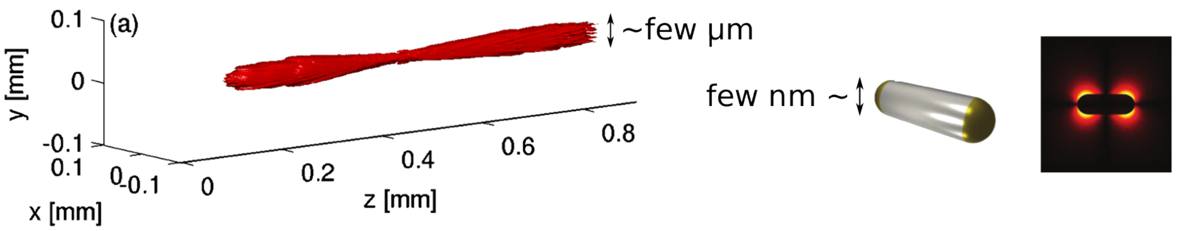


[S. Hasan et al., PRB 88, 205125 (2013)]

→ transverse size of plasma $D_\mathrm{p} \lesssim$ plasma wavelength $\lambda_\mathrm{p}^\mathrm{min} \propto 1/\sqrt{n_\mathrm{e}}$

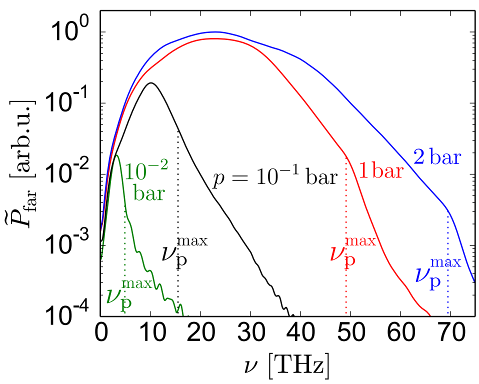
Plasma as Plasmonic Particle

gas plasma | plasmonic nanoparticle



[I. Babushkin et al., PRL 105, 053903 (2010)] [S. Hasan et al., PRB 88, 205125 (2013)]

- ➜ transverse size of plasma $D_\mathrm{p} \lesssim$ plasma wavelength $\lambda_\mathrm{p}^\mathrm{min} \propto 1/\sqrt{n_\mathrm{e}}$
- ➜ we observe THz spectral broadening dependent on the gas pressure
- ➜ spectral width seems to be correlated with plasma frequency
- ➜ in a microplasma we can exclude nonlinear propagation effects



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➜ proof that plasmonic resonances influence the THz spectrum?

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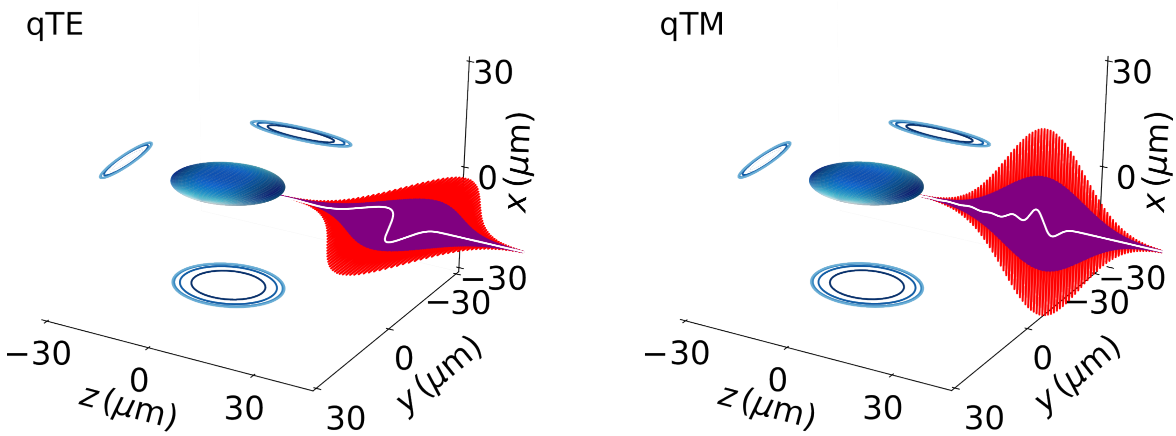


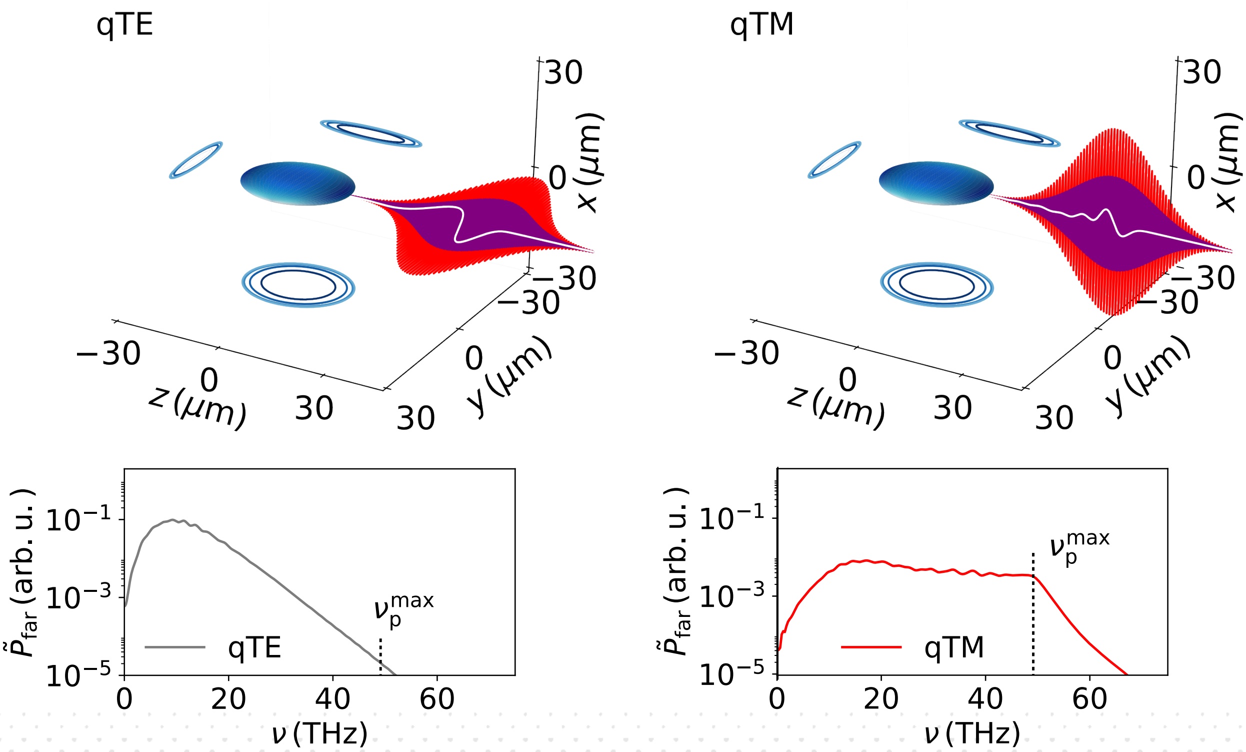
➜ use elliptical beams → elliptical plasmas $10\ \mu m > \lambda_p^{min} \sim 6\ \mu m > 1\ \mu m$

➜ qTE polarization sees large transverse width (weak gradients)

➜ qTM polarization sees small transverse width (strong gradients)

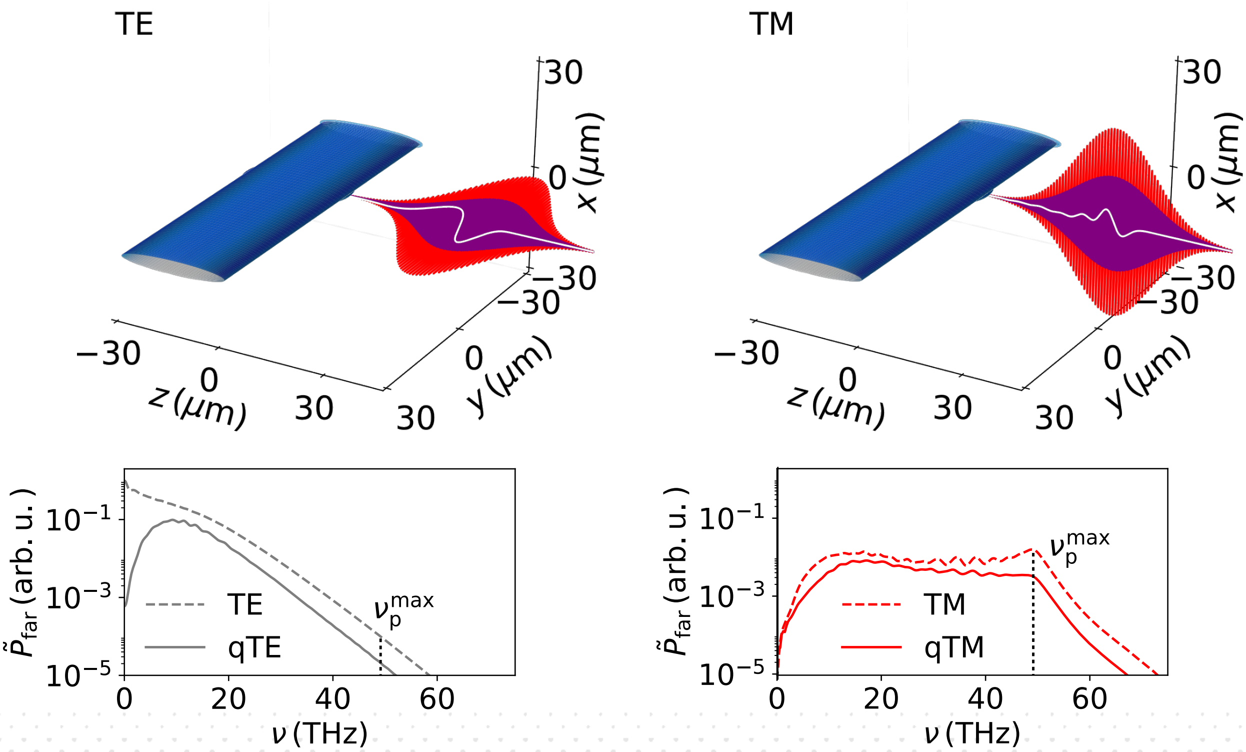
Plasma as Plasmonic Particle

➜ proof that plasmonic resonances influence the THz spectrum?



Plasma as Plasmonic Particle

➜ what about going to 2D system with proper TE,TM polarization?



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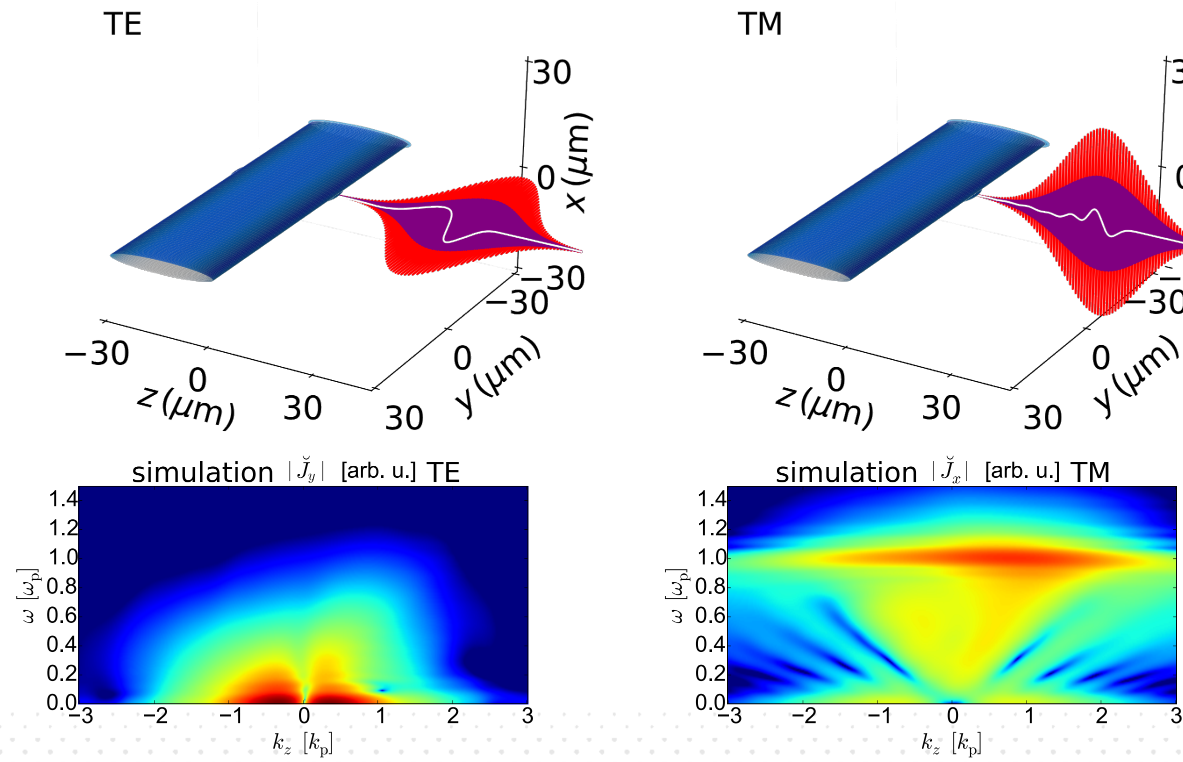
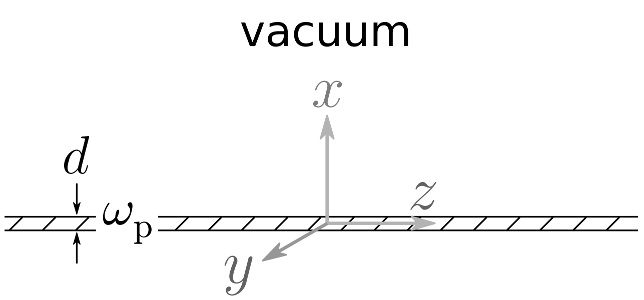


The Plasma Slab Model (2D)



$$\partial_t \mathbf{J} + \nu_{\mathrm{ei}} \mathbf{J} = \frac{q_e^2 n_0}{m_e} \mathbf{E}$$

coupled to Maxwell's equations

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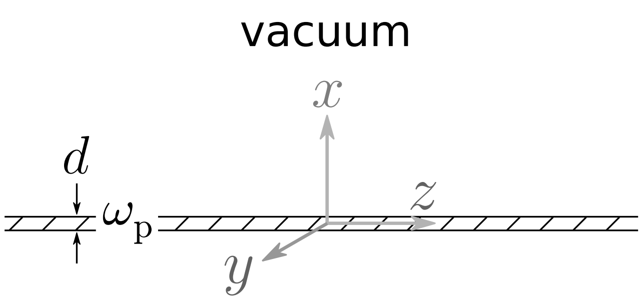

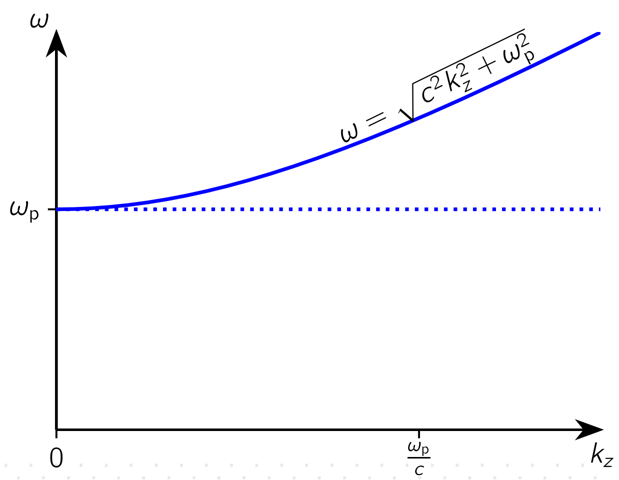

$$\partial_t \mathbf{J} + \nu_{ei} \mathbf{J} = \frac{q_e^2 n_0}{m_e} \mathbf{E} + \boldsymbol{\iota}$$

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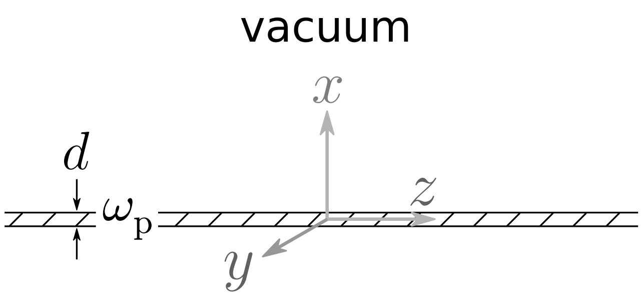
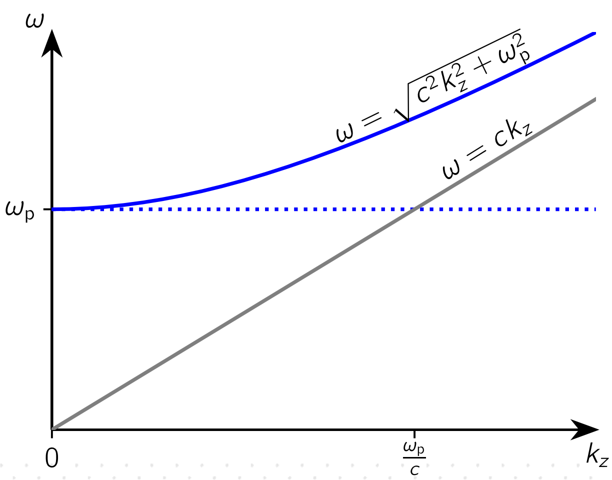
The Plasma Slab Model (2D)





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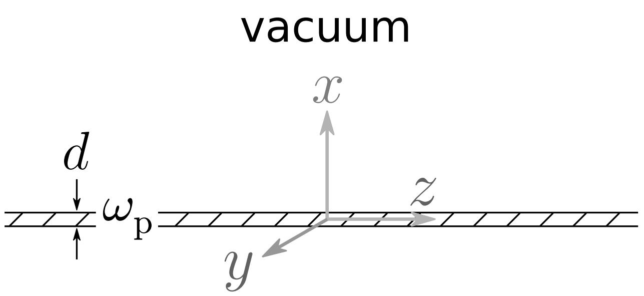

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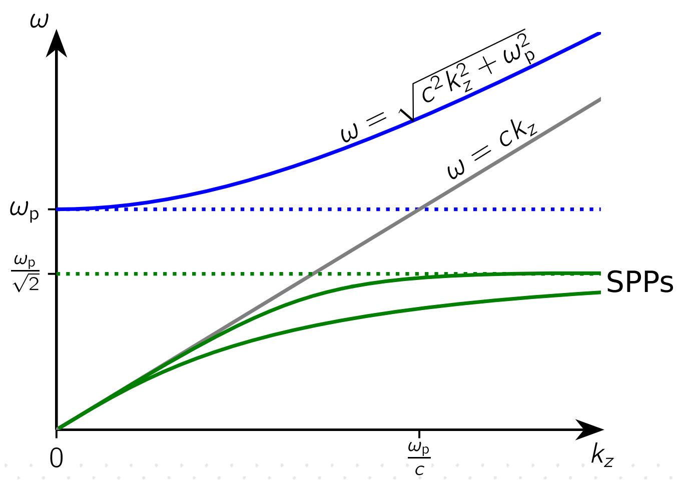
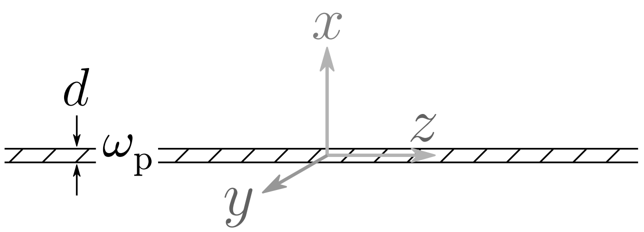


- ➜ guided modes
- ➜ no coupling to radiative field

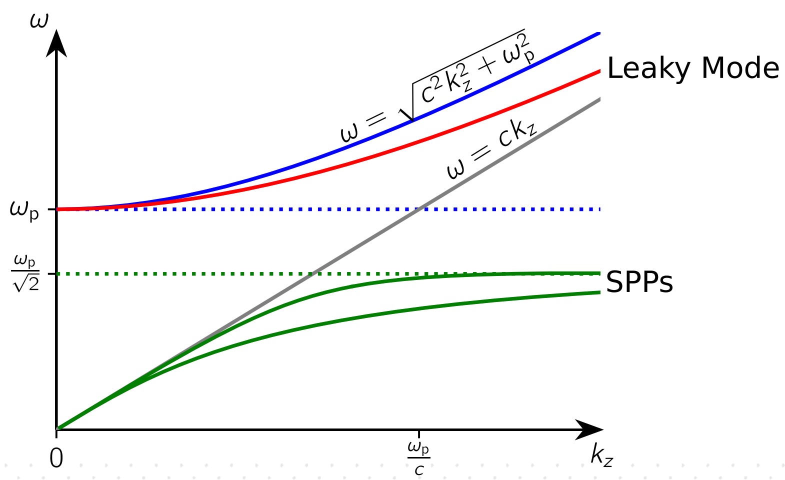
The Plasma Slab Model (2D)

vacuum



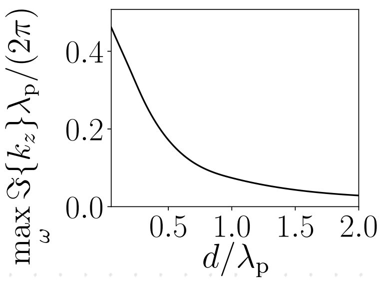
$$\partial_t \mathbf{J} + \nu_{\rm ei} \mathbf{J} = \frac{q_{\rm e}^2 n_0}{m_{\rm e}} \mathbf{E} + \iota$$

coupled to Maxwell's equations

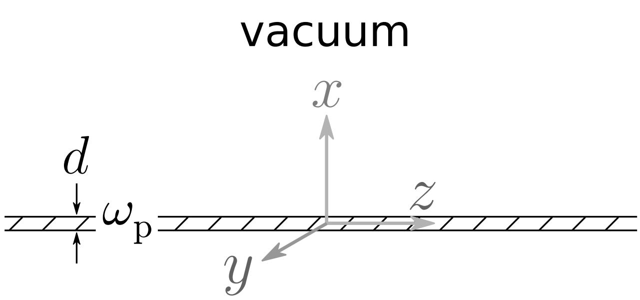


➜ complex resonance

➜ coupling to radiative field



The Plasma Slab Model (2D)



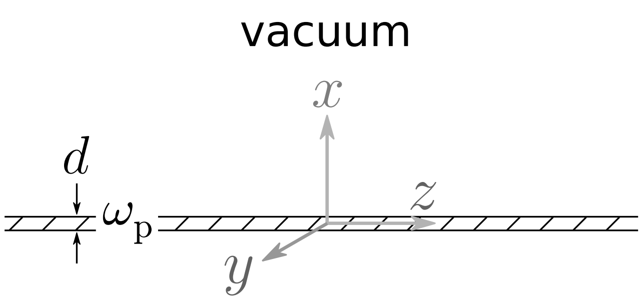
$$\partial_t \mathbf{J} + \nu_{\mathrm{ei}} \mathbf{J} = \frac{q_e^2 n_0}{m_e} \mathbf{E} + \boldsymbol{\iota}$$

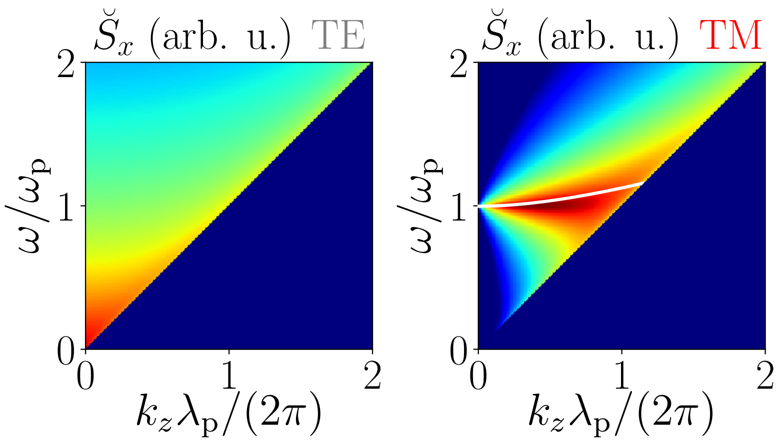
coupled to Maxwell's equations

$$\boldsymbol{\iota} \propto \delta(t)\delta(z)\mathbf{e}_{x,y}$$

➜ let us drive the system with Dirac-δ-excitation

The Plasma Slab Model (2D)





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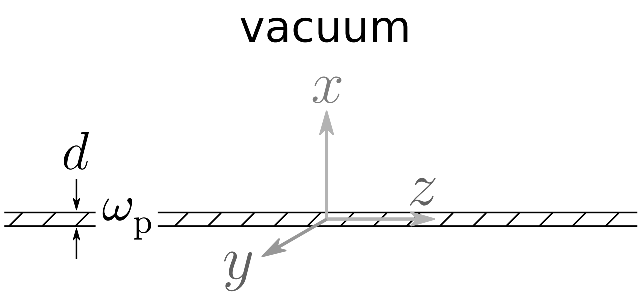
coupled to Maxwell's equations

$$\boldsymbol{\iota} \propto \delta(t)\delta(z)\mathbf{e}_{x,y}$$

$$\check{S}_x \propto \Re\{\check{\mathbf{E}} \times \check{\mathbf{B}}^\star\}_x$$

Poynting flux into the vacuum

The Plasma Slab Model (2D)



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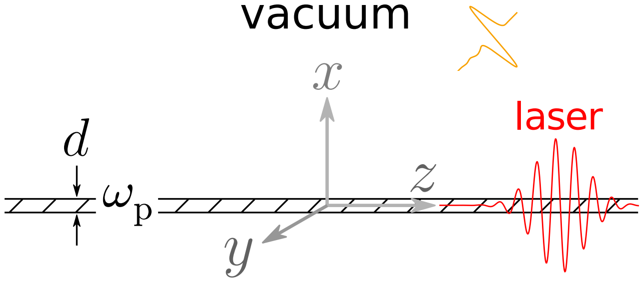
coupled to Maxwell's equations

$$\boldsymbol{\iota} \propto n_e \mathbf{E}_L$$

➜ let us drive the system with ionization by the laser and compute emitted THz spectra from current

The Plasma Slab Model (2D)



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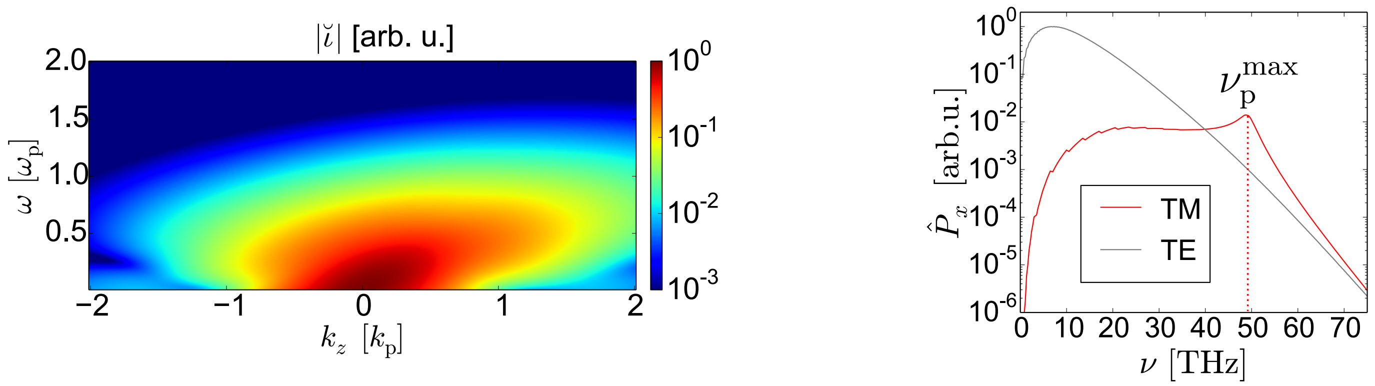

➜ Leaky mode resonances can cause THz spectral broadening!

The Plasma Slab Model (2D)

➜ what about larger beams and plasmas (15 μm thick, $\lambda_p^{min} \sim$ 30 μm, centimeters long)?

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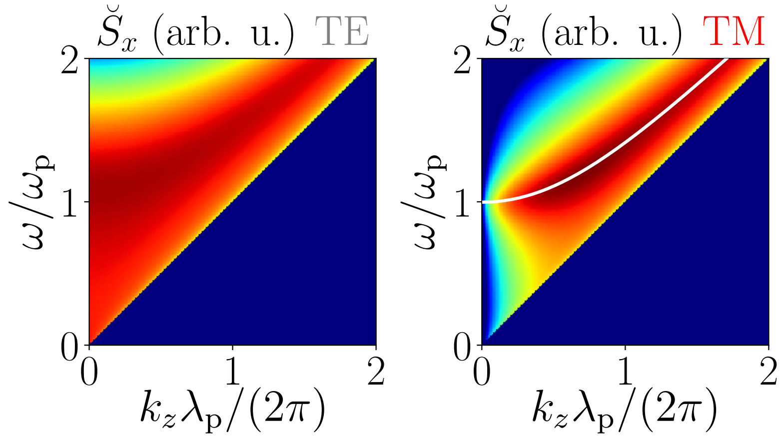

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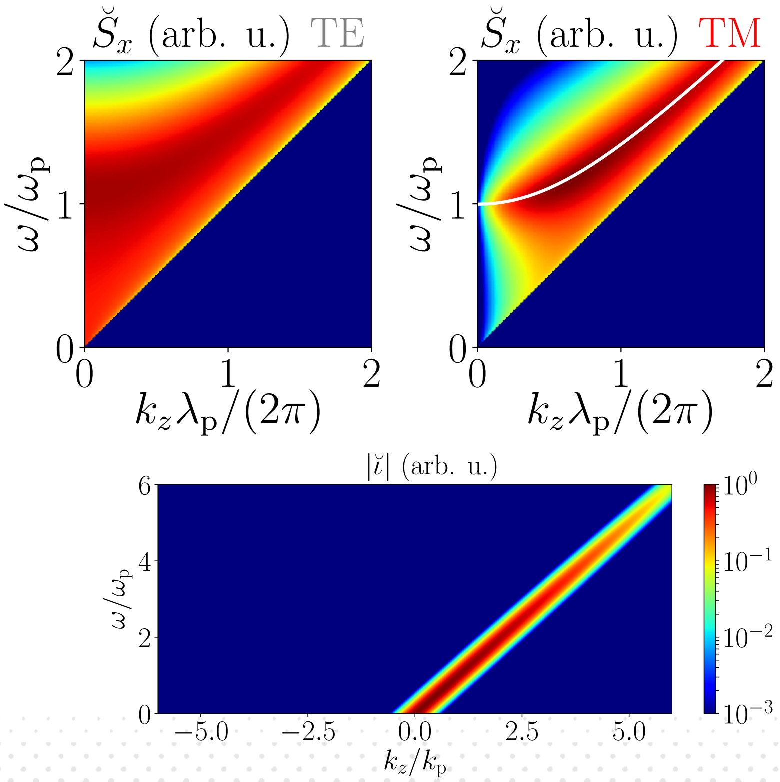

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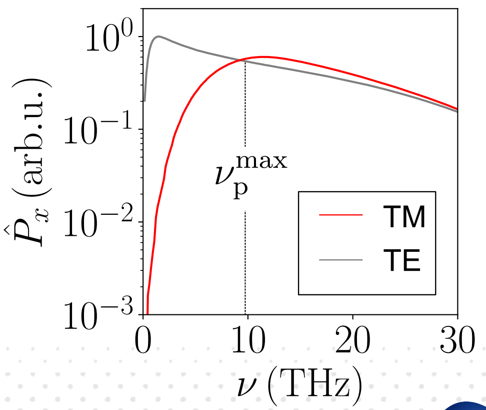
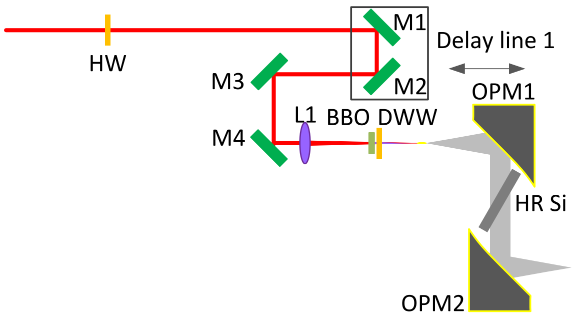
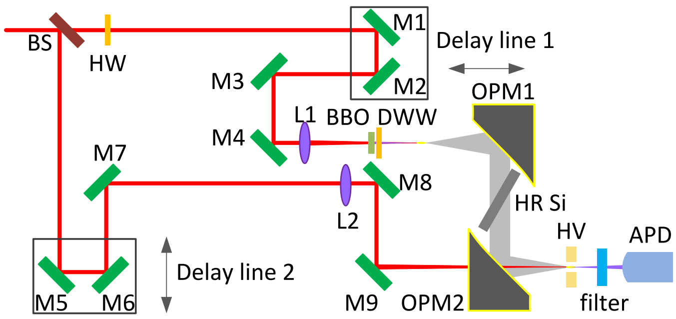


Experimental Verification



➜ air-based two-color THz generation

Experimental Verification

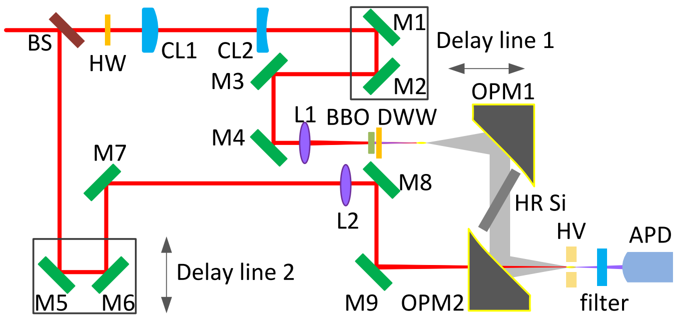


➜ air-based two-color THz generation

➜ air-biased coherent detection

[J. Dai, Phys. Rev. Lett. 97, 103903 (2006)]

Experimental Verification



➜ air-based two-color THz generation

➜ air-biased coherent detection

[J. Dai, Phys. Rev. Lett. 97, 103903 (2006)]

➜ rotatable cylindrical lenses in pump arm for elliptical beam profiles

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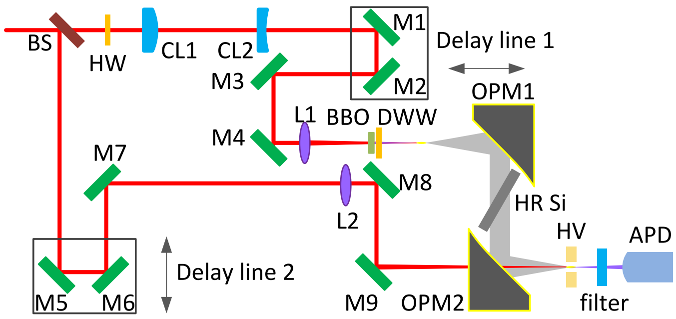

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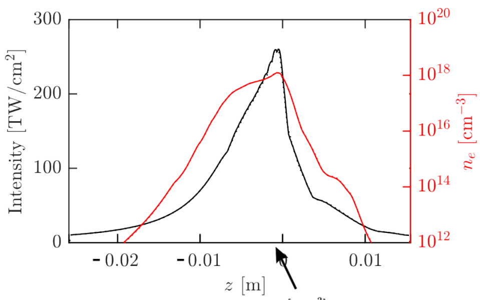
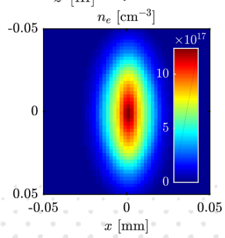


➜ plasma is much larger (no microplasma)

about 50 × 20 μm near focus, centimeters long

➜ plasma density is lower (no full ionization)

$n_e^{max} \sim 1.2 \times 10^{18}$ cm^{-3} $\rightarrow \nu_p^{max} \sim 10$ THz $\rightarrow \lambda_p^{min} \sim 30\ \mu$m



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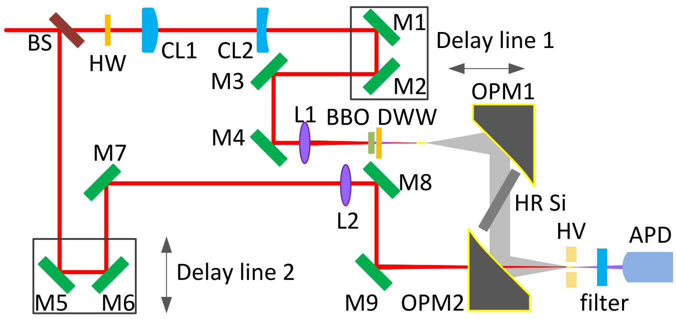

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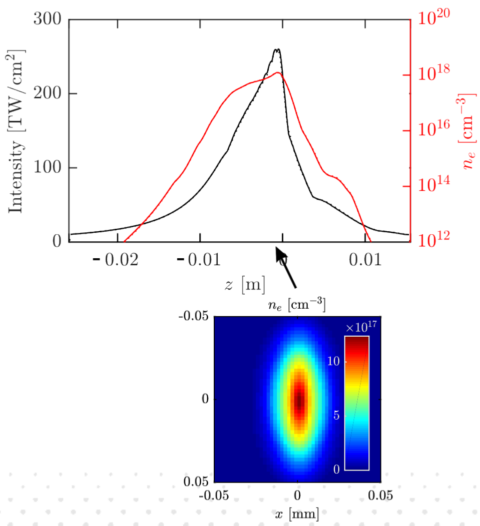
- we have 50 μm $> \lambda_p^{min} >$ 20 μm



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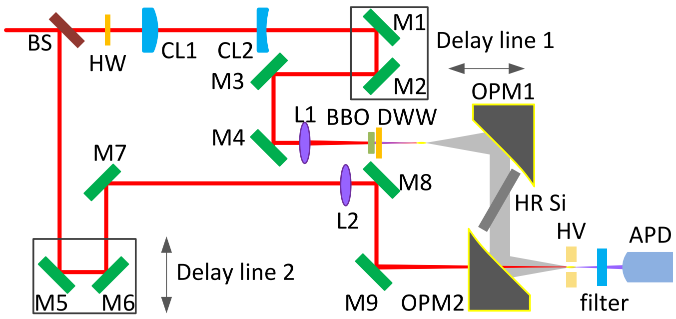

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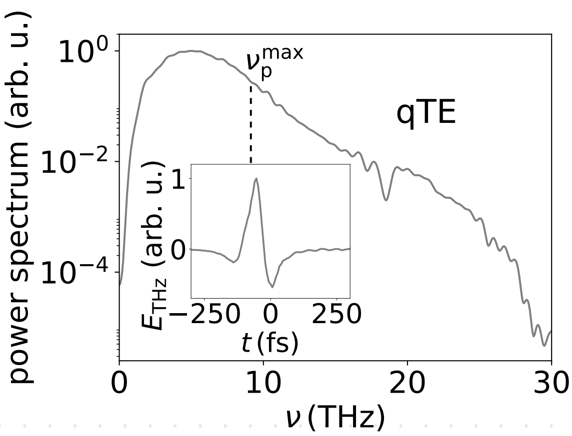
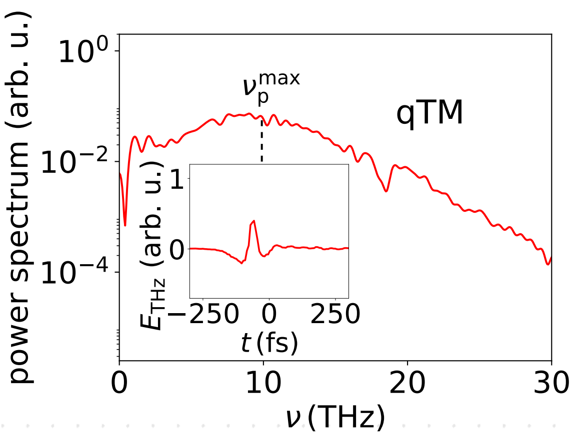
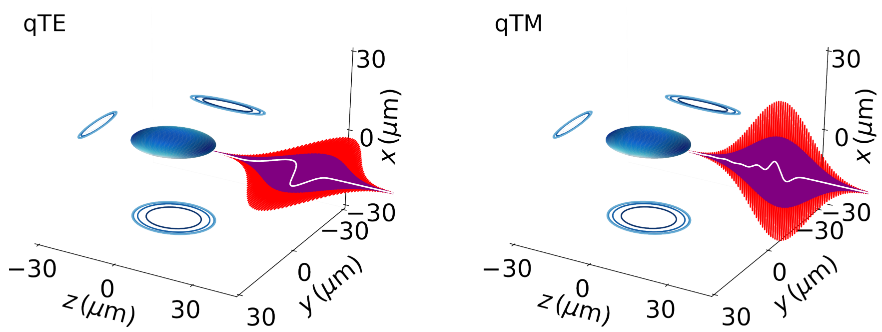




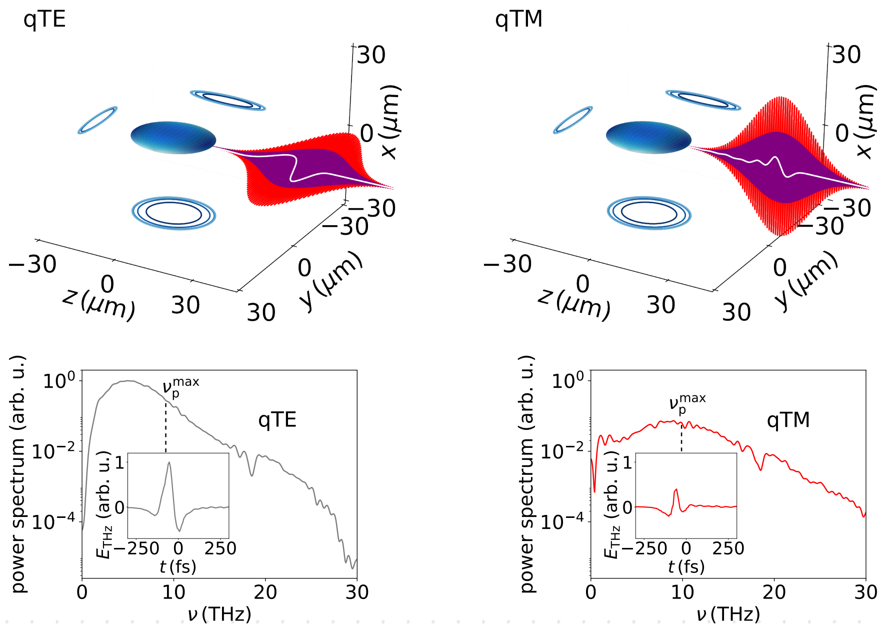
Conclusions

➜ plasma may act as plasmonic particle
$\rightarrow$ strong impact of leaky mode resonance on THz spectra



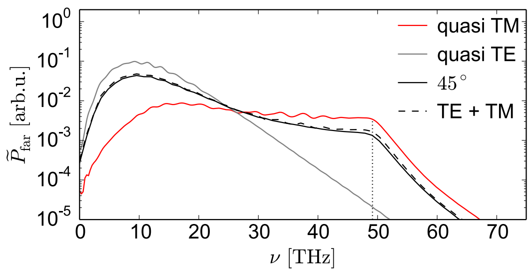
Conclusions

➜ plasma may act as plasmonic particle
→ strong impact of leaky mode resonance on THz spectra
→ relevant to typical air-based two-color setup



Outlook

➜ simulations suggest that superposition of qTE and qTM spectra is possible → tunable THz spectra



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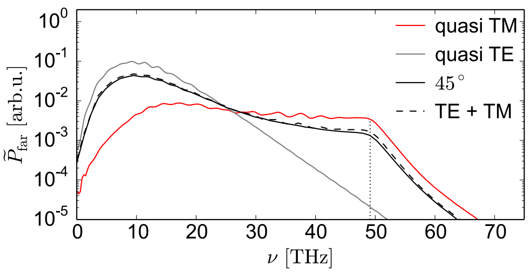
- simulations and experiments show that THz yield in qTE configuration is significantly higher



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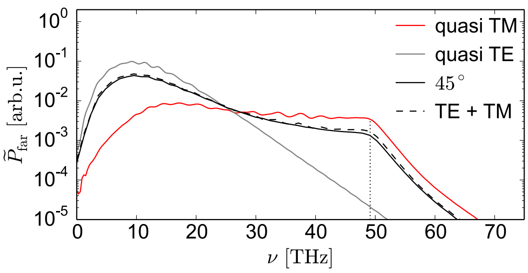

- Strongly elliptical beams and plasmas are promising route towards higher THz energies → (at least) linear scaling with beam width