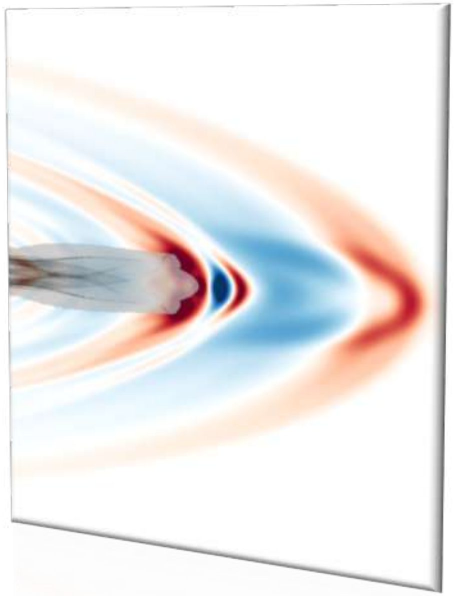

Intense THz fields generated by laser-driven particle acceleration

Luc Bergé

Commissariat à l'Énergie Atomique et aux Énergies Alternatives

CEA, DAM, DIF – 91297 Arpajon - France

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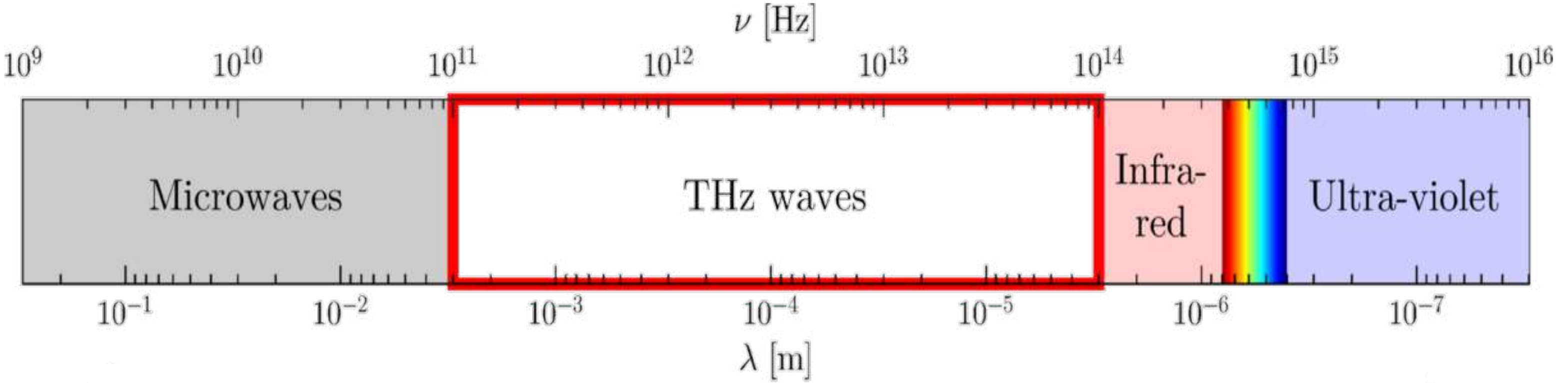
Centre Lasers Intenses et Applications (CELIA), UMR 5107, 33405 Talence, France

3rd EPS-TIG Hands-on Science, Technology and Interfaces Event

7 – 9 July 2023

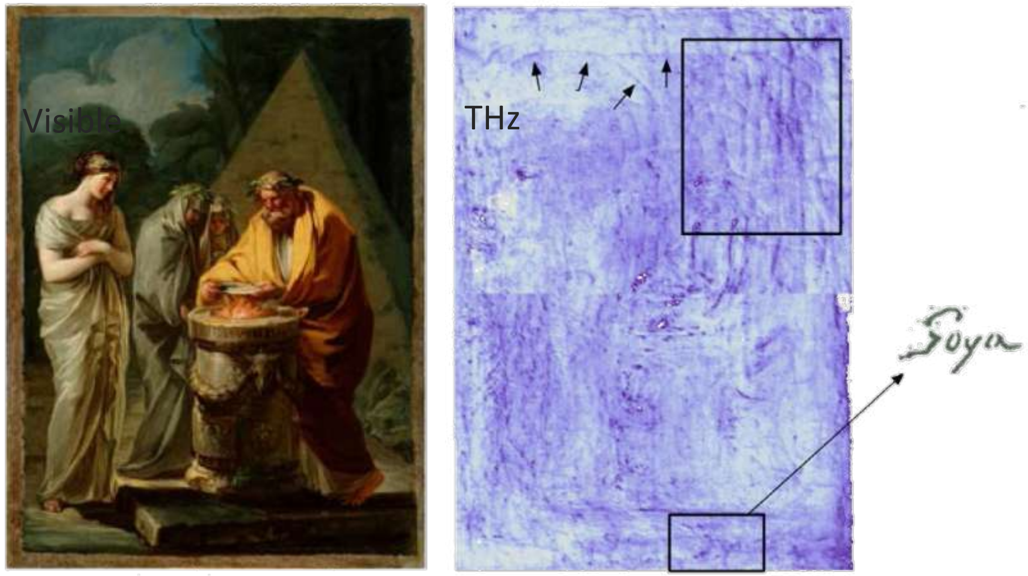
Petrovac, Montenegro

Terahertz (THz) waves



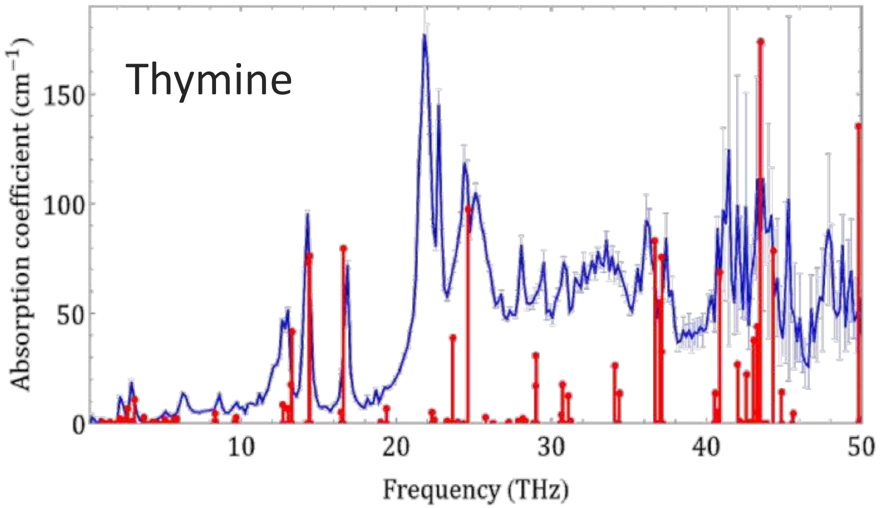
1 THz = 10^{12} Hz (visible light ~ 5 × 10^{14} Hz)
THz domain: **0.1—10(0) THz**
Wavelength: ~**10—1000 µm** (visible light: 0.4—0.8 µm)

Interesting properties:
- Non/slightly ionizing
- Can penetrate tissues (skin, fabric, plastic, …) over a few mm



C. Seco-Martorell *et al.*, Opt. Express **21**,17800 (2013)

Applications requiring strong or broadband THz fields

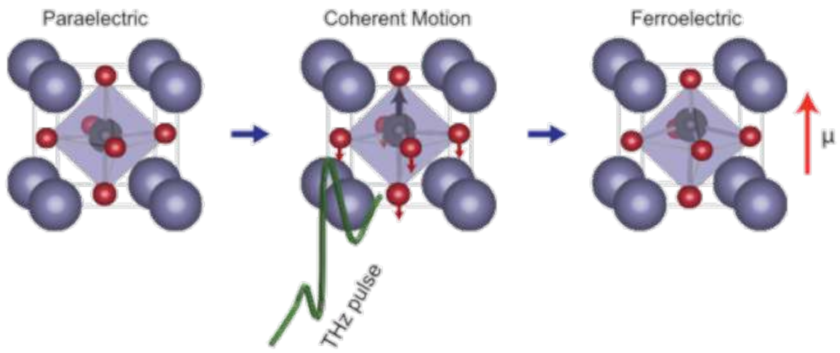


Molecular rotational-vibrational modes in the THz domain.
Need broad THz spectra (>10 THz)

L. Bergé *et al.*, Europhys. Lett. **126**, 24001 (2019)

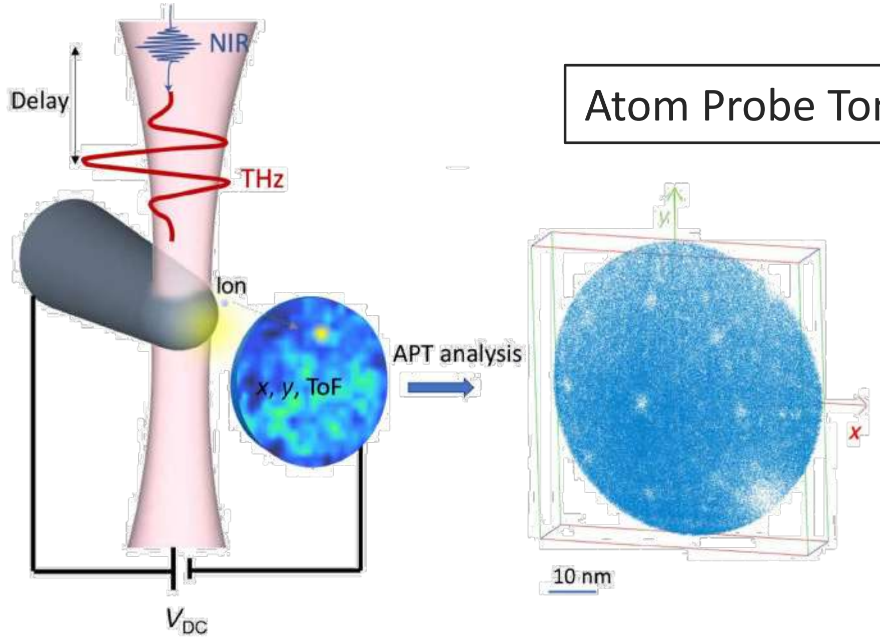
Active manipulation of matter requires
strong THz fields: $\gtrsim 0.1-1$ GV/m

THz-induced phase transition



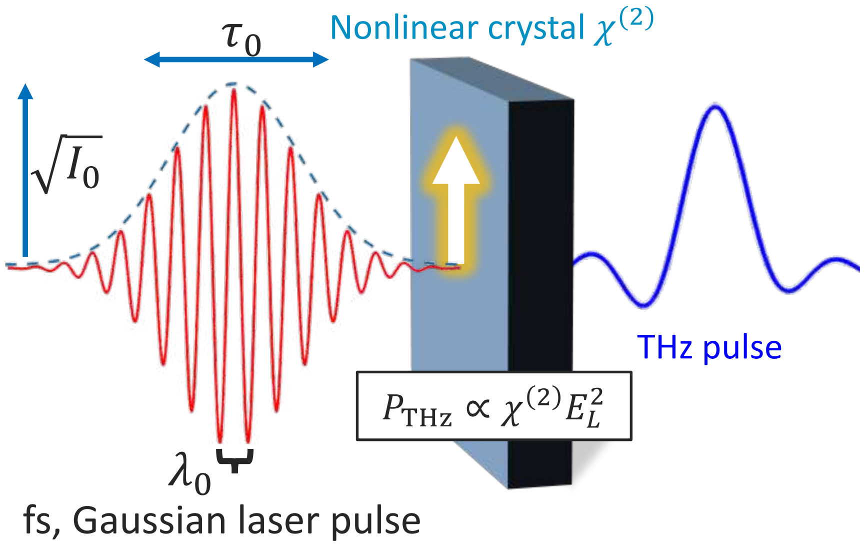
X. Li *et al.*, Science **364**, 1079 (2019)

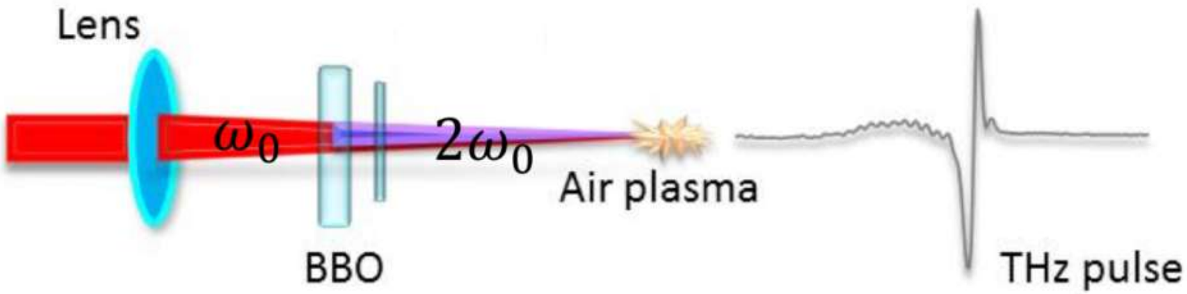
Atom Probe Tomography



A. Vella *et al.*, Sci. Adv. **7**, eabd7259 (2021)

Laser-based THz emitters





Femtosecond lasers:

- Optical / near-IR wavelengths: $\lambda_0 \sim 1$ µm
- Duration: $\tau_0 \lesssim 50$ fs
- Intensities up to 10^{23} W/cm^2

Optical rectification in crystals

- THz amplitudes up to 1 GV/m! [1]
- Phase-matching condition → **narrowband** emission
- Limited by the crystal **damage threshold**

[1] C. Vicario *et al.*, Phys. Rev. Lett. **112**, 213901 (2014)

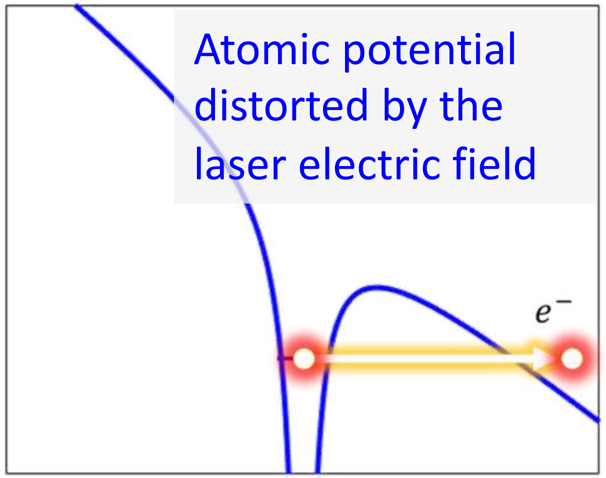
Gas plasmas created by two-color lasers

- THz amplitudes up to 0.1 - 1 GV/m
- **Broadband** emission 0.1 – 100 THz!
- No **damage threshold**

D. J. Cook & R. M. Hochstrasser., Opt. Lett. **25**, 1210 (2000)

K. Y. Kim et al., Nat. Photon. **2**, 605 (2008)

Field ionization and « two-color » plasmas



Atomic potential distorted by the laser electric field

Electron tunnel emission

$$I_L \approx 10^{13-14}\ W.cm^{-2}$$

ADK model for ionization rate[1]:

$$W_{\mathrm{ADK}}^{\mathrm{inst}} = \frac{\alpha(n^*, l^*, l)}{|E(t)|^{2n^*-1}} \mathrm{e}^{-\beta/|E(t)|}$$

α, β constants depending on quantum numbers and ionization energies

[1] G. L. Yudin and M. Y. Ivanov, Phys. Rev. A **64**, 013409 (2001)

$$\partial_t n_e = W(E_L)(n_a - n_e)$$

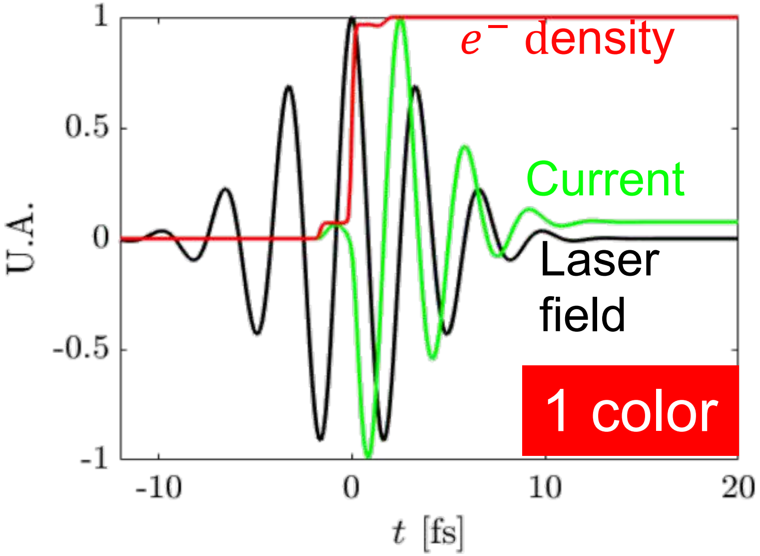
$$J_e(t) \propto \frac{e^2}{m_e} \int_{-\infty}^{t} n_e(\tau) E_L(\tau) d\tau$$

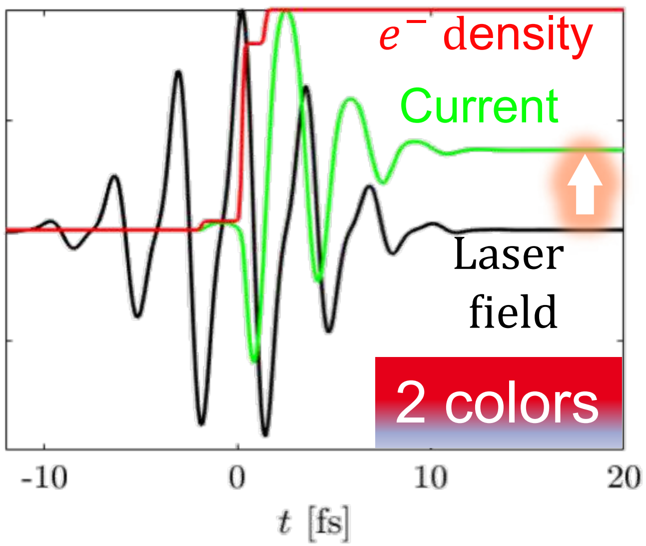
Photocurrents

$$\boxed{\rightarrow E_{THz} \propto \partial_t J_e \Big|_{THz}}$$

$$E_L(t) = A_1 e^{-\frac{t^2}{t_p^2}} \cos(\omega_0 t)$$

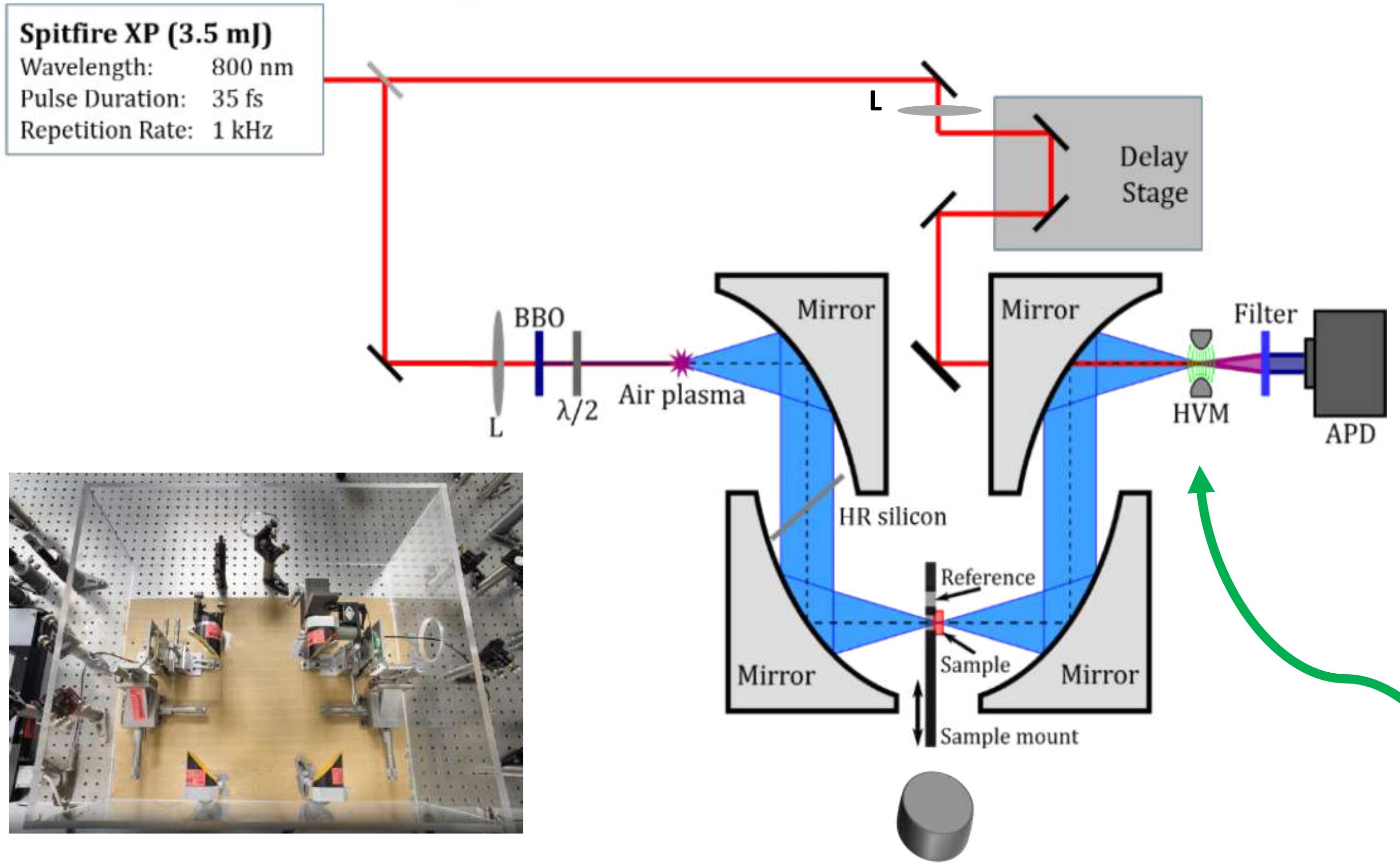
$$E_L(t) = A_1 e^{-\frac{t^2}{t_p^2}} \cos(\omega_0 t) + A_2 e^{-\frac{2t^2}{t_p^2}} \cos(2\omega_0 t + \phi)$$





The ALTESSE Project

Air-Biased Coherent Detection (ABCD) Technique



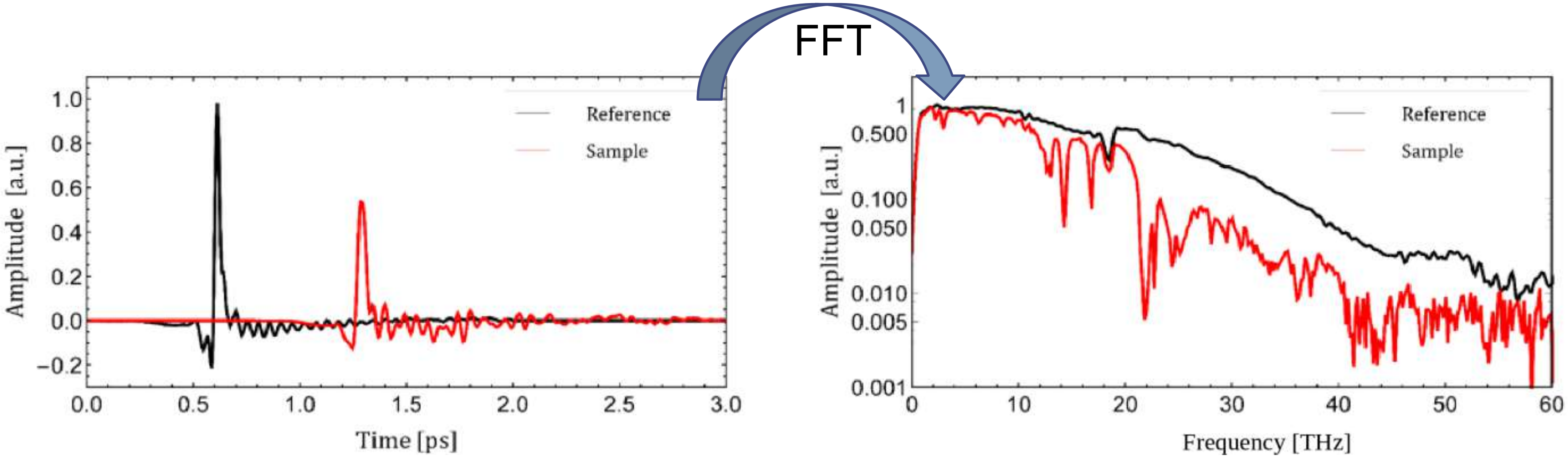
A	Air
L	Laser-based
T E	TErahertz
S S	SpectroScopy of
E	Explosives

N. Karpowicz *et al.*, Appl. Phys. Lett. **92**, 011131 (2008)

$$I_{2\omega}(\tau) \propto \int \left(\chi^{(3)} I_{\omega}\right)^2 \left[E_{\mathrm{THz}}^2(t-\tau) \boxed{\pm 2E_{\mathrm{bias}}E_{\mathrm{THz}}(t-\tau) + E_{\mathrm{bias}}^2}\right] dt$$

Coherent ABCD THz-time-domain spectroscopy

THz signature of thymine pellet (time & Fourier domains)

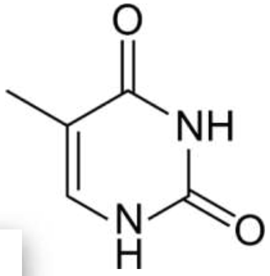


Emission up to 60 THz!

$$\frac{E_{sam}(\omega)}{E_{ref}(\omega)} = Ae^{i\phi(\omega)} = Te^{-\frac{\alpha d}{2}} e^{\frac{i(n-1)\omega d}{c}}$$

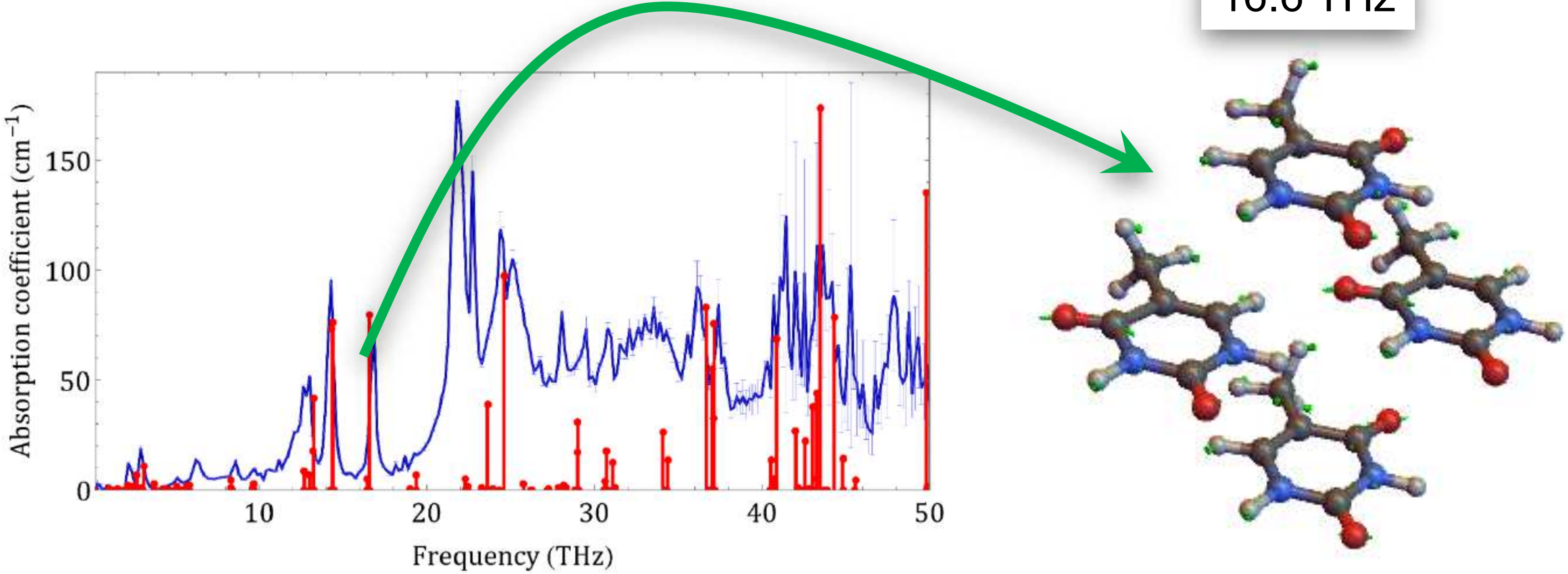
$$\alpha(\omega) = -\frac{2}{d}\ln\left(\frac{(n+1)^2}{4n}\cdot\frac{|E_{sam}(\omega)|}{|E_{ref}(\omega)|}\right)$$

Thymine phonon spectra interpreted using density functional theory (DFT) simulations



CASTEP DFT simulations

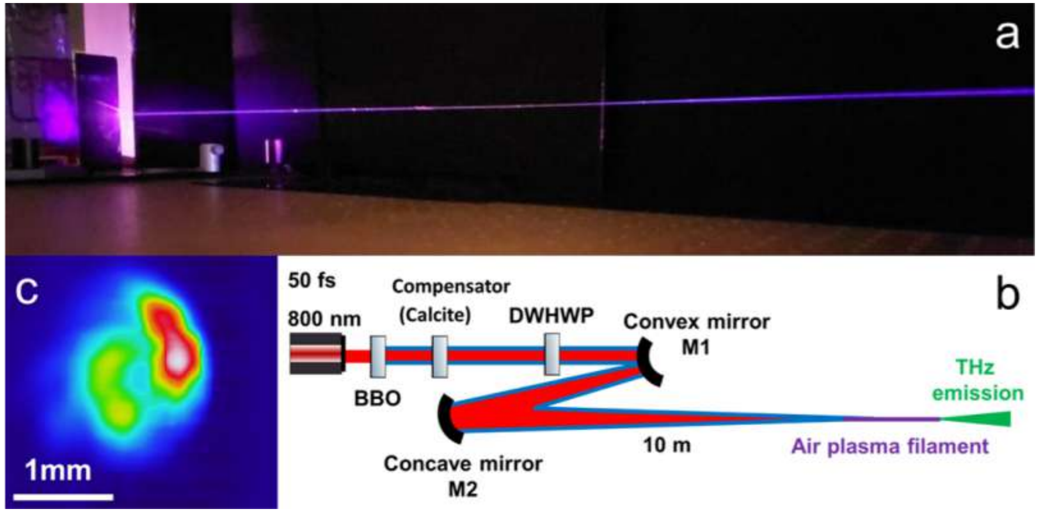
16.6 THz



L. Bergé *et al., EPL (*Europhys. Lett.) **126**, 24001 (2019)

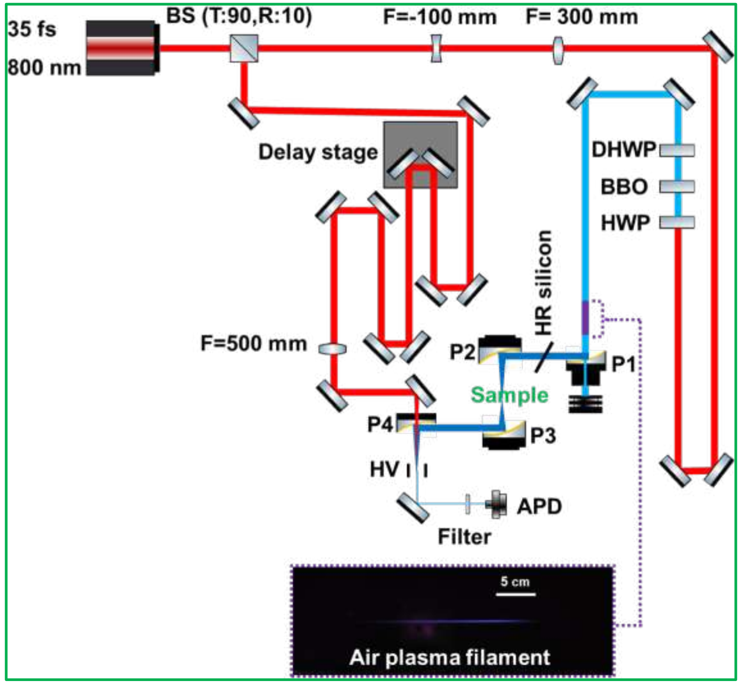
ALTESSE 2: Filamentation regime

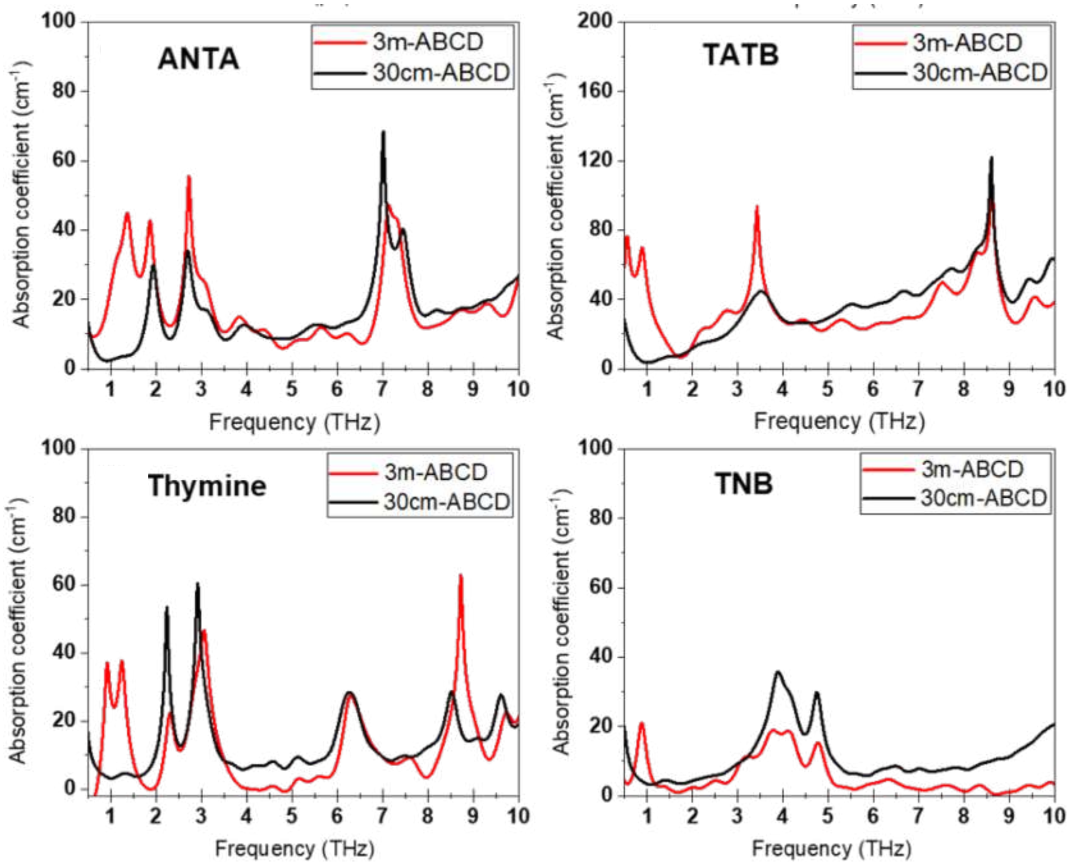
A. Talbi *et al.*, EPL **143**, 10001 (2023)



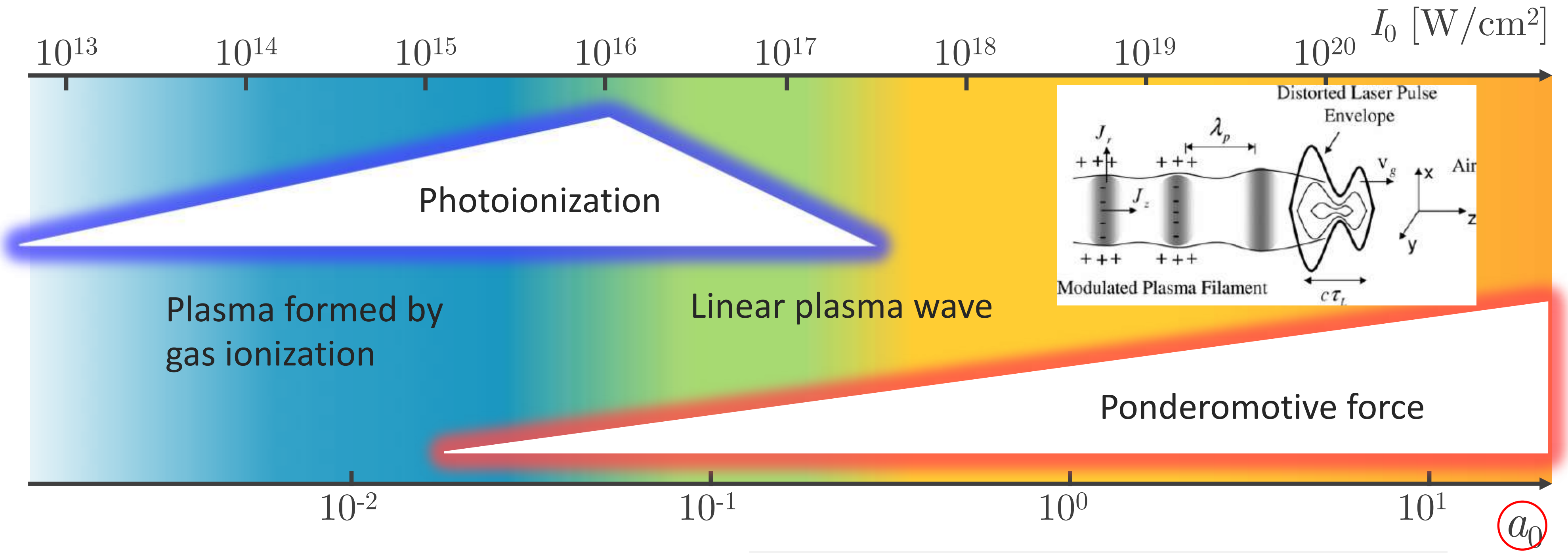
1 - 1-m long emissive filaments formed at 10 m from laser
Up to 100 μW THz power measured!

2 - Successful Spectroscopy of materials
through 15-cm long plasmas





THz sources from moderate to relativistic laser intensity

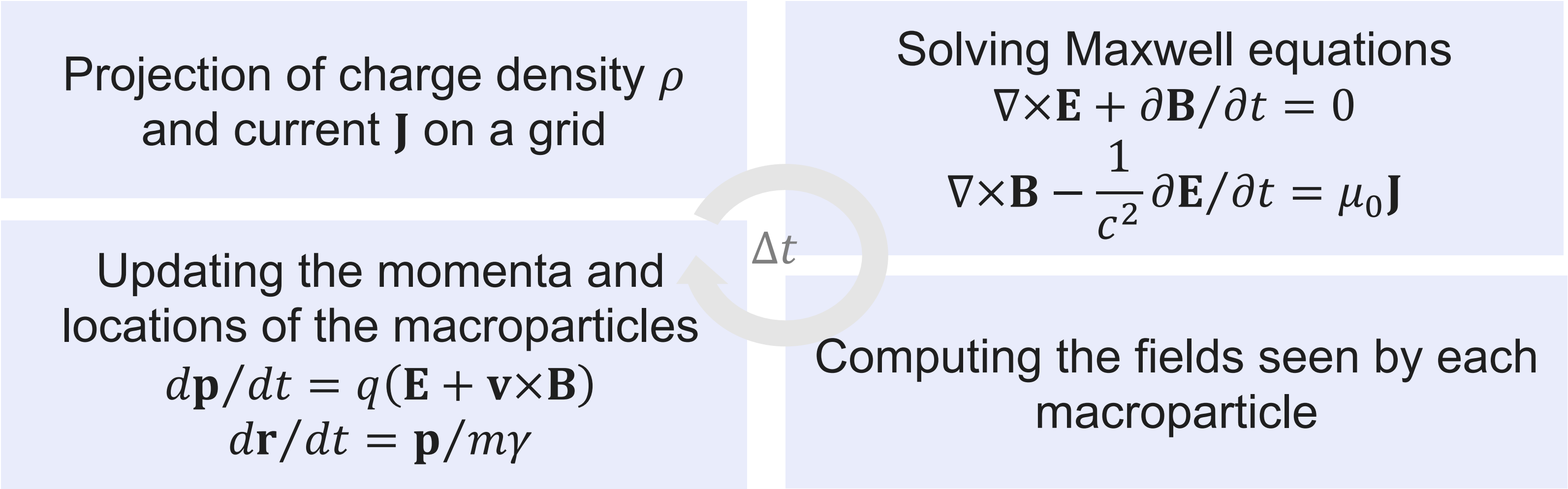


Normalized laser amplitude $a_0 = \frac{eE_0}{m_e c \omega_0}$

I. **Photoionization**
And application to a coherent THz spectroscopy

II. **THz emissions driven by relativistic particle acceleration**
Towards THz field amplitudes > 100 GV/m (with strong magnetic fields)

Principle of the *particle-in-cell* (PIC) *method*[1]



Projection of charge density ρ and current $\mathbf{J}$ on a grid

Solving Maxwell equations

$$\nabla\times\mathbf{E} + \partial\mathbf{B}/\partial t = 0$$

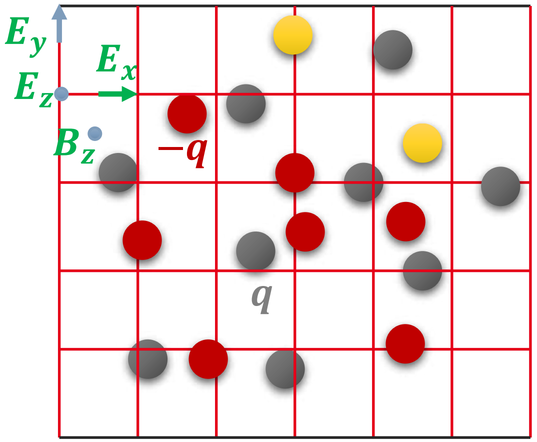
$$\nabla\times\mathbf{B} - \frac{1}{c^2}\partial\mathbf{E}/\partial t = \mu_0\mathbf{J}$$

Computing the fields seen by each macroparticle

Updating the momenta and locations of the macroparticles

$$d\mathbf{p}/dt = q(\mathbf{E} + \mathbf{v}\times\mathbf{B})$$

$$d\mathbf{r}/dt = \mathbf{p}/m\gamma$$



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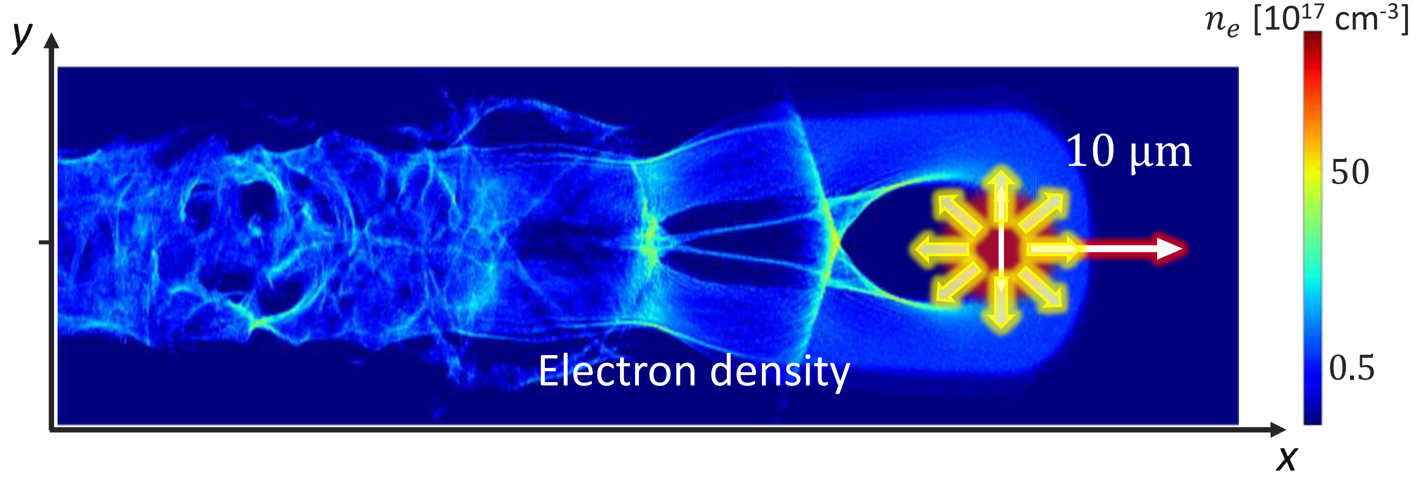
[1] C. K. Birdsall and A. B. Langdon, *Plasma Physics via Computer Simulation* (1985)

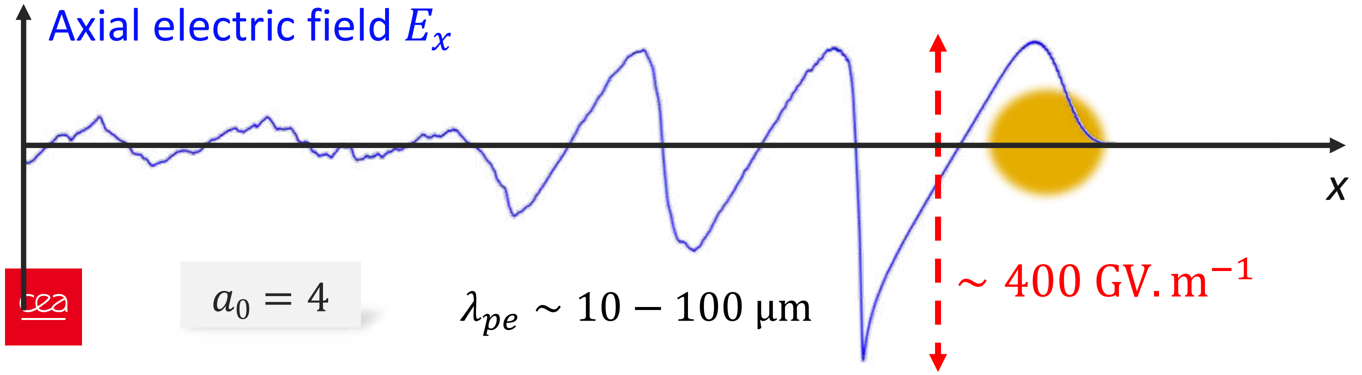
Wakefield properties in mildly/strongly relativistic regimes

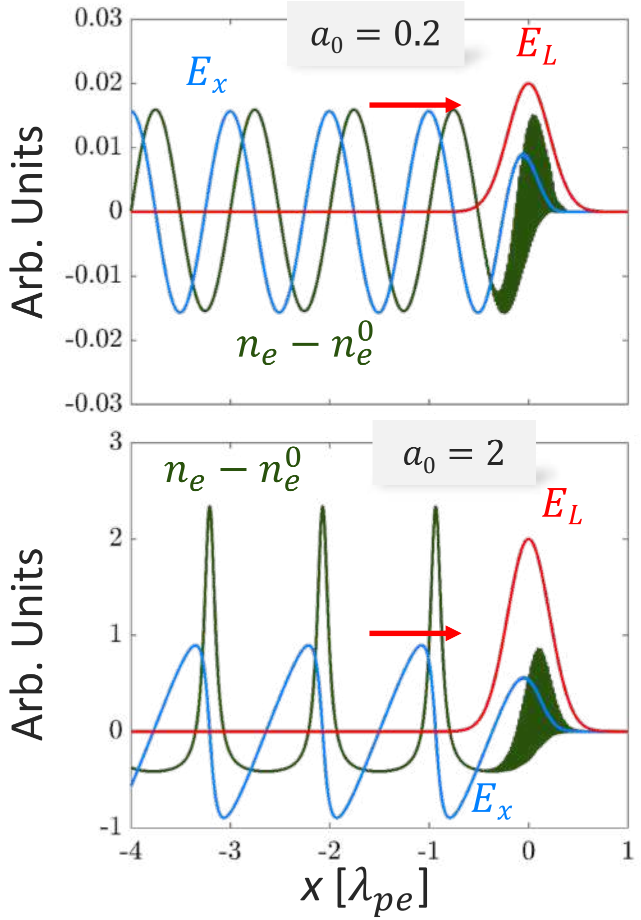
Laser pulse exerts a ponderomotive force on plasma electrons: $\vec{F}^P = -\frac{e^2}{2m_e\langle\gamma\rangle}\vec{\nabla}\langle\vec{A}^2\rangle$

Formation of a plasma wave with **frequency** $\omega_{pe} \simeq \sqrt{\frac{e^2 n_e^0}{\epsilon_0 m_e}}$ ∈ THz domain

Electrostatic longitudinal field with > 100 GV/m amplitude arises for $a_0 \gg 1$







➡ Laser Wakefield Acceleration

Blowout nonlinear regime in 3D geometry

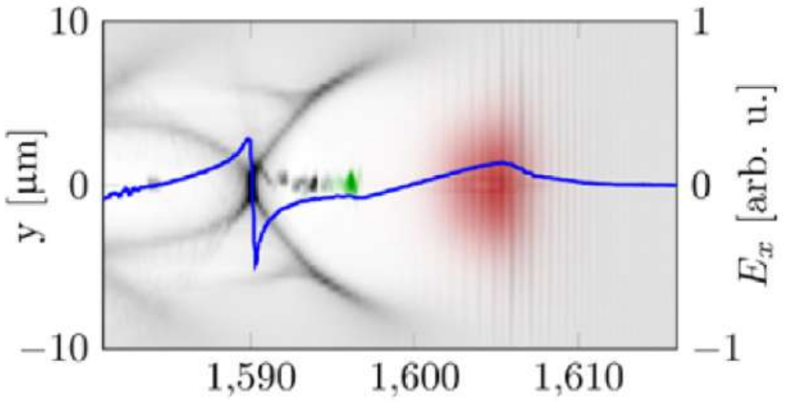
3D wakefield generation by a short laser pulse with $I_L = 7\times10^{18}\ \mathrm{Wcm}^{-2}$,
$w_L = 18\ \mu\mathrm{m}$, $\tau_L = 30\ \mathrm{fs}$ in a $n_\mathrm{e} = 5\times10^{18}\ \mathrm{cm}^{-3}$ plasma[1]

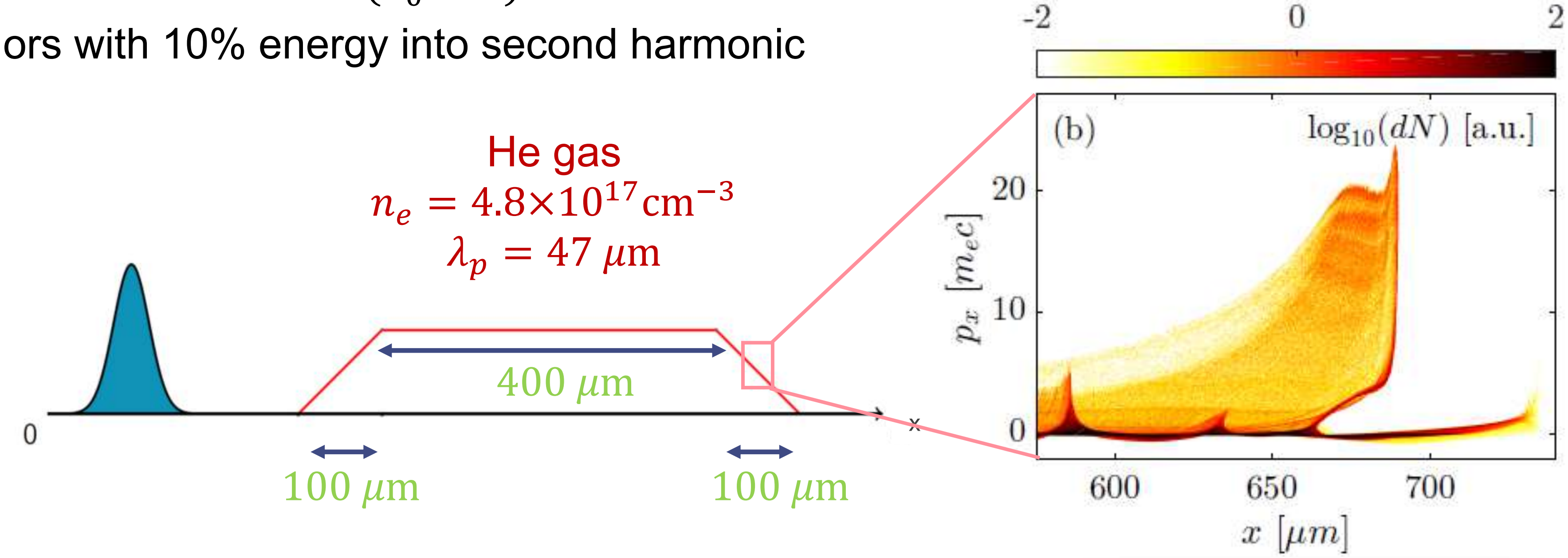
- Transverse ponderomotive expulsion of electrons by the laser leads to an ion cavity (“bubble”)[2]
- Self-injection occurs at the back of the cavity where electron trajectories cross and their density peaks
- Record of > 8 GeV electron energies[3]
- Applications: Ultrafast X/γ radiation (betatron, Compton scattering, Bremsstrahlung) for radiography, nuclear physics… and THz emission

[1] H. Ekerfelt *et al.*, Sci. Rep. **7**, 12229 (2017)
[2] A. Pukhov & J. Meyer-ter-Vehn, J. Appl. Phys. B **74**, 355 (2002)
[3] A. J. Goncalves *et al.* , Phys. Rev. Lett. **122**, 084801 (2019)

Relativistic laser-gas interactions lead to high-energy, high-density electron bunches leaving the plasma

- PIC simulation with quasi-3D CALDER-CIRC code[1]
- Laser parameters:
  - $E_L = 3.7$ J
  - $w_L = 20\ \mu\text{m}, \lambda_0 = 1\ \mu m$
  - $\tau_L = 35$ fs
  - $I_L = 2.2{\times}10^{19}\ \text{W.cm}^{-2}\ \ (a_0 = 4)$
  - 2 colors with 10% energy into second harmonic





$x - p_x$ phase space of outgoing electrons

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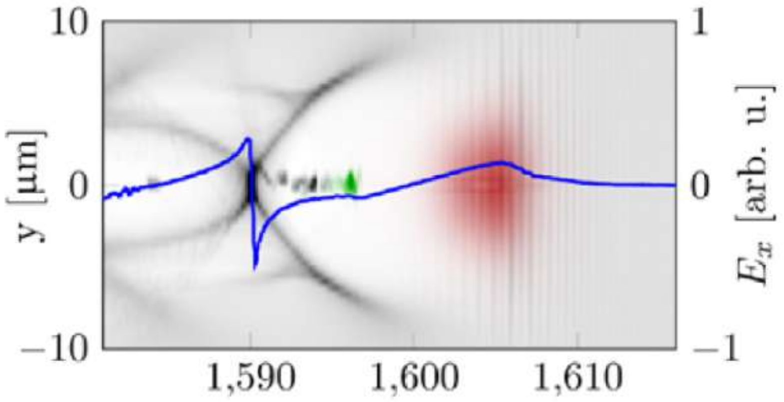
[1] A. Lifshitz *et al.*, J. Comp. Phys. **228**, 1803 (2009)
[2] J. Déchard *et al.*, Phys. Rev. Lett. **120**, 144801 (2018)

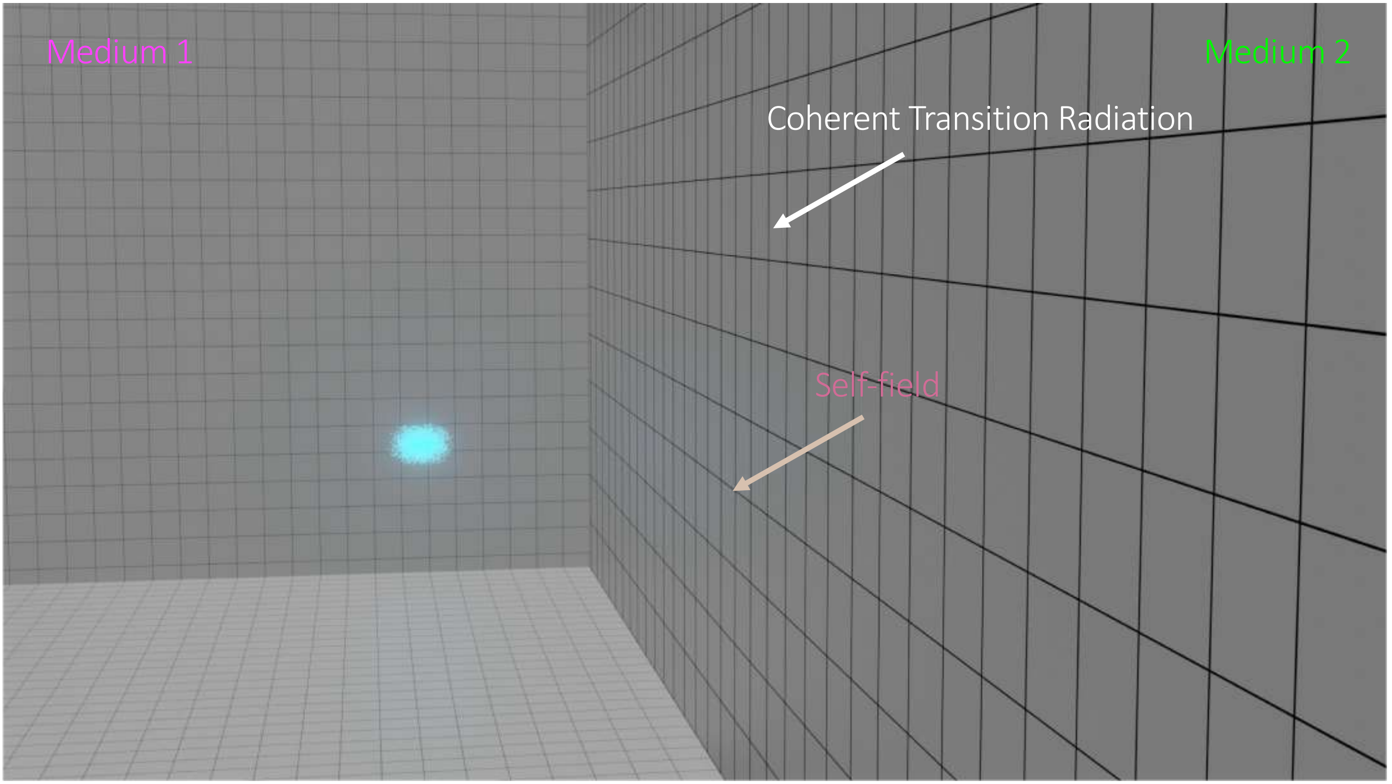
Coherent Transition Radiation (CTR)

$a_0 > 1$



[1]V. L. Ginzburg and I. M. Frank, J. Phys. (USSR) **9**, 353 (1945)
[2]C. B. Schroeder *et al.,* Phys. Rev. E **69**, 016501 (2004)

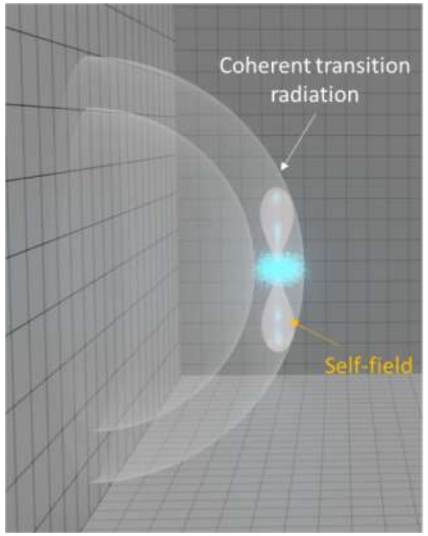
$x = -\infty$



$x = +\infty$

THz CTR prevails over photocurrent-induced radiation in relativistic two-color laser-gas interactions

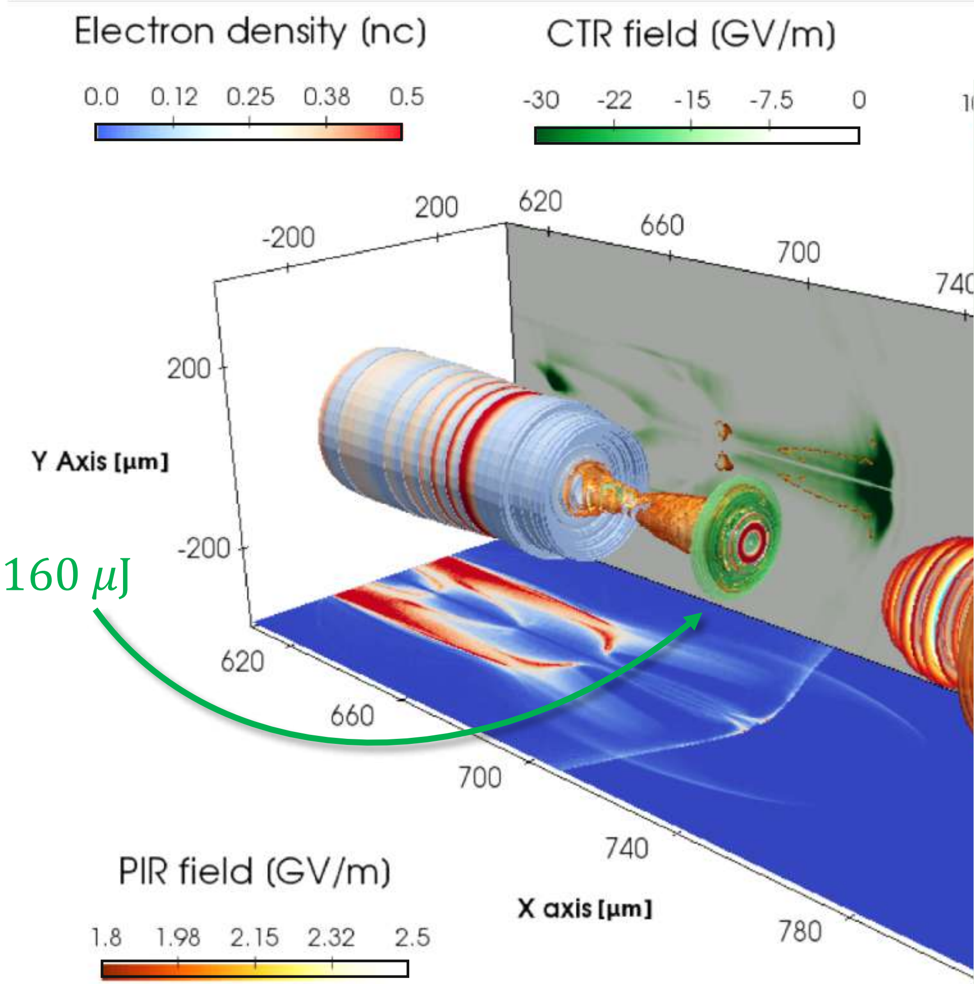
$\varepsilon_L = 3.7$ J



$$\omega_{\max} \simeq \gamma_e \omega_{pe} \approx 0.3\omega_0$$

$\nu < \nu_{co} = 90$ THz

$\varepsilon_{\mathrm{CTR}} = 160\ \mu$J



123

PHYSICAL
REVIEW
LETTERS

Articles published 11 days ending 31 December 2019

PRL 123 (26), 260401–268002, 31 December 2019 (242 total pages)

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APS physics

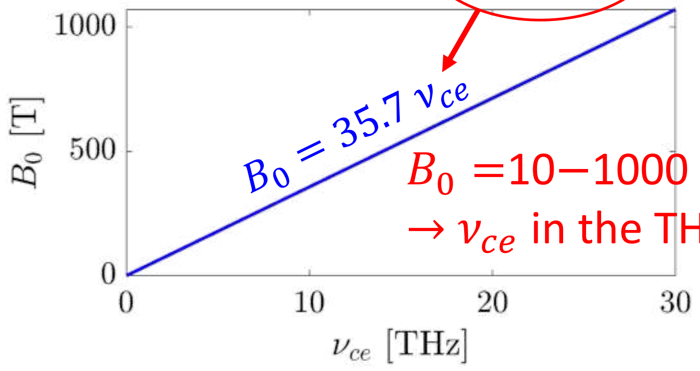
Volume 123, Number 26

J. Déchard *et al.*, Phys. Rev. Lett. **120**, 144801 (2018); Phys. Rev. Lett. **123**, 264801 (2019)

Intense external magnetic fields

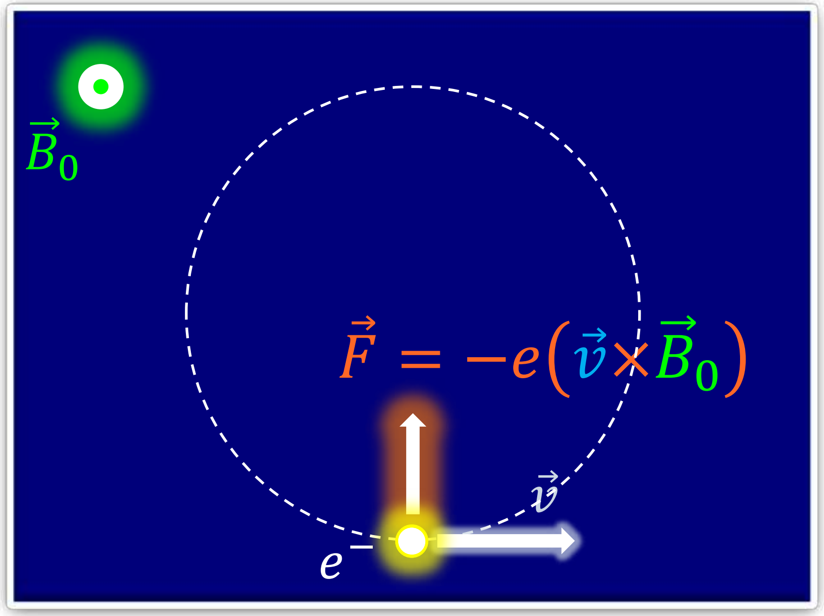
Magnetized plasmas have interesting properties to boost THz generation.

Cyclotron frequency: $\boxed{\omega_{ce} = \frac{eB_0}{m_e}}(= 2\pi\nu_{ce})$



B_0 =10–1000 T

→ ν_{ce} in the THz domain



Electron dynamics in a magnetic field

Circular motion at frequency ν_{ce}

Plasma magnetization parameter

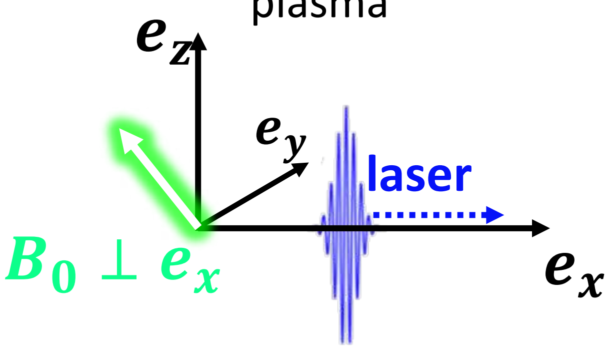
$$b = \frac{\omega_{ce}}{\omega_{pe}}$$

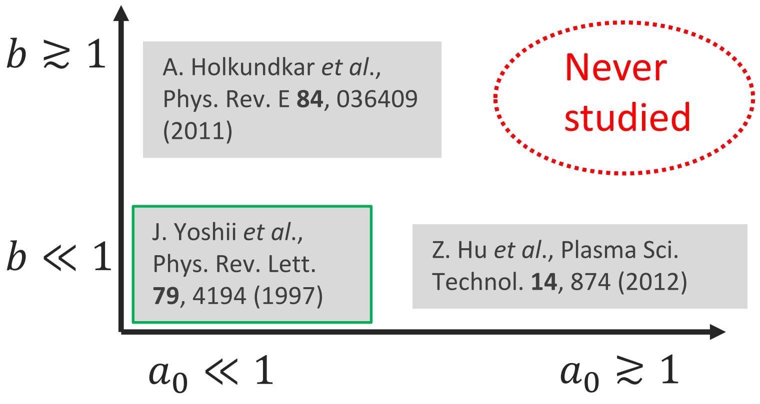
Intense B-field generation method	Max B	Destructive
Nondestructive pulsed magnet[1]	100 T	No
Electromagnetic flux compression[2]	1200 T	Partially

[1] M. Jaime *et al.*, PNAS **109**, 12404 (2012)
[2] D. Nakamura *et al.*, Rev. Sci. Instrum. **89**, 095106 (2018)

Magnetized plasmas as THz sources

Orthogonally magnetized plasma





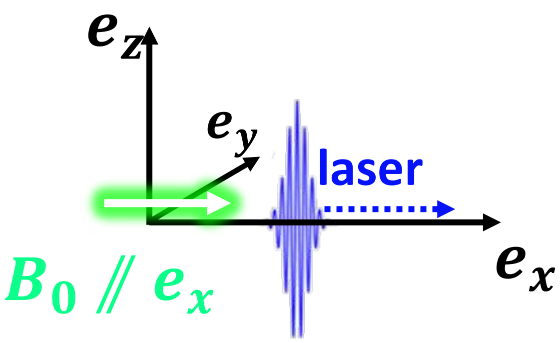
A. Holkundkar *et al.*, Phys. Rev. E **84**, 036409 (2011)

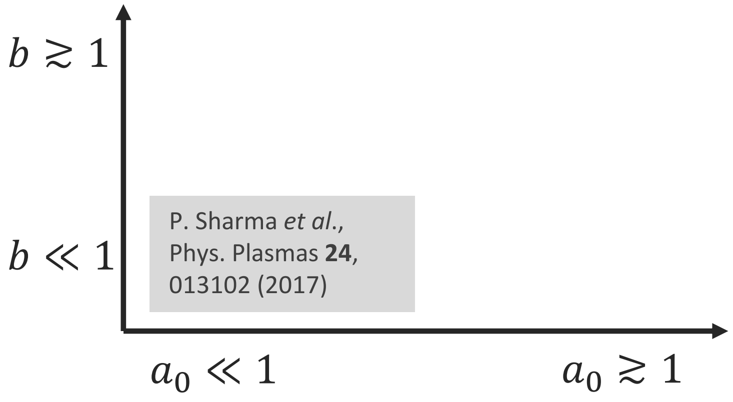
Never studied

J. Yoshii *et al.*, Phys. Rev. Lett. **79**, 4194 (1997)

Z. Hu *et al.*, Plasma Sci. Technol. **14**, 874 (2012)

Axially magnetized plasma





P. Sharma *et al.*, Phys. Plasmas **24**, 013102 (2017)

$$\boldsymbol{a_0 \lesssim 1}$$

At resonance $\omega = \omega_{pe}$: $\boldsymbol{E_\perp = bE_x}$

Excitation of an **extraordinary mode**

- A longitudinal wakefield E_x
- A transverse component $E_\perp = bE_x$

$$\boldsymbol{a_0 > 1}$$

Under QSA:[1,2]

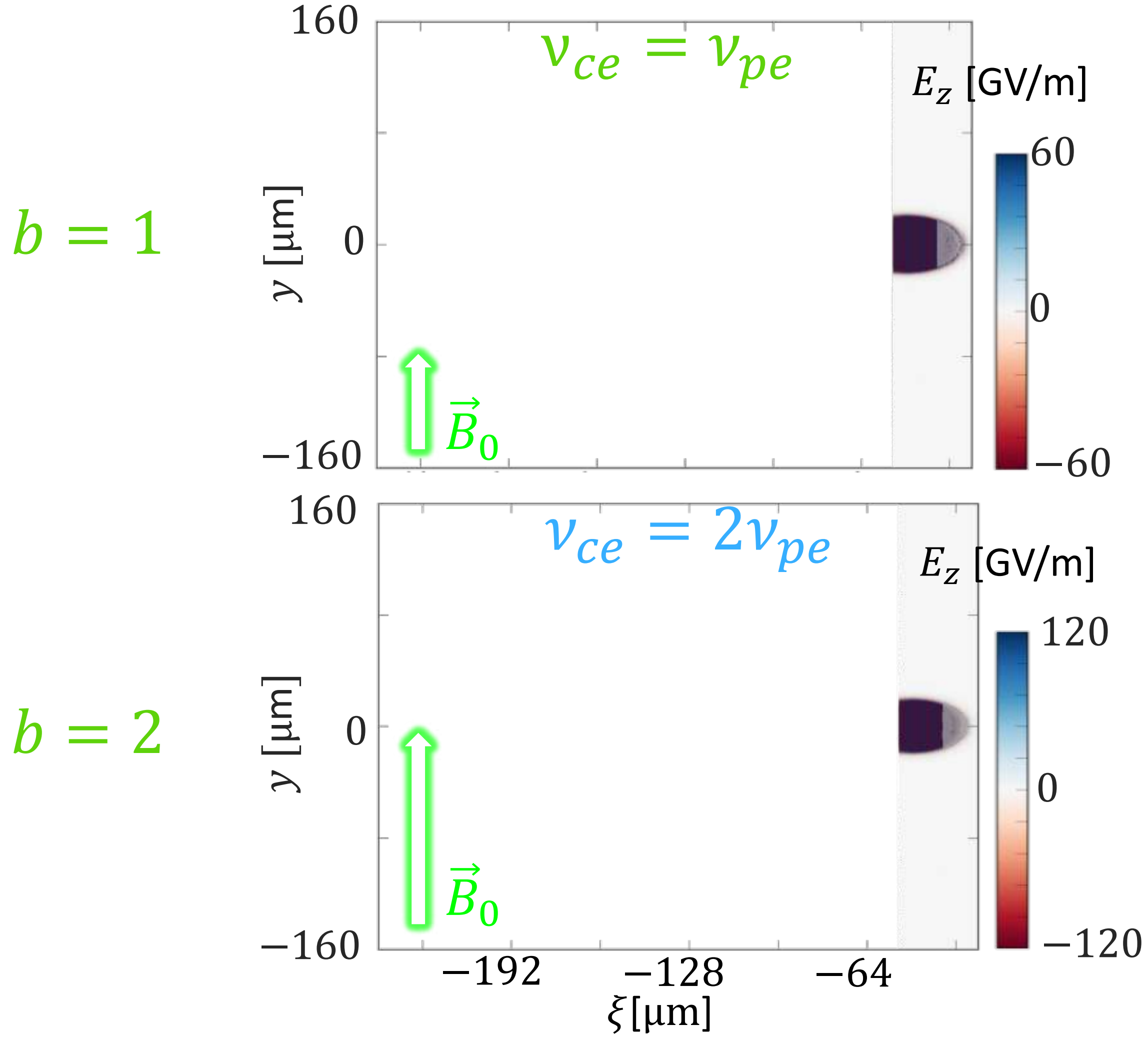
$$\xi = x - ct, \tau = t$$

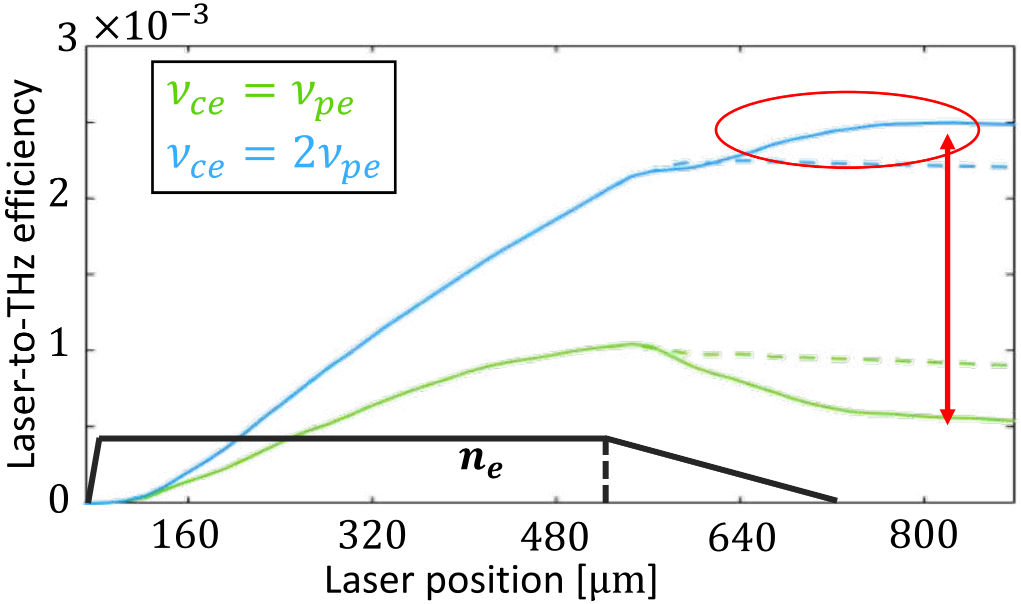
$$\partial_\tau \to 0$$

$$E_\perp = \pm \frac{b}{\omega_{pe}} \partial_\xi E_x$$

[1] Z. Hu *et al.*, Plasma Sci. Technol. **14**, 874 (2012)
[2] C. Tailliez *et al.*, Phys. Rev. Lett. **128**, 174802 (2022)

> 100 GV/m record THz amplitudes for $a_0 \gg 1$, $b \gtrsim 1$





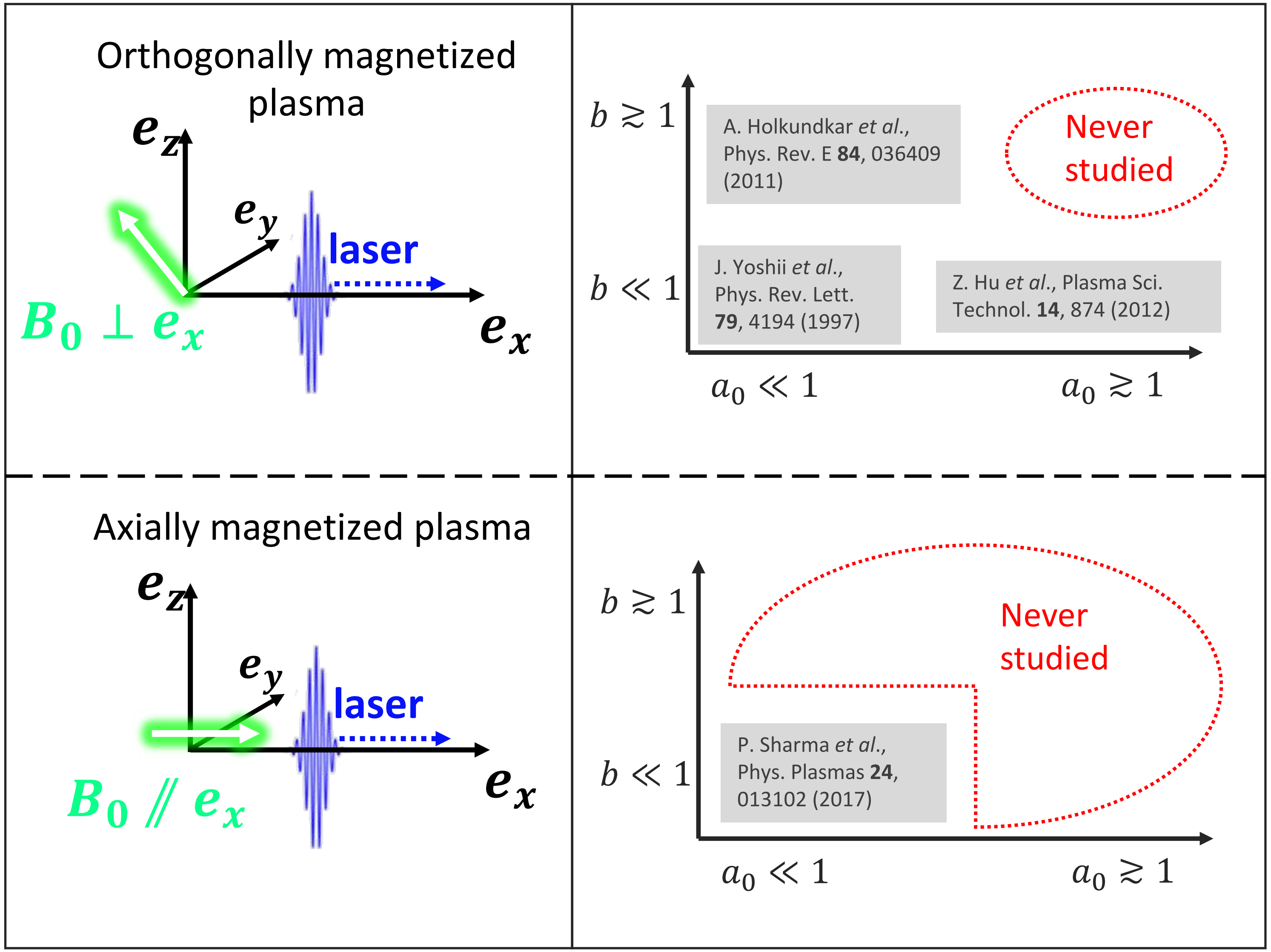
- Record amplitudes: 60 GV/m and 160 GV/m
- Gradient attenuation for $\tilde{b} \equiv \frac{b}{\sqrt{\gamma}} \sim 0.67$
- Record THz conversion efficiency $\eta = 2.5\times10^{-3}$

2D PIC Simulations

$a_0 = 4$, $\lambda_0 = 1$ μm, $\tau_L = 35$ fs FWHM, $w_0 =$ 10 μm FWHM, $\nu_{pe} = 8$ THz, $\nu_{ce} = \nu_{pe}$ or $2\nu_{pe}$

C. Tailliez *et al.*, Phys. Rev. Lett. **128**, 174802 (2022)

Axially magnetized plasmas for $a_0 \gtrsim 1$, $b \gtrsim 1$



A. Holkundkar *et al.*, Phys. Rev. E **84**, 036409 (2011)

J. Yoshii *et al.*, Phys. Rev. Lett. **79**, 4194 (1997)

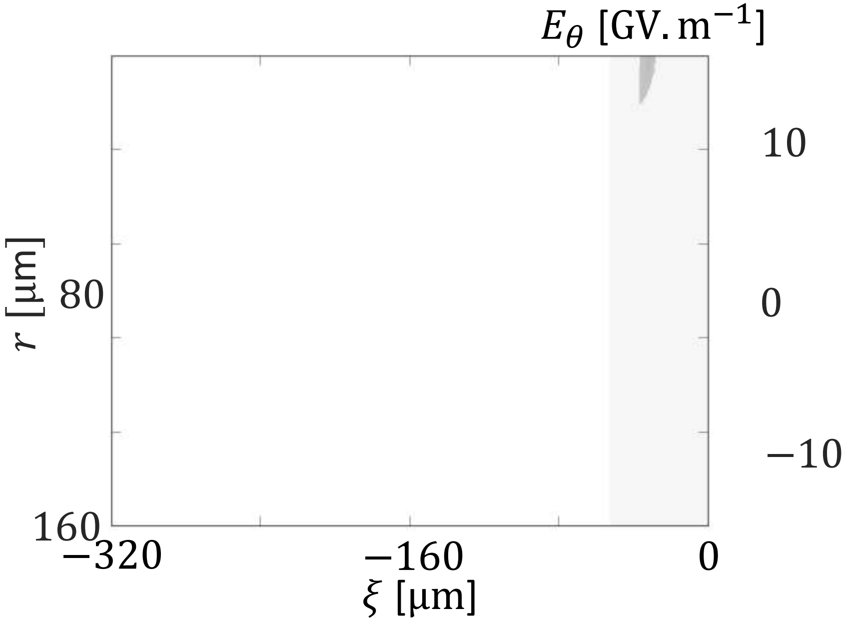
Z. Hu *et al.*, Plasma Sci. Technol. **14**, 874 (2012)

P. Sharma *et al.*, Phys. Plasmas **24**, 013102 (2017)

Under QSA: $E_\theta \sim -b\, \partial_r E_x$

$E_\theta > 30$ GV/m

Conversion efficiencies ~ 0.35%



$a_0 = 4$, $\lambda_0 = 1$ µm, $\tau = 35$ fs FWHM, $w_0 = 10$ µm FWHM, $\nu_{ce} = \nu_{pe} = 10$ THz

C. Tailliez *et al.*, Phys. Rev. Res. **5**, 023143 (2023)

Conclusions

1. **THz pulse generation by two-color laser pulses**
    - Photocurrents generate high fields and broadband spectra
    - THz spectroscopy by air plasmas works!

2. **Ultrahigh intensity laser-gas interactions**
    - Laser-plasma accelerators produce THz coherent transition radiation
    - Much higher fields and mJ energies delivered
    - Wake radiations amplified by intense magnetic fields
    - THz fields of hundreds of GV.m^{-1} can be achieved when the magnetization parameter is above unity

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Colomban Tailliez
Xavier Davoine
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Stefan Skupin
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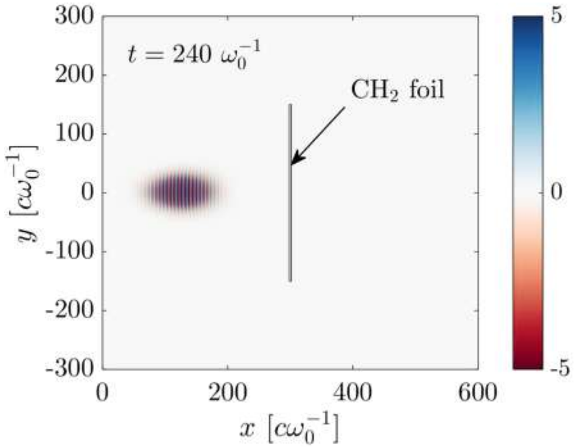
Alisée Nguyen
Pedro González de Alaiza Martínez
Korbinian Kaltenacker
Binbin Zhou
And many others ….

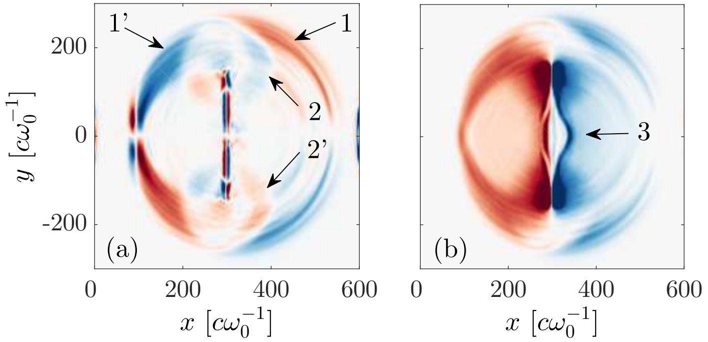
cea

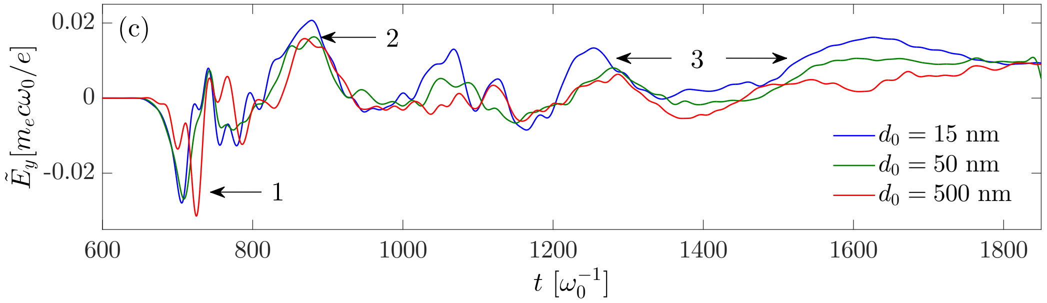
THz emissions from relativistic

- **Laser parameters**
  - $I_L = 1.4{\times}10^{20}$ Wcm^{-2}($a_0 \simeq 10$)
  - $\tau_L = 30$ fs (FWHM)
  - Focal spot $w_L = 5\ \mu$m (FWHM)
  - Wavelength $\lambda_L = 1\mu$m

- **Target parameters**
  - Fully ionized CH$_2$ foil targets ($n_e = 400n_c$)
  - Transverse width $D = 47.7\mu$m
  - Thickness $d \in (15{,}50{,}500)$ nm







J. Déchard et al., Phys. Plasmas **27**, 093105 (2020)

Topic: Study of low-frequency radiation produced by particle acceleration at ultra-high laser intensity in relativistic plasmas

Context: Laser-matter interaction – Laser-induced low-frequency radiation

Thesis objective: Today, petawatt laser sources deliver optical pulses lasting a few tens of femtoseconds with an intensity exceeding 10^{20} W/cm^2. When such light beams impinge onto a gas or a solid target, their electromagnetic field can drive electrons to MeV or GeV energies, depending on the interaction parameters. While the dynamics of those relativistic electrons is an efficient source of secondary high-energy photons, the laser-plasma interaction also gives rise, through the production mechanisms of plasma waves and particle acceleration, to low-frequency emissions in the gigahertz (GHz) and terahertz (THz) ranges.

Having high-power emitters operating in this frequency band is attracting more and more interest in Europe, overseas and in Asia. On the one hand, the generation of intense electromagnetic pulses with GHz-THz frequencies is harmful for any electronic device used on large-scale laser facilities like, e.g., the PETAL/LMJ laser in the Aquitaine region. It is therefore necessary to understand their nature to better circumvent them. On the other hand, the waves operating in this field not only make it possible to probe the molecular motions of complex chemical species, but they also offer new perspectives in medical imaging for cancer detection, in astrophysics, in security as well as for environmental monitoring. The processes responsible for this violent electromagnetic field emission also open new ways to modify some properties of condensed matter in strong field.

The objective of this thesis is to study the generation of such giant electromagnetic pulses by ultrashort laser pulses interacting with dense media, to build a model based on the different THz/GHz laser-pulse conversion mechanisms, and validate this model by available experimental data. The PhD student will be invited to deal with this problem theoretically and numerically, by means of a kinetic, particle-in-cell code whose Maxwell solver will be adapted to describe radiation coming from different electron/ion populations. Particular attention will be given to the different radiations associated with particle acceleration on femto- and picosecond time scales by dense relativistic plasmas and their respective roles in target charging models available in the literature. This field of physics requires a new theoretical and numerical modeling work, at the crossroads of extreme nonlinear optics and the physics of relativistic plasmas.

The candidate should have an advanced training in plasma physics and/or scientific computing, with an ability to handle simulation codes or for programming (Python, Fortran, C++).

Thesis Director & CoDirector: Luc Bergé & Emmanuel d'Humières – Centre Lasers Intenses et Applications (CELIA), Université de Bordeaux, CNRS, CEA, 33405 Talence, France.

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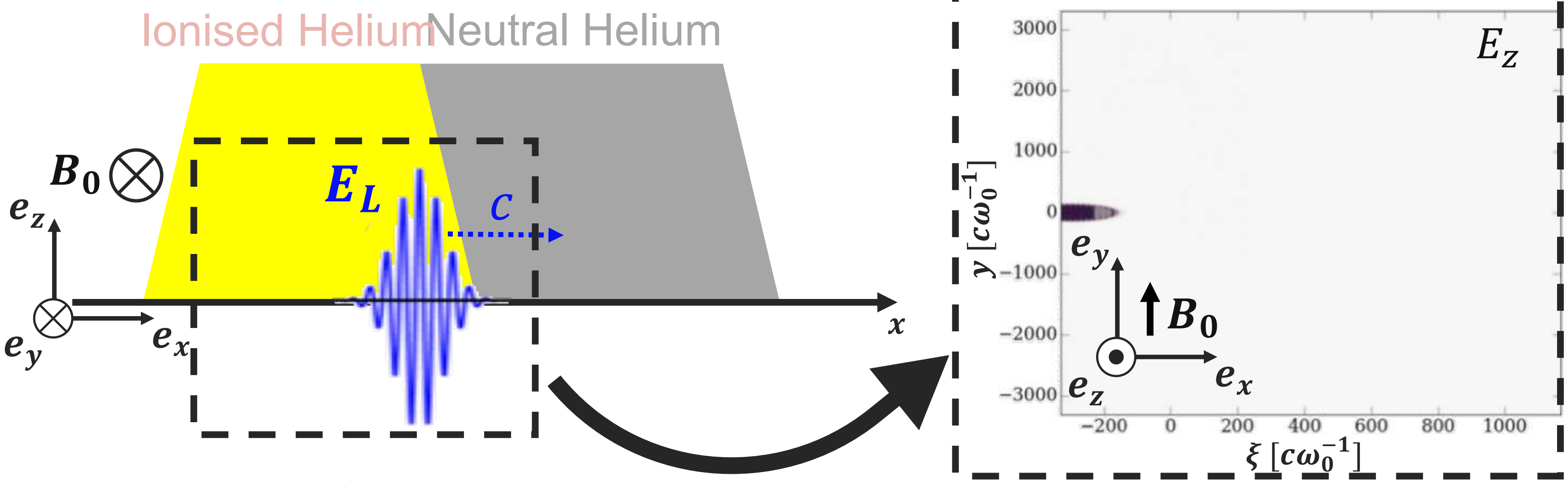
Financement: Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA)

Intense magnetic field generation techniques

Method	B [T]	Duration [s]	Size [m]	Destructive
Hybrid superconductive / resistive magnet[1]	50	Continuous	10^{-2}	No
Nondestructive pulsed magnet[2]	100	10^{-3}	10^{-2}	No
Single-turn coil[3]	300	10^{-6}	10^{-3}	Partially
Electromagnetic flux compression[4]	1200	10^{-6}	10^{-3}	Partially
Explosive flux compression[5]	2000	10^{-7}	10^{-2}	YES
Capacitor-coil target driven by laser[6]	1500	10^{-9}	10^{-4}	Partially
Laser-driven microtube implosions[7]	10^{6}	10^{-14}	10^{-6}	Partially

[1] S. Hahn *et al.*, Nature **570**, 496 (2019)
[2] M. Jaime *et al.*, PNAS **109**, 12404 (2012)
[3] O. Portugall *et al.*, J. Phys. D **32**, 2354 (1999)
[4] D. Nakamura *et al.*, Rev. Sci. Instrum. **89**, 095106 (2018)
[5] A. I. Bykov *et al.*, Instrum. Exp. Tech. **58**, 531 (2015)
[6] S. Fujioka *et al.*, Sci. Rep. **3**, 1170 (2013)
[7] M. Murakami *et al.*, Sci. Rep. **10**, 16653 (2020)

2D PIC simulation of a wakefield-driven THz pulse in a magnetized plasma



- **Helium slab** of length $\mathbf{400\ \mu m}$
- **Up/Down ramps** of length up to $\mathbf{200\ \mu m}$
- $\nu_{pe} \in [4,6,8,10]$ THz
- $\nu_{ce} \in [0,4,6,8]$ THz ↔ $B_0 \in [0,143,215,286]$ T
- Laser : $\boldsymbol{a_0 = 4}$ $(\gamma_L \sim 3)$, duration $\boldsymbol{\tau = 35}$ **fs** FWHM, waist $\boldsymbol{w_0 = 10\ \mu m}$, wavelength $\boldsymbol{\lambda_0 = 1\ \mu m}$

Moving simulation box
→ Comoving coordinates
$(\xi = x - ct, y, \tau = t)$

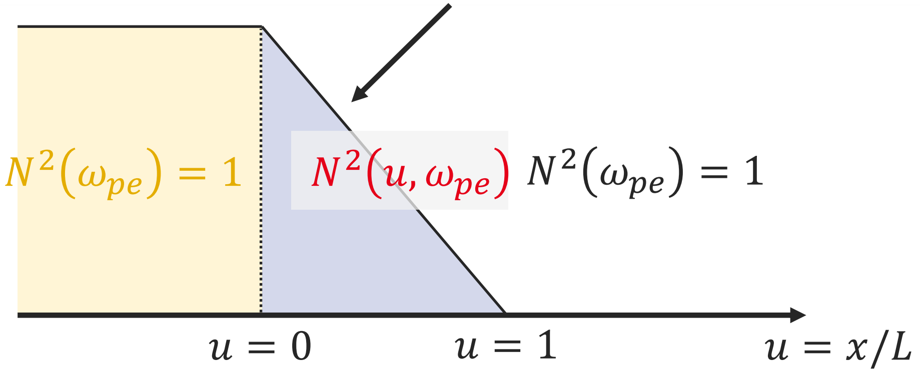
→ PIC units
Distance : $\boldsymbol{c\omega_0^{-1}} \simeq \mathbf{0.159\ \mu m}$
Time : $\boldsymbol{\omega_0^{-1}} \simeq \mathbf{0.531\ fs}$

Attenuation by the plasma down ramp

Density down ramp of length L : decay due to dispersion relation variation (only when $b < 1$)

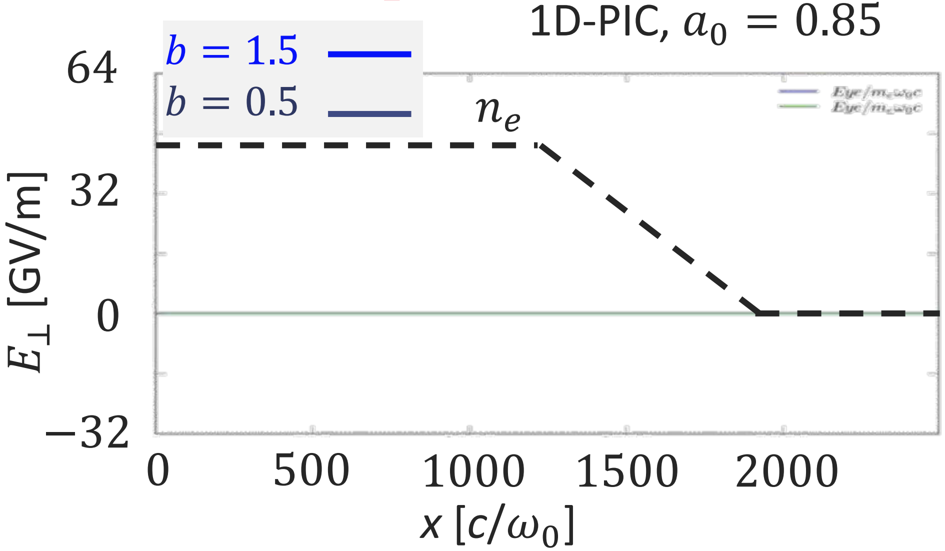
$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega^2}\frac{\omega^2 - \omega_{pe}^2}{\omega^2 - \omega_H^2}$$

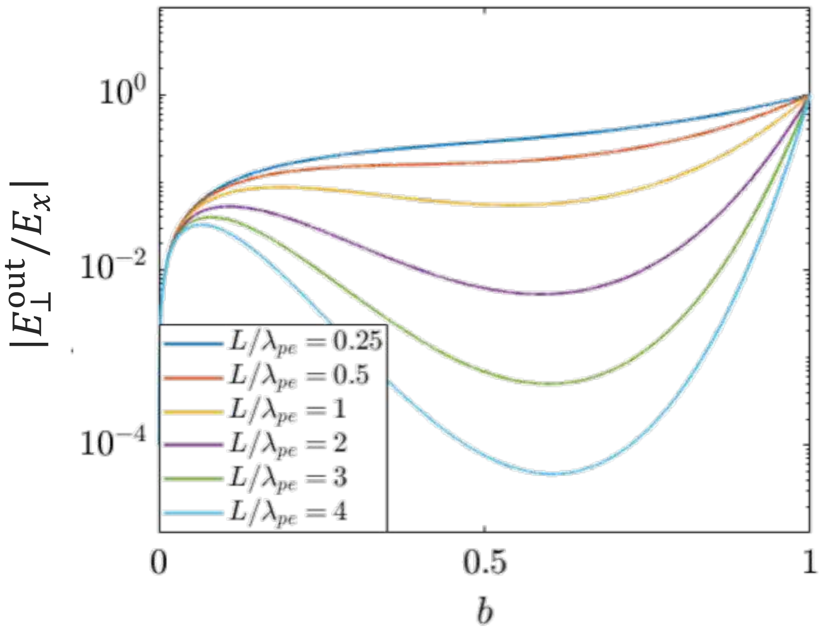
$N^2(\omega) = c^2k^2(\omega)/\omega_{pe}^2$ takes **negative values** when $b < 1$…



$$E_\perp^{\text{out plasma}} = E_\perp^{\text{in plasma}} \times e^{-\int_L \mathrm{Im}(k)dx}$$

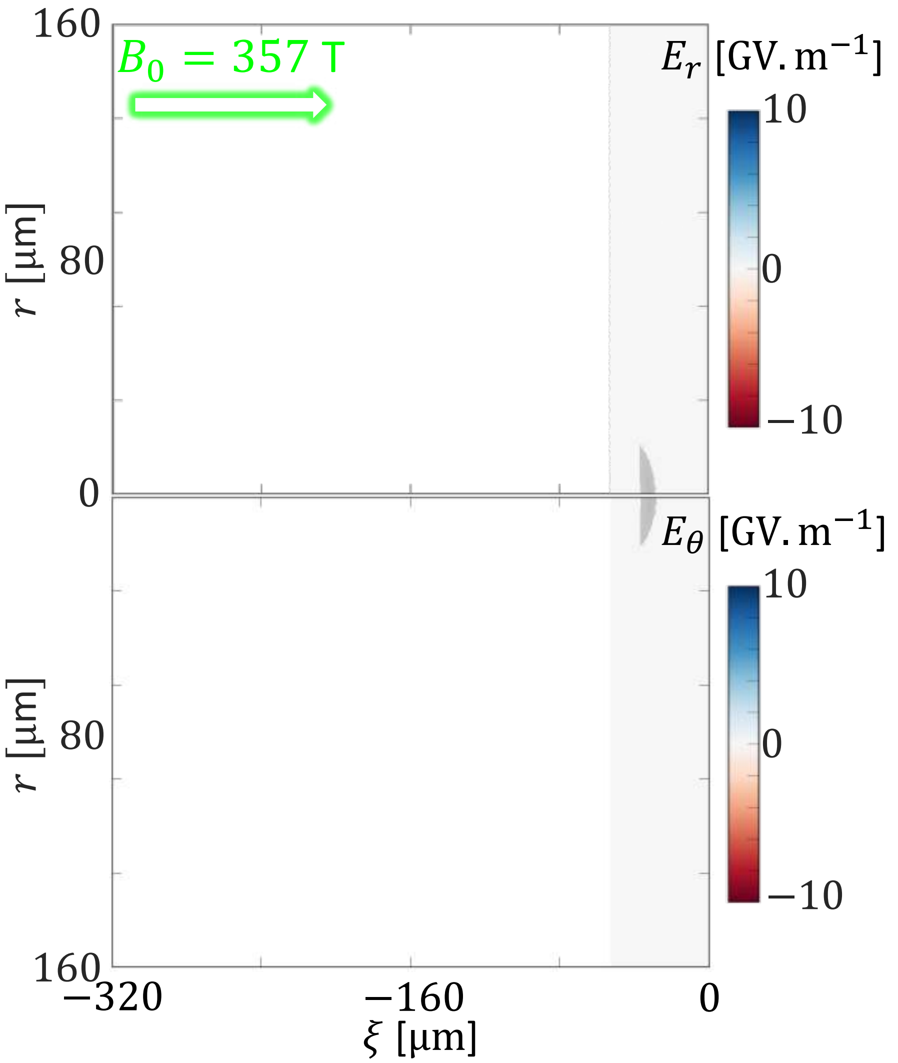
… resulting into a **damping** of the wave initially generated inside the plasma

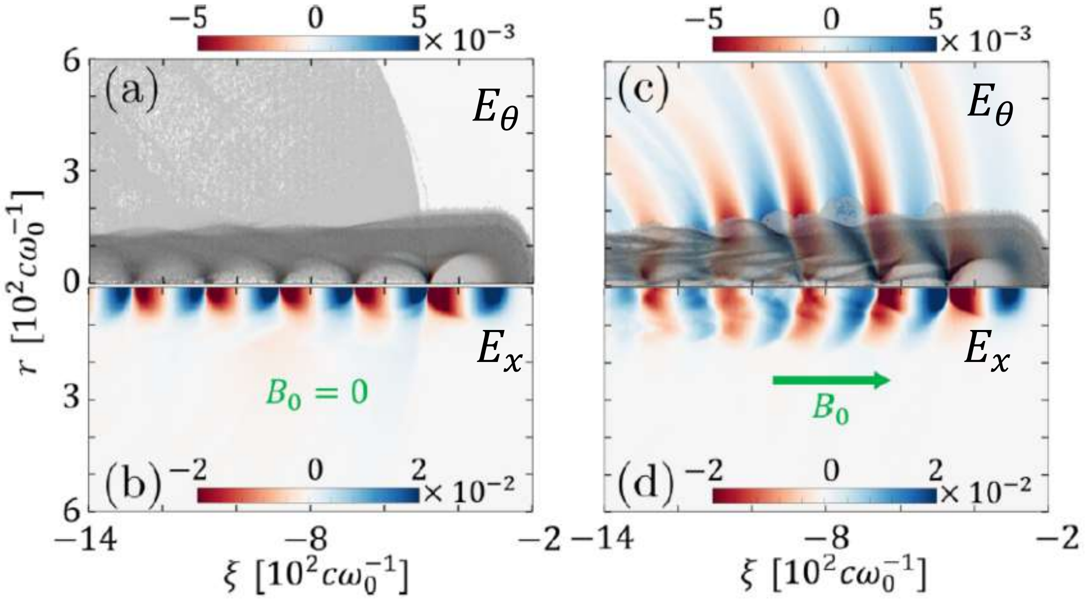




J. Yoshii *et al.*, Phys. Rev. Lett. **79**, 4194 (1997)

Quasi-3D PIC simulation: > 30 GV/m THz fields





$E_\theta > 30$ GV/m, generated at **plasma frequency**

- Radial component E_r with lower amplitude
- Conversion efficiencies ~ 0.35%

$a_0 = 4$, $\lambda_0 = 1$ µm, $\tau = 35$ fs FWHM,
$w_0 = 10$ µm FWHM, $\nu_{ce} = \nu_{pe} = 10$ THz

C. Tailliez *et al.*, Phys. Rev. Res. 5, 023143 (2023)