Génération d'impulsions THz à partir de sources laser ultrabrèves : Principes et applications

DE LA RECHERCHE À L'INDUSTRIE

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PTC – Instrumentation & Détection - THz

11 OCTOBRE 2019

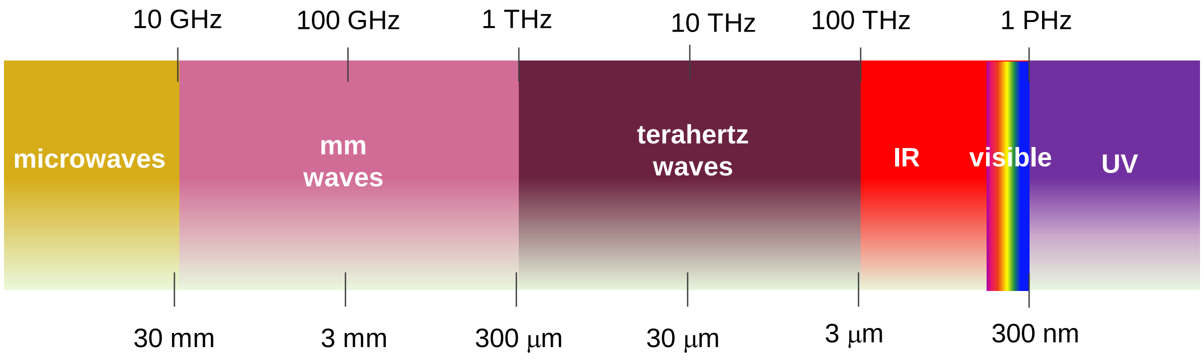
OUTLINE

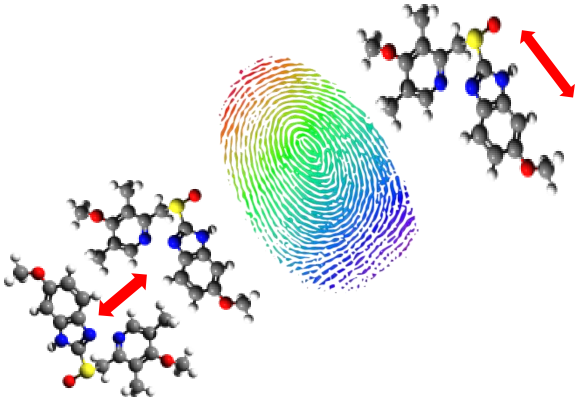
1. THz pulse generation by two-color lasers

2. ALTESSE Project

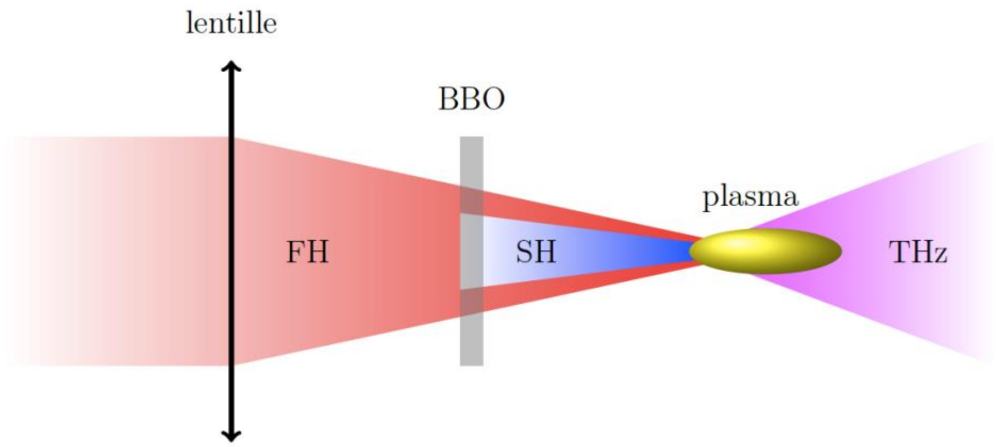
3. Laser-plasma relativistic interactions

THz Emitters: Go to plasma-based sources



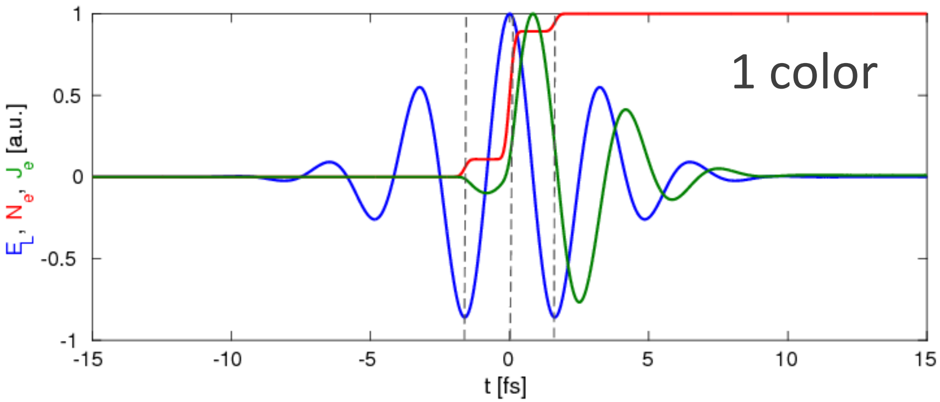


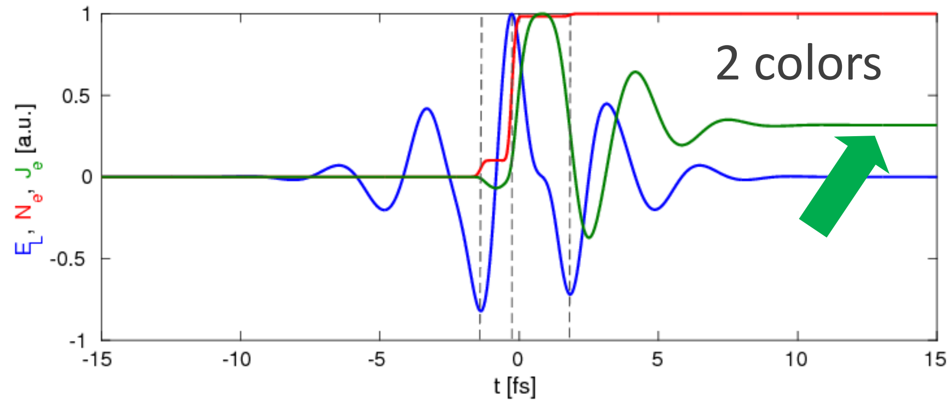
K. Y. Kim et al., Nature Photon. **2**, 605 (2008)



CONVENTIONAL DEVICES	LASER-DRIVEN THz SOURCES
< 0.1 GV/m	~ GV/m
< 10 THz	1-100 THz

Laser-driven THz sources: The Photocurrents

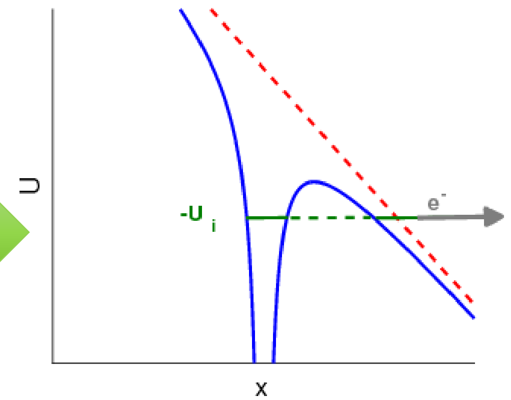




$$E_L(t) = A_1 e^{-\frac{t^2}{t_p^2}} \cos(\omega_0 t) + A_2 e^{-\frac{2t^2}{t_p^2}} \cos(2\omega_0 t + \delta\phi)$$

$$\partial_t N_e = W(E_L)(N_0 - N_e)$$

$W(t)$: tunneling rate



The laser field accelerates the extracted electrons:

$$J(t) \propto \frac{e^2}{m_e} \int_{-\infty}^{t} N_e(\tau) E_L(\tau) d\tau \rightarrow E_{THz} \propto \partial_t J$$

maximized for $\delta\phi = \pi/2$

I. Babushkin *et al.*, New J. Phys. **13**, 123029 (2011)

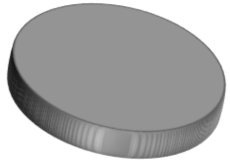
2. ALTESSE Project

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

1. Grinding and mixing of sample material and polyethylene (PE)

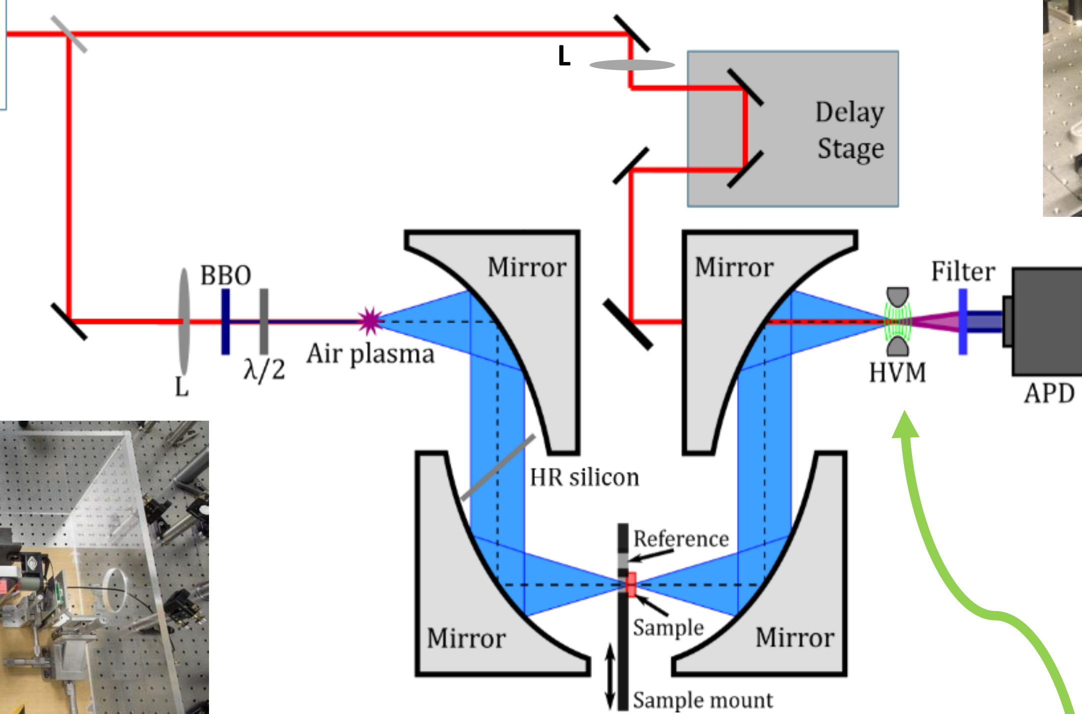
2. Pressing of PE pellets

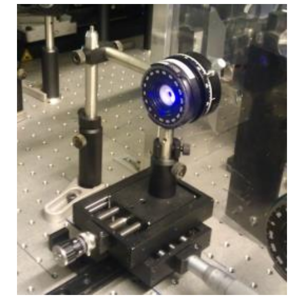
m_{total}:	~100 mg
Thickness:	~1 mm
Diameter:	~1 cm

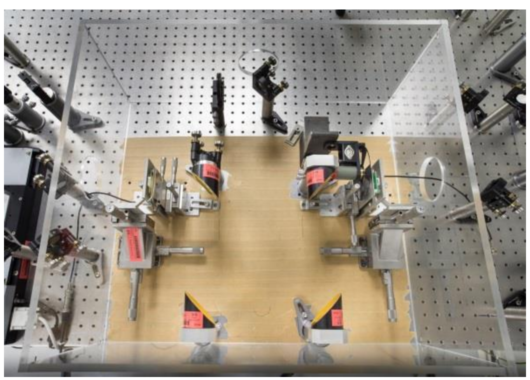


ABCD Technique

THz-TDS Spectroscopy based on « Air-Biased Coherent Detection » (ABCD in transmission)







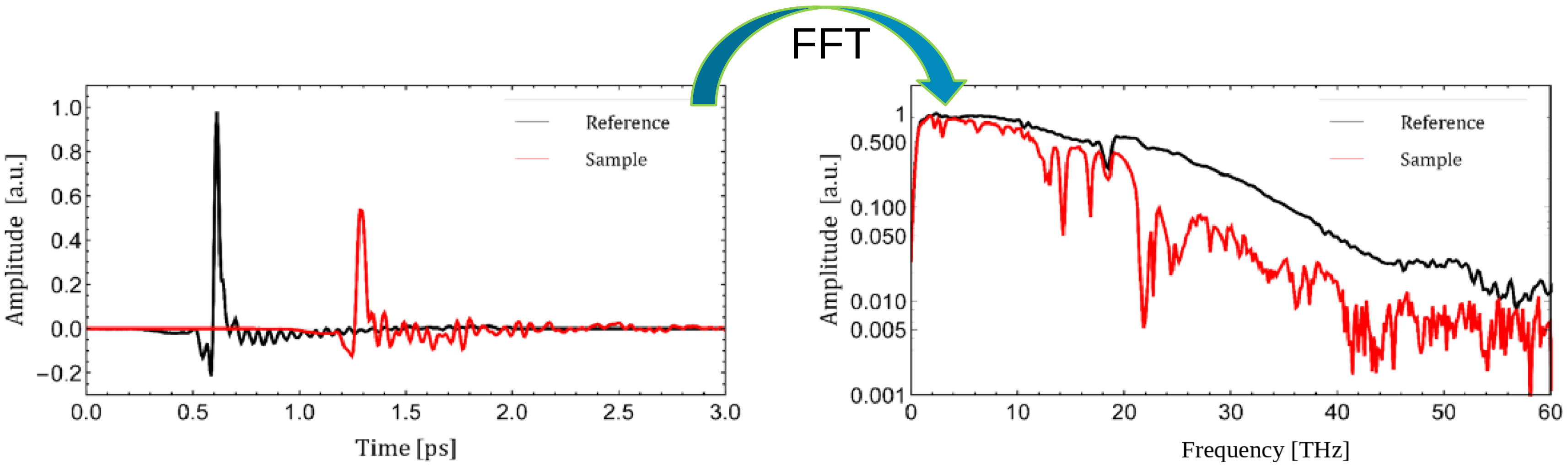
N. Karpowicz et al., Appl. Phys. Lett. **92**, 011131 (2008)

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

Coherent THz Spectroscopy

ABCD THz-TDS Spectroscopy

THz signature of thymine pellet (time & Fourier domains)



Emission up to 60 THz !

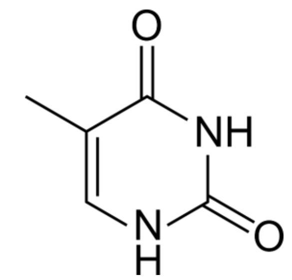
$$\frac{E_{sam}(\omega)}{E_{ref}(\omega)} = Ae^{i\phi(\omega)} = Te^{-\frac{\alpha d}{2}}e^{\frac{i(n-1)\omega d}{c}}$$

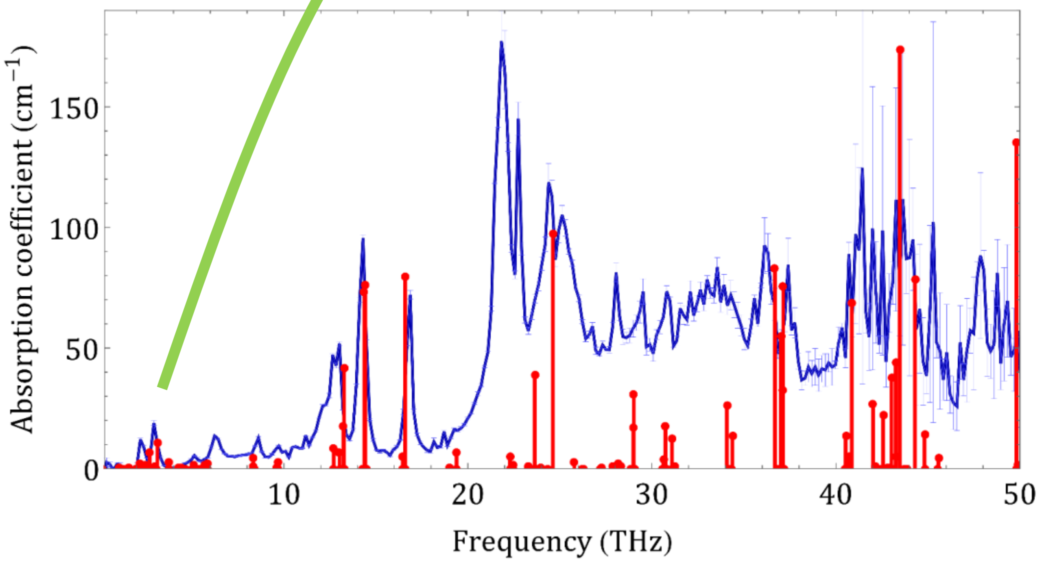
$$\alpha(\omega) = -\frac{2}{d}\ln\left(\frac{(n+1)^2}{4n}\cdot\frac{|E_{sam}(\omega)|}{|E_{ref}(\omega)|}\right)$$

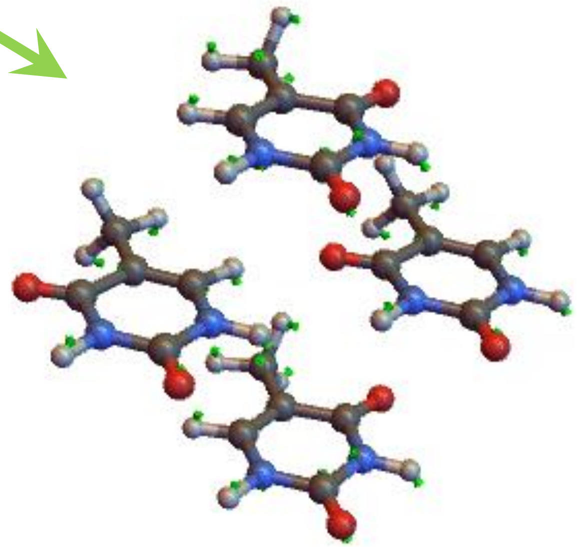
Example: Thymine

DFT Simulations

3.1 THz

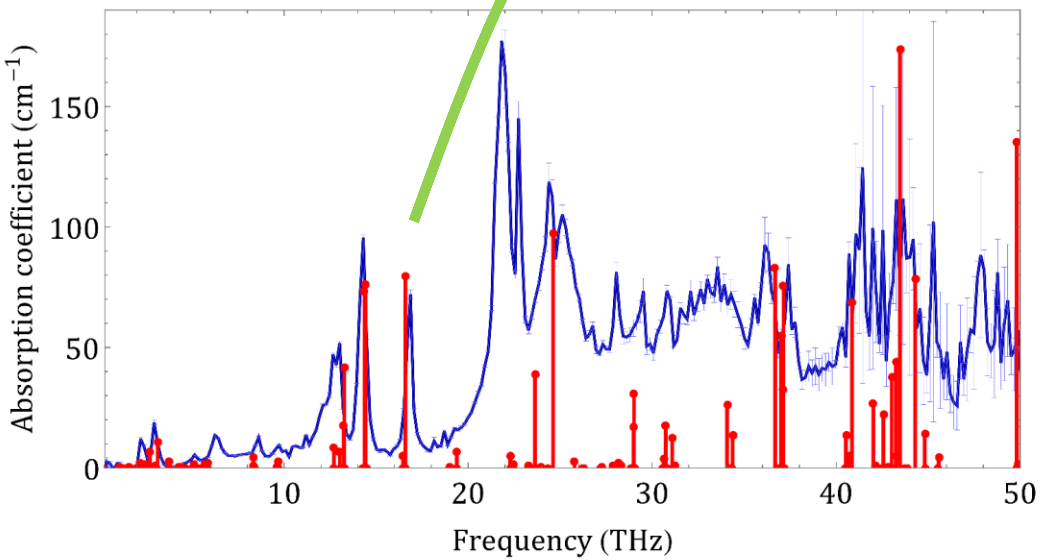




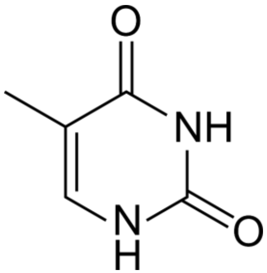


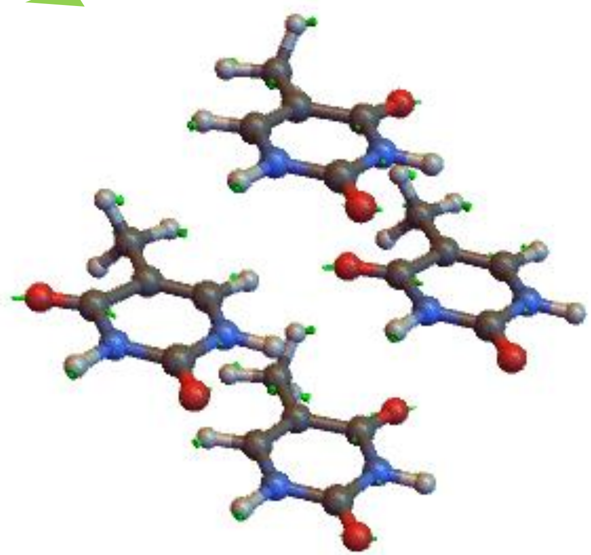
DFT CASTEP Simulations
for interpreting experimental spectra
from phonon modes of thymine

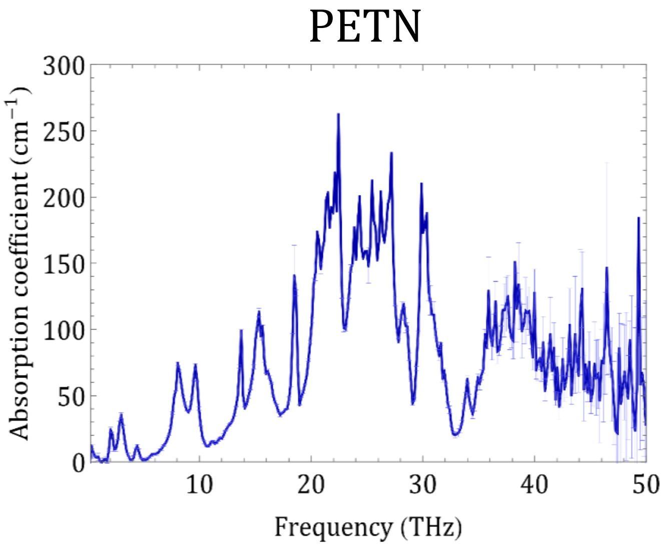
DFT Simulations

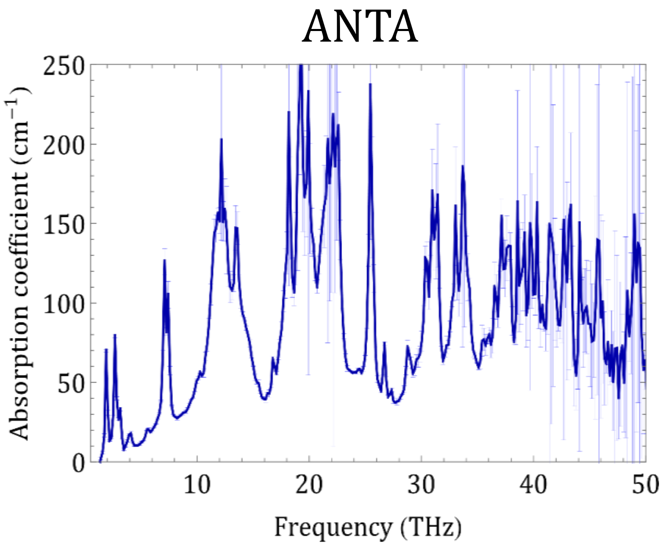


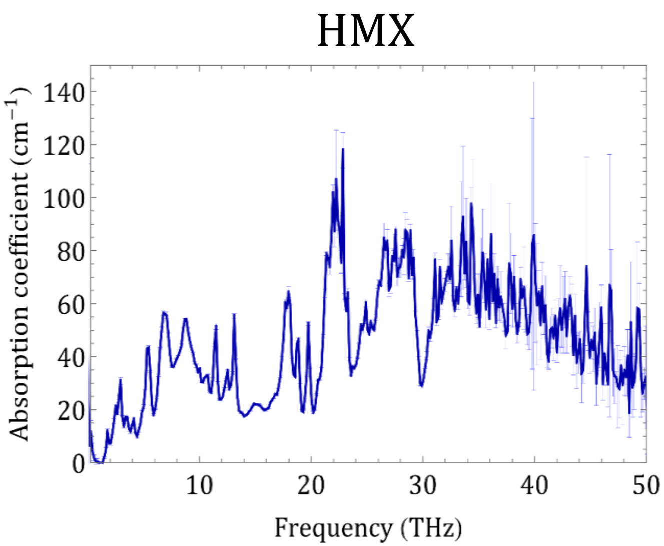
16.6 THz

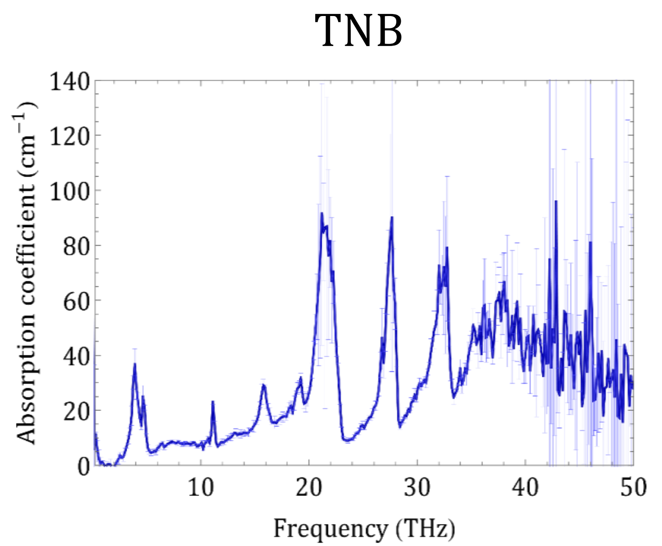




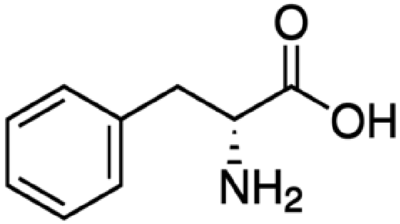

PETN
Absorption coefficient (cm−1)
Frequency (THz)
300
250
200
150
100
50
0
10
20
30
40
50

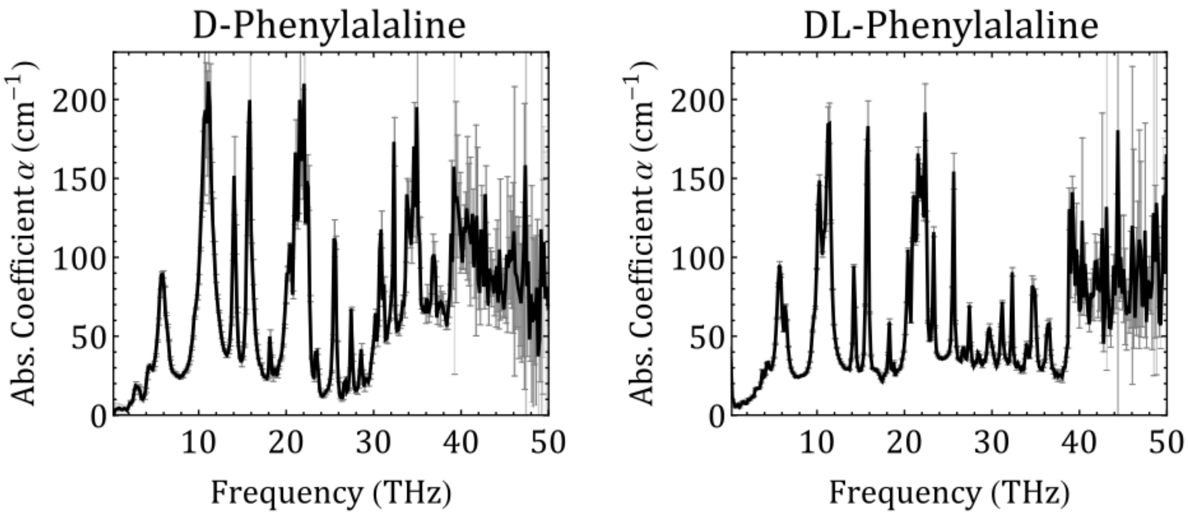

ANTA
Absorption coefficient (cm−1)
Frequency (THz)
250
200
150
100
50
0
10
20
30
40
50


HMX
Absorption coefficient (cm−1)
Frequency (THz)
140
120
100
80
60
40
20
0
10
20
30
40
50

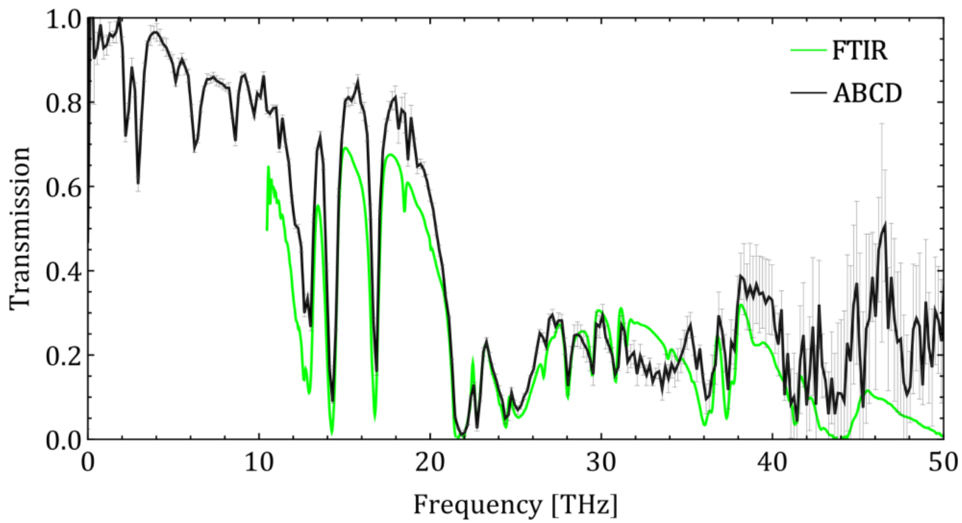

TNB
Absorption coefficient (cm−1)
Frequency (THz)
140
120
100
80
60
40
20
0
10
20
30
40
50

ABCD may distinguish different isomers



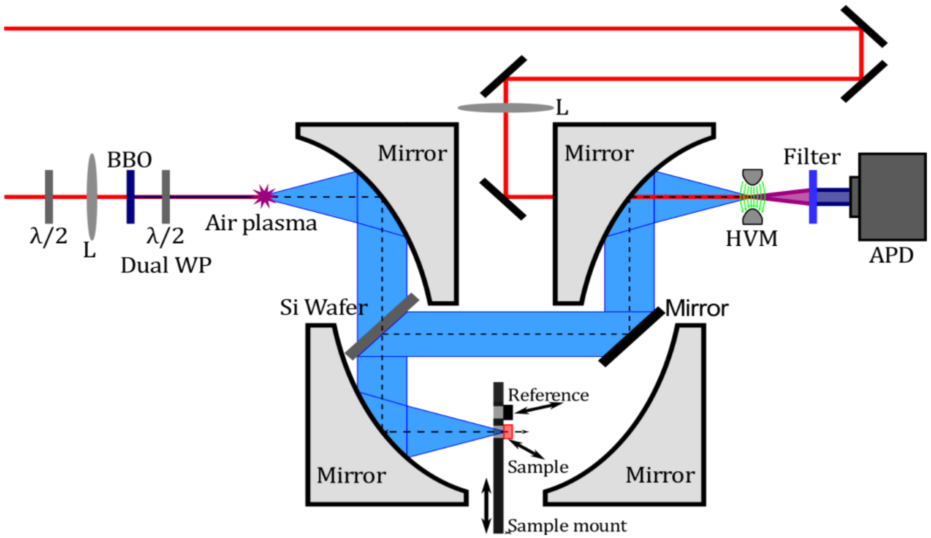


Comparison ABCD vs FTIR

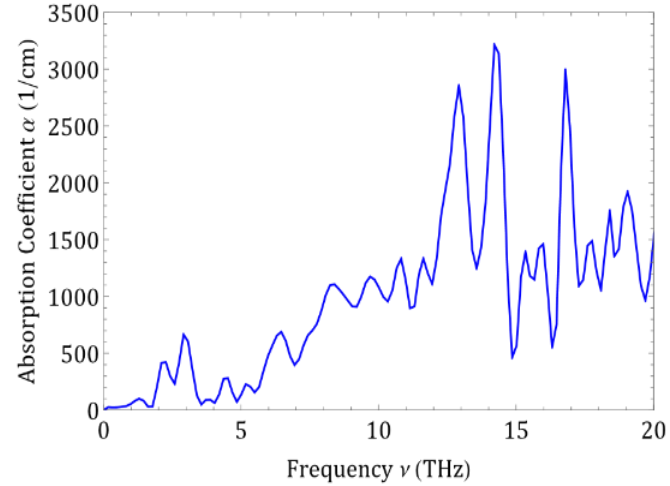


Reflection Spectra

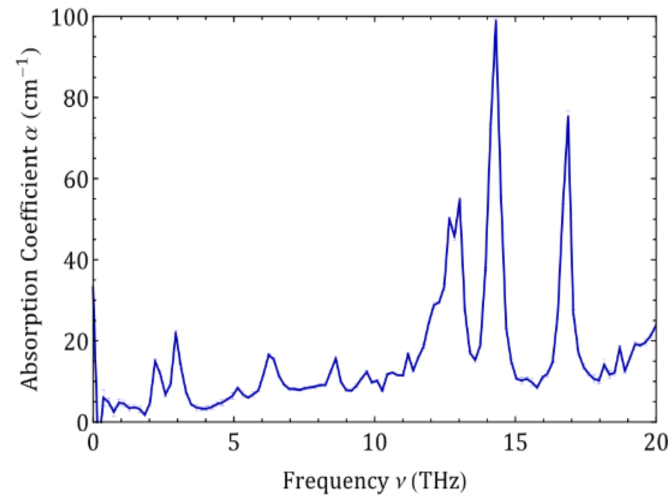
ABCD THz-TDS Spectroscopy



Reflection measurements



Transmission measurements



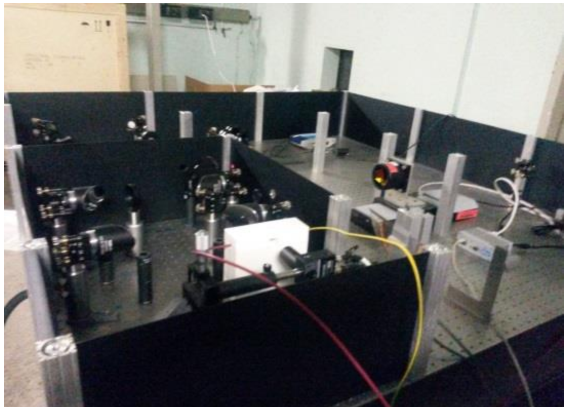
Absorption coefficients (Thymine) are several orders of magnitude higher than in transmission:

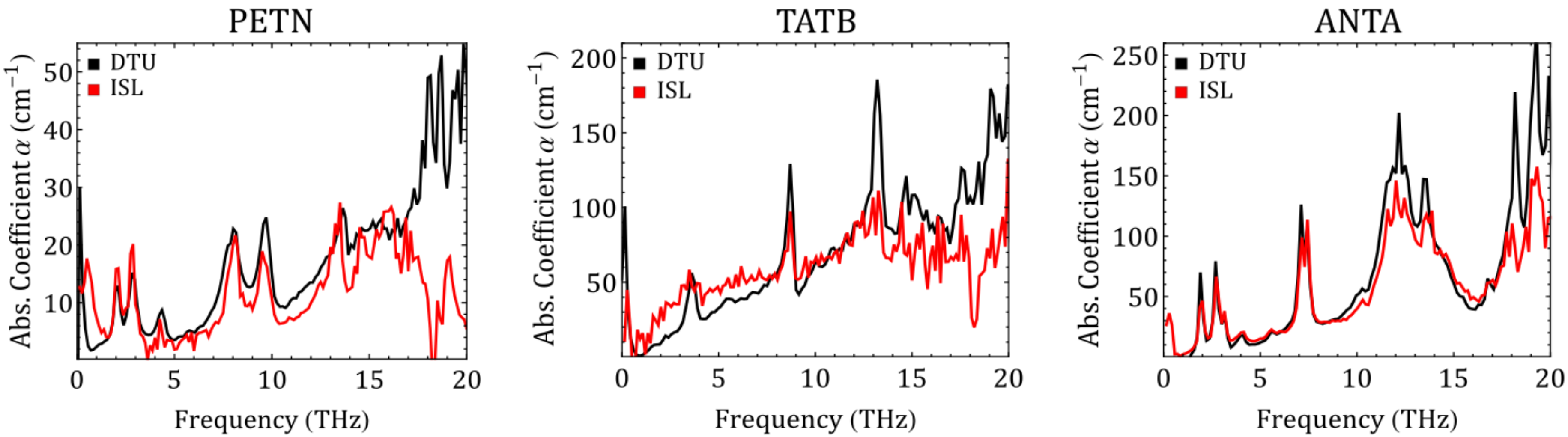
- Sample pellets made of pure material instead of mixture with PE
- Oscillations in the reflection spectrum cause the emergence of additional small peaks

Towards remote sensing

NOISY detection conditions

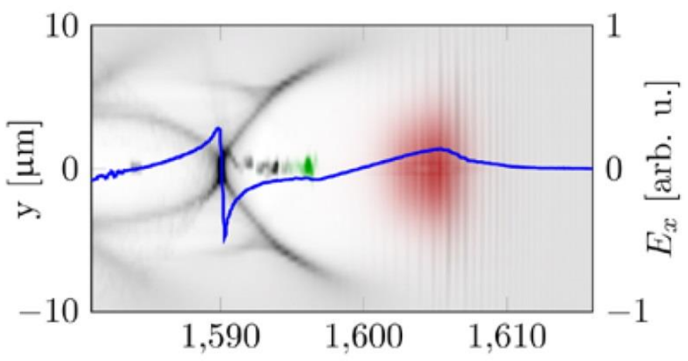
15 m





LB et al., EPL **126**, 24001 (2019)

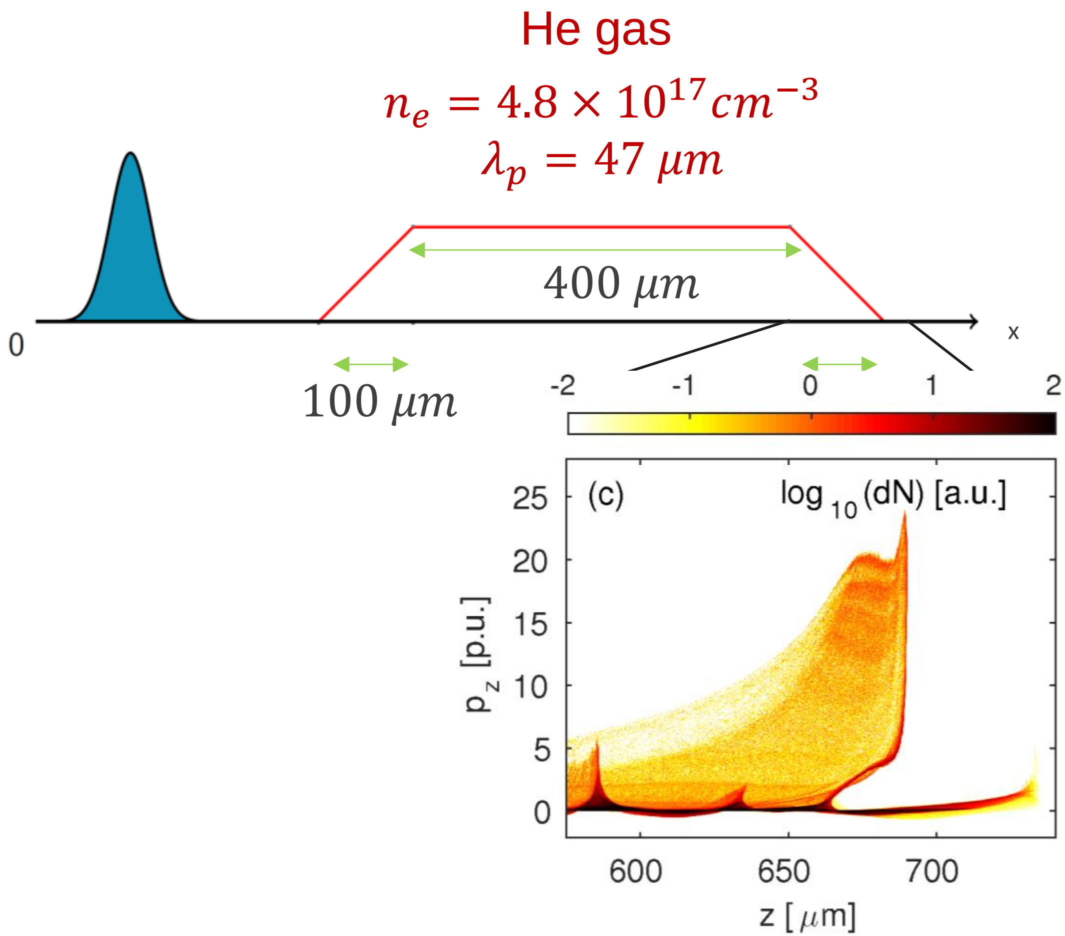
$$a_0 = 0.85\sqrt{I_{18}}\lambda_0[\mu m] > 1$$



Accelerated electrons escape from the plasma

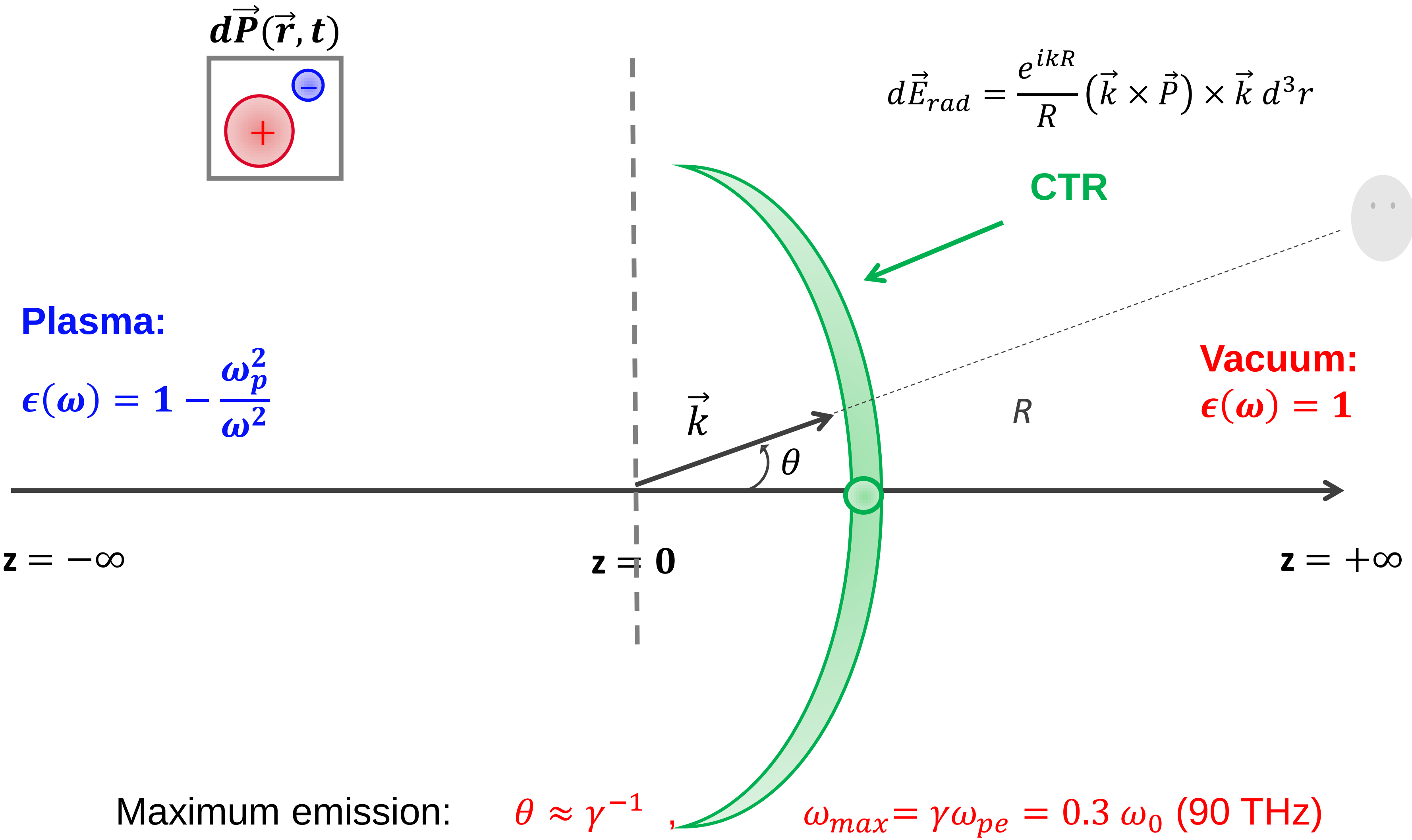
- Simulation with Particle-in-Cell code (CALDER)
- Laser-plasma parameters: 2 colors with 10% second harmonic

Laser
$E_0 = 3.7\ J$
$\lambda_0 = 1\ \mu m$
$w_0 = 20\ \mu m$
$\tau_0 = 35$ fs
$I_0 = 2.2\ \times\ 10^{19}\ W/cm^2$
$a_0 = 4$



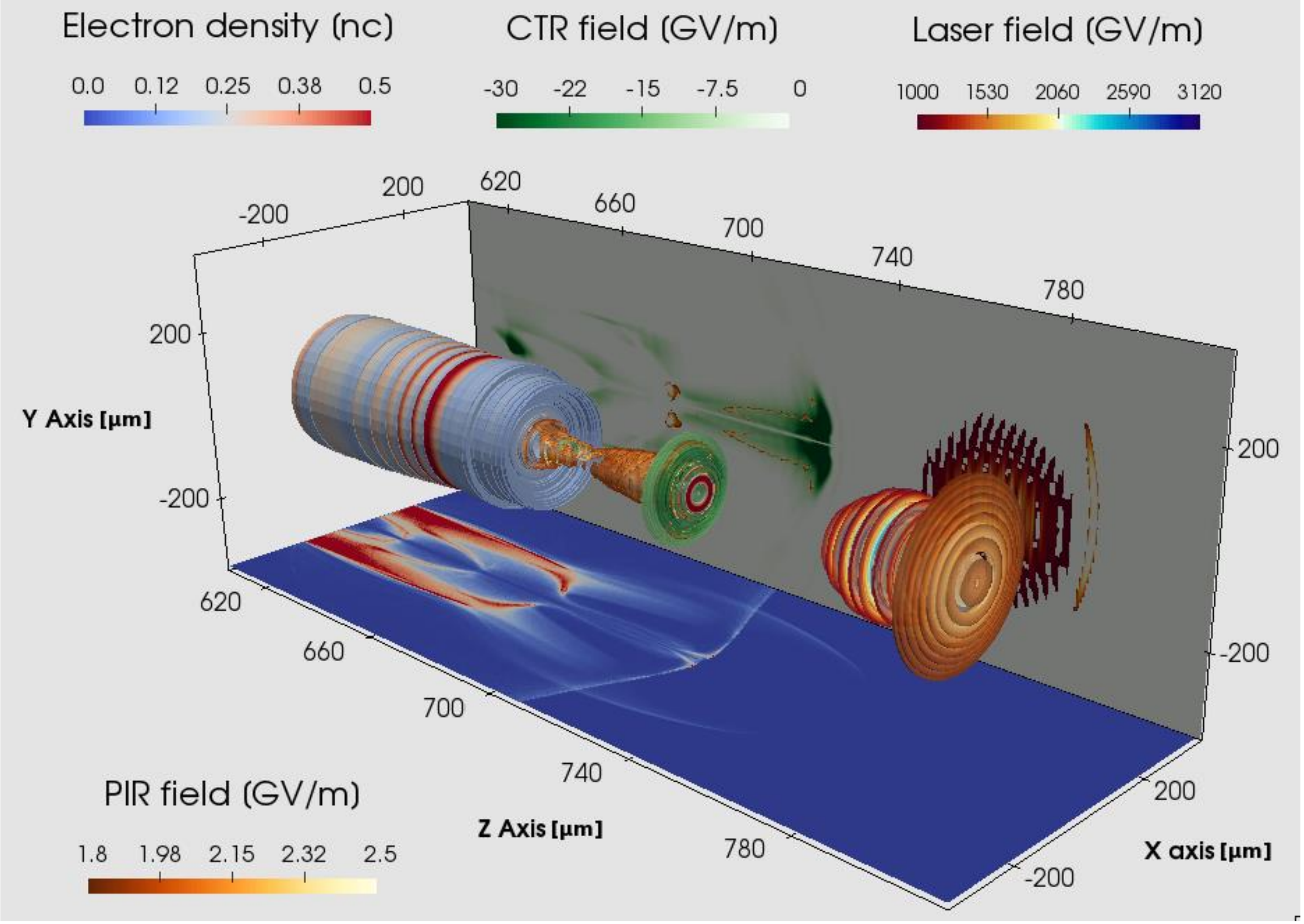
Coherent Transition Radiation (CTR)

Ginzburg & Frank (1946) : 'emission whenever a charged particle passes suddenly from one medium into another'



Maximum emission: $\theta \approx \gamma^{-1}$, $\omega_{max} = \gamma\omega_{pe} = 0.3\ \omega_0$ (90 THz)

PIC results: CTR THz field at the plasma exit



PIR: 1.3 µJ with 2 GV/m field strength - CTR: 160 µJ with 30 GV/m field strength

J. Déchard et al., PRL **120**, 144801 (2018)

Conclusion

ALTESSE:

First spectral measurements of explosives capturing molecular fingerprints:
- up to 60 THz to identify solid explosives, confirmed by Ab-initio simulations
- up to 20-THz bandwidths at 15 m from the laser source

LB et al. EuroPhys. Lett. **126**, 24001 (2019)

Strong increase, by a factor close to 10, in the THz energy yield measured for laser fundamental wavelengths operating in the mid-IR

A. Nguyen et al., Opt. Lett. **44**, 1488 (2019)

Future: Laser-plasma accelerators produce Coherent Transition Radiation (CTR) yielding much higher fields and mJ energies

J. Déchard et al., PRL **120**, 144801 (2018)

Jérémy Déchard

"Terahertz sources produced by ultra-intense lasers"

Monday 14th of October – 14h Amphitheatre J. Horowitz, INSTN - CEA Saclay

"… Despite the inherent difficulty in accessing the THz spectral window (0.1-100 THz), many coming applications use the ability of THz frequencies to probe matter (spectroscopy, medicine, material science). In this perspective, laser-driven THz sources appear well-suited to provide simultaneously an energyetic and broadband signal compared to other conventional devices. By means of the particle-in-cell code CALDER, we explore previously little studied interaction regimes in order to optimize the laser-to-THz conversion efficiency. We show that the standard photocurrent mechanism is overtaken by coherent transition radiation induced by wakefield-accelerated electron bunch. Next, successive studies reveal the robustness of this latter process over a wide range of plasma parameters. We also demonstrate the relevance of long laser wavelengths in augmenting THz pulse generation through the ionization-induced pressure that increases the laser ponderomotive force …"

Jury Members: H. Milchberg, O. Lundh, J. Faure etc…

Thanks a lot!

Alisée Nguyen

Jérémy Déchard

Pedro González de Alaiza Martínez

Illia Thiele

Stefan Skupin

Ihar Babushkin

Peter Uhd Jepsen

Korbinian Kaltenacker

Binbin Zhou

Xavier Davoine

Arnaud Debayle

Laurent Gremillet