High-Power THz-Wave Generation and Its Application to Nonlinear Spectroscopy

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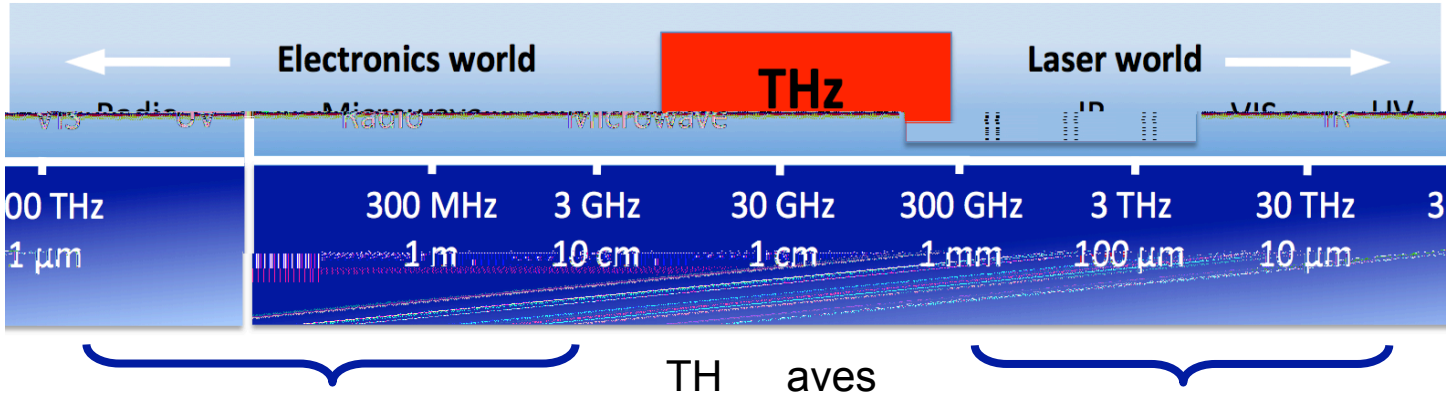
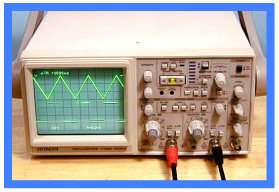
Contents

- Background (Extreme nonlinear optics)
- High-power THz-wave generation
- Non-linear THz spectroscopy in solids
- Perspectives

Background THz wave



TH aves are manipulated as light ith access to the electric field

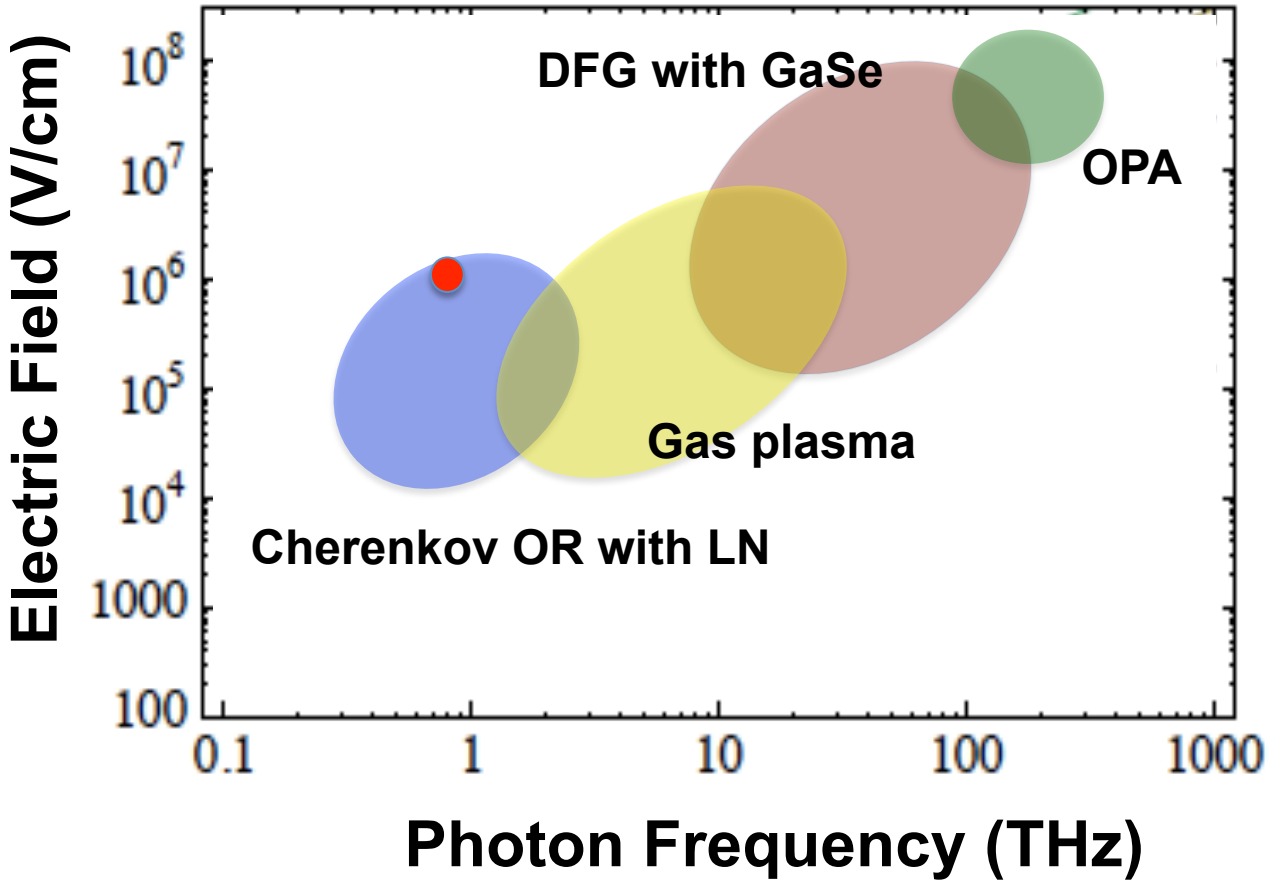


Sensitive to:

Inter molecular vibrations and rotational transitions in molecules
Electric transitions and vibrations modes in solids
H_2O d namics (strong absorption in ater based material)

Background

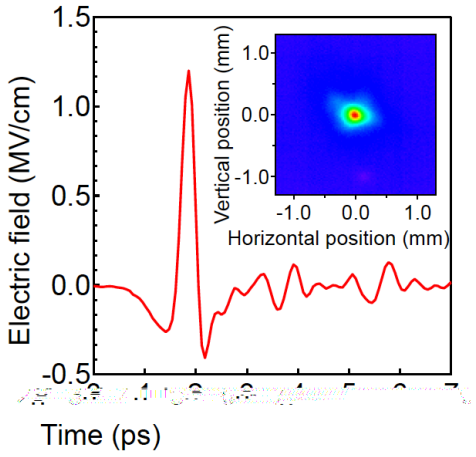
State-of-the-art of the high-power THz generation with femtosecond laser



Extreme nonlinear THz optics

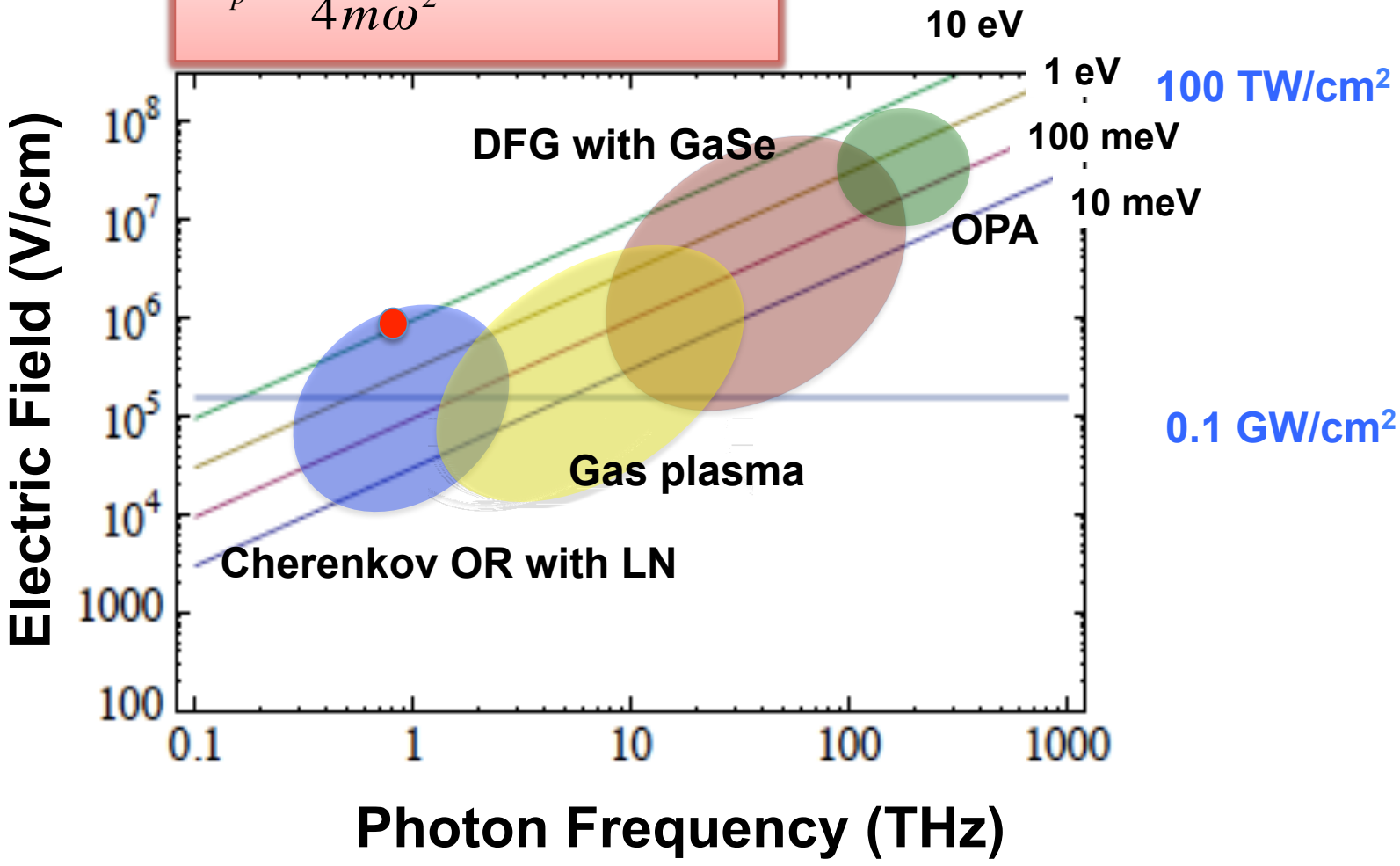
- ✓ single cycle = Broad band covering many octaves
- ✓ Carrier-envelope phase locking ready
- ✓ **Large ponderamotive energy**
- ✓ Large Rabi frequency

$$\Omega_R \sim \omega_c$$



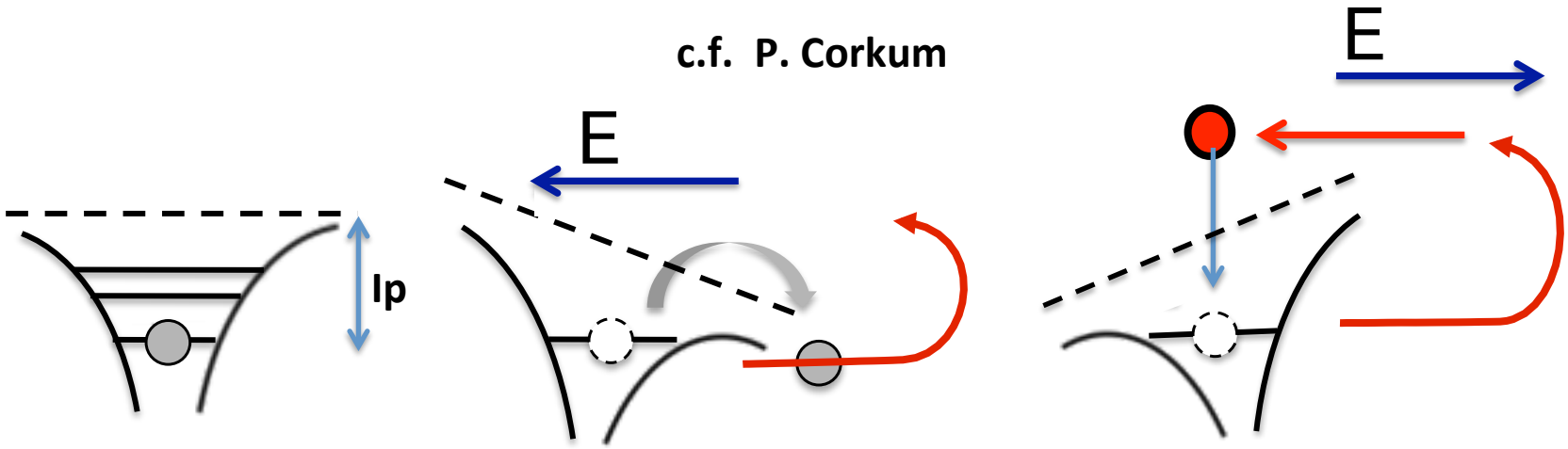
Ponderamotive Energy

$$U_p = \frac{e^2 E^2}{4m\omega^2} = 9.3 \times 10^{-14} I\lambda^2$$



Higher Harmonic Generation

c.f. P. Corkum



THz extreme nonlinear optics in solids !

Atom vs. Solids

Ip	10 ~ 20 eV	10 ~ 50 meV (impurity, exciton) 0.3 ~ 3 eV (band gap)
Surface damage	○	x

Extreme nonlinear THz optics

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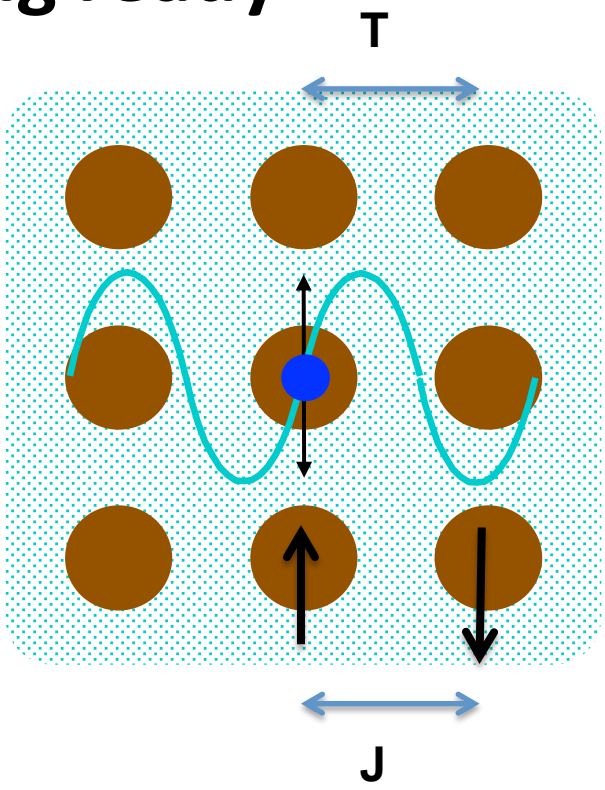
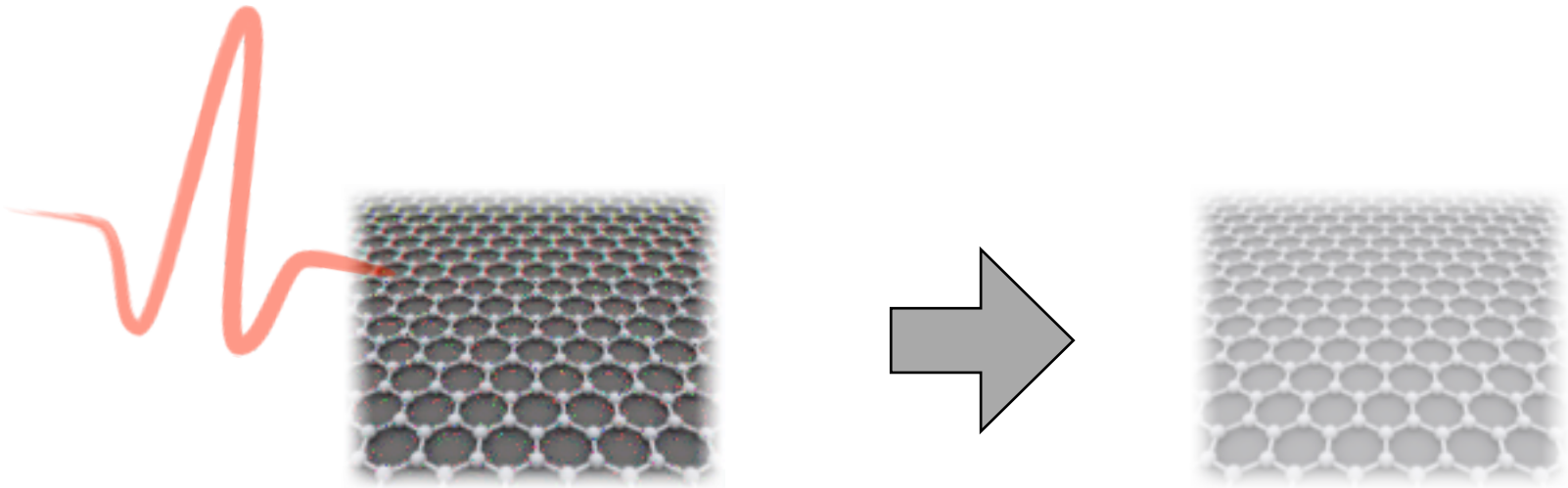
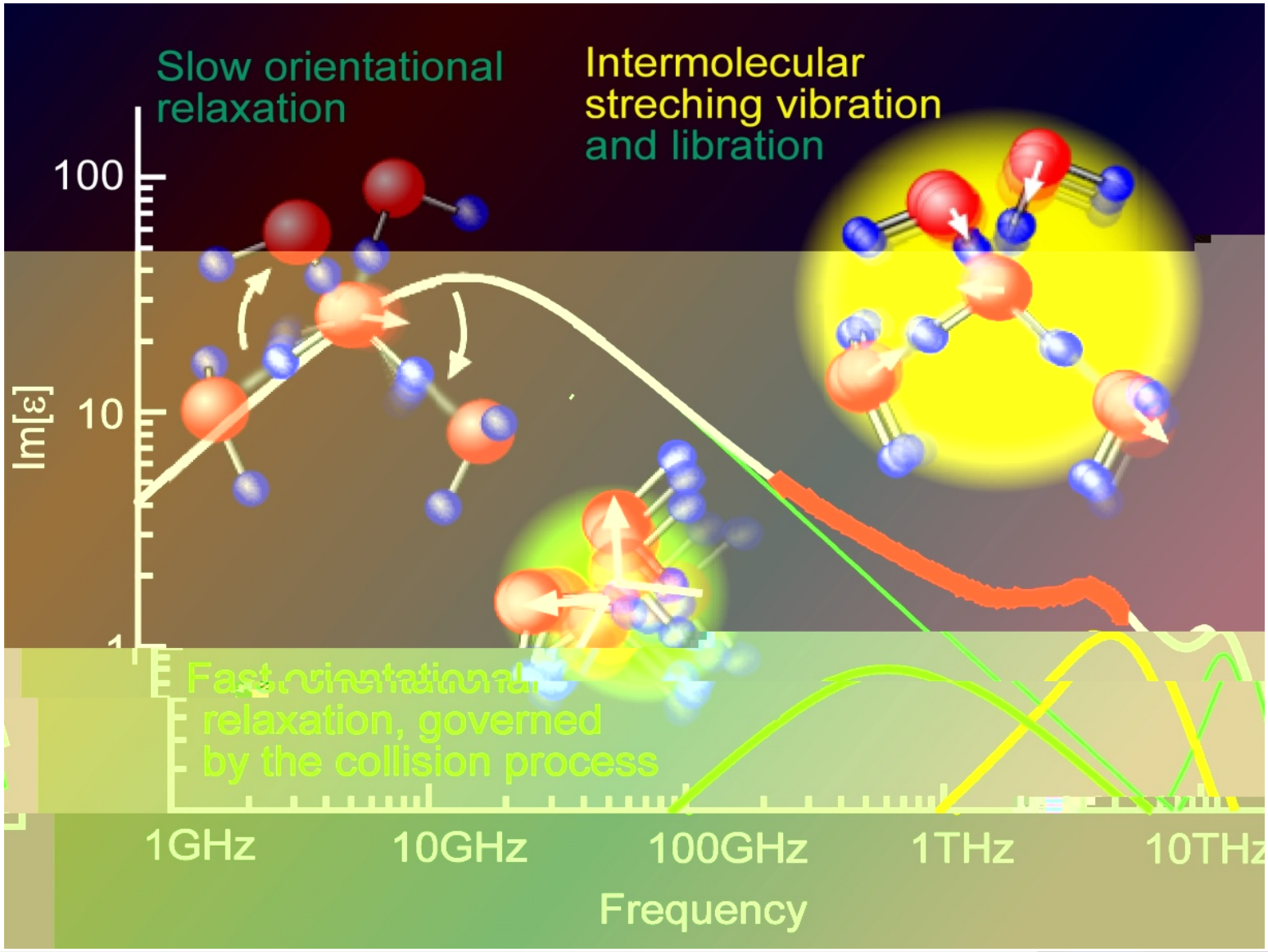


Targets to be controlled by Intense THz field

- ✓ Carrier dynamics in solids
- ✓ Spin dynamics
- ✓ Lattice dynamics
- ✓ Water dynamics



Water dynamics



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Phase matching condition

long interaction length → reasonable efficiency of generation and detection

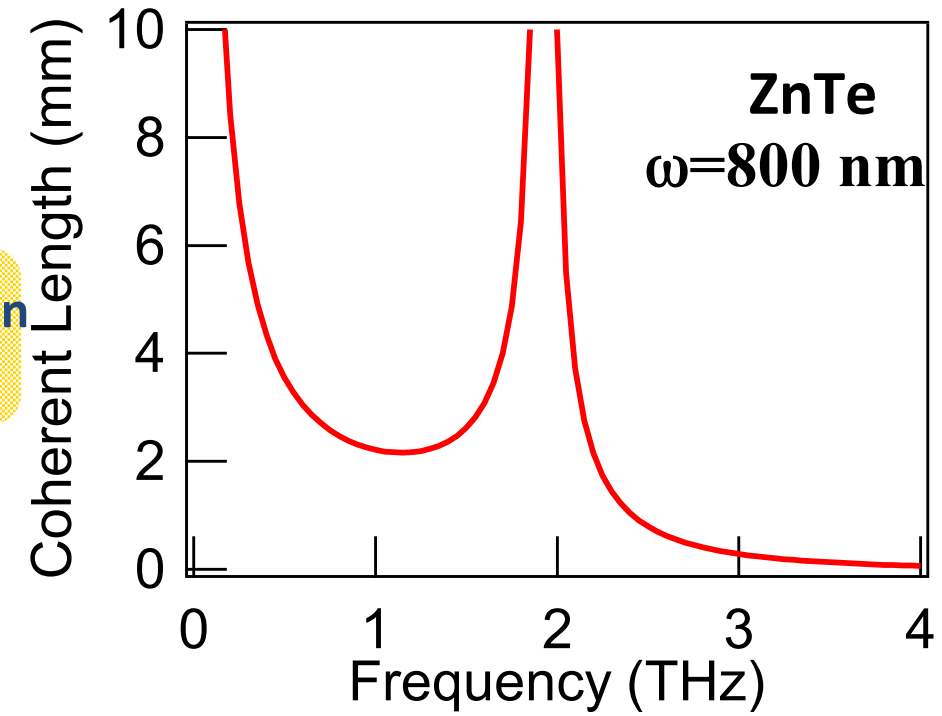
Phase match condition:

$$k(\omega+\Omega) - k(\omega) - k(\Omega) = 0$$

optical Index of group velocity = refractive index in THz region

$$n_g \sim n_{THz}$$

Naha a e al., APL 69, 2321 (1996).

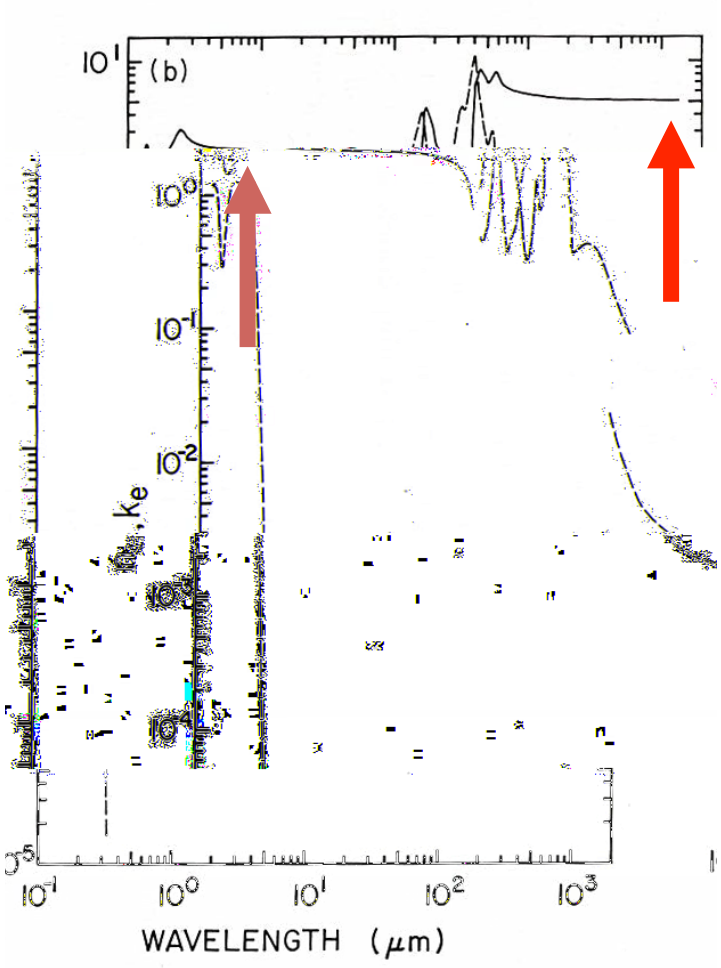


Coherent length:

$$l_c = \frac{c}{2f\left|n_{THz} - n_g\right|}$$

Refractive index in $LiNbO_3$

n_g~2.2

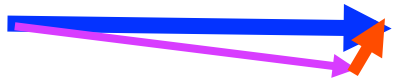


n_{THz}~5

"Handbook of Optical Constants of Solids",
edited by Edward D. Palik, Academic Press (1985).

THz wave generation in high χ^2 material

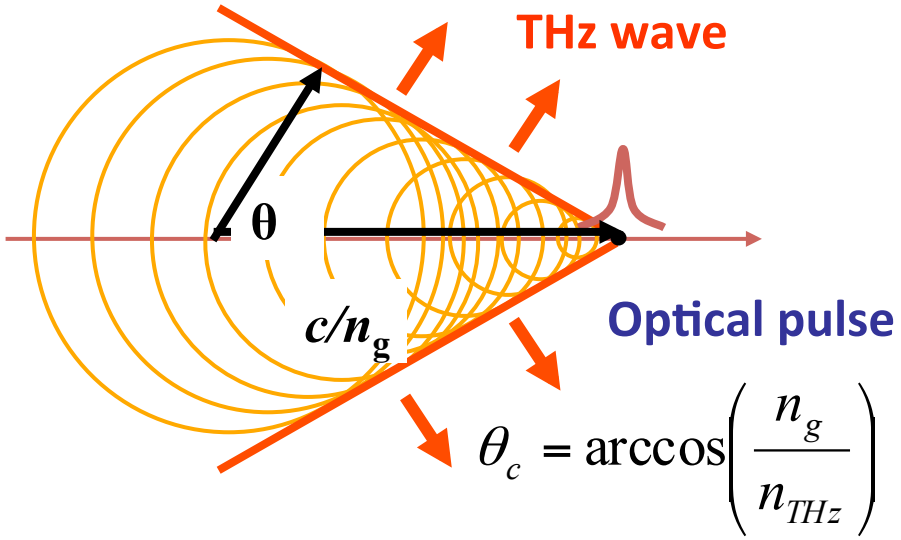
Non-collinear phase matching condition



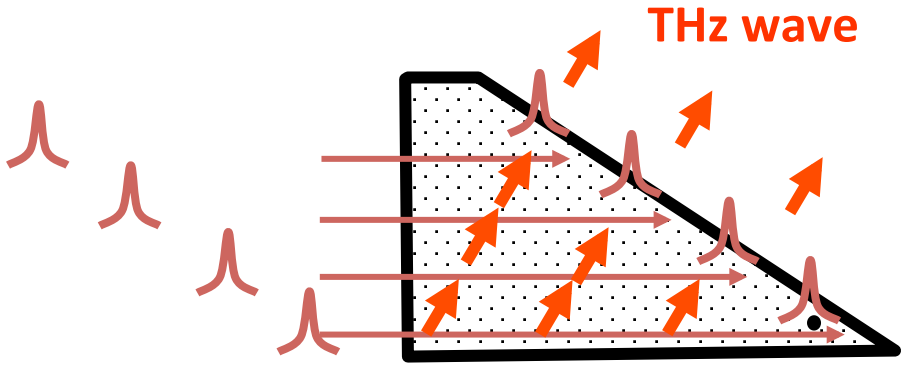
High χ^2 materials ($LiNbO_3$ and $LiTaO_3$)

$n_i << n_{TH}$ Phase match condition is not satisfied

$V_g^{vis} >> V_p^{THz}$



$$\theta_c = \arccos\left(\frac{n_g}{n_{THz}}\right)$$

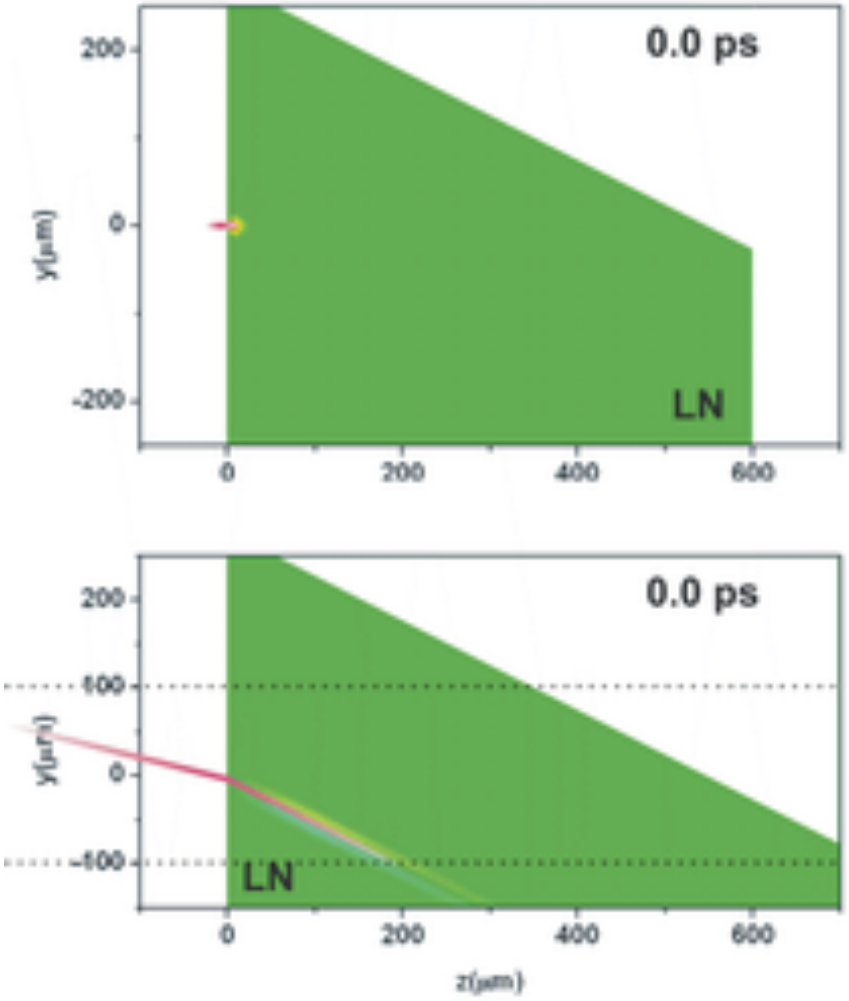


excitation pulse
with spatially tiled wavefront

High power THz pulse with 10μJ!

B. Bartal et al. Appl. Phys. B. 86, 419 (2007).

THz wave generation in high χ^2 material



Stepanov et al. Opt. Express (2005)

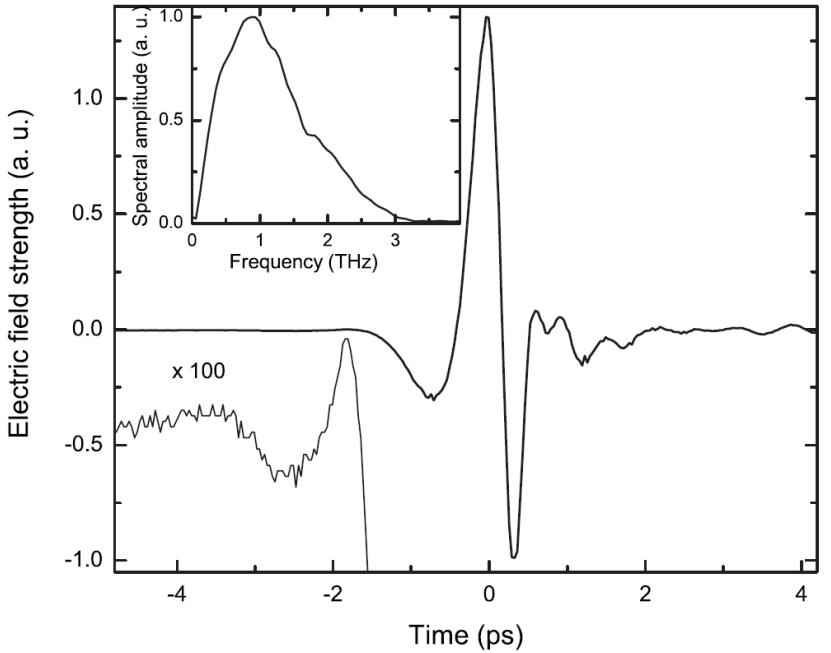
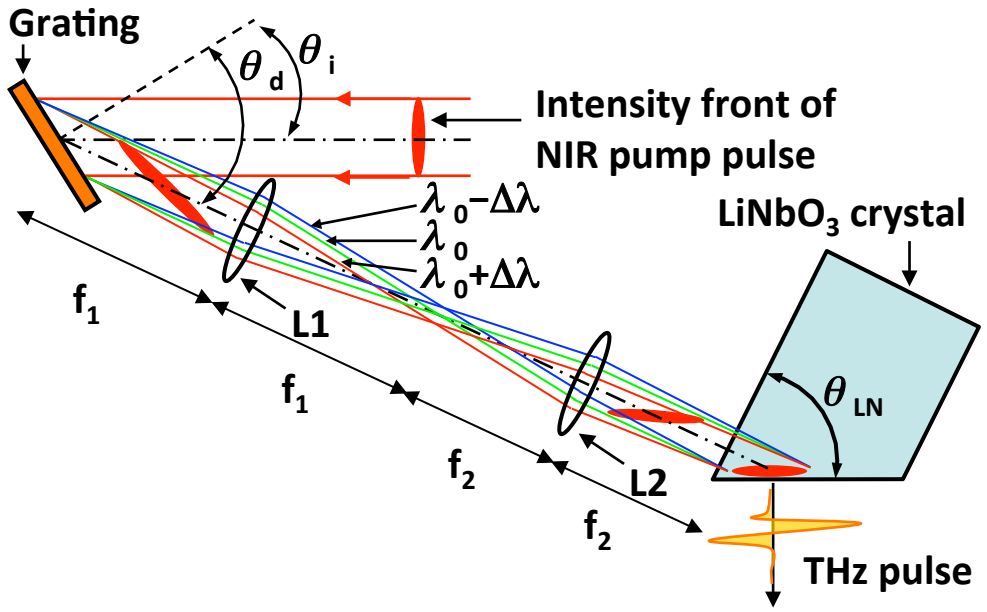


Fig. 12. Pulse shape of THz pulses generated at room temperature with a 1 kHz laser system and 6 mJ pump pulse energy. Insets, amplitude spectrum of the pulse, and beginning part of the temporal shape with 100 times vertical expansion.

Hebling, J. Opt. Soc. Am. B 25, 6 2008

New configuration for THz generation from LN

Set-up for LN-THz generation



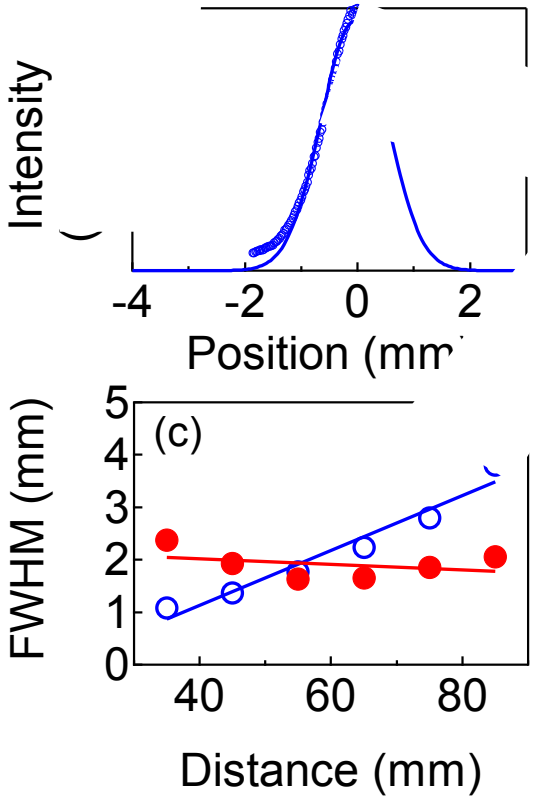
- Image of grating is parallel to the tilted pulse front for large area THz spot.

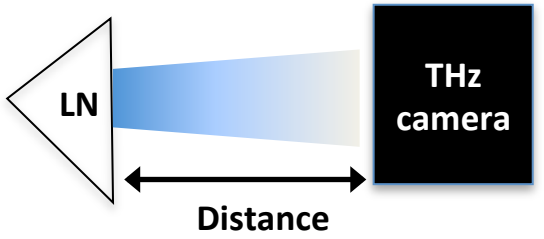
J. A. Fül p, J, Hebling, OE 18, 12311(2010).

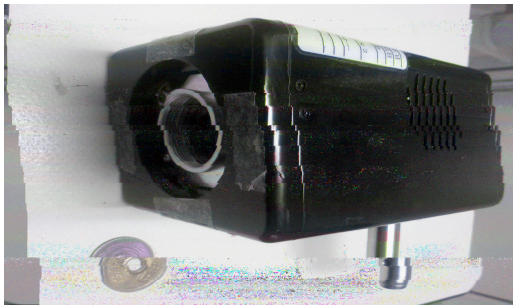
- 4-f configuration for making the different colors beam parallel in LN crystal. Generated THz at different positions are parallel each other.

Characterization of spatial THz pattern

Observed THz image with THz microbolometer camera (NEC)



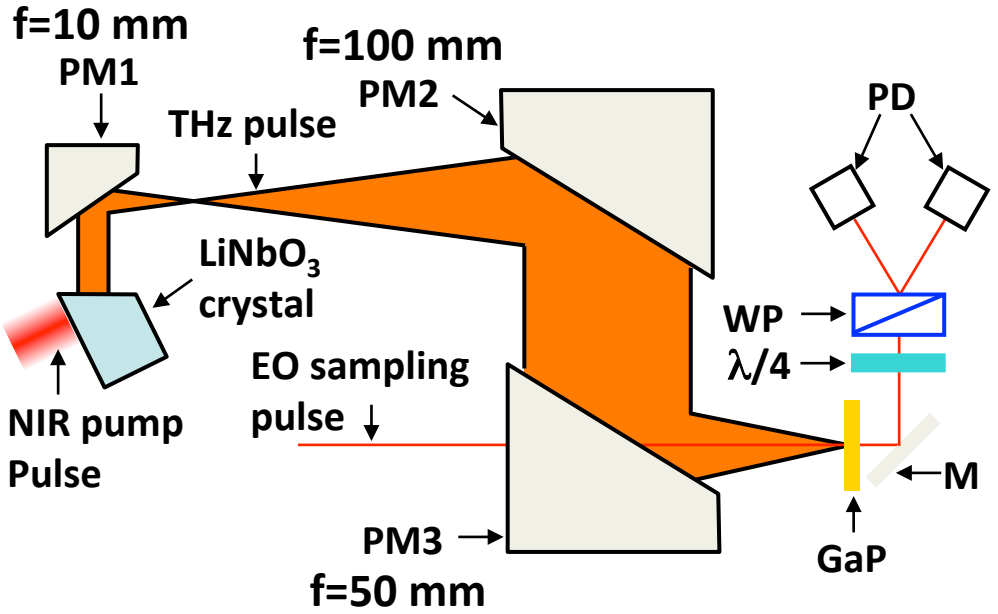




Almost collimated THz beam (2 x 3 mm spot size).

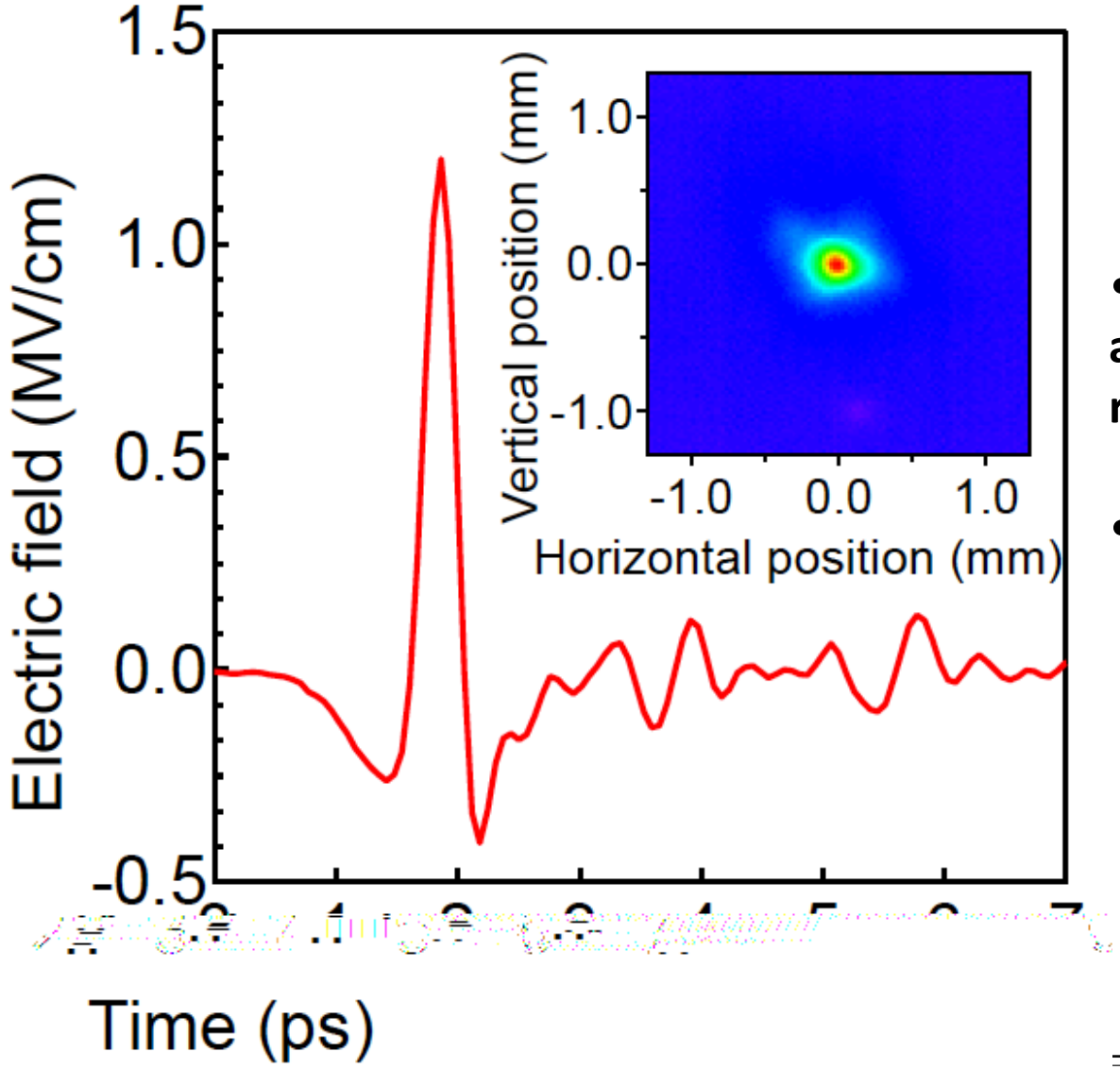
Tightly focused THz beam

Set-up for measurement of THz



- Expanding the collimated THz beam 10 times for making tightly focused spot.
- Oscillator sampling for avoiding the dull THz temporal profile due to the chirped EO sampling pulse.

H. Hirori et al., Appl. Phys. Lett., vol. 98, pp. 091106, 2011 .



- **Highest electric field amplitudes in this frequency region in the world**
- **Centered around 0.8 THz**

E_{THz} ~ 1.2 MV/cm
H_{THz} ~ 0.4 Tesla