

17A-2

# Real-time Two-dimensional Terahertz Tomography

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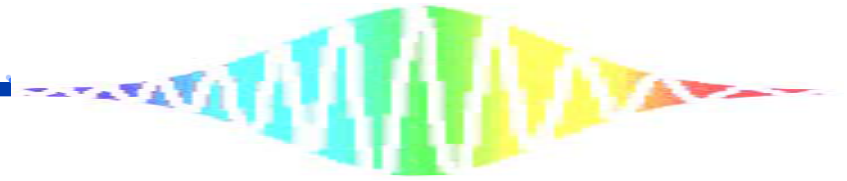
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Mr. Sawanaka  
(Osaka Univ.)

# Financial Support

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from the Ministry of Internal Affairs and Communications (MIC) of Japan  
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Industrial Technology Development Organization (NEDO) of Japan



# Outline

(1) Background

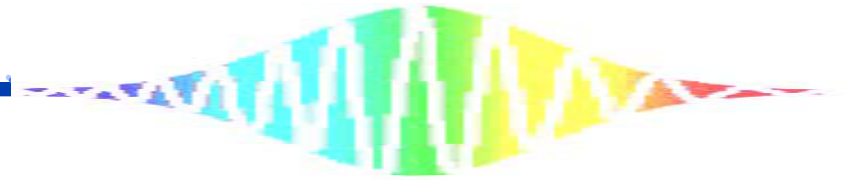
(2) Single-shot measurement of THz temporal waveform

(3) Real-time 2D spatiotemporal THz imaging for THz tomography

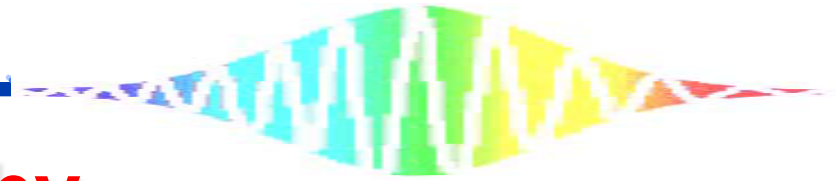
(4) THz tomographic movie of paint film

(5) Real-time THz-TDS imaging

(6) Summary



# (1) Background

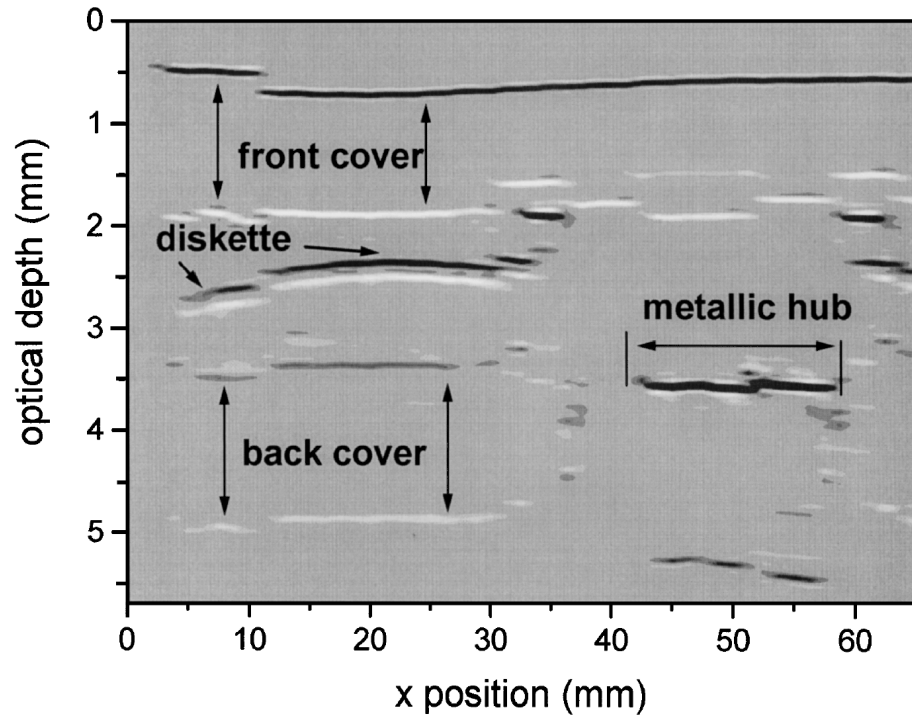


# THz tomography

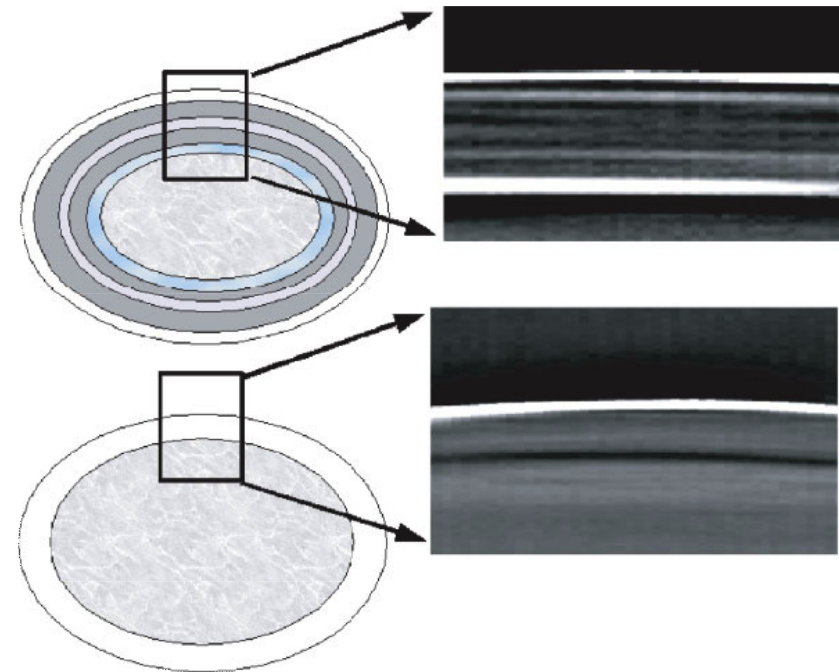
## Nondestructive inspection

alternative to “*invasive*” X-ray and “*contact*”  
ultrasound

### Floppy Disk



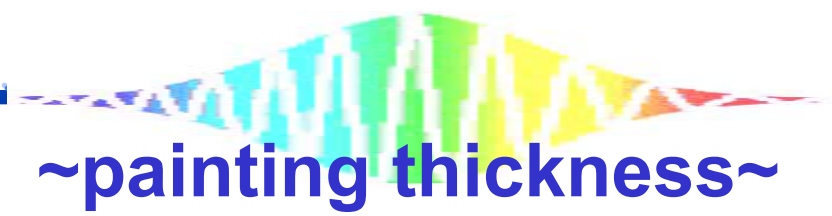
### Pharmaceutical coating



D.M.Mittleman et al. Opt. Lett. , Vol.22, p904(1997)

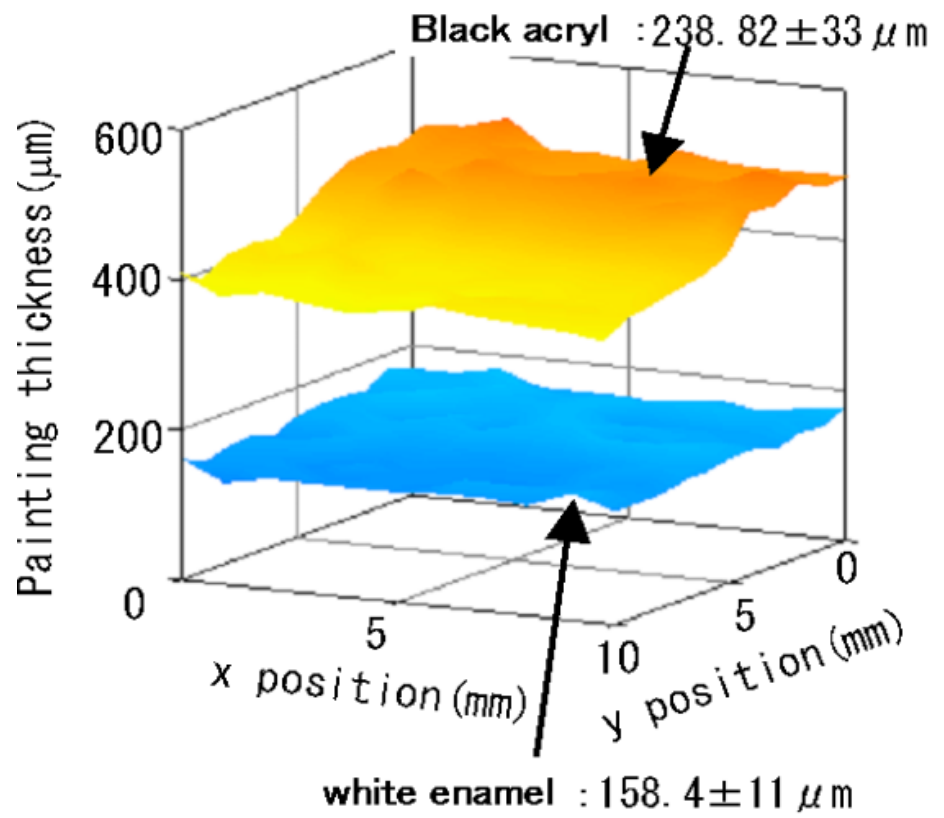
A. J. Fitzgerald et al. J. Pharmaceutical Sci. ,  
Vol.94, pp. 177 (2005).

# THz paintmeter (1)

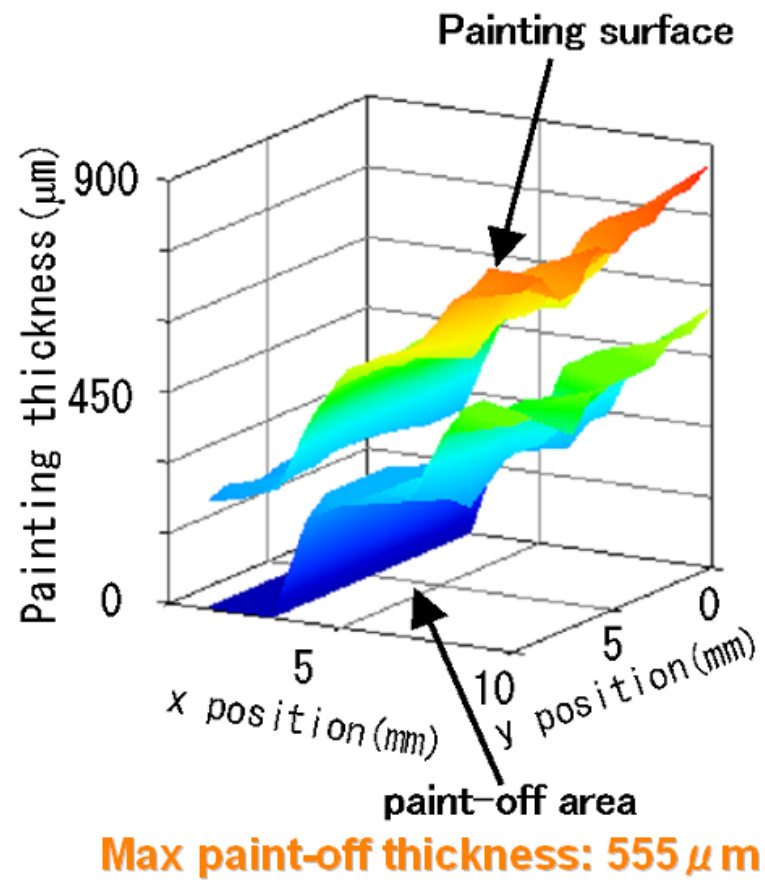


~painting thickness~

Multi-layer paint film



Paint-off film



thickness precision =  $4\mu\text{m}$ , thickness resolution =  $40\mu\text{m}$ , transverse resolution =  $1.7\text{mm}$

T.Yasui et.al., "A terahertz paintmeter for non-contact monitoring of thickness and drying progress in paint film," Appl.Opt., Vol. 44 (32), pp. 6489-6850 (2005)

# THz paintmeter (2)

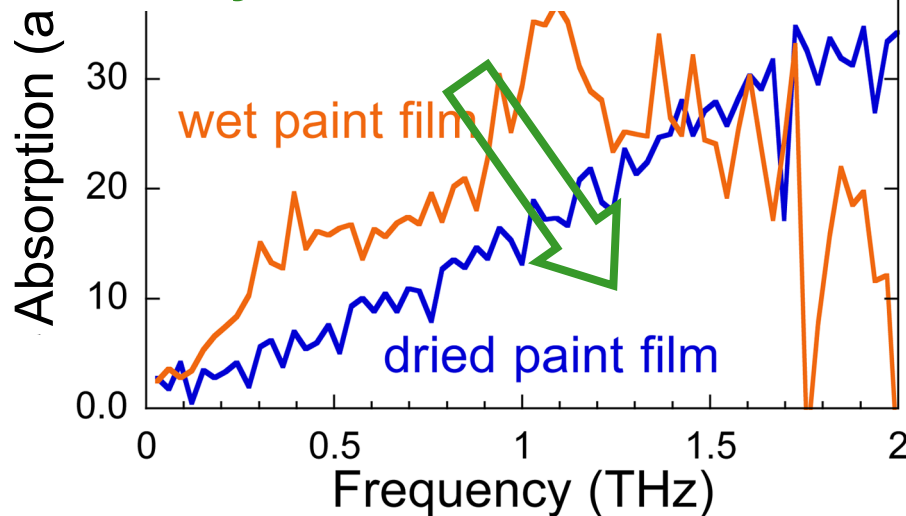
~drying degree~

## THz absorption spectra

@THz-TDS at transmittance configuration

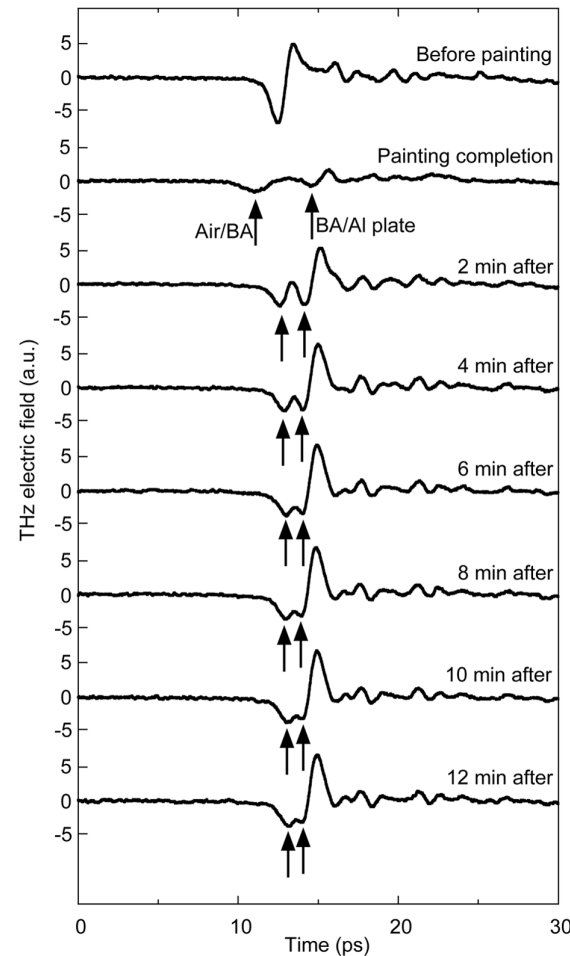
(Sample thickness = 900 $\mu$ m)

### Spectral change accompanying wet-to-dry transformation

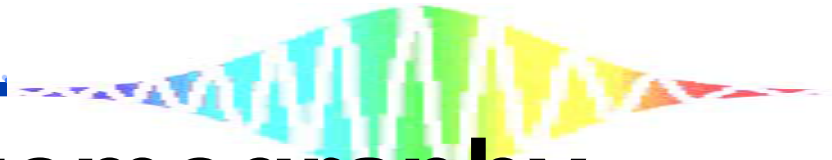


T.Yasui et.al., "A terahertz paintmeter for non-contact monitoring of thickness and drying progress in paint film," *Appl.Opt.*, Vol. 44 (32), pp. 6489-6850 (2005)

## Temporal change of THz echo signal before and after painting

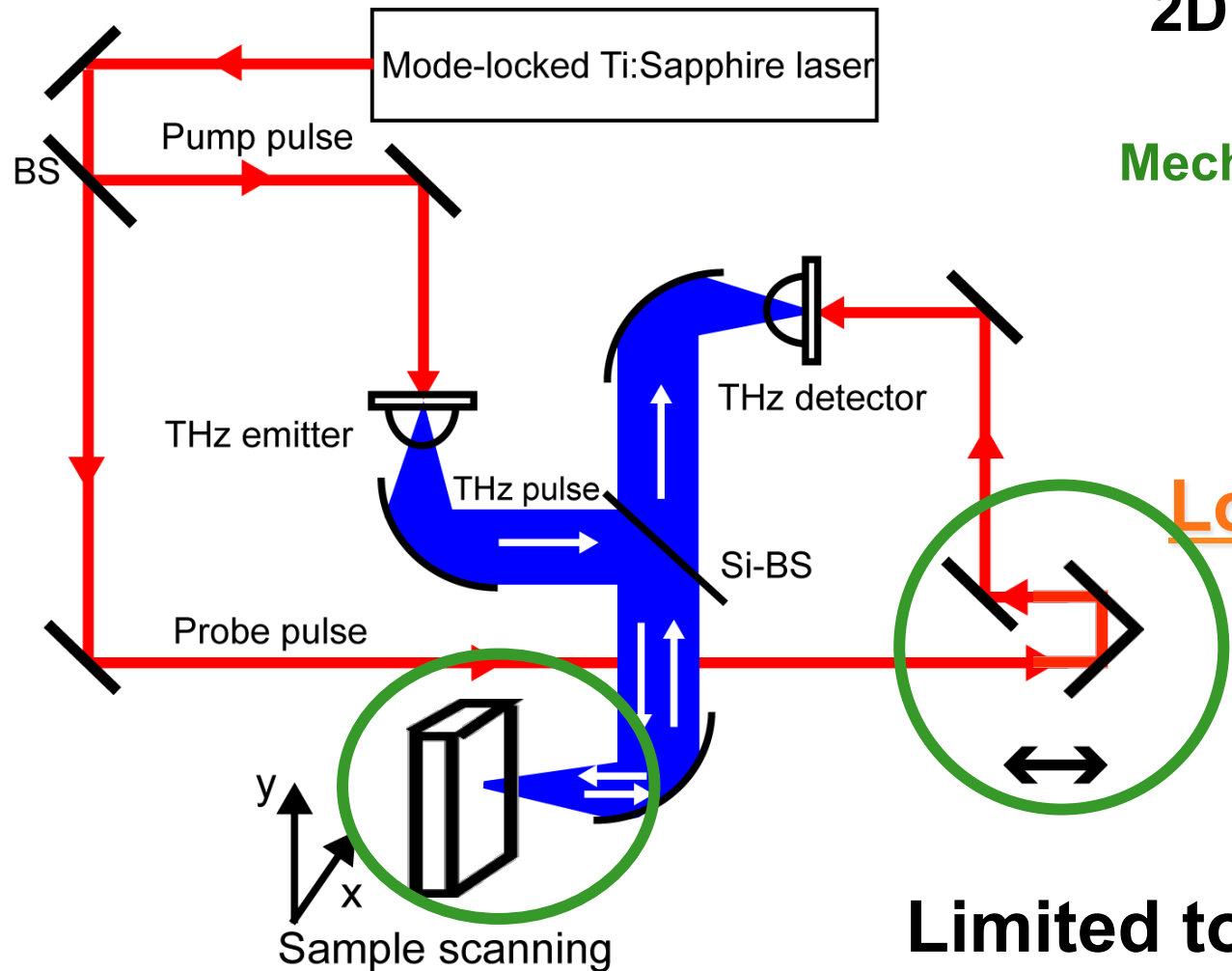


Attenuation, delay and distortion of THz echo



# Conventional THz tomography

(Point-to-point measurement)



2D tomographic image



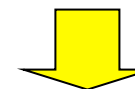
Mechanical scanning stages

- time delay
- sample position



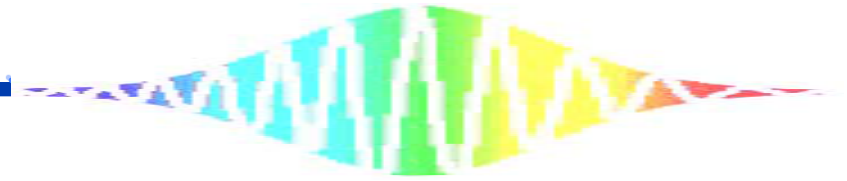
Long acquisition time

- A few minutes @temporal waveform
- Several hours @2D image



Limited to **stationary objects**





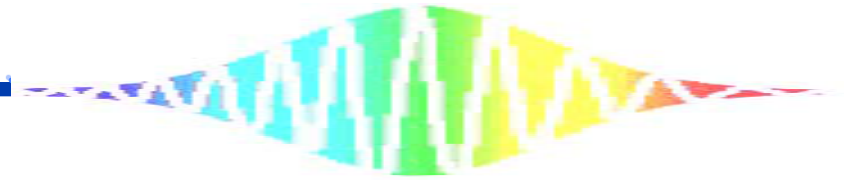
To extend THz tomography to **moving objects**, **real-time image acquisition** is strongly required !



**Omit any mechanical stages  
for time delay and sample position!**



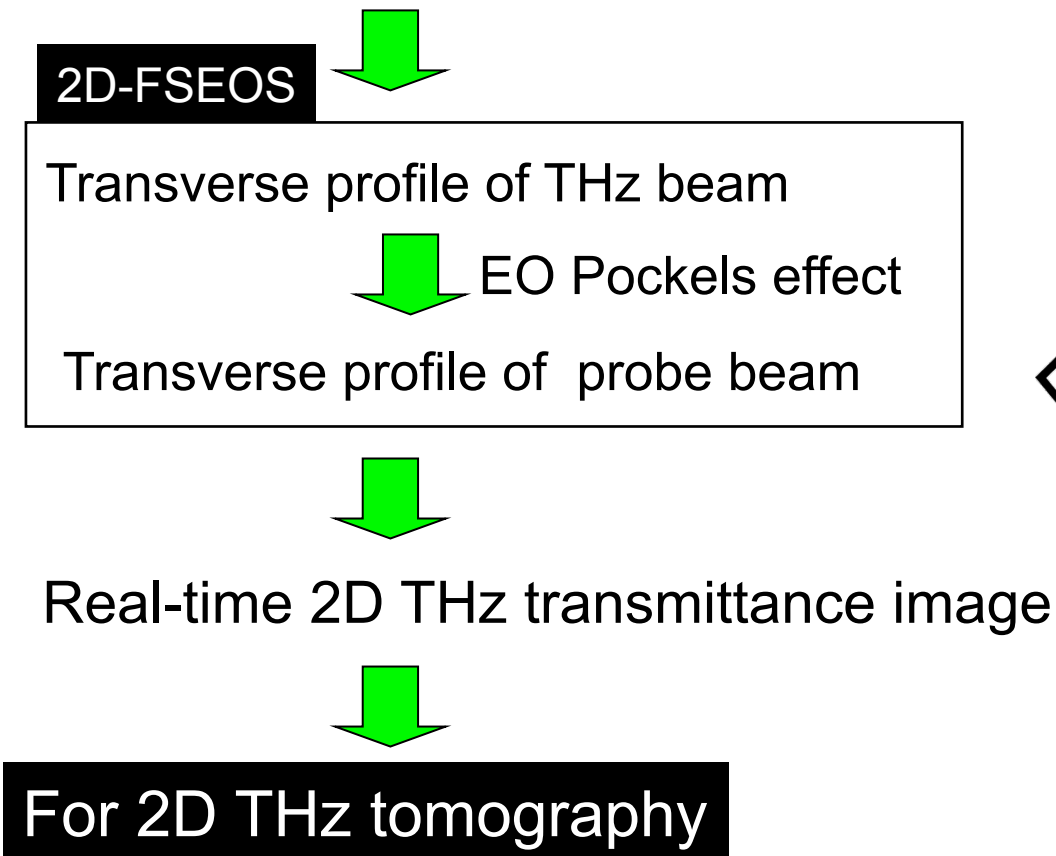
**Single-shot measurement of THz temporal waveform  
and its 1D transverse imaging**



## (2) Single-shot measurement of THz temporal waveform

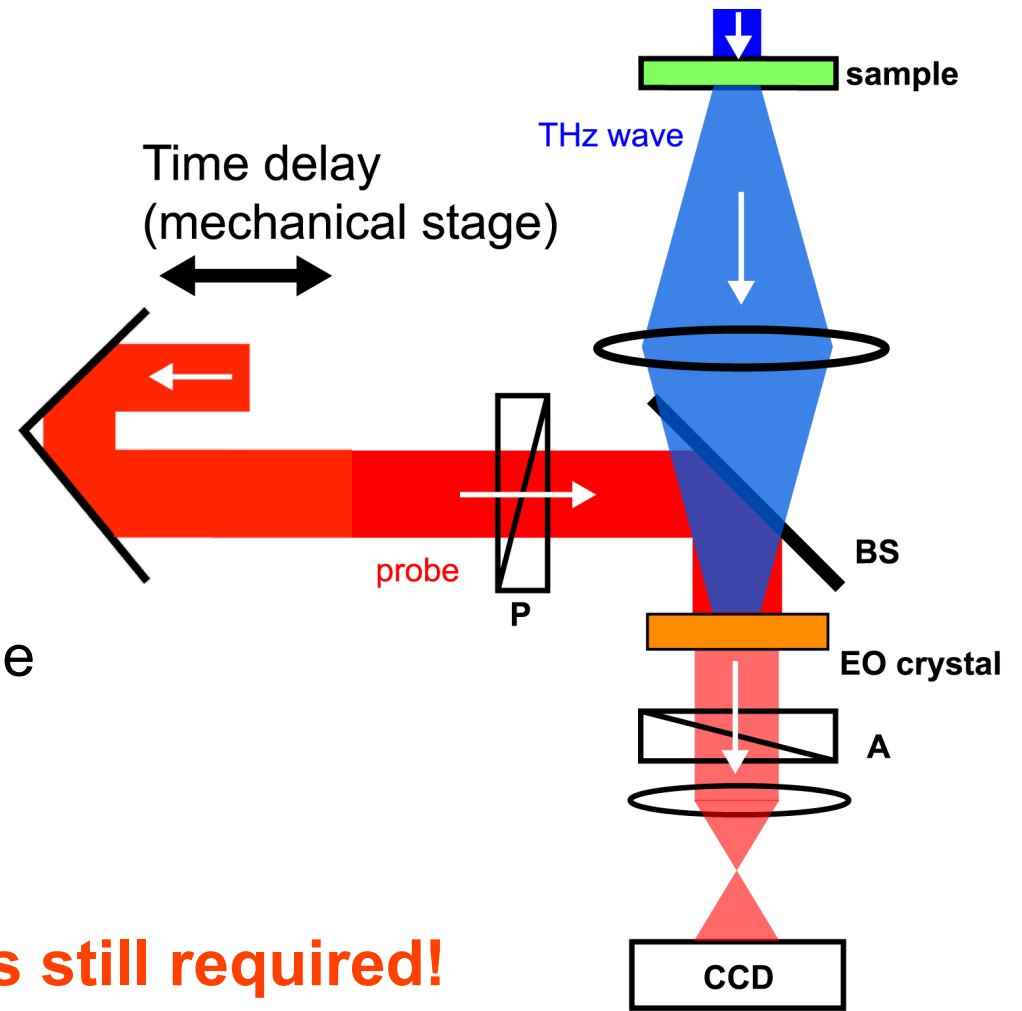
# 2D Free-Space EO-Sampling (2D-FSEOS)

**Collinear configuration**  
of THz beam and probe beam



**Mechanical time-delay scanning is still required!**

**→ Long measurement time**



# Single-shot measurement of THz temporal waveform based on 2D Free-Space EO-Sampling (2D-FSEOS)

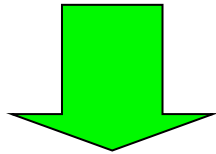
	Principle	Method
(1)	<b>Time-to-wavelength conversion</b> ref) Z. Jiang et al, APL, Vol.73, pp. 1945 (1998).	Chirped probe pulse Multi-channel spectrometer
(2)	<b>Time-to-space conversion</b> ref) Z. Jiang et al, APL, Vol.24, pp. 1245 (1999).	Long probe pulse Streak camera
(3)	<b>Time-to-space conversion</b> ref) J. Shan et al, OL, Vol.25, pp. 426 (2000).	<b>Non-collinear 2D-FSEOS</b> <b>1D photodiode array</b>

Because of simple configuration without any expensive apparatuses, the method (3) is suitable for **single-shot measurement and its 1D transverse imaging (real-time 2D spatiotemporal THz imaging)**.

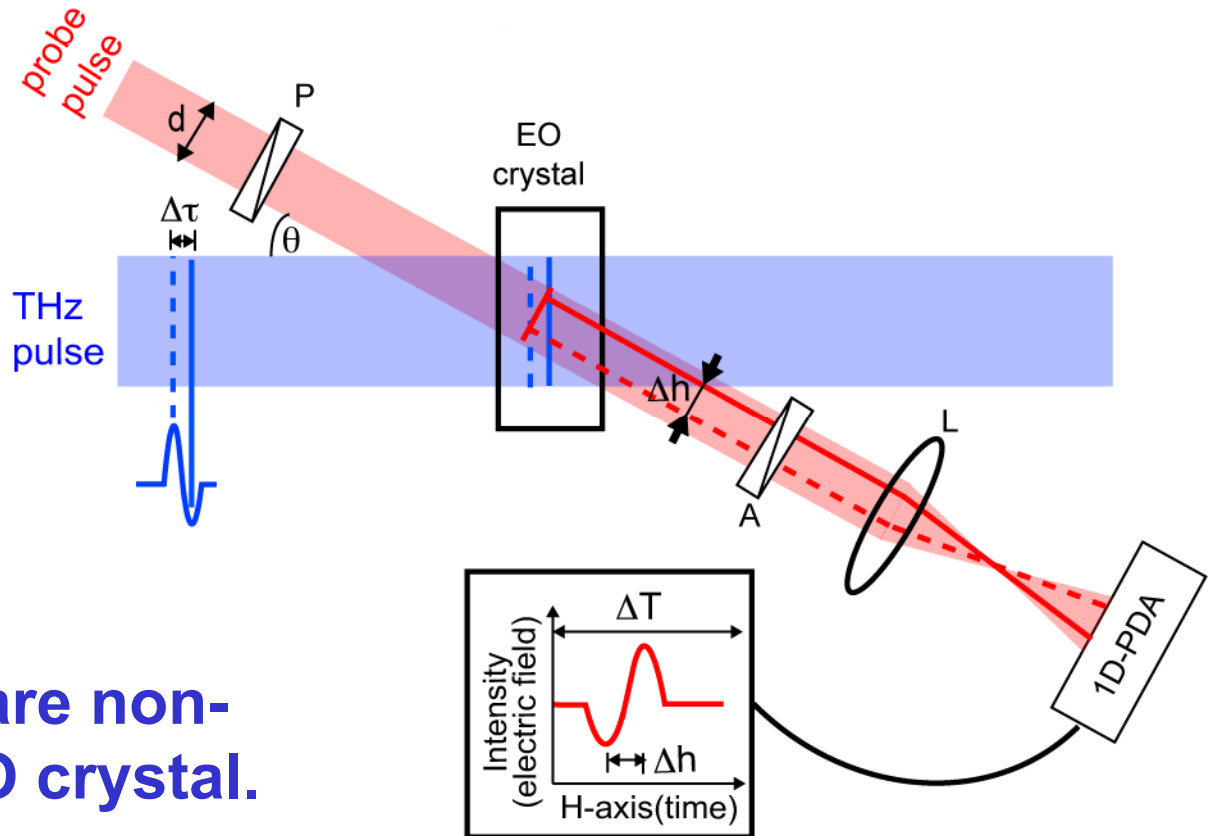
# Non-collinear 2D-FSEOS

ref) J. Shan et al, OL, Vol.25, pp. 426(2000)

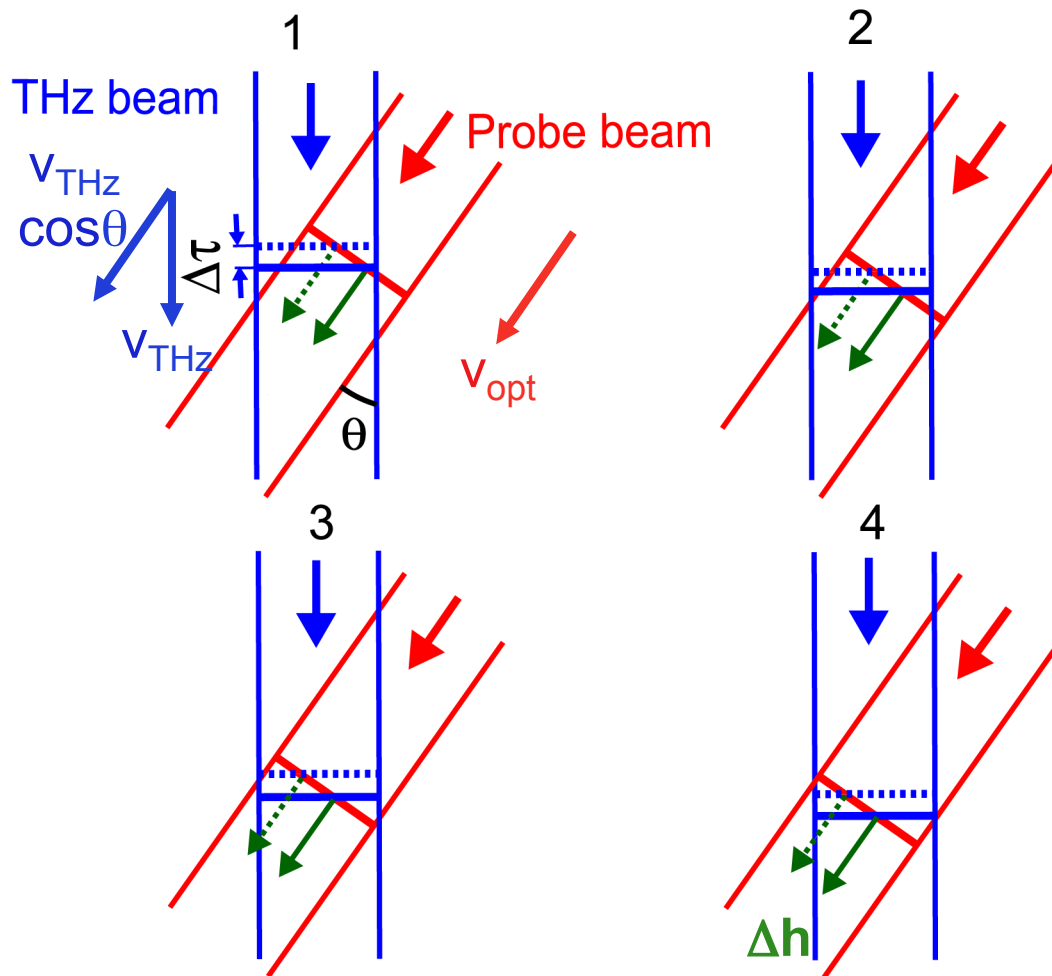
**Non-collinear configuration**  
of THz beam and probe beam



**Wavefronts in two beams are non-collinearly overlapped in EO crystal.**



# Propagation of THz and probe beams in EO crystal



Two different wavefronts of THz beam overlap with a wavefront of probe beam on different transverse position of probe beam.

$$V_{\text{opt}} = V_{\text{THz}} \cos \theta$$

Overlapping of each wavefront keeps the same transverse position during propagation in EO crystal.

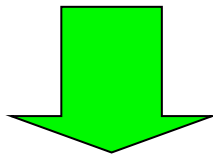
**Time delay  $\Delta \tau$  is converted into spatial distribution  $\Delta h$ .**

$$\Delta \tau = \frac{\Delta h \tan \theta}{c}$$

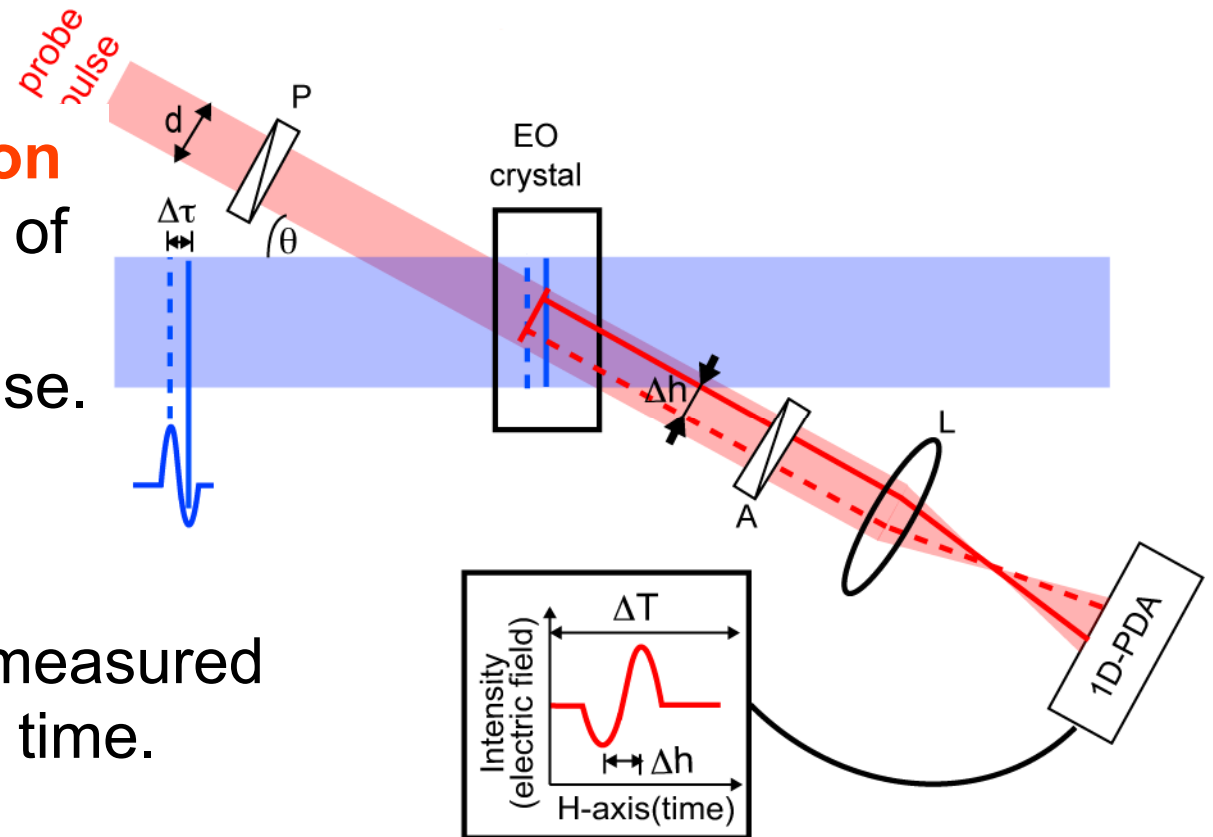
# Non-collinear 2D-FSEOS

ref) J. Shan et al, OL, Vol.25, pp. 426(2000)

**EO time-to-space conversion**  
modulates spatial distribution of  
probe beam depending on  
temporal waveform of THz pulse.



**Temporal waveform** can be measured  
as a position signal at real time.



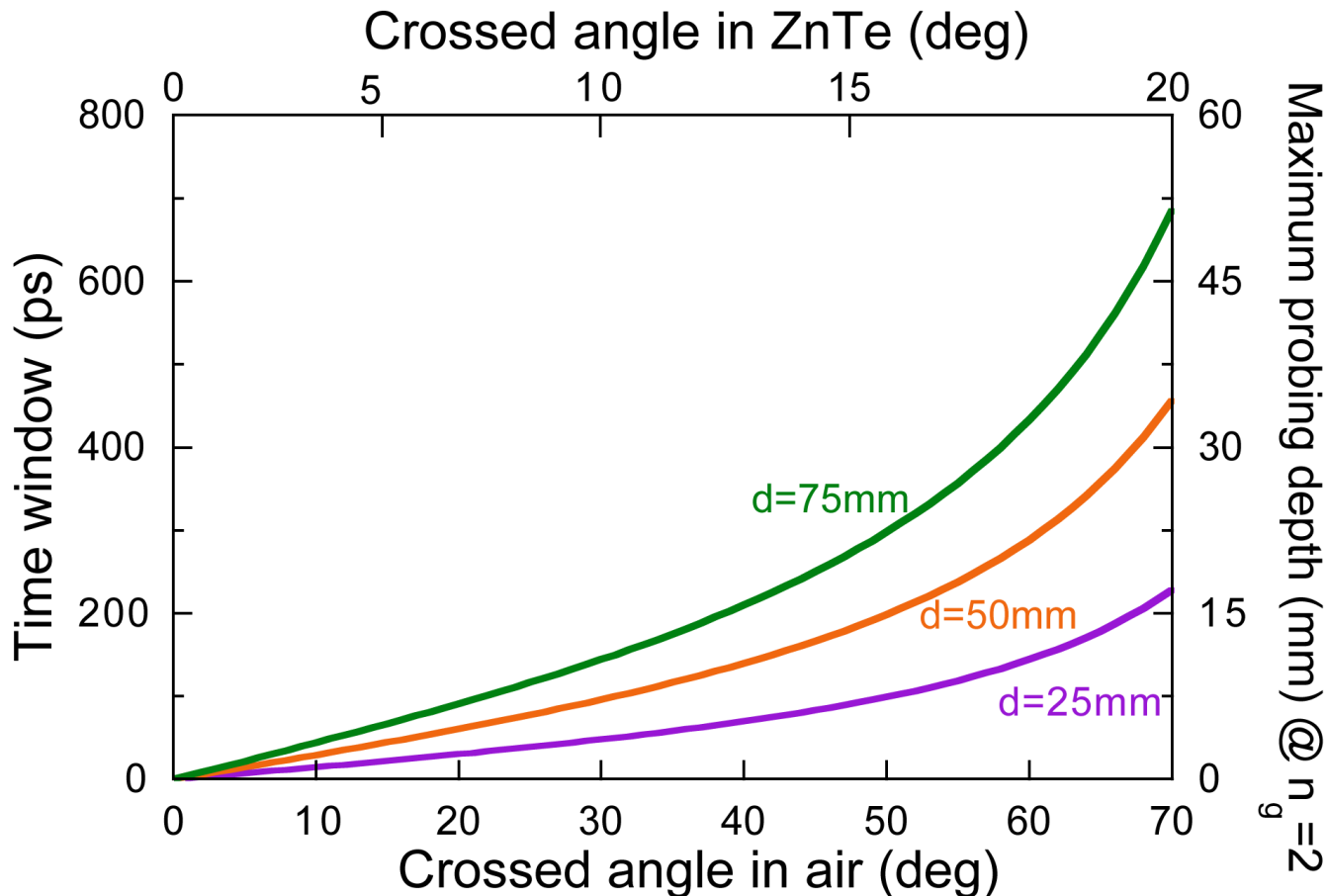
# Time window and maximum probing depth

**Time window**

$$\Delta T = \frac{d \cdot \tan \theta}{c}$$

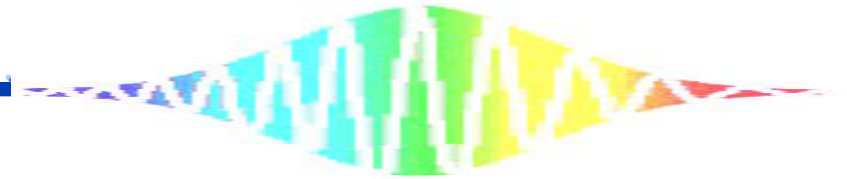
**Maximum Probing depth**

$$MPD = \frac{c \Delta T}{2n_g}$$



d: diameter of probe pulse  
 $\theta$ : crossed angle of two beams in air  
 c: velocity of light in vacuum  
 $n_g$ : group refractive index

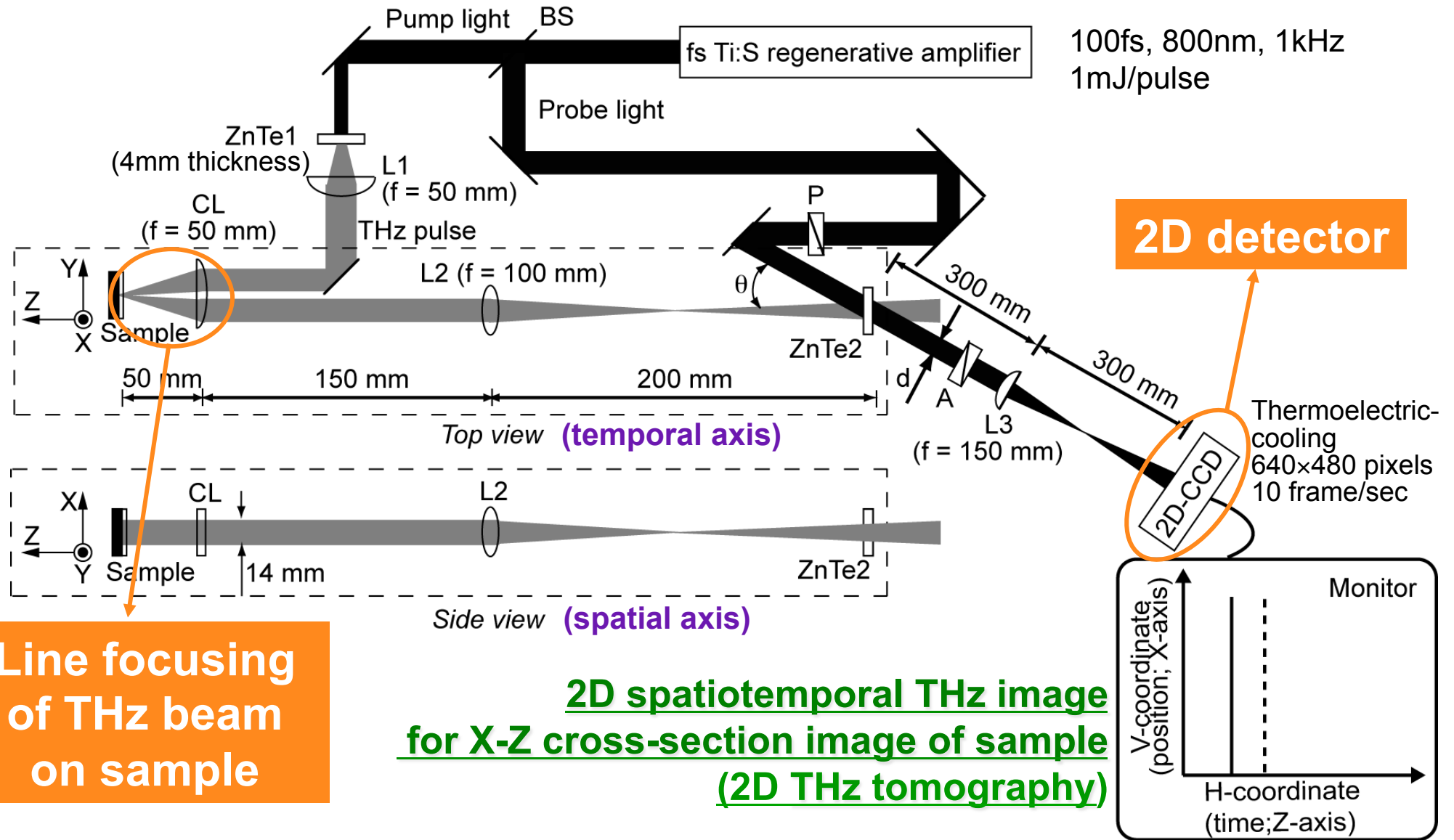




## (3) Real-time 2D spatiotemporal THz imaging for THz tomography



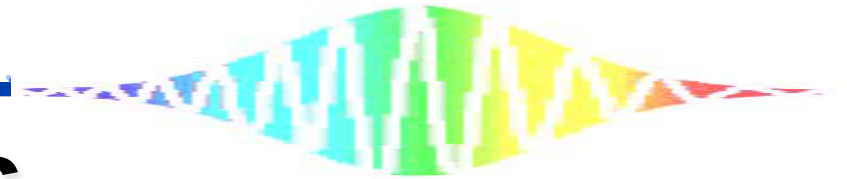
# Experimental setup of real-time 2D THz tomography





# Performance of present system

CCD camera	Resolution	12 bit
	Temperature	-15 °C by thermoelectric cooling
	Size	640*480 pixels
	Frame rate	10 frame/s
2D spatiotemporal THz image	Temporal window	9 ps or 6 ps
	Spatial window	5 mm
	Width of focus line	1 mm
	Spatial resolution	1.5mm @ 1THz
	Dynamic range	71dB



# Features

## (1) Slight modification of usual 2D-FSEOS

- Collinear → Non-collinear
- Line focusing of THz beam on sample

## (2) Single-shot measurement

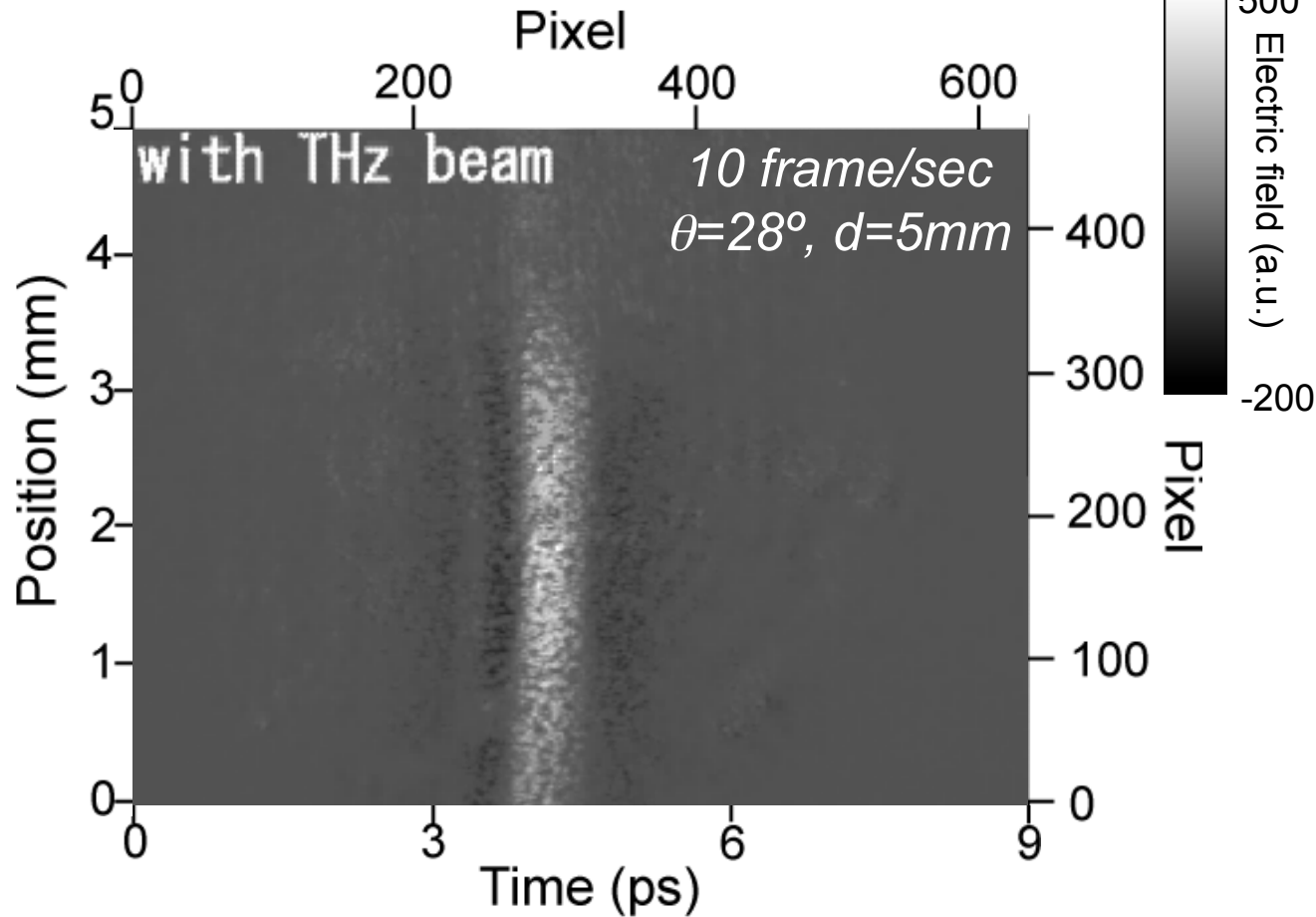
- Frame rate up to a laser repetition rate is possible
- Suppress effect of pulse-to-pulse fluctuation in amplified fs pulse
- Improve signal-to-noise ratio

## (3) Applicable to moving objects

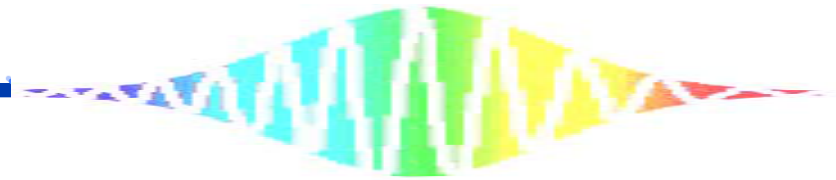
- On-line products (e.g., industrial products on moving stage)
- Human body

# 2D spatiotemporal THz movie of metal mirror surface (9ps×5mm)

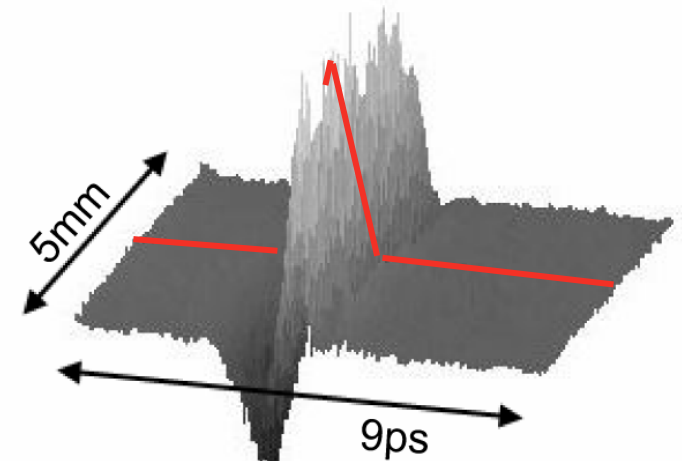
(Subtracted CCD image from BG noise image)



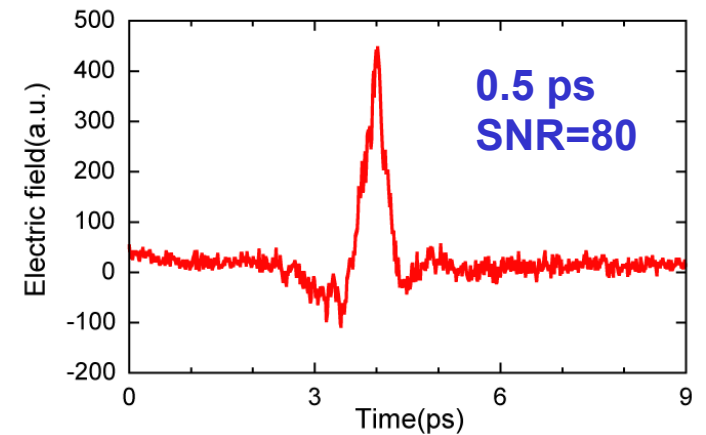
**Time increment = 14 fs/pixel**

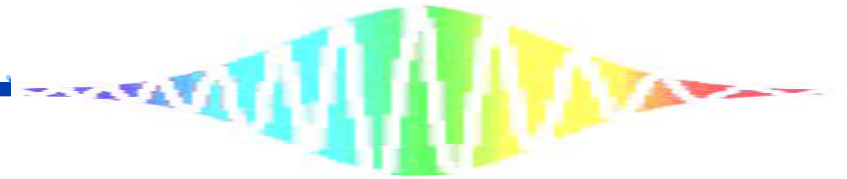


3D distribution



Temporal waveform





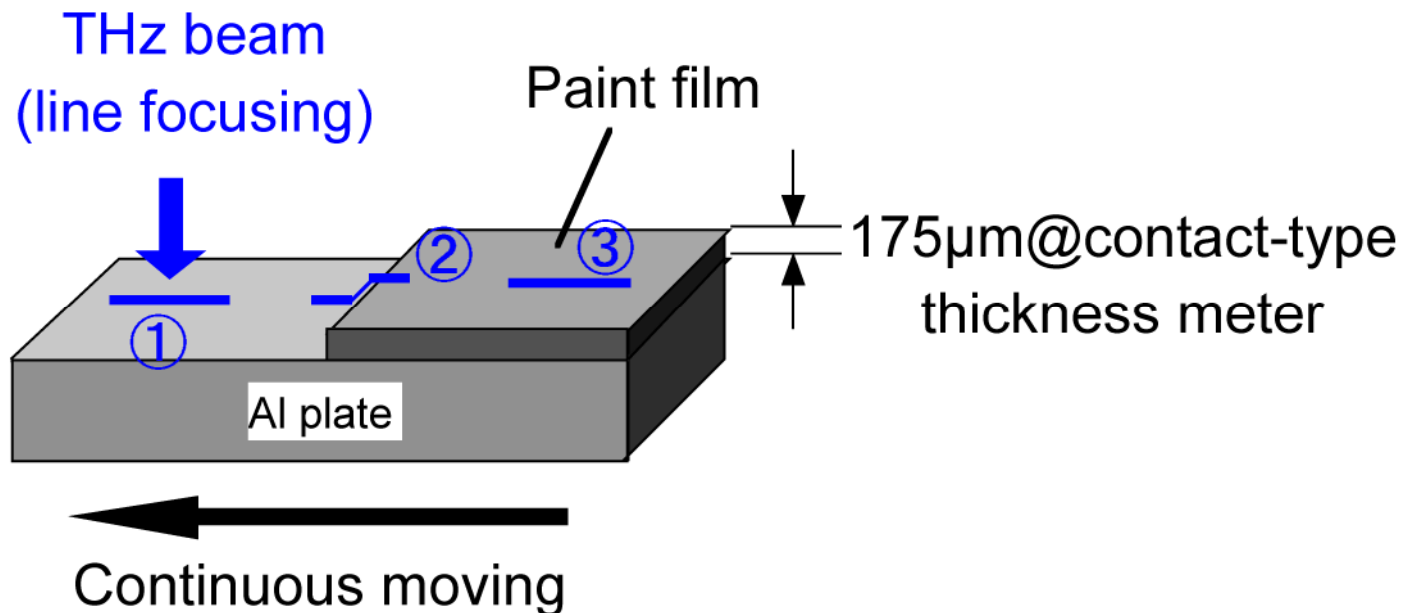
# (4) THz tomographic movie of paint film



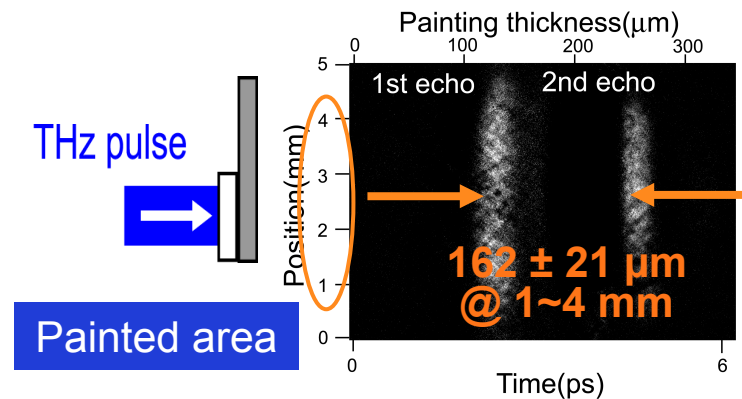
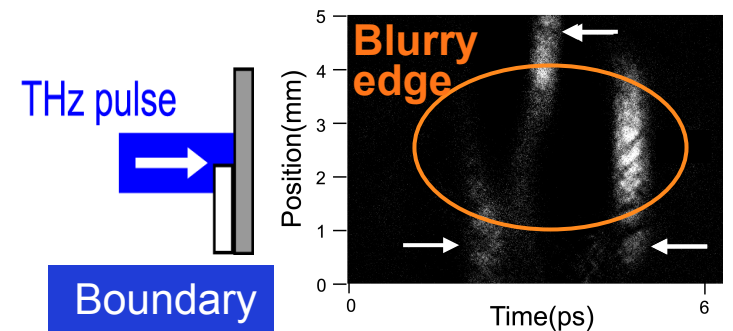
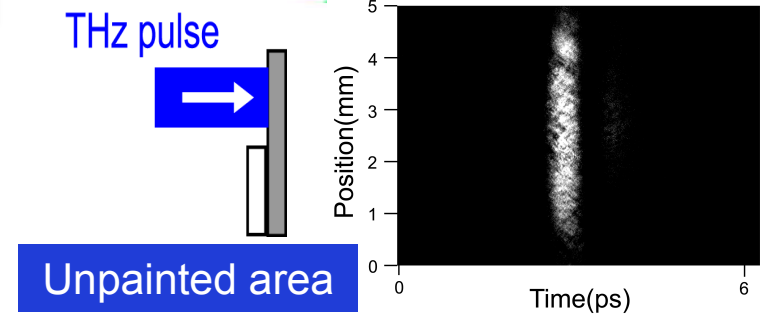
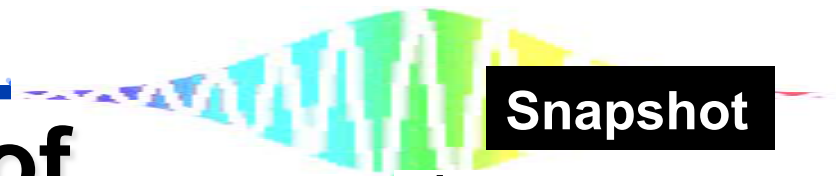
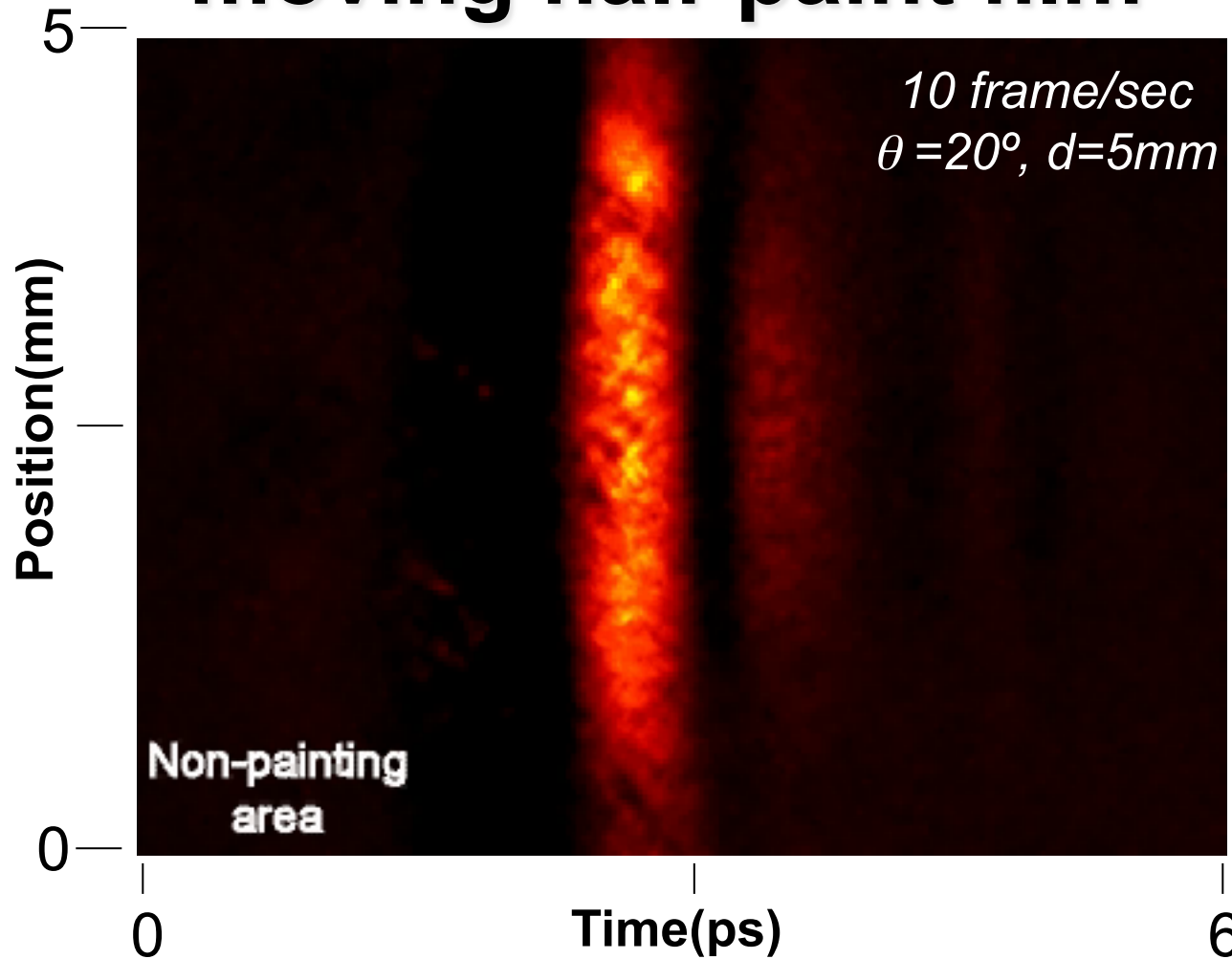
# Real-time 2D THz tomography of moving paint film

~ in-process THz paintmeter for moving object ~

- Sample : half-paint film on metal plate  
(thickness=175 $\mu\text{m}$ @contact-type thickness meter)
- Continuous moving of a paint sample  
(moving speed = 5 mm/s)



# THz tomographic movie of moving half-paint film



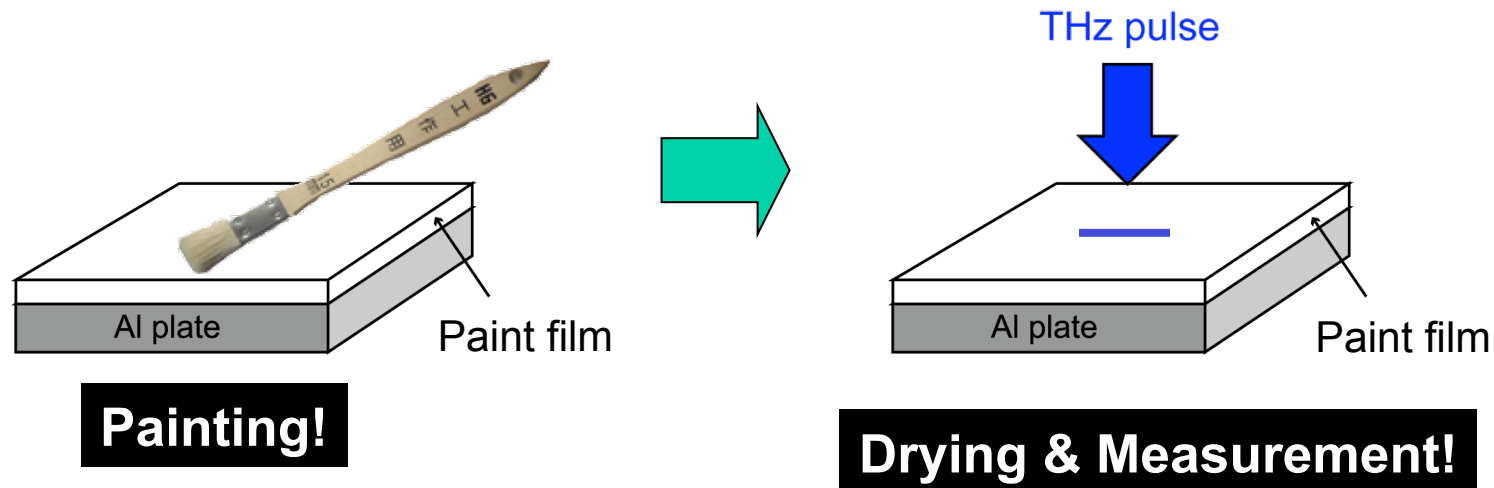
First demonstration of real-time THz tomography of moving object



# Real-time 2D THz tomography of wet paint film

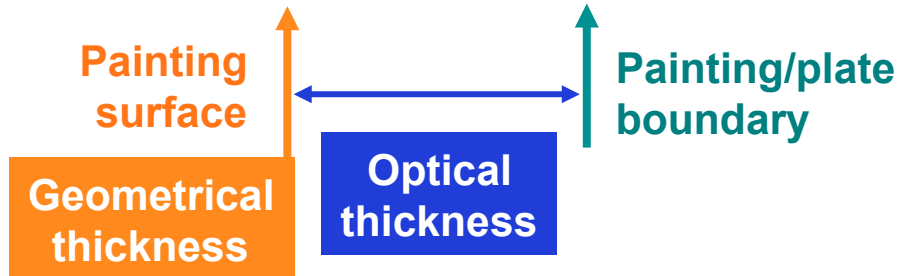
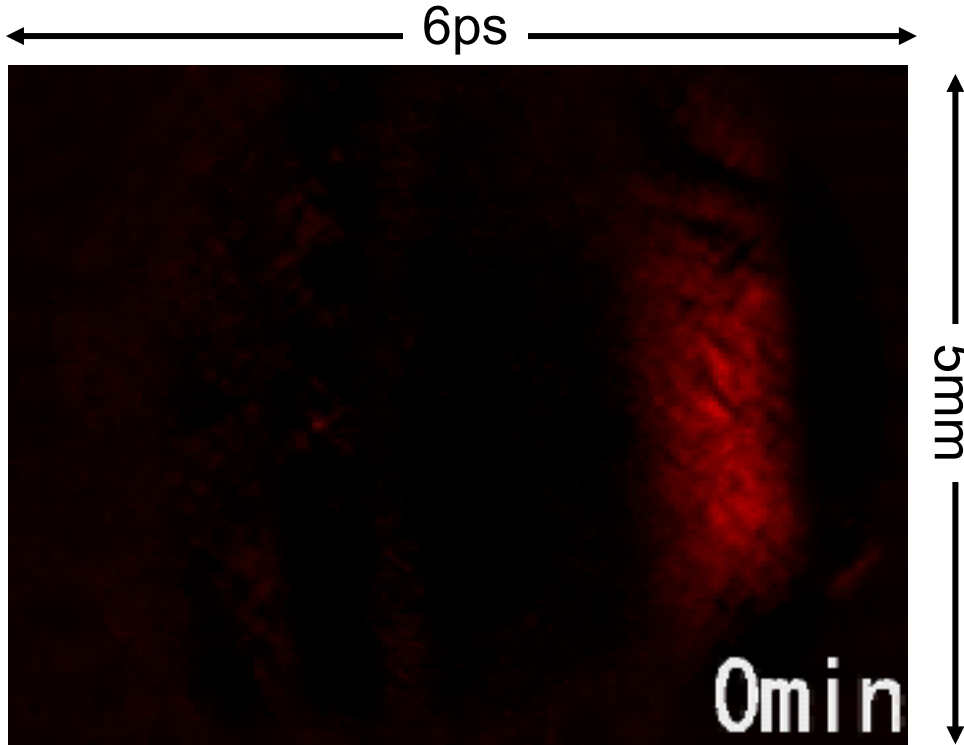
~ in-process THz paintmeter for monitoring of drying progress ~

- Sample : quick-drying paint film on Al plate

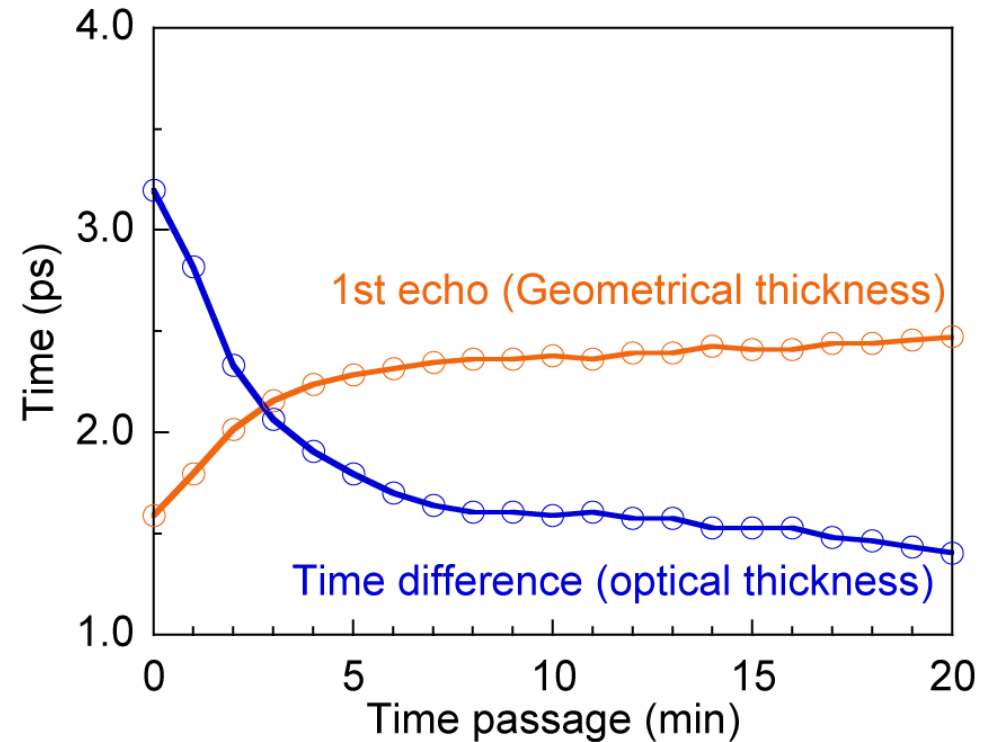


# THz tomographic movie of drying progress

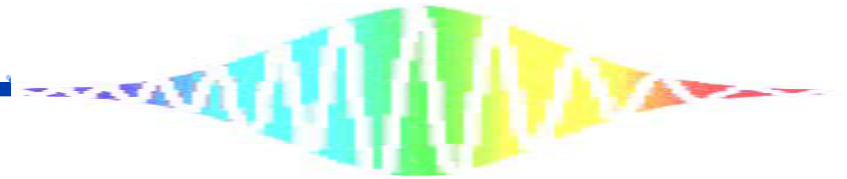
Quick movie (20min)



Temporal change of THz echo

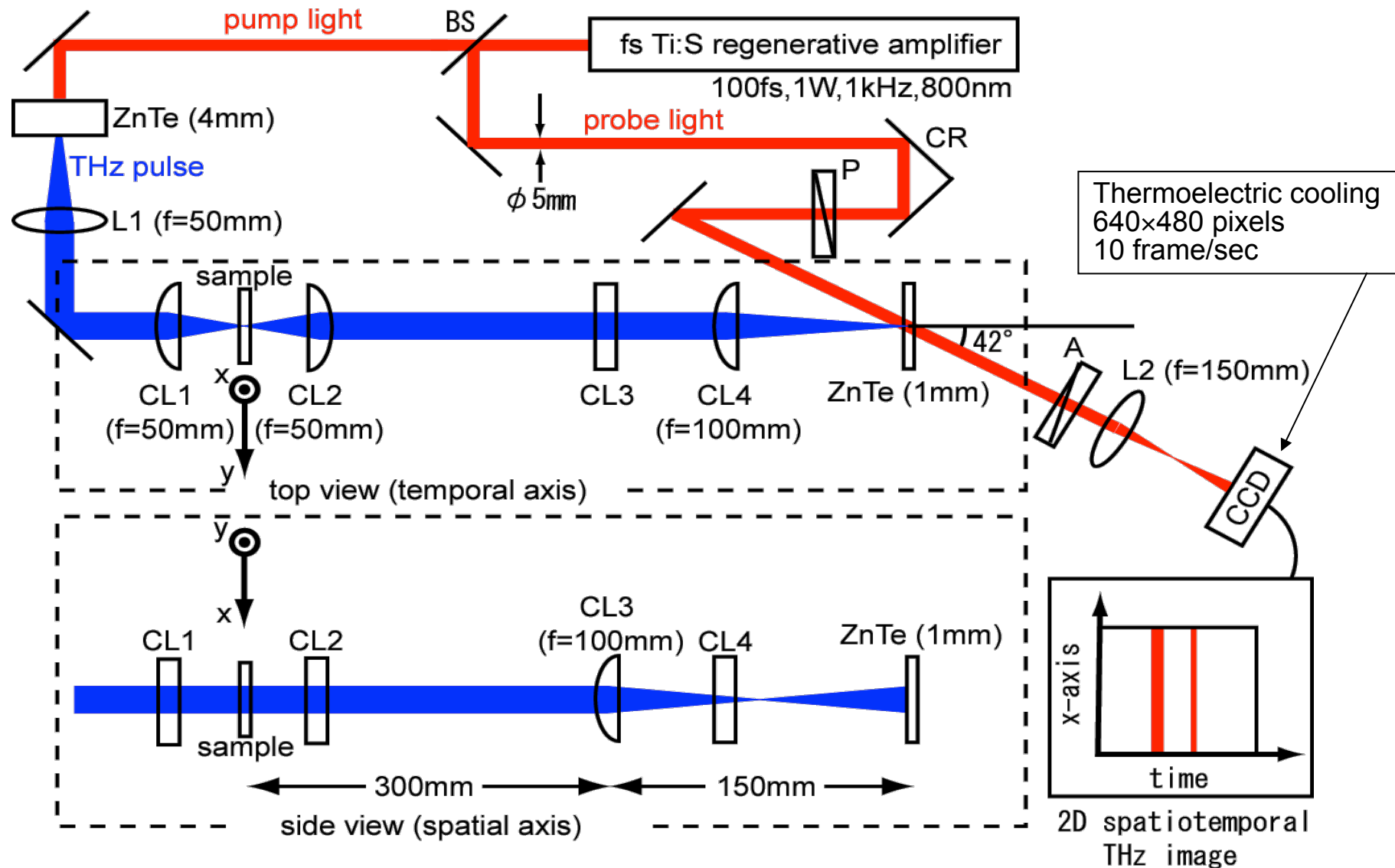


**Geometrical and optical shrinking of paint film through wet-to-dry transformation**

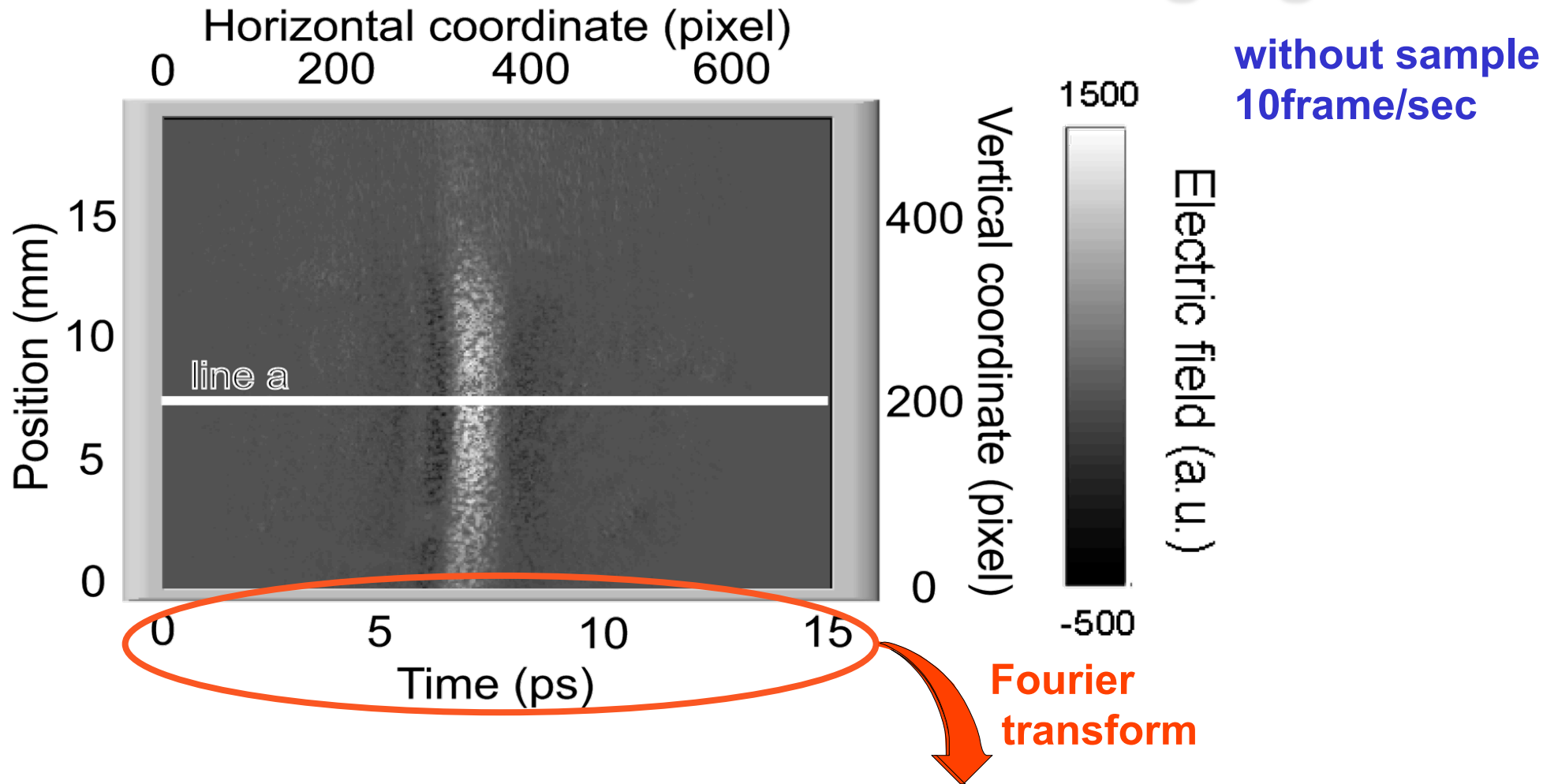


## (5) Real-time THz-TDS imaging

# Experimental setup of real-time THz-TDS imaging



# 2D spatiotemporal THz image (15ps\*19mm) for real-time THz-TDS imaging

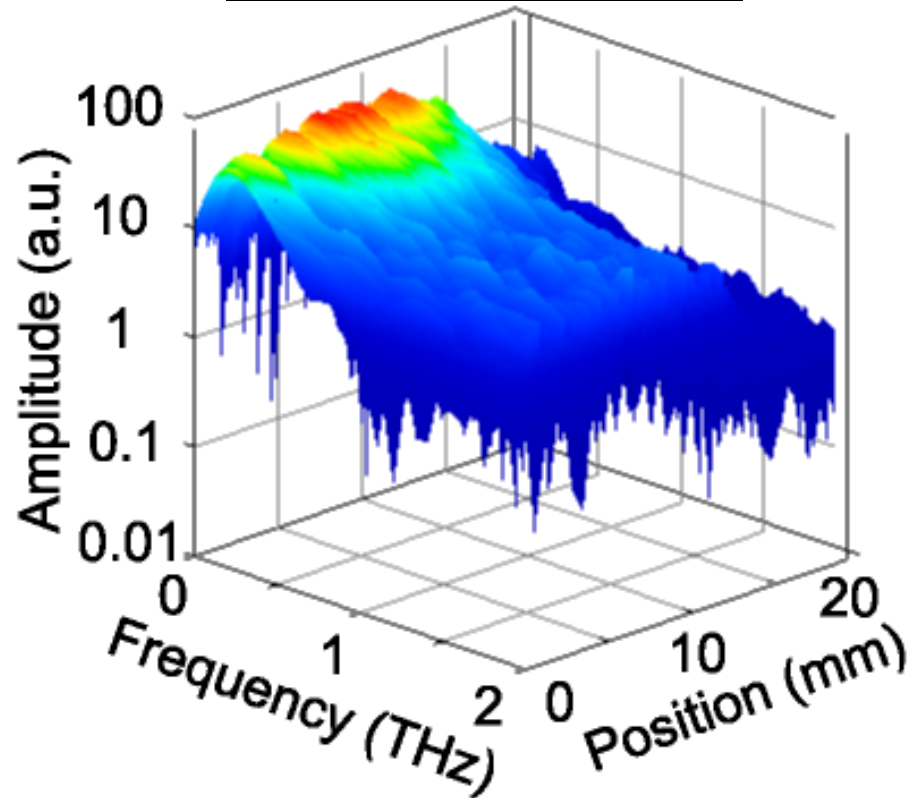


THz-TDS line image

# Real-time THz-TDS line image

without sample  
@ 100ms

Amplitude image



Phase image

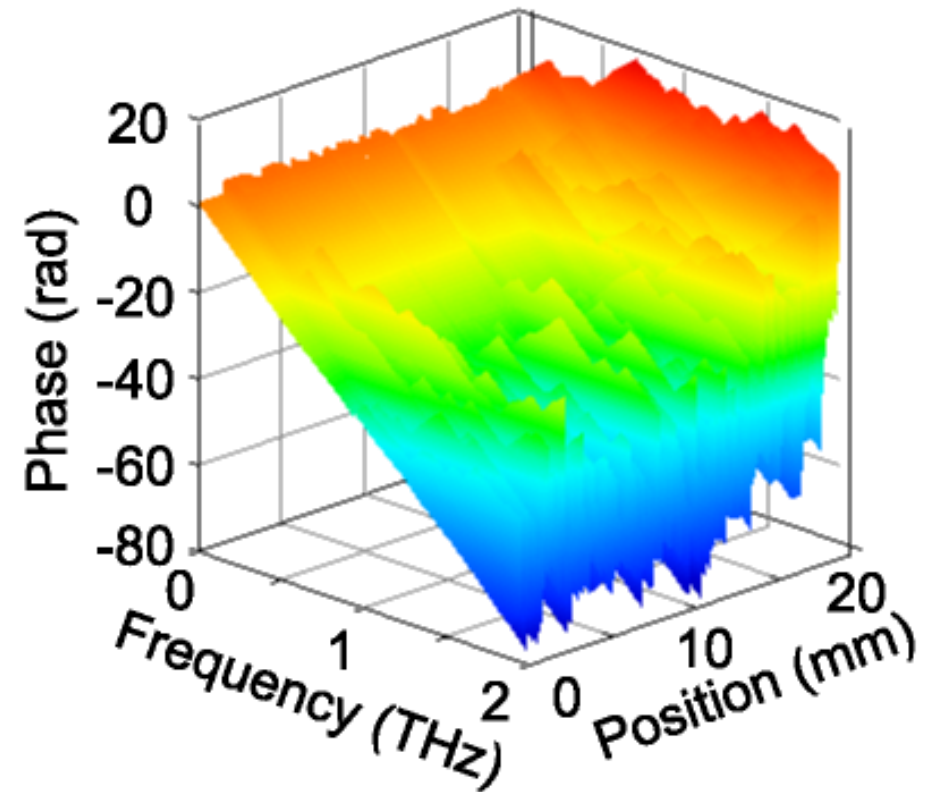
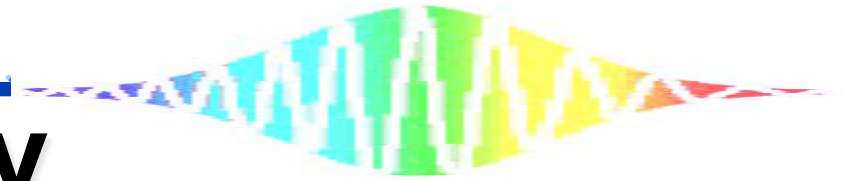


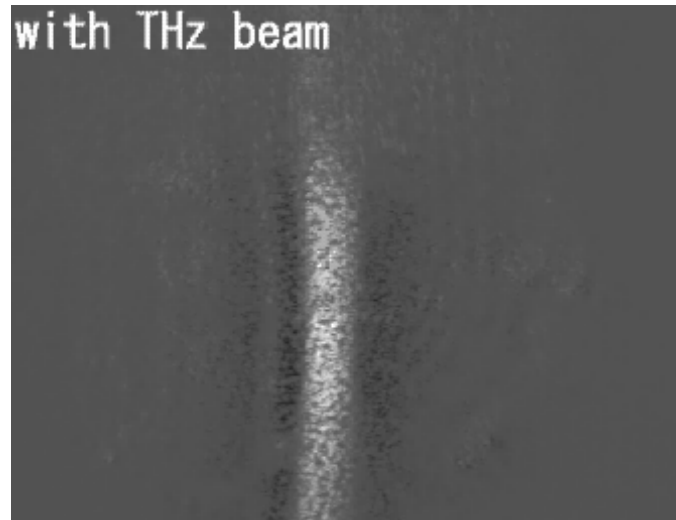
Image size: 1THz × 19mm

Frequency resolution = 67GHz @ time window = 15 ps

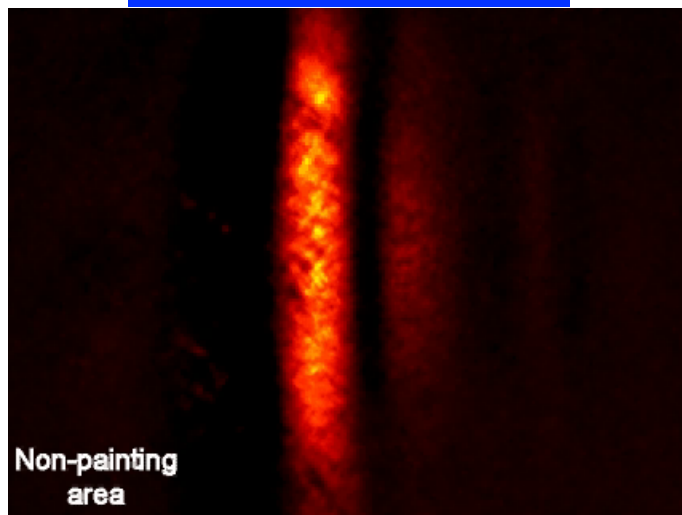


# Summary

## Real-time 2D THz tomography for moving object



Moving half-paint film



2D spatiotemporal THz image

Drying progress in wet paint

