THz per Applicazioni Scientifiche e Trasferimento Tecnologico
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# Non linear phenomena by intense THz wave from free electron laser

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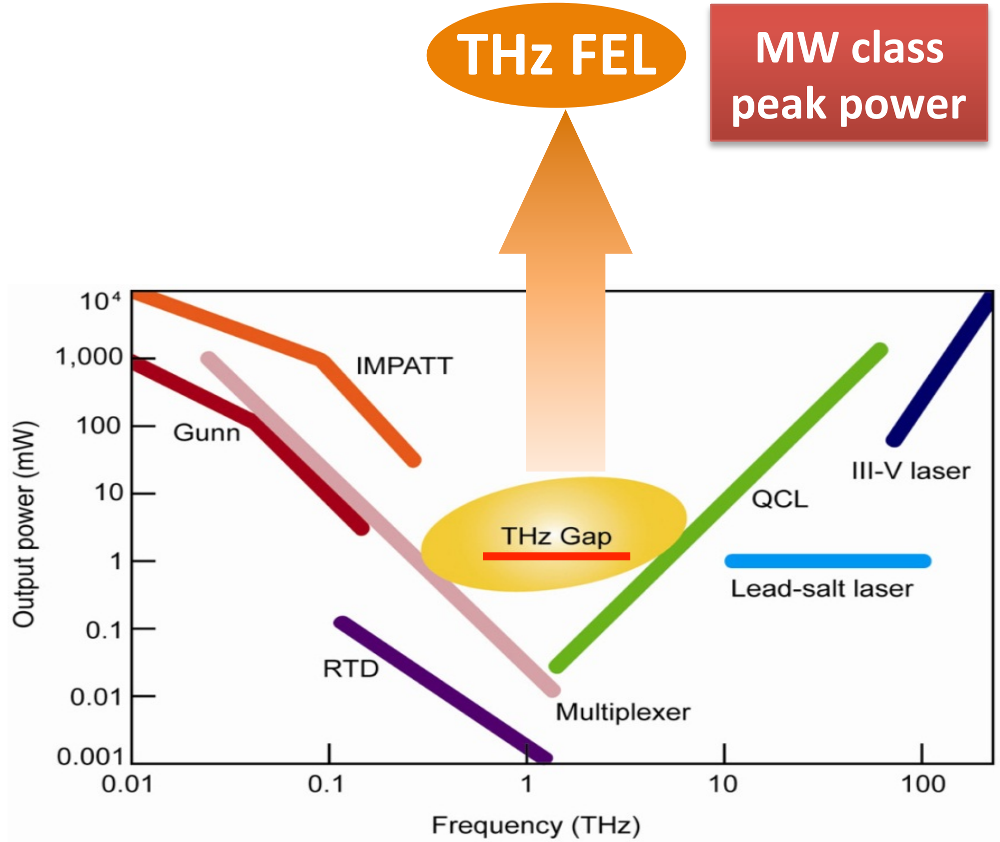
# THz FEL

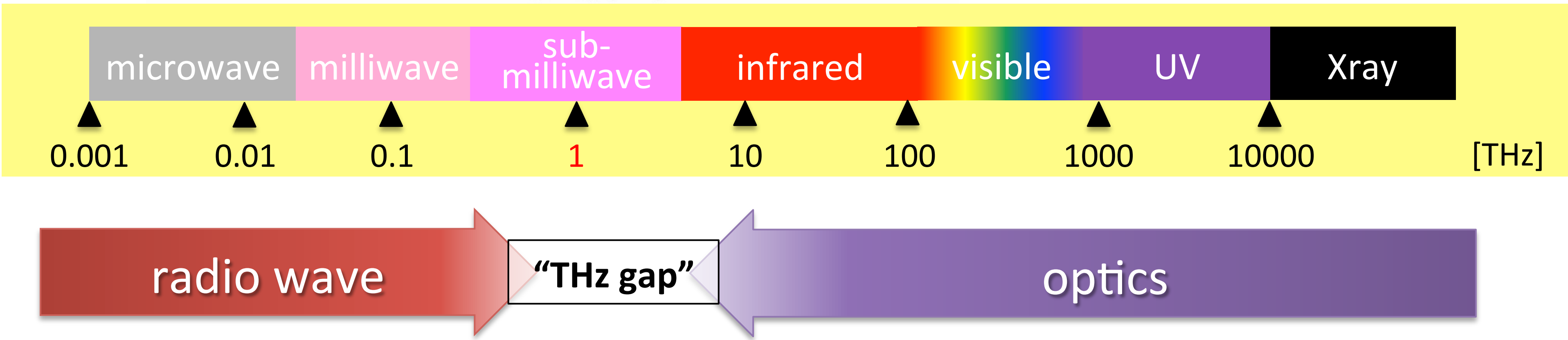



MW class peak power

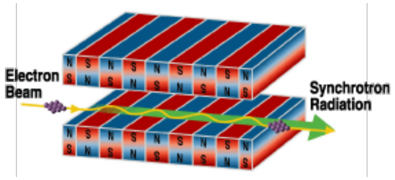
**THz FEL**

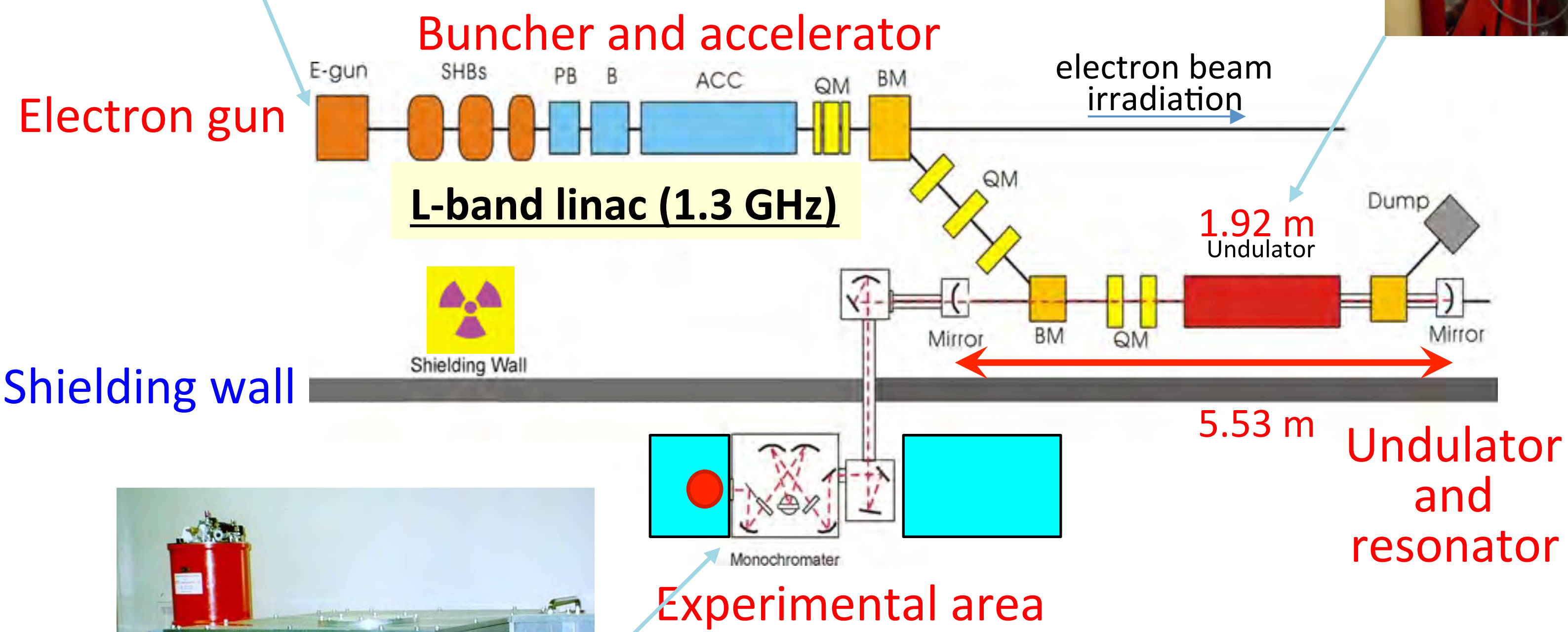
- Monochromatic
- Frequency tunable
- Pulse
- Polarize

3 THz
=12 meV
=100 μm
=100 $cm^{-1}$

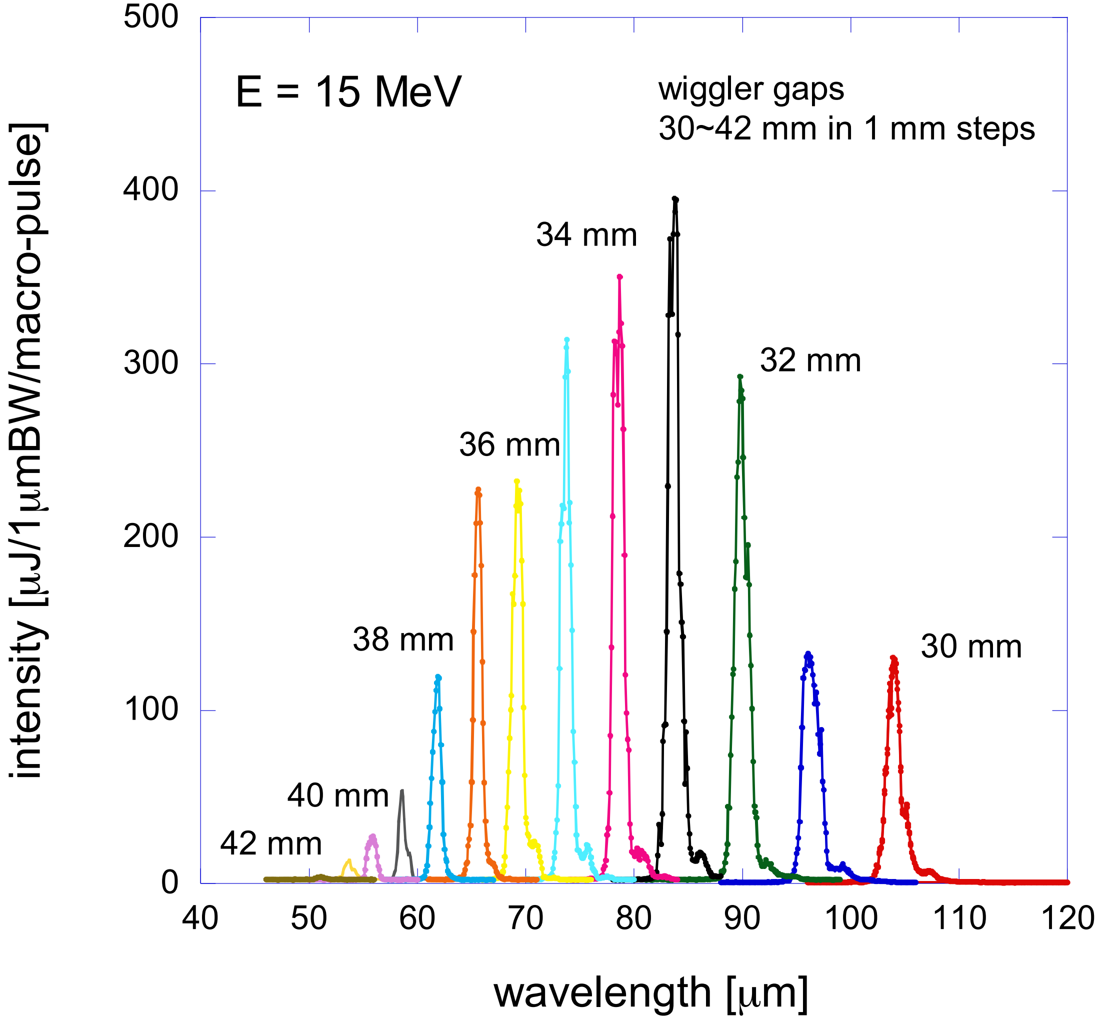


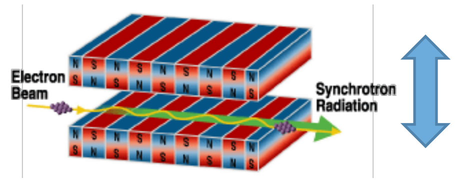
# ISIR THz-FEL formation




# Generated THz FEL

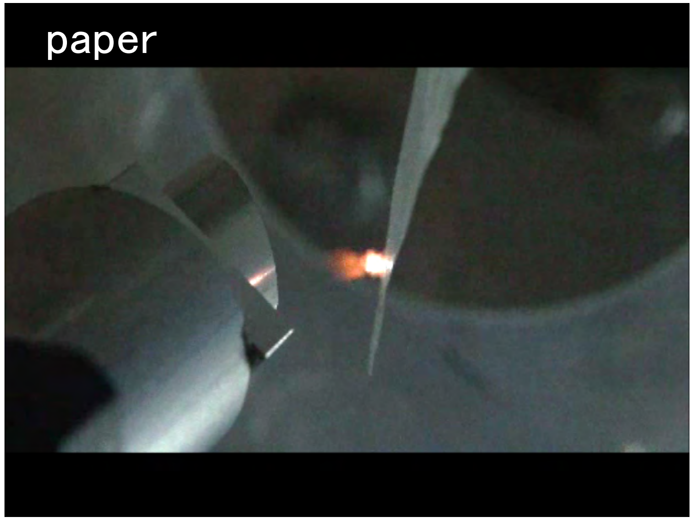


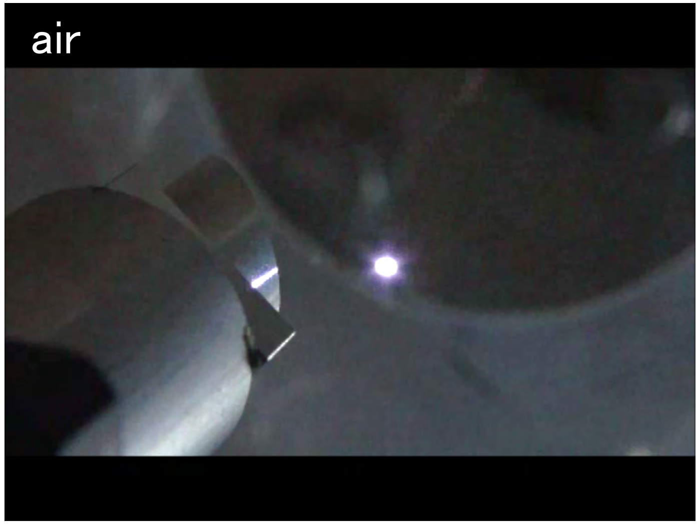



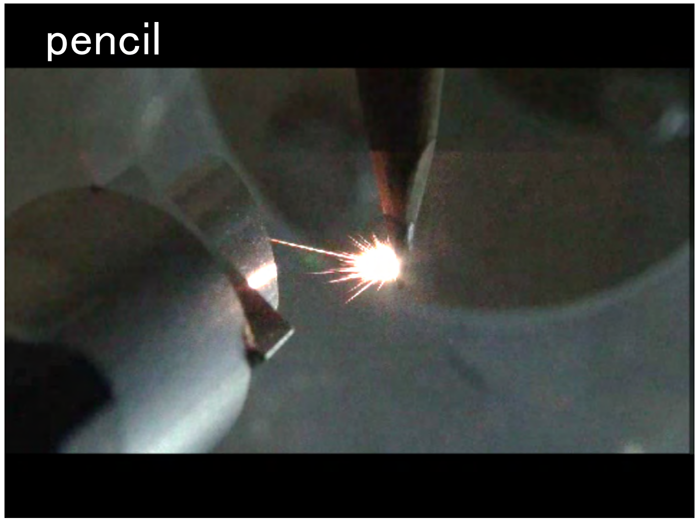

Undulator gap

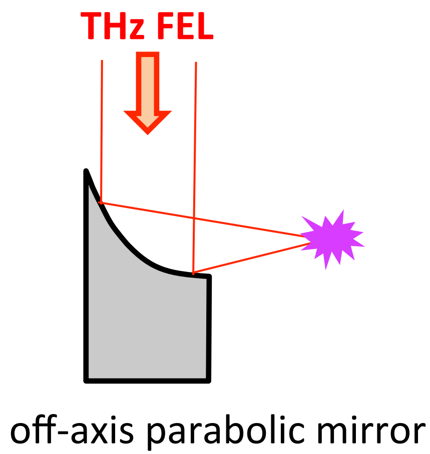
Wavelengths for different undulator gaps

# High photon flux



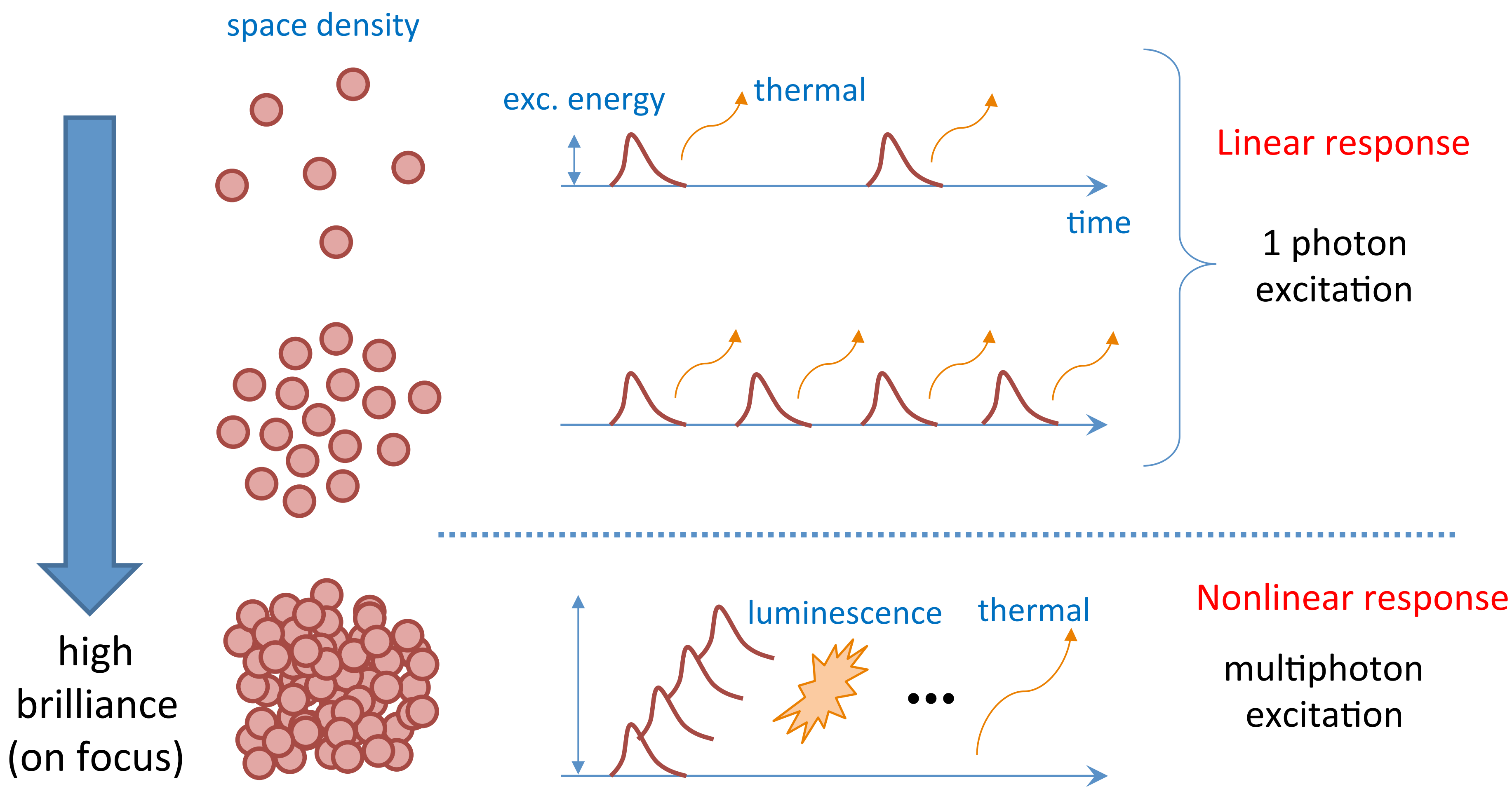




High brilliance achieves luminescence phenomena.

3.6 [MV/cm] (electric field)

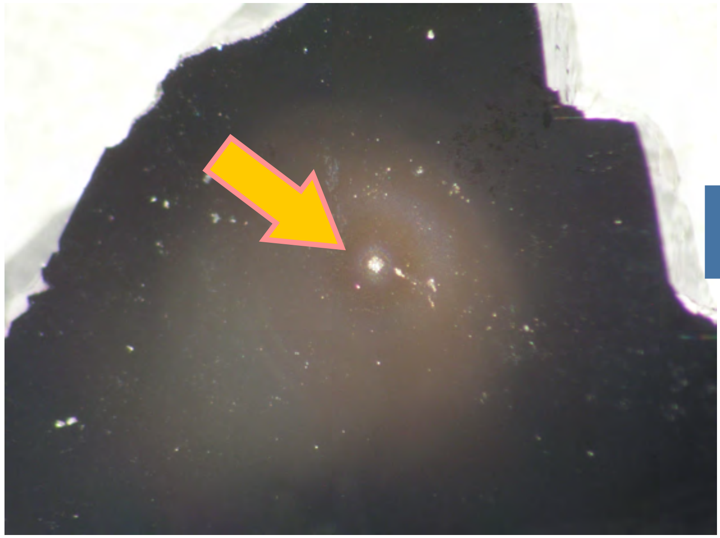
# Multiphoton excitation




Several photons absorption at once affects as a higher energy excitation.

# Focused on materials

Si wafer



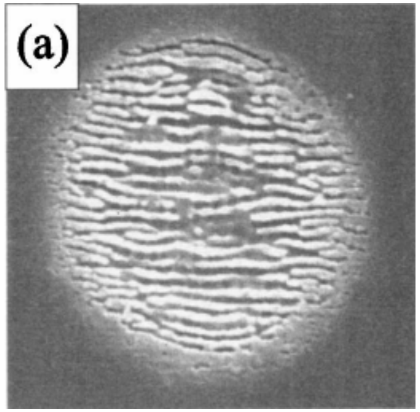
Damage.


€ 40,000 ~

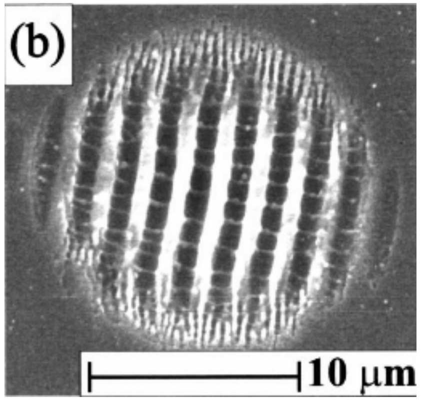
# LIPSS

Lase Induced Periodic Surface Structure (1965-)

Using fs-laser (λ = 800 nm) (1996-)




?




electric field

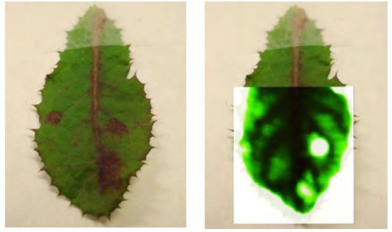
from A. Borowiec and H. K. Haugen
Appl. Phys. Lett., Vol. 82, No. 25, 23 June 2003

LIPSS period Δ = 0.4 λ ~ λ

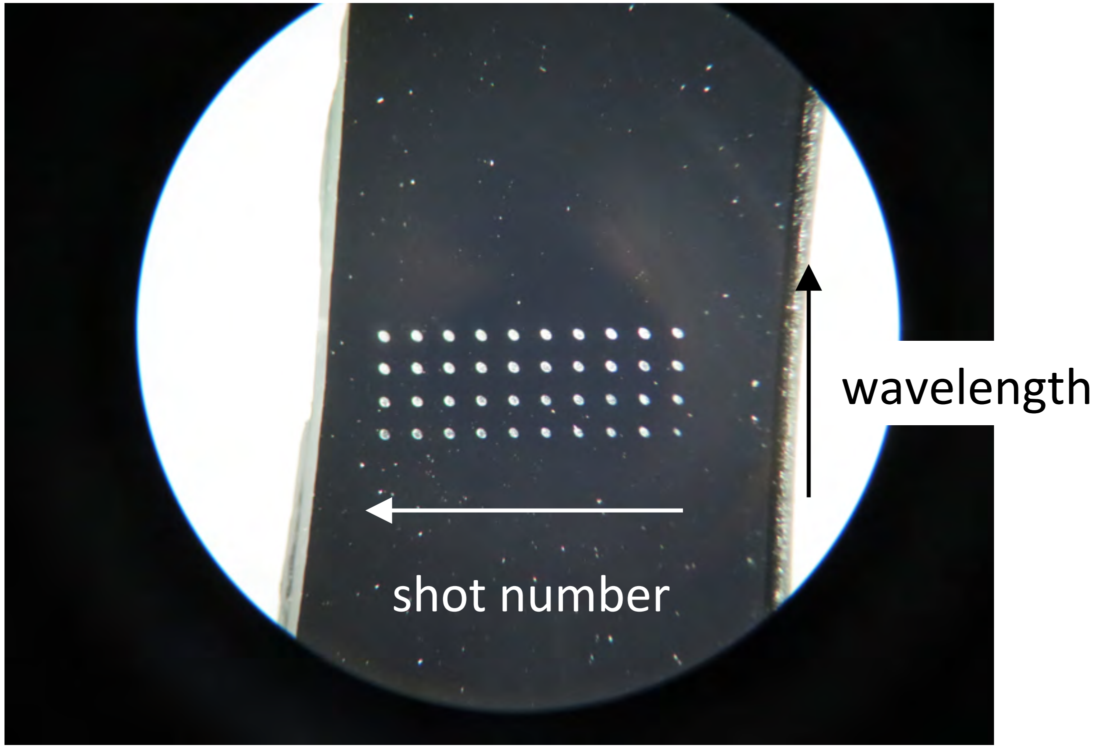
Fine structure beyond the diffraction limit

But, in case of THz-FEL (λ = 80 μm), Δ ~ 0.04λ.

# LIPSS by THz-FEL



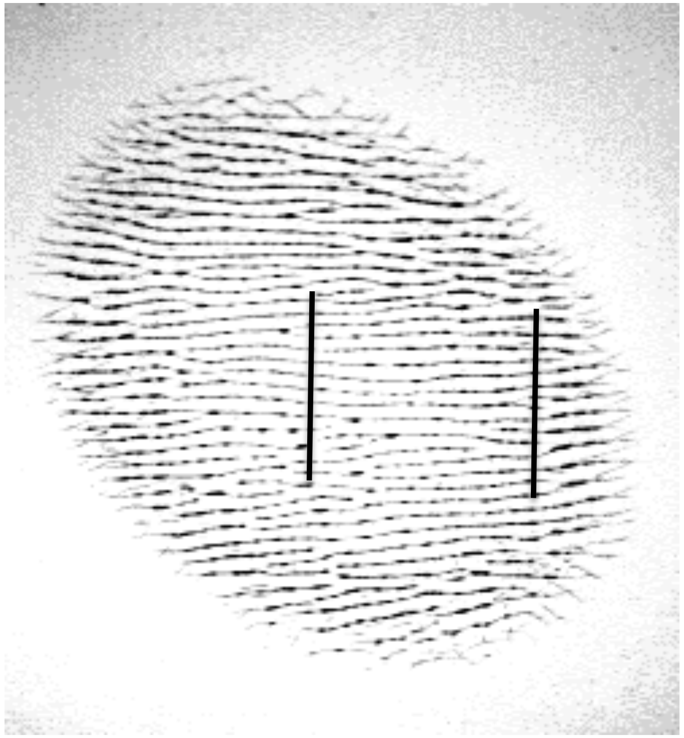
2D scanning technique

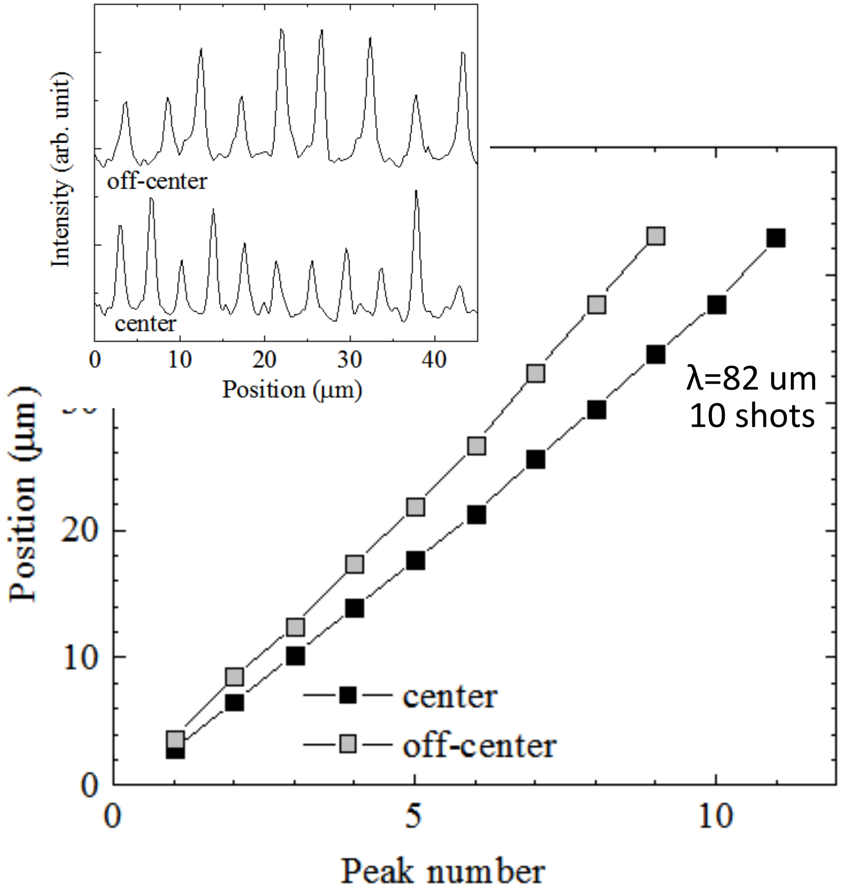



Systematically shooting with different wavelength, different shot number.

# Periodicity

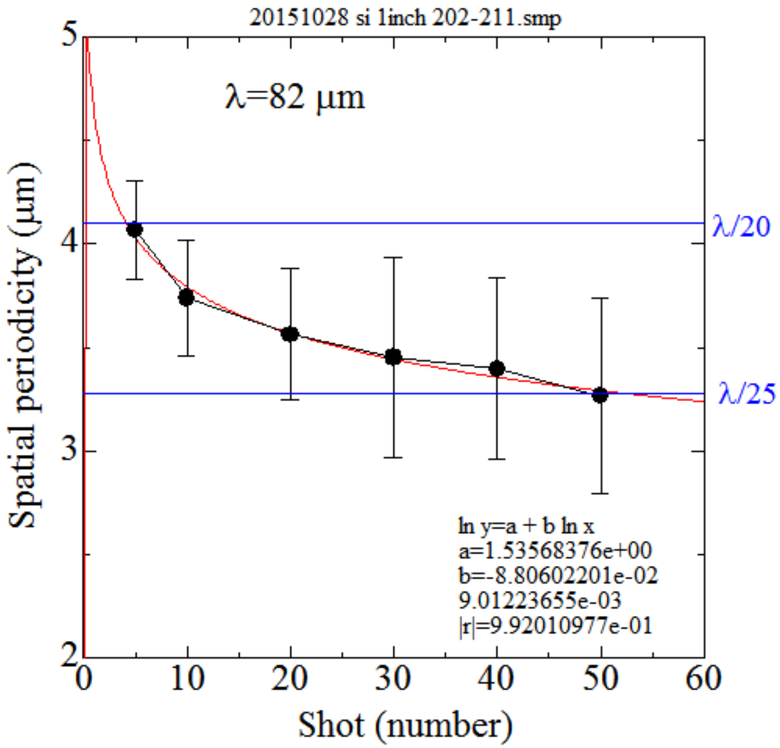
LIPSS of THz-FEL

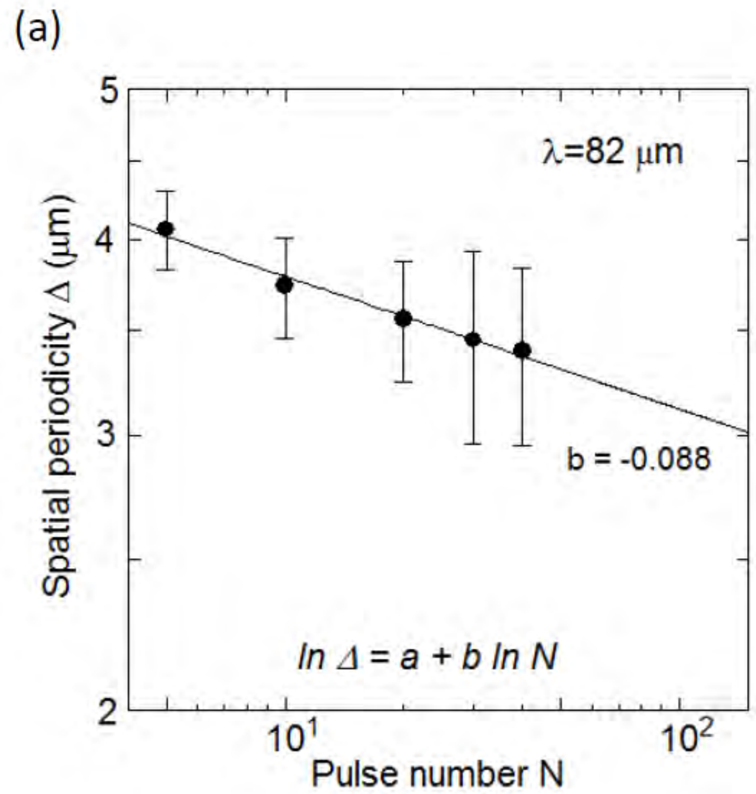





Periodicity: [center] < [off-center]

# Power law for pulse number

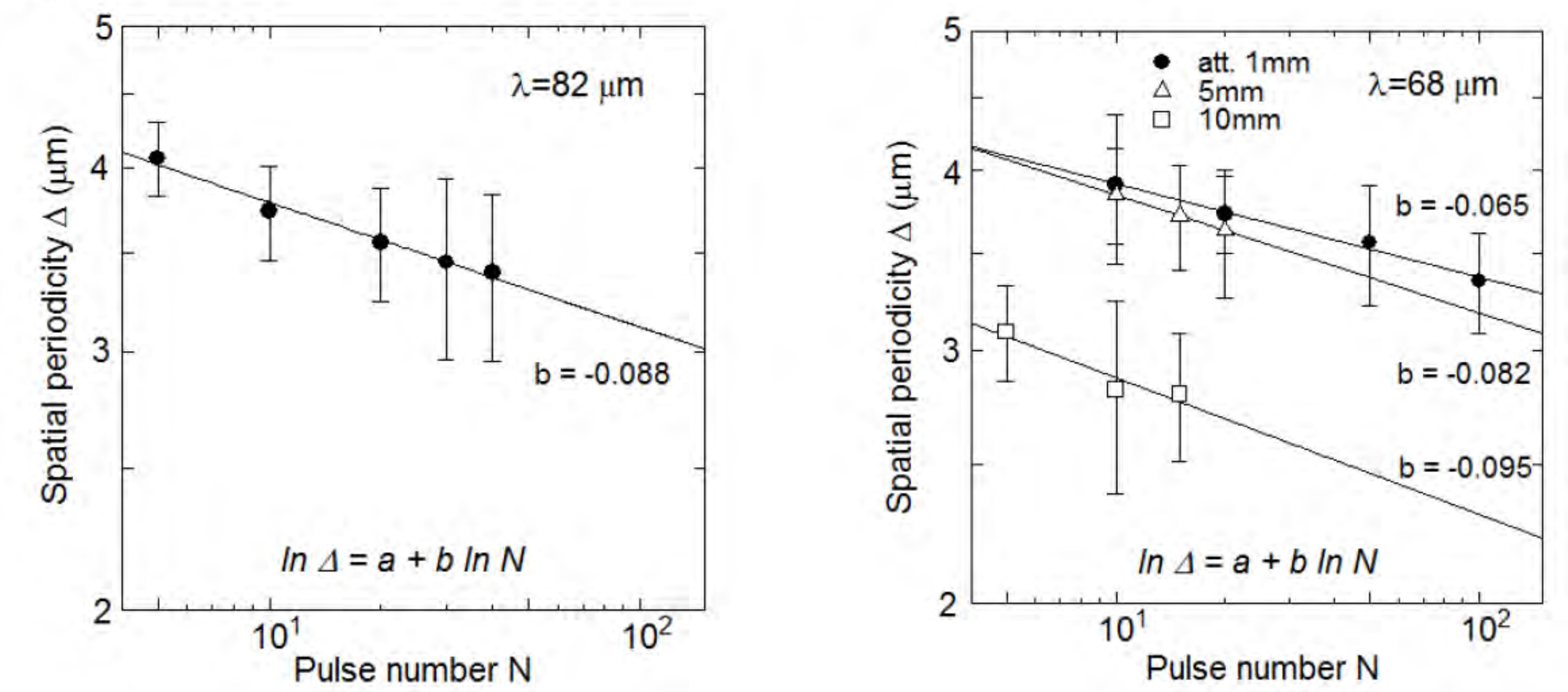


# Power law for pulse number

(a)

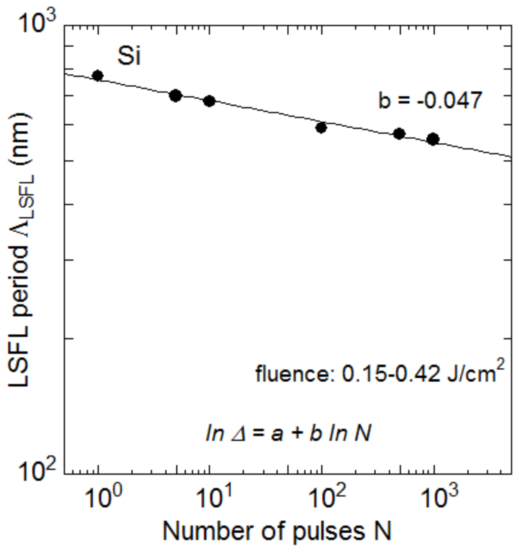
(b)



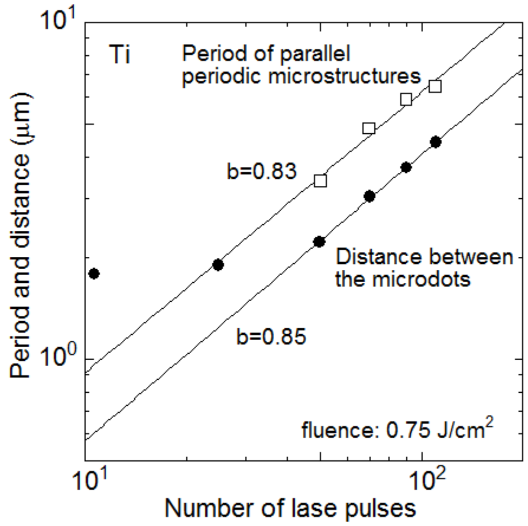

<u>Scaling law</u>

# Power law for pulse number

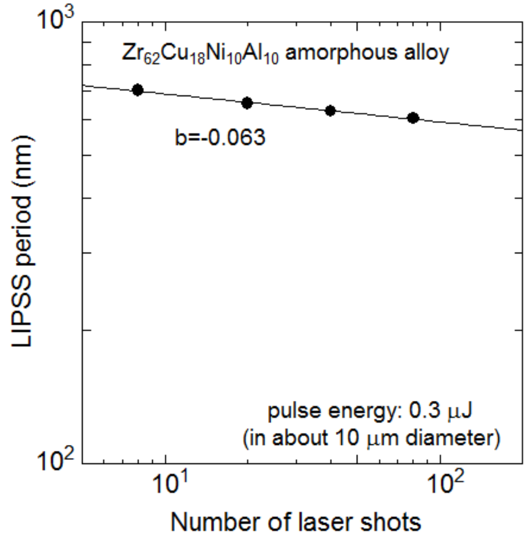
*From FIG. 3(a) in ref. 16: J. Bonse et al., J. Appl. Phys. 108, 034903 (2010)*




*From Fig. 4 and 5 in ref. 19: M. Tsukamoto et al., Vacuum 80, 1346 (2006)*




*From Table 1 in ref. 20: L. Ran et al., Appl. Surf. Sci. 256, 2315 (2010)*




<u>Scaling law in other materials, other wavelength</u>

⇩

Universal mechanism of LIPSS ?

*Irizawa et al., Appl. Phys. Lett. **111**, 251602 (2017)*

# Dissipative structures in non-equilibrium open system

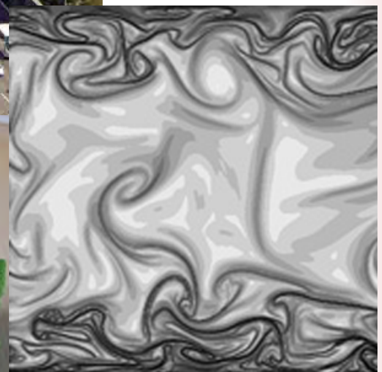
IN → system → OUT

fluctuation
(pattern, fractal, chaos)

Ilya Prigogine 

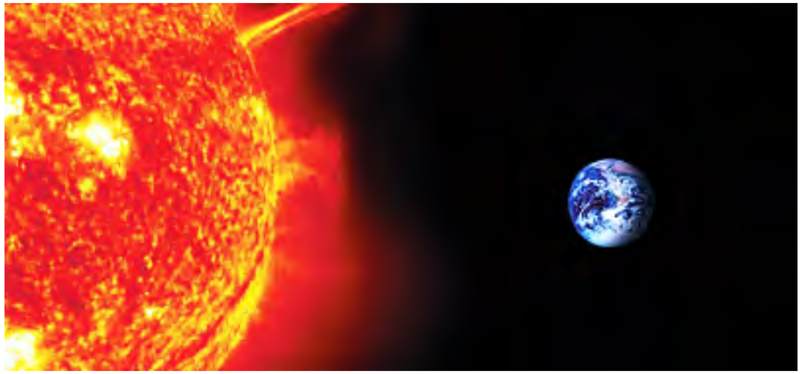
1977, Nobel Prize in Chemistry

**Ordered state**

**Disordered state**

# Dissipative structures in nature

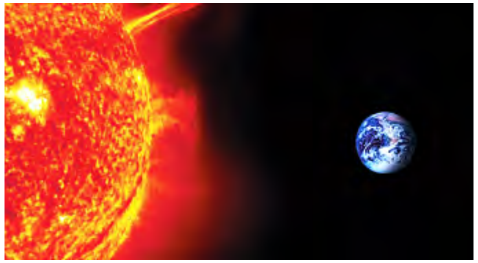


non-equilibrium
open system

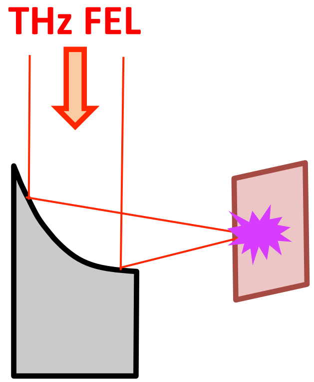
散逸構造

Self-organized dissipative structures

# Origin of LIPSS



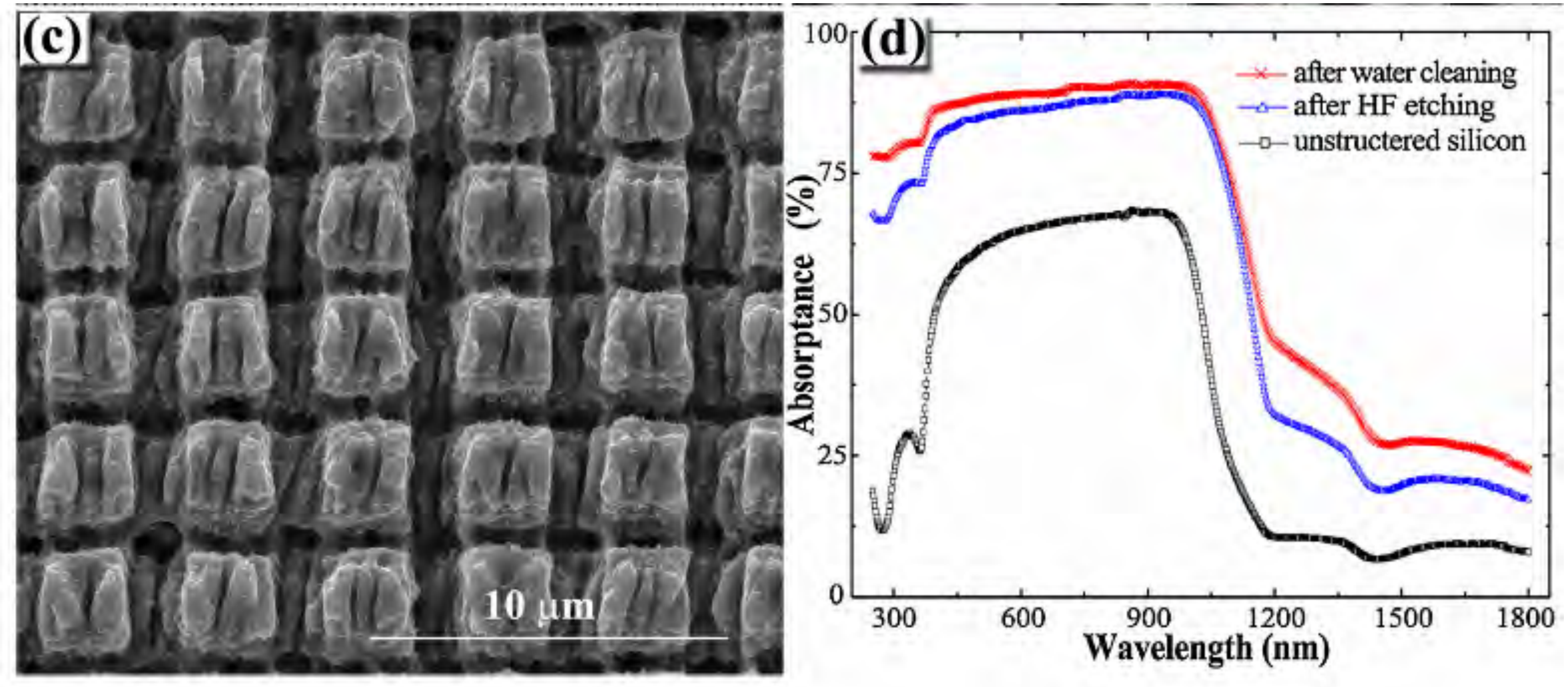
non-equilibrium open system




similar situations?

Self-organized dissipative structures

# Applications




Focused laser with aperture (interference)

Control the spectra

*A. Pan et al. Appli. Surf. Sci. 368 (2016) 443-448*

# Applications

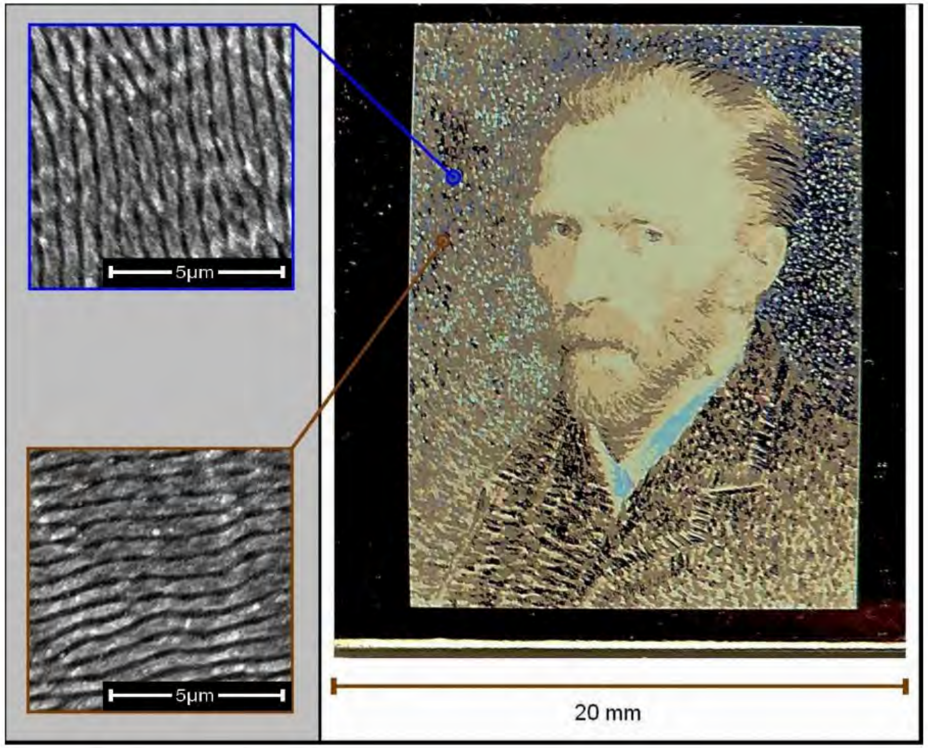



Fig. 1. On the right, example of color effects obtained by controlled nanostructures with a femtosecond laser chain on a 316L stainless steel sample, on the left, SEM X6000 images of controlled nanostructures marked with two different orientations.

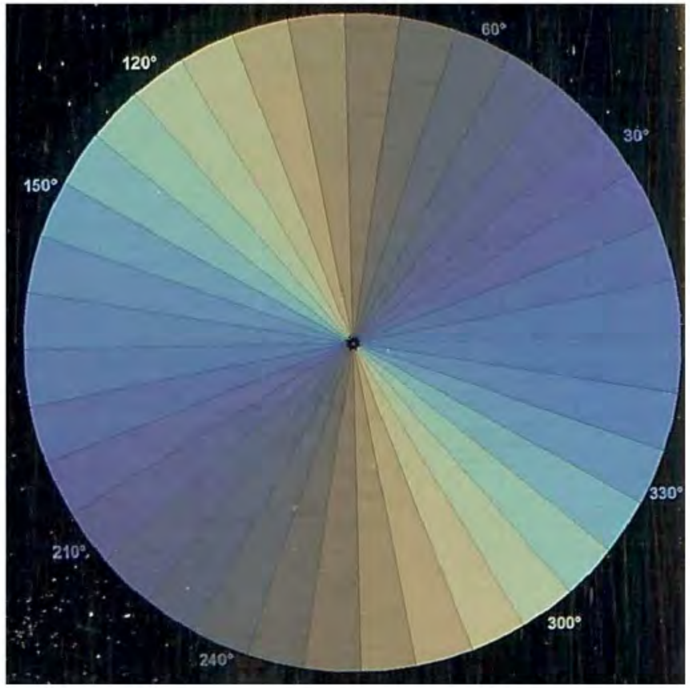


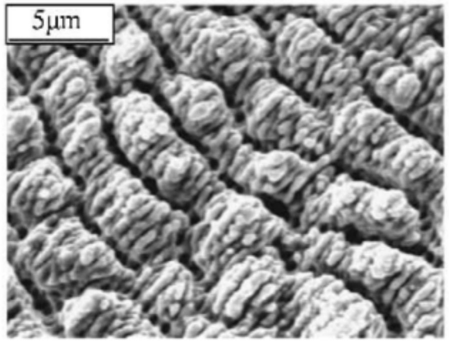

Fig. 9. Scanned image (1200 dpi) of stainless steel sample (316L) marked by thirty six discs section obtained with the "optical way 1" femtosecond laser chain (P = 25 mW, F = 0.4 J.cm-2). Each section have been marked with different ripples orientations (from 0° to 350°).

Control the color

*B. Dusser et al. Optics Express 18 (2010) 2913-2924*

# Applications

double-scale structure



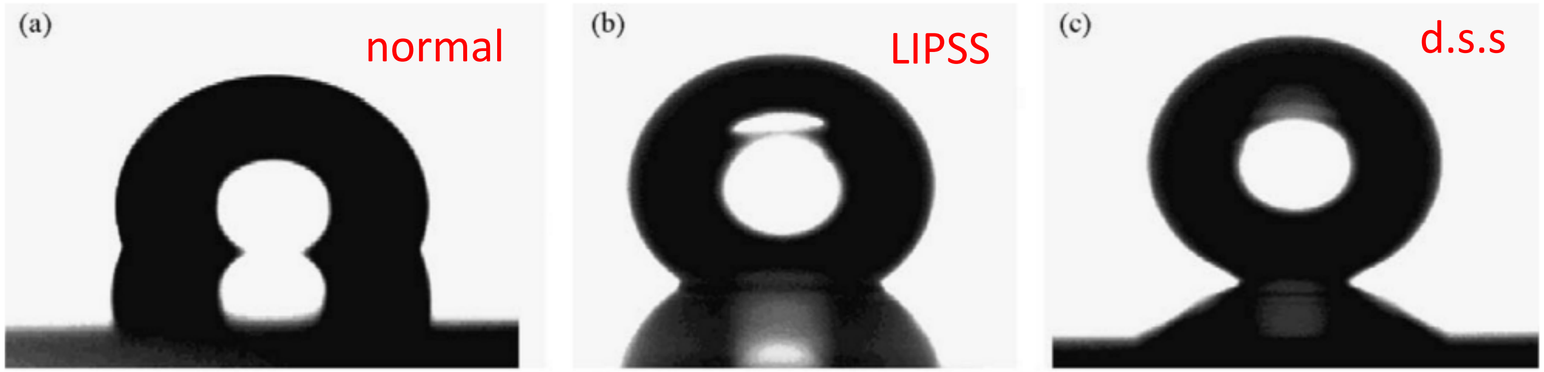




**Fig. 2.** Photographs of water droplets on flat (a), LIPSS (b) and double-scale structure (c) AISI 316L type austenitic stainless steel-based surfaces after silanization.

## Superhydrophobic surface

*B. Wu et al. / Applied Surface Science 256 (2009) 61–66*

# Summary

- LIPSS was found in THz-FEL irradiated Si that is the first case for FIR-THz region.
- The mechanism is still unknown for its fineness structure of $\sim 0.04\lambda$ .