Novel Responses of Solids by Terahertz Free Electron Laser

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Focus

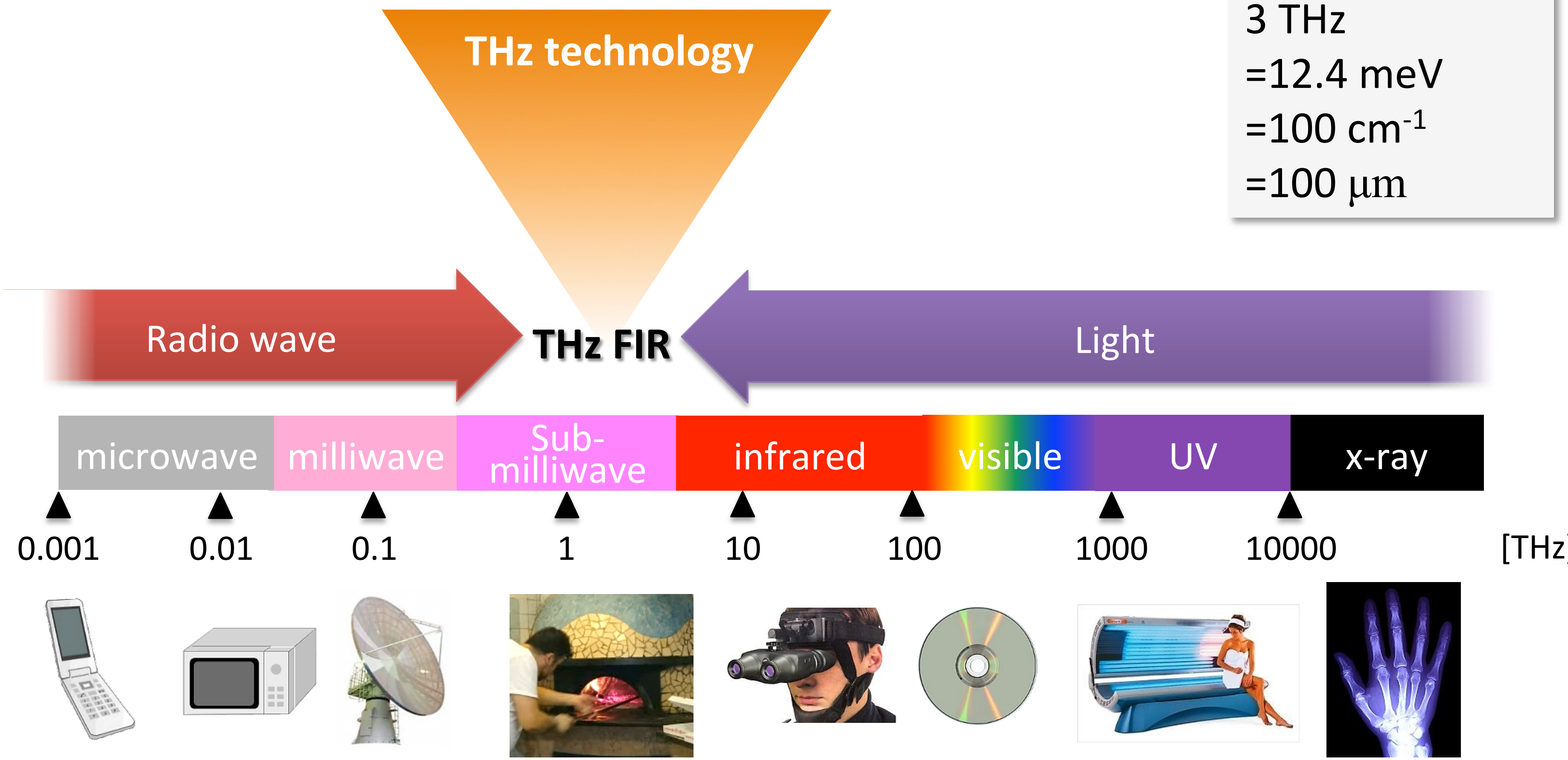
What happening on solids
irradiation by
low energy, intense, laser ?
(= THz-FIR FEL)

- "low energy"
  far infrared < UV, x-ray *:photon energy*
- "intense"
  large number of photons *:total energy*
- "laser"
  monochromatic coherent light *:electromagnetic wave*

THz-FIR region

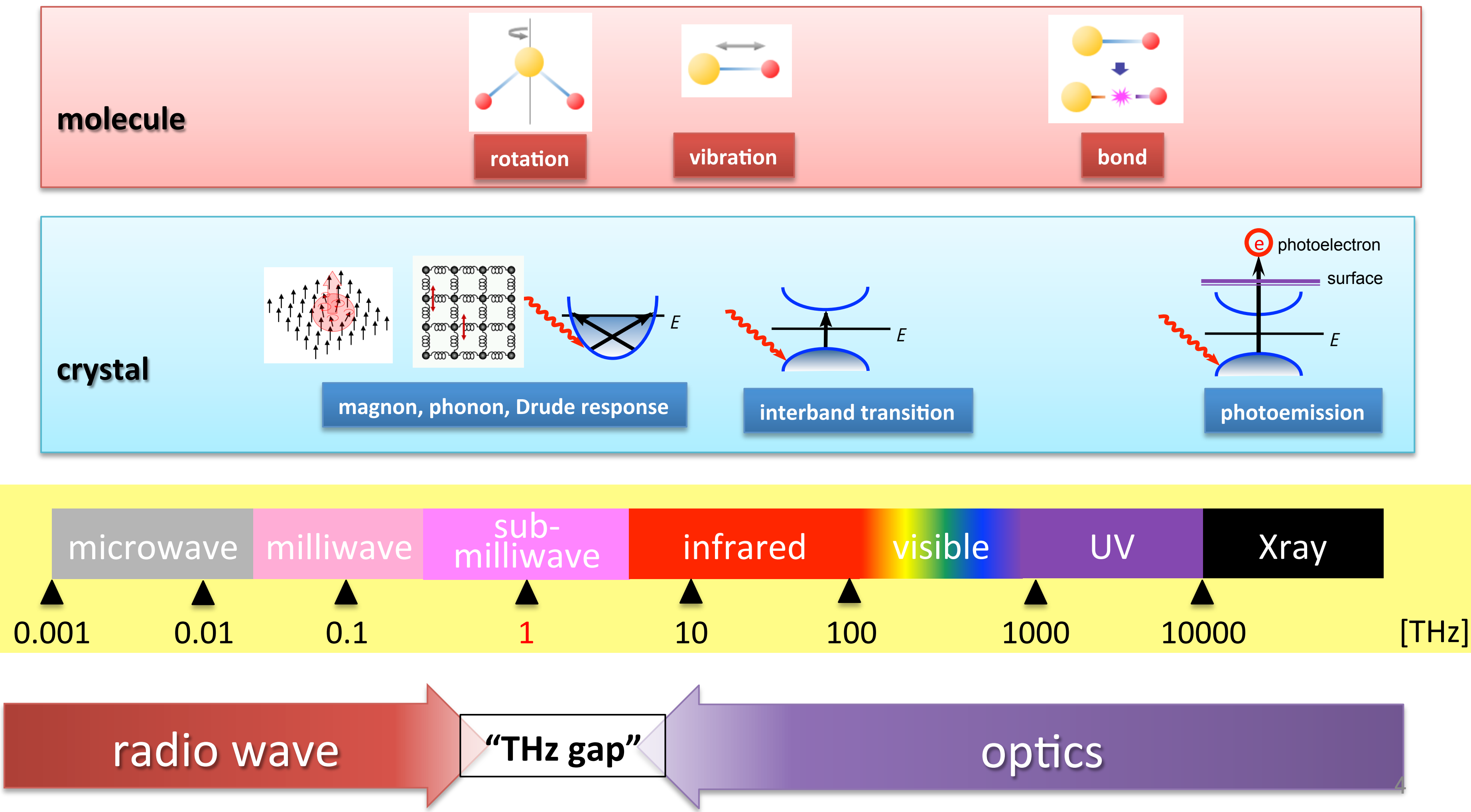
THz-FIR region is said to be a frontier in various fields: medical, sensing, engineering, chemistry, …

Unit conversion
3 THz
=12.4 meV
=100 cm^{-1}
=100 μm

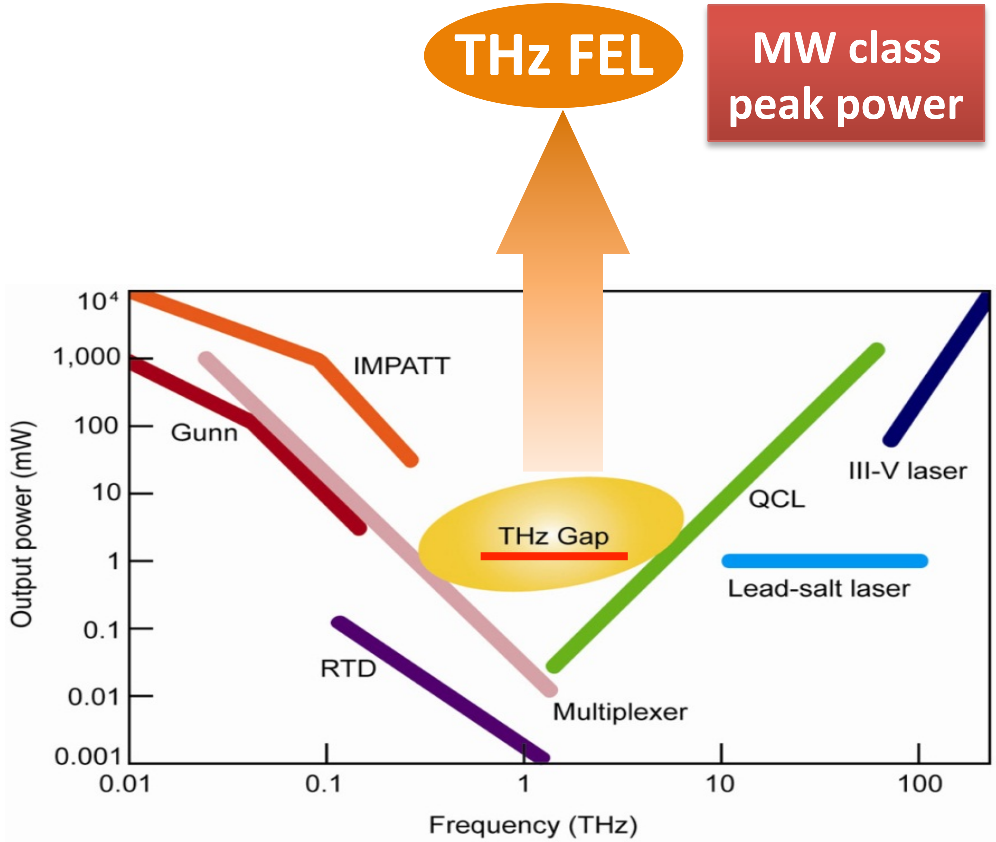


FIR-THz region

FIR light, THz wave correlates with
organic materials, molecules: rotational, vibrational absorption (“fingerprint region”),
inorganic materials: magnon, phonon, electronic excitation near E_F

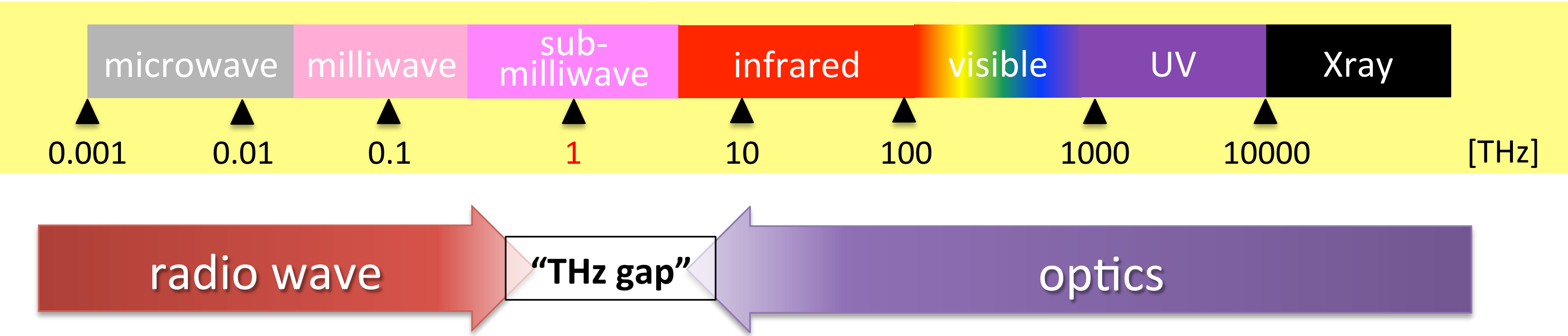


Advantages of THz-FEL

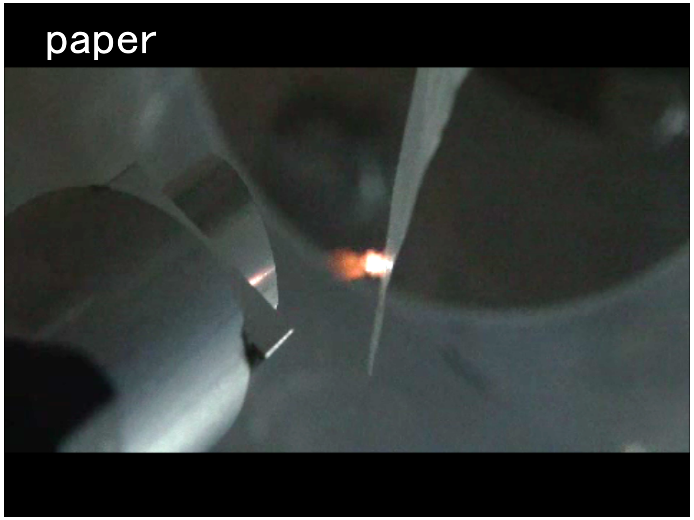


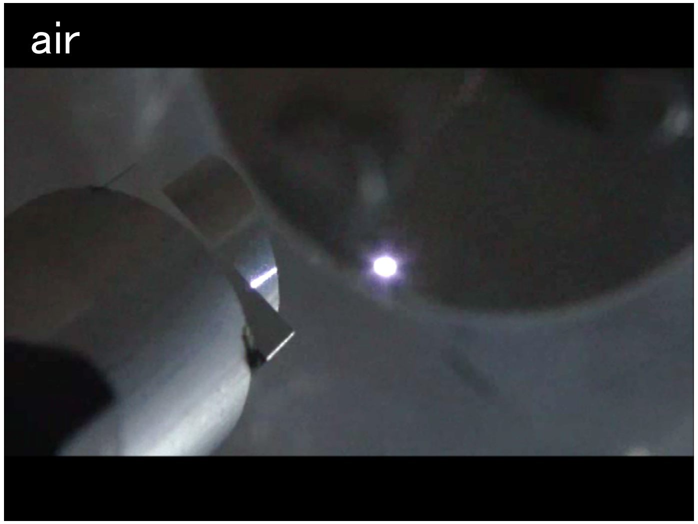
THz-FEL

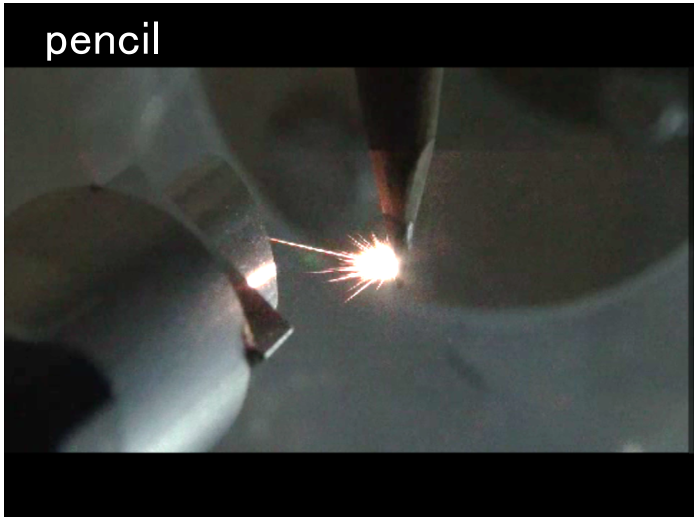
- Monochromatic
- Frequency tunable
- Pulse
- Polarize

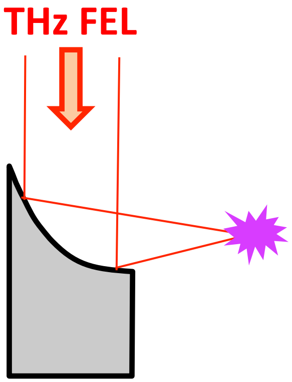


Excitations







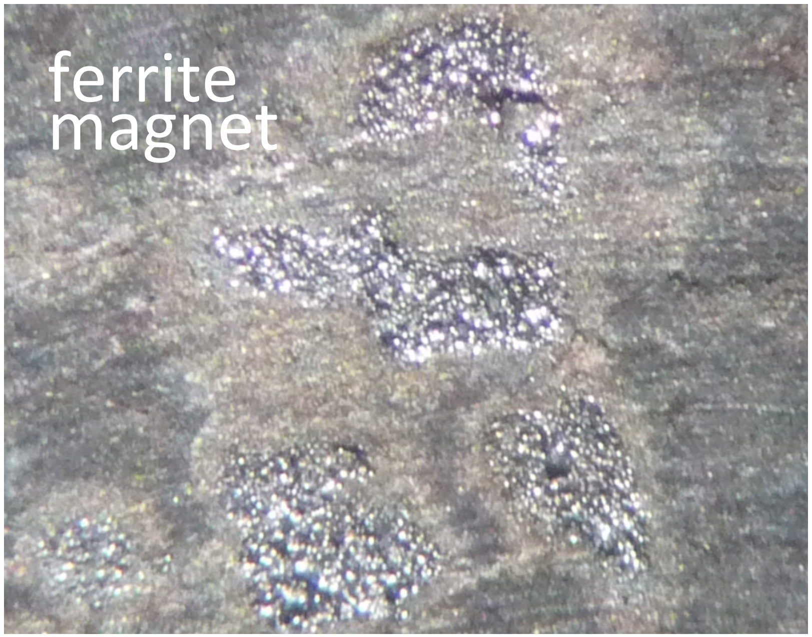


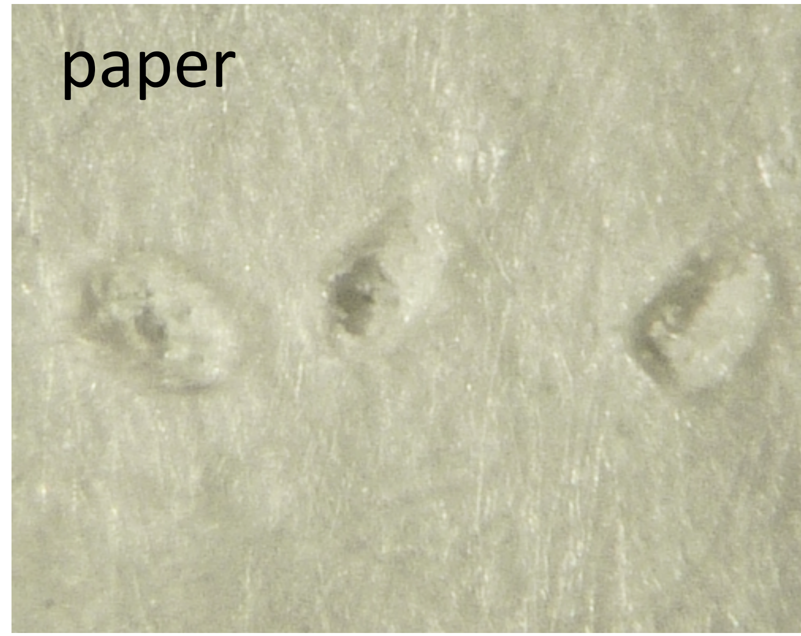
off-axis parabolic mirror

High brilliance achieves luminescence phenomena.

Just a thermal effect?

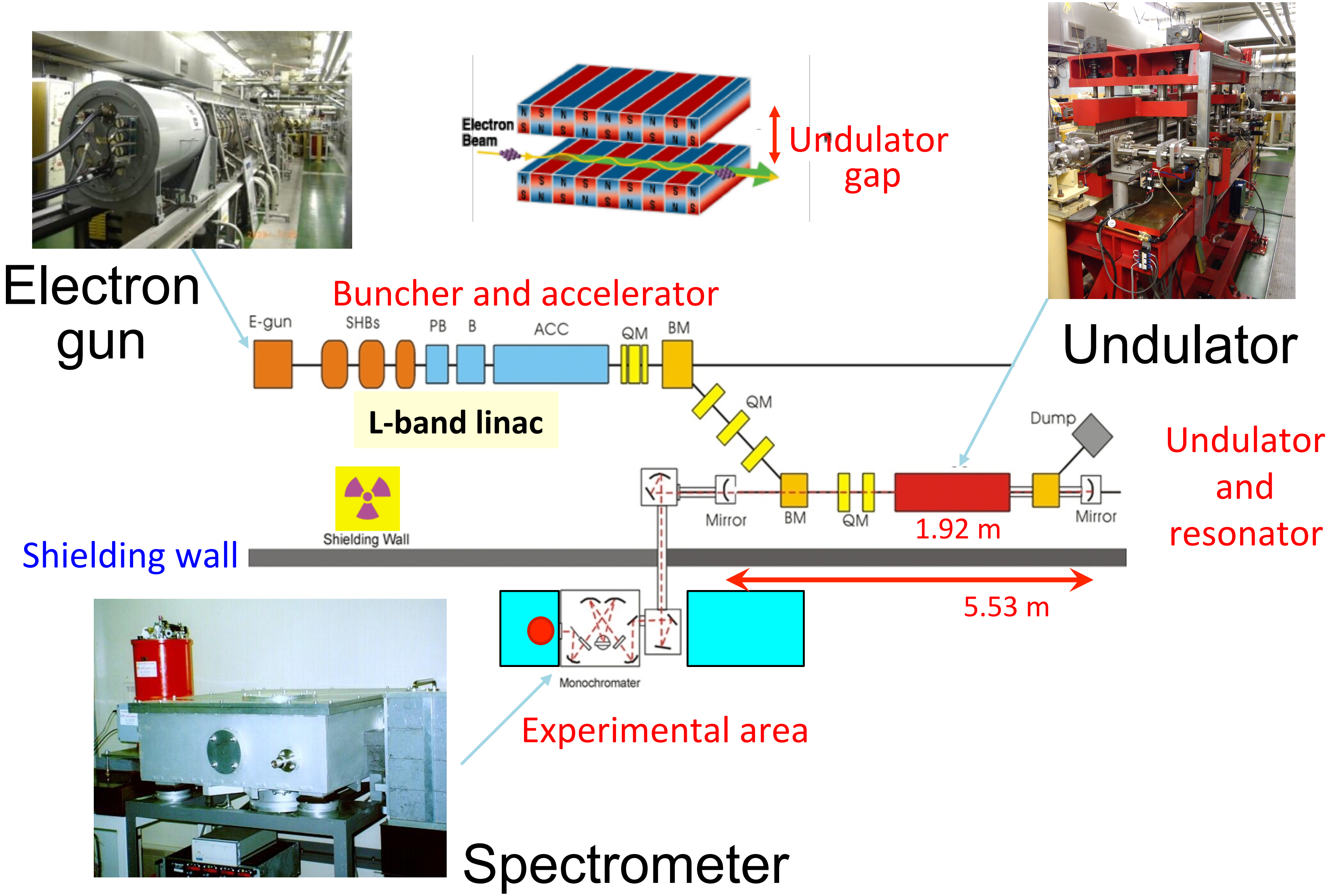
Melting or ablation





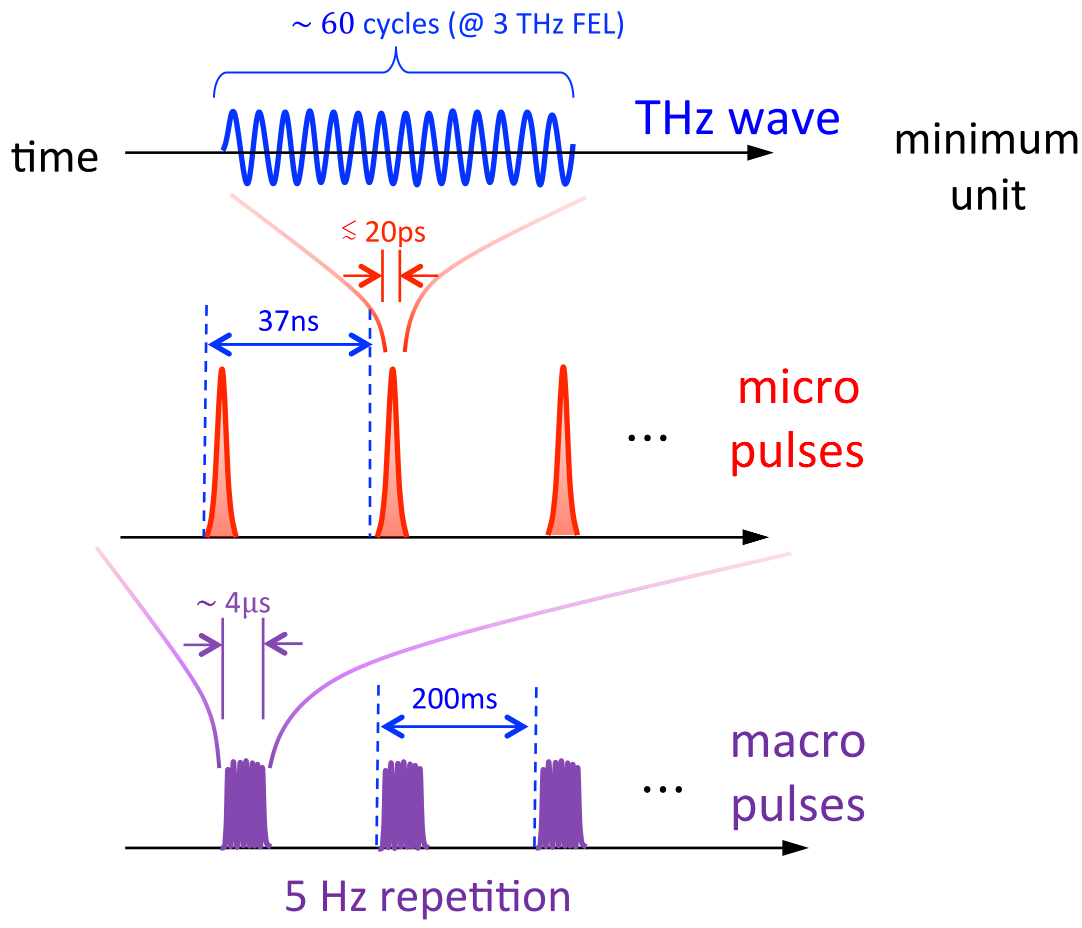
Different materials feel different "temperatures."

ISIR THz-FEL system

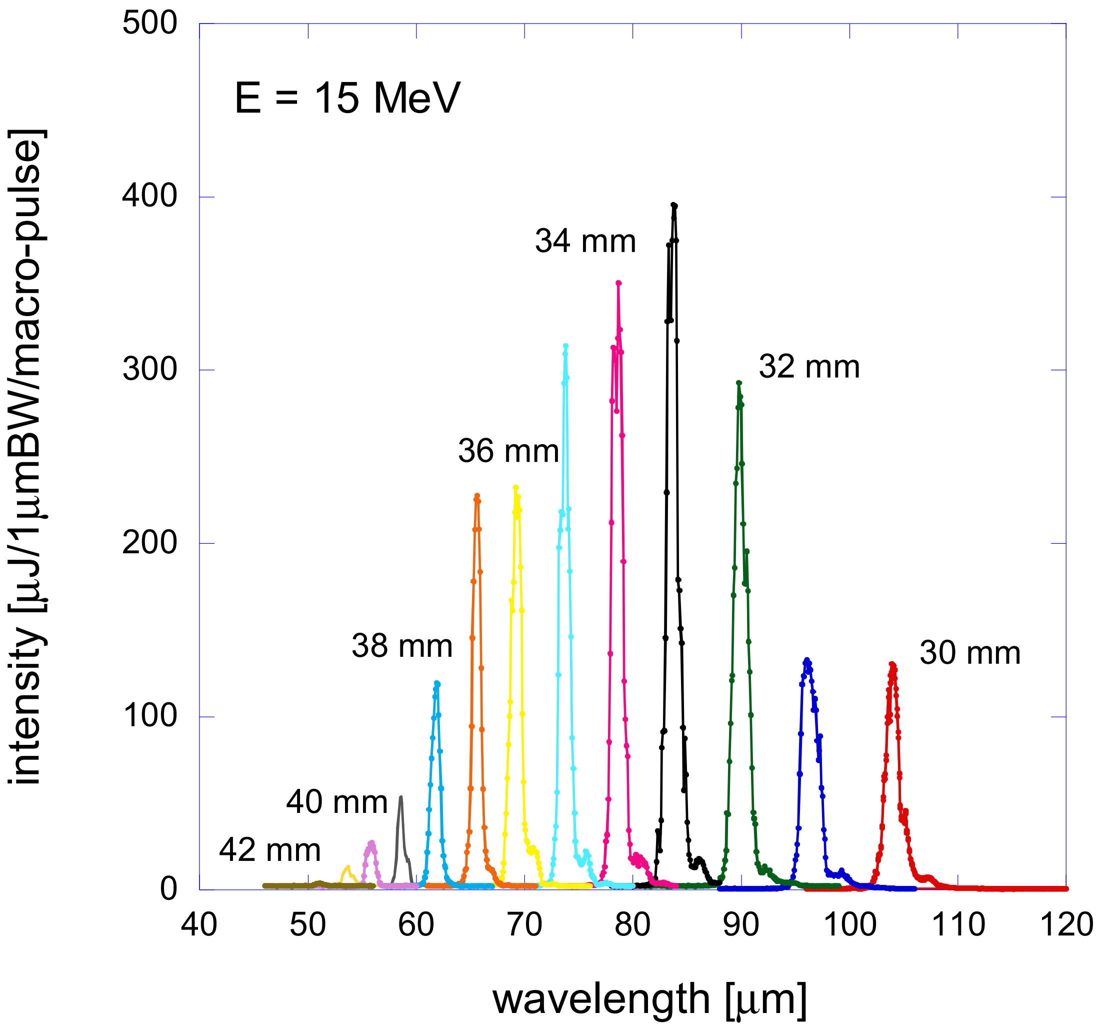


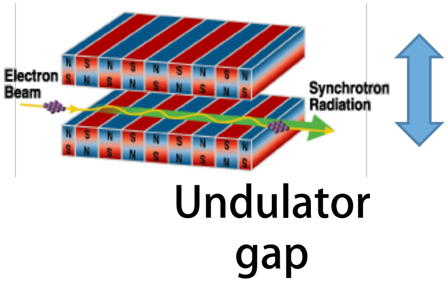
Obtained THz-FEL time structure

FEL pulse structure reflects the e-beam structure.



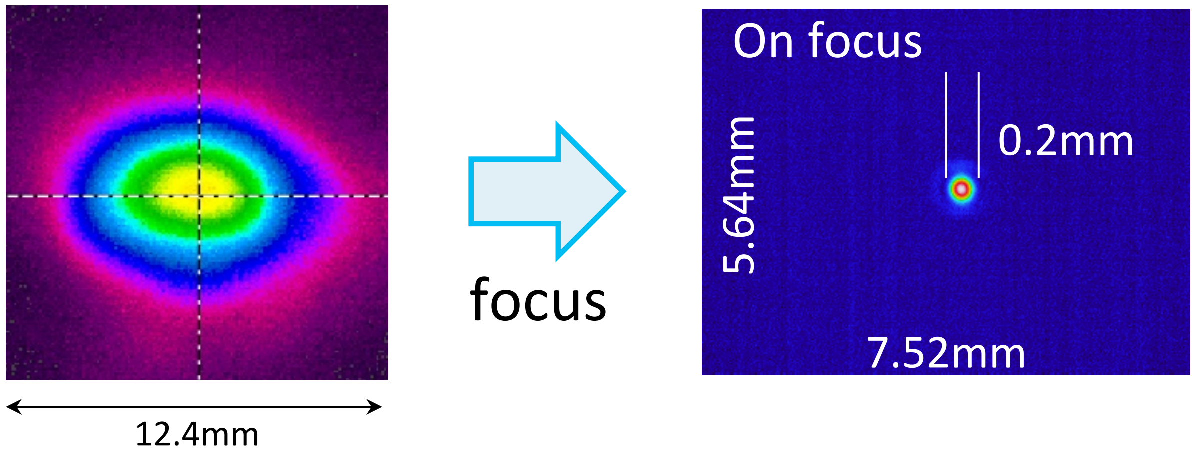
Generated THz FEL





Wavelengths for different undulator gaps

Beam profile & intensity



Simple Gauss-like dispersion
with nearly parallel

Condensable less than 200 μm

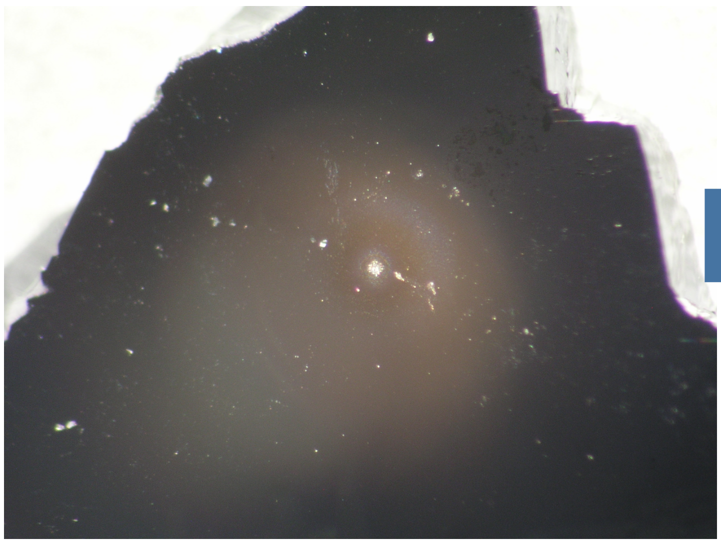
+

Max energy ~ 5 [mJ] / macro pulse

35 [GW/cm^2] (power density)

3.6 [MV/cm] (electric field)

Damage on Si



Irradiated on Si wafer

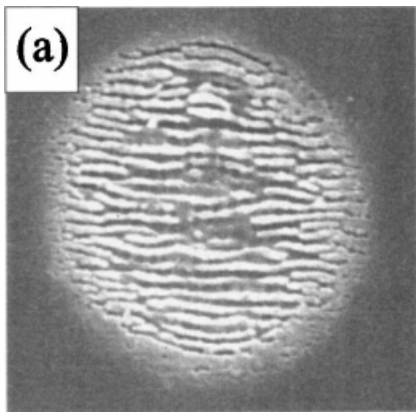
~ € 40,000

Rent for demonstration

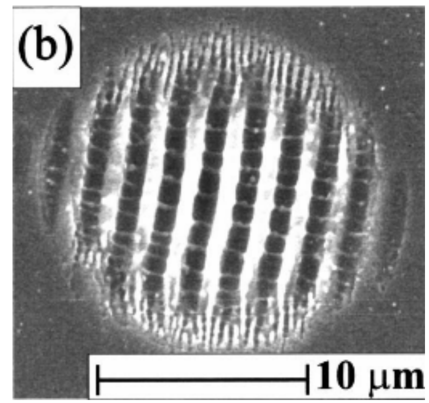
LIPSS

Lase Induced Periodic Surface Structure (1965-)

Using fs-laser (λ = 800 nm)



?



Not just a thermal effect

electric field

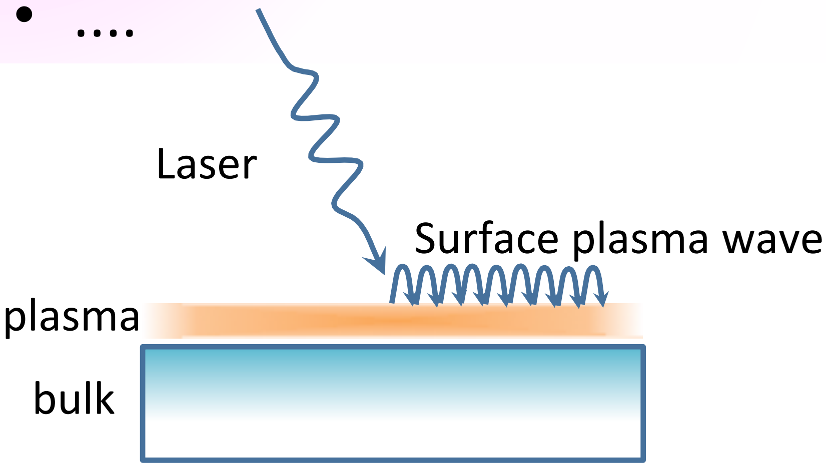
from A. Borowiec and H. K. Haugen
Appl. Phys. Lett., Vol. 82, No. 25, 23 June 2003

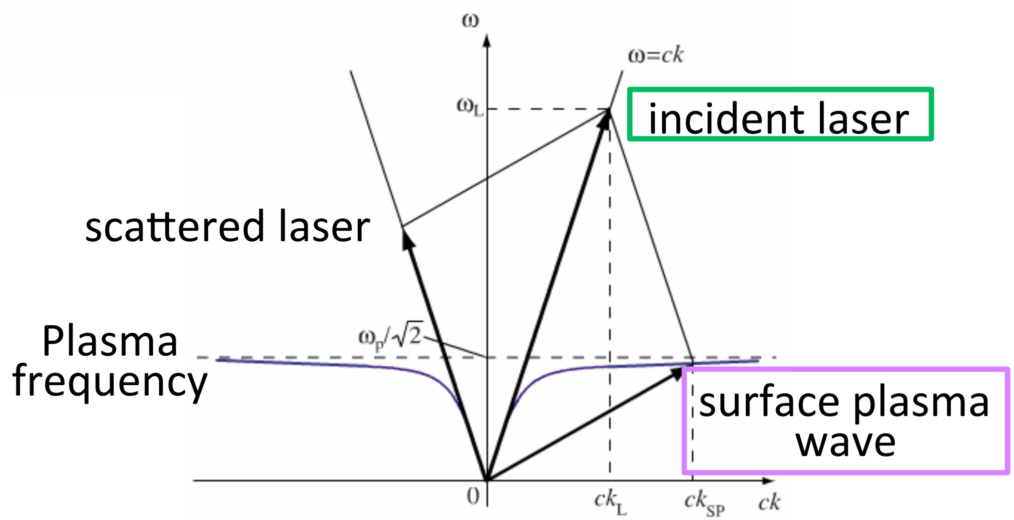
LIPSS period $\Delta = 0.4\ \lambda \sim \lambda$

Fine structure beyond the diffraction limit

Mechanisms

- Parametric decay of laser light to surface plasma waves ($E_{gap} < E_{photon}$)
- Surface plasmon polariton excitation ($E_{gap} > E_{photon}$)
- Higher harmonic wave
- ....



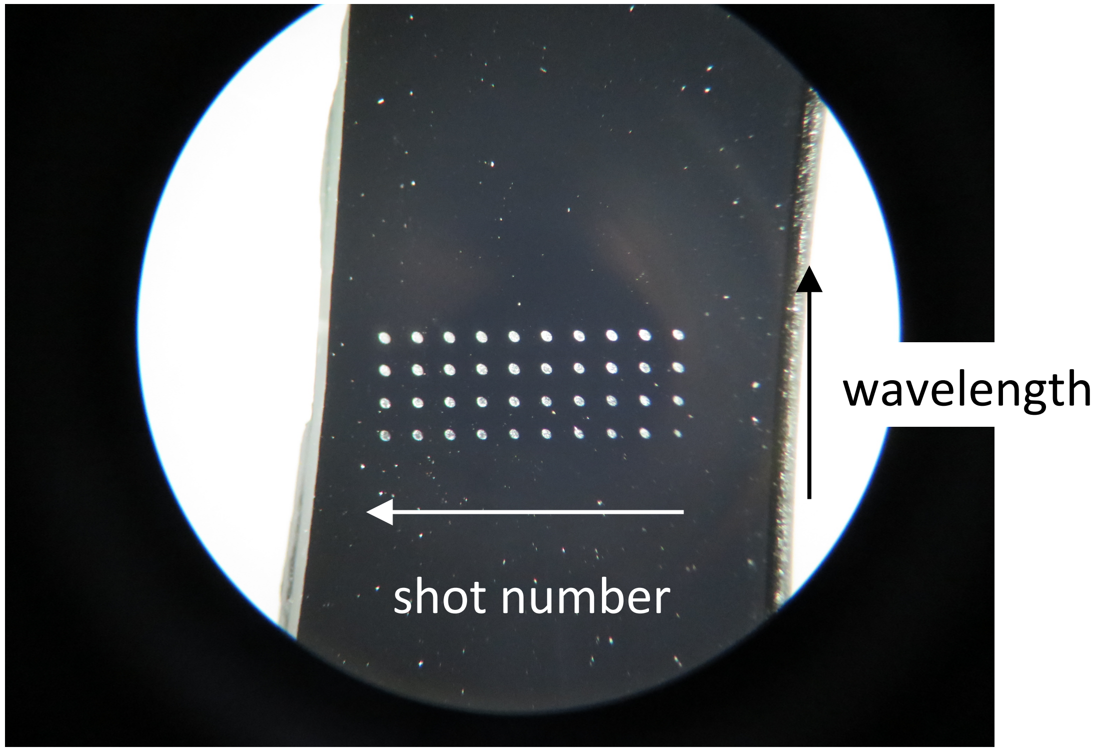


Interference between incident light and surface wave

These mechanisms can generate fine structures with $\Delta = 0.4\lambda \sim \lambda$

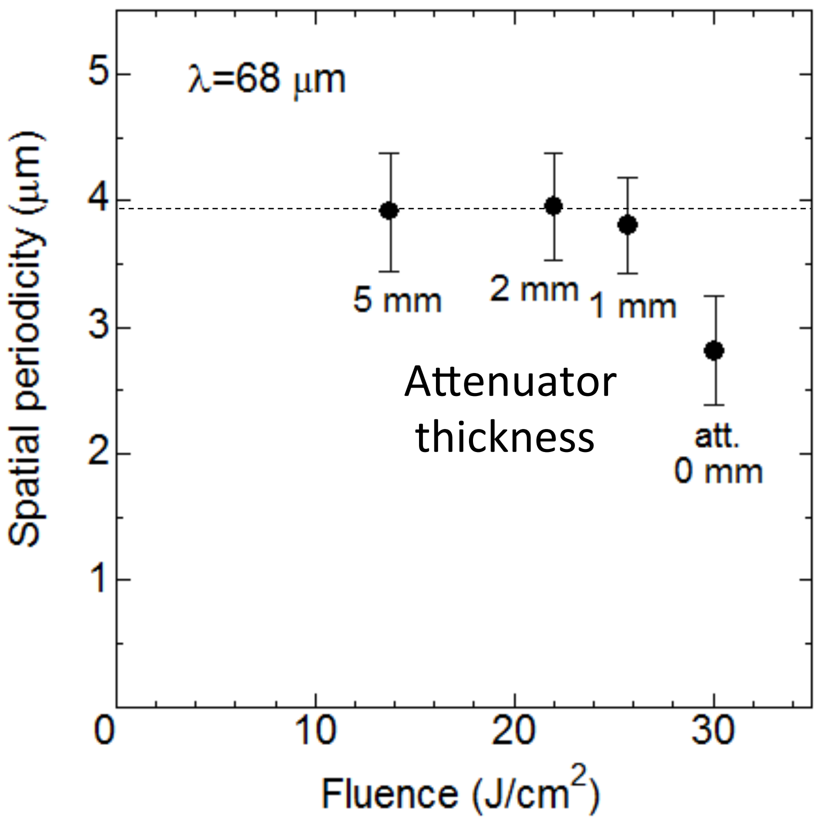
In case of THz-FEL, $\Delta \sim 0.04\lambda$. → <u>Contradict these models.</u>

LIPSS by THz-FEL

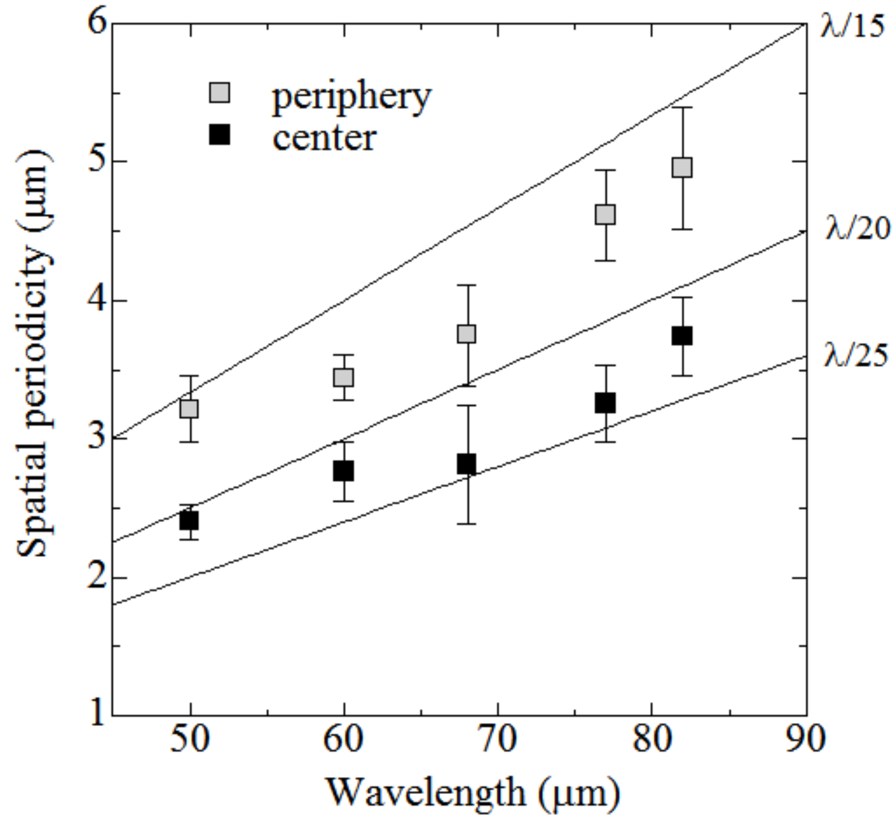


Systematically shooting with different <u>wavelength</u>, different <u>shot number</u>, and different <u>fluence</u>.

Change for fluence, wavelength



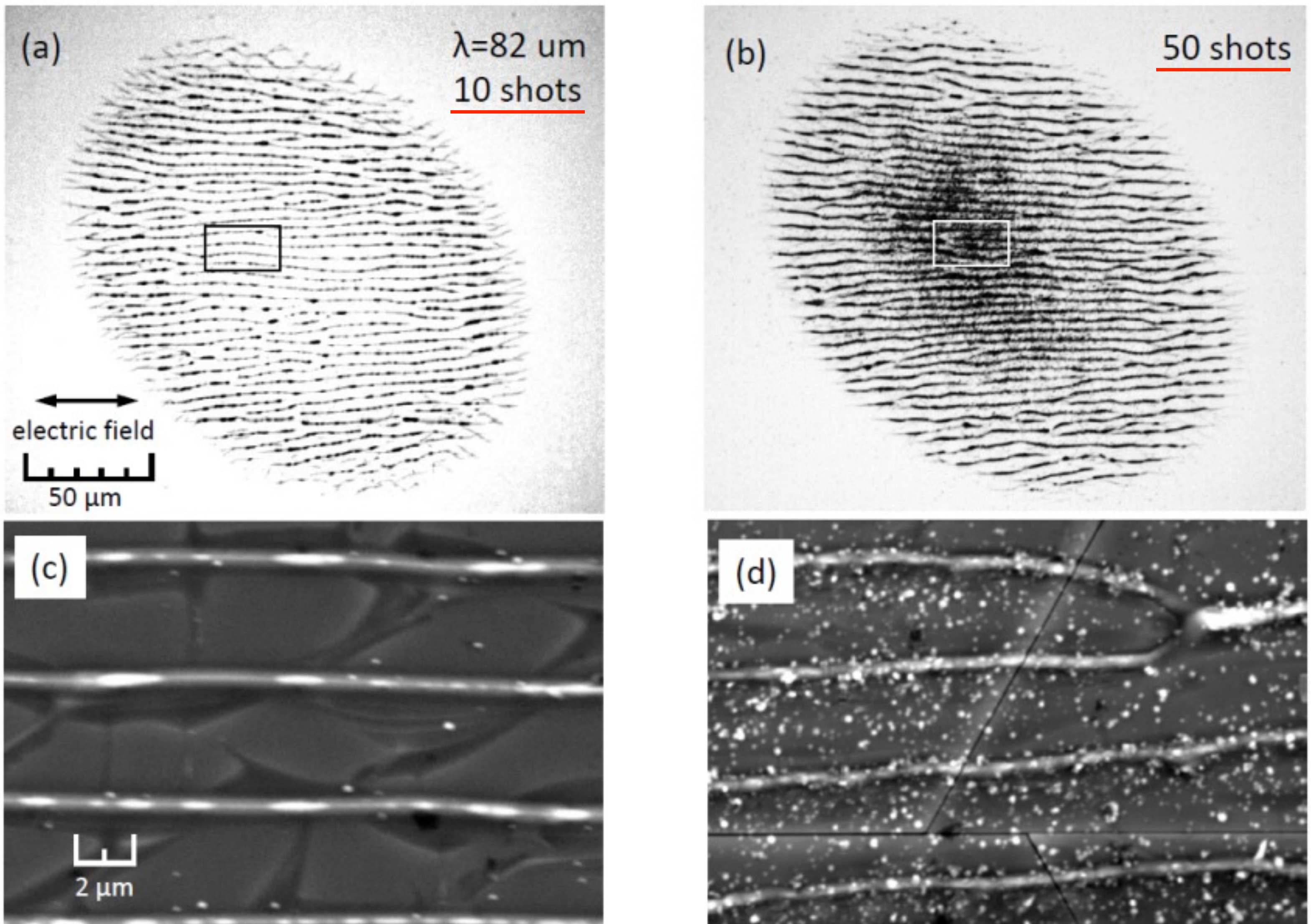
Fluence dependence of LIPSS period.



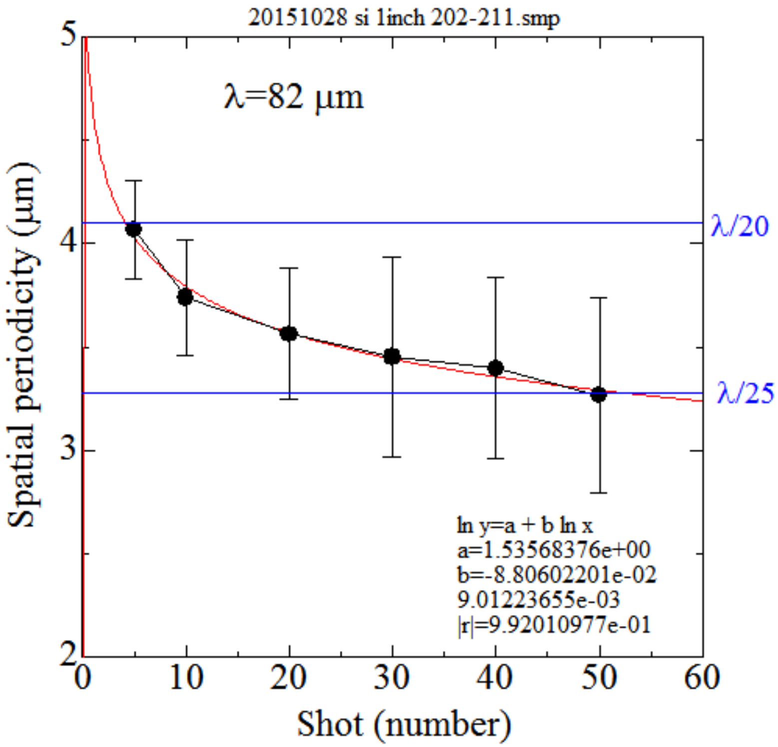
Wavelength dependence of LIPPS period.

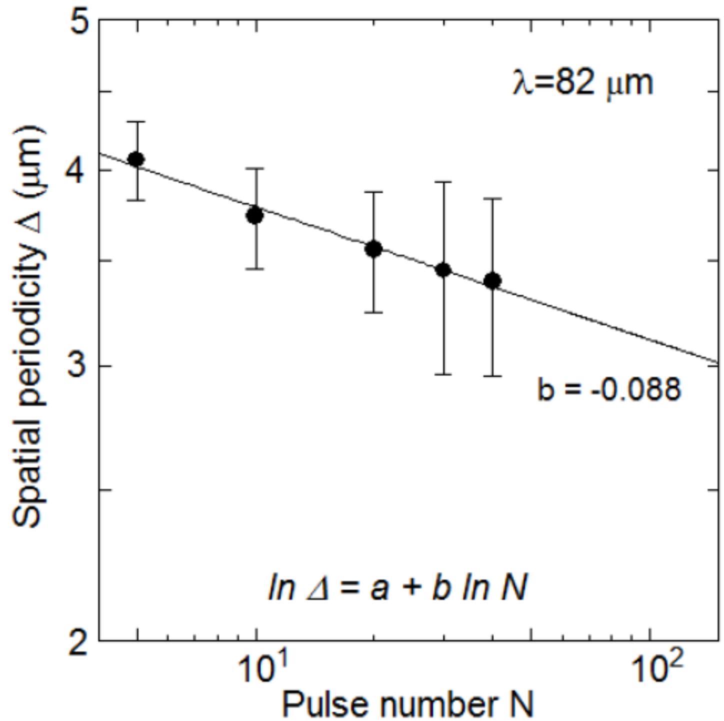
Increase shot number

λ=82 um



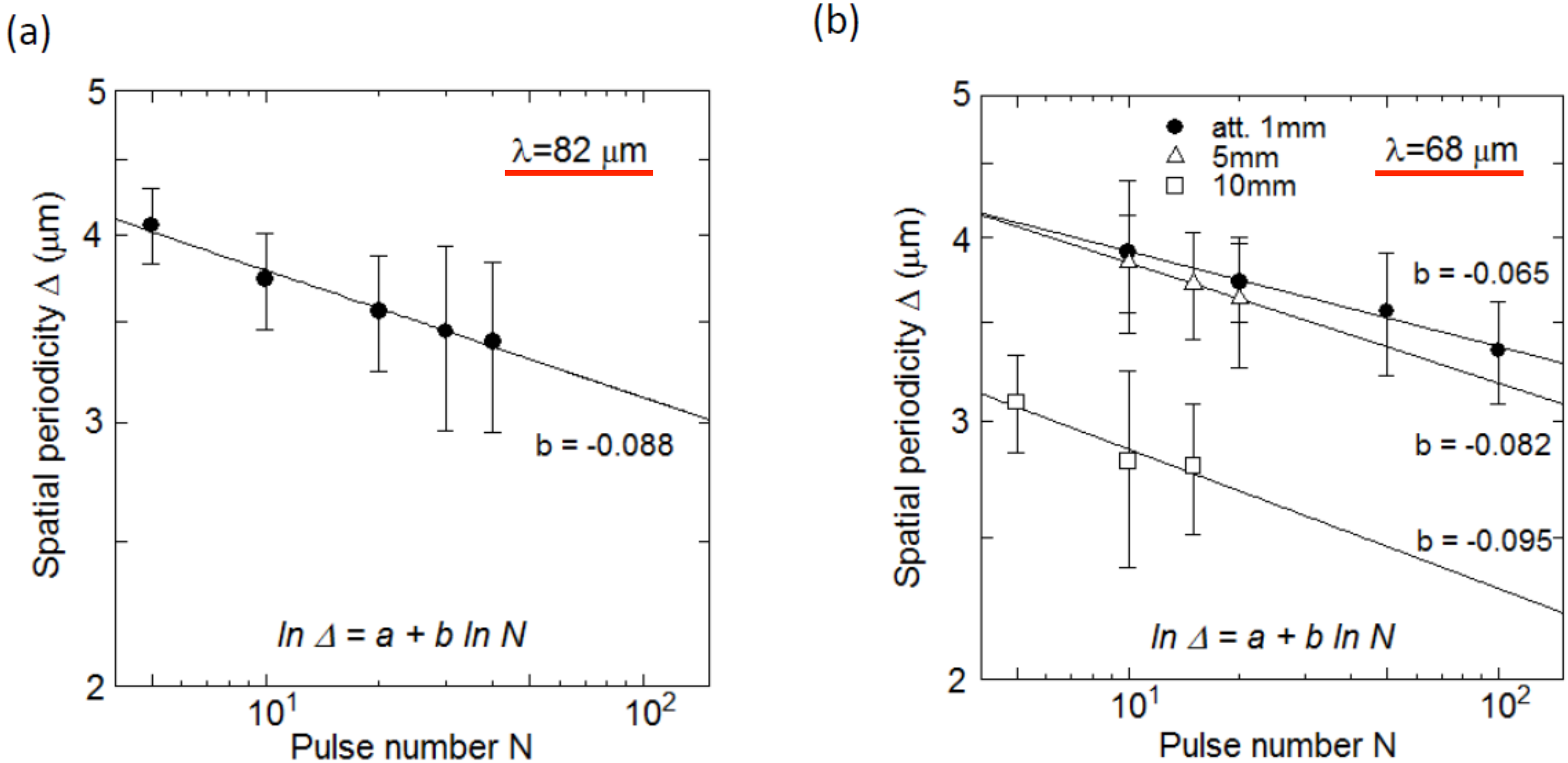
Change for pulse number





Power law

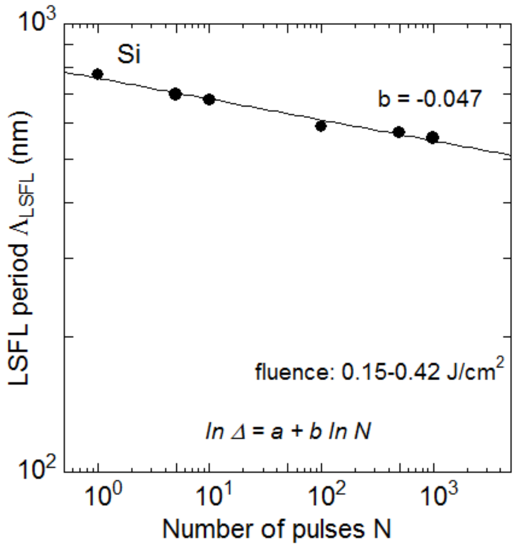
Power law for pulse number



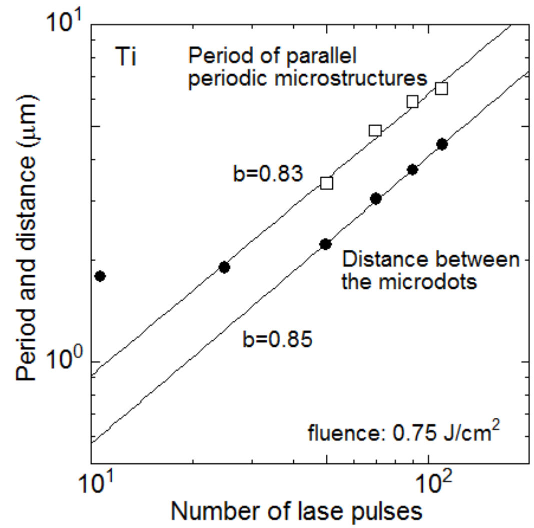
In different wavelength,
different fluence.

In other works (fs-laser)

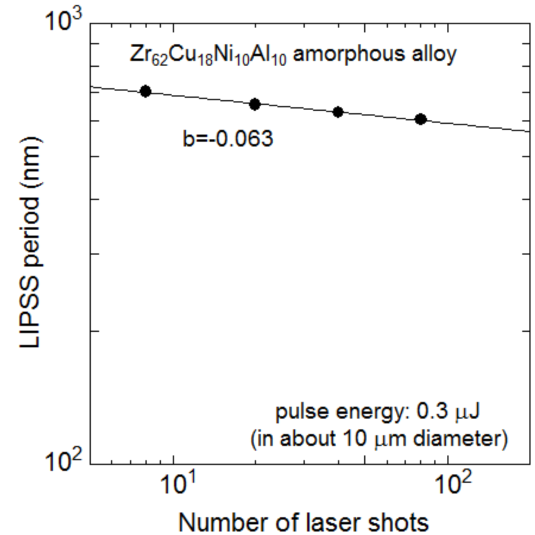
From FIG. 3(a) in ref. 16: J. Bonse et al., J. Appl. Phys. 108, 034903 (2010)



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)

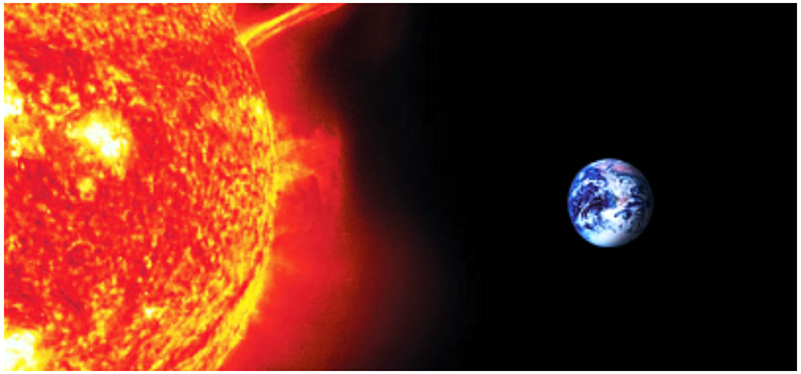


Si, Ti, alloy NIR

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

Scaling law indicates <u>universal mechanism</u> of LIPSS ?

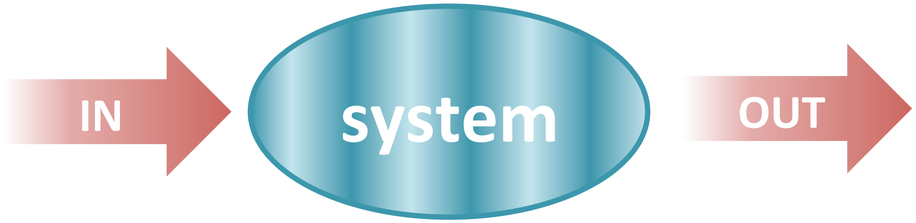
Periodic structures in nature



non-equilibrium
open system

Self-organized dissipative structures

Dissipative structures in non-equilibrium open system



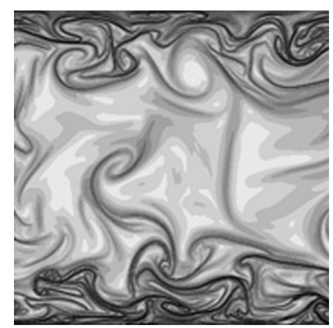
fluctuation in time & space
(pattern, fractal, chaos)

Ilya Prigogine

1977, Nobel Prize in Chemistry

Lower energy

Ordered state

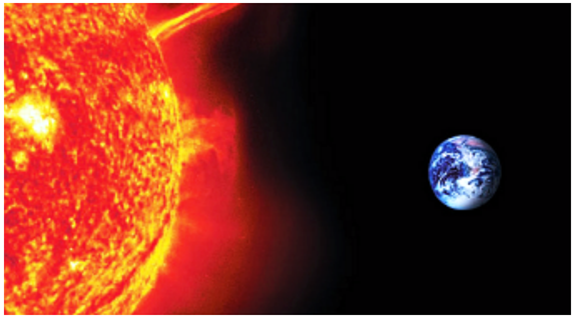


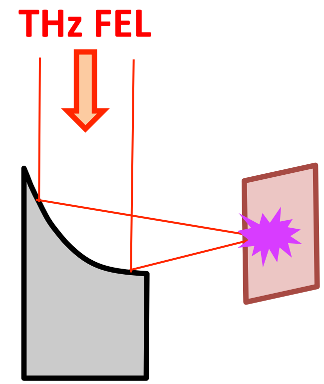
Higher energy

Disordered state

Self-organized criticality (scaling law)

Origin of LIPSS





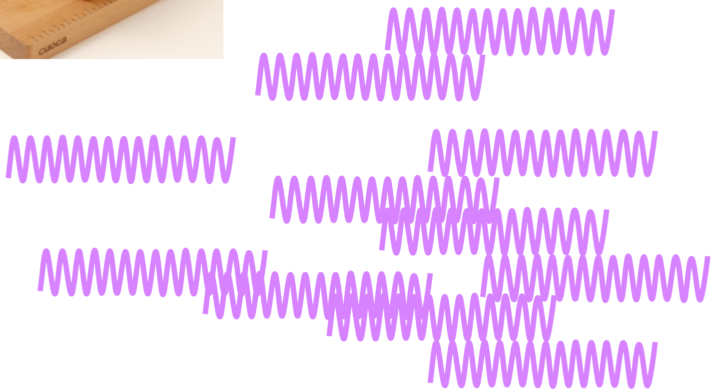
Non-equilibrium open system

Self-organized dissipative structures

Changing in time and space

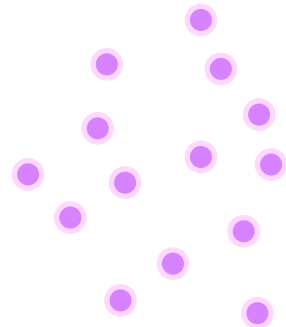
Irizawa et al., Appl. Phys. Lett. ***111****, 251602 (2017)*

Essential point

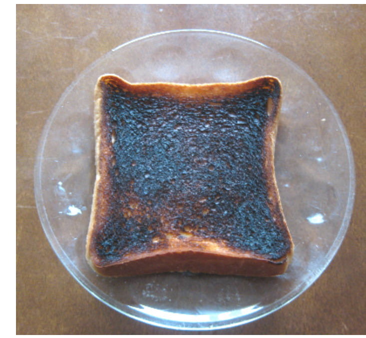


incoherent (time, space)

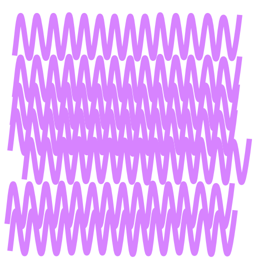
≒



like many photons.

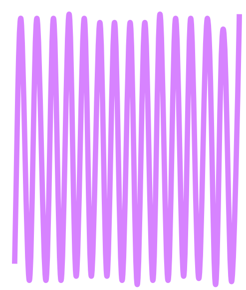


Burn.



coherent (time, space)

=



Intense wave.

Nonthermal.

Many thanks

- Samples & Discussion:
  Takeshi Nagashima (Setsunan Univ.)
  Atsushi Higashiya (Setsunan Univ.)
  Kazuyuki Sakamoto (Chiba Univ.)
  Shin-ichi Kimura (Osaka Univ.)
  Shigemasa Suga (Osaka Univ.)
  Nobuya Mori (Osaka Univ.)

- Experimental setup:
  Masaya Nagai (Osaka Univ.)

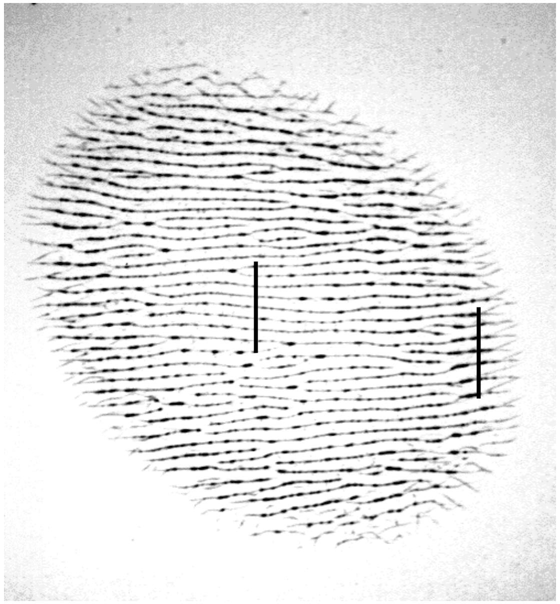
and ISIR THz FEL group:

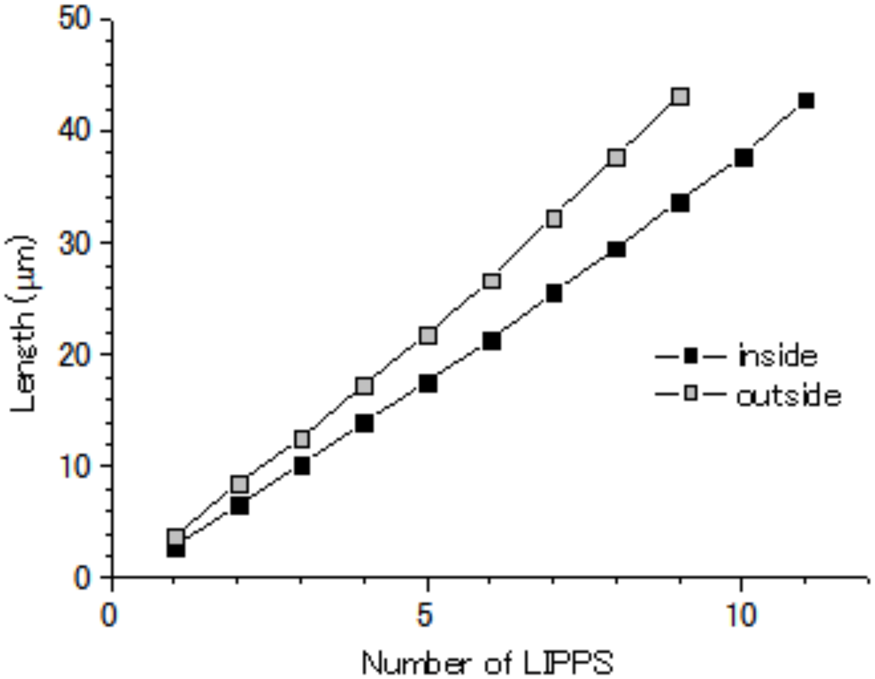
K. Kawase , M. Fujimoto, R. Kato, G. Isoyama, S. Funakoshi, R. Tsutsumi, M. Yaguchi...

Thank you for your attention.

Center vs Periphery

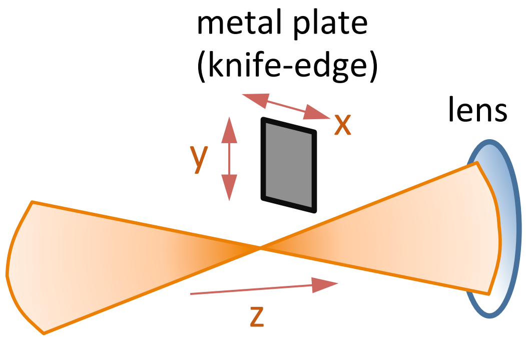
λ=82 um, 10 shots





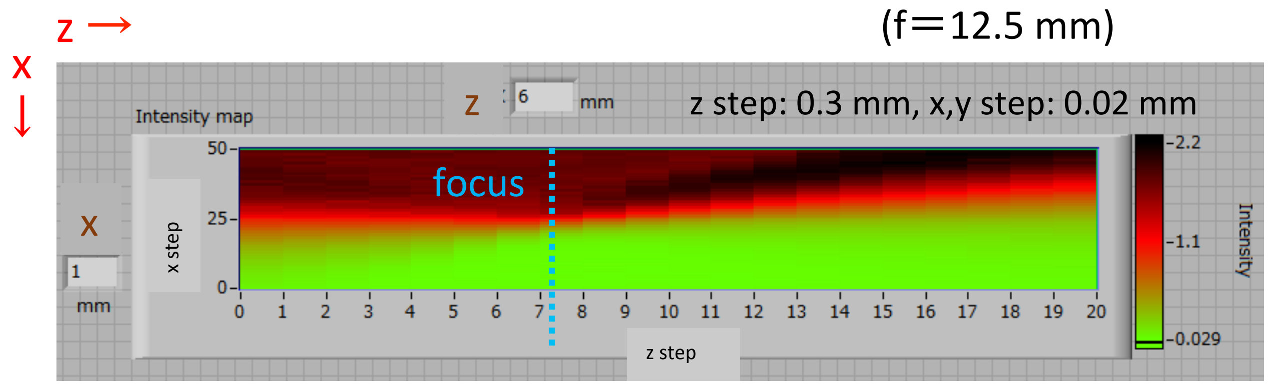
Difference of periodicity between center and periphery.

Beam profile

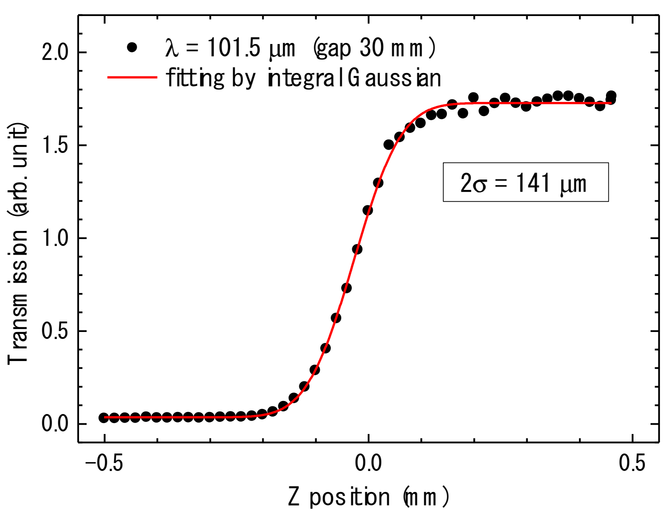


knife-edge scanning

(f＝12.5 mm)

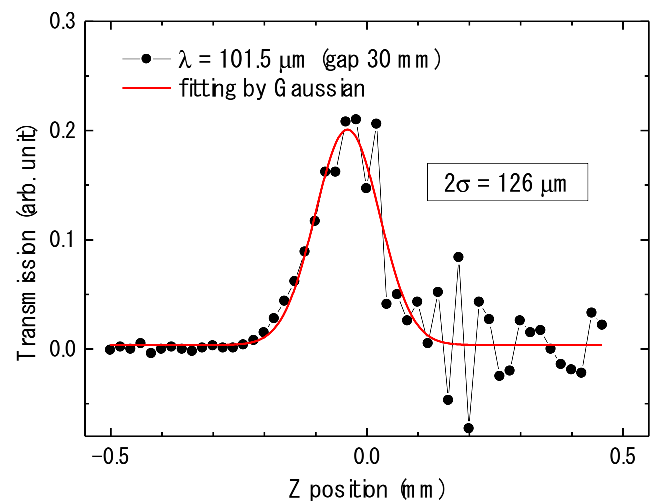


Intensity distribution by knife-edge scanning



x-scanning transmittance (on focus)

derivative



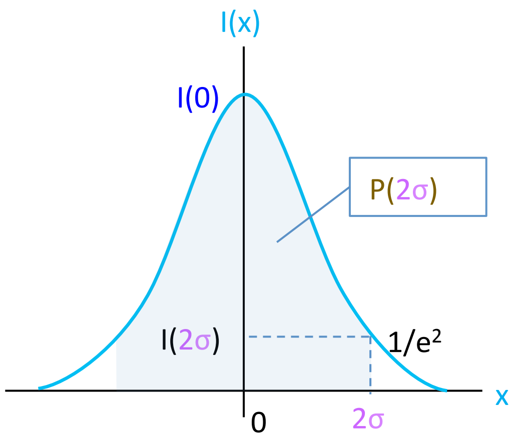
Derivative transmittance (Gauss fit)

Power density & electric field

Most of the power (95.5 %) is in 2σ radius.

P(2σ) [W] = P(∞) [W] ∗ 0.955

Estimated Gaussian radius:
$2\sigma = 0.65 * 10^{-2}$ cm = 65 μm (λ= 70 μm)
(radius: 2σ, standard deviation: σ)



Power distribution (Gaussian)

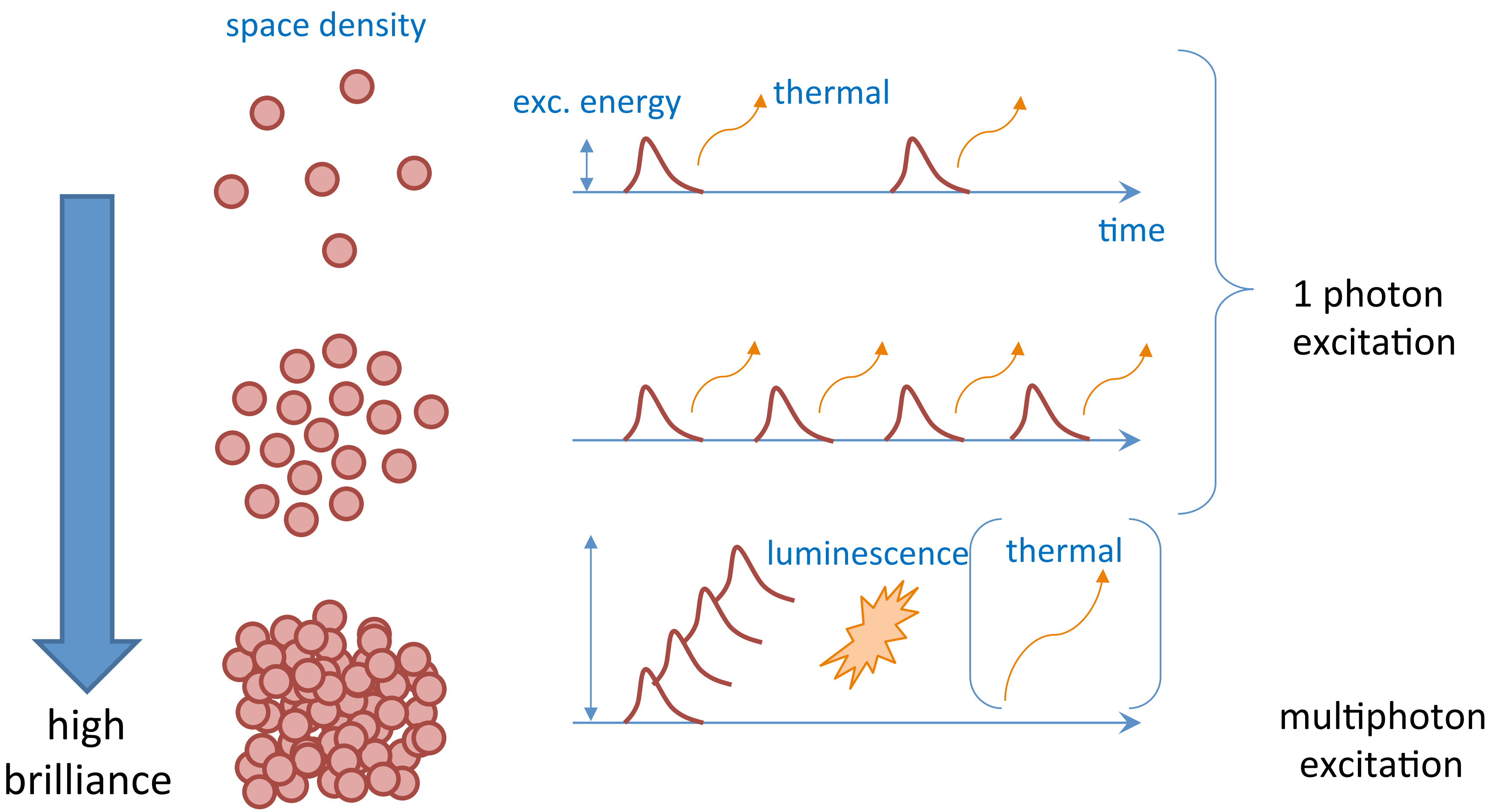
On focus power density and electric field can be estimated from 2σ and input energy.

- Max energy ~5 [mJ] / macro pulse

⇔ 5 [mJ] / 108 pulses / 20 [ps] = 2.32 [MW] ⇒ **35 [GW/cm²] (power density)**

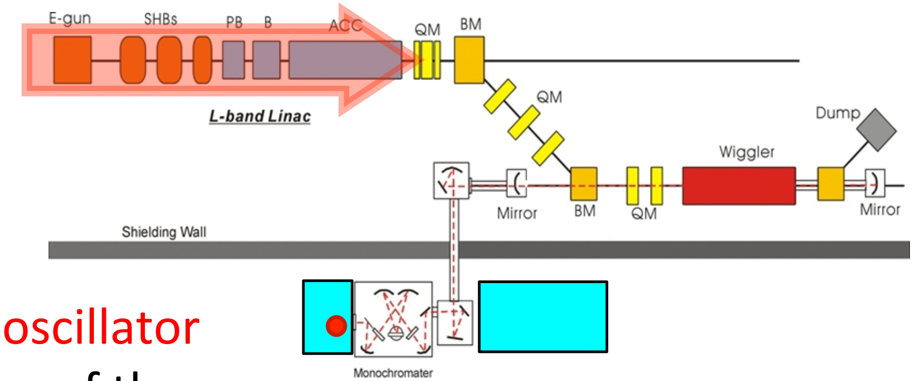
⇔ 35 [GW/cm²] ∗ 377 [Ω] = $13.2 * 10^{12}$ [V²/cm²] ⇒ **3.6 [MV/cm] (electric field)**

Multiphoton excitation



Gap_{Si} = 1.1 eV ~ 10 meV * 100

Improvements of electron beam system



Quartz type master oscillator controls all the timing of the system.

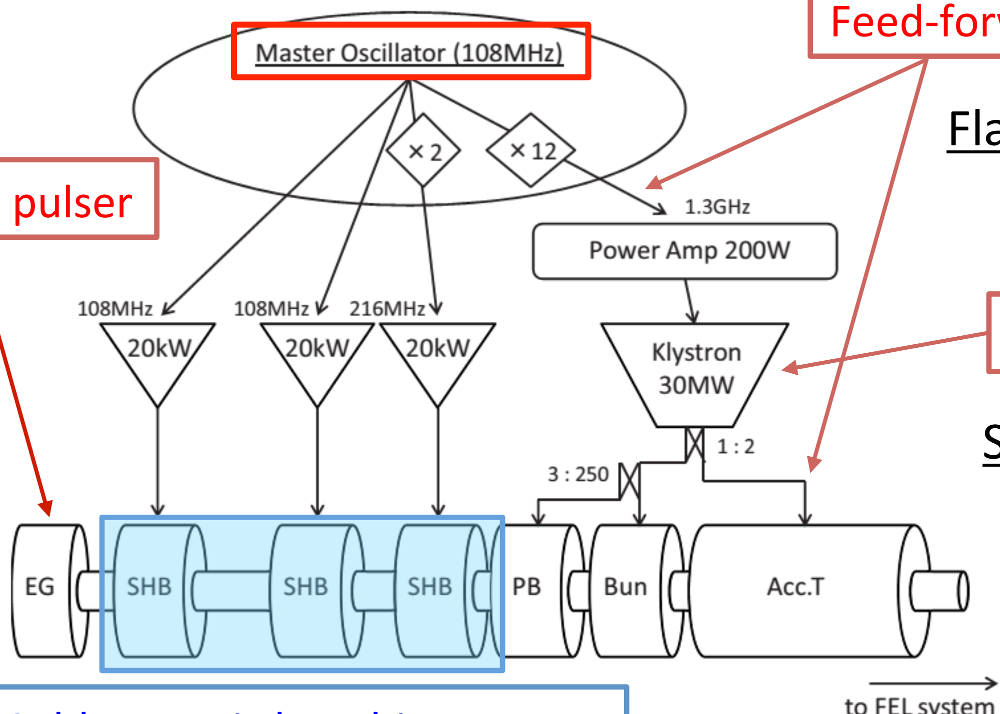
accuracy; ±10^{-8} MHz

Feed-forward RF control (low level)

Flatten RF power and phase

27 MHz Grid pulser

Increase bunch charge



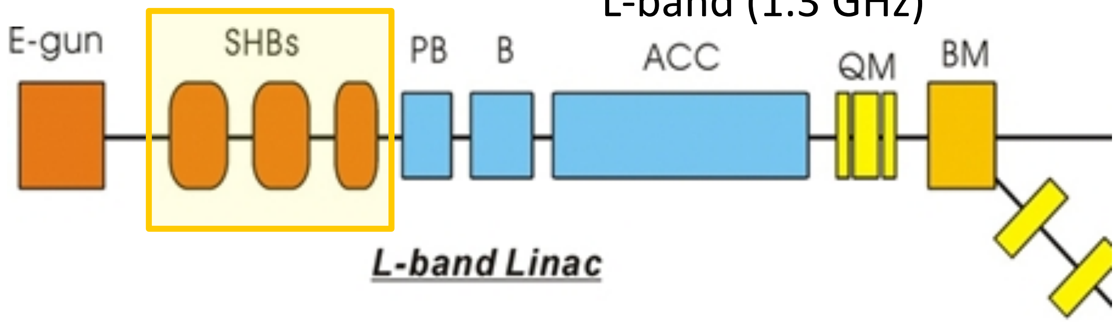
Semiconductor type switch

Stabilize RF power and phase

Subharmonic bunching system

Sub Harmonic Bunching

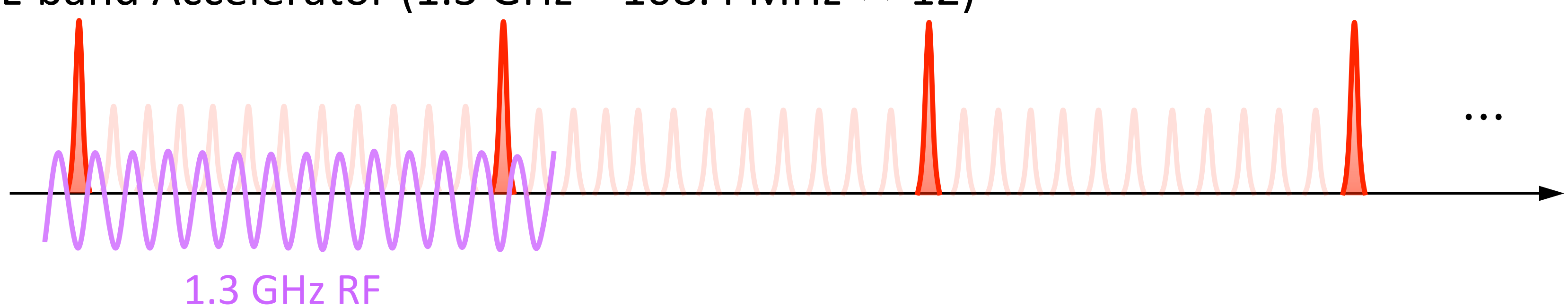
L-band (1.3 GHz)



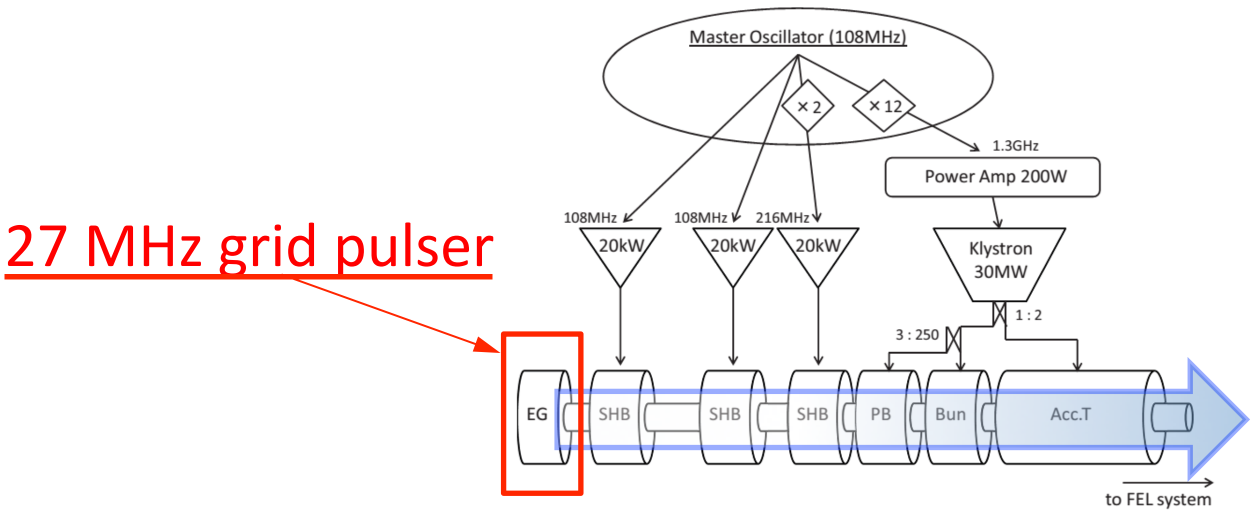
E-gun (CW)

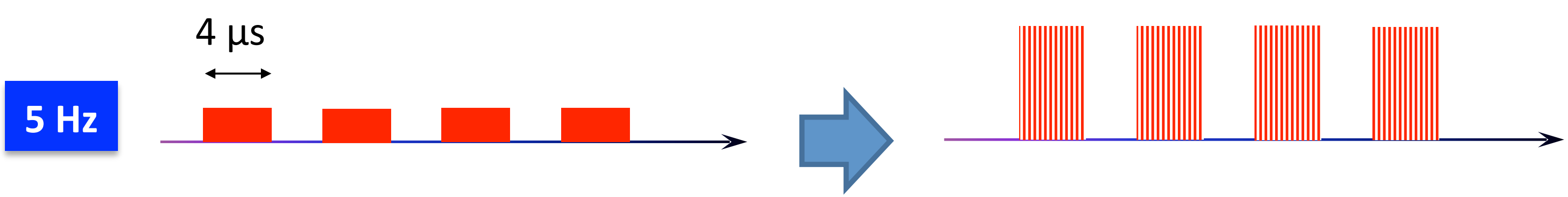
Sub Harmonic Buncher (108.4 MHz)

L-band Accelerator (1.3 GHz = 108.4 MHz × 12)



27 MHz grid pulser installed in e−gun

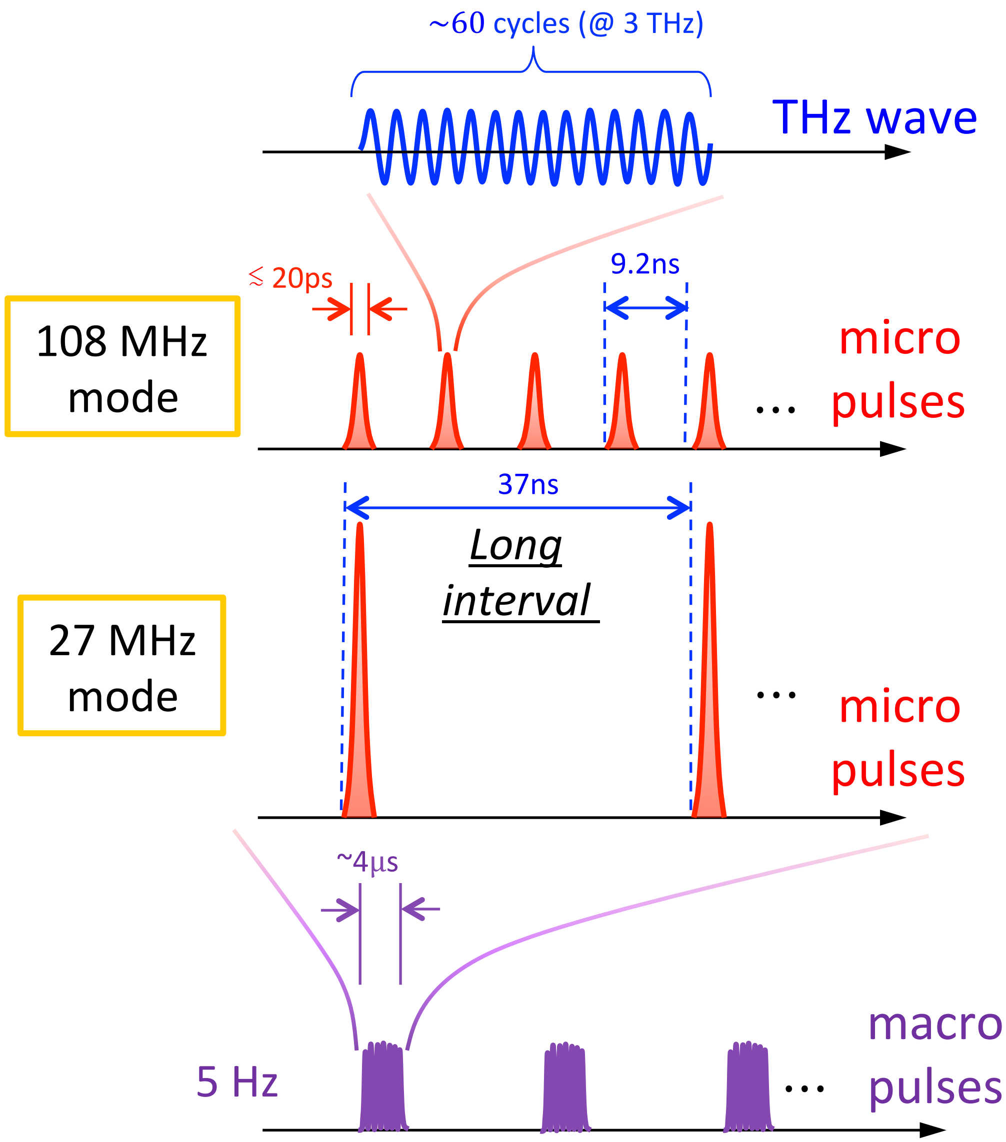




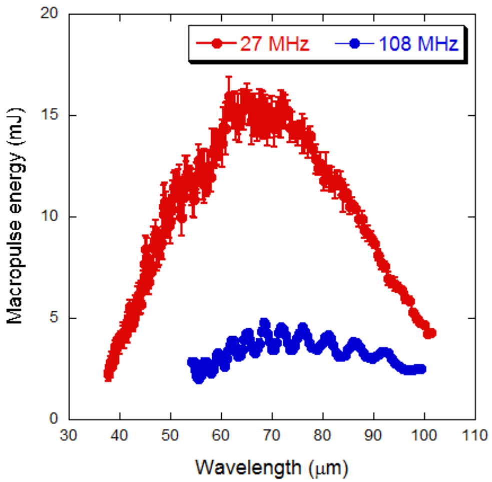
108 MHz mode **27 MHz mode**

CW e-beams is separated by 27 MHz.
The bunch number is reduced by a quarter (27 MHz = 108 MHz / 4).

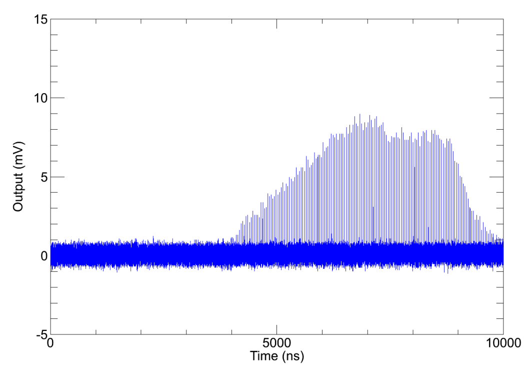
Pulse structures of THz-FEL



As a result, pulse structures of FEL reflect the e-bunch structures.



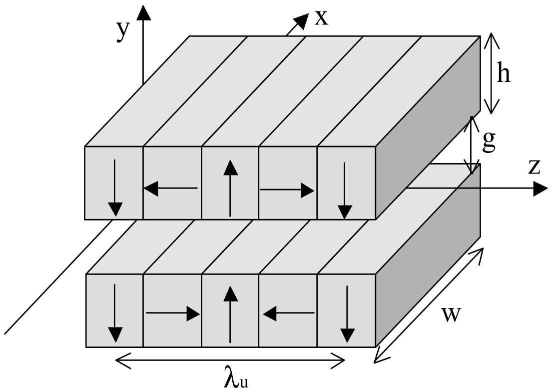
FEL spectra of 108 and 27 MHz modes.



Observed FEL micro pulses (in one macro pulse)

Undulator

Halbach type undulator



Deflection constant (planar type)

$$K_{rms} = K_0/\sqrt{2} \qquad K_0 = \frac{e}{2\pi mc} B_0 \lambda_u = 93.37\, B_0 \lambda_u$$

$$B_0 = 2 B_r \cdot F_n(4) \cdot G_n \cdot H_n$$

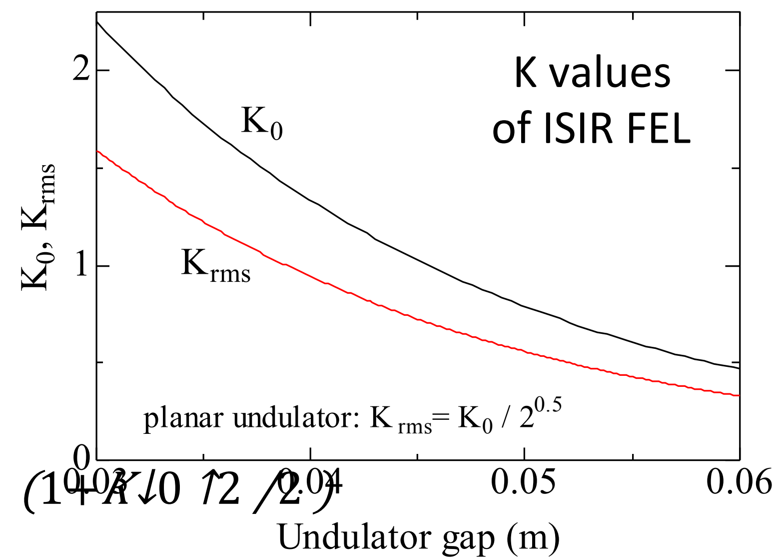
$$= 2 B_r \cdot \frac{\sin(\pi/4)}{\pi/4} \cdot \exp(-\pi g/\lambda_u) \cdot \{1 - \exp(-2\pi h/\lambda_u)\}$$

amplitude factor *F*: magnet number per period, *G*: undulator gap, *H*: magnet height

variable

Parameters of magnet

Period length λ_u:	60 mm
Height h:	20 mm
Magnet gap g:	30-60 mm
Remanent magnetic field B_r:	1.32 T



Wavelength of emitted light

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + K_{rms}^2\right) = \frac{\lambda_u}{2\gamma^2}\left(1 + K_0^2/2\right)$$

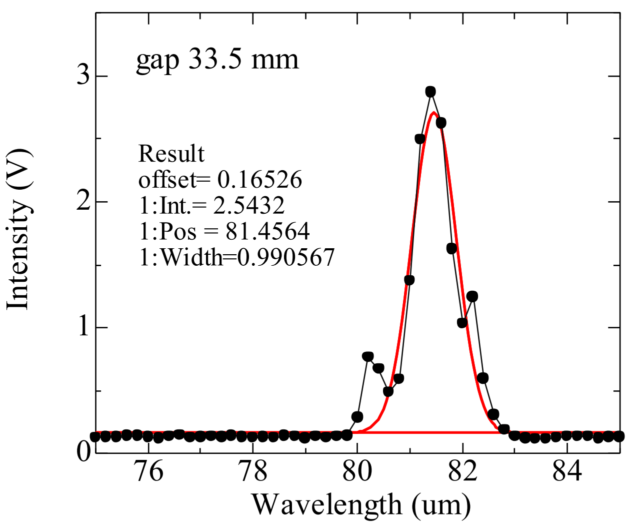
Gap and wavelength relation

<u>Wavelength of emitted light</u>

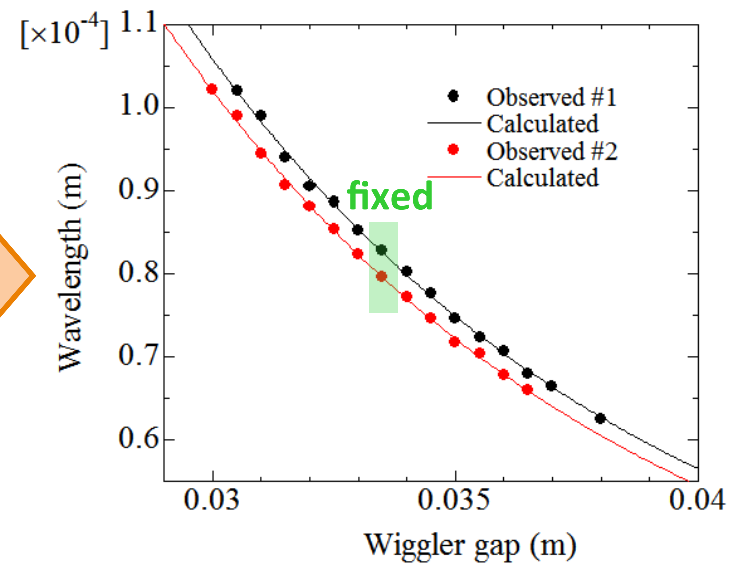
$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K_0^2}{2}\right)$$

$$K_0 = \frac{e}{2\pi mc} B_0 \lambda_u = 93.37 B_0(g) \lambda_u$$

Once Lorentz factor ϒ can be derived from an observed wavelength at a certain gap, required gap size for an expected wavelength can be estimated using this correlation function.



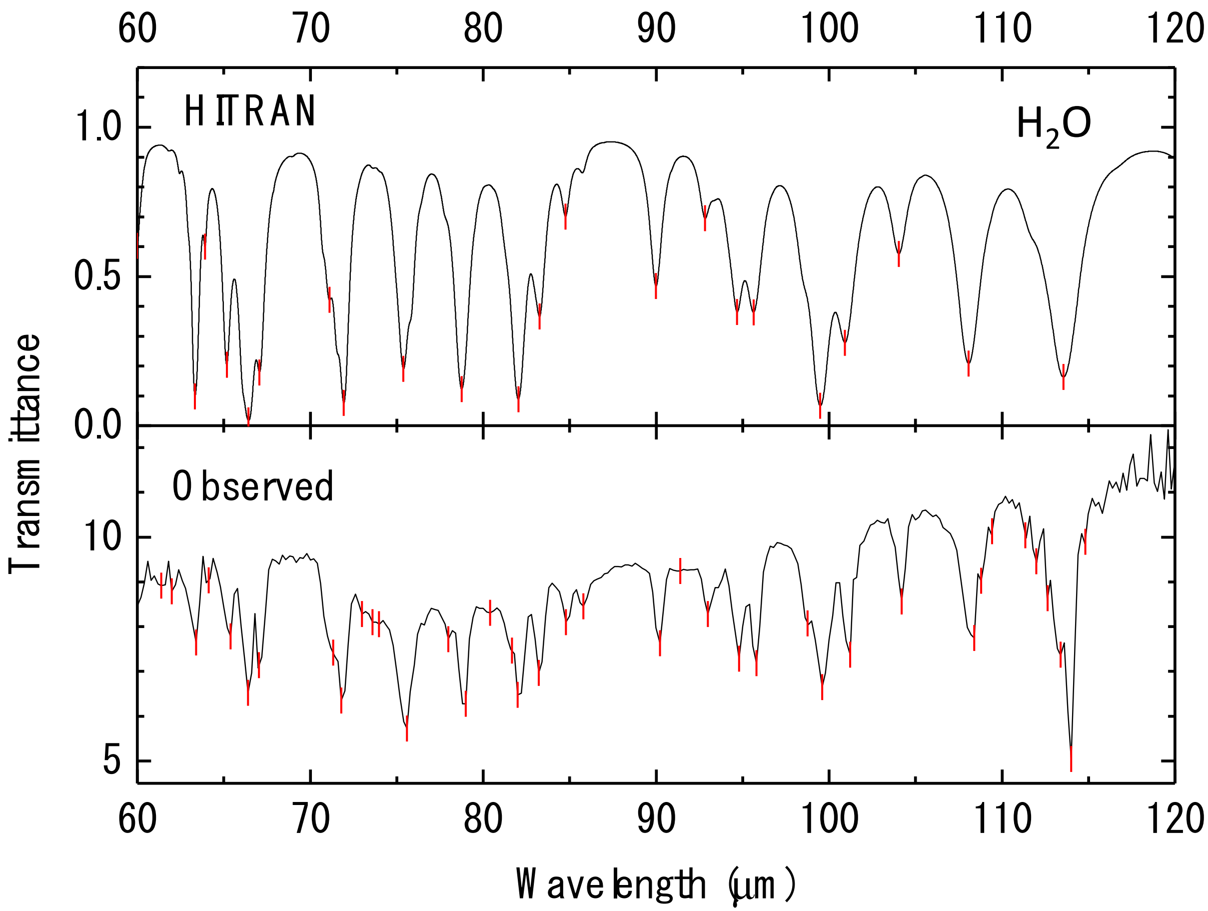
Observed wavelength at gap 33.5 mm



Gap-WL correlation is varied by a beam lasing condition.

Center of FEL wavelength can be chased by controlling gap size.

Spectroscopy



Simulation and measured water vapor absorptions