JSPS-ESF CTC program
Nan0-Science and Engineering in Superconductivity

# Intense, Coherent and Continuous THz Electromagnetic Waves from High-$T_c$ Superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ Single Crystal Mesa Structures

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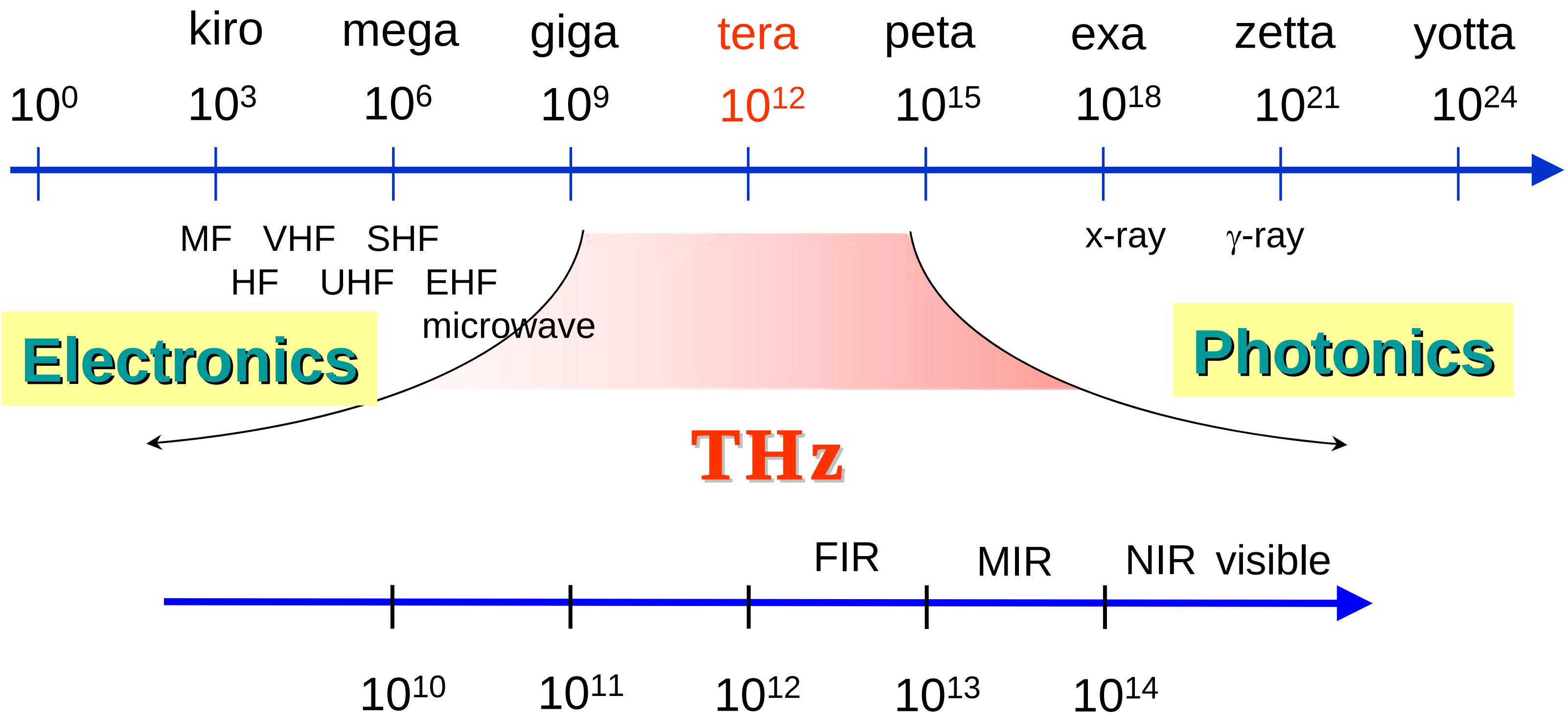
# Outline

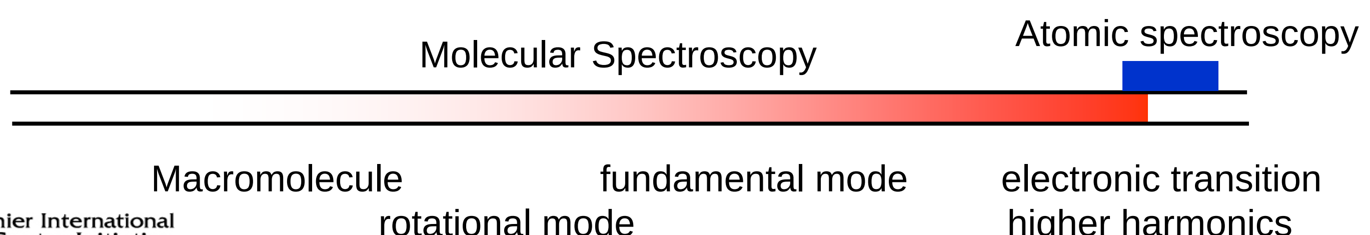
- *THz waves and THz gap*
- *Single crystals*
- *Observation of THz emission*
- *Emission of electromagnetic waves*
- *Experimental setup*
- *Mesa structures*
- *Two mechanisms: **STAR-emitter** and **CASER***
- ***Applications***
- *summary*

*Reference;*
*Ozyuzer et al., Science, **318** 1291 (2007).*
*K. Kadowaki, et al., Physica C 468, 634-639 (2008).*

# FREQUENCY (Hz)




| | | | | | |
|---|---|---|---|---|---|
| frequency | 10[GHz] | 100[GHz] | 1 [THz] | 10[THz] | 100 [THz] |
| wave length | 3[cm] | 3[mm] | 300[μm] | 30[μm] | 3[μm] |
| wave number | 0.33[cm$^{-1}$] | 3.3[cm$^{-1}$] | 33[cm$^{-1}$] | 330[cm$^{-1}$] | 3300[cm$^{-1}$] |



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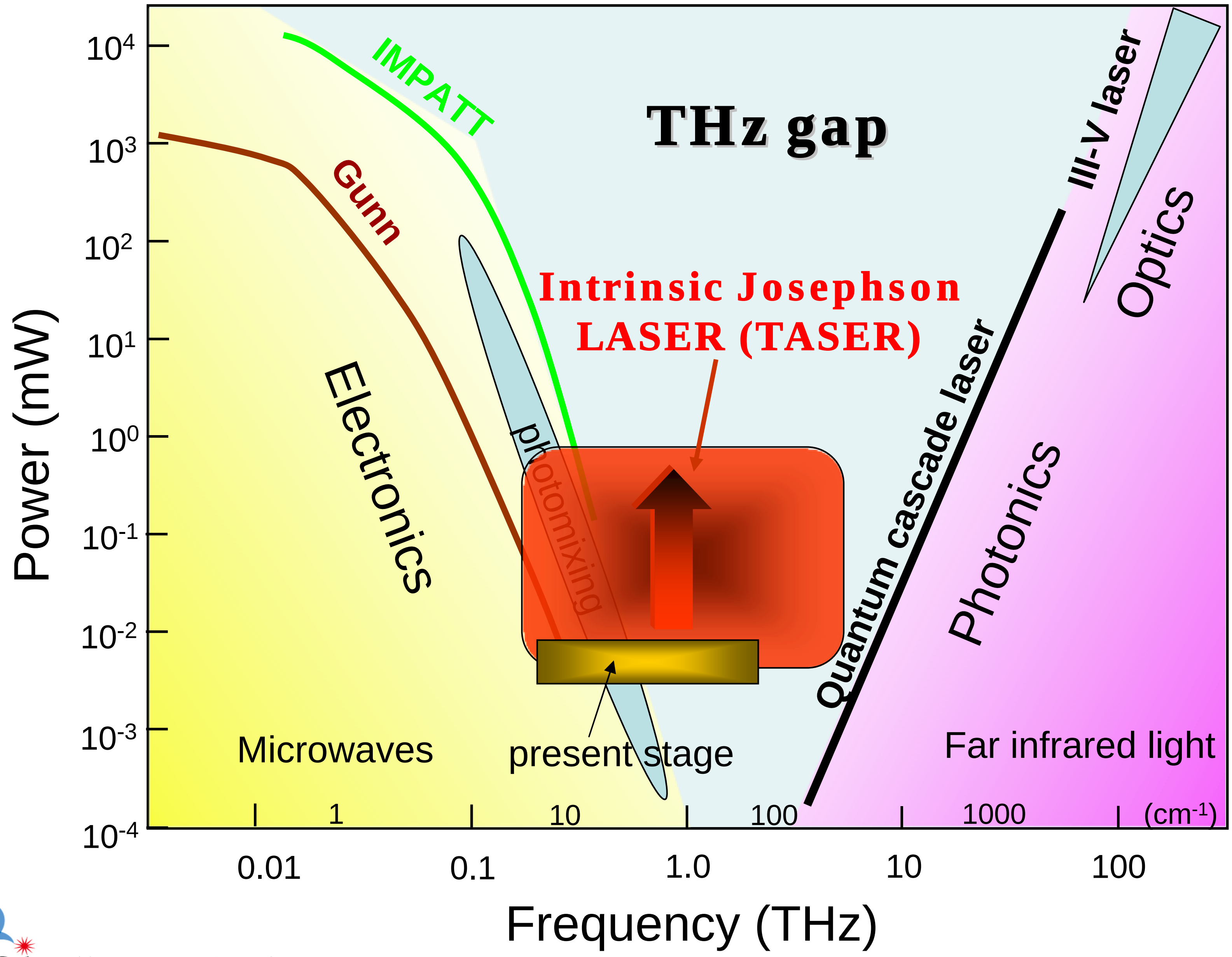
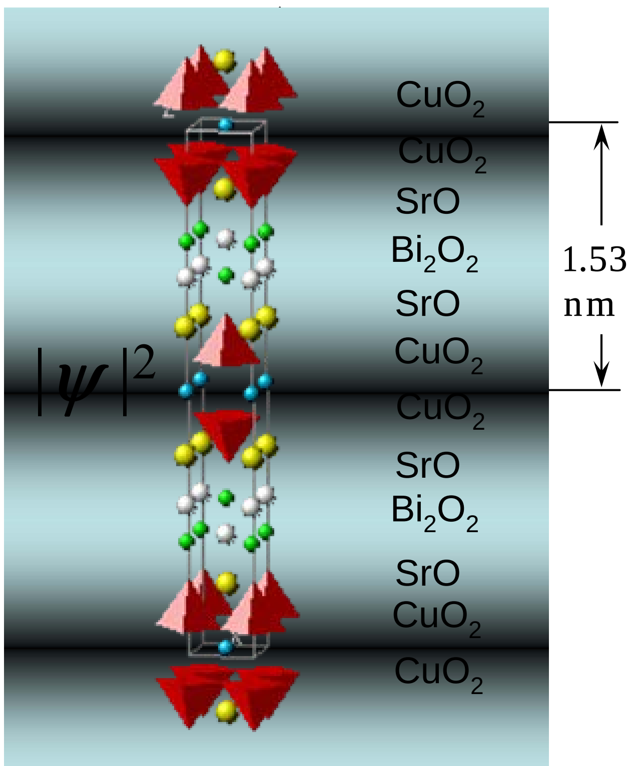


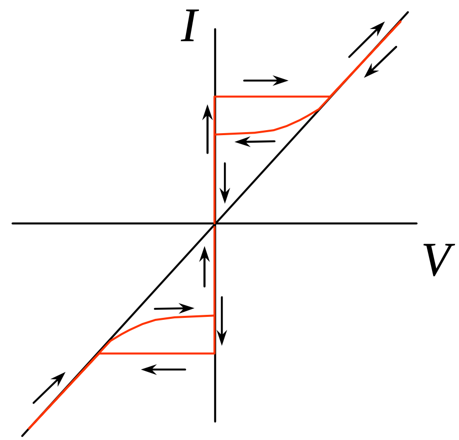

*After M. Tonouchi, Nature Photon. 1, 97 (2007).*

# Intrinsic Josephson Junctions: Crystal Structure

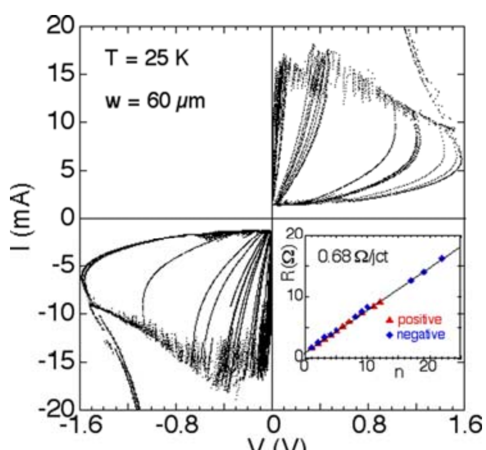
*unit cell of Bi2212*
*Bi-2212 order parameter $\psi$*

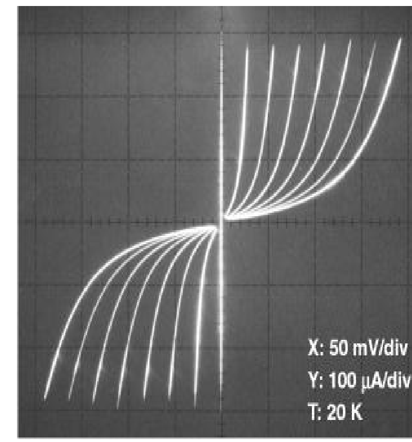



*Intrinsic inhomogeneity*




*I-V characteristics in conventional planer junctions*




*I-V Characteristics in IJJ's*

*multilayer effects*

⇩

*1 $\mu m$ corresponds to n~760*

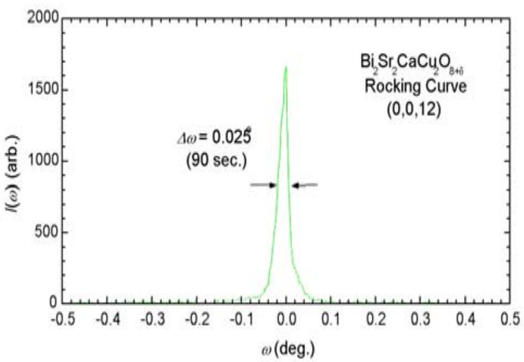
# Single Crystal of $Bi_2Sr_2CaCu_2O_{8+\delta}$

***IJJ's are densely packed at the atomic level!***

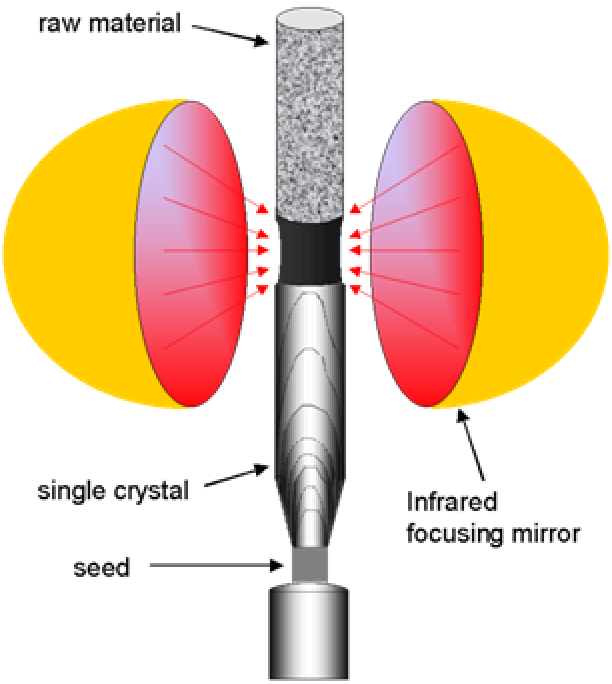
*Large anisotropy parameter γ*

| *underdope* | | *overdope* |
|---|---|---|
| γ~1000 | ⇒ | γ~80 |

*Rocking Curve*




*Single Crystal*




High Quality Large Single Crystal Growth
Sophisticated ILSTSFZ Method

# Mesa Structures

## 1. Conventional mesa

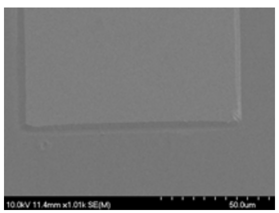
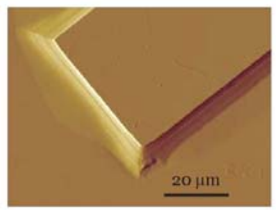
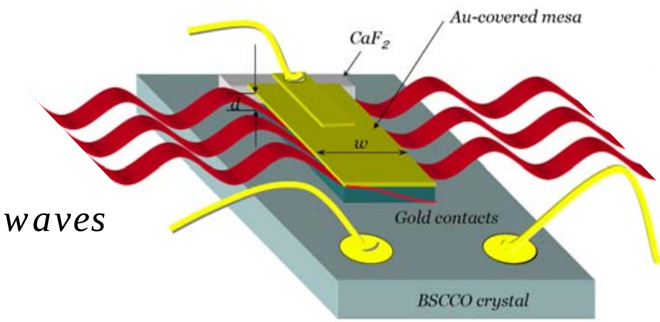




*Photo of the sample by SEM*

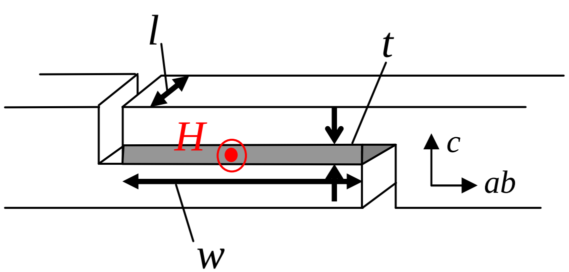
THz *waves*

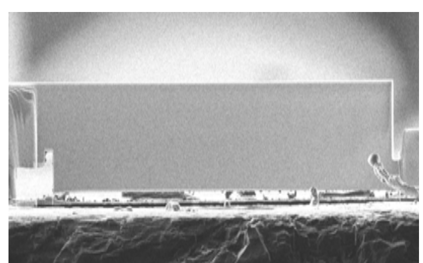



THz *waves*

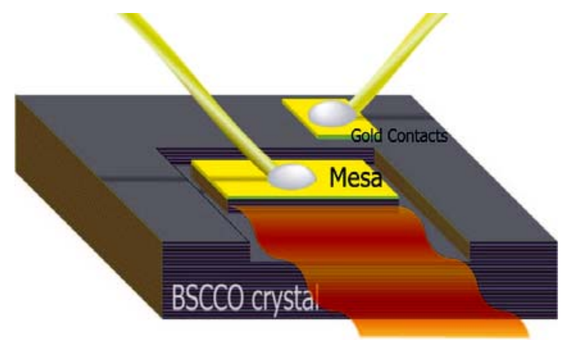
*Schematic view of the sample*

## 2. Z-type mesa

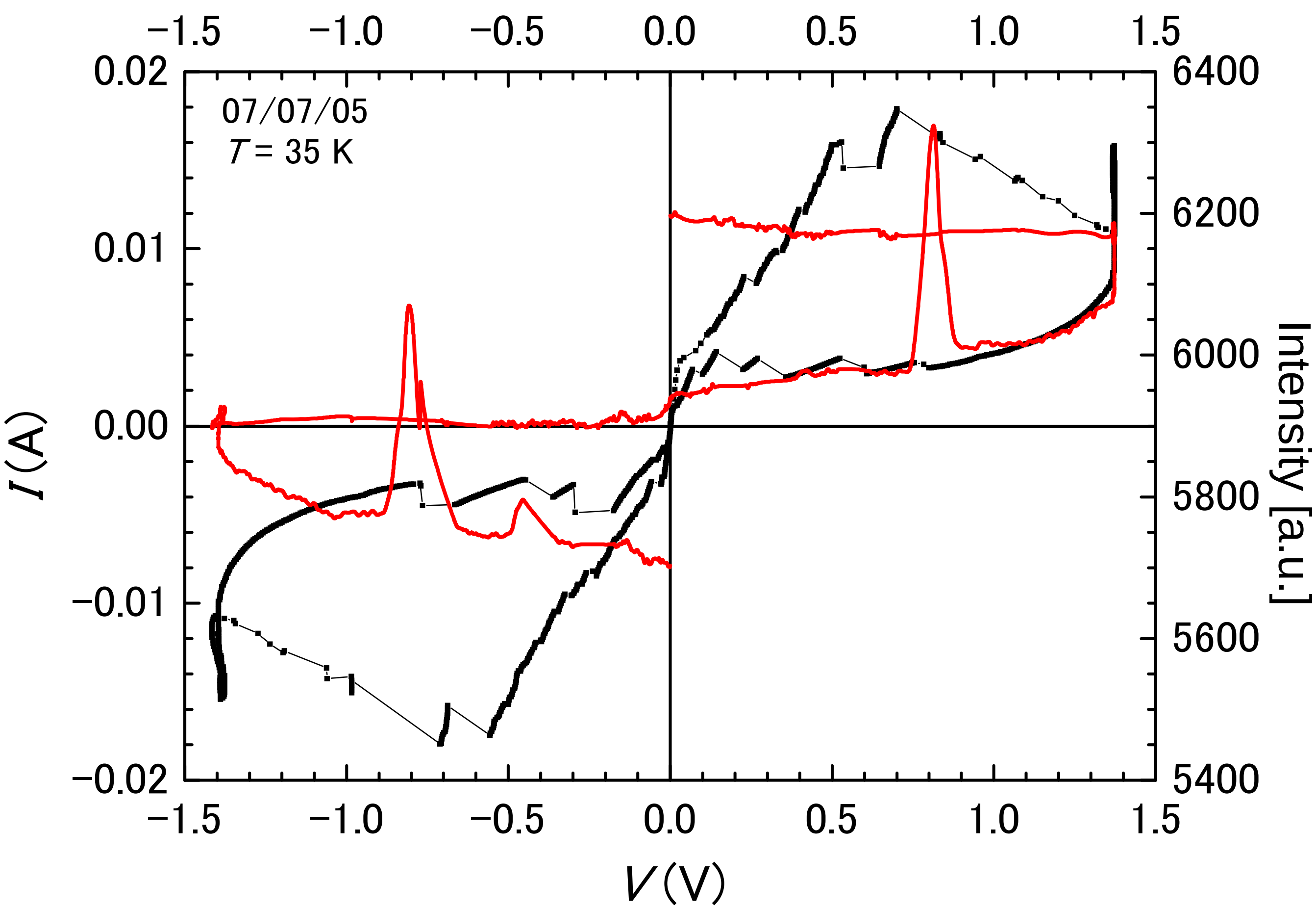


## 3. Groove type mesa



# Experimental Results

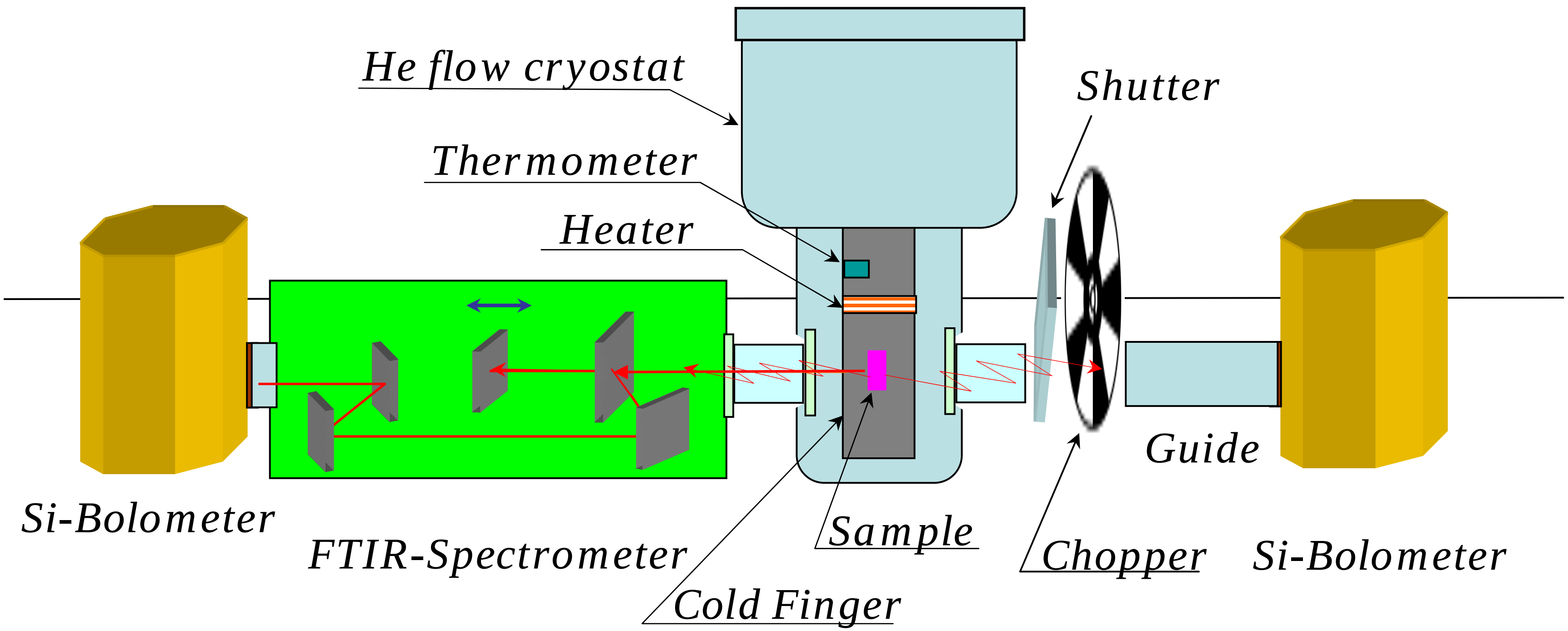


# THz Emission

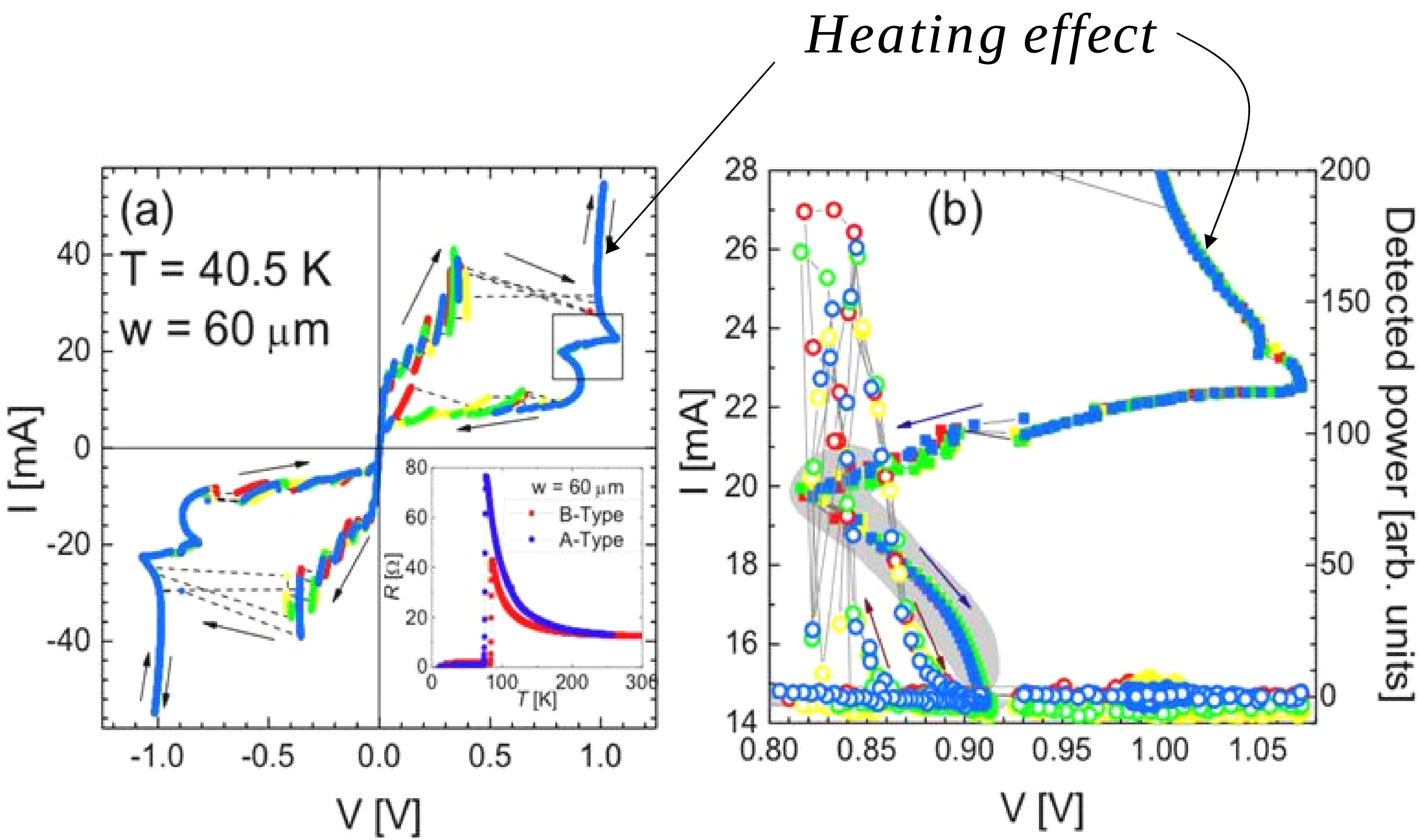
| $L$ (μm) | $w$ (μm) | $d$ (μm) | $f_{cal}$ (GHz) | $f_{obs}$ (GHz) | $2f_{obs}$ (GHz) | $3f_{obs}$ (GHz) | $4f_{obs}$ (GHz) |
|---|---|---|---|---|---|---|---|
| 300 | 100 | 1.0 | 358 | 357 | - | - | - |
| 300 | 80 | 1.0 | 447 | 480 | 990 | - | - |
| 300 | 60 | 1.0 | 597 | 560 | - | - | - |
| 400 | 60 | ~2 | 597 | 624 | 1249 | - | - |
| 400 | 60 | ~1.0 | 597 | 648.3 | 1296 | 1944 | 2589 |
| 300 | 40 | 1.0 | 894 | 870 | | | |

# Experimental Setup

*simultaneous detection*



# *I*-*V* Characteristics and THz Detection



# More Recent Works

- E. Kume, *et al*., Appl. Phys. Lett **75** (1999) 2809.
  - film, in zero field, no cavity
- I. Iguchi, *et al*., Phys. Rev. **B62** (2000) 5370.
  - $P_{out}$~1 μw, YBCO film, zero field, no cavity
- K. Lee, *et al*., Phys. Rev. **B61** (2000) 3616.
  - YBCO film, zero field, no cavity
- I. E. Batov, *et al*., Appl. Phys. Lett. **88** (2006) 262504.
  - $P_{out}$=~pW, BSCCO, zero field, no cavity
- K. Kadowaki, *et al*., Physica **C 437-438** (2006) 111.
  - $P_{out}$=~mW, BSCCO, Xtal, in fields
- M. H. Bae, *et al*., Phys. Rev Lett. **98** (2007) 027002.
  - $P_{out}$=~nW, BSCCO, Xtal, in fields

c.f.
Blog Yamashita: http;//tyamasuper.exblog.jp/

# Radiation Power *P* vs. *n*

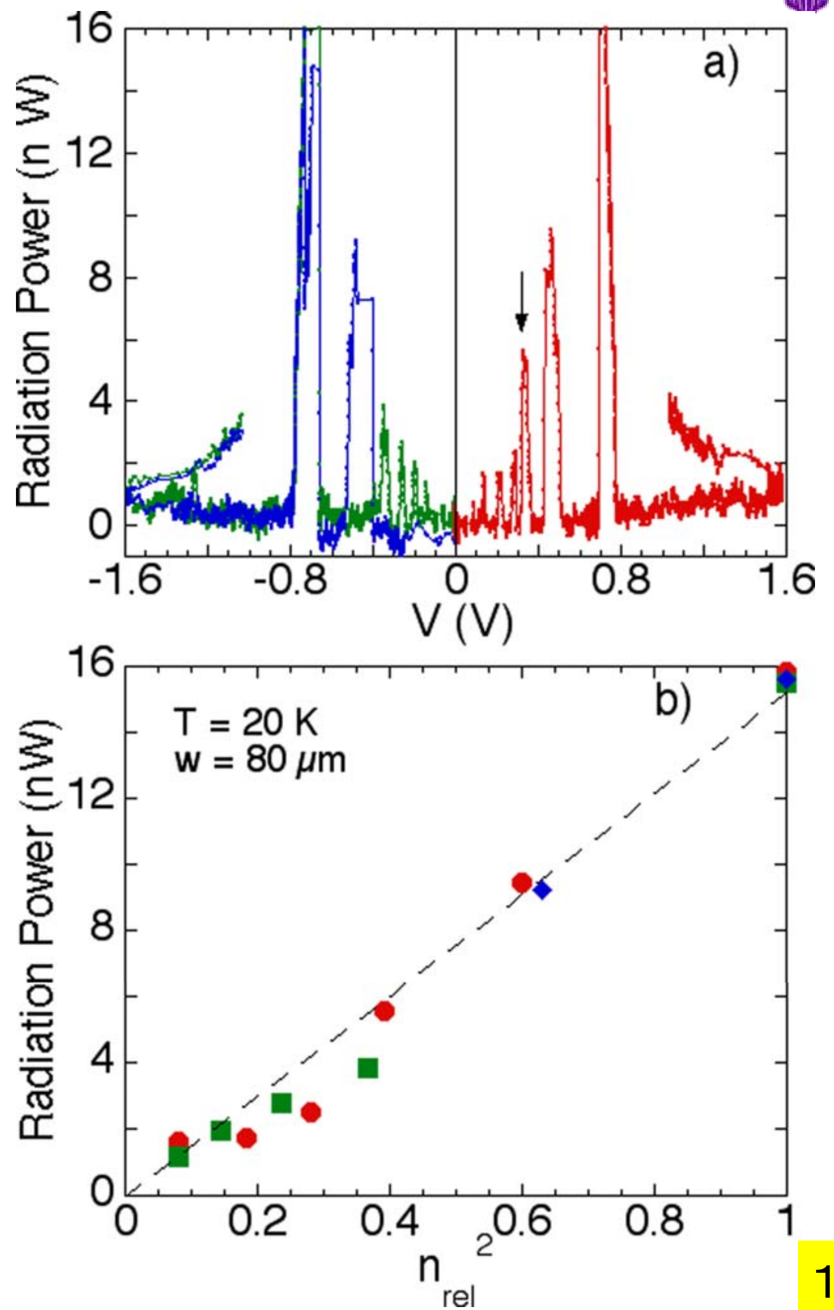
$$P_{rad} \propto n^2$$

**Coherent Radiation!**

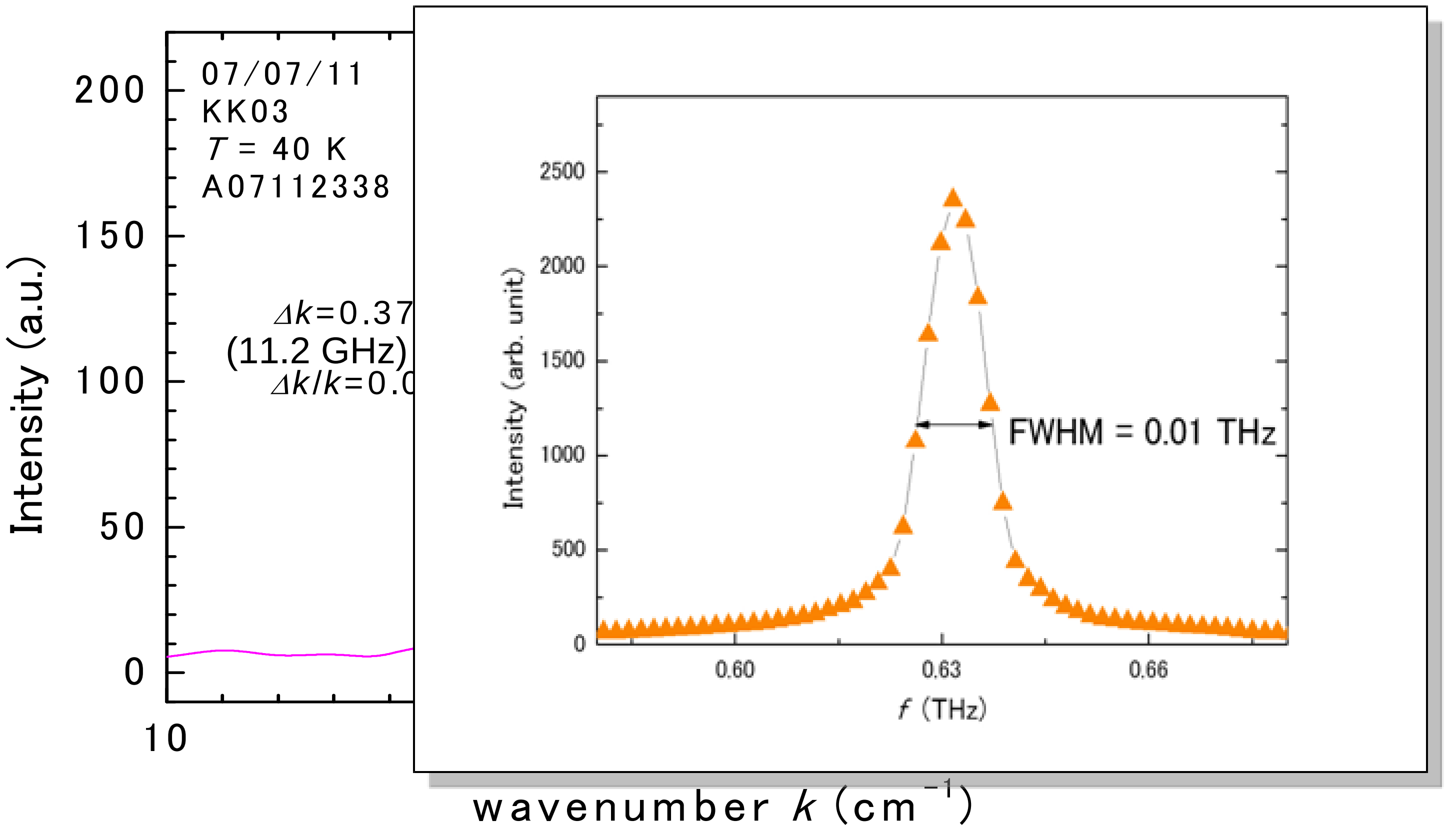
*single layer JJ*: $P_{single} \sim \mathrm{pW}$

$10^5$-$10^6$ times more power!

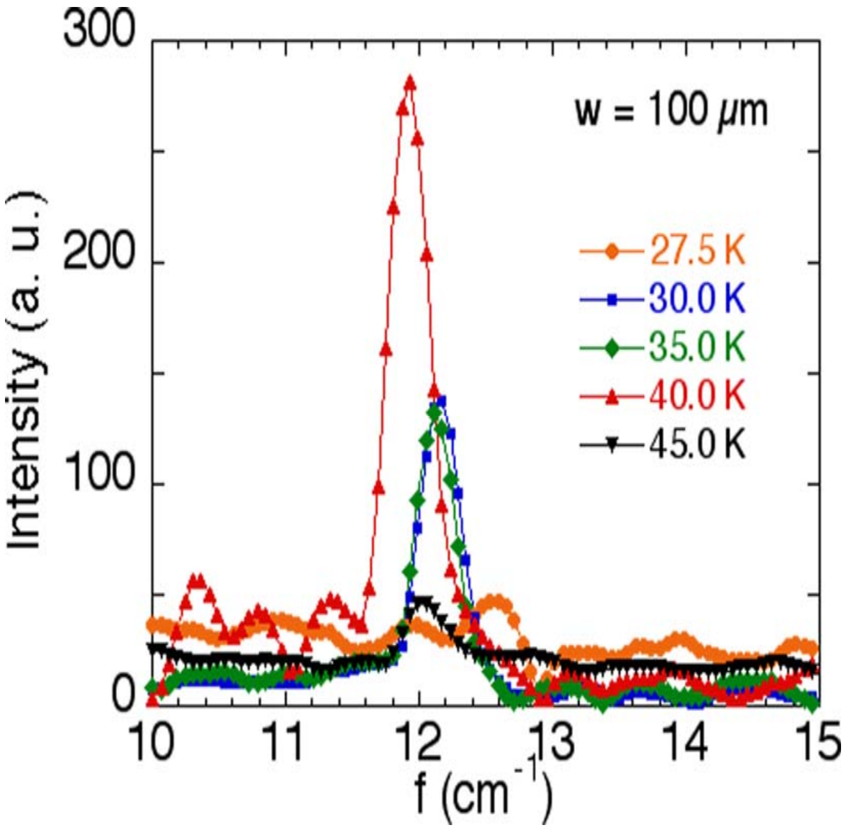
**multilayered IJJ:**
$P_{IJJ} \geq \mu\mathrm{W} - \mathrm{mW}$

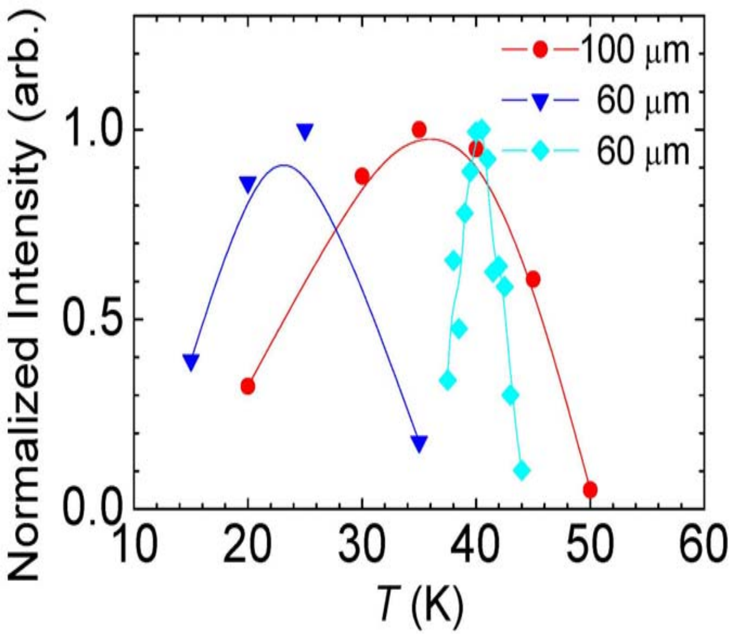


# Radiation Spectra



# Temperature Dependence

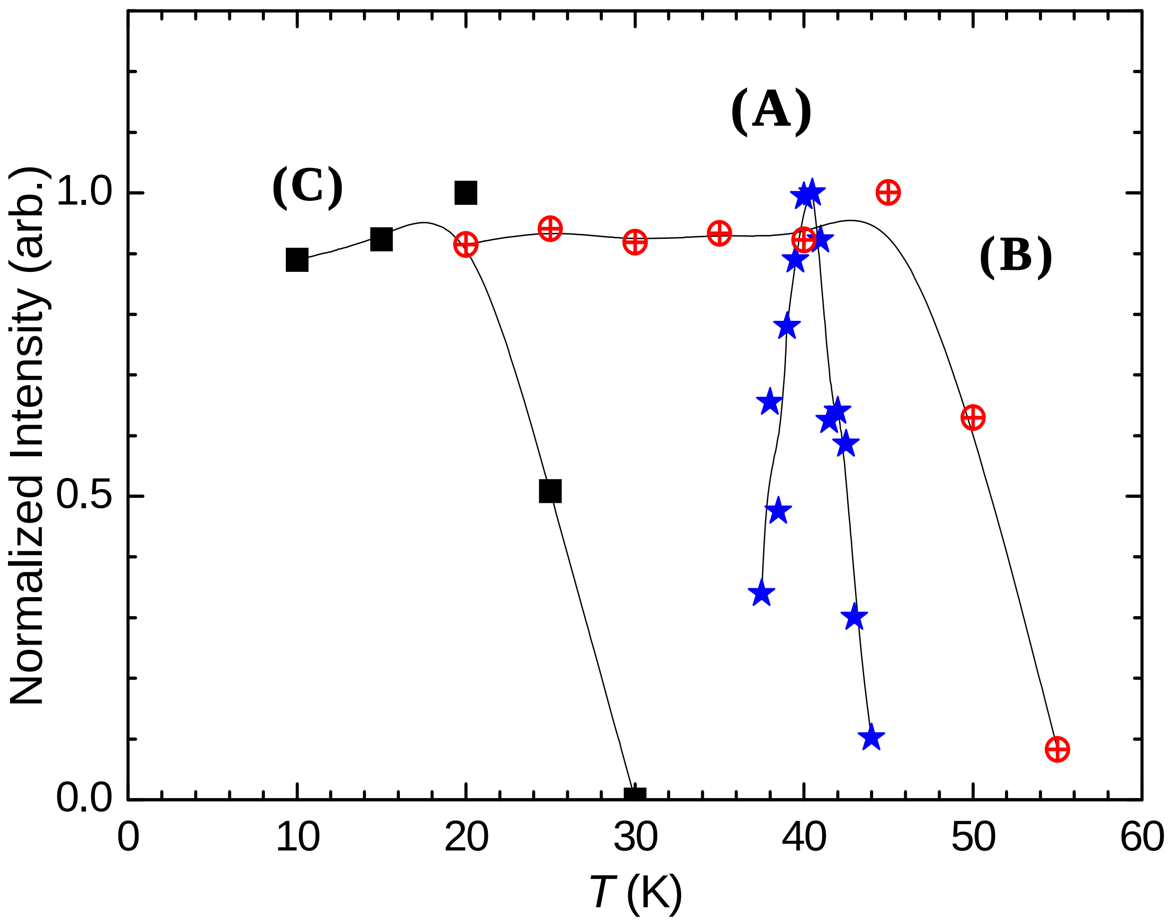


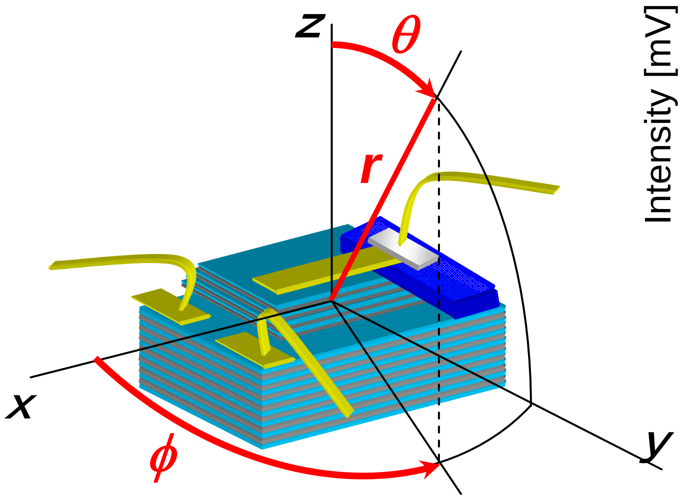

*Emission occurs only in a limited temperature region !*

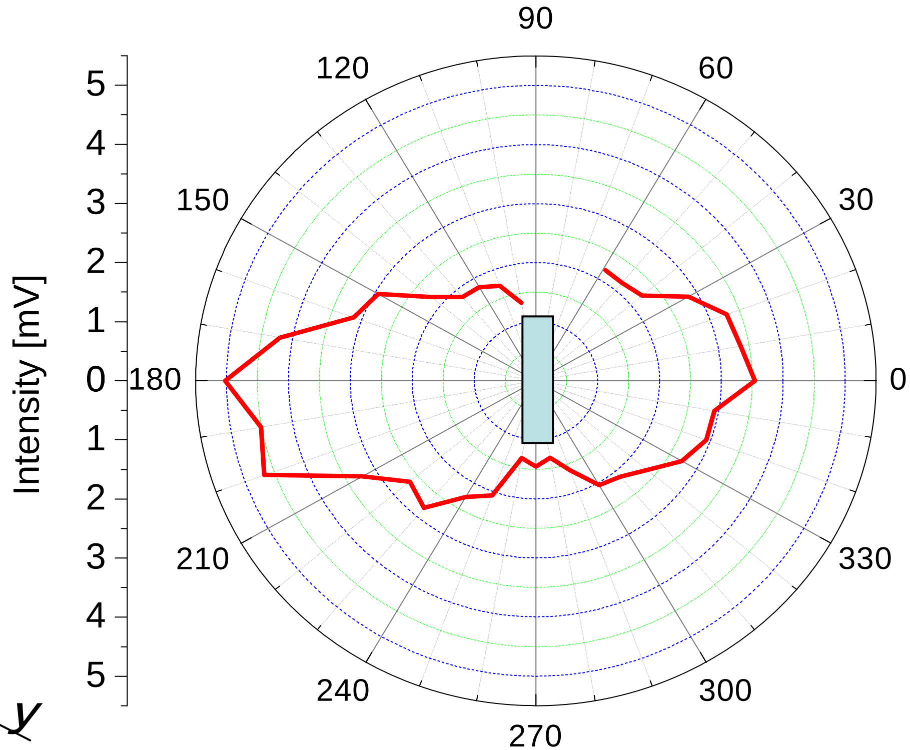
***Non-equilibrium state is important for radiation!***

# New Data



# Angular Dependence (I)




*in ab-plane*

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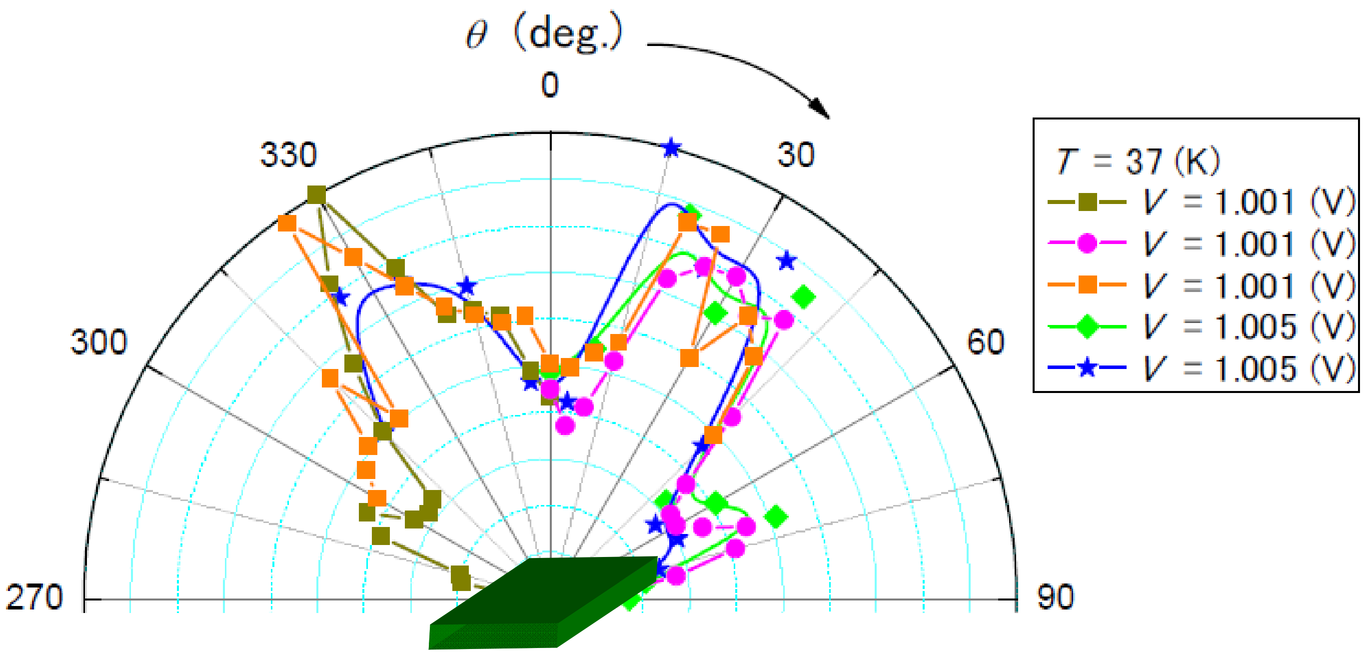
# Angular dependence (II)




$$\theta = 0^{\circ}, I(0)/I_{\max} \approx 0.5(\neq 0)$$

$$\theta = 90^{\circ}, I(90)/I_{\max} = 0$$

***Contradictory to the simple dipole model!***

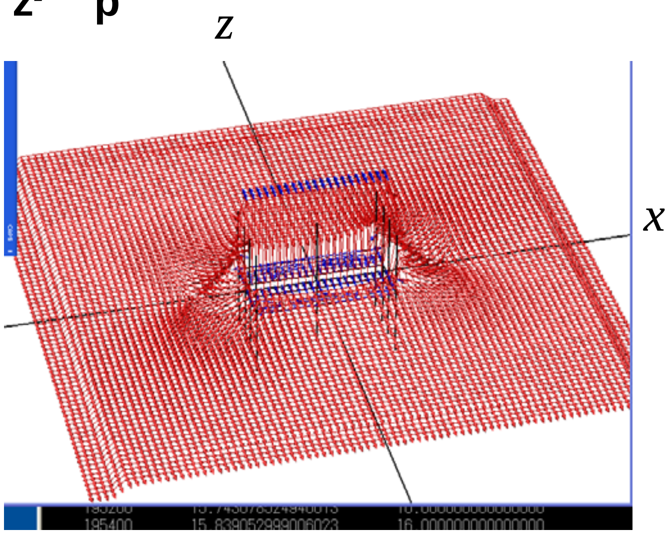
Dipole radiation movie

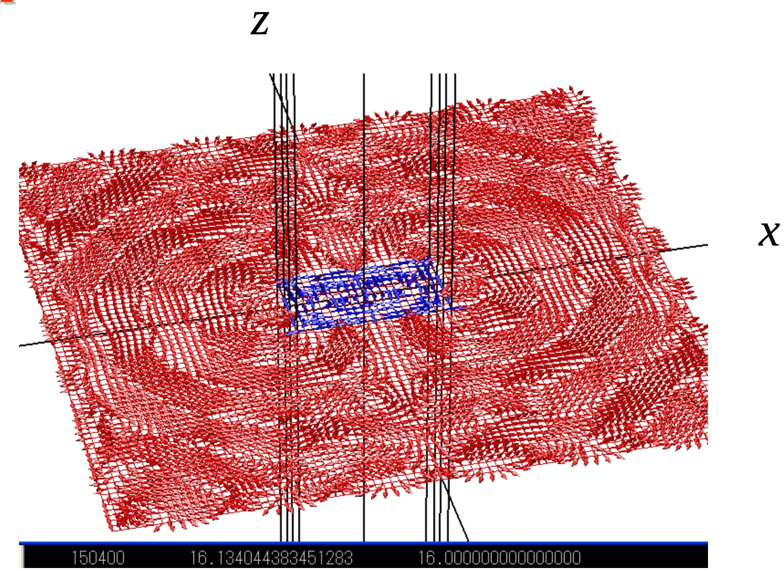
# Simulation (I)
## (Matsumoto, Koyama, Machida)



### *Electric Field*

$E_z/E_p$



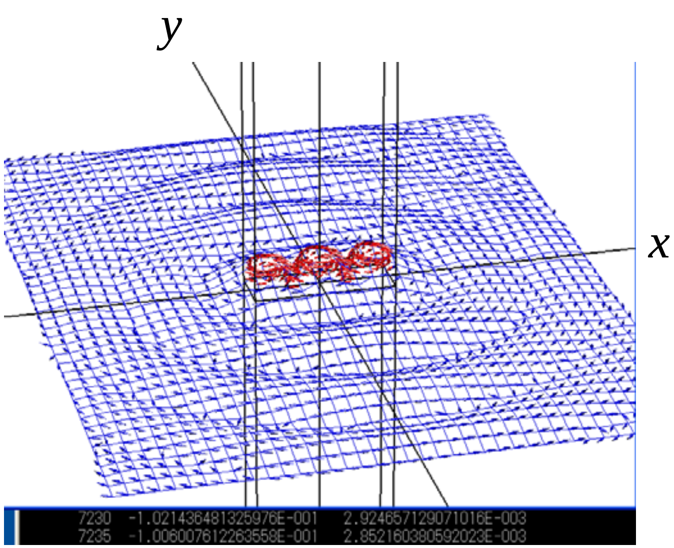




Lx/ λ c=2.0, β =0.05, β L=100.0, jext/jc=0.8

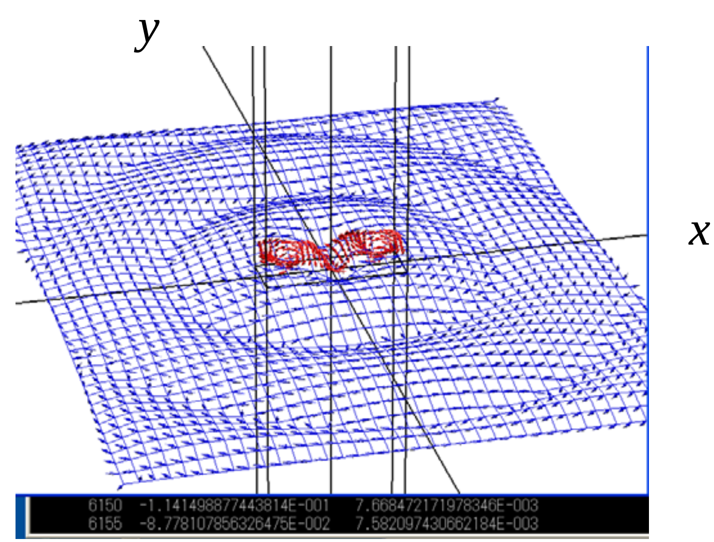
# Simulation (II)

**Magnetic field**

$j_{ext}/j_c$=0.3



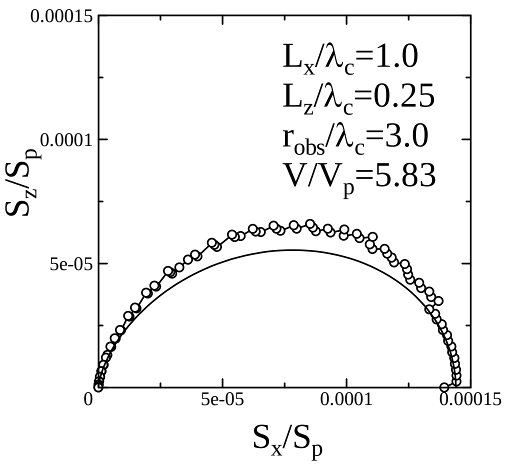

$j_{ext}/j_c$=0.2

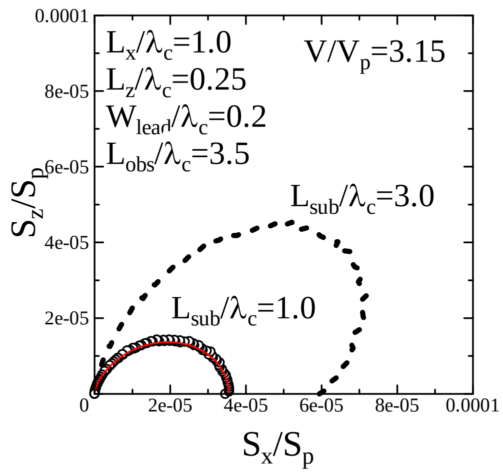


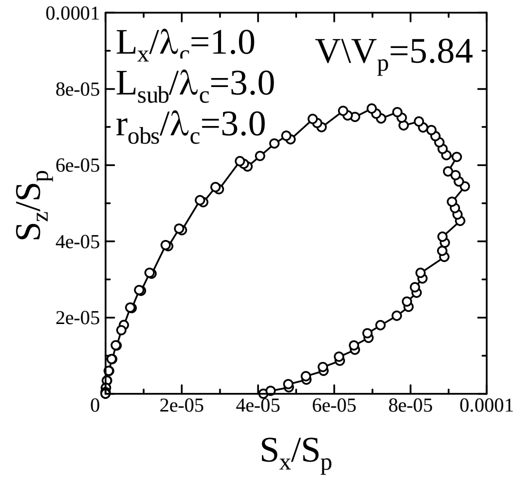

$L_x/\lambda_c=3.0, L_y/\lambda_c=1.0, \beta=0.05, \varepsilon=10.0$

# Simulation (III)

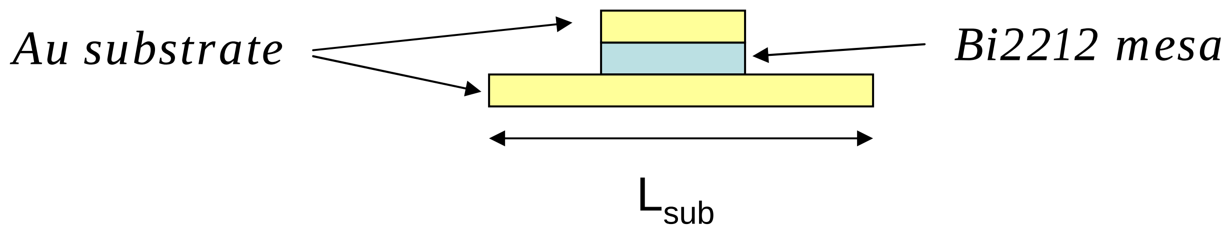




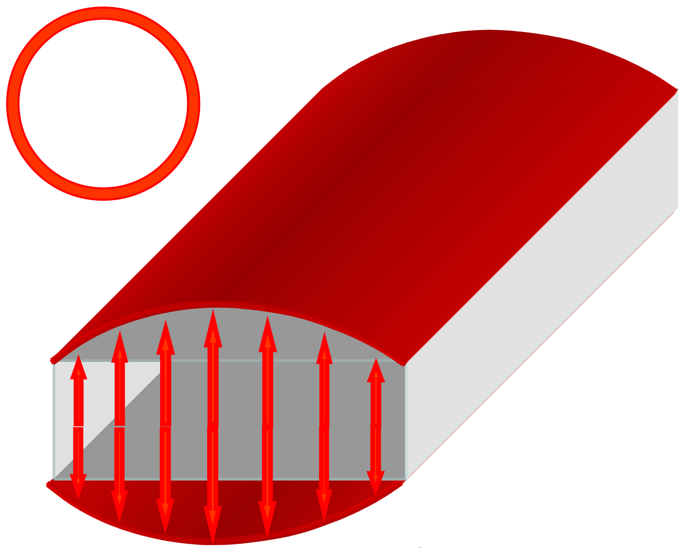



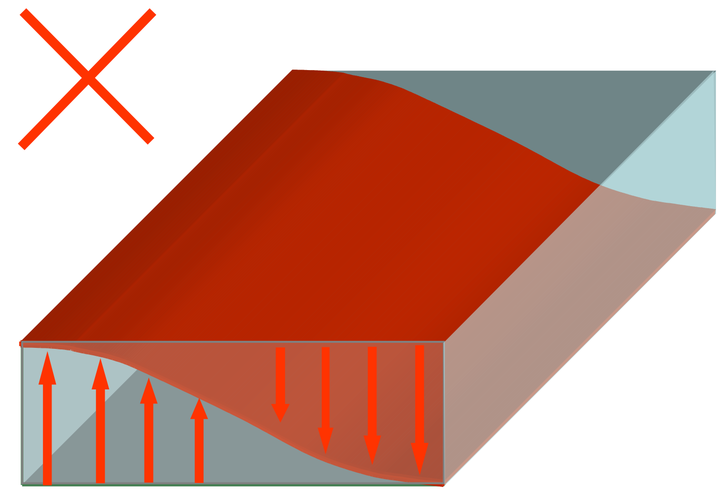

*model*



# Possible Excitation Modes



**Symmetric**



**Anti-symmetric**

*Dipole radiation-like*
***E**: linearly polarized*

*Cancelling dipole radiation*
***E**: linearly polarized*

# Frequency vs. sample width

$$f = \frac{c_0}{2nw} = \frac{c_0}{n\lambda}$$

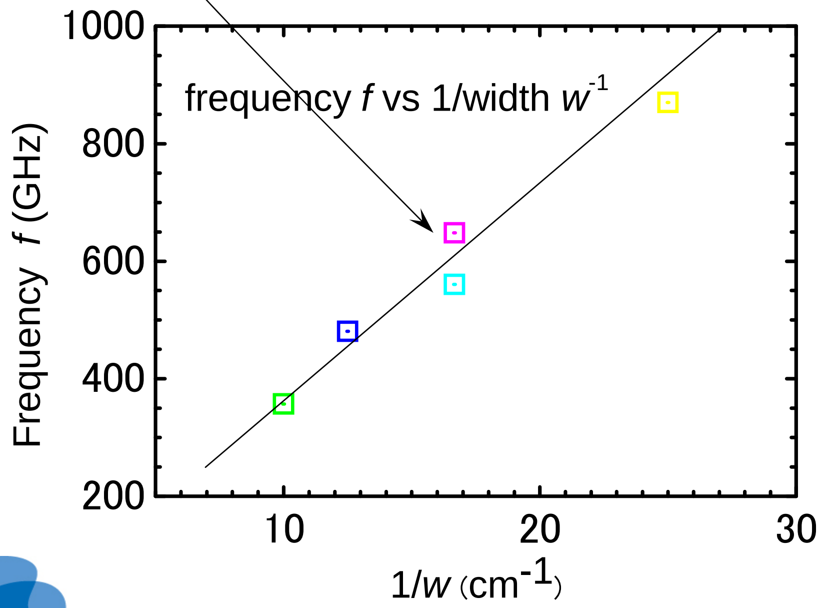
*standing wave*

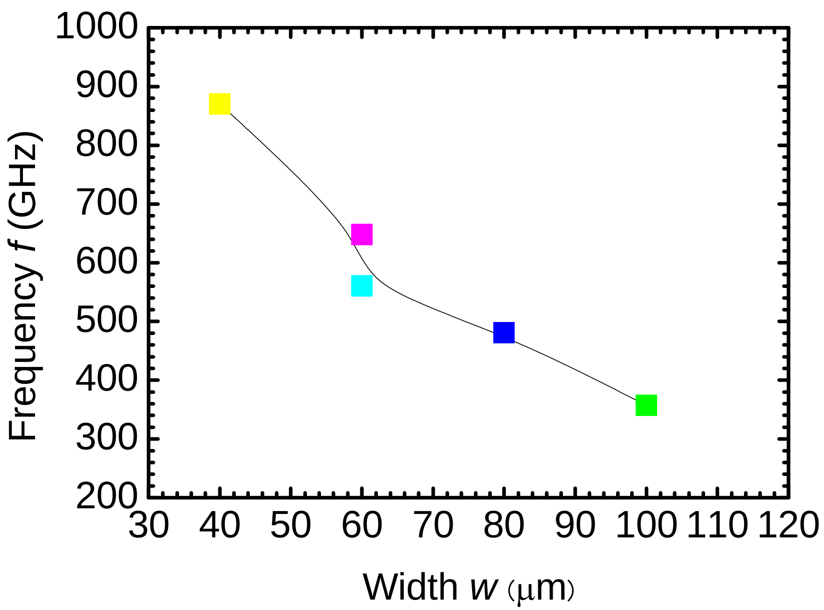
⇩

***sample plays as a cavity***

refractive index $n$=4.19

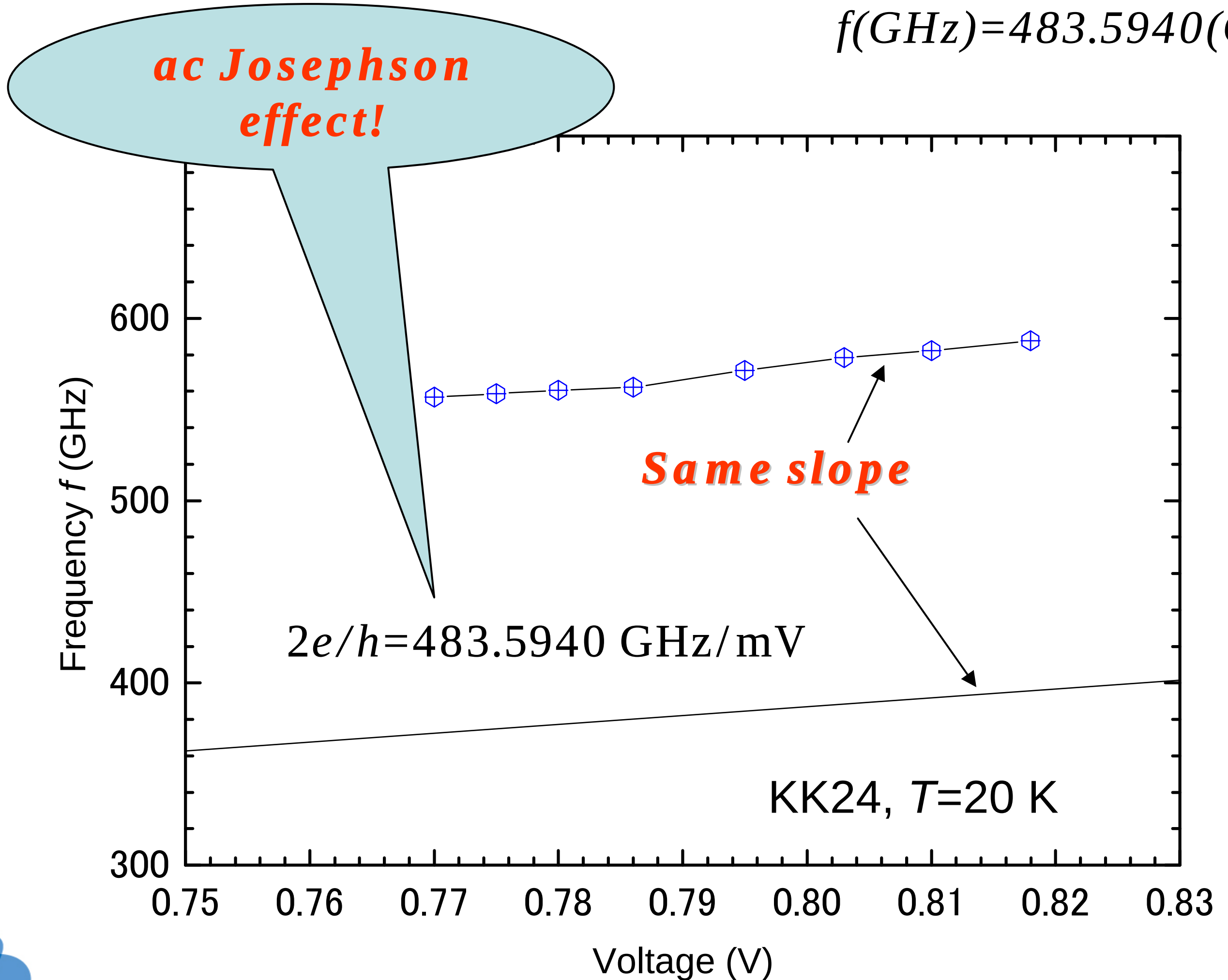
dielectric constant $\varepsilon$=4.19²=17.53



# Frequency vs. voltage

$f$(GHz)=483.5940(GHz/mV) x $v$




$v=V/N$

$N$=672.4 layer (corresponding to 1.03μm thickness) (653.6 layer/1 μm)

$f$: frequency
$V$: total voltage
$N$: number of layers
$v$: voltage for single junction

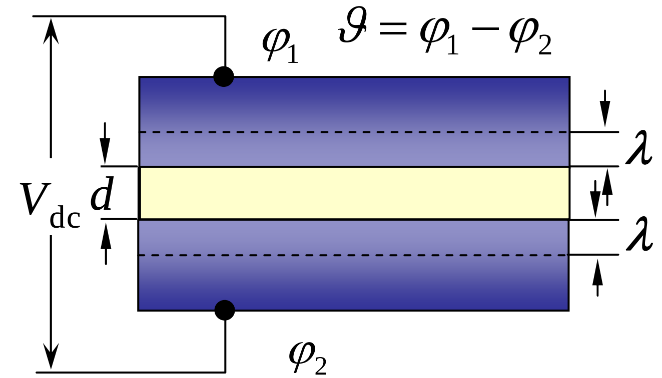
# AC Josephson effect

– Single junction

*ac Josephson effect*

$$\hbar \frac{\partial \vartheta}{\partial t} (= \hbar \omega = h\nu) = 2eV$$

$$\nu = \frac{V_{dc}}{\phi_0} = 0.483 \ \ \mathrm{THz/mV}$$




*Josephson junction*

$$\phi_0 (= h/2e) = 2.067833636 \times 10^{-15} \ \ \mathrm{Wb}$$

***Theory***

*B. D. Josephson, Phys. Lett.* ***1****, 251 (1962).*

***Experiments (Indirect)***

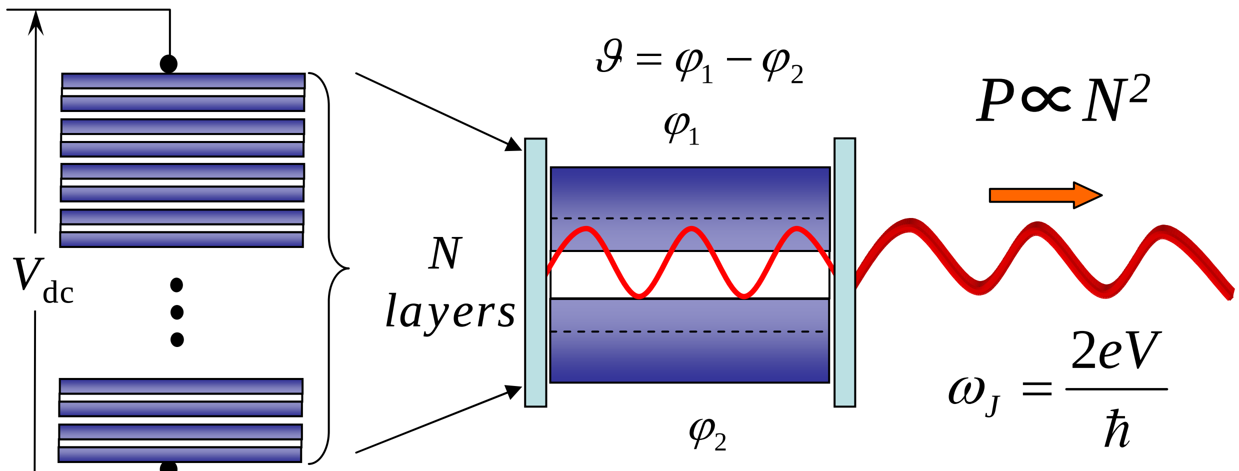
*S. Shapiro, PRL* ***11****, 80 (1963), S. Shapiro, et al., Rev. Mod. Phys.* ***36****, 223 (1964), I. Giaever, PRL* ***14****, 904 (1965).*

*Direct measurements*

*I. K. Yanson, V. M. Svistunov and I. M. Dmitrenko, ZhETF,* ***48****, 976 (1965), D. N. Langenberg, et al., PRL* ***15****, 294 (1965).*

# Emission mechanism






Giant Josephson junction

Multi-stacked Josephson junction

$$\omega_J = \frac{2eV}{\hbar}$$

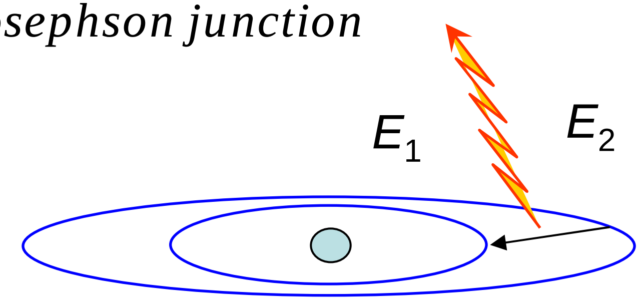
ac-Josephson Effect

$$\theta = \theta_B - \theta_A$$

$$\frac{d\theta}{dt} = \frac{2e}{\hbar} V_{dc}$$

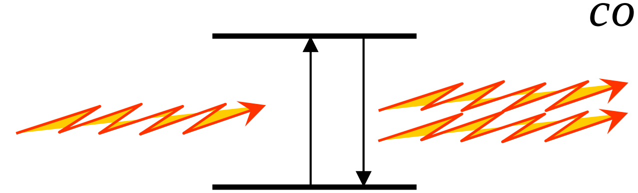
$$\therefore \theta = \omega_J t + \theta_0$$

$$f = \frac{2eV_{dc}}{h} = \frac{V_{dc}}{\phi_0}$$




$$h\nu = \hbar\omega = E_2 - E_1$$

atom

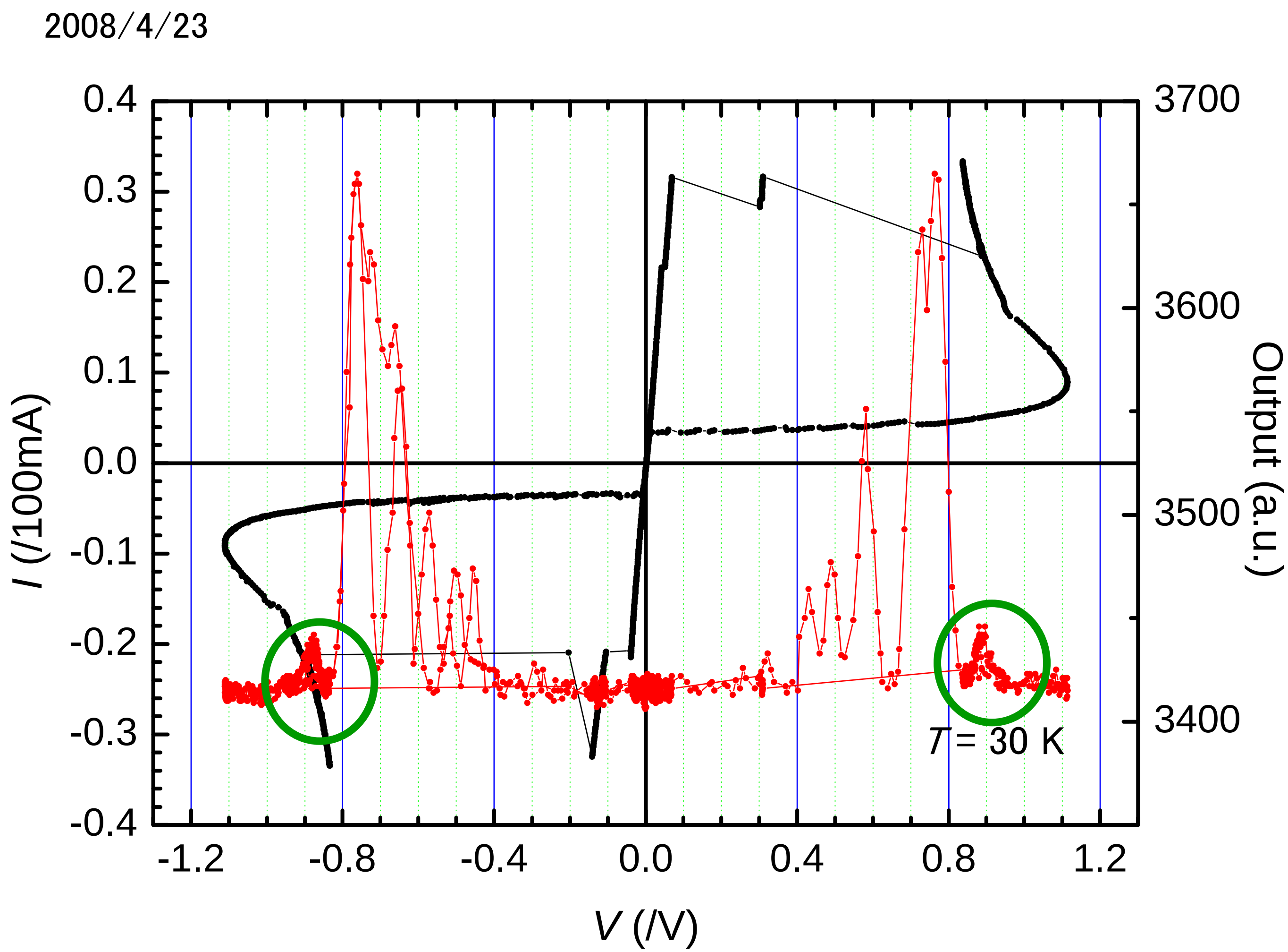


coherent

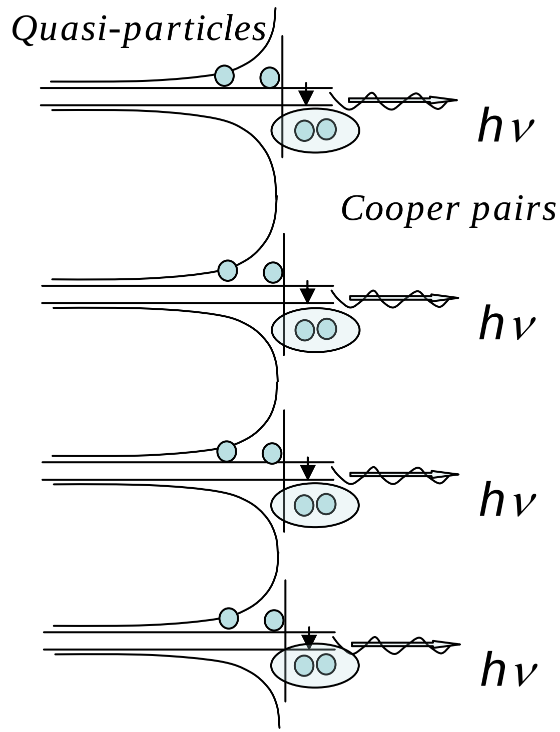
stimulated radiation

**Similar to LASER**

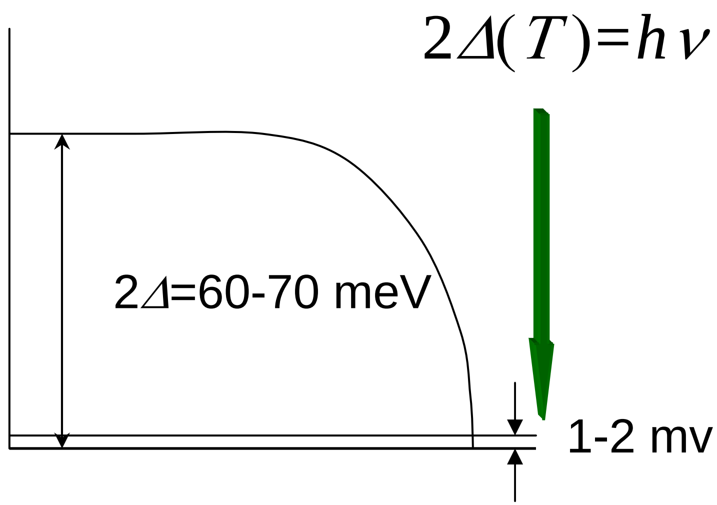
# New emission



# Another Mechanism

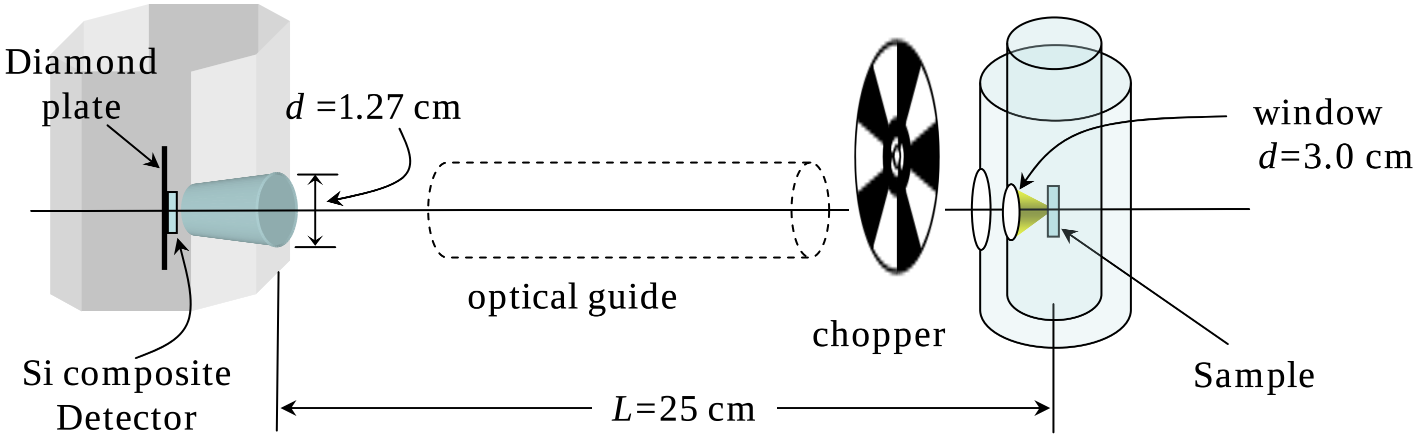



***Quasi-particle recombination process occurs near $T_c$***




***Cascade Amplification of Stimulated Emission of Radiation (CASER)***

# Estimation of Emission power




$$P_{sample} \le e_{eff} P_{obs}$$

$$P_{obs} = S^{-1} \times V_{out} = \frac{17mV/200}{2.73\times10^{5}} = 0.311nW$$

Detector sensitivity

$$e_{eff}^{max} = \frac{4\pi(25)^2}{\pi\times(0.635)^2} \times 2 \times \frac{1}{(0.8)^2} = 1.93\times10^{4}$$

Geometrical factors

chopper

2 x windows

$P_{sample}$~5 μW

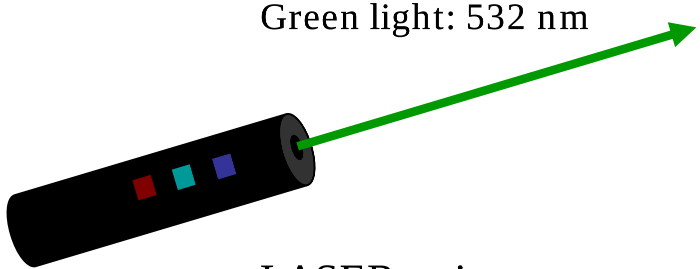
# Efficiency of emission

| | at present | desired in future |
|---|---|---|
| input power | 17～20 mW | 10-20 mW |
| output power (at detector) | ～5 μW (36.6 nW ) | 1 mW |
| area energy density | ～1 $W/cm^2$ | ～100 $W/cm^2$ |
| volume energy density | ～300 $W/cm^3$ | ～$5x10^4$ $W/cm^3$ |
| efficiency | ～$3x10^{-4}$ | ～5-10% |

***For useful applications,***
***a factor of 100-200 is necessary!***

# Comparison of power

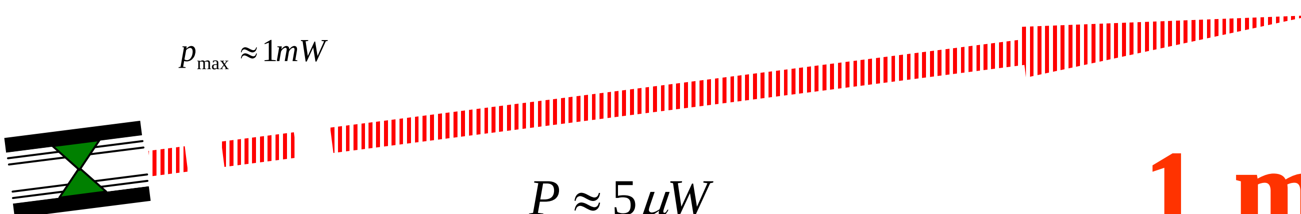
Green light: 532 nm



LASER pointer
(class 2)

$p_{\max} \approx 1mW$

**Coherent, Continuous, and Compact size**
**(Co³ STAR-emitter)**



IJJ TEASER
(STAR-emitter)

$P \approx 5\mu W$
at present

x 200

**1 mW**

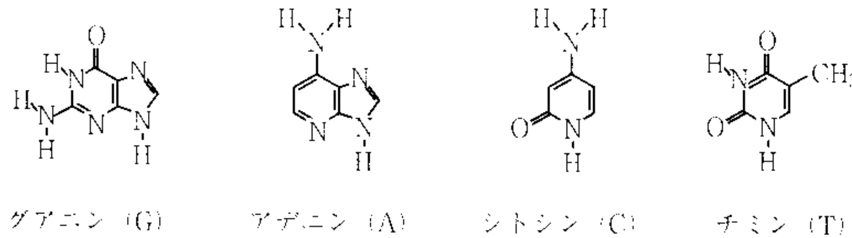
efficiency

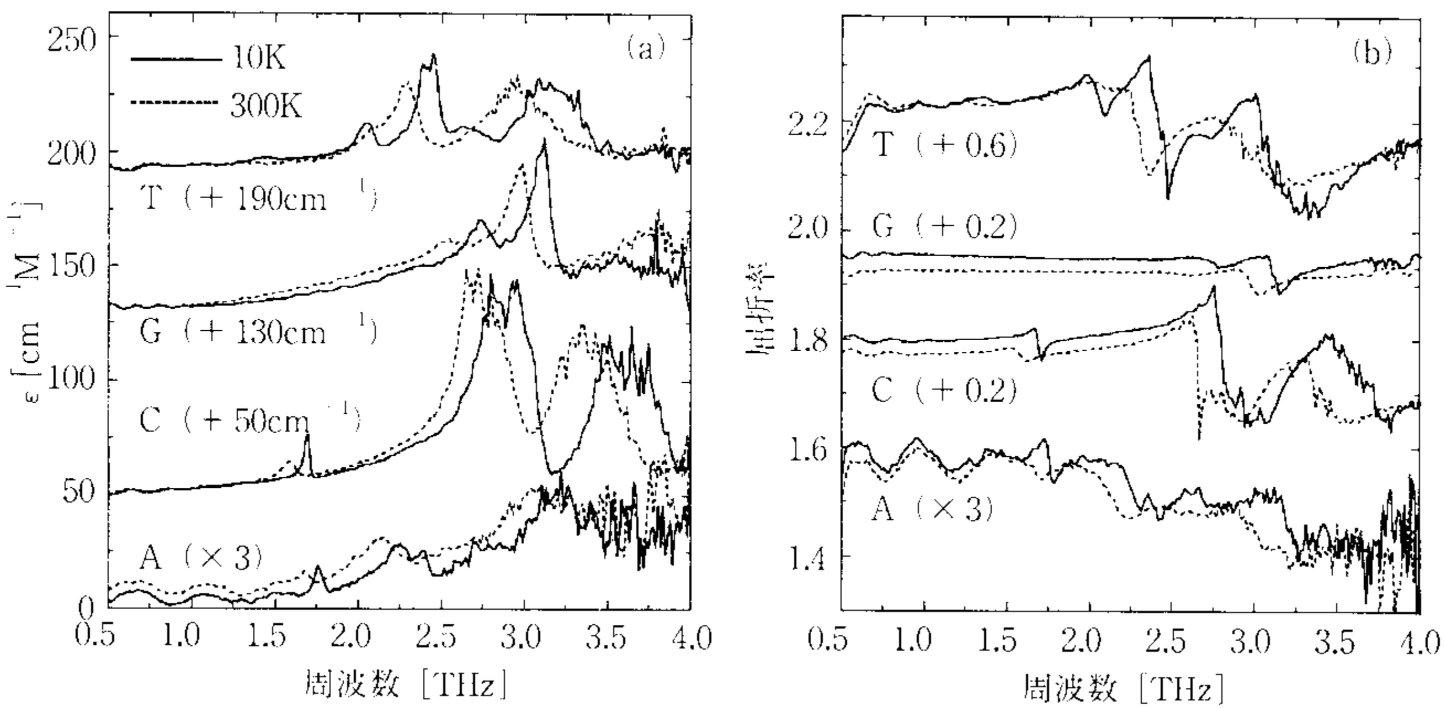
$3 \times 10^{-4}$

$6 \times 10^{-2} = 6\ \%$

# Applications (Case I)

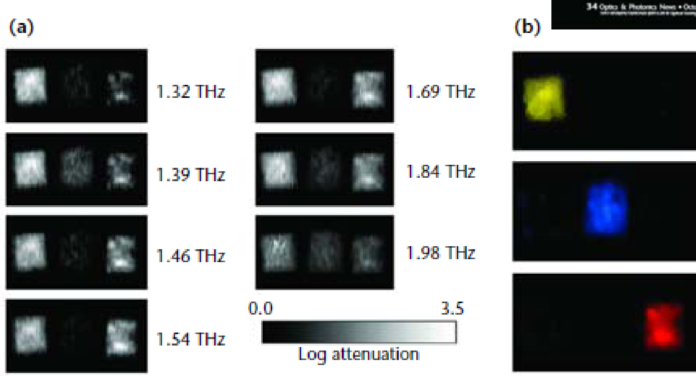
DNA
finger spectrum

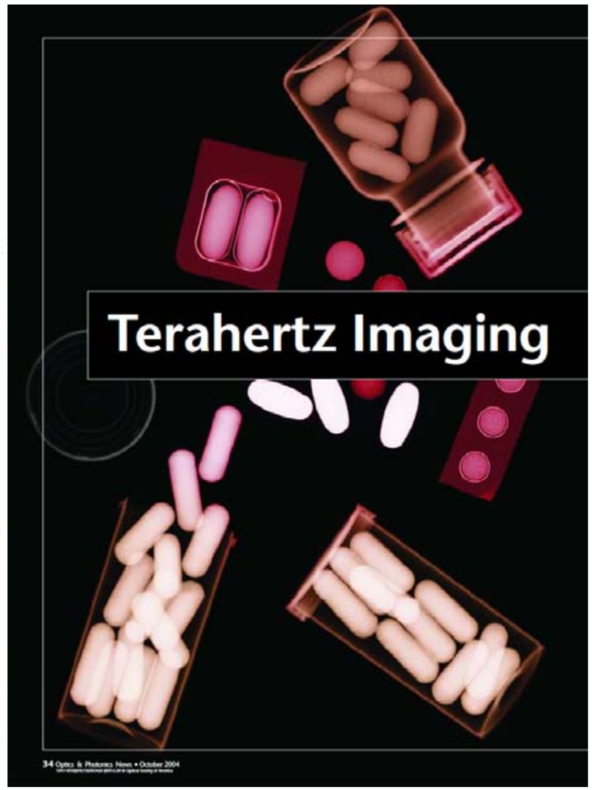


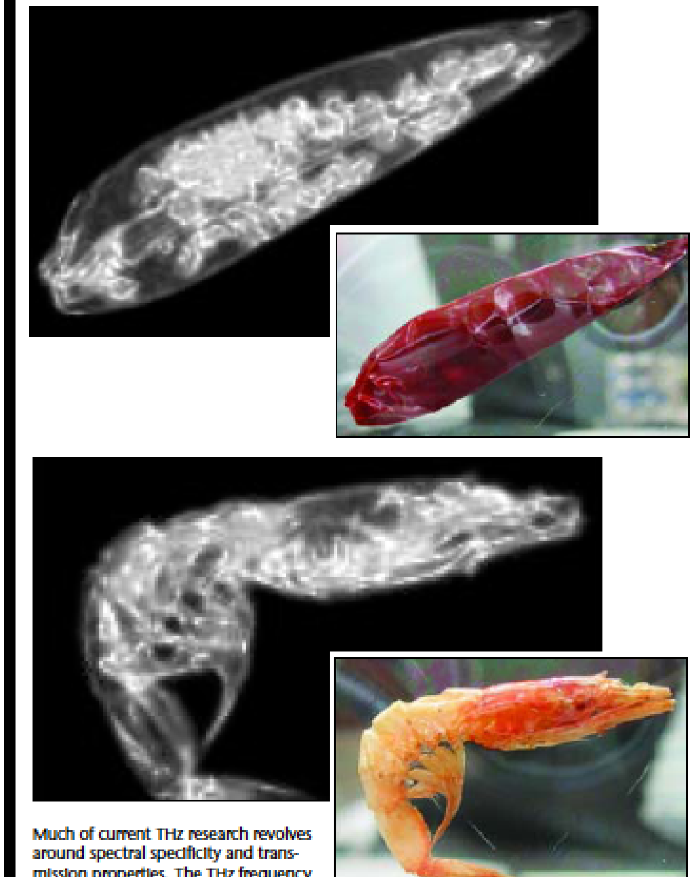



# Case (II)

- *imaging*

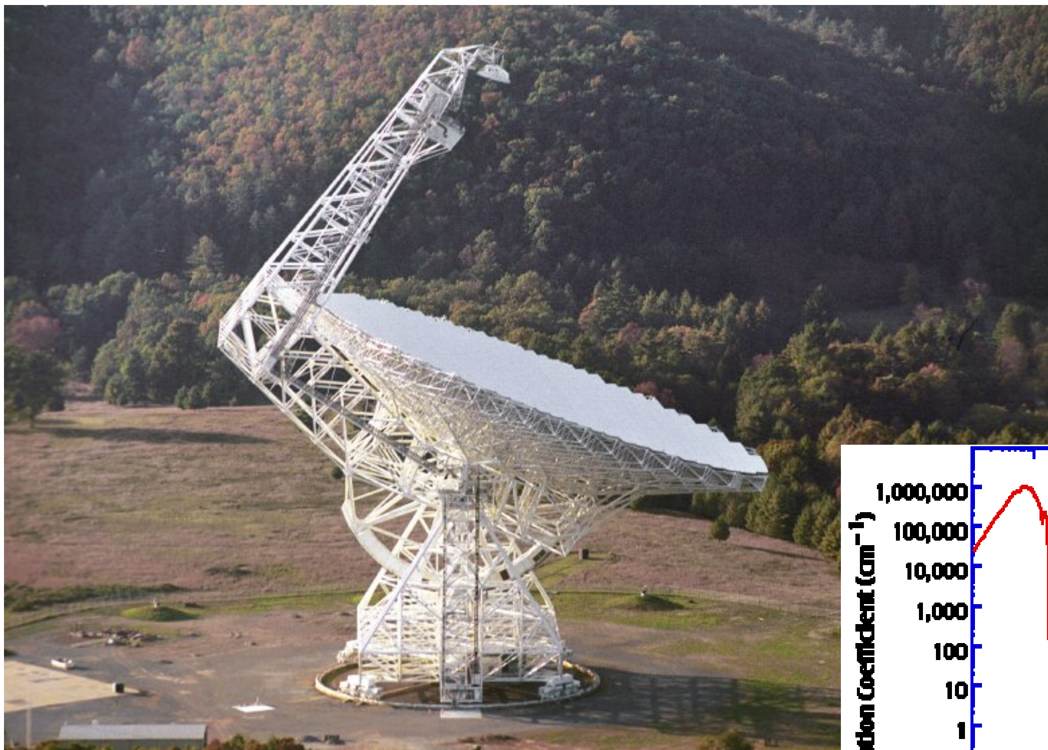



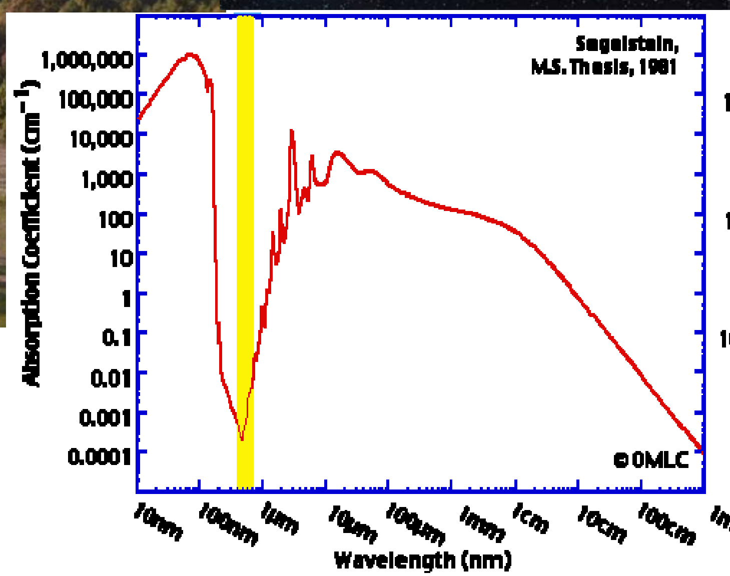
Much of current THz research revolves around spectral specificity and transmission properties. The THz frequency is more selective than X-rays and is therefore more sensitive to the nature of the materials it passes through. Here, a red pepper and a prawn are presented alongside their THz images. [Yuichi Oshima, RIKEN.]

*After K. Kawase,*
*Optics and Photonics News, Oct. 2004, p.38*

# Case (III)

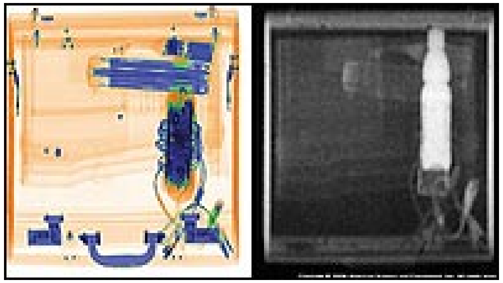



VDI


Segelstein, M.S. Thesis, 1981
Absorption Coefficient (cm⁻¹)
1,000,000
100,000
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
Penetration Depth (µm)
10nm
100nm
1µm
10µm
100µm
1mm
10mm
100mm
1m
10m
100m
©OMLC
10nm
100nm
1µm
10µm
100µm
1mm
1cm
10cm
100cm
1m
Wavelength (nm)

# Case (IV)

*Night vision*



*security*

# Summary (I)

1. $$f_{obs} = \frac{c_0}{2nw}$$

*$C_0$: velocity of light*
*n: refractive index =1/$\sqrt{\varepsilon}$ =4.19*
*w: width of the sample*

**Resonance mode with** $\lambda = 2w, w, w/2, \ldots$

2. $$f_{obs} = \frac{2e}{h}\frac{V_{obs}}{N}$$

$$N = \frac{h}{2e}\frac{V_{obs}}{f_{obs}} = \frac{483.5940}{0.001} \times \frac{0.791523}{568.1617} = 673 (= 1.029 \mu m)$$

**ac Josephson effect**

3. $$P_{obs} \propto N^2 \quad (\sim 5\ \mu\text{W})$$

**All junctions are coherent!**

***N intrinsic junctions work together as if they are a big single junction.***

*Coherent resonant emission occurs when*

$$V_{obs} = 88.7 \times \frac{N}{w} \quad (\text{mV})$$

*is satisfied. ([w]=[μm])*

## ac Josephson Laser (STAR-emitter)!

# Summary (II)

4. Monochromatic spectrum
   within the limitation of FTIR spectrometer

$$\Delta f \leq 7.5GHz$$

## Two Types of Radiation Mechanisms

1. *Synchronous Oscillation:*
   ***STAR-emitter***
   *Nonlinearlity and nonequilibrium are important!*
2. *Cascade Amplification of Emission:* ***CASER***
   ***direct Cooper pair recombination process near $T_c$***

# Summary (III)

**There is a room**
**for increase output power of radiation**

**It needs about 200 times more power**

$$P_{out} \sim 1 \text{ mW}$$

***Thank you very much for your attention!***

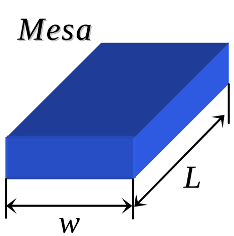
*JSPS-ESF CTC program*
*Nan0-Science and Engineering in Superconductivity*

# Properties of IJJ's

$$\lambda_J \approx 0.5\mu m$$

| *Short junction:* $w \geq \lambda_J$ | *Long junction:* $w >> \lambda_J$ |
|---|---|
| *R(H) oscillation* | *R(H) oscillation* |
| *Fraunhofer pattern* | *No Fraunhofer pattern* |
| *Fiske steps* | *No Fiske steps* |
| *MQT* | *Collective modes (resonances)* |
| *(Macroscopic Quantum Tunneling)* | *(geometrical resonance)* |

*In zero magnetic field,* $\lambda_J << w \leq \lambda_c \leq L$ $\lambda_c = 150 - 200\mu m$

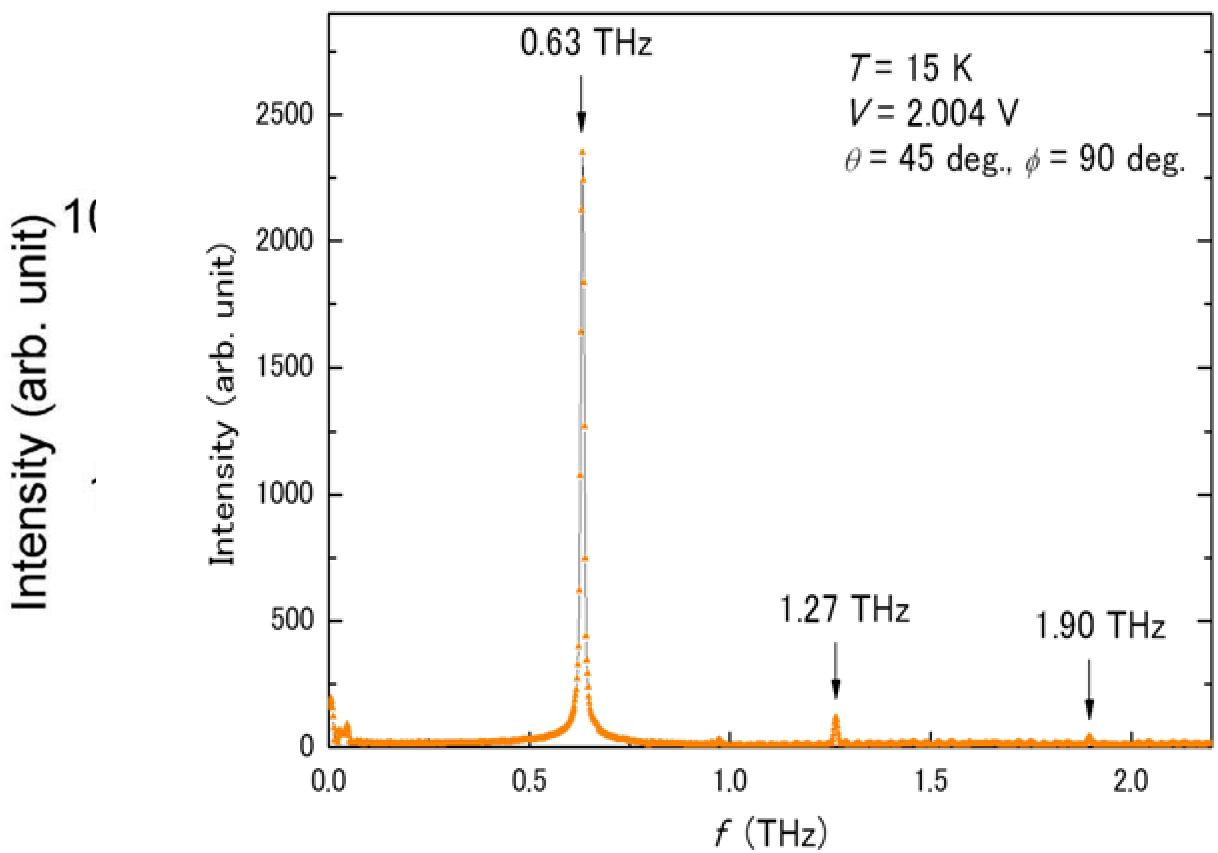



***In zero field, the system behaves as if it is a short junction.***

↓

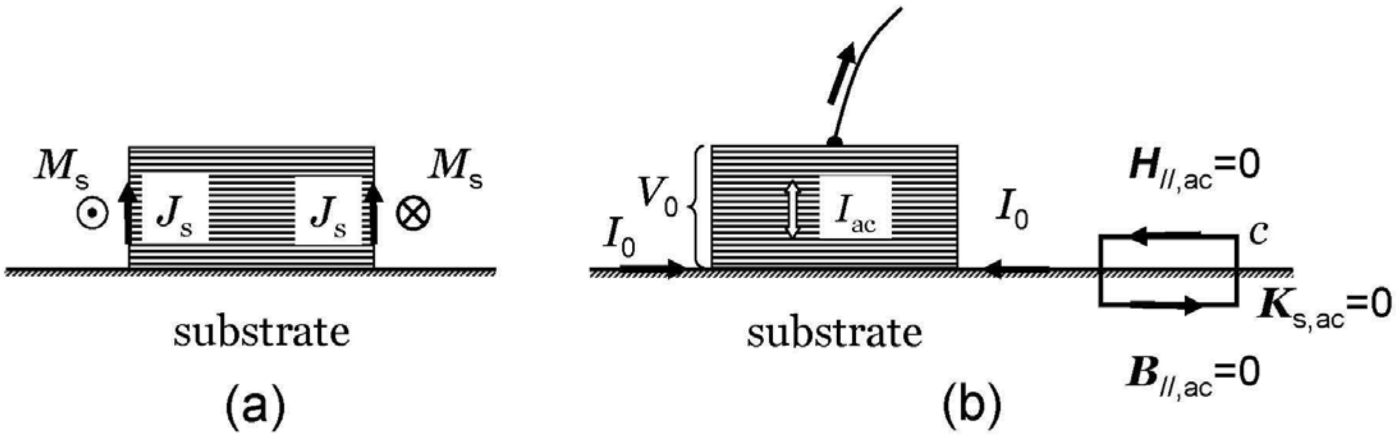
***THz radiation***

# Higher Harmonics




**Note: higher harmonics may contain some background contaminations!**

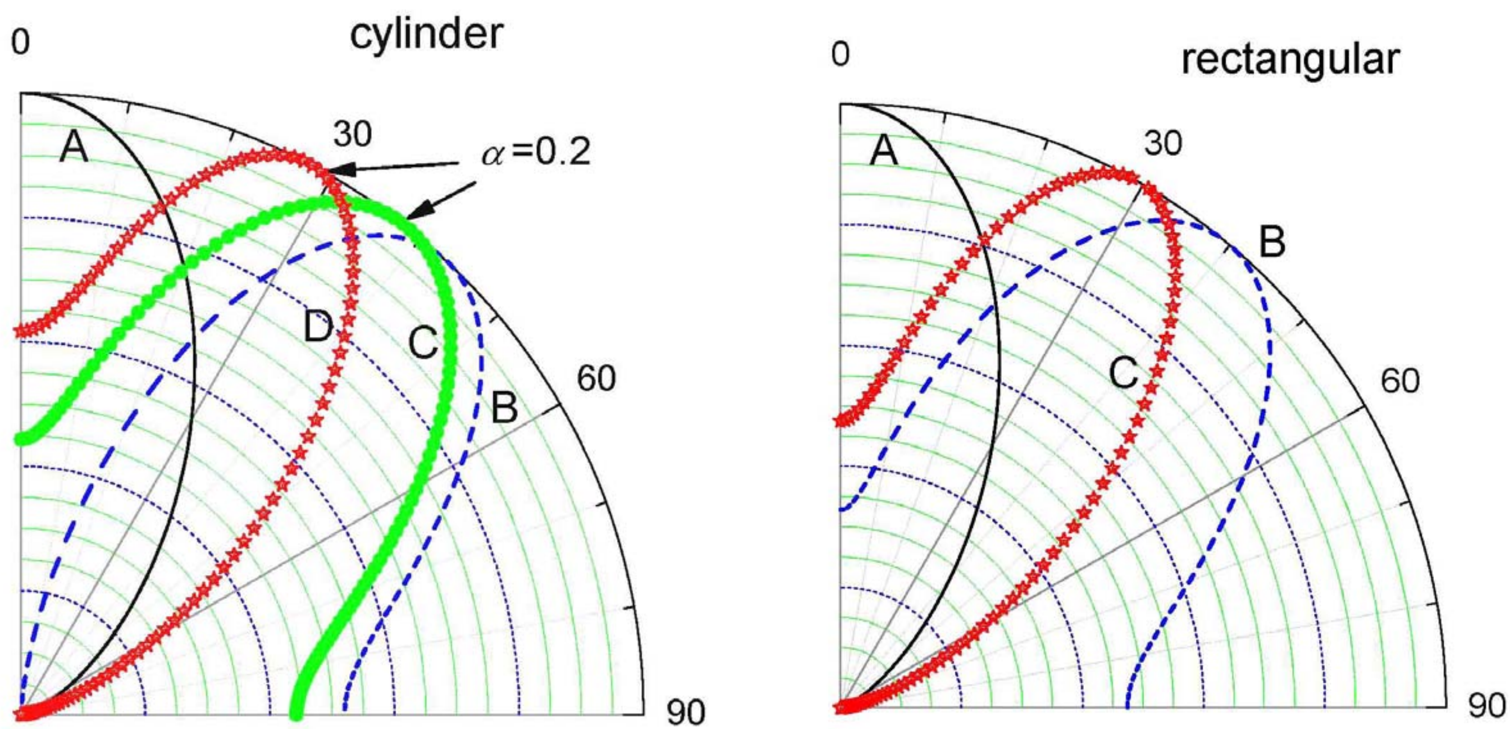
# Finite Intensity at $\theta = 0^\circ$ (I)




## *Dipole radiation: example*

*Condmat #08073082, R. Klemm and K. Kadowaki,*
*"Angular dependence of the radiation power of Josephson STAR-emitter"*

# Finite Intensity at $\theta = 0^\circ$ (II)




*After R. Klemm and K. Kadowaki*

# Comparison with other sources