# Measurement of a phase of a radio wave reflected from rock salt and ice irradiated by an electron beam for detection of ultra-high-energy neutrinos

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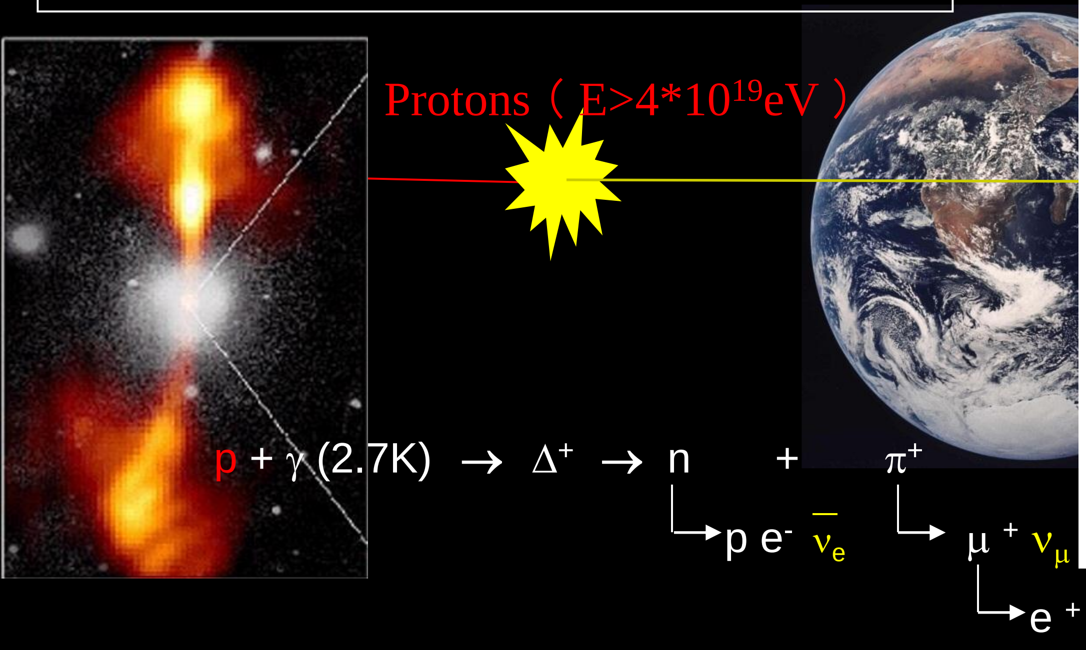
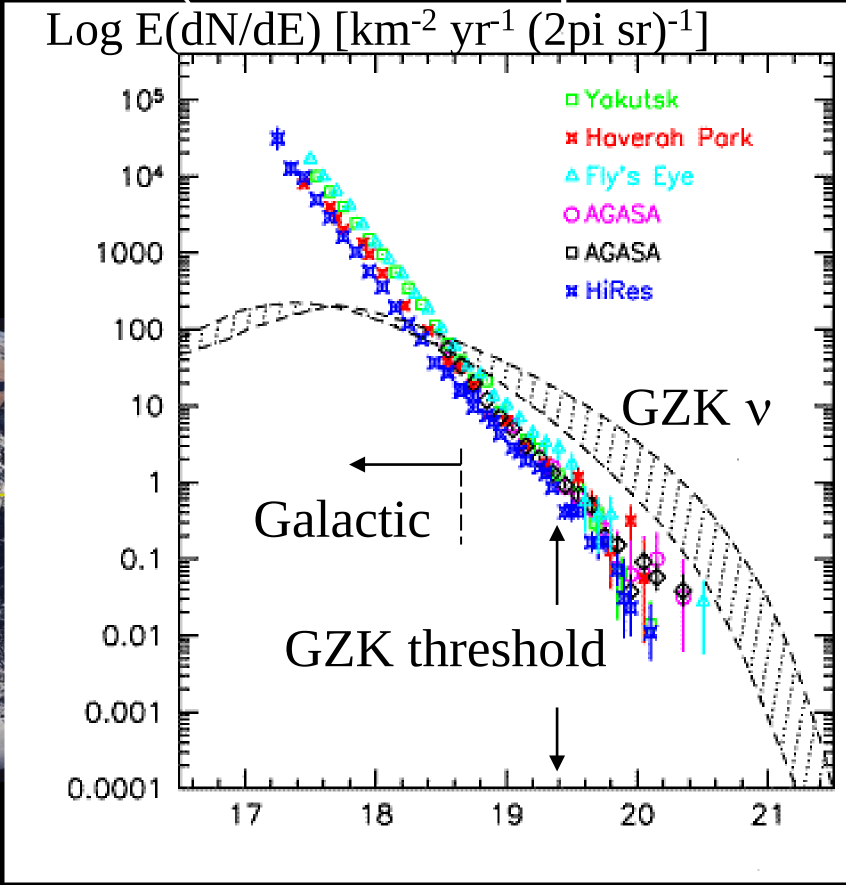
# Ultra-high energy neutinos generated in GZK(Greisen-Zatsepin-Kuzmin) Process

Ultra-high-energy cosmic ray is generated in
Active Galactic Nuclei
Gamma-ray Burst etc.

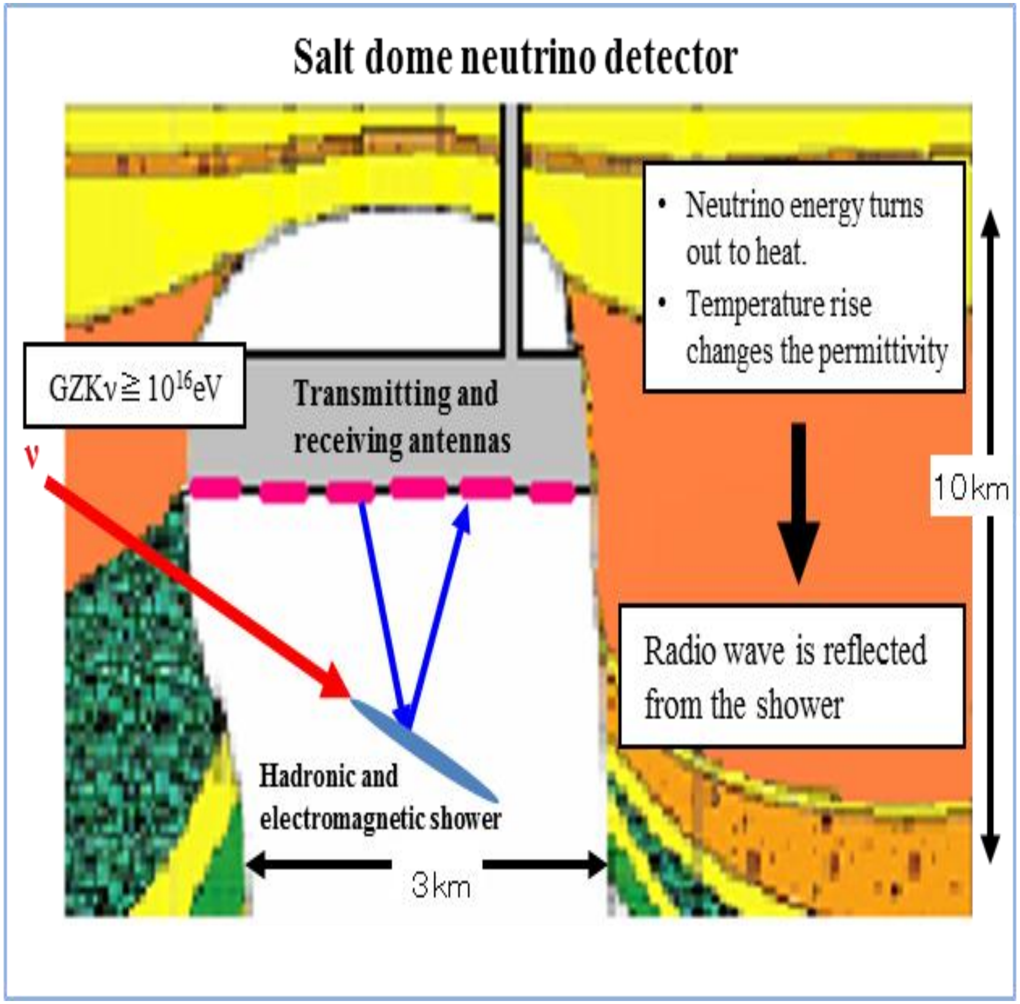


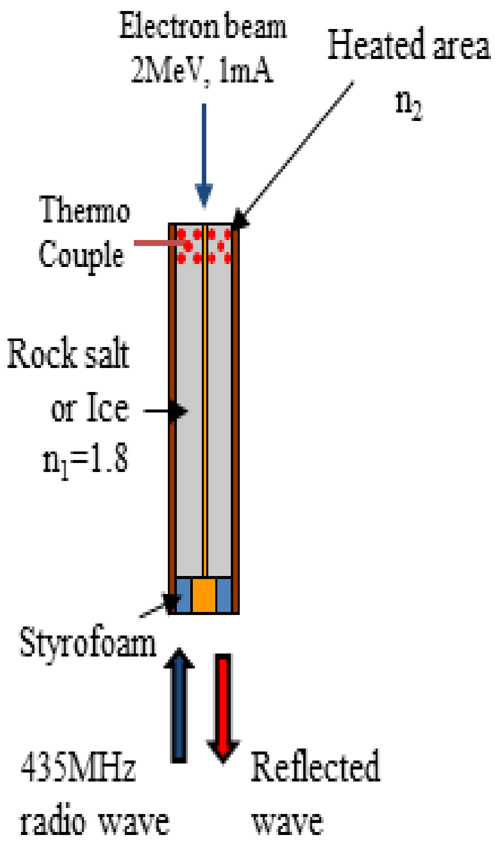

・ Detection of cosmic ν（$10^{16}$～$10^{21}$eV）
using a rock salt formation or the Antarctic ice sheet

◦ ■The flux is extremely low (≒1/ km$^2$・day), we need a gigantic mass of the detection medium of 50 Gt (≒ 10 events/year) a million times as large as Super Kamiokande.

# Radar method and a coaxial tube for ice and rock salt

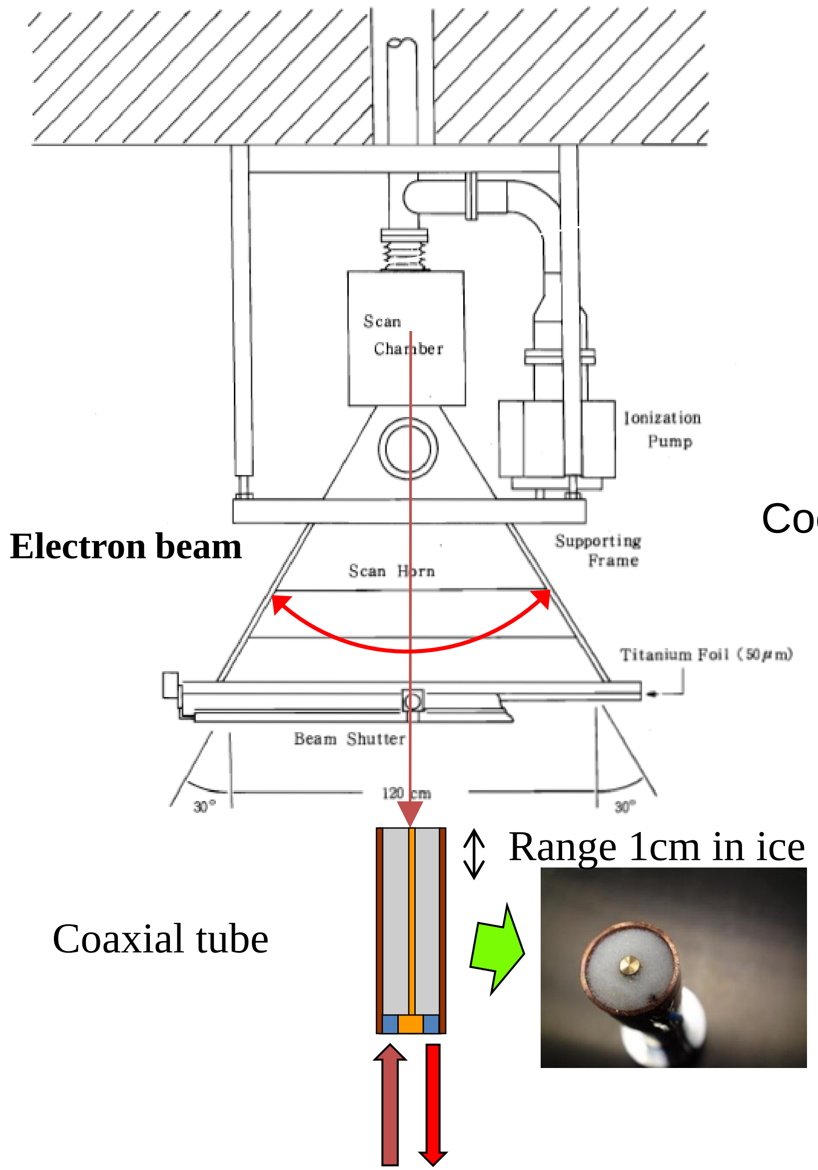


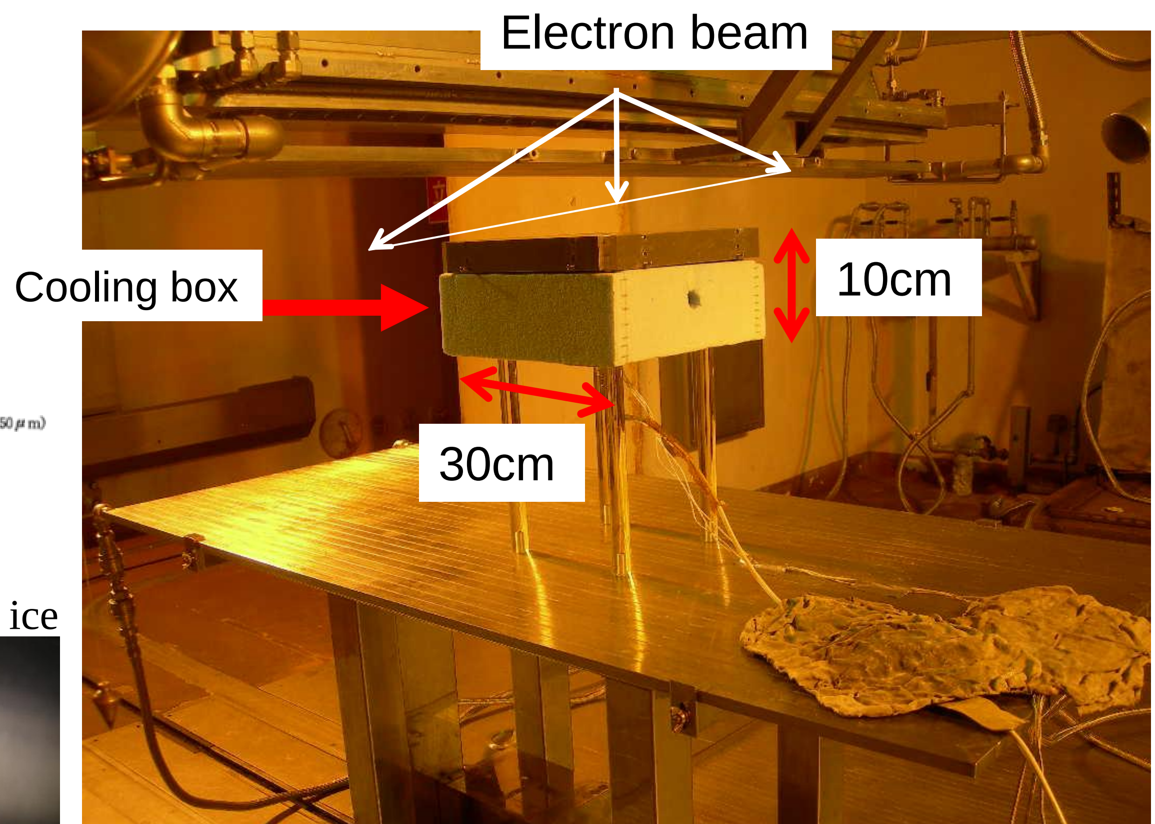

Coaxial tube with 2 cm diameter



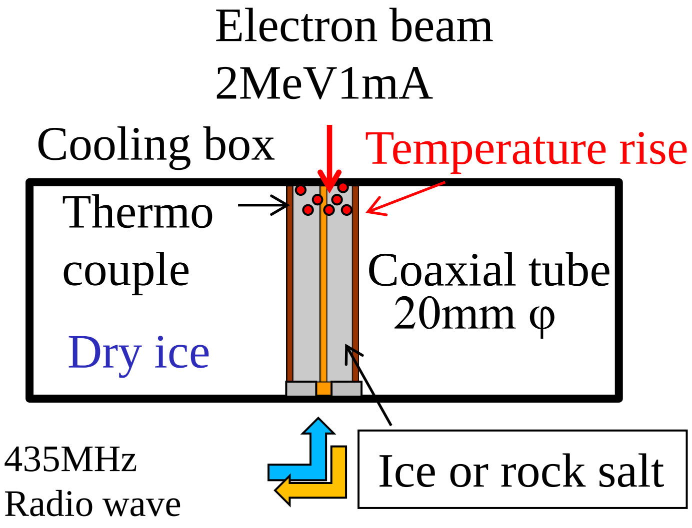
# Electron beam irradiation on ice or rock salt

- Cockcroft-Walton accelerator located at Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency



# Coaxial tube and radio-wave reflection




・Coaxial tube was filled with ice or rock salt.

・2MeV electron beam irradiate the open end of the coaxial tube.

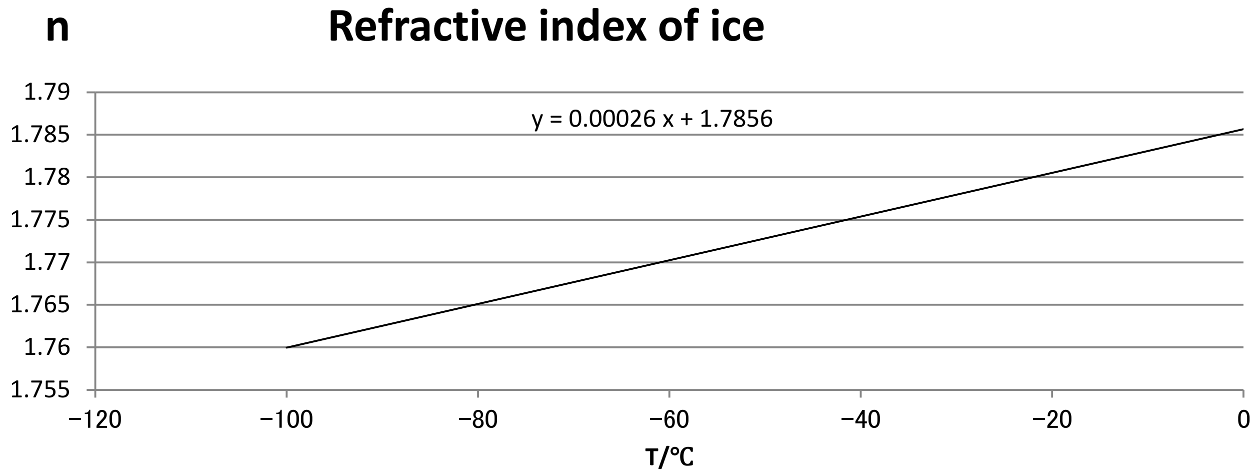
(4 J/s = 2 × $10^{19}$ eV/s at 1mA)

・Temperature rise(ΔT)

→ Increase of refractive index(Δn)

→ Radio wave reflection changes

# Power reflection rate with a change of refractive index




Matzler, C and Wegmuller, U., J. Appl. Phys. 80, 1623-1630(1987)

Matsuoka,T, Fujita, S and Mae, S., J. Appl Phys. 80,5884-5890(1996)

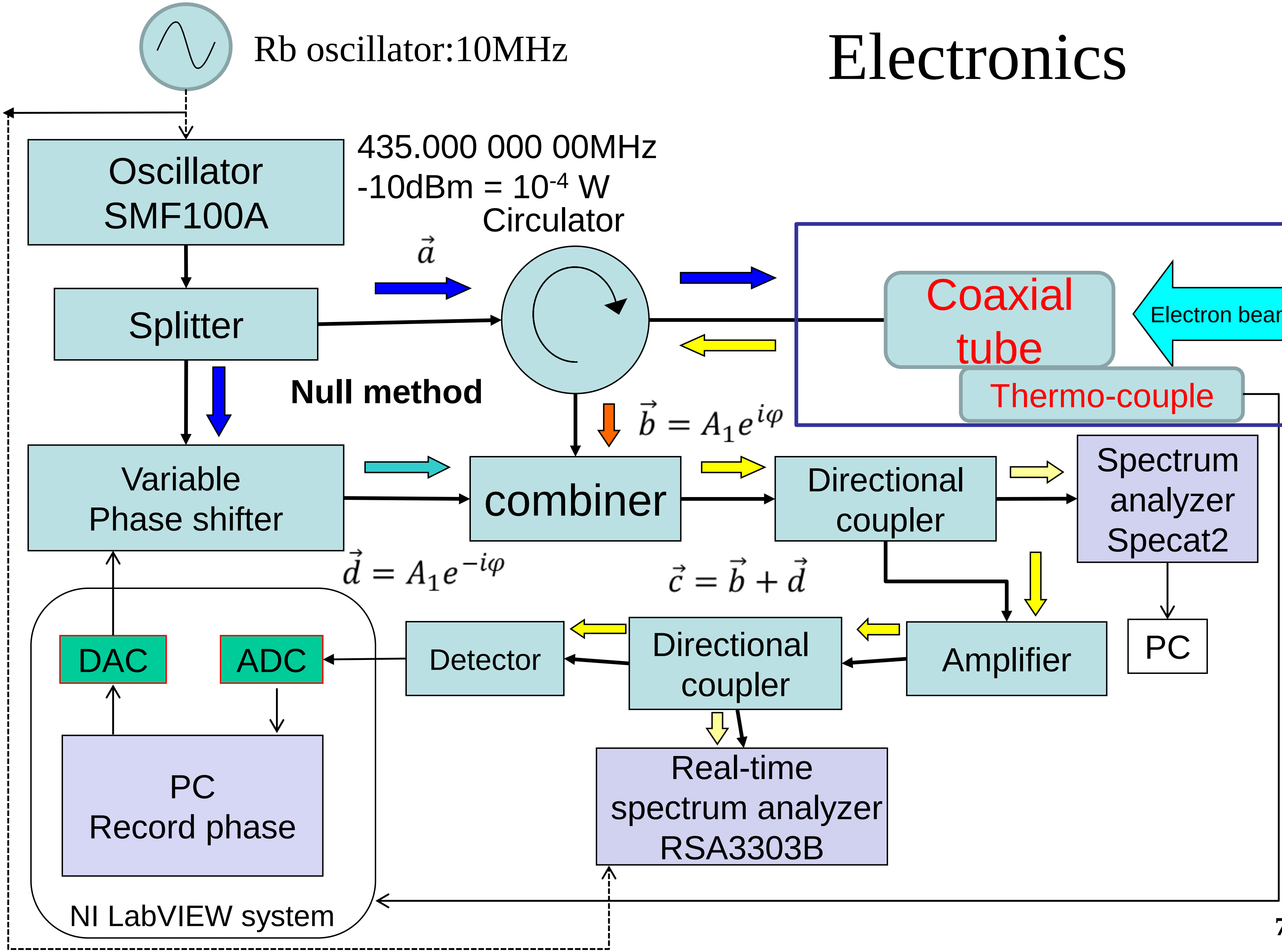
- $\Delta n \propto \Delta T$ for ice and rock salt
- Power reflection rate ($\Gamma$) is proportional to $\Delta T^2$

Fresnel equation

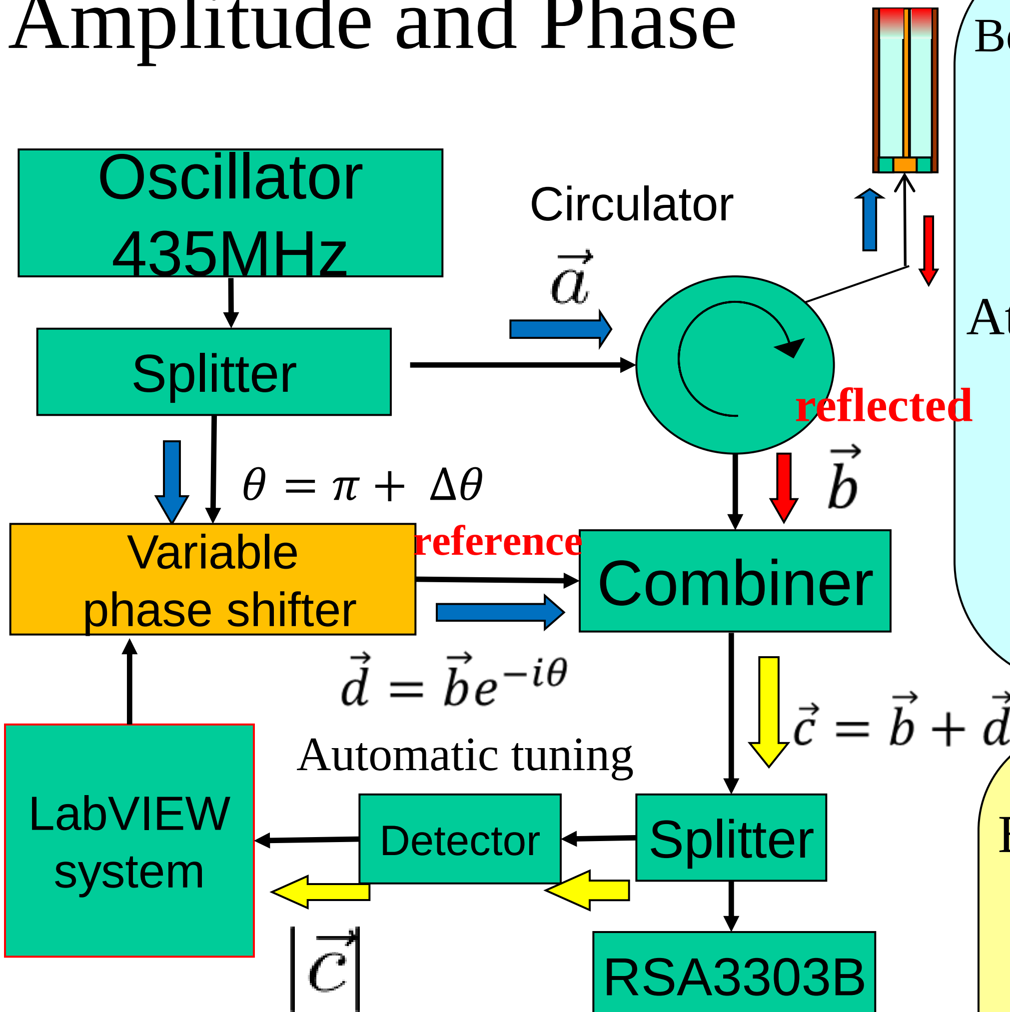
$$\Gamma = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2} \propto \Delta T^2$$

$n_1$: Before irradiation
$n_2$: Irradiation

# Electronics



# Amplitude and Phase




Due to open end of coaxial tube

$|\vec{a}| / |\vec{b}|$=1

## Amplitude measurement

Before irradiation: automatic tuning of $\theta$ is ON

$$\vec{c} = \underline{\vec{b}e^{-i\theta}} + \underline{\vec{b}}$$

reference reflected wave

$$\theta = \pi \qquad |\vec{c}|^2 = 0$$

At irradiation: automatic tuning OFF

$$\vec{c} = \underline{\vec{b}e^{-i\pi}} + \underline{\vec{b}e^{-i\Delta\varphi}}$$

reference reflected wave

$$\vec{c} = \vec{b}(e^{-i\Delta\varphi} - 1)$$

$$|\vec{c}|^2 = 2\left|\vec{b}\right|^2\{1 - \cos(\Delta\varphi)\}$$

## Phase measurement

Before and at irradiation:

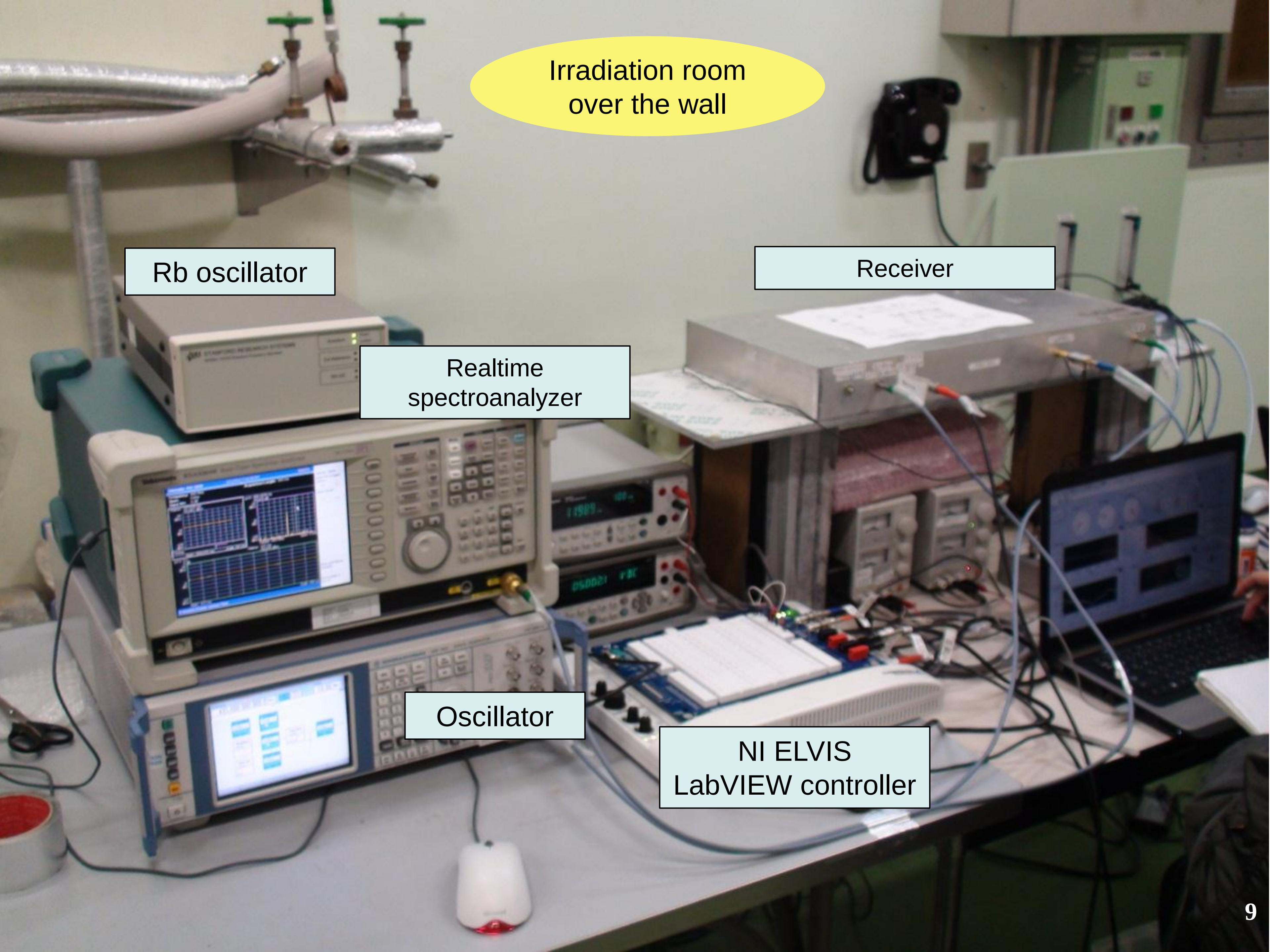
automatic tuning ON

*Tuned* $\Delta\theta$ is recorded

$$\vec{c} = \underline{\vec{b}e^{-i(\pi+\Delta\theta)}} + \underline{\vec{b}e^{-i\Delta\phi}} = 0$$

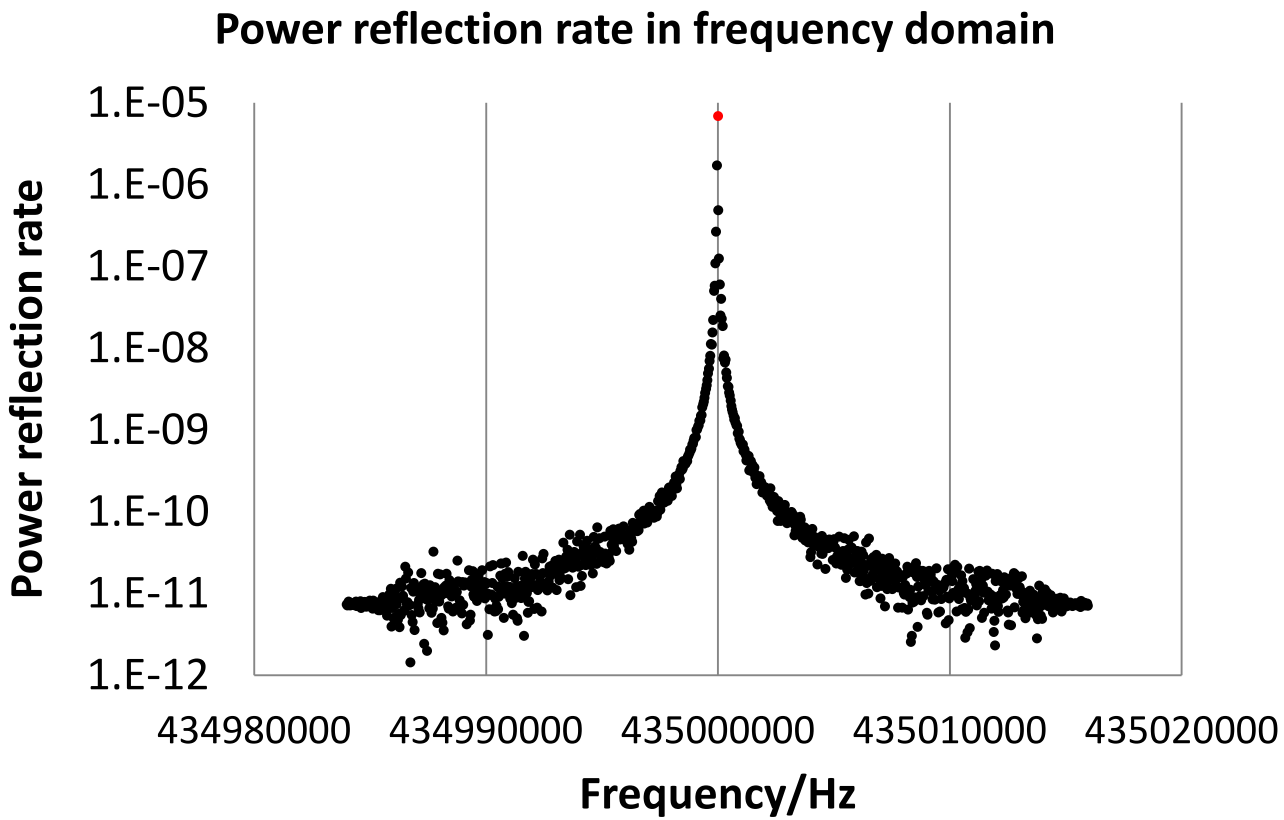
Reference Reflected wave

$\Delta\theta = \Delta\phi$ then $\Delta\phi$ Is measured


Irradiation room over the wall
Rb oscillator
Realtime spectroanalyzer
Receiver
Oscillator
NI ELVIS LabVIEW controller

# Frequency domain spectrum

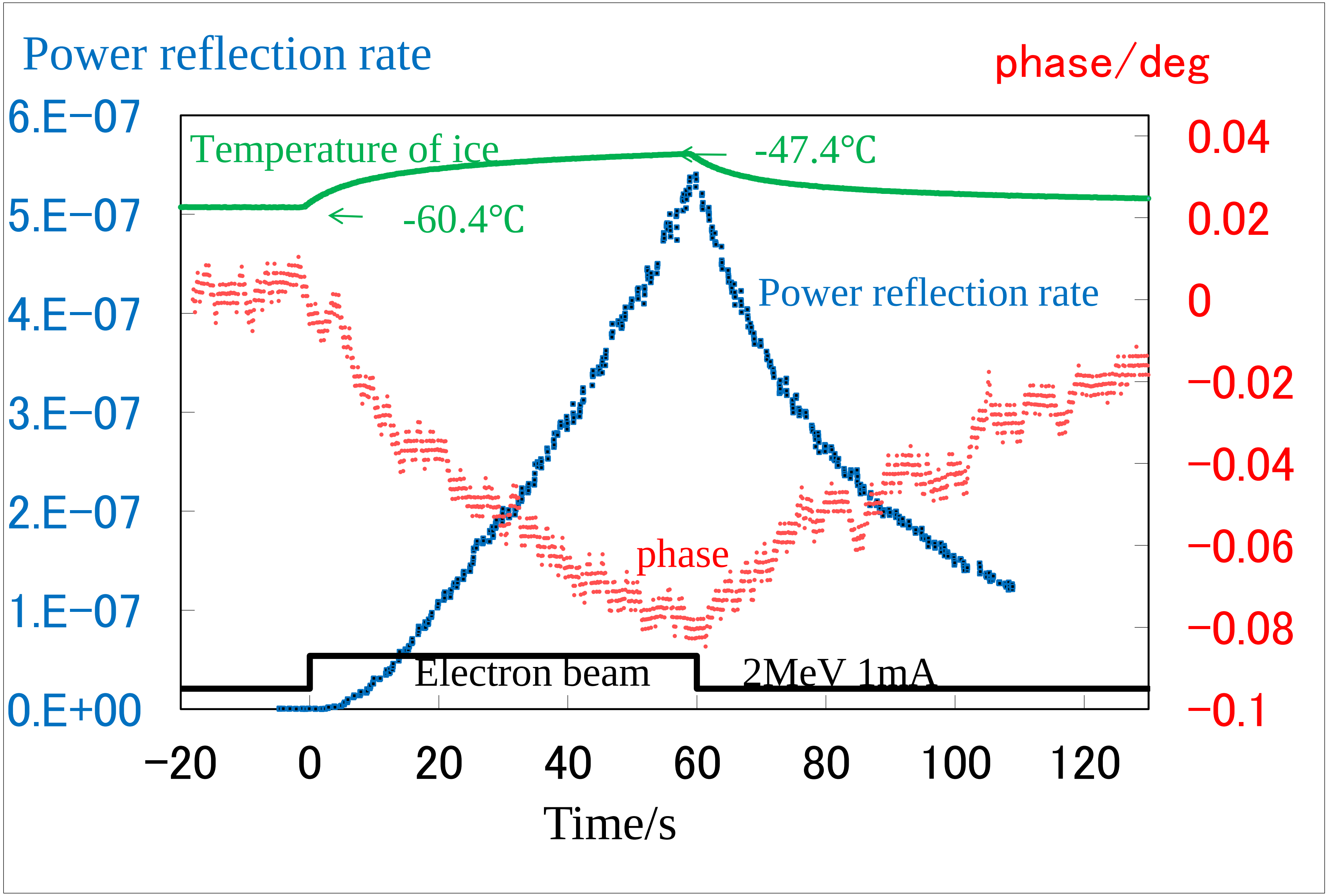
- Rejection of noises from electric power source of 50 Hz.



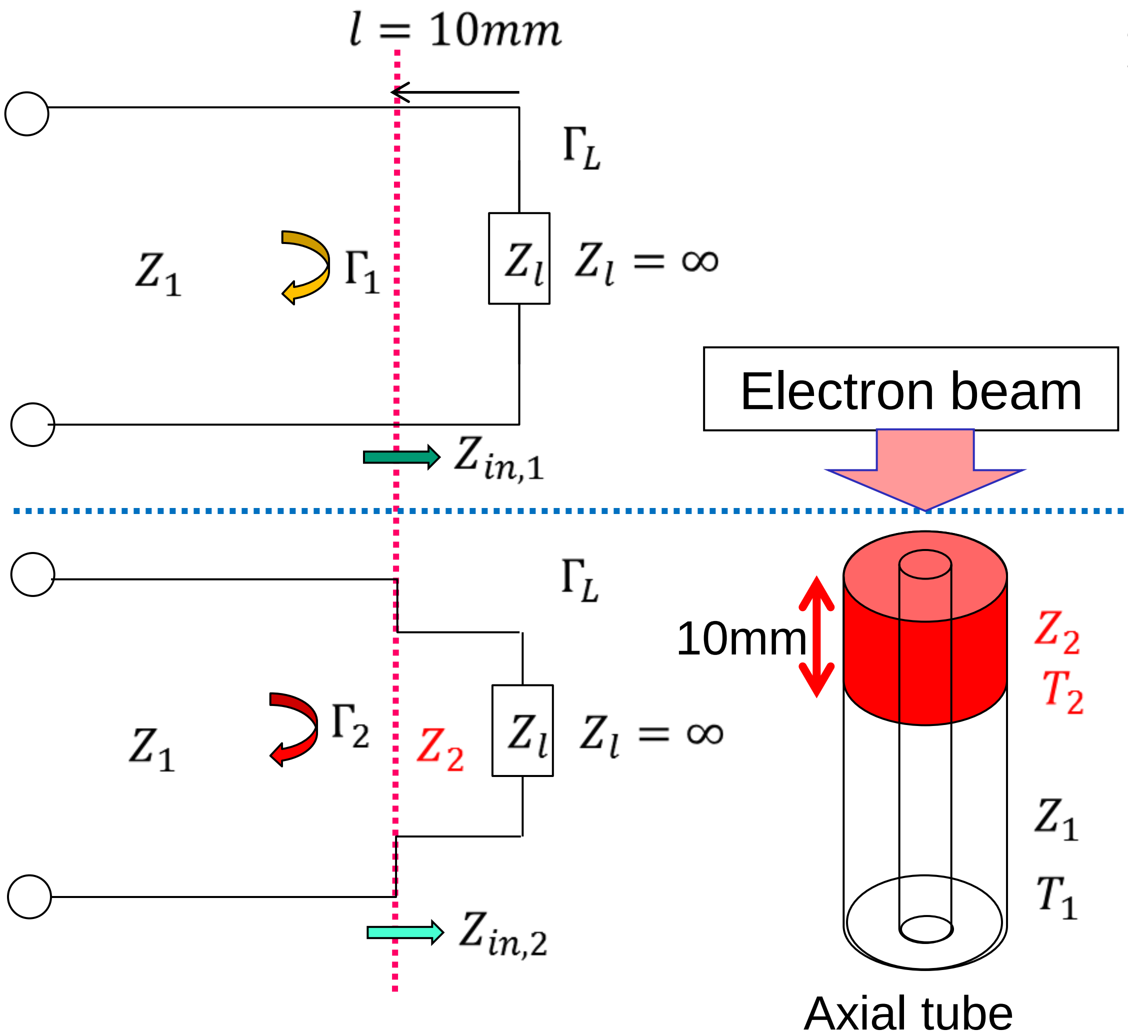

Data analysis of Real Time Spectrometer

- Time domain data of 1024points × 5 for 640 ms
- 1 datum for 128ms
- Conversion of time domain to frequency domain by FFT

# Reflection phase and rate in Ice



# Calculation of phase difference of reflected wave by a model (based on Telegrapher's equation)




$$\Gamma_L = \frac{Z_L - Z_1}{Z_L + Z_1} = 1 \ (\because Z_L = \infty)$$

$$\beta_1 = \frac{2\pi}{\lambda}\sqrt{\varepsilon_1}$$

$$\varepsilon_1 : T_1 = -60°\mathrm{C}$$

$$\Gamma_1 = \Gamma_L \exp(-j\, 2\beta_1 l)$$

$$Z_{in,1} = Z_1 \frac{1}{j\tan(\beta_1 l)}$$

$$\Gamma_L = \frac{Z_L - Z_2}{Z_L + Z_2} = 1 \ (\because Z_L = \infty)$$

$$\beta_2 = \frac{2\pi}{\lambda}\sqrt{\varepsilon_2}$$

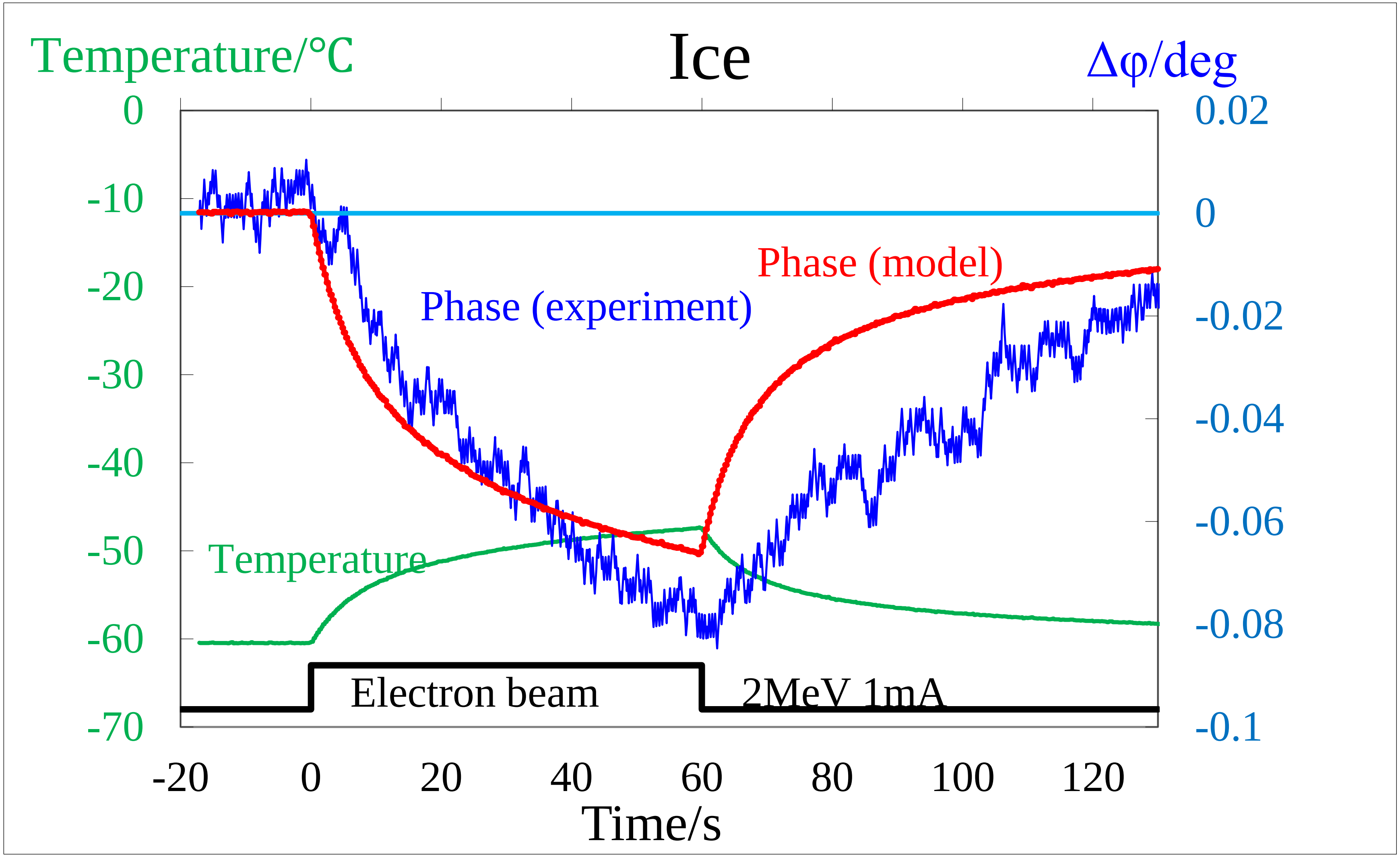
$$\varepsilon_1 : \mathrm{T} = T_2$$

$$Z_{in,2} = Z_2 \frac{Z_L + j\, Z_2 \tan(\beta_2 l)}{Z_2 + j\, Z_L \tan(\beta_2 l)} = Z_2 \frac{1}{j\tan(\beta_2 l)}$$

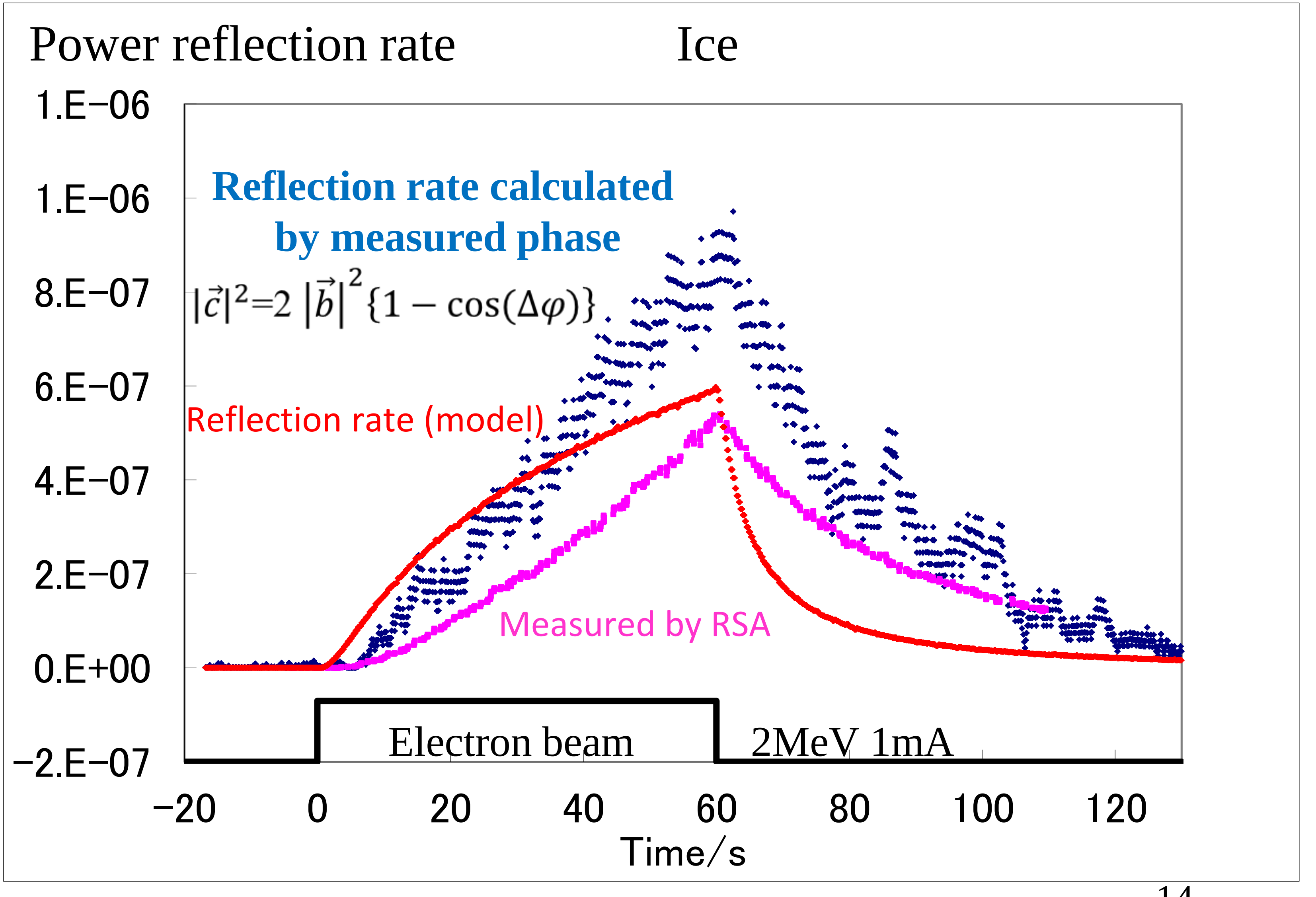
$$\Gamma_2 = \frac{Z_{in} - Z_1}{Z_{in} + Z_1}$$

**Phase difference Δφ between Γ1 and Γ2**

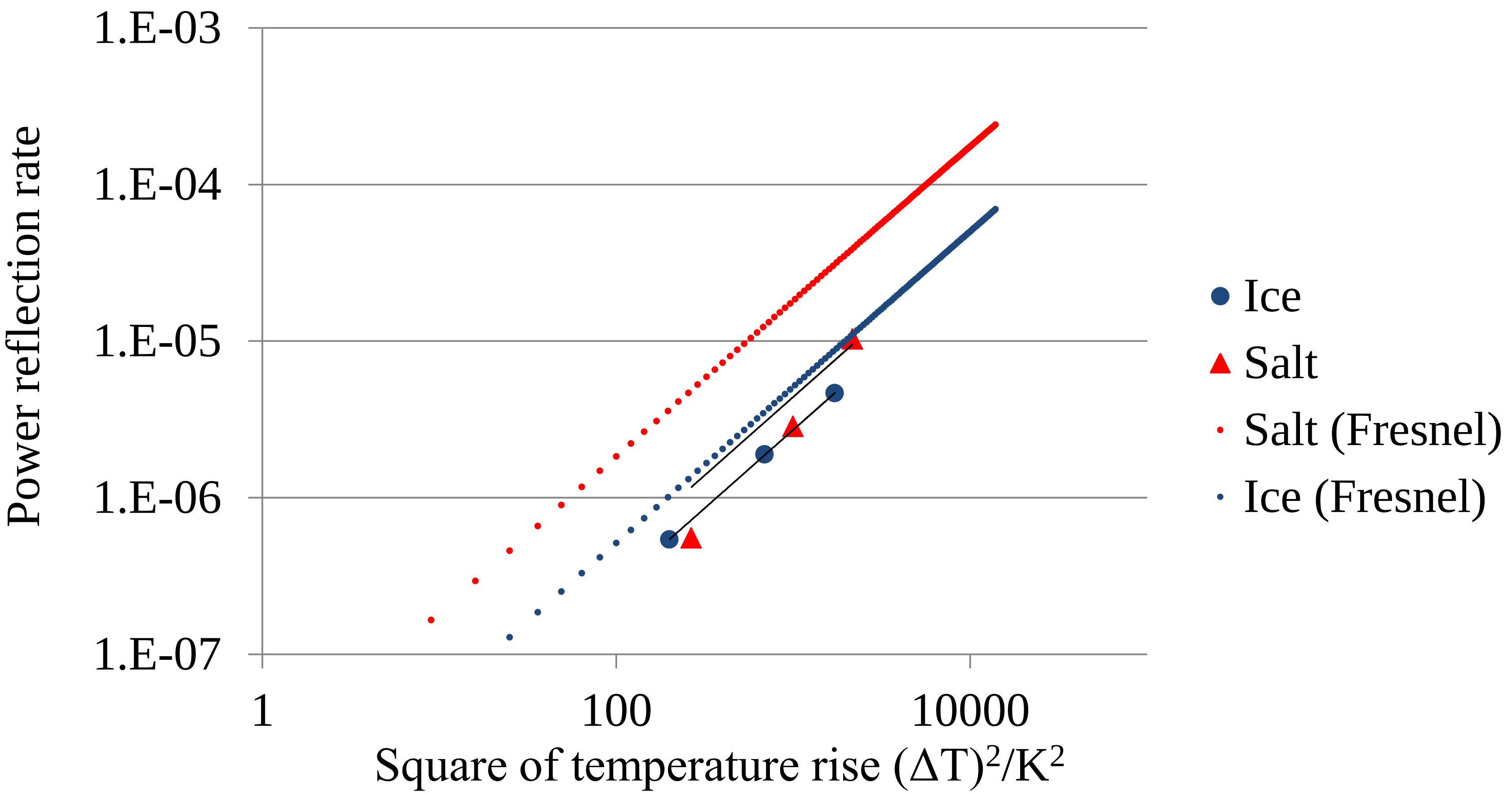
# Comparison of phases between experiment and calculation



# Reflection rate calculated by measured phase



# Power reflection rate vs. square of temperature



Radiation detectors using heat effects.

| | **Bolometer** | **Cloud chamber** | **Bubble chamber** | **Acoustic detector** | **Radar chamber** |
|---|---|---|---|---|---|
| Inventor | S.P. Langley | C.T.R. Wilson | D.A. Glaser | G.A. Askaryan | M. Chiba, et al. |
| Year | 1878 | 1911 | 1952 | 1957 | 2007 |
| Medium | Solid | Gas | Liquid | Solid, Liquid | Solid |
| Wave length | - | ～500nm | ～500nm | ～1m | ～10m |
| Body | Solid | Liquid particle, | Bubble, | Heated portion, | Heated portion, |
| Body size | - | ～0.5mm | ～0.1mm | 10cmφ×5m | 10cmφ×5m |
| Reflection or emission | - | Reflection | Reflection | Emission | Reflection |
| Operation | - | Decompression | Decompression | — | — |
| Process | Heating | Super cooling | Super heating | Heating | Heating |
| Amplification | Small heat capacity | Growth of liquid particle | Growth of bubble | — | Coherent reflection |
| Sensitivity | >1eV | ～100eV | ～100eV | $>10^{12}$eV | $>10^{12}$eV |
| Position reso. | - | ～0.5mm | ～0.1mm | ～30m | ～30m |
| Detector size | ～ 1cm | ～m | ～m | ～km | ～km |
| Memory time | ～ 1s | ～10ms | ～1μs | — | ～10s |

# Summary

- We found radio wave reflection from ice as well as rock salt with electron beam irradiation.
- Constructing an automatic-negative-feedback circuit in which variable phase shifter was tuned to get the null output, we measured the phase of the reflected-radio wave.
- The reflected amplitude was reproduced by the measured phase and was explained by a model in which the temperature is taken into account.
- Due to the long memory time, a stand-alone-GZK-neutrino detector could be constructed with a peak power of 1 GW (Equivalent Isotropic Radiation Power) radar supplied by a phased array antenna on a surface.
- Rock salt formation, Antarctic ice sheet and the moon crust would be candidates for the detector media.
- A new radiation detector “Radar Chamber” is established utilizing for all dielectric media. It is not only for radiation detection but also for other purposes using materials with inhomogeneous refractive index in space and time.