Radar for Detection of Ultra-High-Energy Neutrinos Reacting in a Rock Salt Dome

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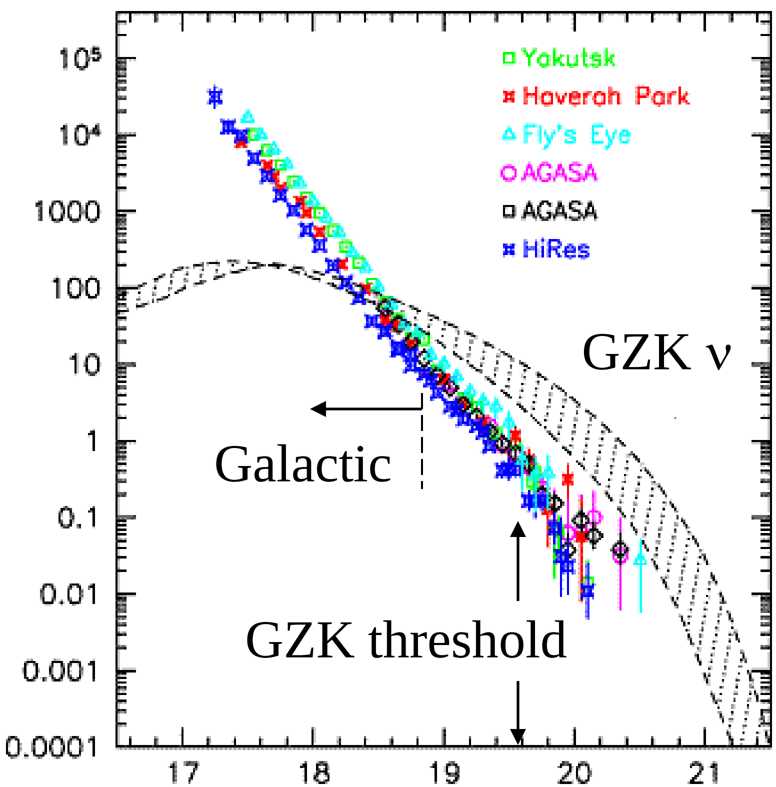
Talk at ARENA2010 – July 2, 2010

UHE Neutrinos Originate in UHE Cosmic Rays & CMB

Cosmic ray energy spectrum
Log E(dN/dE) [km^{-2} yr^{-1} (2π sr)$^{-1}$]



Log E [eV^{-1}]

●Hireso group observed Greisen-Zatsepin-Kuzmin(GZK) cutoff. Abbasi et al., PRL **100**, 101101(2008)

- The energy exceeds Δ production threshold.

$$p + \gamma_{2.7\,\mathrm{K}} \rightarrow \Delta \rightarrow n + \pi^+$$

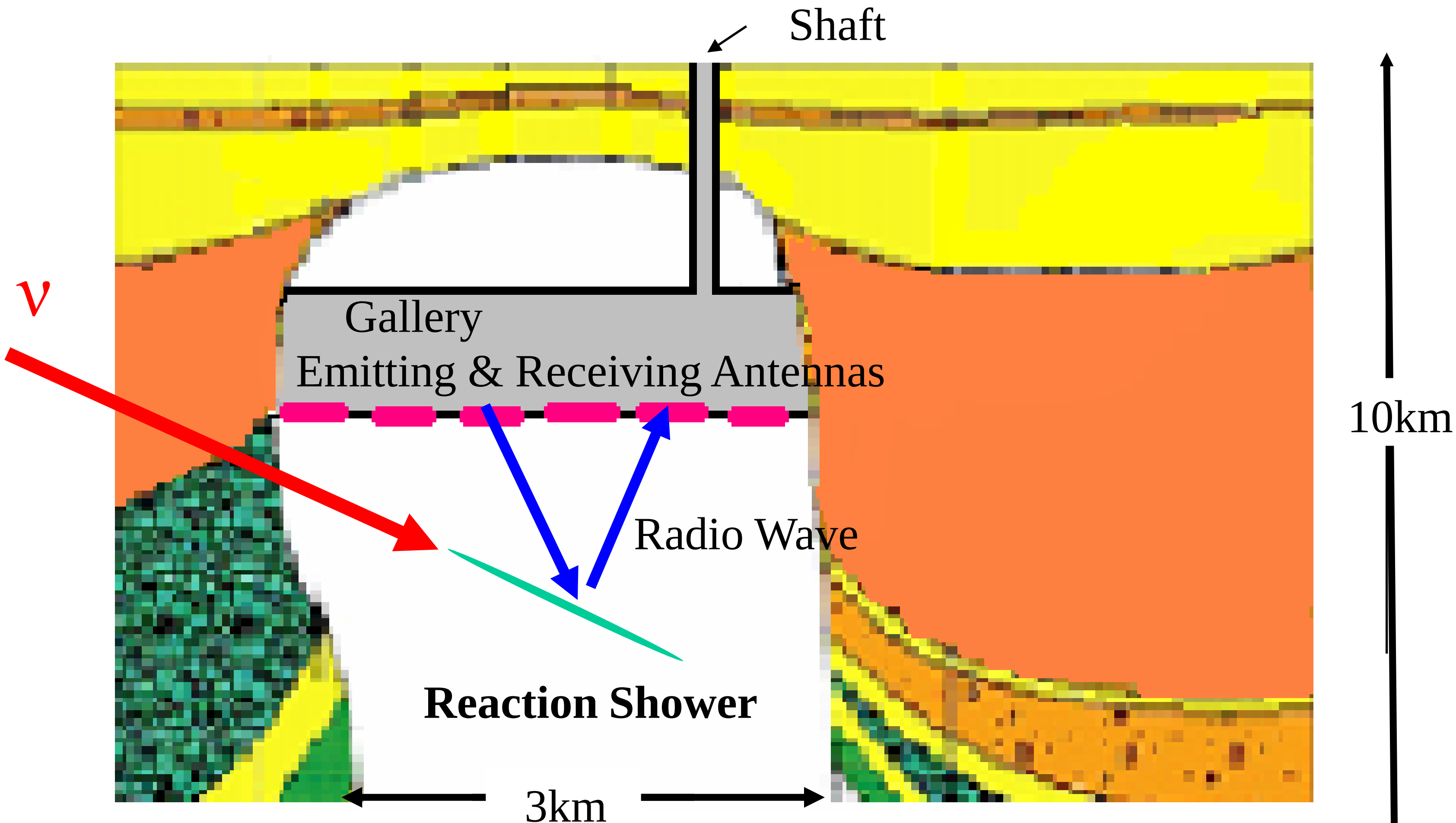
(CMB)

$$\pi^+ \rightarrow \mu^+ \nu_\mu, \quad \mu^+ \rightarrow e^+ \nu_\mu \nu_e$$

- GZK neutrino flux is as low as 1[/km^2/day] .

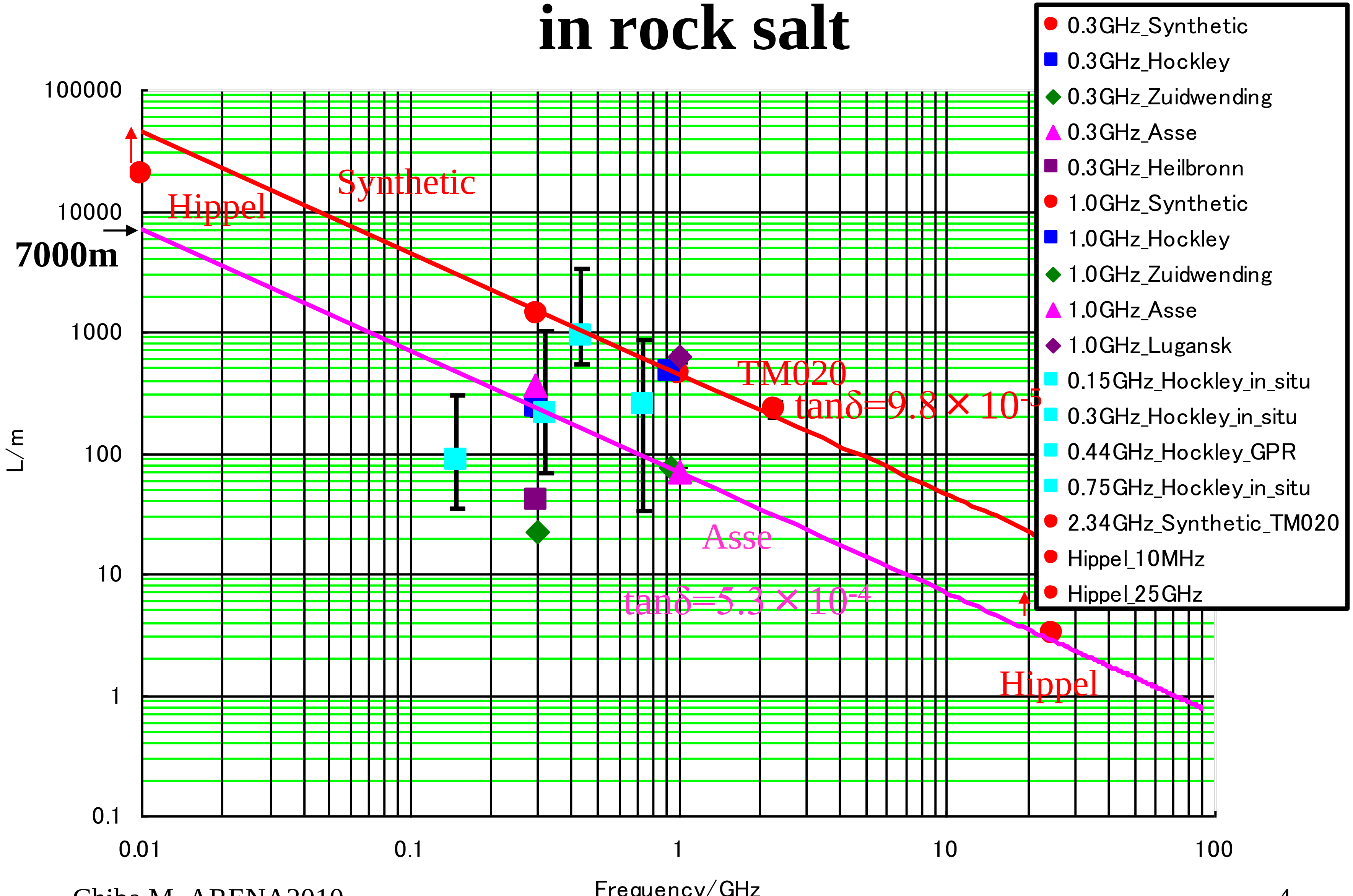
→Need a huge mass of detection medium

Radar for a salt dome



Rock Salt
Density 2.2[g/cm^3]
Refractive Index 2.43

Attenuation length of radio wave for electric field in rock salt

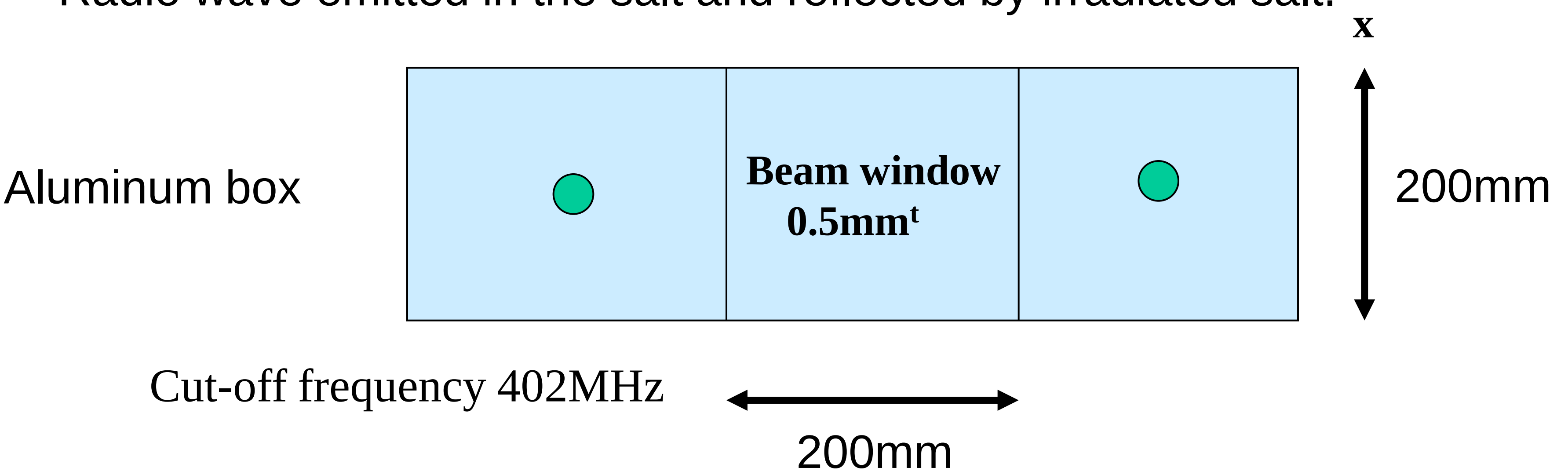


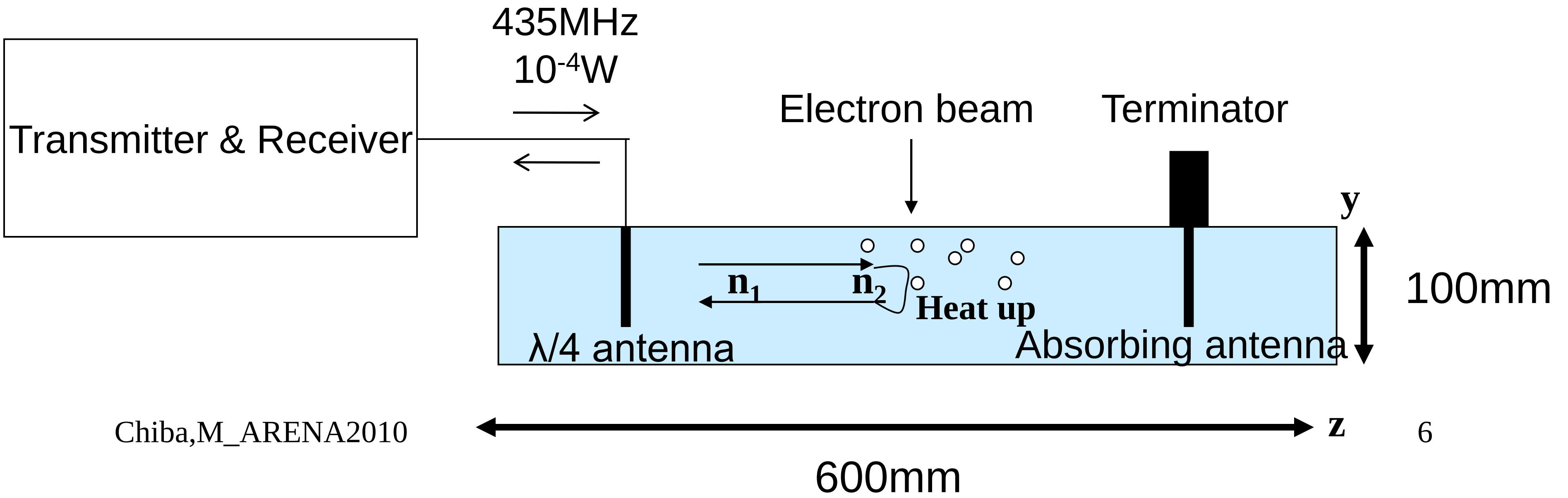
Radio Wave Reflection from Irradiated Rock Salt

Accel-erator	Beam	Radio wave	Tar-get inside	Target size	Reflection p. ratio Γ	Γ
1. KEK PF-AR	X ray	9.4 GHz	Wave guide	$2 \times 2 \times 10 mm^3$	10^{-6}@ 10^{19}eV	$\propto I^2$
2. TARRI	2MeV e^-	435 MHz	Free space	$100 \times 100 \times 100 mm^3$	10^{-6}@ 10^{19}eV	$\propto I^2$
3. TARRI	2MeV e^-	435 MHz	Salt filled wave guide	$200 \times 200 \times 100 mm^3$	10^{-6}@ 10^{19}eV	$\propto I^2$

A Waveguide Filled by Salt Powder（TE_{10}）

Low density (66%) salt powder (n_1=1.6) : λ=431mm@ 435MHz,
Radio wave emitted in the salt and reflected by irradiated salt.

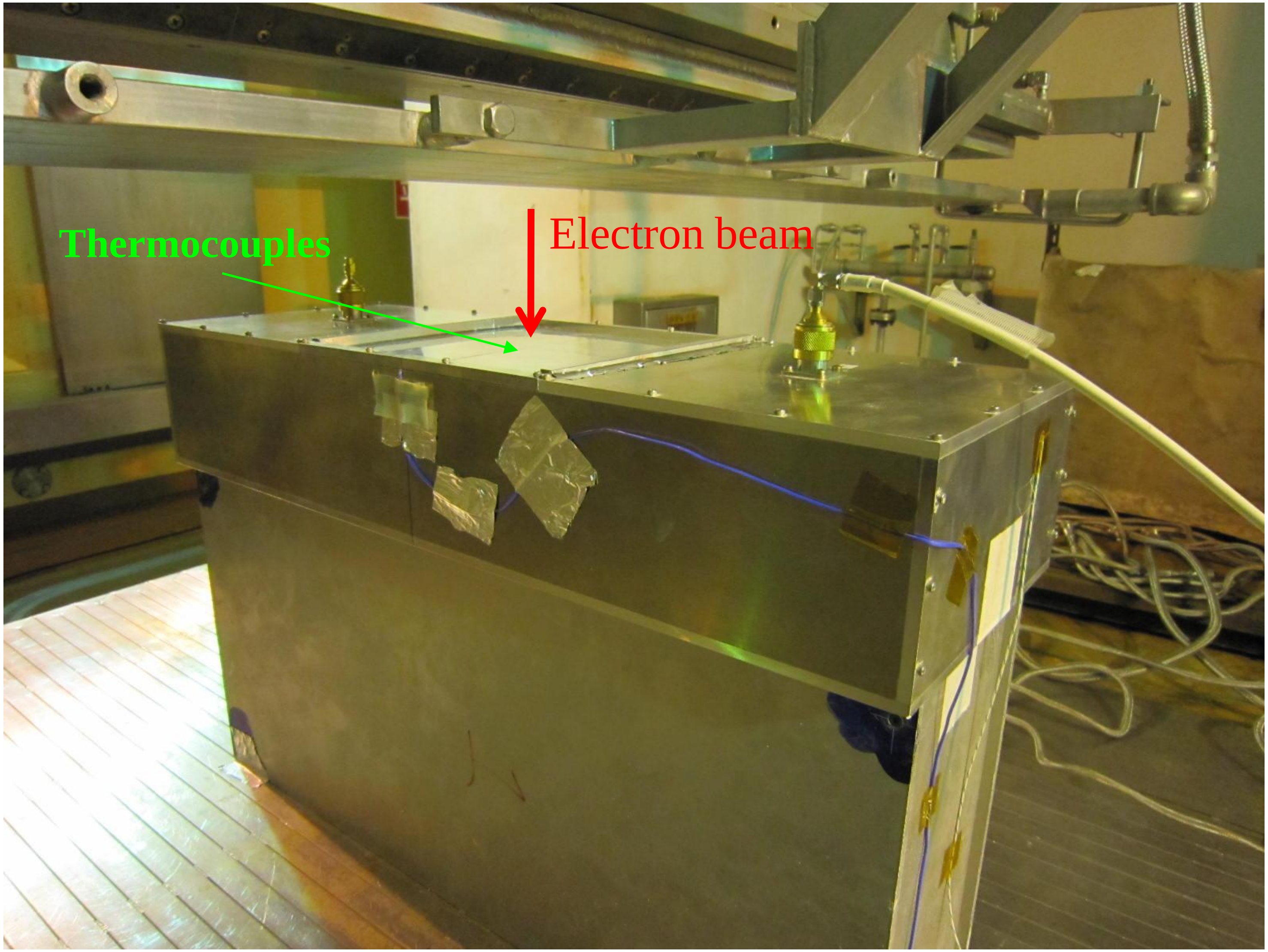




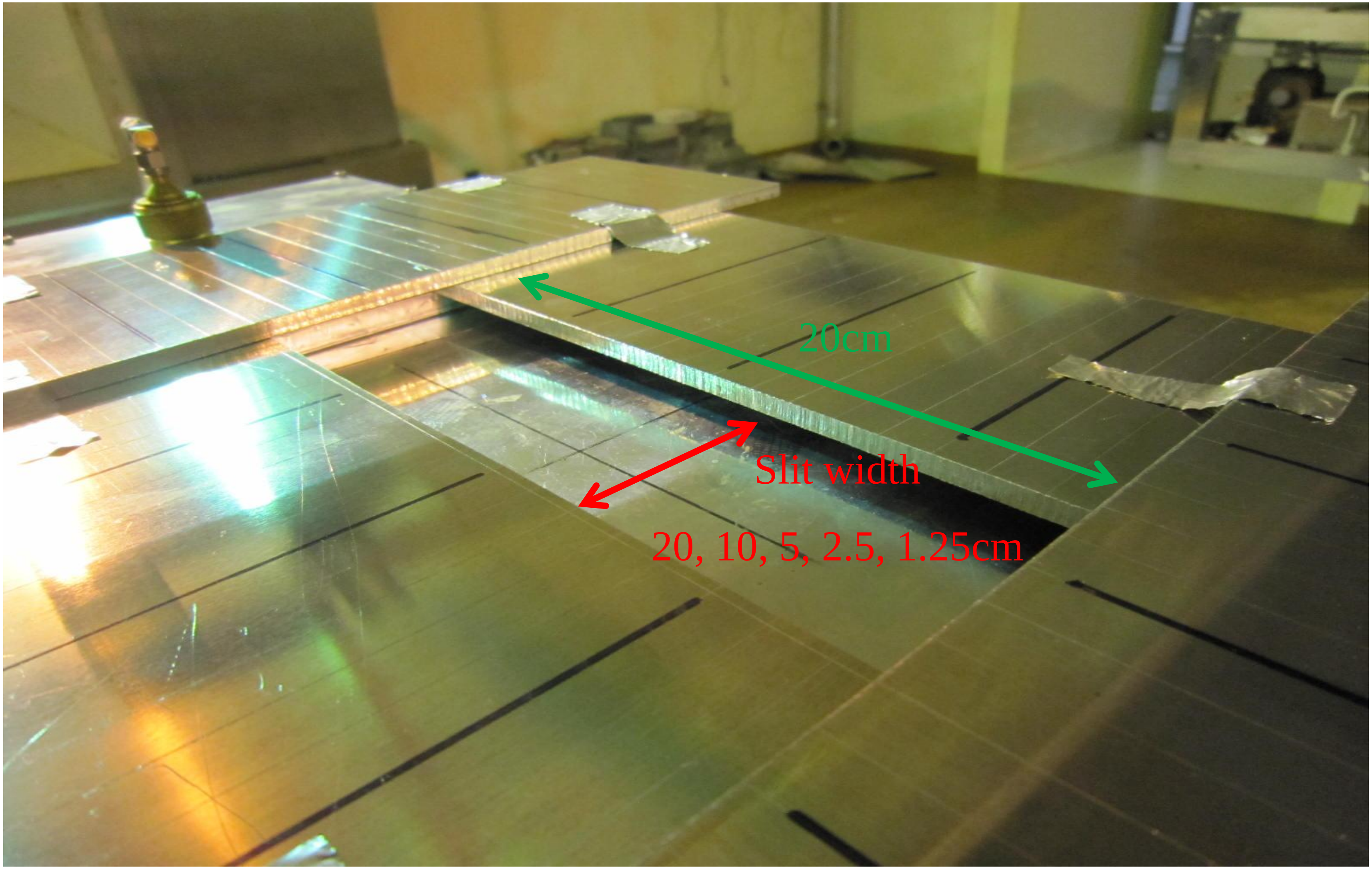
Wave Guide filled with salt powder

Beam exit window

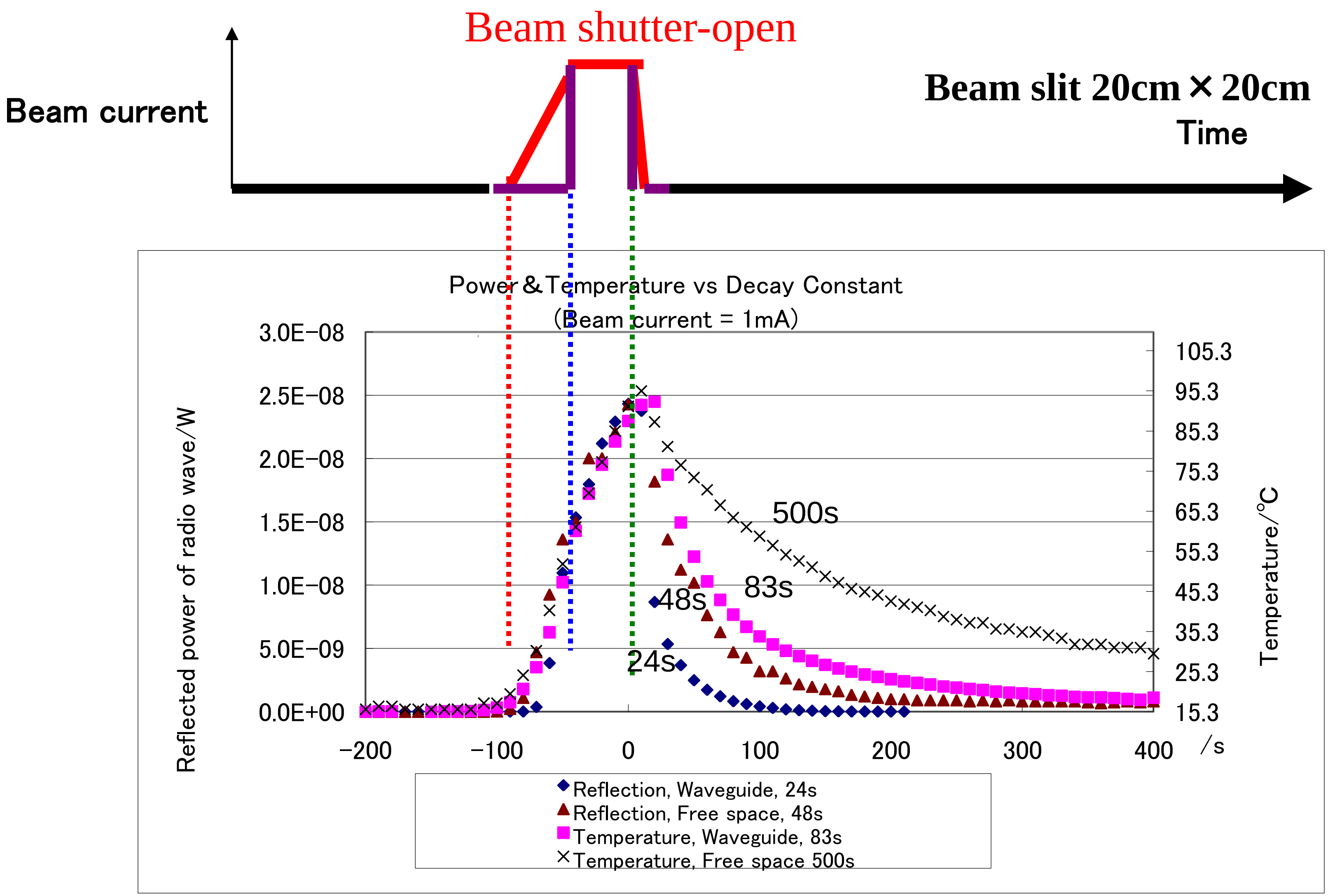
Beam shutter



Beam slit of wave guide



Reflected power of radio wave & temperature vs. time

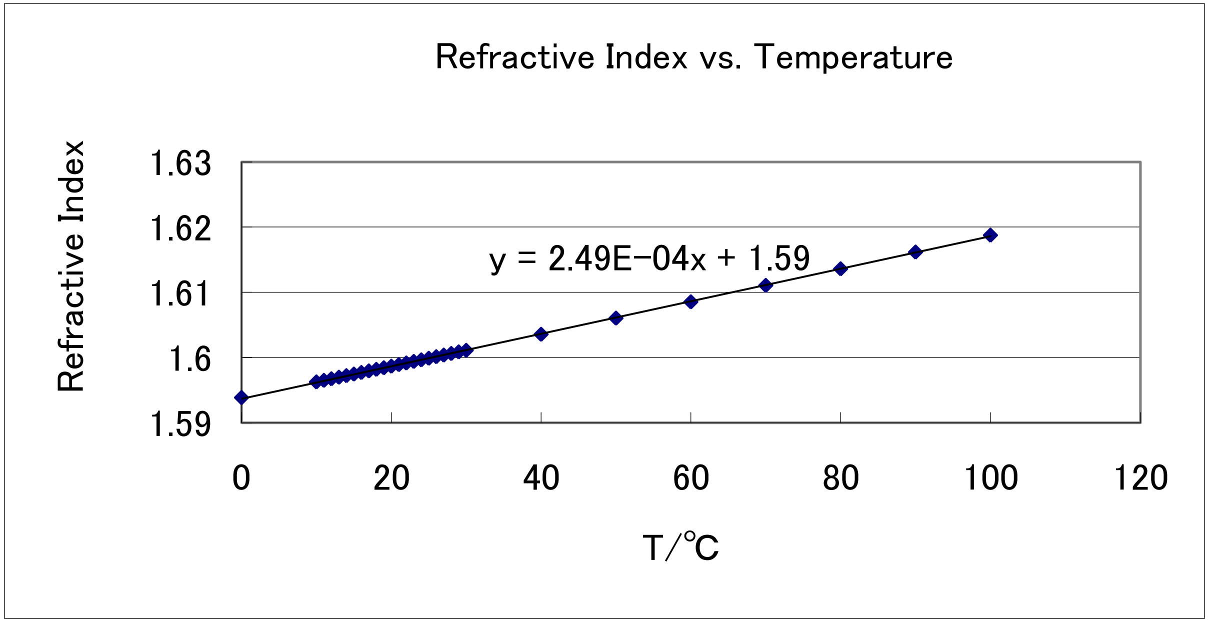


Refractive Index of Salt Powder vs. Temperature (model)

Phys.Rev. vol181Number3 15May1969, page1228-1236, James C. Owens, Harvard Univ.

Rock Salt
Density 2.2[g/cm^3]
Refractive Index 2.43

Salt powder, density ratio to rock salt=0.659
Density 1.45[g/cm^3]
Refractive Index 1.597@15℃

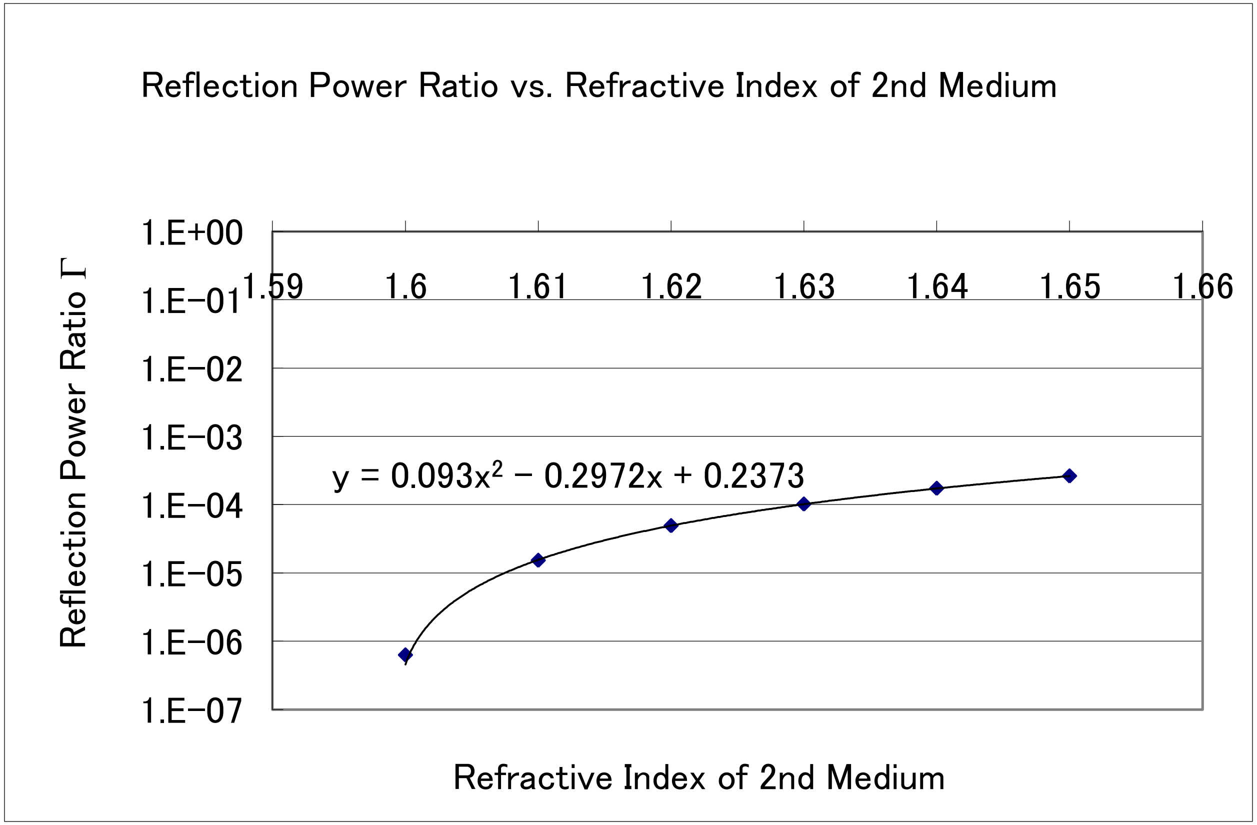


Reflection Power Ratio vs.Refractive Index

Fresnel equation

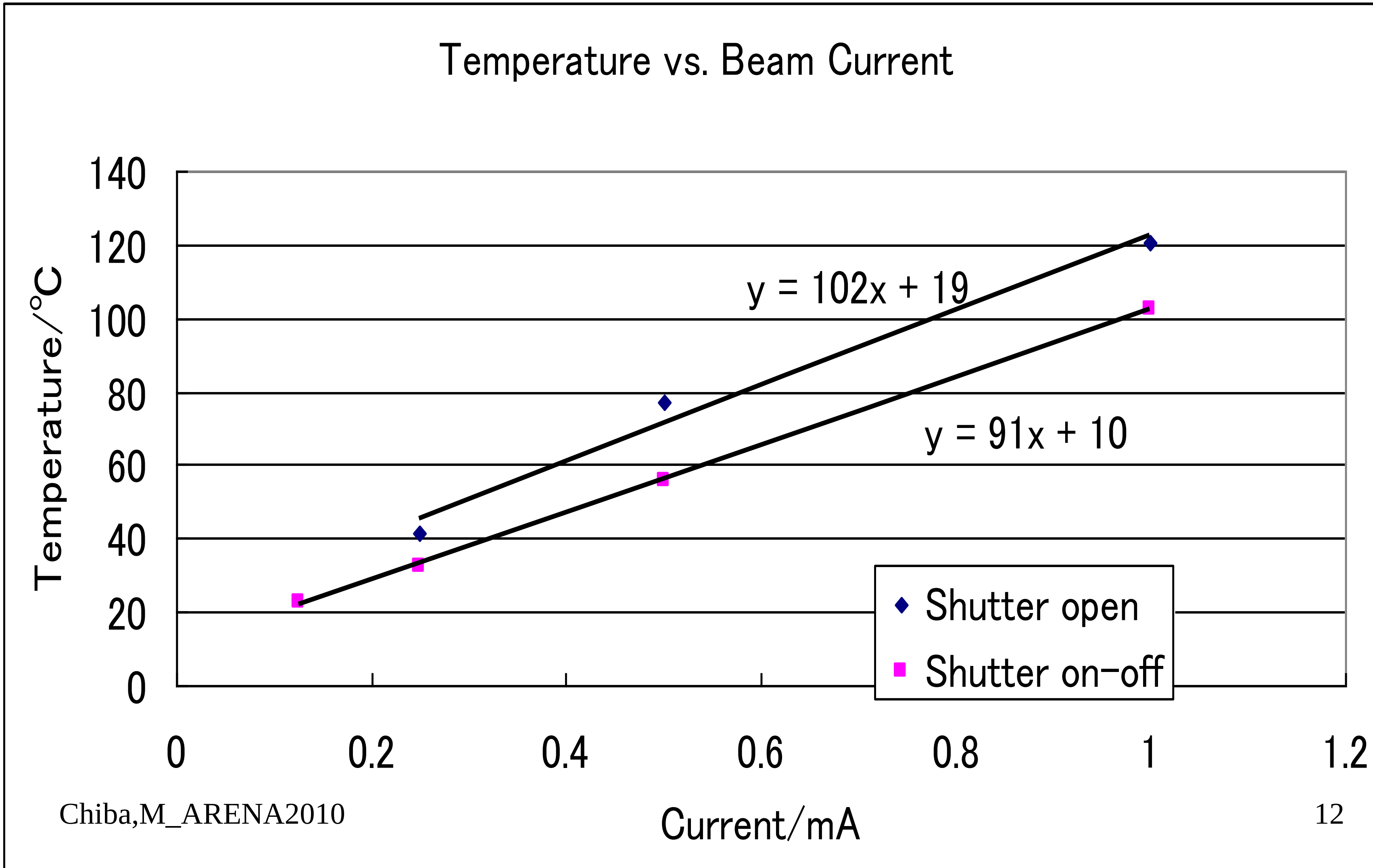
$$\Gamma = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$$

n_1(Refractive index of salt powder)=1.597@15℃
n_2(Refractive index rise in temperature)



Maximum temperature vs. Beam Current

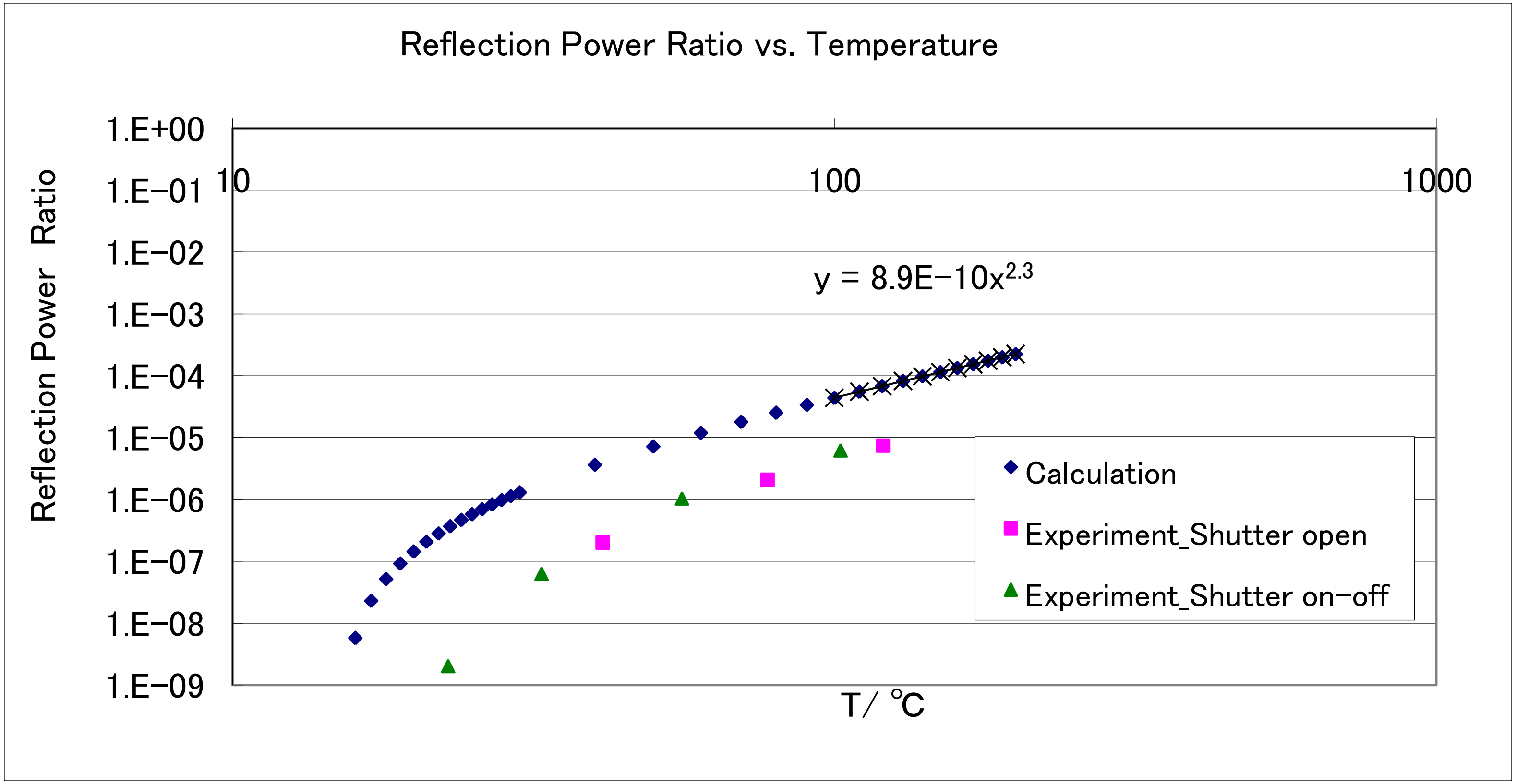
●Alumel-Cromel thermocouples set 5mm deep in salt at the center of the irradiated area of 20cm×20cm



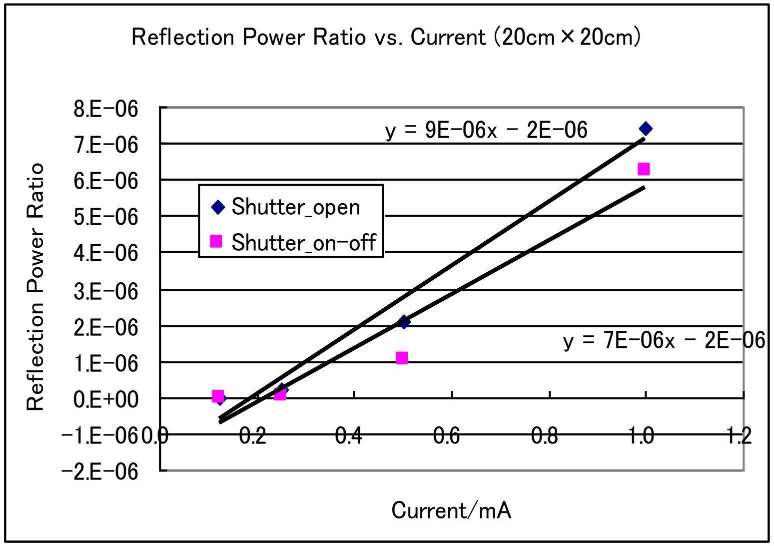
Radio Wave Reflection Power Ratio vs. Temperature

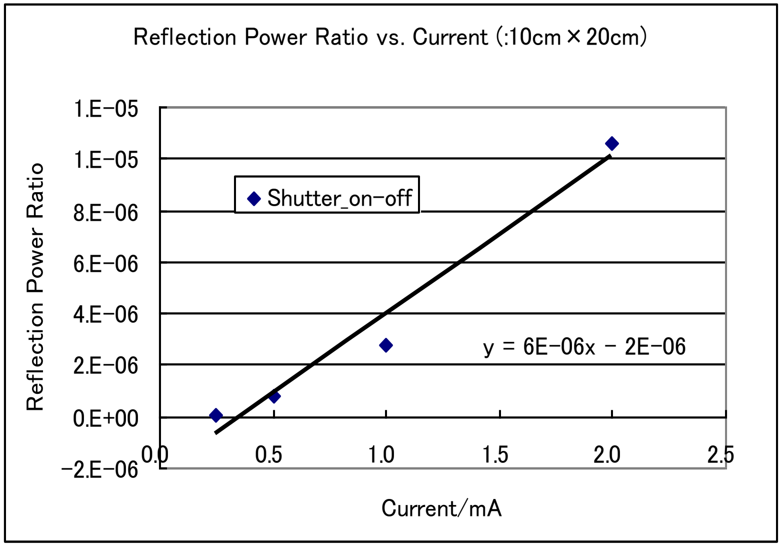
Temperature increase→Refractive index increase→Reflection power ratio increase

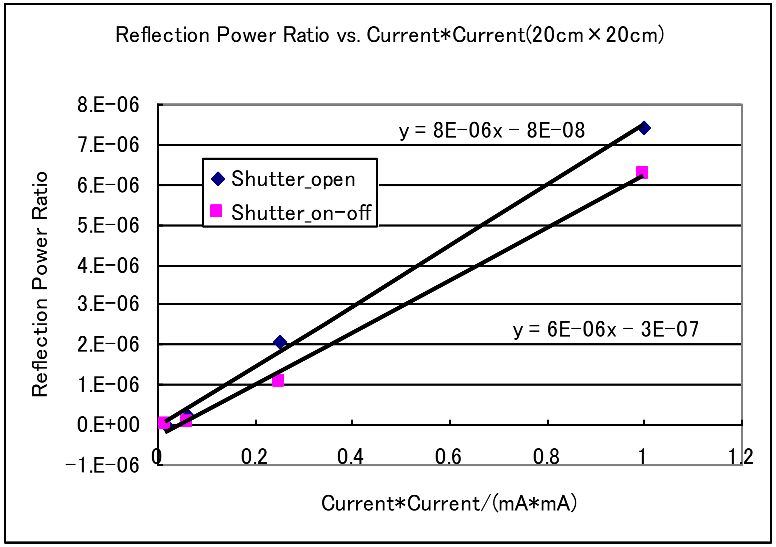
n1=1.5975 at 15℃　Beam window:20cm×20cm

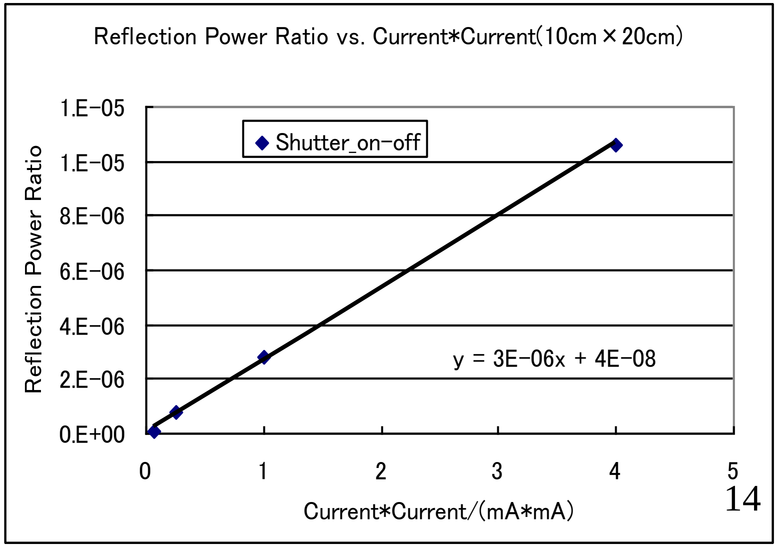


Reflection Power Ratio vs.Beam Current^2



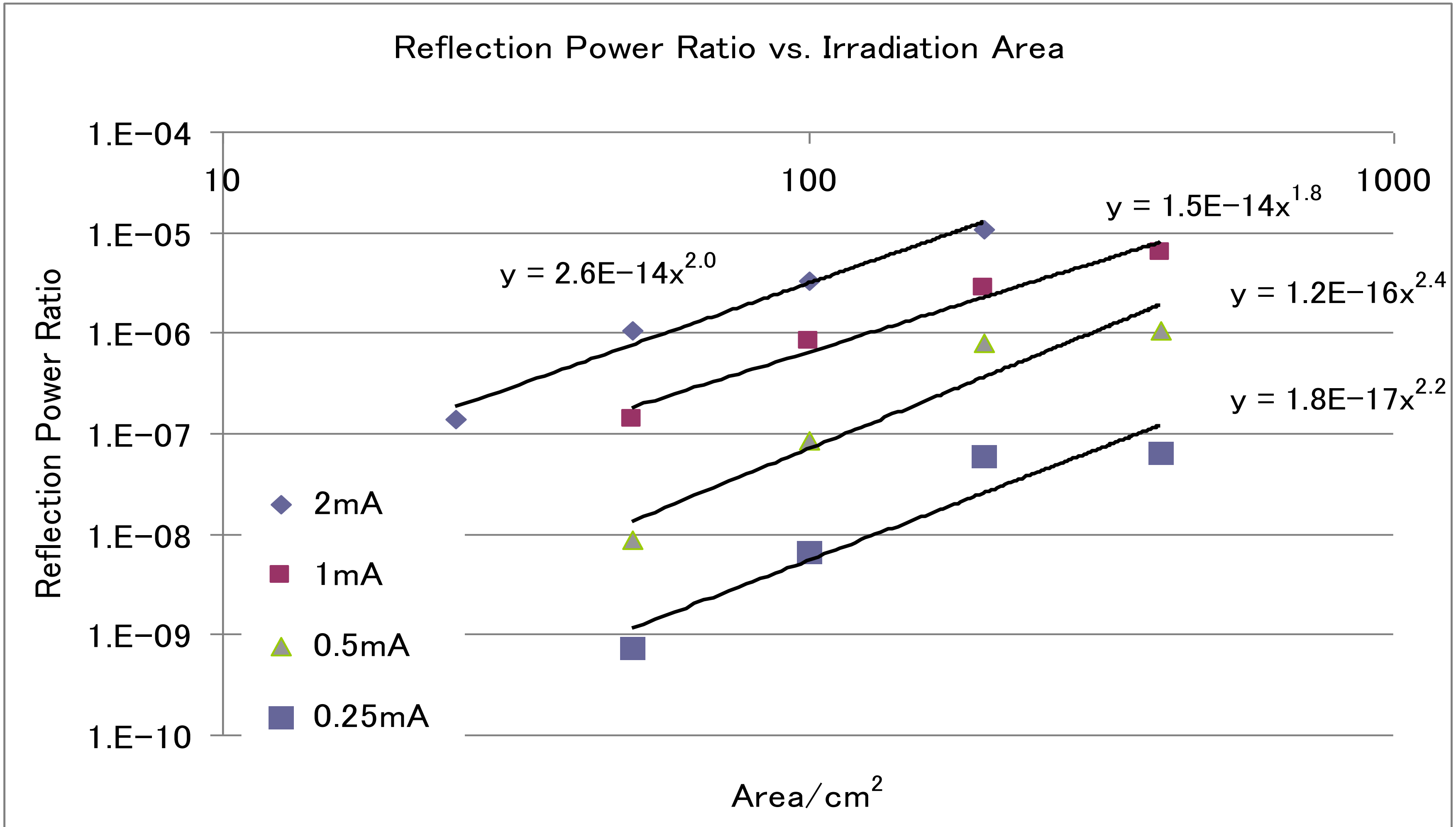






Reflection Power Ratio vs. Irradiation Area

● **Reflection power ratio increases with square of the area**



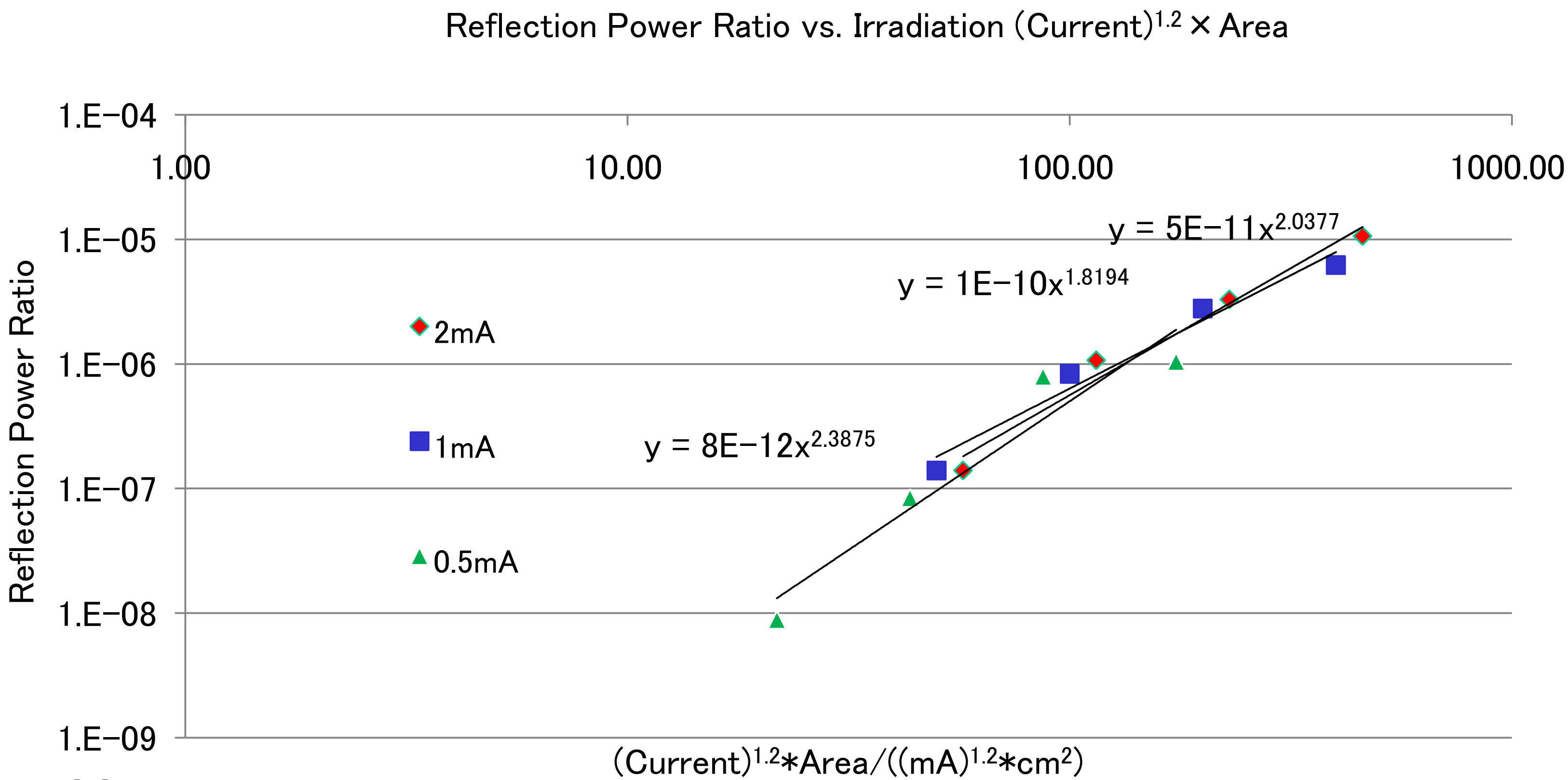
Reflection Power Ratio Γ vs. $(\text{Current})^{X} \times$ Area

Temperature ∝ Beam current,

Volume=Area × Range

X=1.2 is regarded as 1.0,

$\Gamma \propto (\text{Temperature} \times \text{Volume})^2 = (\text{Deposited energy})^2$



Radiation detectors using thermal effect

	Cloud chamber	Bubble chamber	Radar chamber	Bolometer
Medium	Gas	Liquid	Solid	Solid
Wave length	～500nm	～500nm	～10m	−
Body, Reflection	Liquid particle, Refrac. index	Bubble, Refrac. index	Heated portion, Refrac. index	− Thermome.
Body size	～0.5mm	～0.1mm	10cmφ ×5m	−
Operation	Decompression	Decompression	—	−
Process	Super cooling	Super heating	Heating	Heating
Amplification	Growth of liquid particle	Growth of bubble	Coherent reflection	Small heat capacity
Sensitivity	～100eV	～100eV	＞10^{12}eV	＞1eV
Position reso.	～0.5mm	～0.1mm	～30m	−
Detector size	～m	～m	～km	～ 1cm
Memory time	～10ms	～1μ s	～10s	～ 1s

Summary

●We found radio wave reflection effect due to the refractive index boundary caused by irradiated heat.

●A new radiation detector (Radar Chamber), in a sense “Remote Sensing Bolometer”, using the radio wave reflection effect would be suitable to construct for detection of ultra-high-energy neutrinos reacting in a rock salt dome.

●Antarctic ice would be another candidate of the medium using the radio wave reflection effect having a huge mass and a long attenuation length in radio wave.

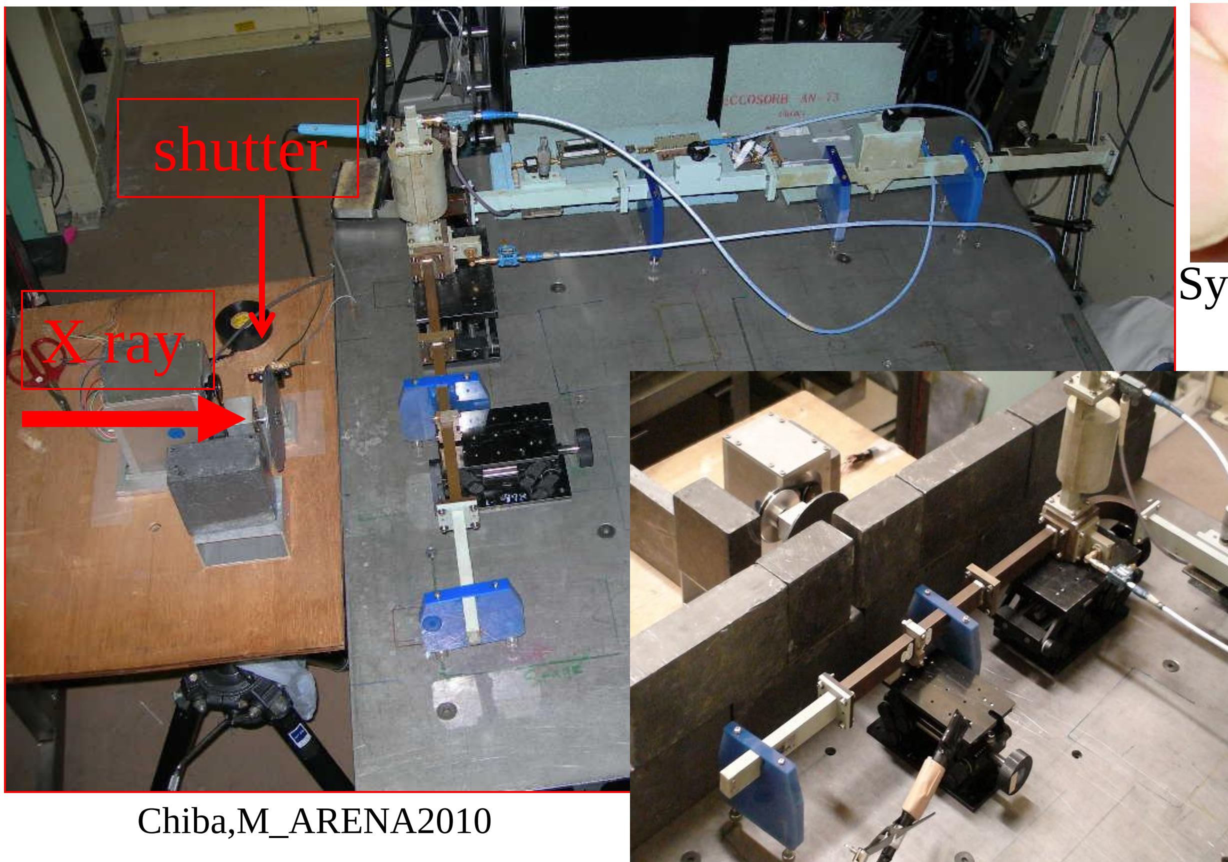
	Δε/10℃	Heat capacity mJ/(mK)	Thermal conductivity W/(mK)
Rock salt (20℃)	0.017	100	6
Ice (-30℃)	0.01	270	2.8

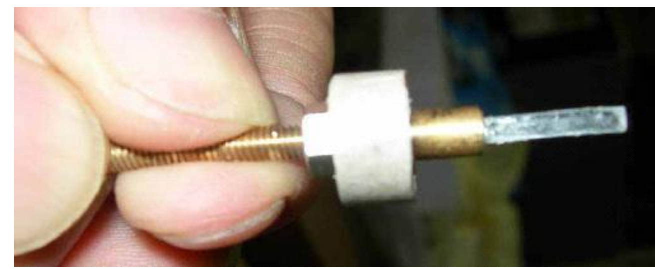
Backup

Experimental setup at KEK PF-AR

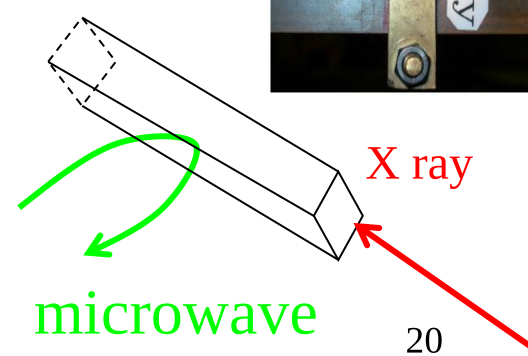
- X ray and microwave (9.4 GHz, 10^{-4} W) are irradiated to a rock salt sample, simultaneously.
- Null detection method is employed for detecting minimal signal.
- Measure microwave reflection change due to X ray irradiation.

Rotary X ray disc shutter
- Lead: $4mm^t$
- Φ:100mm,
- Orifice: $4x4mm^2$



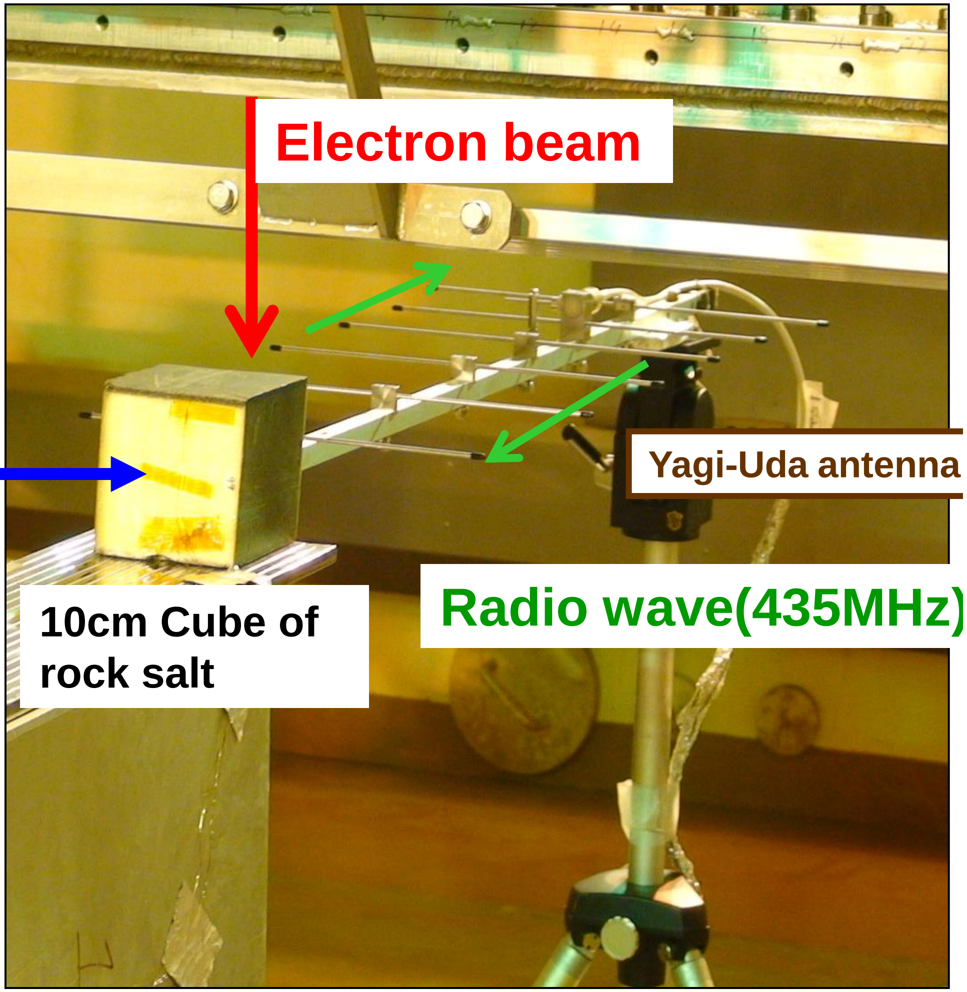


Synthesized rock salt
$2 \times 2 \times 10$ mm^3

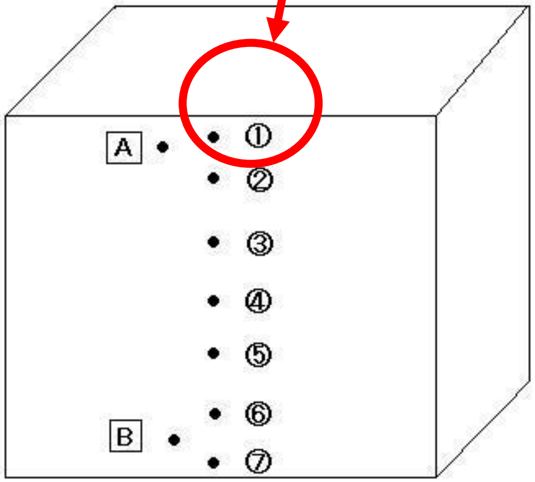


TARRI, Free space

Radio wave length
69cm (in air)

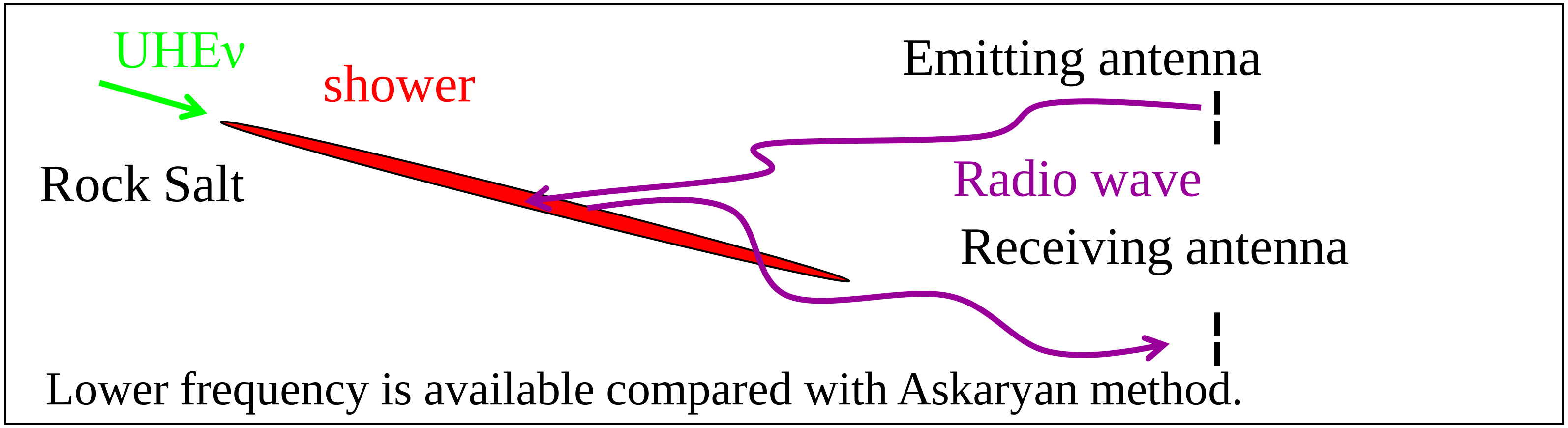


Thermo couples



Reflection power of radio wave and the temperature of the target were measured under irradiated by 2MeV electron Cockcroft-Walton accelerator.

Radar method: microwave reflection experiment



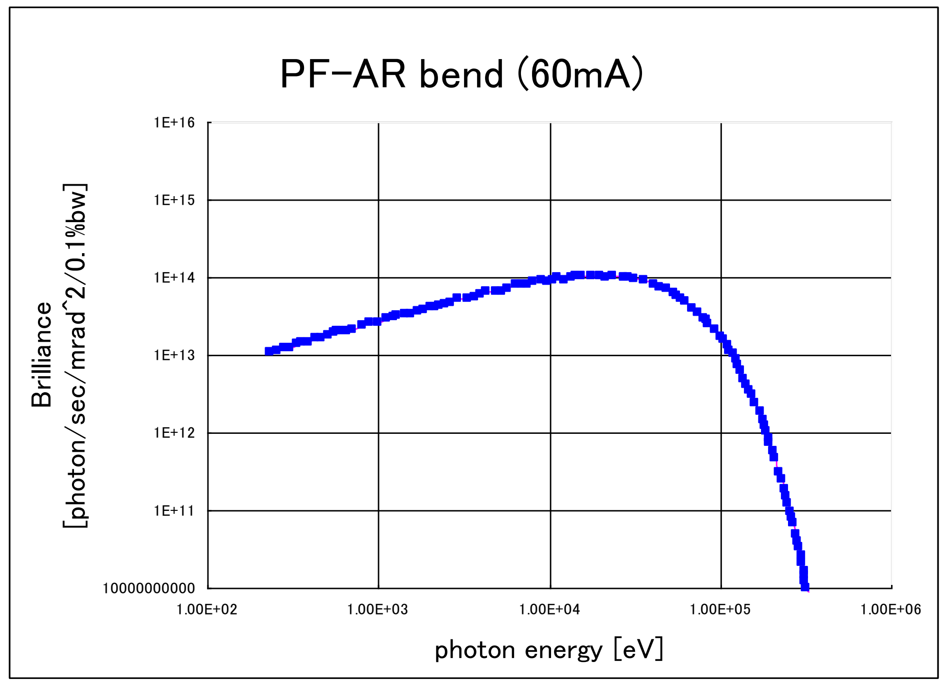
Electromagnetic ionization in rock salt generated by X ray irradiation

- ●X ray Spectrum: white
- ●Energy: 8-100 keV
- ●Repetition: 800 kHz
- ●Pulse width: 30ps

Synchrotron radiation from KEK AR electron accumulation ring

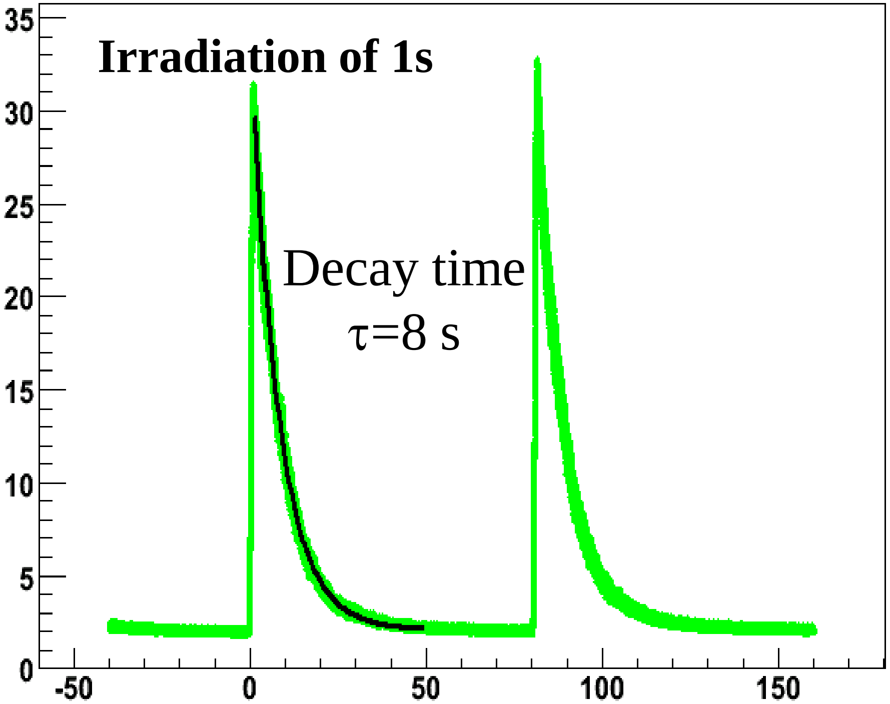
- ●Electron energy: 6.5GeV
- ●Current: 60mA
- ●Lifetime 10 hours

Brilliance of X ray source

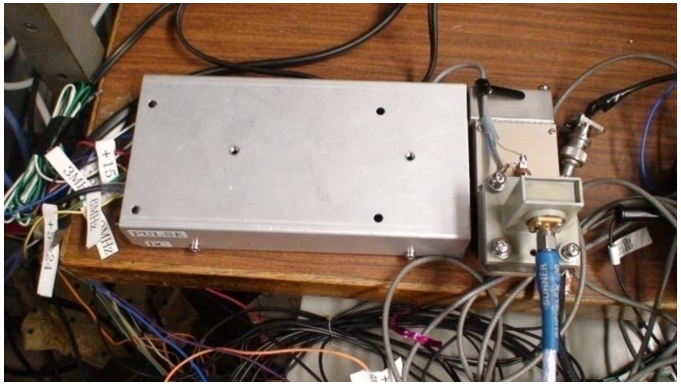


Reflected power vs. elapse of time

10^{-13} /W



Elapse of time/s



Receiver:

Ueda-NEC Co. Ltd.: NRG-98

- Logarithmic amplification: 10^{12}
- Receiving power range ; 10^{-14}-10^{-4} W
- 9.4GHz, Band width: 3MHz

- Microwave reflection rate of 10^{-6} at the X ray energy deposit of 10^{19} eV/s.
- Reflection target candidates: free electrons, local thermal blobs, color centers, phonons, polarons, polaritons?

Coherency of the reflection

Reflection Power: P

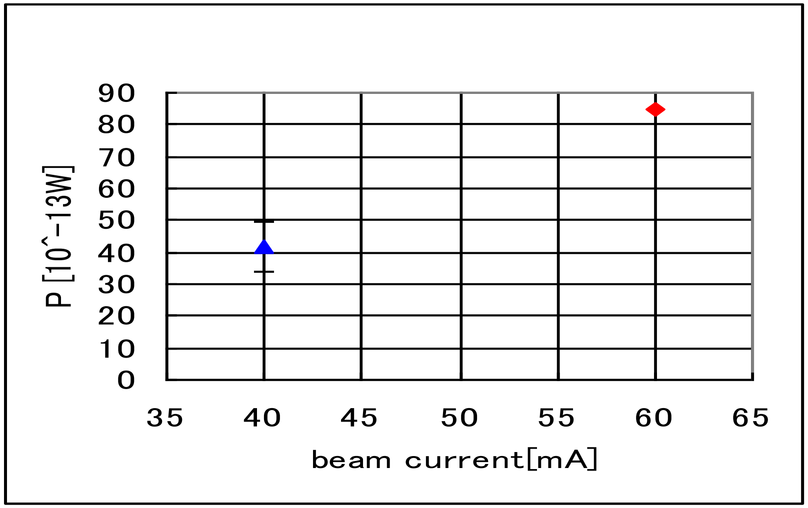
X ray intensity dependence

Complete coherence

P ∝ (intensity)^2 ∝ (AR beam current)^2

P(40mA) =41.7±7.9 [10^{-13}W]

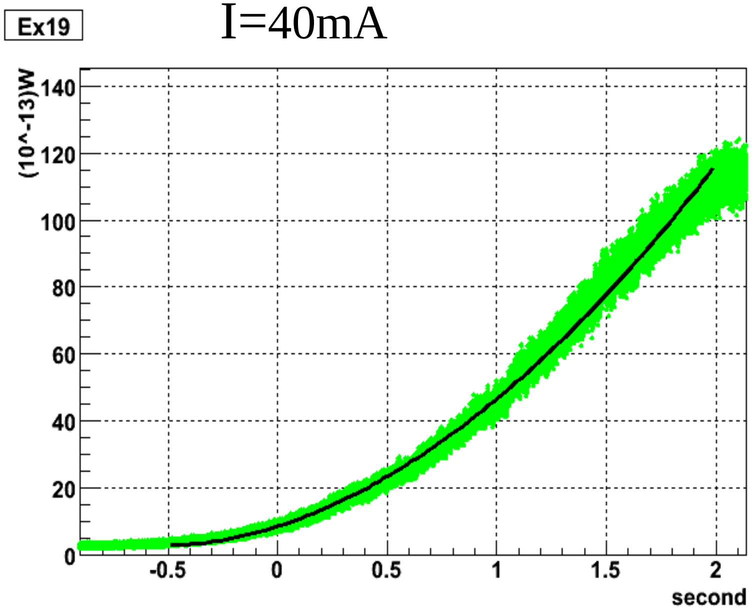
P(60mA) =84.6±0.5 [10^{-13}W]



$$\frac{P(40mA)}{P(60mA)} = 0.49 \pm 0.09 = \left[\frac{40}{60}\right]^x$$

Irradiation time dependence

I=40mA



P=At^X+B

↓

X=2.1±0.1

↓

X=1.8±0.4 → P ∝ (intensity)^2 ∝ (Irradiation time)^2 → Coherent

Temperature dependence of reflected power

J. C. Owens, Phys.Rev. 181(1969)1228

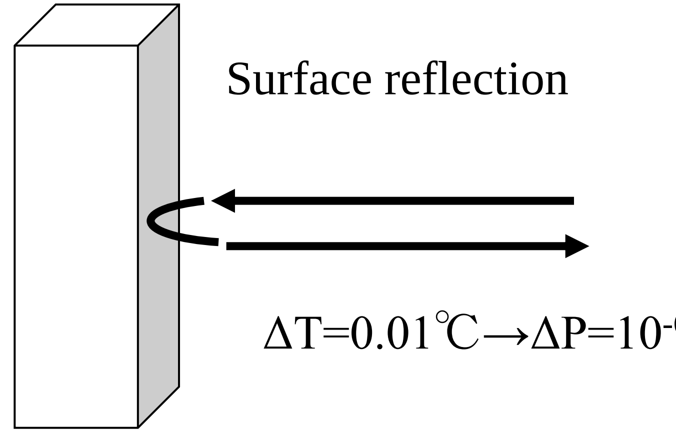
$\varepsilon' = 6860/(1980-T)+2.385$

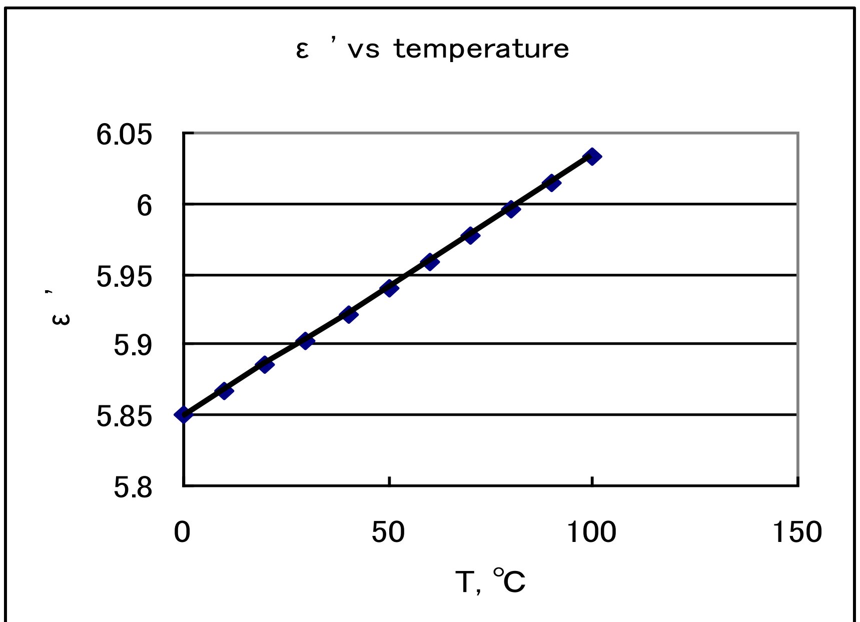
$n=\sqrt{\varepsilon'}$

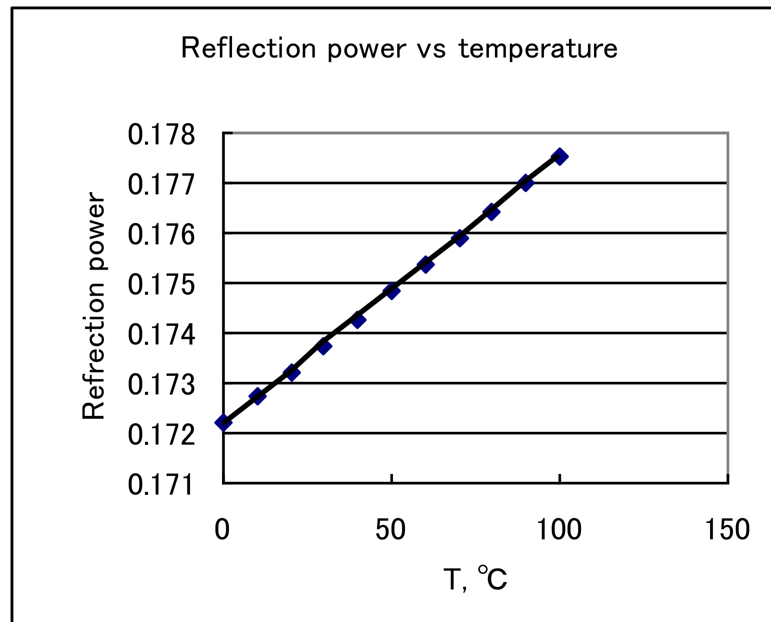
Reflected power $\propto (n-1)^2/(n+1)^2$

Temperature $\propto$ Energy deposit

$\propto$ Irradiation time





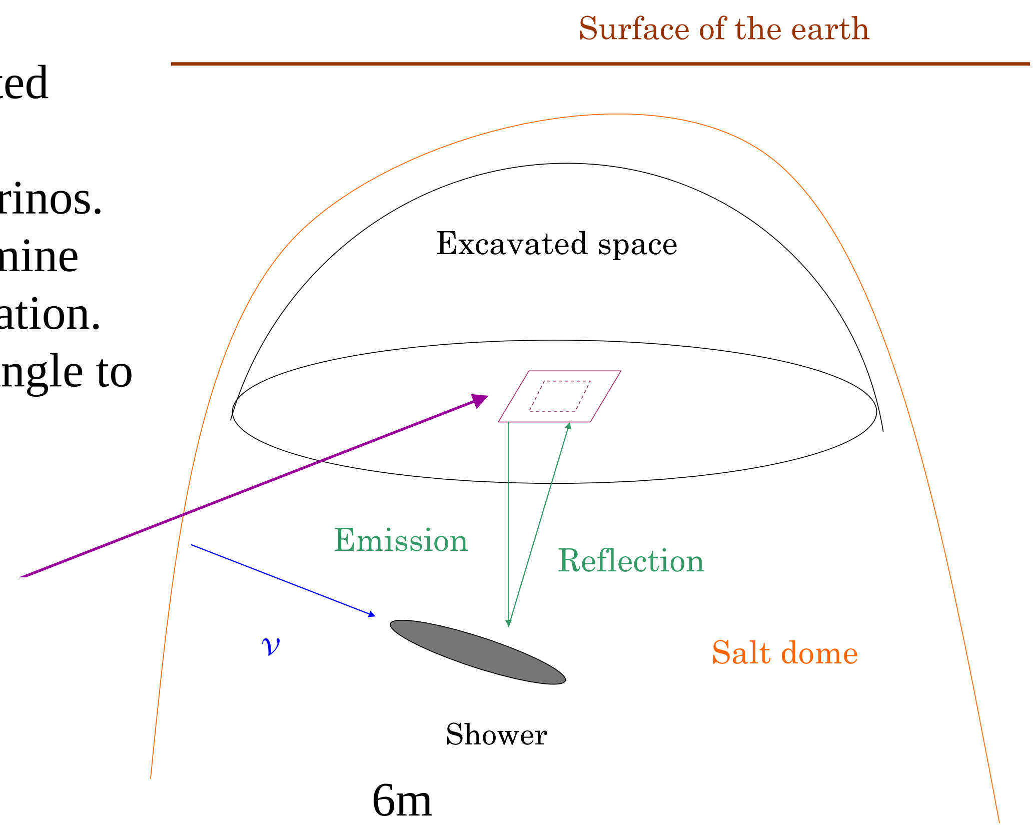


Radar method：Minimum setup

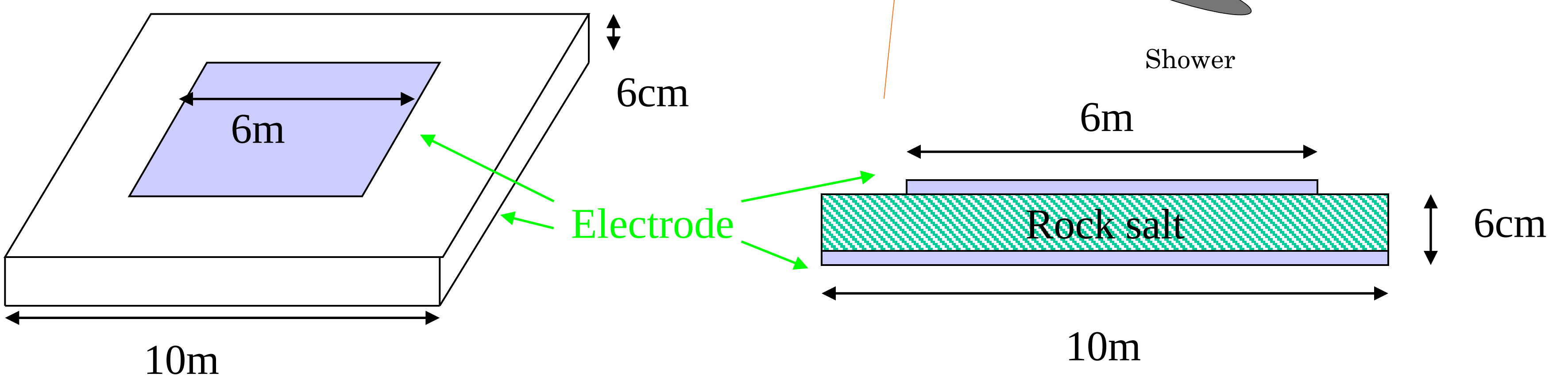
- Need no expensive boreholes.
- Utilize low frequency radio wave around 10MHz where attenuation length is expected as long as 7000m.
- Minimum setup can only count # of neutrinos.

Increased receiving antennas help to determine the shower axis without directional information. Reflection efficiency is different with the angle to the antenna. Up going UHE neutrinos are absorbed by the earth.

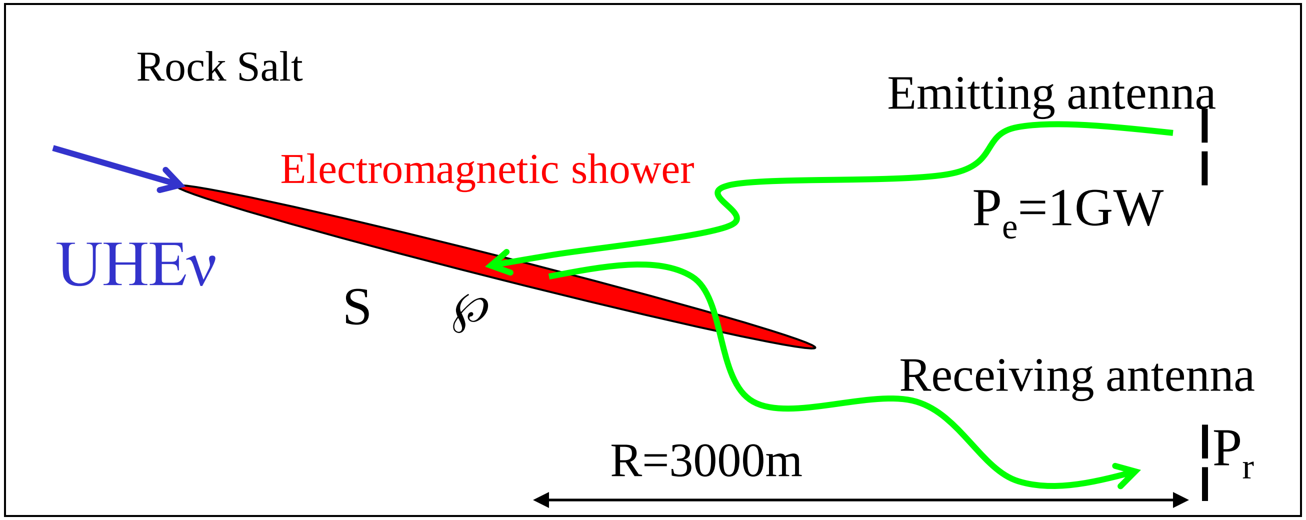
Minimum setup



Plane antenna on the surface（10MHz）



Receiving power vs. Range



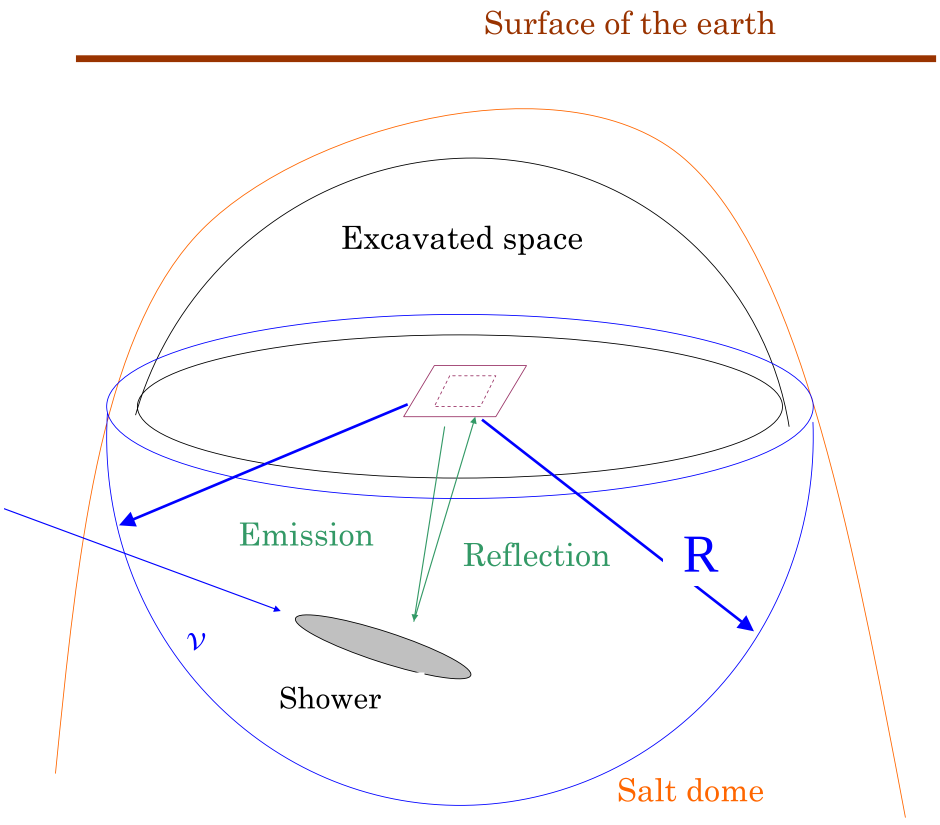
- Attenuation length in rock salt : L=7000m@ 10MHz
- Energy attenuation @R=3000m : $\alpha=(\exp(-2R/L)^2=(\exp(-6000/7000))^2=0.18$
- Energy reflection rate : $\Gamma=10^{-6}\cdot(10^{-19}\cdot E)^2=10^{-6}$ (Shower energy: $E=10^{19}$eV)
- $S1\cdot S2=1\ m^2$: radio wave cross sections of shower and antennas
- P_e=1GW : Peak power of radar
- Receiving power : $P_r=P_e\cdot\alpha\cdot\Gamma\cdot S_1\cdot S_2\cdot(4\pi R^2)^{-2}=1.4\times10^{-14}$ W

Effective volume of rock salt for radar

E：Shower energy
Γ：Reflection efficiency
R: Rage of radar
Radar power: 1GW（Peak Power）、10MHz
Receiving power > 1×10^{-14}W

E(eV)	Γ	R/m
10^{17}	10^{-10}	469
10^{18}	10^{-8}	1310
10^{19}	10^{-6}	3180

Effective volume ∝ $2\pi R^3/3$



Number of neutinos

●Radar method does not require expensive boreholes.
●# of GZK neutrinos/year is estimated by a simulation.
[W exchange] + [W-Gluon fusion] processes:
6～18 GZK neutrinos/year > 10^{17}eV
●Minimum setup：
# of GZK neutrinos could be counted.
High peak power radar of 1GW, otherwise array antennas of lower power are needed.

Minimum setup