Hf-STJ development for COBAND
— I-V characteristics studies —

2023年度
第２回TCHoU構成員会議・成果報告＆交流
2023/12/18

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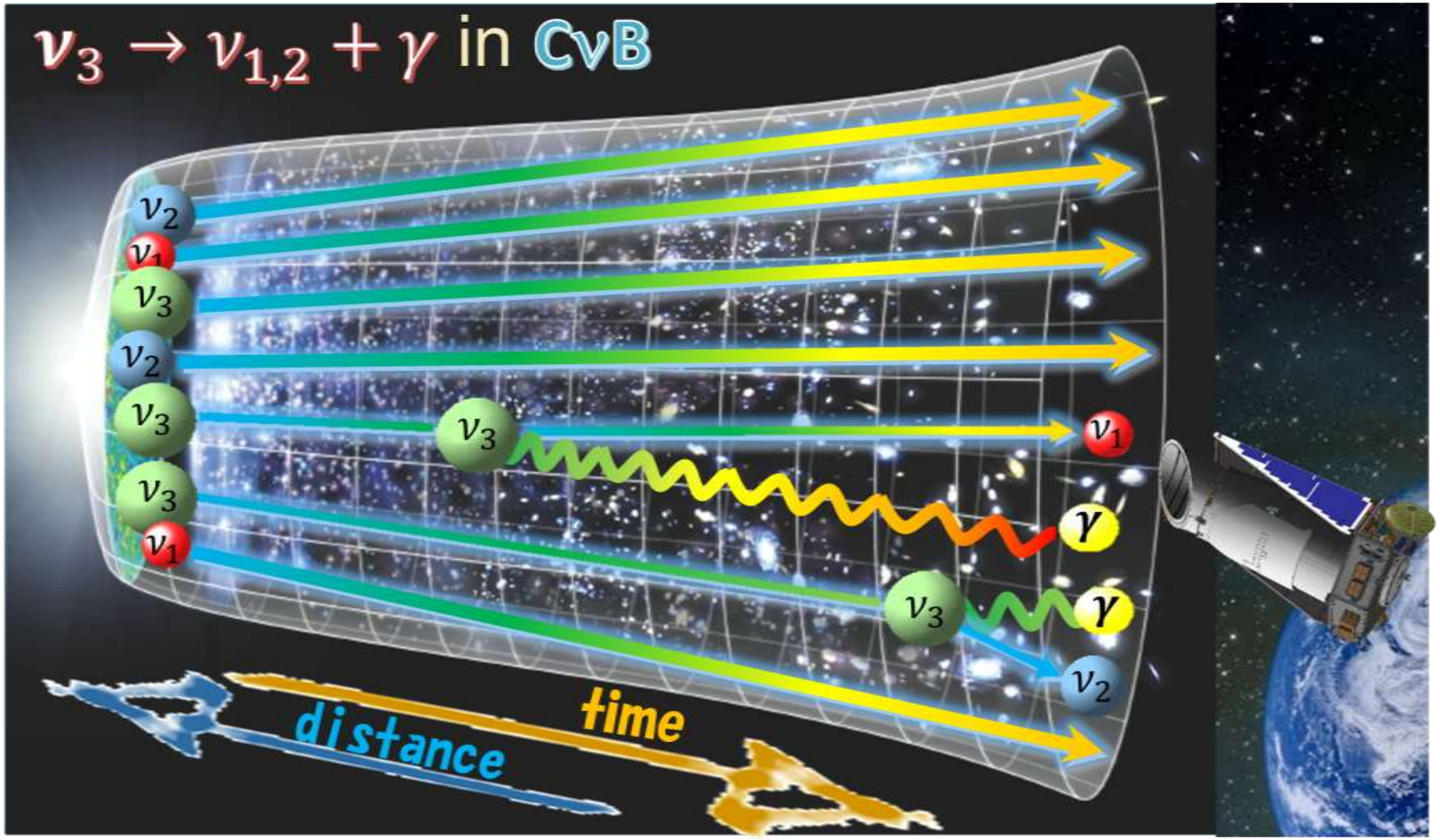
for the COBAND collaboration

COBAND(Cosmic Background Neutrino Decay)

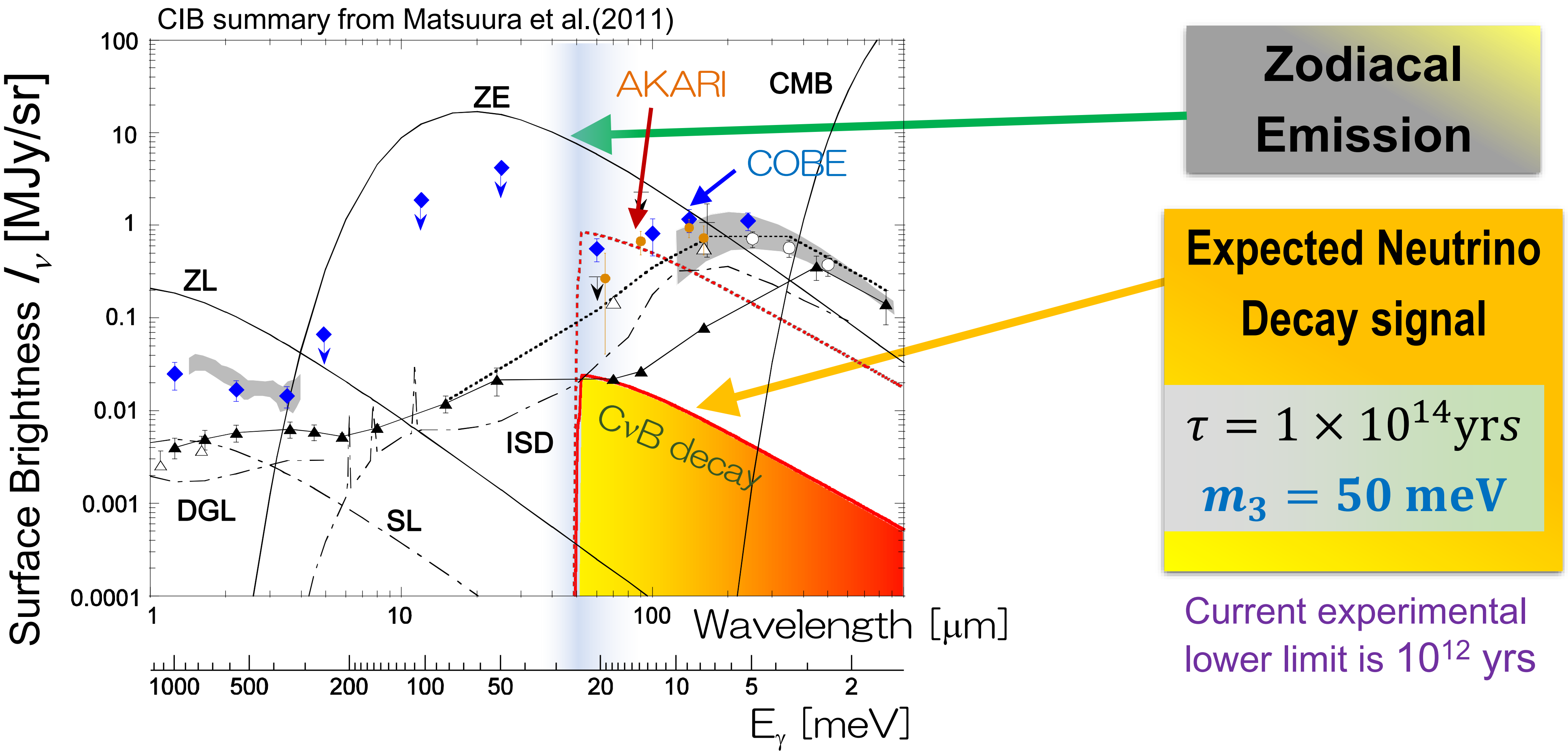
Search for Neutrino decay in Cosmic background neutrino

➔To be observed as FIR photons around λ~50μm



Neutrino Decay

Neutrino Decay signal and backgrounds

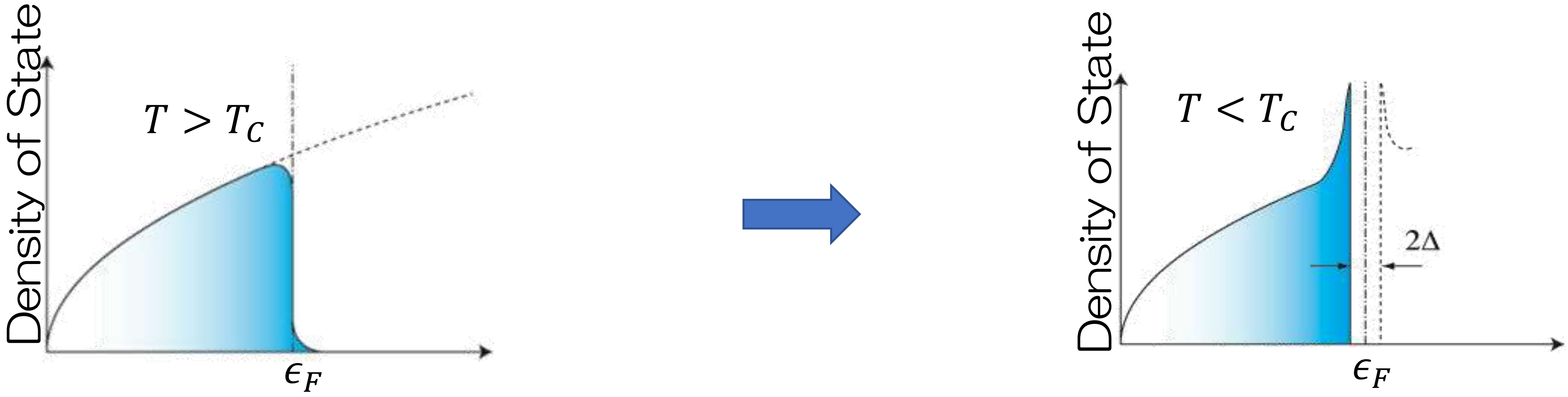


Current experimental lower limit is 10^{12} yrs

We can identify ν decay signal by highly precise measurement of photon energy spectrum around **λ~50μm**

➔ Require for the detector to detect and measure single photon energy at **λ~50μm**

超伝導エネルギーギャップ



超伝導状態では，フェルミ準位ϵ_Fの付近の準位の電子二個が2Δの束縛エネルギーにより，Cooper 対を形成 ➔ エネルギー準位にギャップが生じる

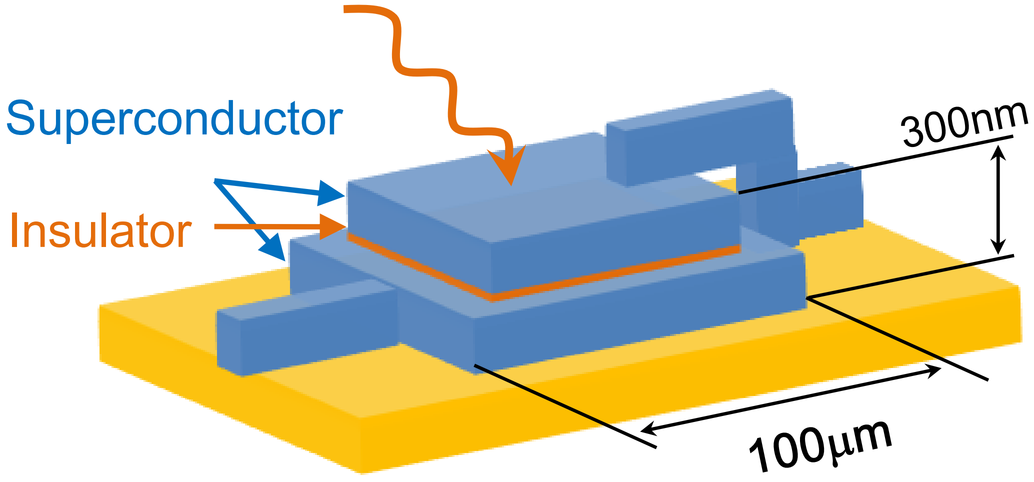
	Si	Nb	Ta	Al	Hf
Tc[K]		9.23	4.48	1.20	0.165
Δ[meV]	1100	1.550	0.7	0.172	0.020

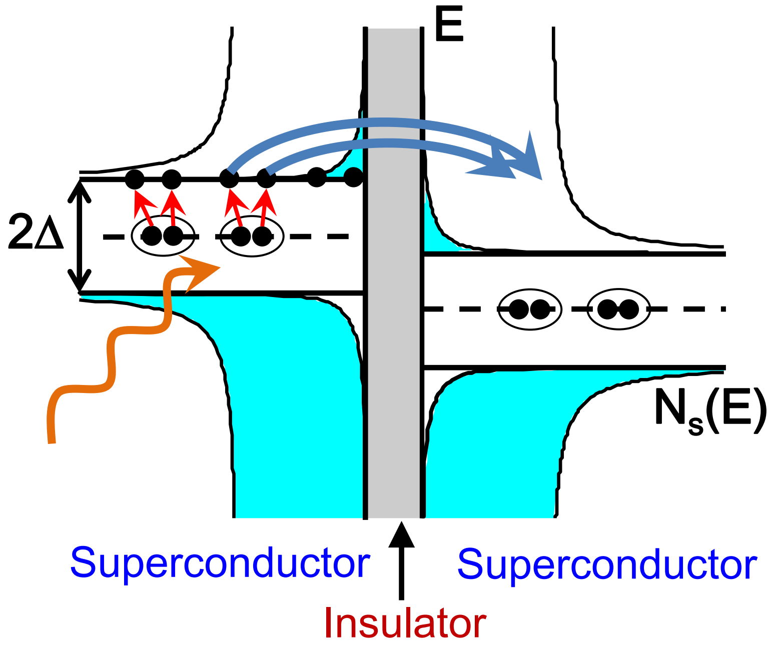
$\Delta \sim 1.8 k_B T_C$ (BCS theory)

Superconducting Tunnel Junction (STJ)

Superconductor / Insulator /Superconductor (SIS)

Josephson junction device





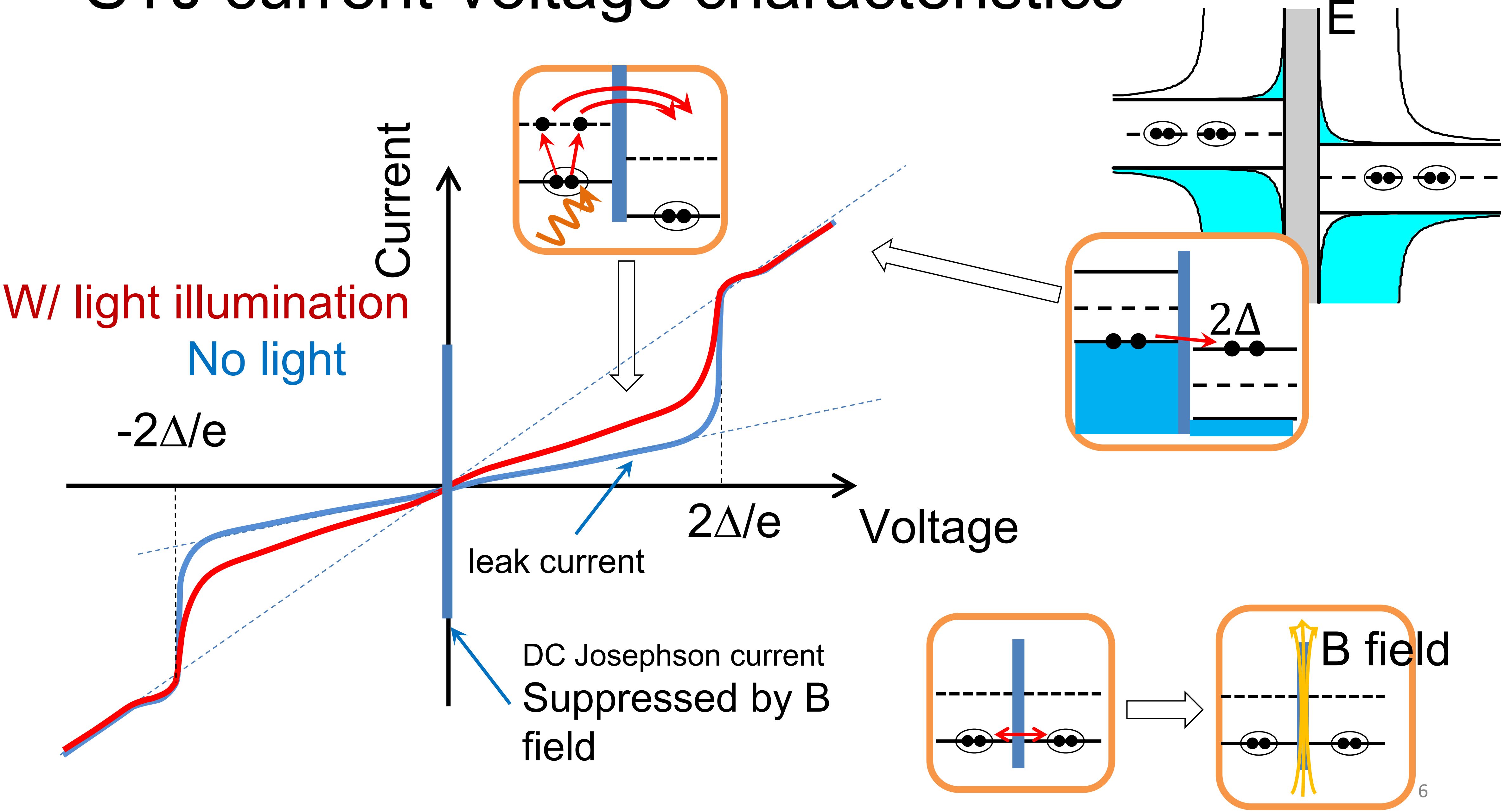
Δ: Superconducting gap energy

A constant bias voltage (|V|<2Δ/e) is applied across the junction.

A photon absorbed in the superconductor breaks Cooper pairs and creates tunneling current of quasi-particles proportional to the deposited photon energy.

- Much lower gap energy (Δ) than FIR photon ➔ Can detect FIR photon and measure its energy.

STJ current-voltage characteristics



STJ candidates

	Si	Nb	Al	Hf
Tc[K]		9.23	1.20	0.165
Δ[meV]	1100	1.550	0.172	0.020

Nb/Al-STJ

- Well-established and commonly used.
- Δ~0.6meV by the proximity effect from Al
- Operation temp. <400mK
- Back-tunnelling gain G ~10
- $N_{q.p.}$=25meV/1.7Δ×10~ 250 σ_E/E~10% for E=25meV (**λ~50μm**)

➔25meV single-photon detection is feasible ideally.

➔Candidate for the rocket experiments with diffraction grating.

Hf-STJ

- Not established as a practical photo-detector yet by any group
- $N_{q.p.}$=25meV/1.7Δ~ 735
- 2% energy resolution for a 25meV single-photon is achievable

➔Spectrum measurement without a diffraction grating.

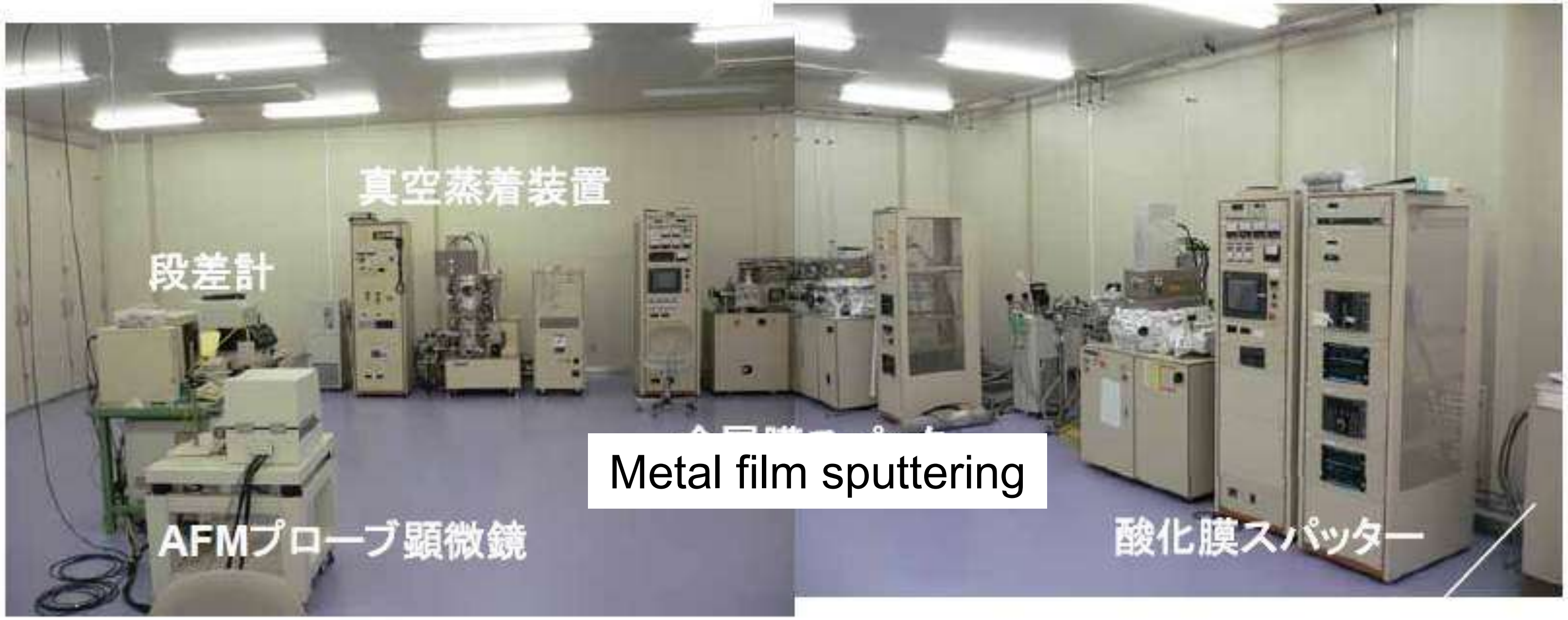
➔Developing for a future satellite experiment

Superconducting device process equipment at KEK clean room

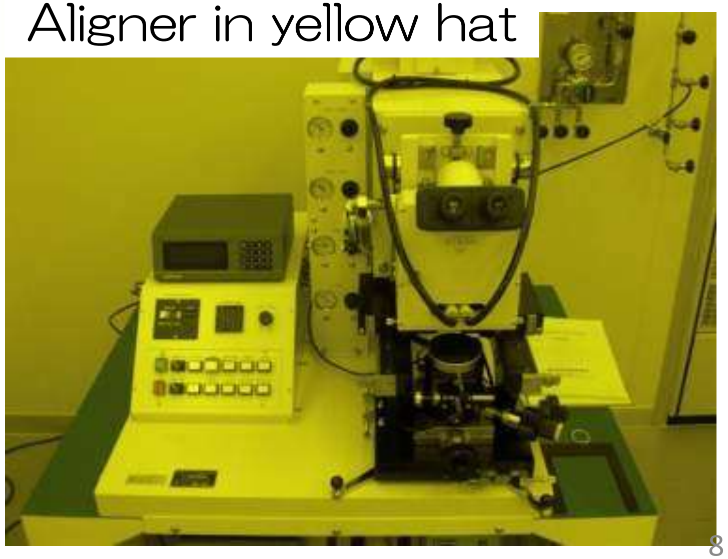
Hf-STJ samples are fabricated at KEK clean room by our group.

- Successful in etching Hf layer in 2008.
- Confirm SIS junction by Hf-HfOx-Hf in 2010.
- Confirm Hf-STJ response to visible light pulse in 2013.

ICP-RIE

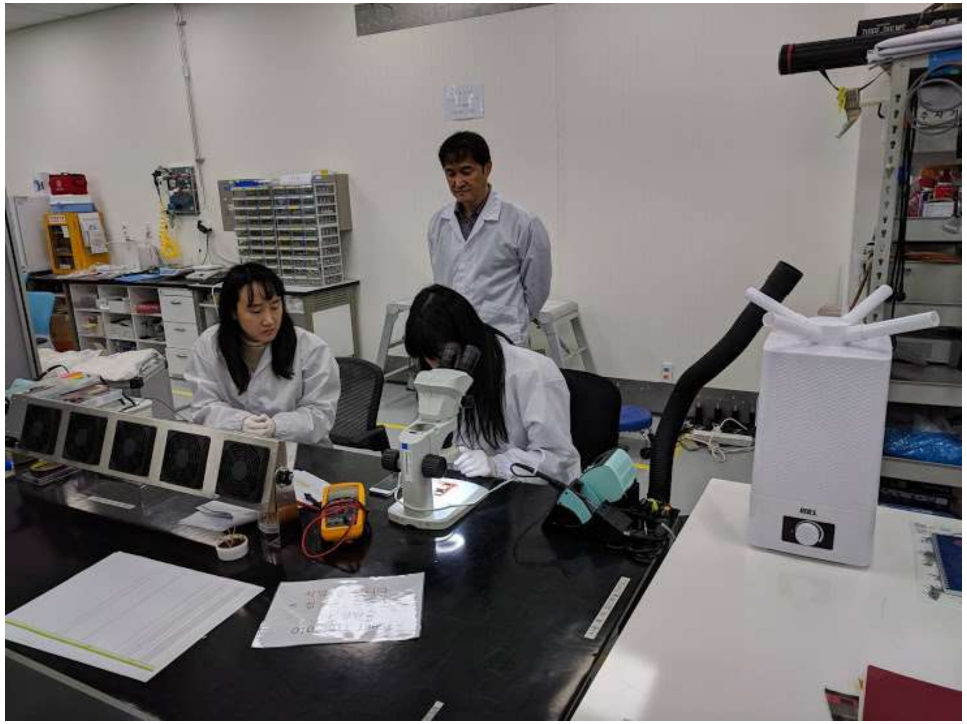


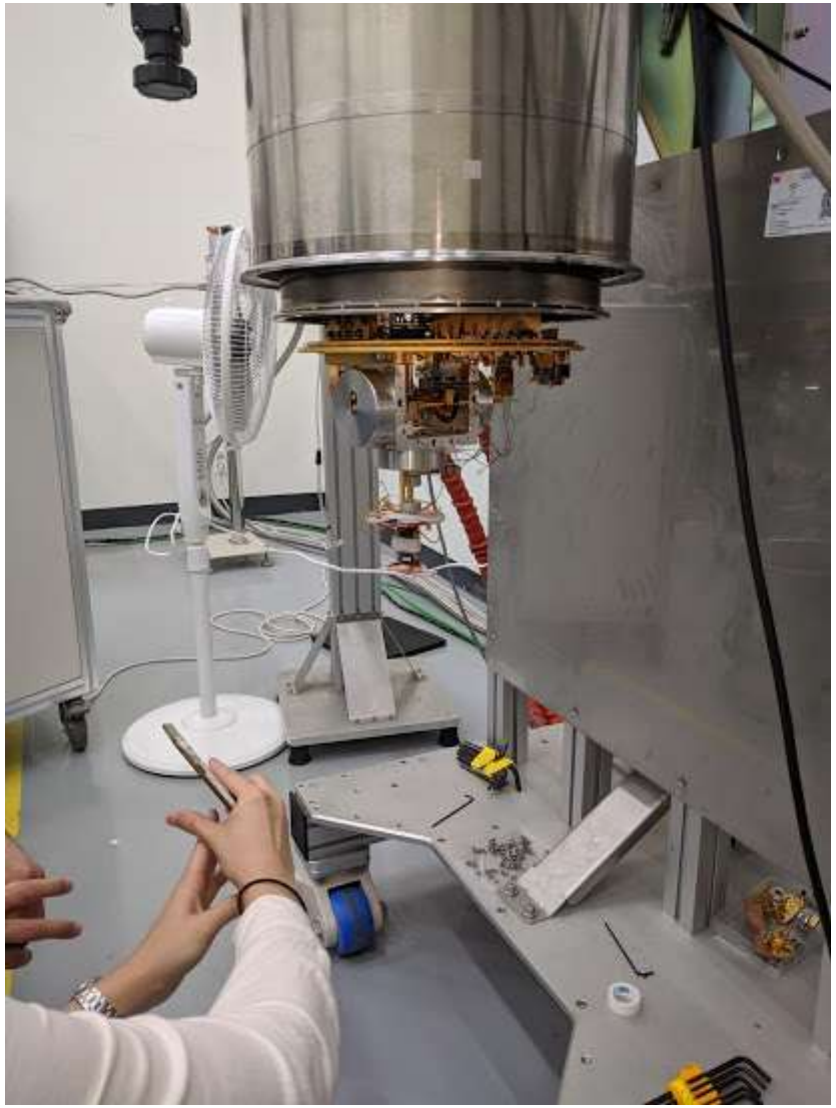
Aligner in yellow hat



Slide from DPPD session, TCHoU workshop on 2021/3/29

X-ray illumination test at IBS CUP in Jun. 2019



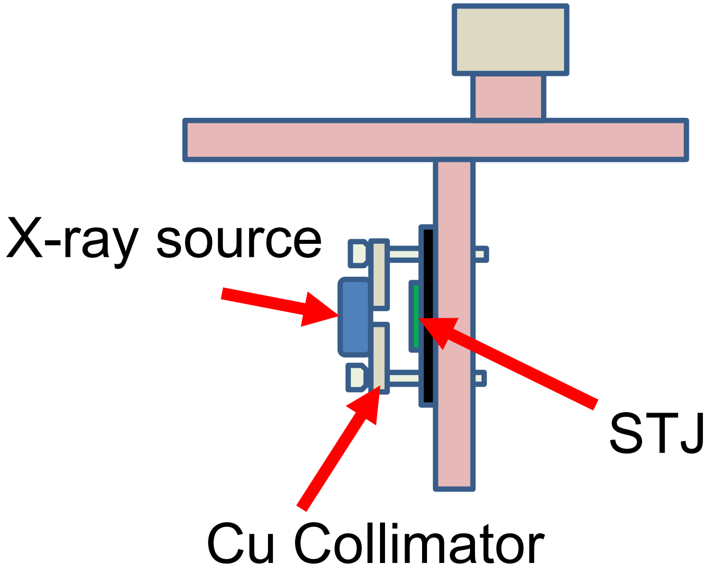


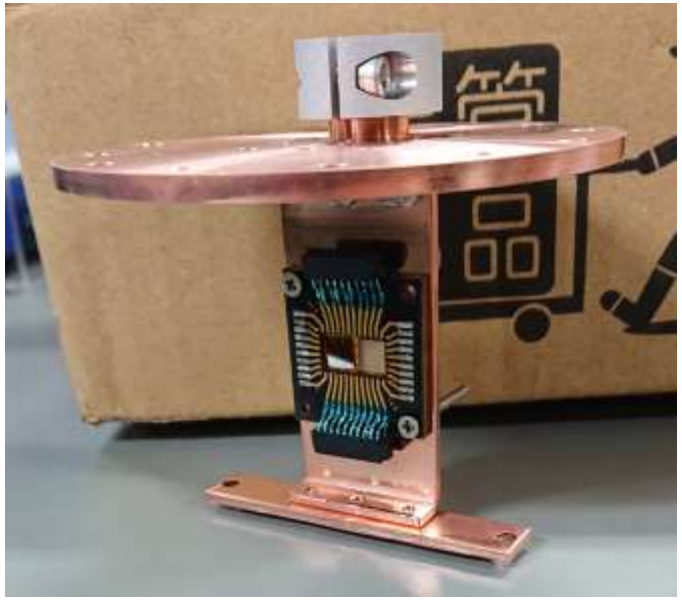
- Adiabatic Demagnetization Refrigeration (ADR) at temperature down to 30mK
- Hf-STJ I-V
- Hf-STJ response to X-ray photon (^{55}Fe)

X-ray illumination test at IBS CUP in Jun. 2019

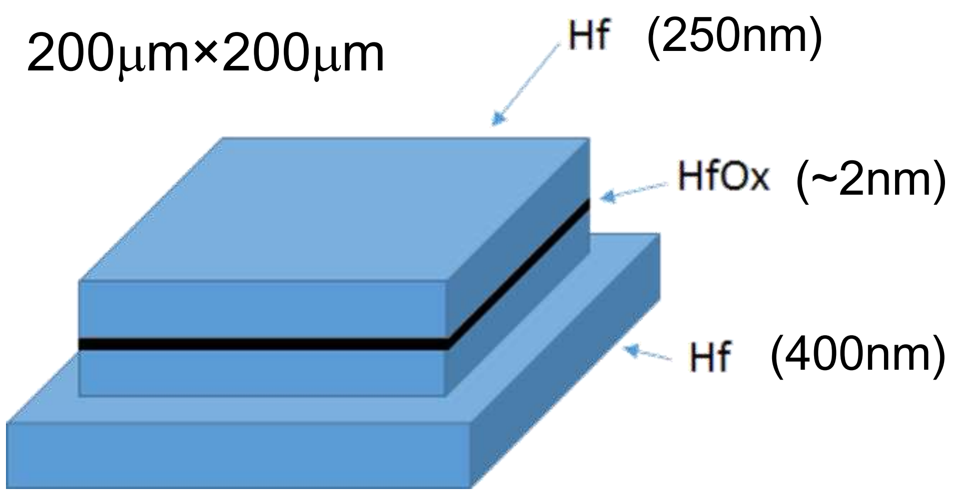
On ADR cold stage

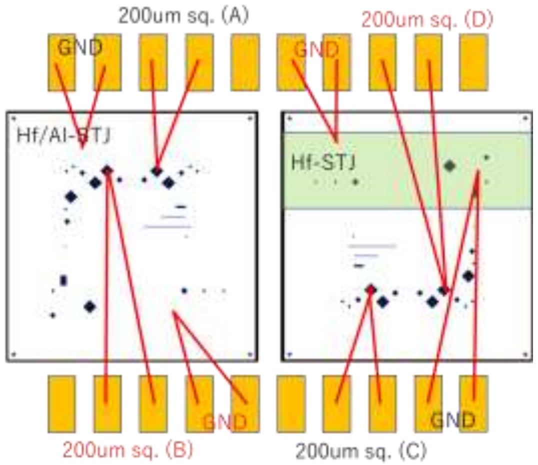
- STJ samples
- Cu collimator
- X-ray source (^{55}Fe) sealed in polyester tape
- Solenoid coil with persistent current switch

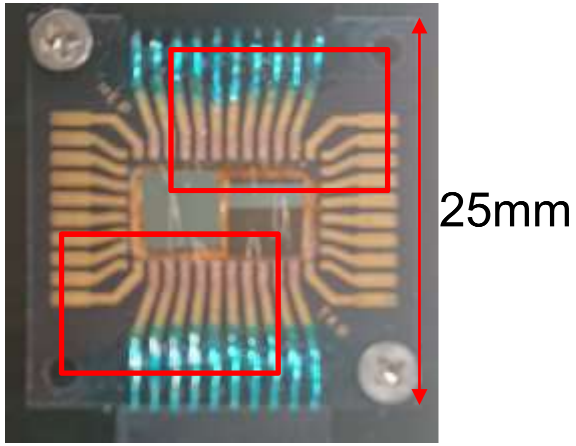




cold stage



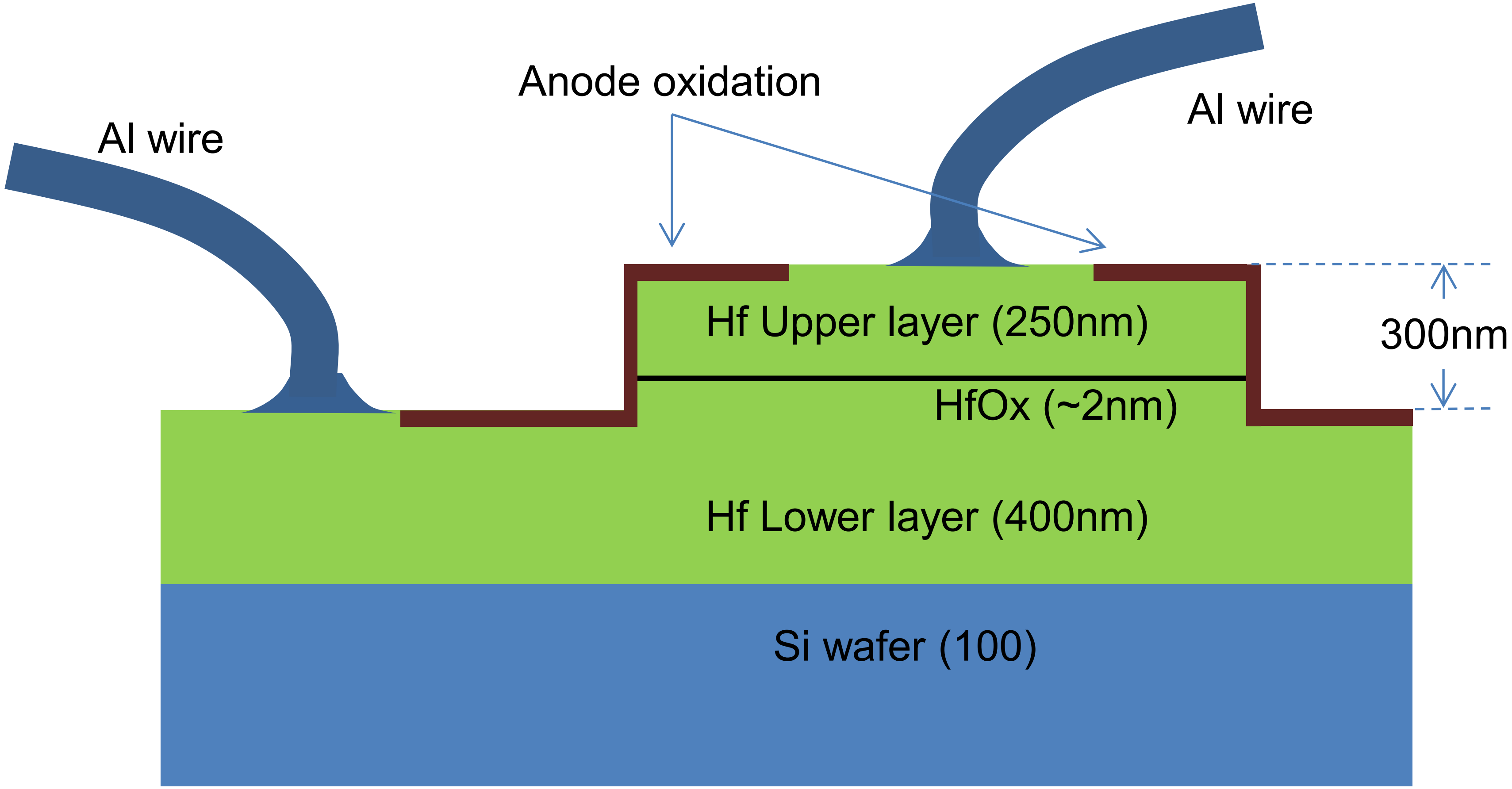




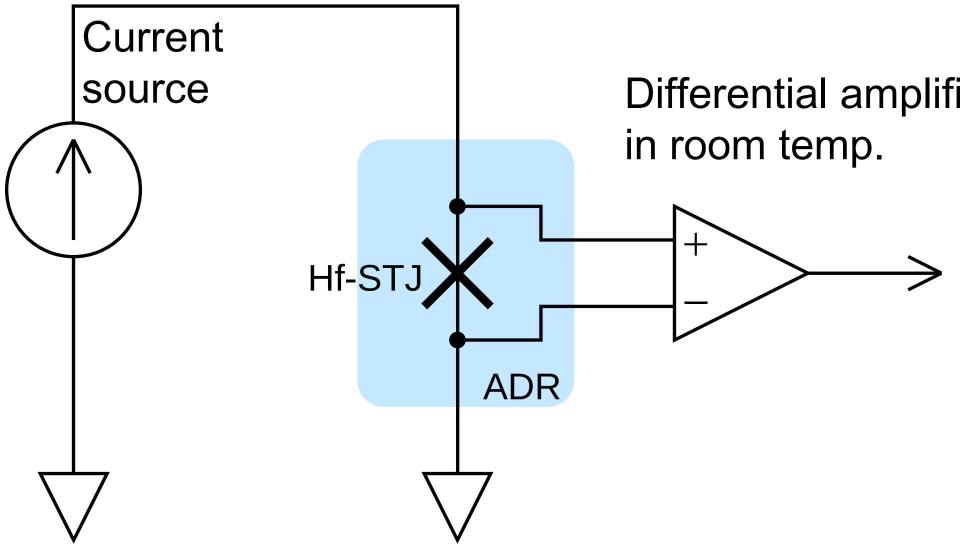
chip carrier

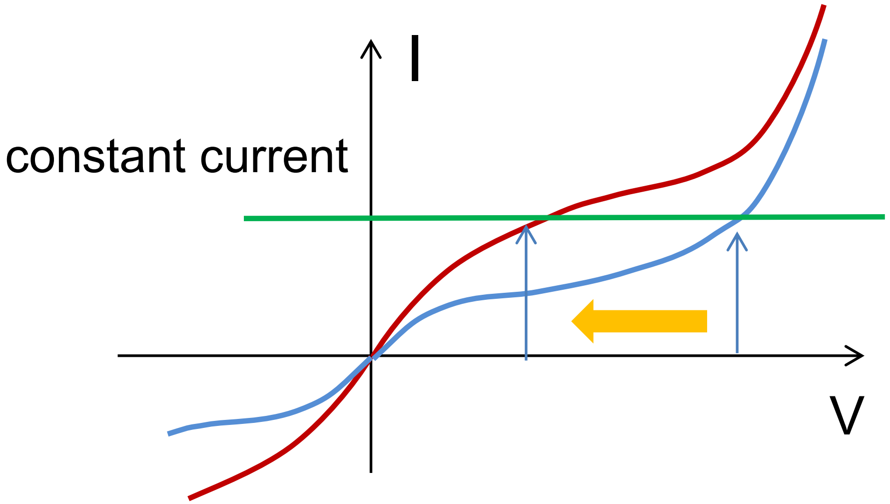
Slide from DPPD session, TCHoU workshop on 2021/3/29

200μm sq. Hf-STJ sample under test



Setup for I-V curve and X-ray response measurements at the IBS CUP





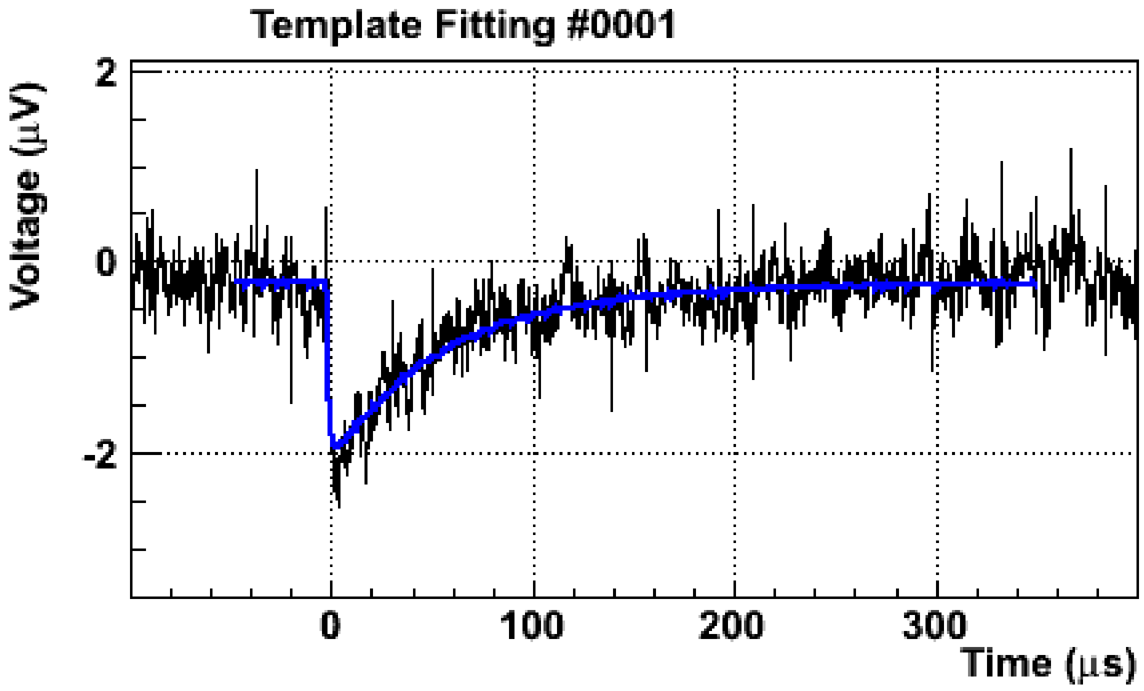
STJ I-V curve w/ light w/o light

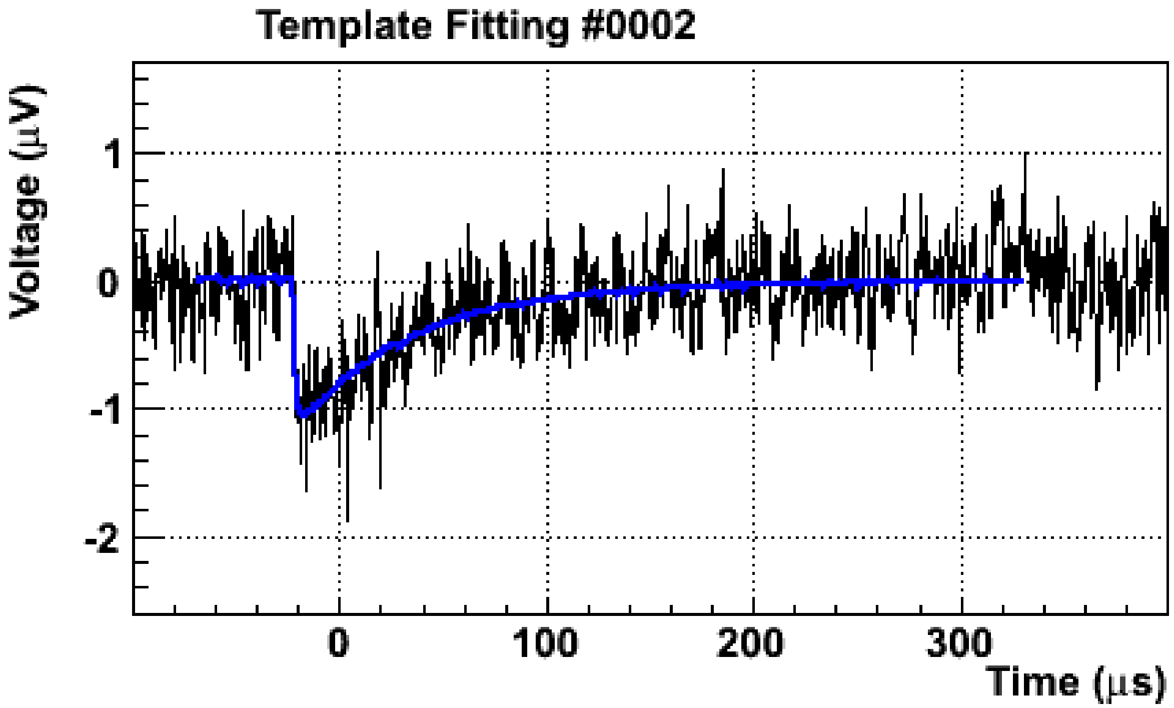
- Sinusoidal current on STJ for I-V measurement
- Constant current on STJ for X-ray response measurement
- Voltage of STJ is read with differential amp. placed at room temp.
- X-ray signal is shown up as a negative pulse in STJ voltage.

Signal fit to the template

Use the region from -50μs to 200μs in the template

- Amplitude and baseline are fitting parameters.
- Also scan Δt from -50μs to +50 μs, and choose the Δt which gives the best χ^2





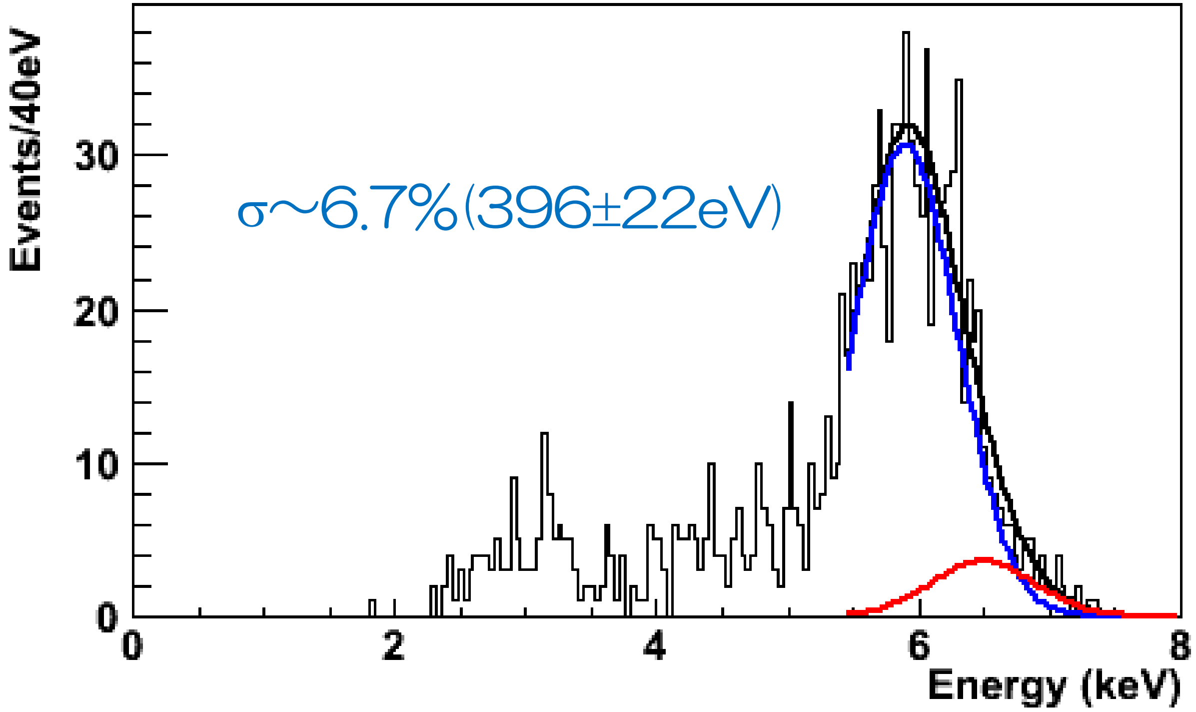
Energy distribution

After selection on fit parameters for candidates, 1138 events left.

- Kα1+Kα2 X-rays with energy of 5.9 keV and a probability about 24.4%,
- Kβ X-rays with nominal energy of 6.5 keV and a probability about 2.85%

Assuming Kα:Kβ ratio and peak energies and same σ for Kα and Kβ,
We fit the distribution and scaled.

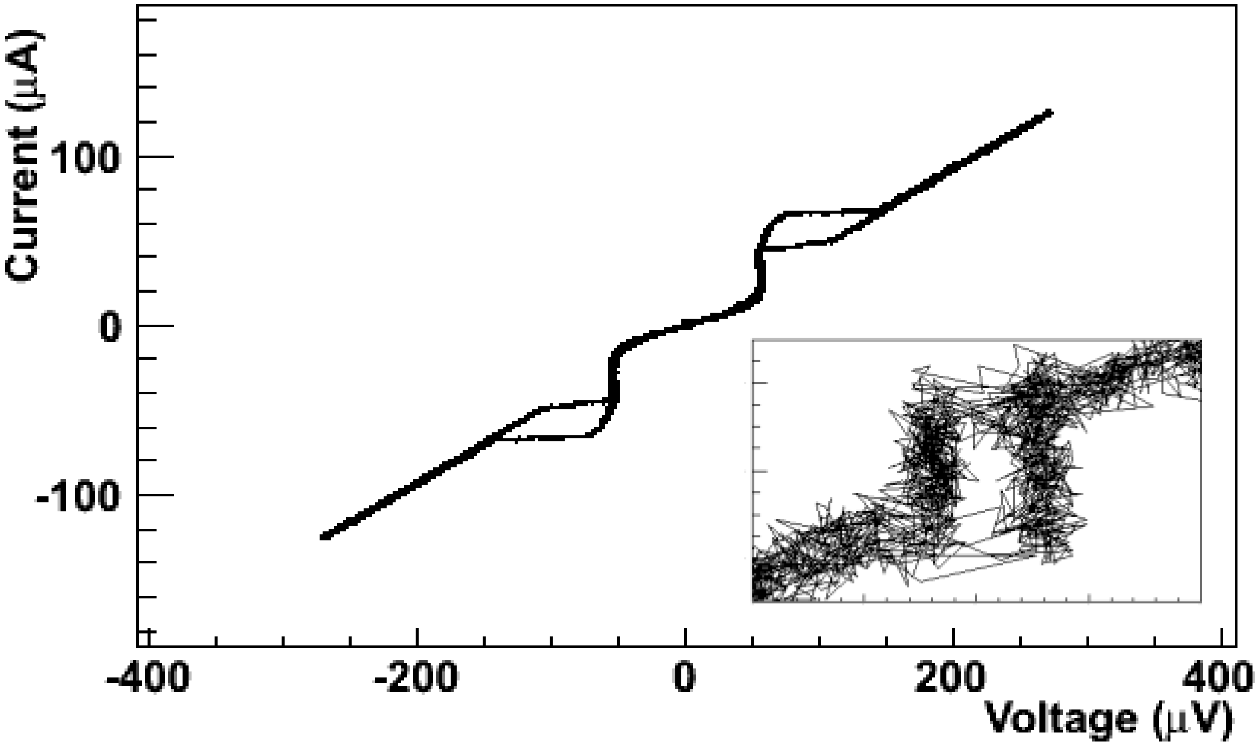
We found the energy resolution is
6.7% (396±22eV)



I-V curve about 34mK w/ B field

200μm square Hf-STJ @ T~34mK

- Applied magnetic field ~10G on STJ
- Leak current of ~3μA(@20μV)



Normal resistance: ~2.15Ω

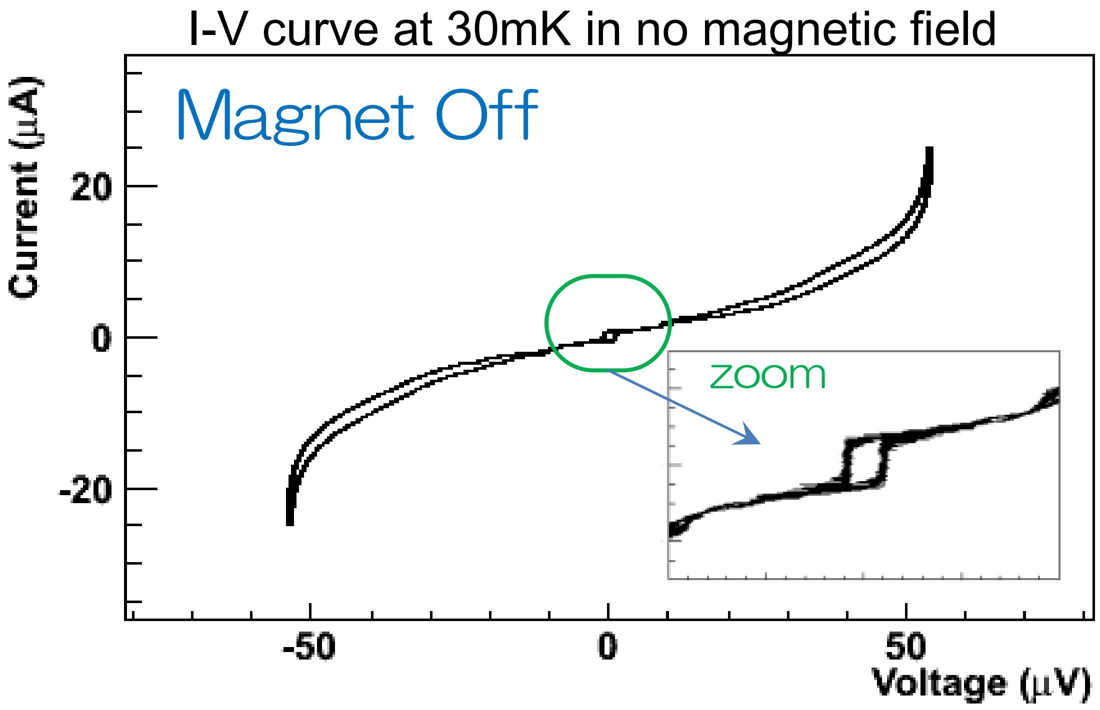
Dynamic resistance: ~4.2Ω

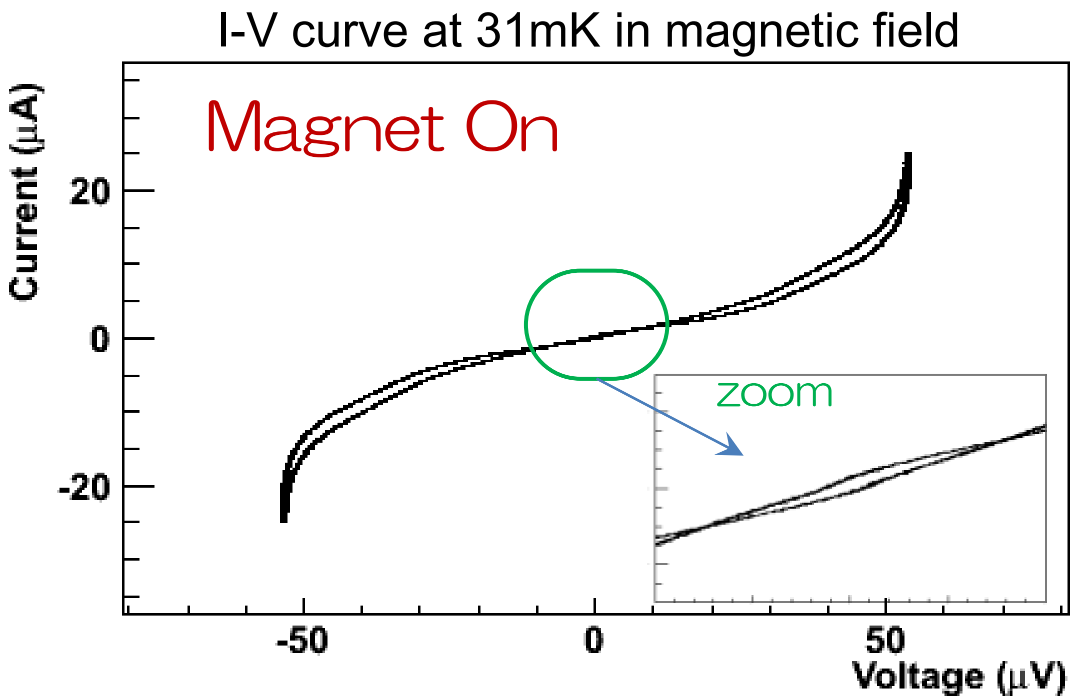
This leakage is much larger than our expectation. (Our goal is ~pA)

I-V curve about 30mK w/o and w/ B field

200μm square Hf-STJ @ T～30mK

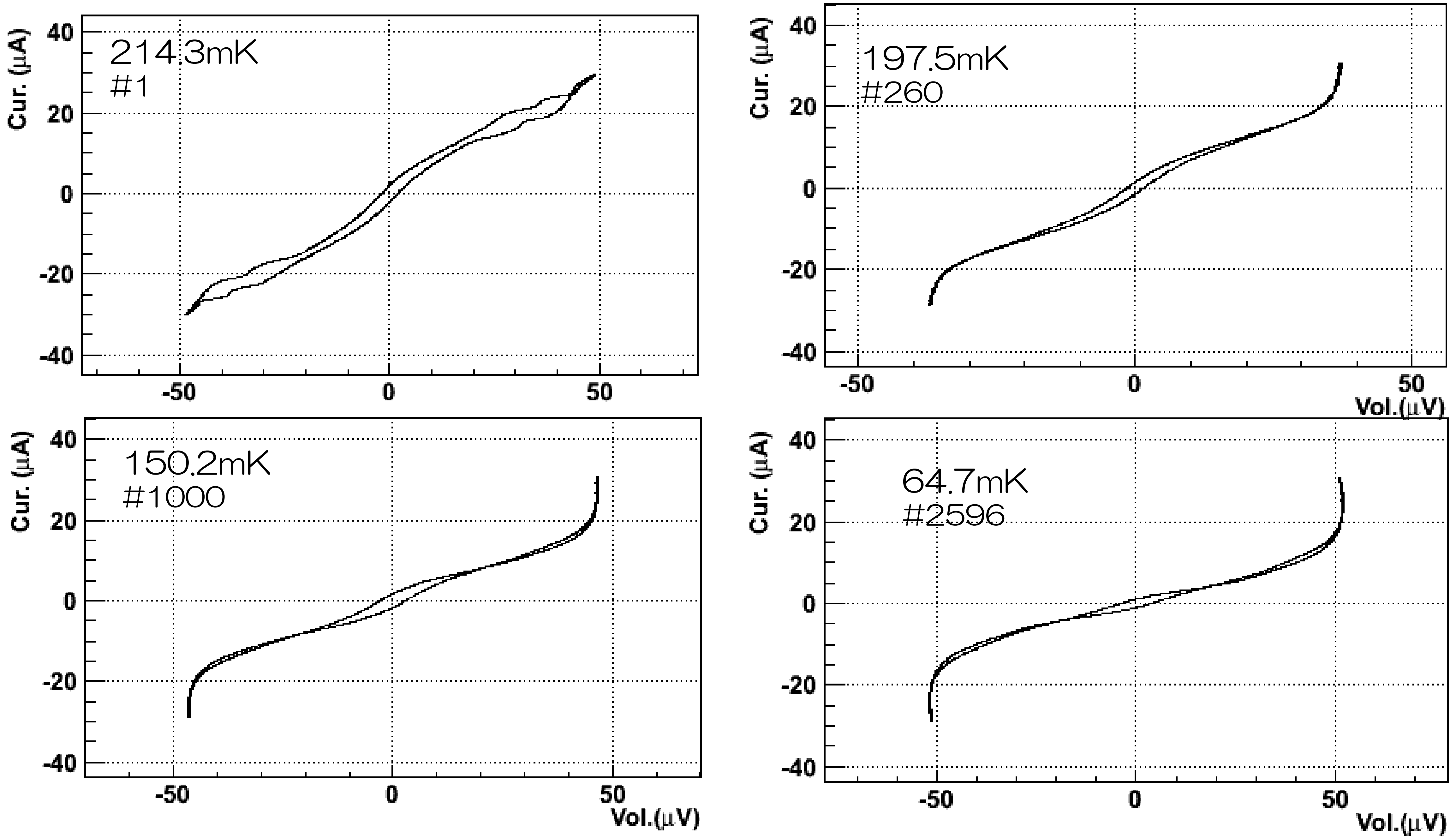
- DC Josephson current is shown up without magnetic field, and it is suppressed with magnetic field (～10G).





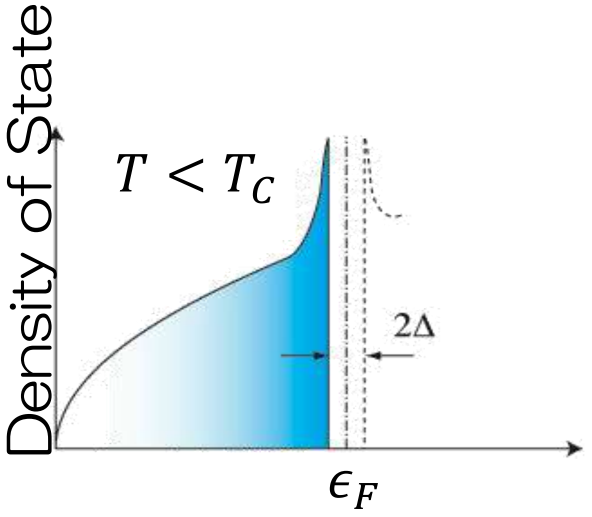
This confirms the SIS junction on the STJ.

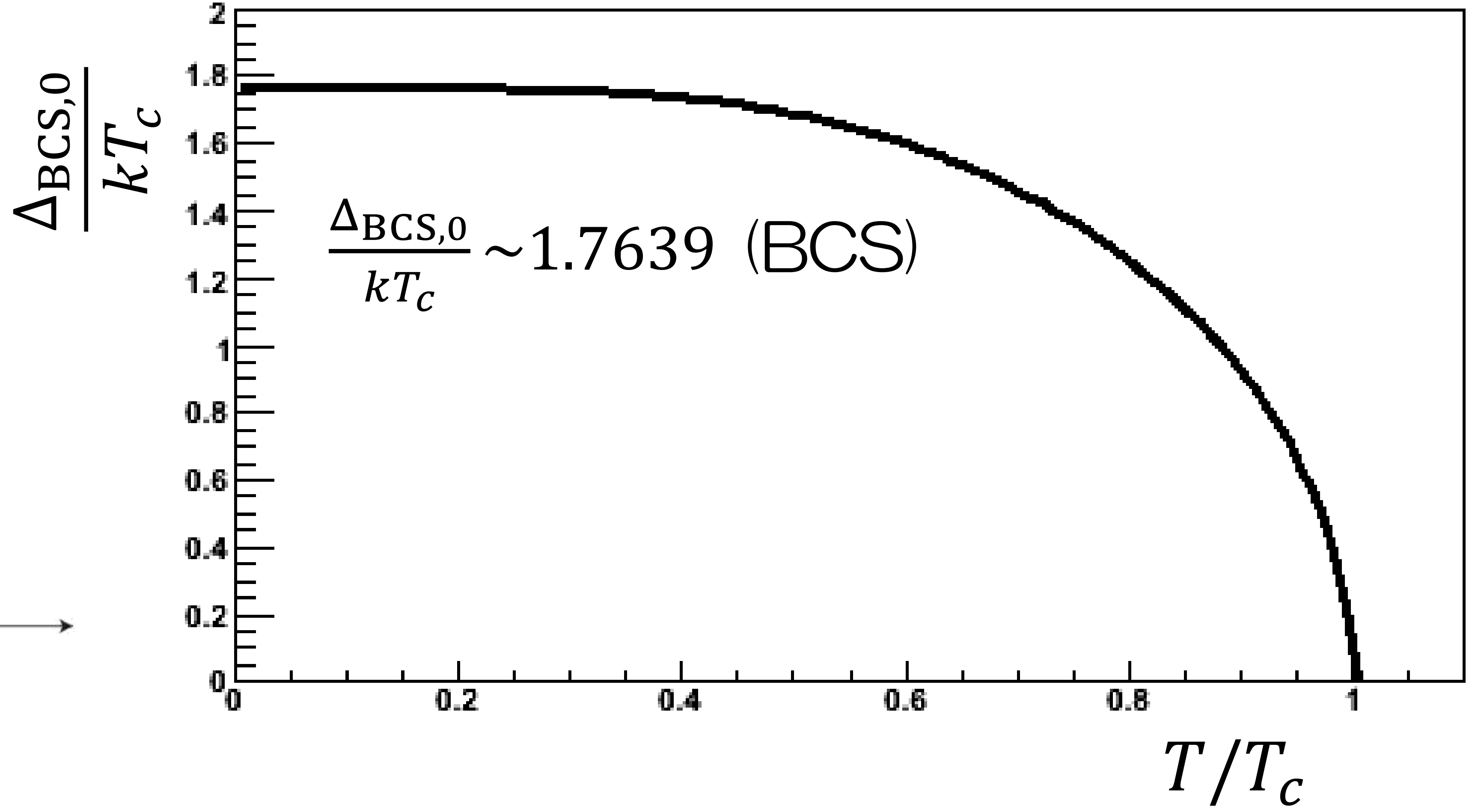
Examples of Hf-STJ smpl.D I-V for temp. dep. after ACC, offset correction



Temperature dependence of Gap energy

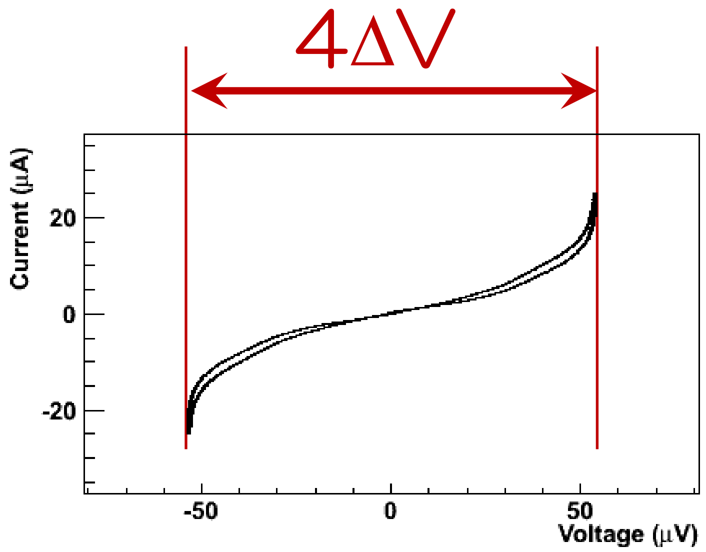
BCS 理論

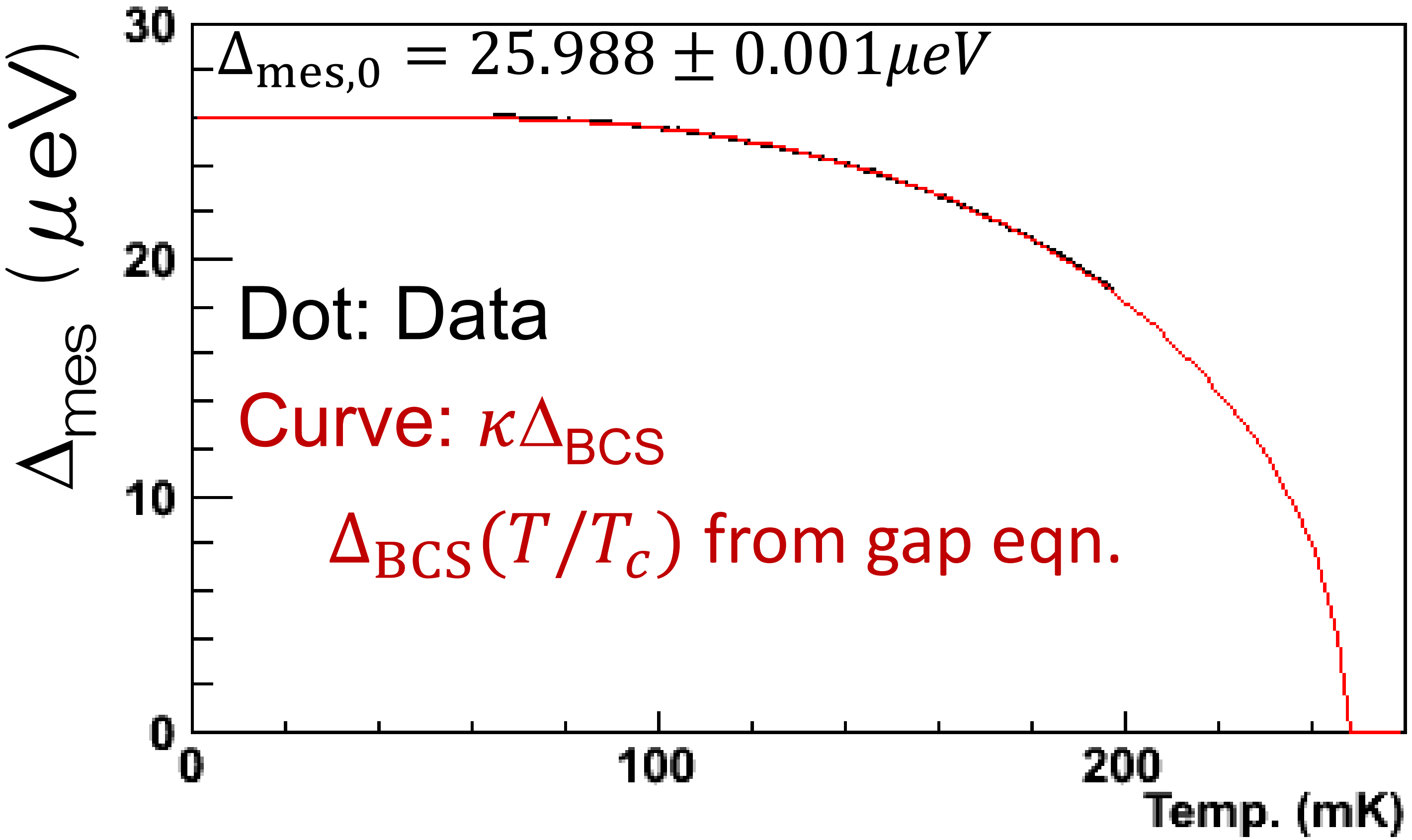




Temperature dependence of Gap energy

Define ΔV from I-V curve





- Temperature dependence of ΔV matched the BCS theory very well.
- Found to be $T_c = 247.742 \pm 0.004 \pm 4.6mK$ $\Leftrightarrow \Delta_{BCS,0} \sim 37.7\mu eV,\ \kappa \sim 0.69$

Temperature dependence of STJ Leakage

BCS 理論 $I_{th} \propto 2N_0\sqrt{2\pi\Delta kT}\exp\left(-\frac{\Delta}{kT}\right)$ BCS theory (P.W.Epperlein 1978)

$$= 2N_0 kT_c\sqrt{2\pi}\sqrt{\frac{\Delta}{kT_c}\frac{T}{T_c}}\exp\left(-\frac{\Delta}{kT_c}\frac{T_c}{T}\right)$$

BCS 理論で T_c に対応するΔより小さくなっていると仮定

$$\frac{\Delta_{\mathrm{BCS}}}{kT_c} \to \frac{\Delta'}{kT_c} = \frac{\nu\Delta_{\mathrm{BCS}}}{kT_c}$$

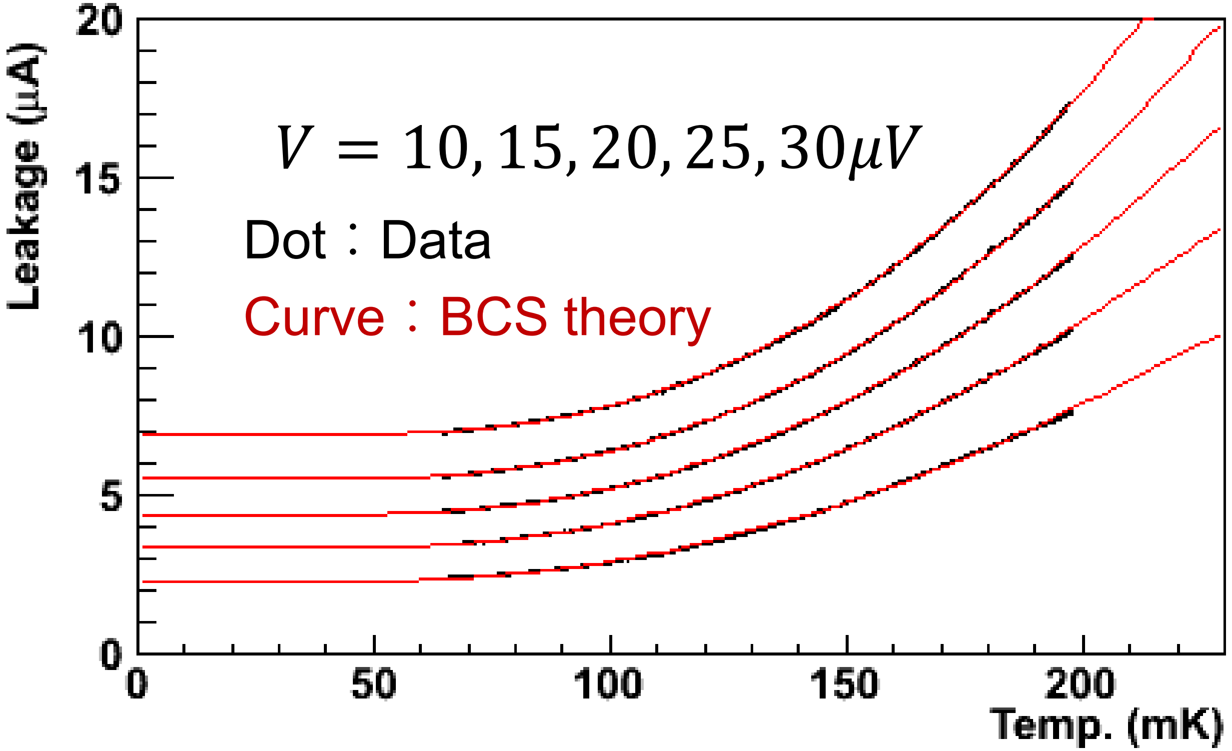
$$\frac{\Delta_{\mathrm{BCS},0}}{kT_c} \sim 1.7639 \text{ (BCS)}$$

Temperature dependence of Leakage

$T_c = 247.7mK$,

$\frac{\Delta_{\mathrm{BCS},0}}{kT_c}$~1.7639を仮定して

$$I_{th} = P_0 \sqrt{\frac{\Delta_{\mathrm{BCS}}}{kT_c}\frac{T}{T_c}} \exp\left(-\frac{\nu\Delta_{\mathrm{BCS}}}{kT_c}\frac{T_c}{T}\right) + P_2$$



Extracted $\nu\Delta_{\mathrm{BCS},0}$

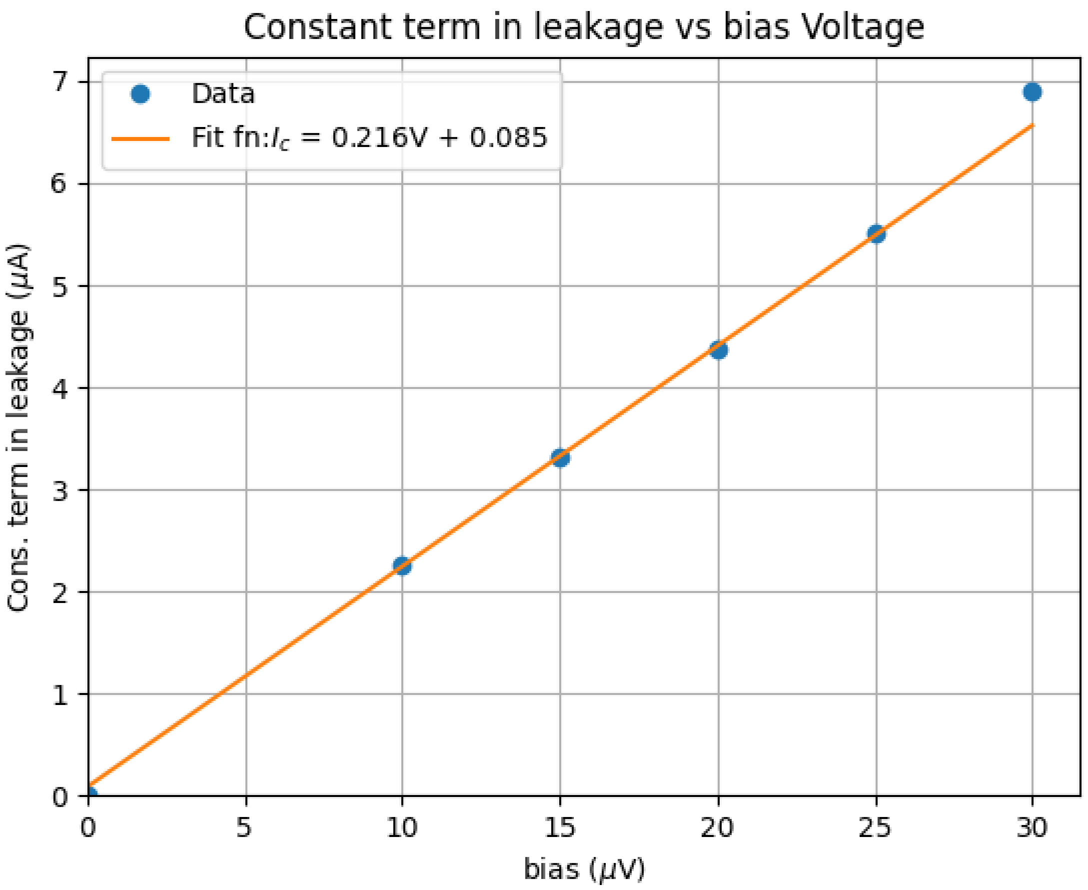
10μV: 27.1 μeV
15μV: 27.7 μeV
20μV: 29.1 μeV
25μV: 30.4 μeV
30μV: 31.5 μeV

- Temperature dependence of leakage matched the BCS theory.
- Found to be $\nu\Delta_{\mathrm{BCS},0}$~$29\mu V$

Constant terms in Leakage

$$I_{th} = P_0 \sqrt{\frac{\Delta_{\mathrm{BCS}}}{kT_c}\frac{T}{T_c}} \exp\left(-\frac{\nu\Delta_{\mathrm{BCS}}}{kT_c}\frac{T_c}{T}\right) + P_2$$

- V dependence of constant term
- V＝10, 15, 20, 25μVの4点を使い直線fit

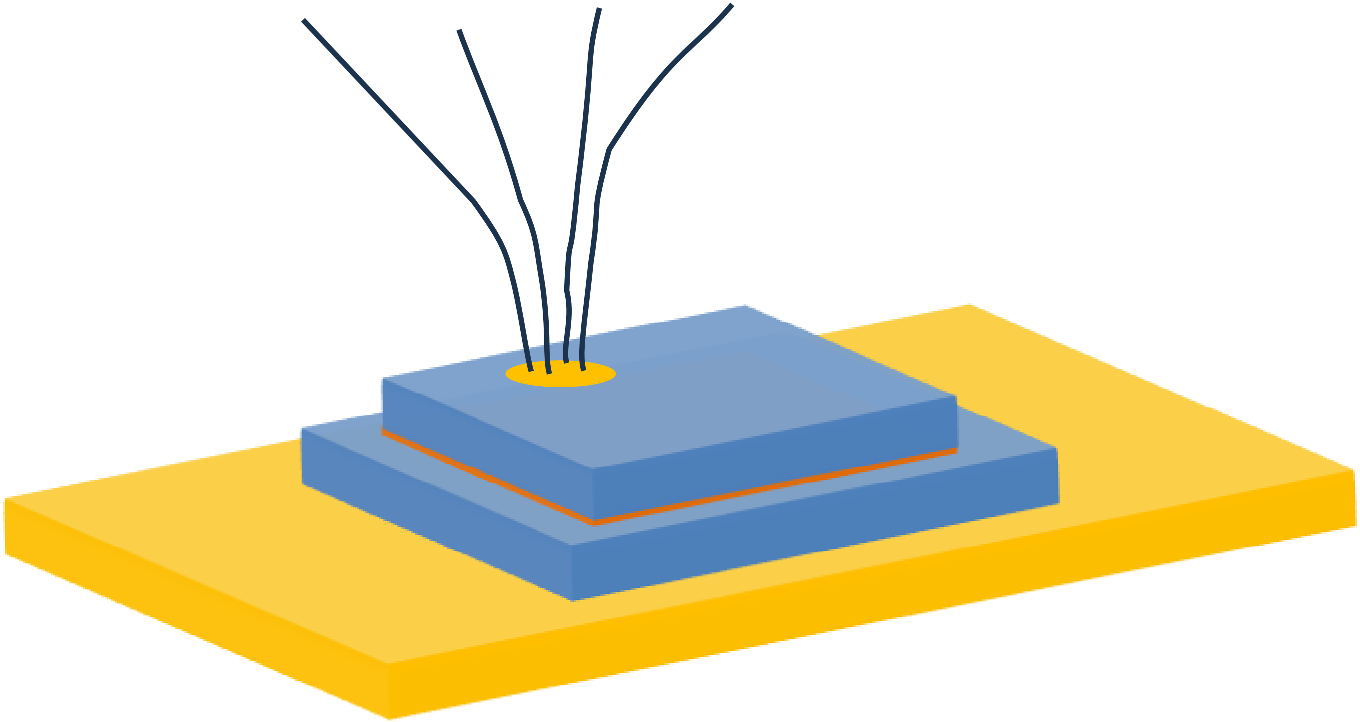


- Constant term は，STJ に並列に存在する抵抗(4.8Ω)成分？

Constant terms in Leakage

パラレル抵抗成分の大きさは，冷凍機のサーマルサイクルごとに異なることが確認されている。

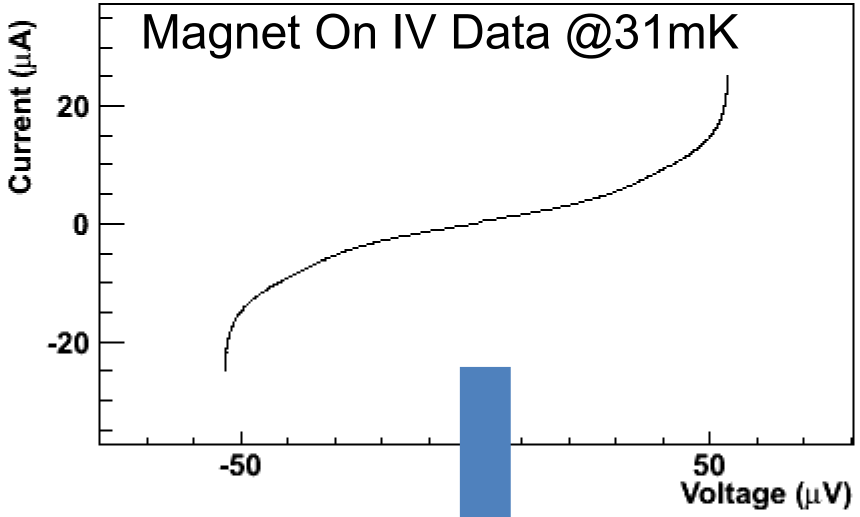
➔絶縁膜層の欠陥ではない？

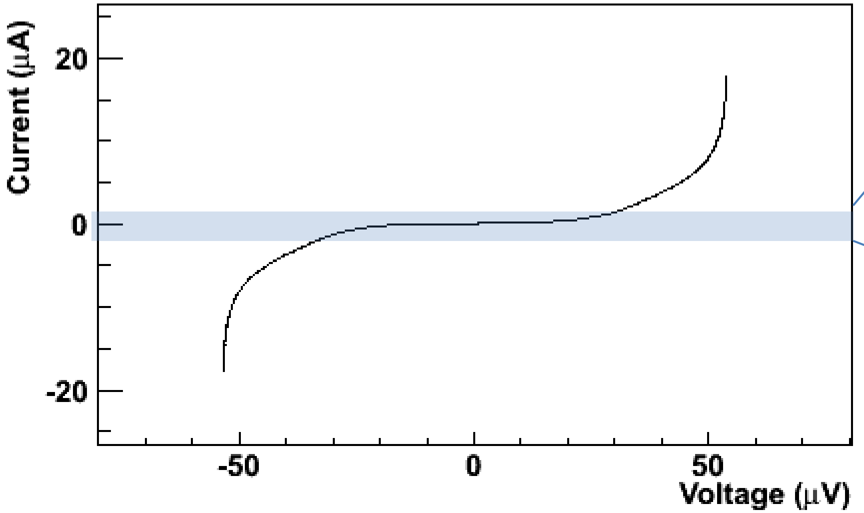


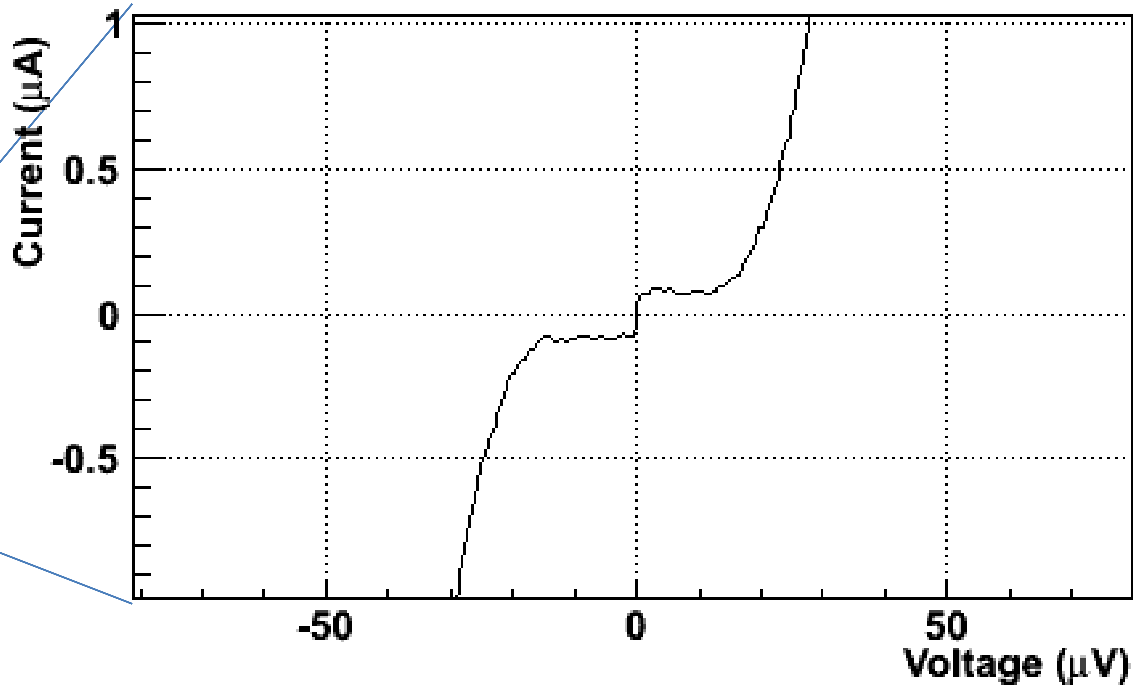
- 地磁気，ADR漏れ磁場などのSTJに対して垂直成分の磁束トラップによるnormal current path の形成？
- 磁気シールドによる改善の可能性。

Constant terms in Leakage

I -Vカーブからパラレル抵抗成分の除去

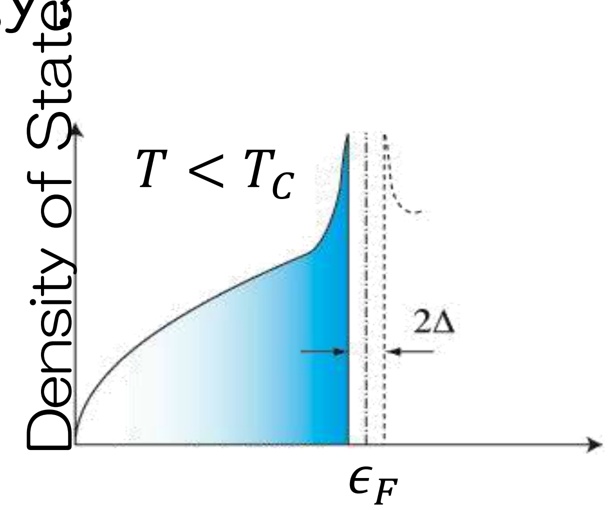


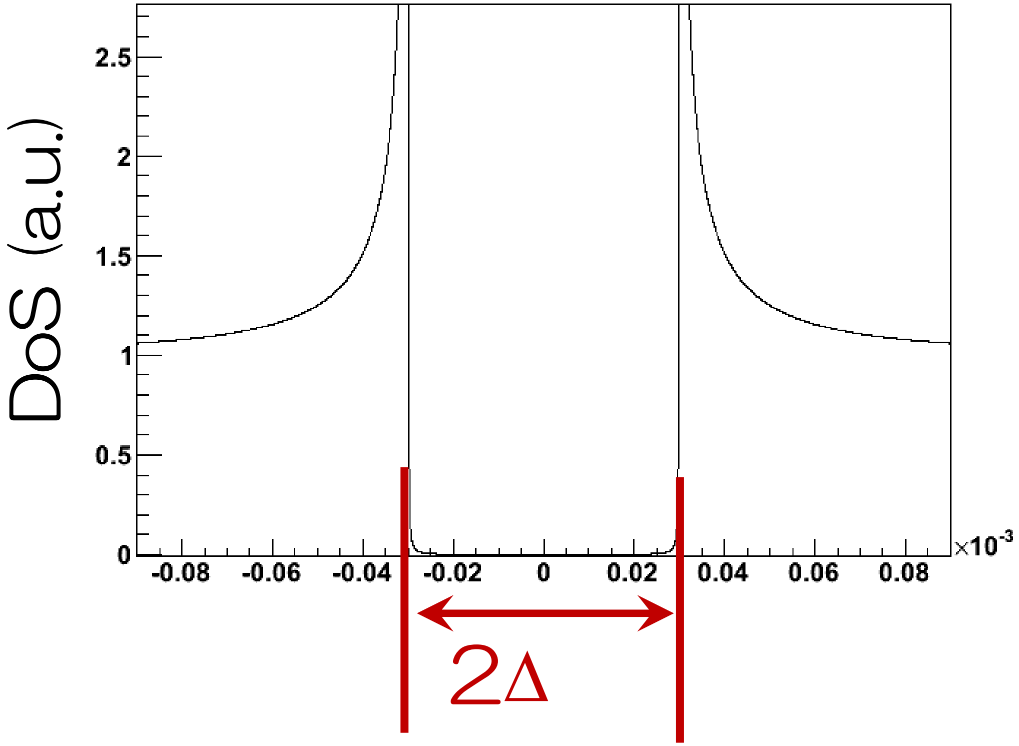


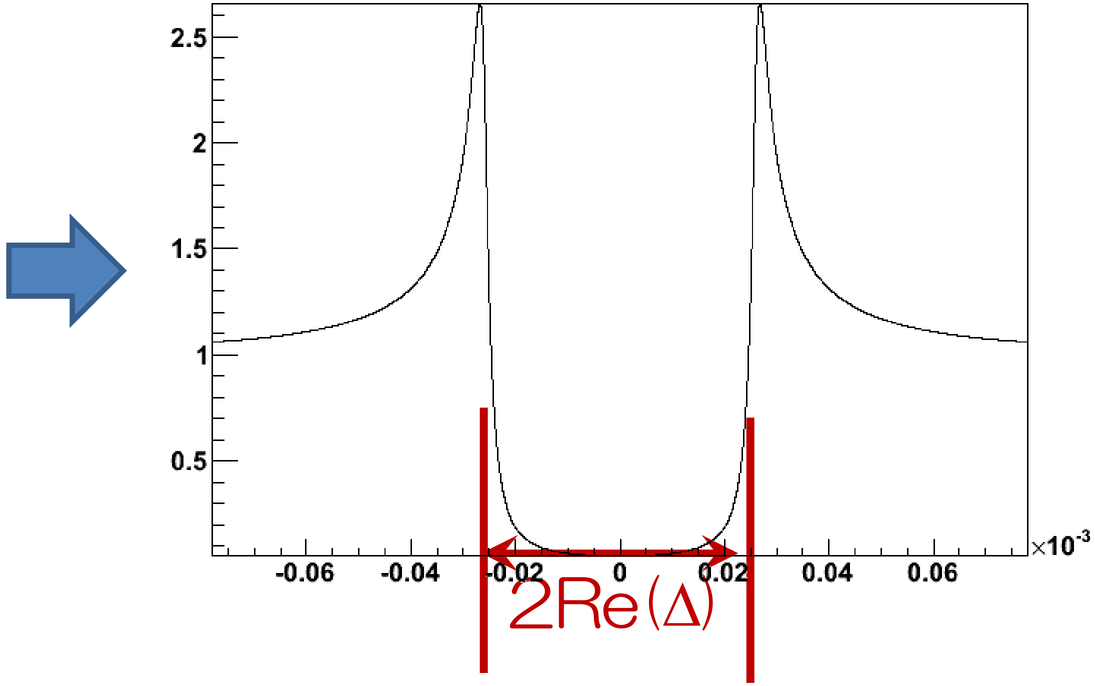


Imaginary component in gap energy?

- Because of quasi-particle lifetime, gap energy Δ has imaginary part. (Dynes 1978).
- In this case, density of state distribution changes



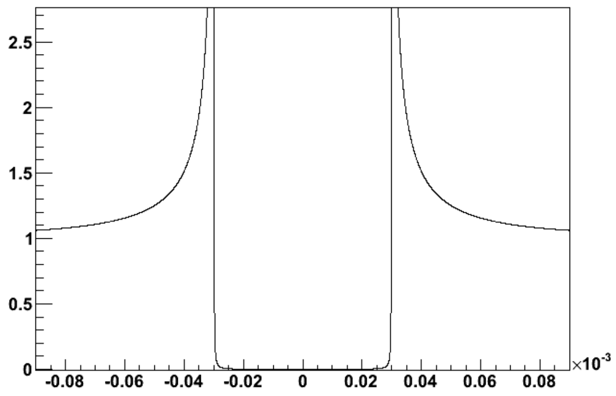


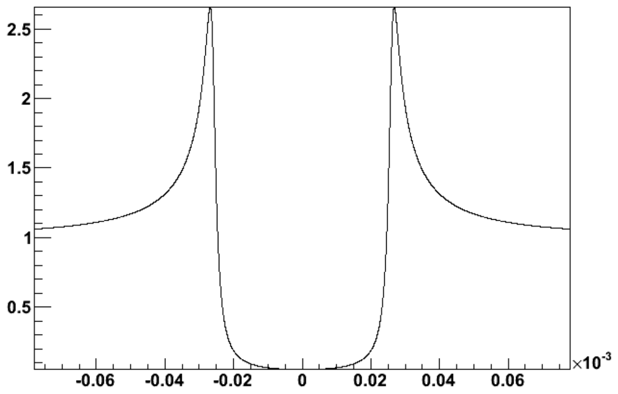


Im(Δ)=0.05Re(Δ)

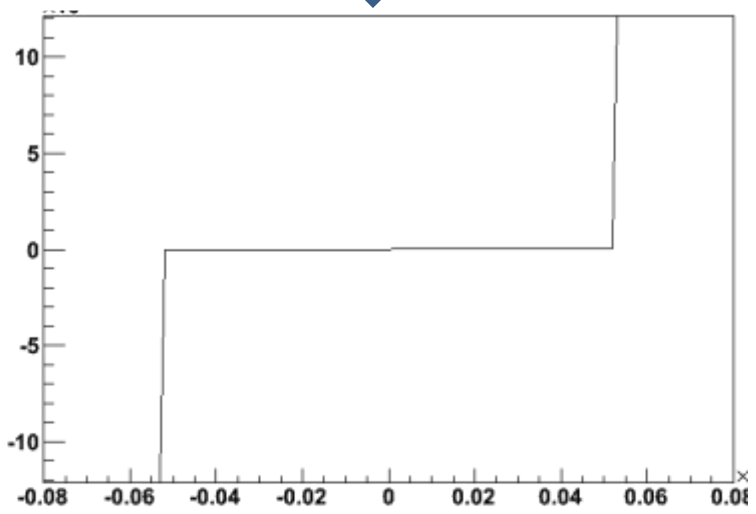
Imaginary component in gap energy?

DoS
(a.u.)



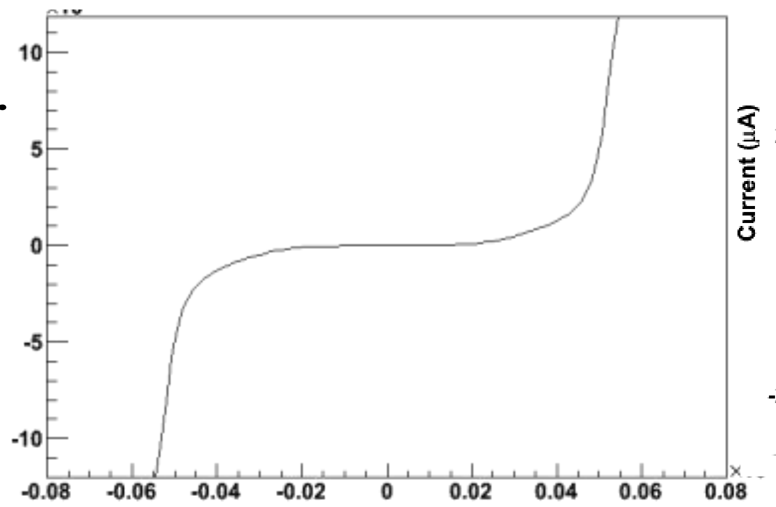


I (μA)



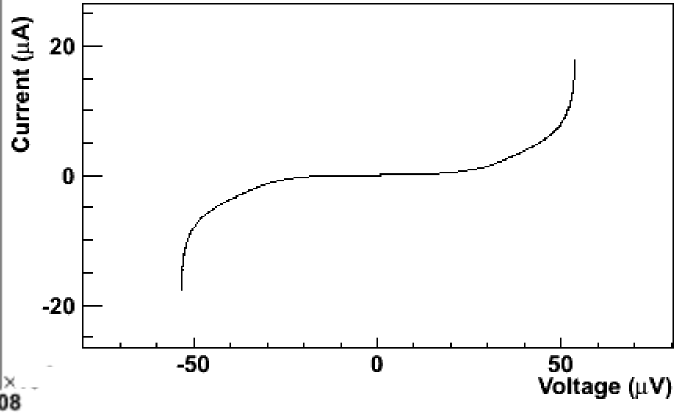
V (mV.)

I (μA)



V (mV.)

Measured I-V



測定されたI-V から gap energy Δの複素成分(準粒子寿命の情報)が
引き出せる可能性

Summary

- Hf-STJ is under development for application to COBAND project, aiming at far-infrared single photon detector and spectrometer.
- We successfully fabricated Hf-STJs with confirmed SIS junction and tested them with X-ray source.
- We confirmed the clear signals for X-ray single photon from ^{55}Fe with a Hf-STJ sample and found that energy resolution is about 6.7% for 5.9keV.

  These are the world first results for Hf-STJ.

- We measured and compare temperature dependence of gap energy Δ and I-V curve of Hf-STJ with BCS theory. These strongly support that our Hf-STJ sample is fabricated as the SIS junction successfully.
- Unexpectedly large leakage is likely due to normal current path other than SIS junction. This indicates the possibility of reducing the leakage.