Updates on TES Activities with Low-Energy Electrons

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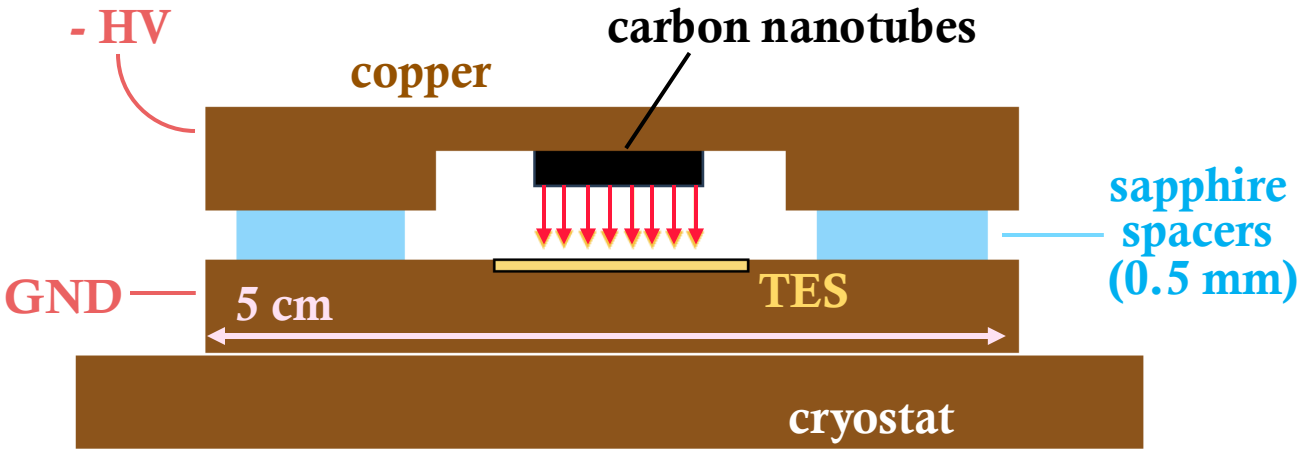
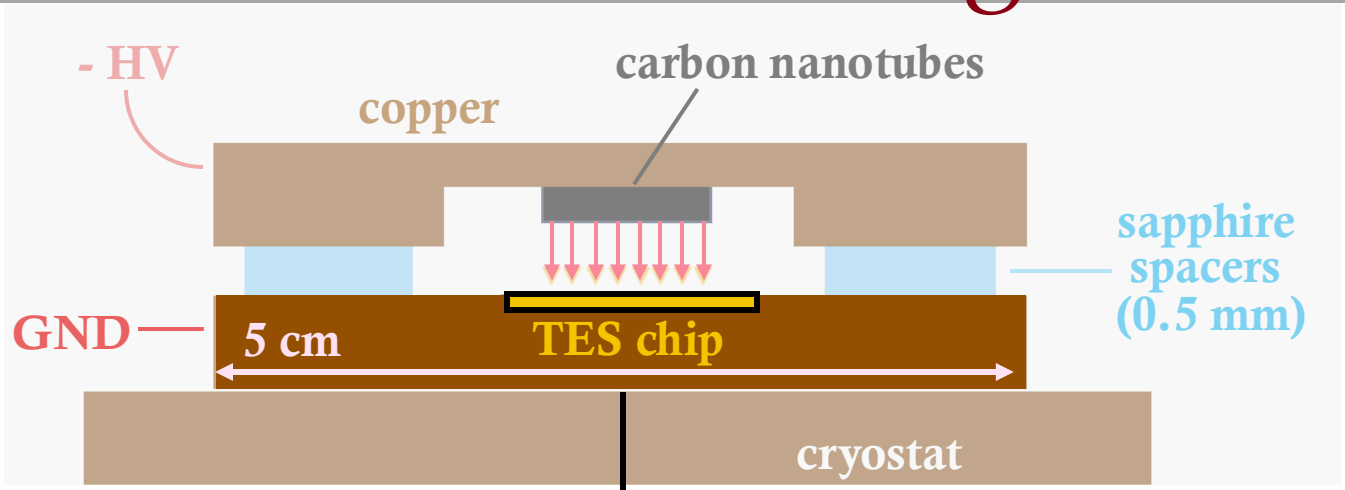
Istituto Nazionale di Fisica Nucleare

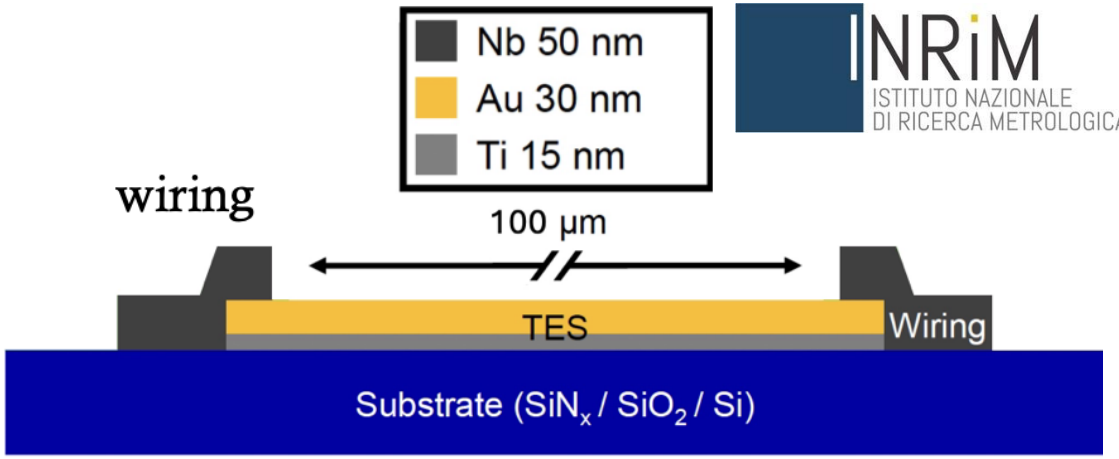
Politecnico
di Torino

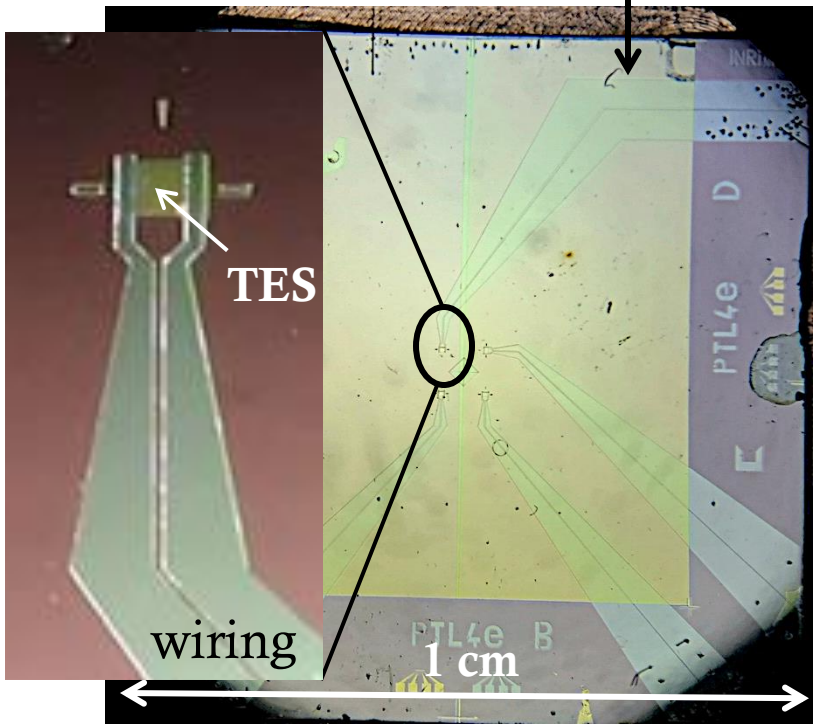
Mozzarella in Carrozza (MiC) Setup



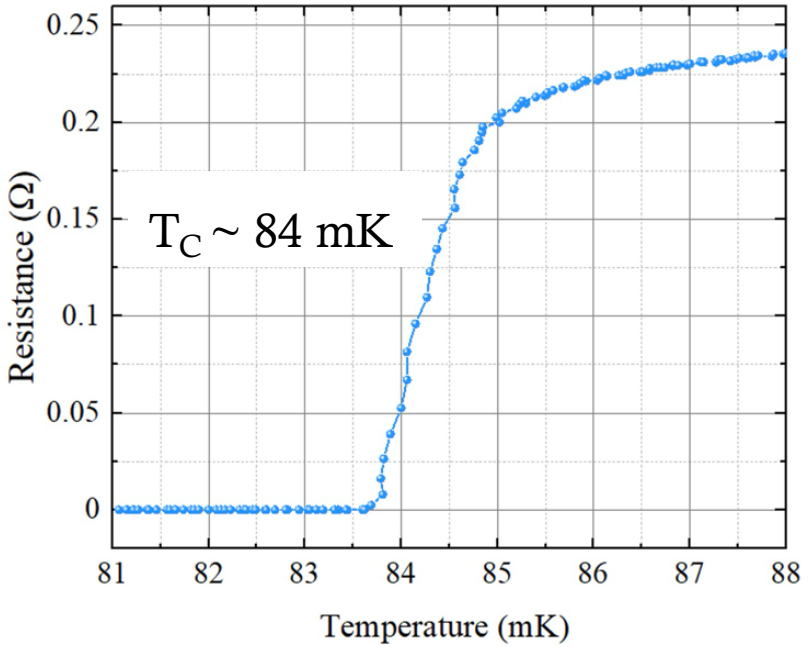
TES to Detect Single Electrons



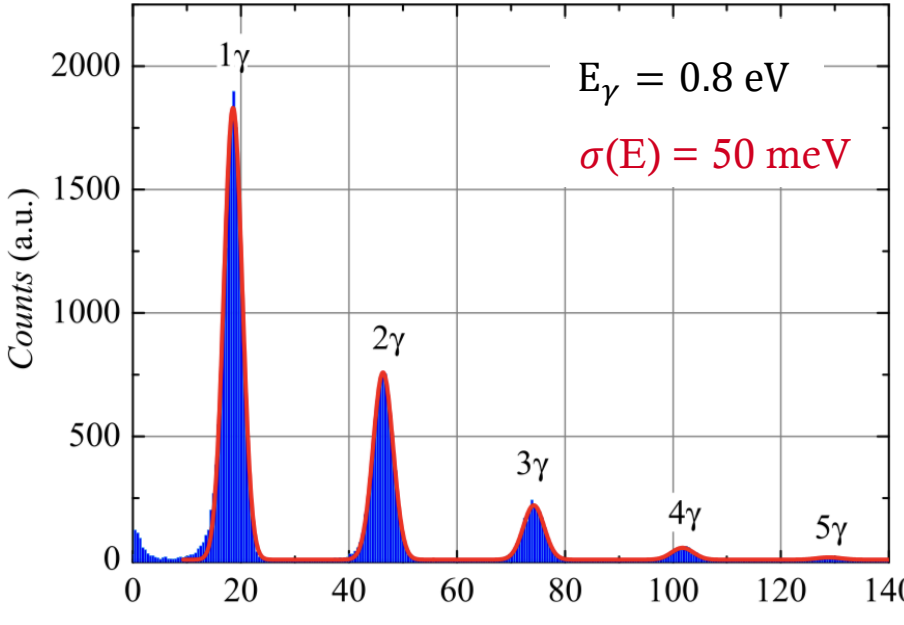




TES superconductive transition

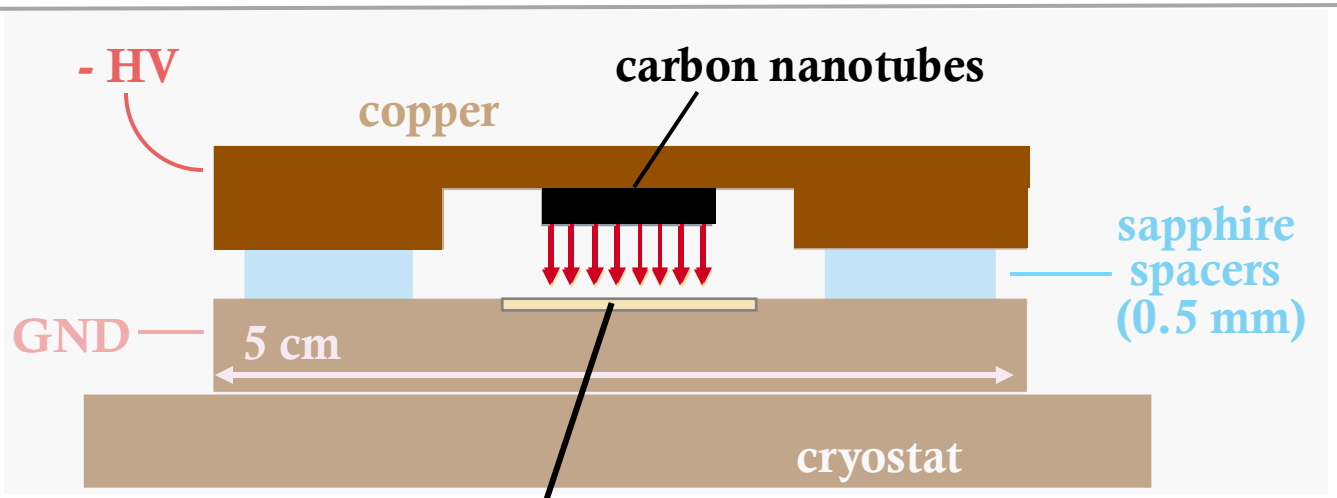


photon-number resolving detector



CNTs as Cold Electron Source

original idea by **Alice Apponi**



- Carbon **nanotubes (CNTs)**: graphene 'straws'
  - diameter ~ 20 nm
  - length ~ 100 μm
- Tip factor $\boldsymbol{\gamma}$ ~ 10^3 - 10^4 enhances local electric field
- Can be used as **field emitters**

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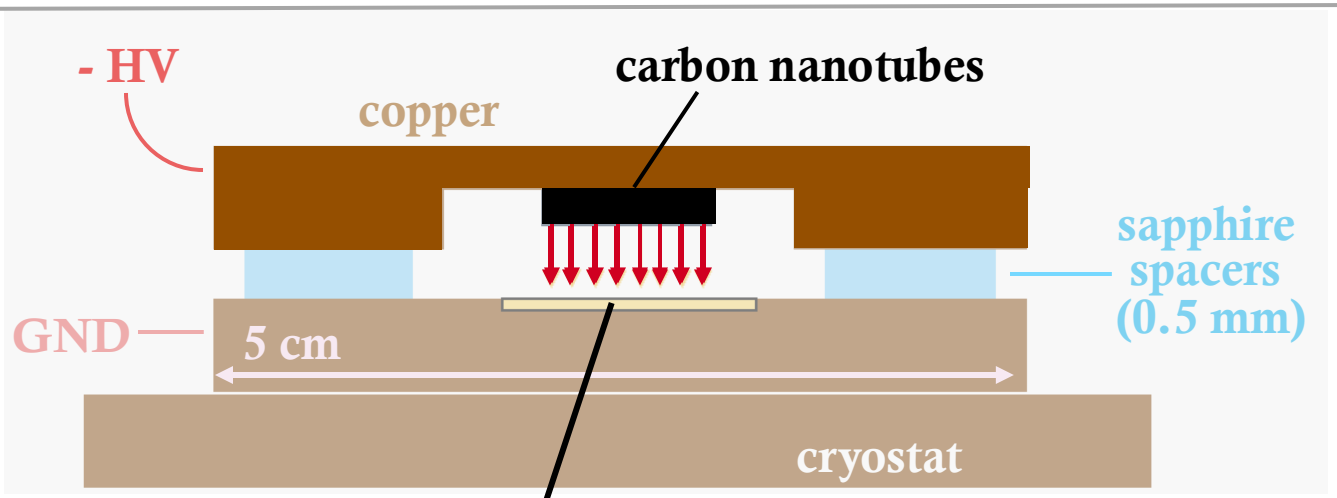

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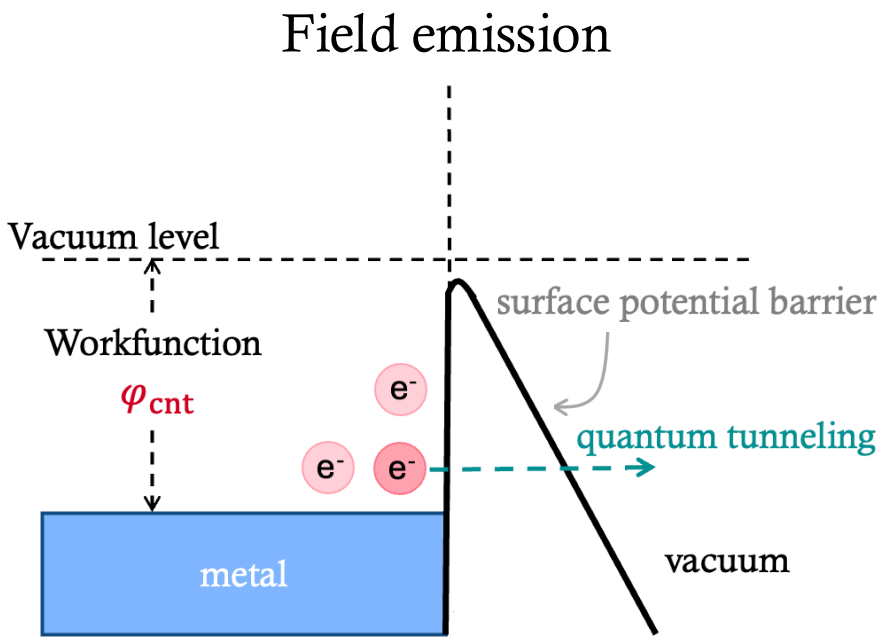

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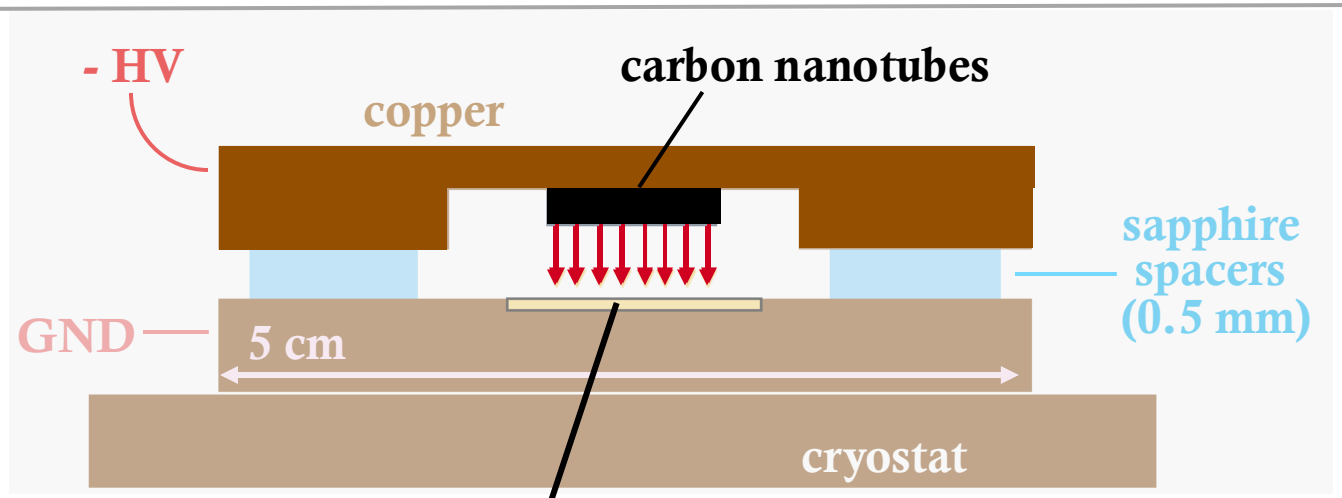

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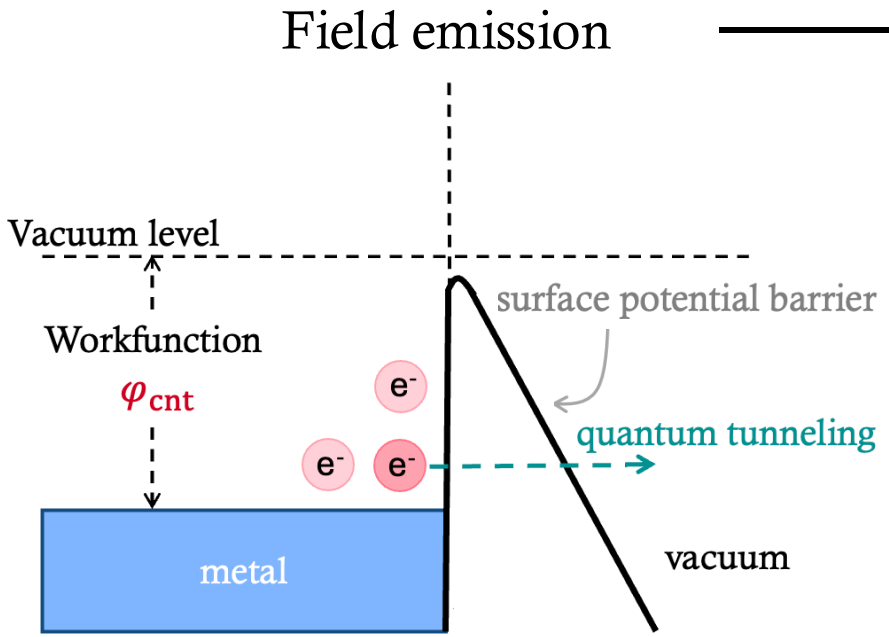

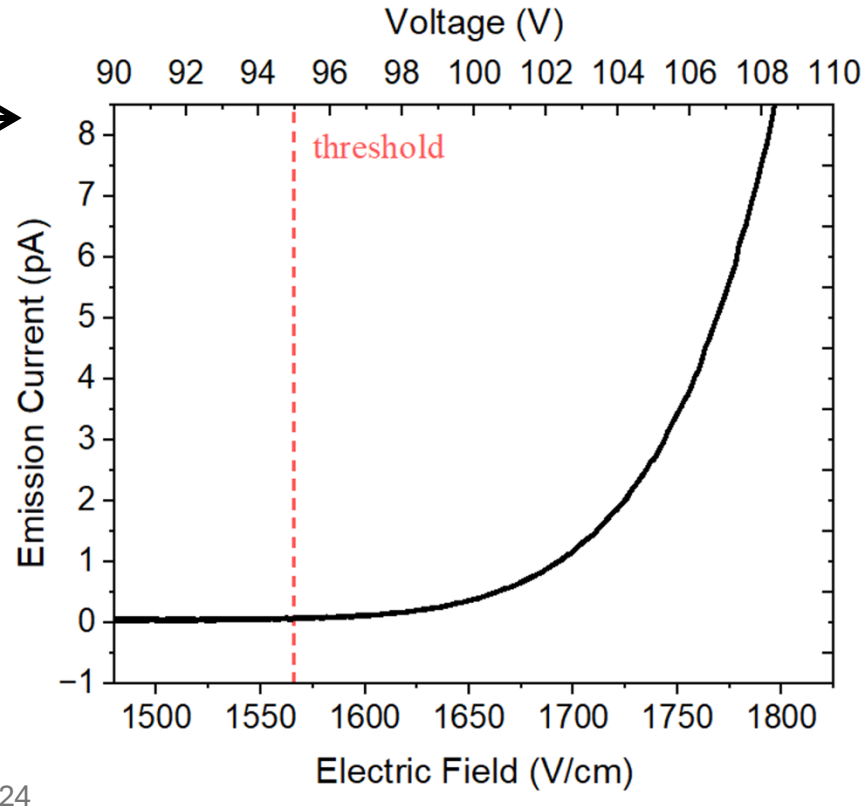

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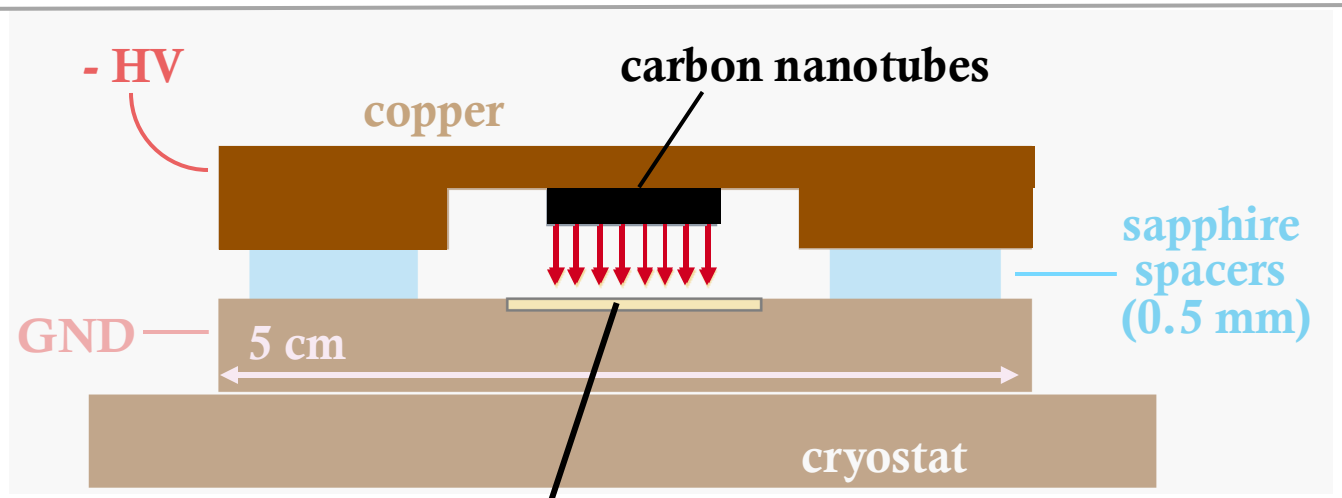

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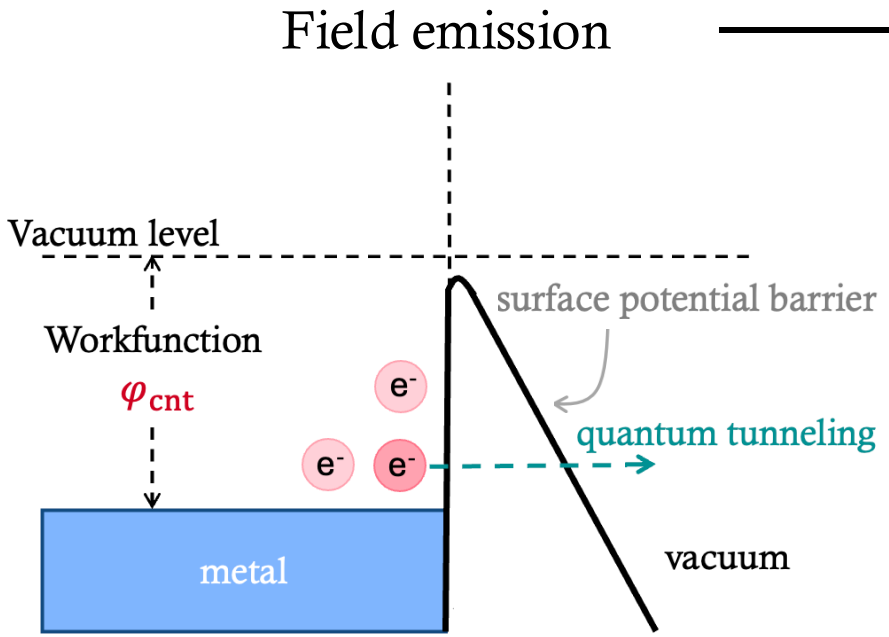

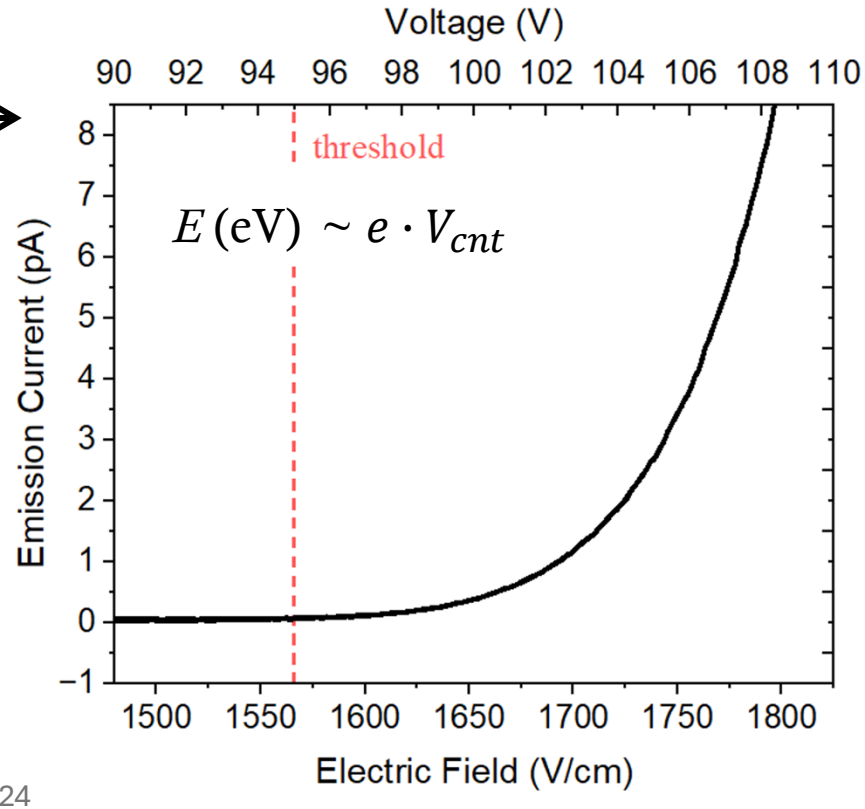

Workfunctions Play a Role in Electron Kinetic Energy

$$E_e = (eV_{cnt} - \varphi_{cnt}) + (\varphi_{cnt} - \varphi_{tes}) = eV_{cnt} - \varphi_{tes}$$

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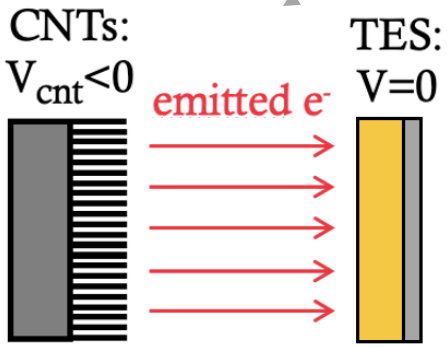
accelerating voltage



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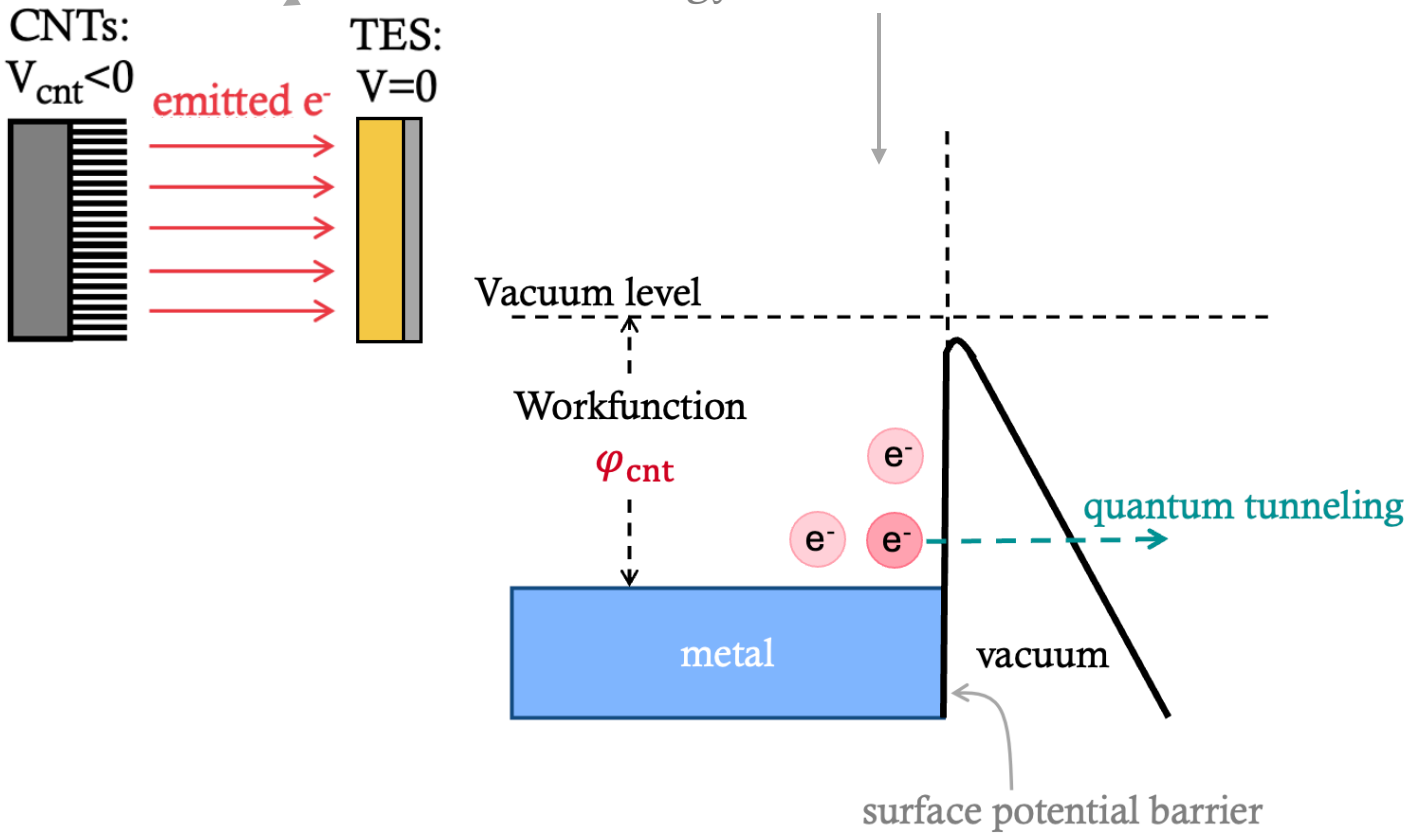
energy level al emission



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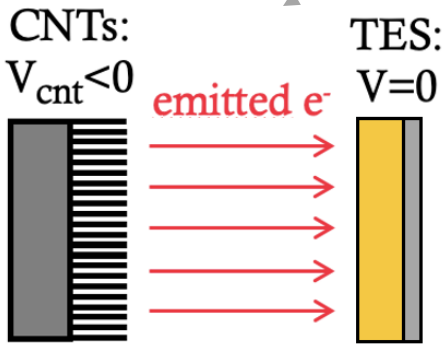
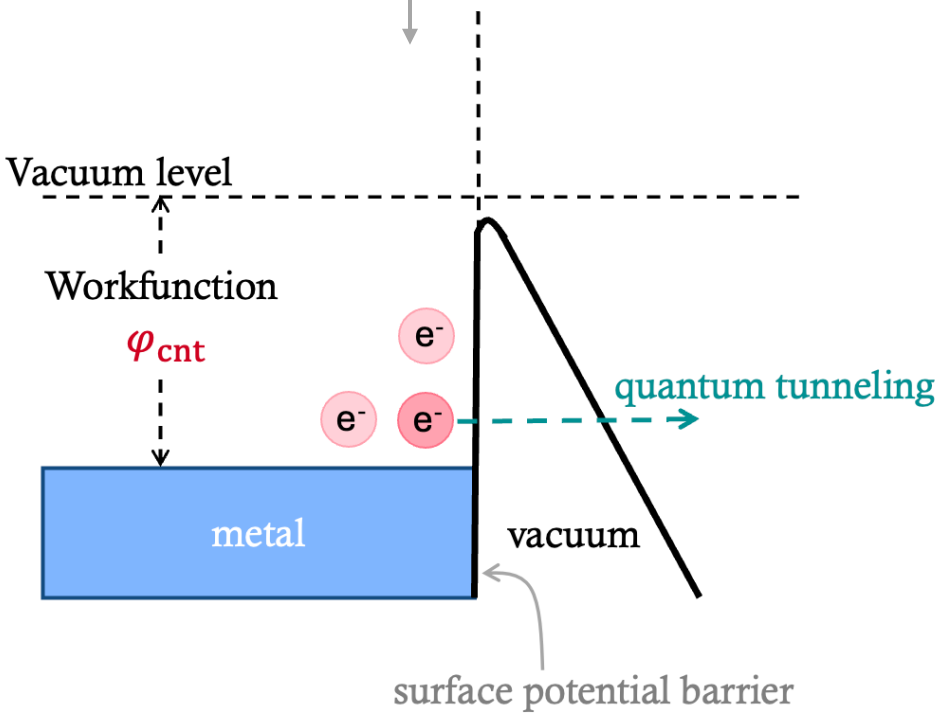
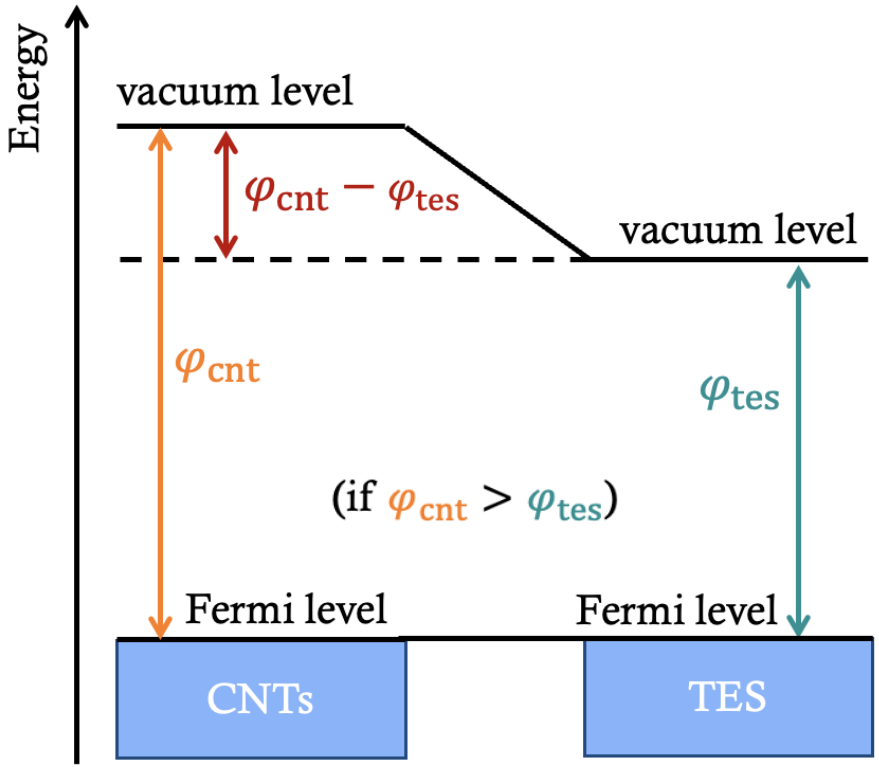
different vacuum levels







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4.4 eV @ LASEC lab in Roma Tre

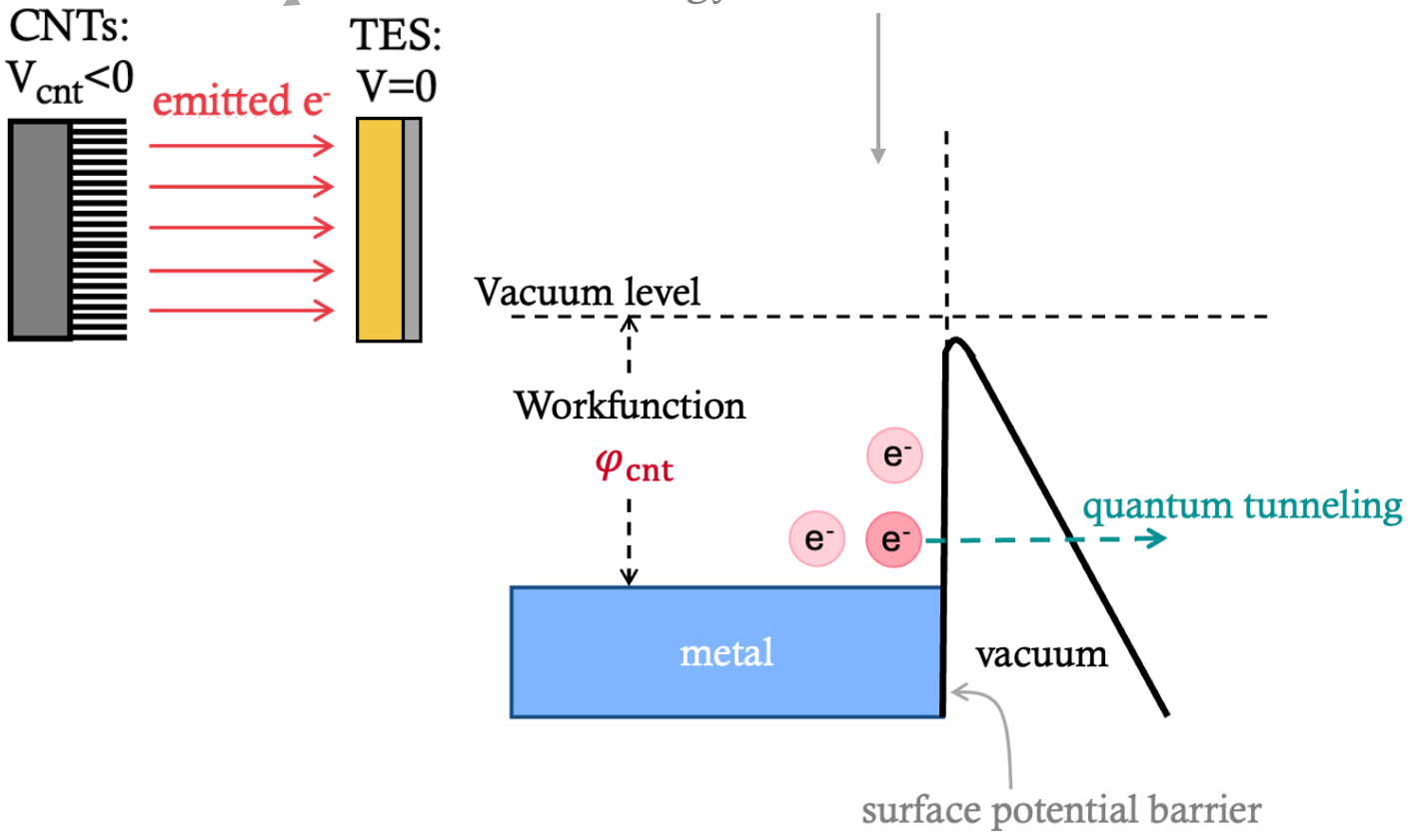
accelerating voltage

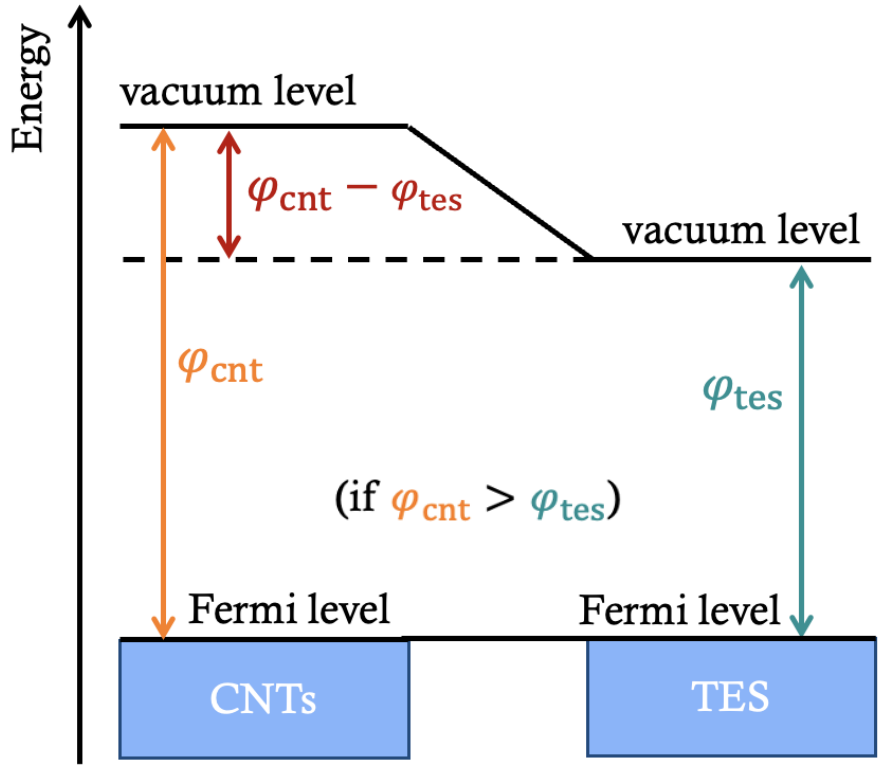
energy level al emission

different vacuum levels

$95\ \text{V} < V_{cnt} < 105\ \text{V}$

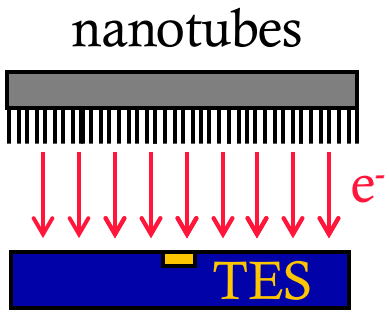
$90.6\ \text{eV} < E_e < 100.6\ \text{eV}$

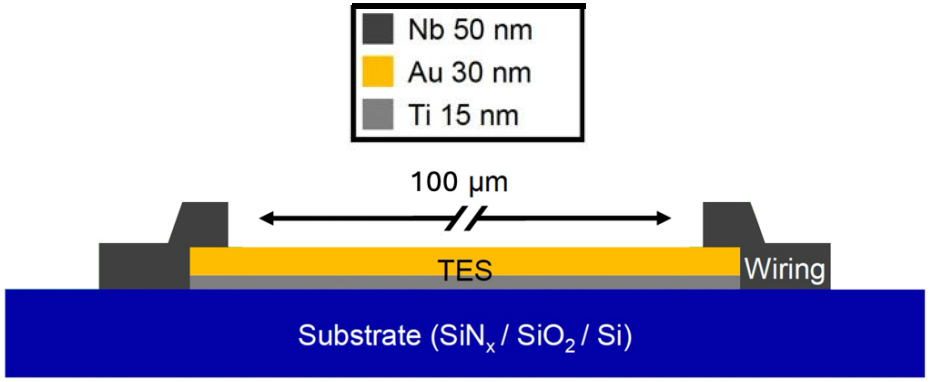




Shield against Unwanted Electron Hits

- CNT surface (**3 mm × 3 mm**) ≫ TES active area (**100 μm × 100 μm**)
- Need to **avoid** electron hits on:
  - wiring (signal interferences)
  - insulating substrate (charge accumulation)





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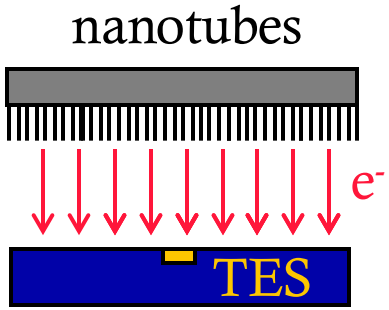
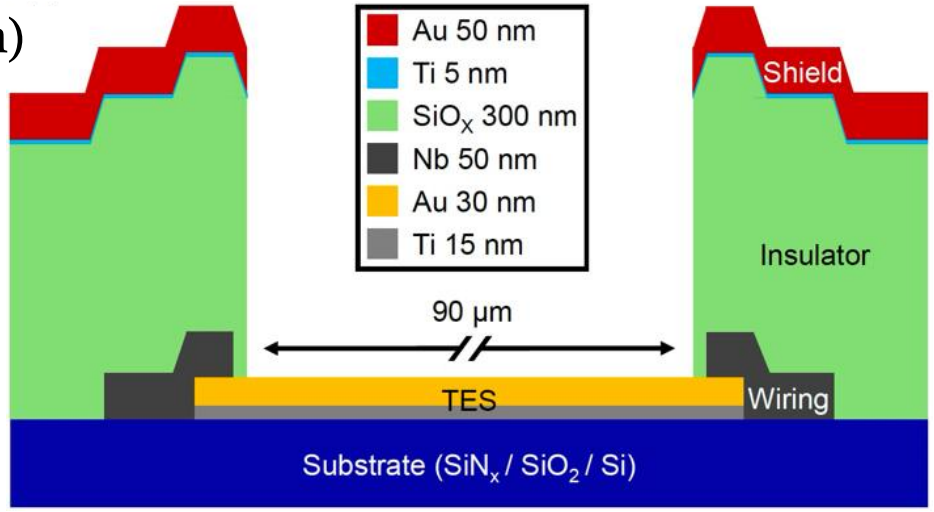
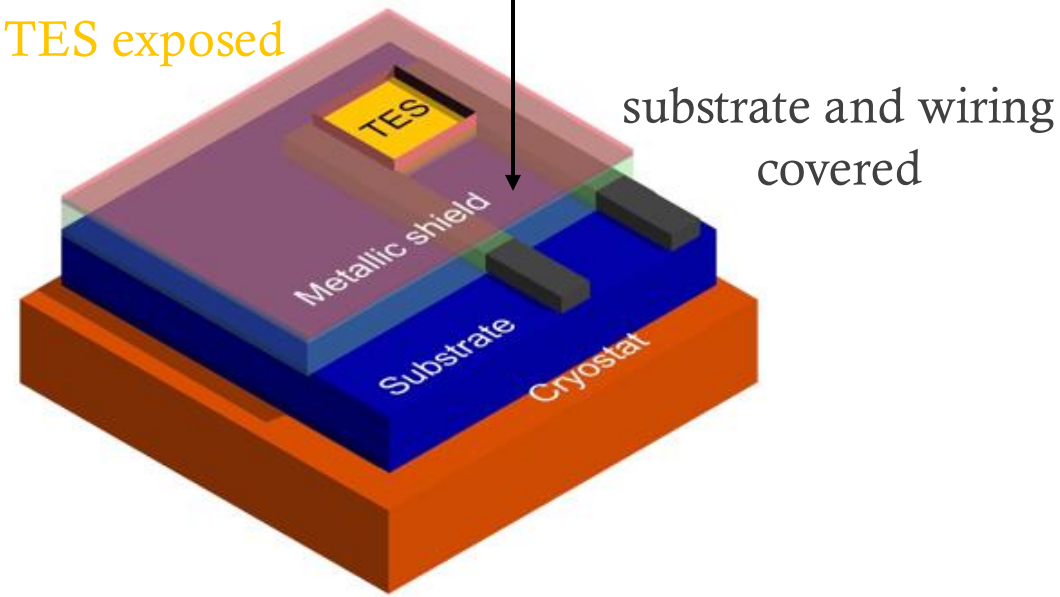
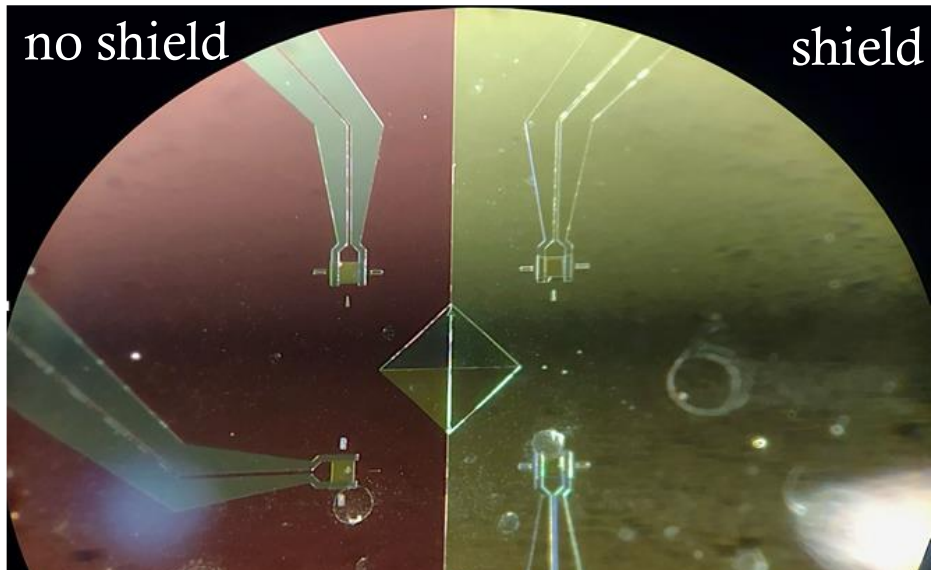
⇒ specifically designed gold shield

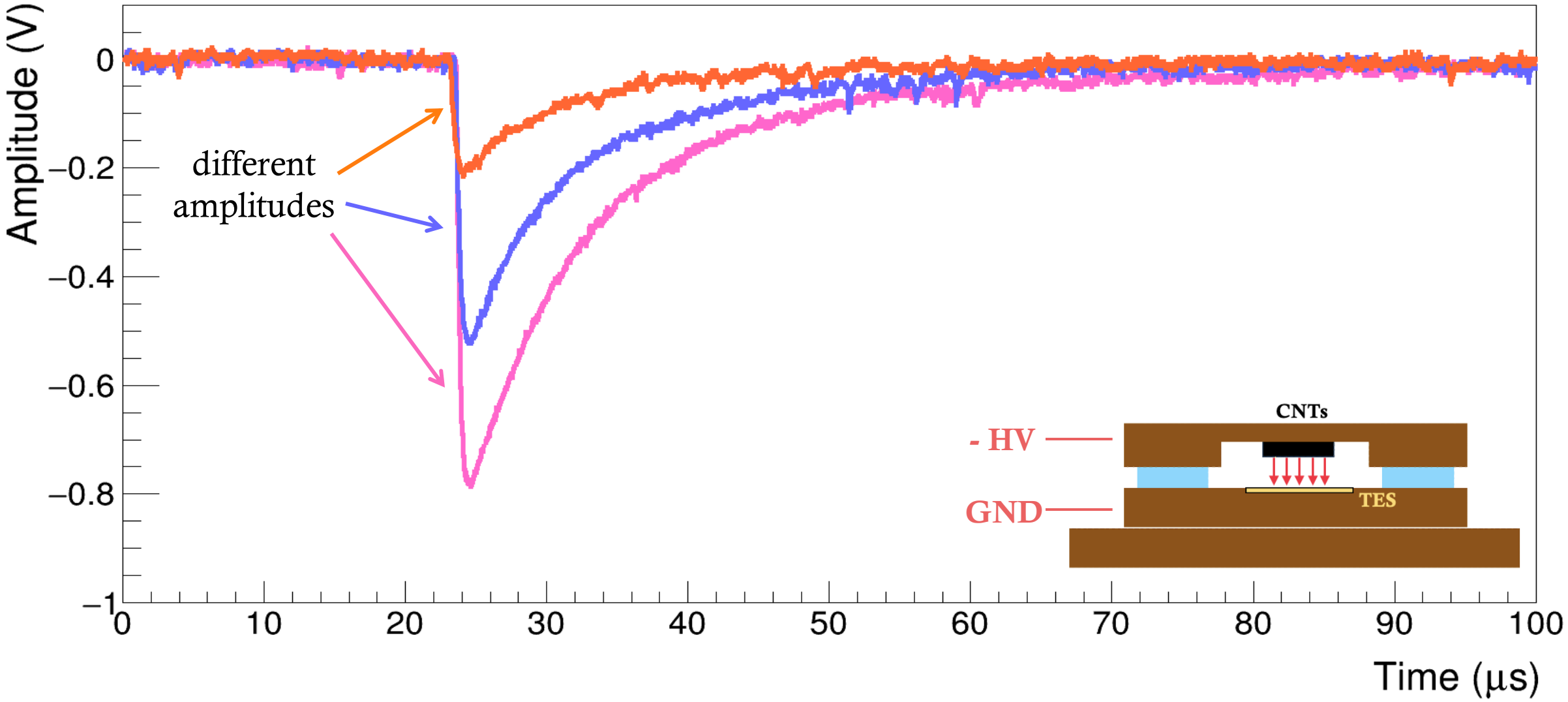






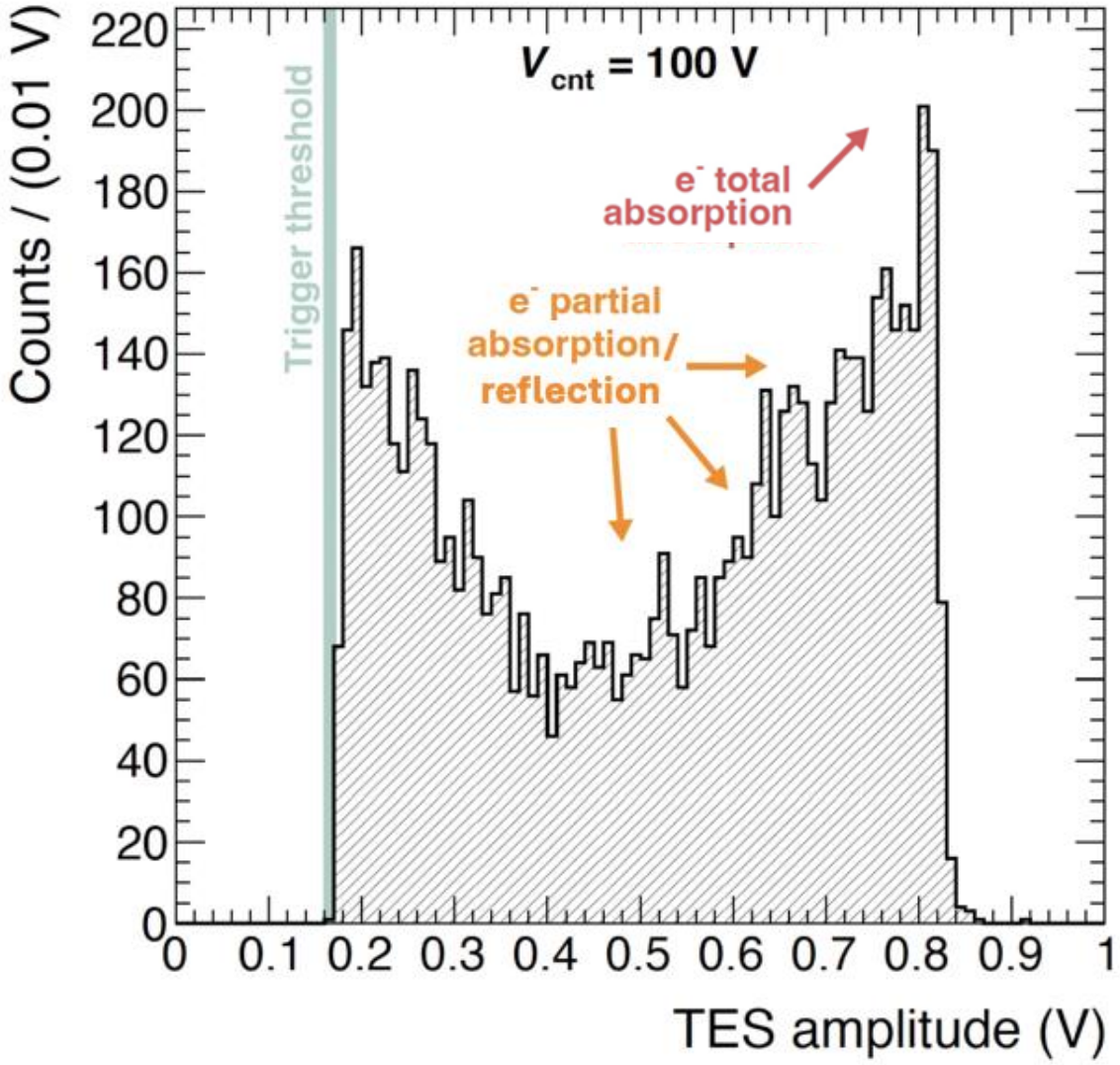


Electron Signals Registered by the TES



Fully-Absorbed Electrons Energy Resolution

Signal amplitude distribution



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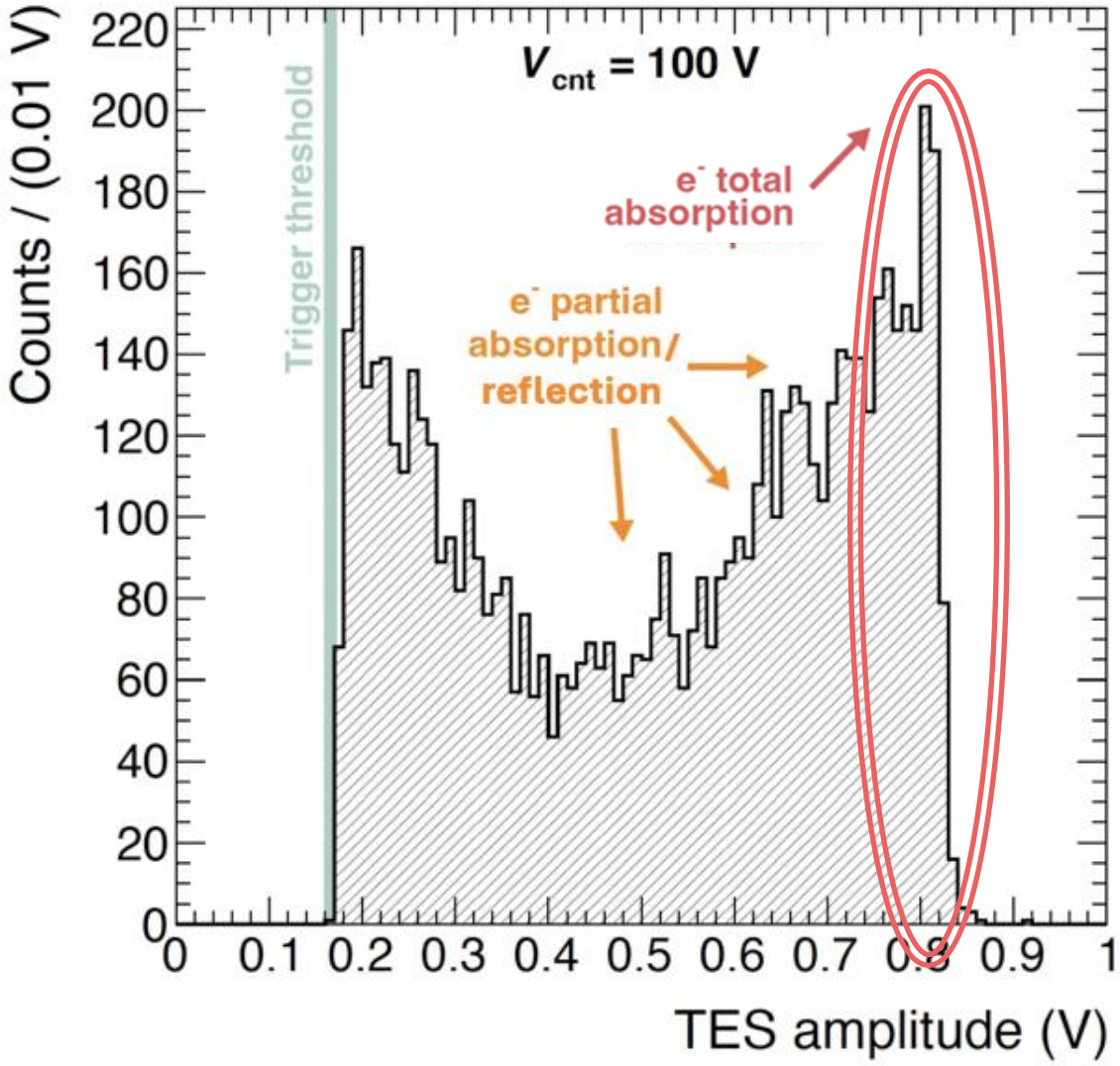

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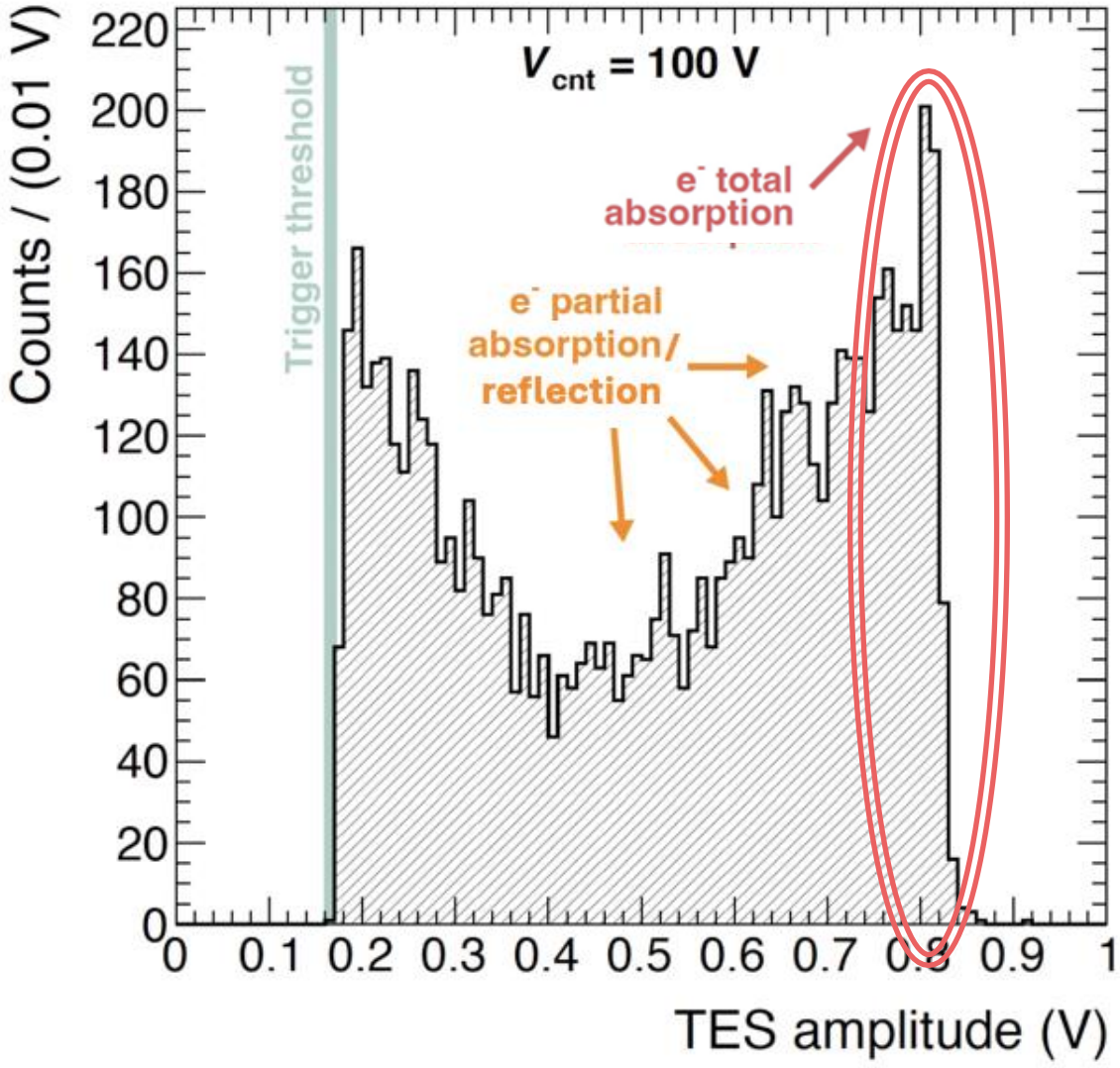
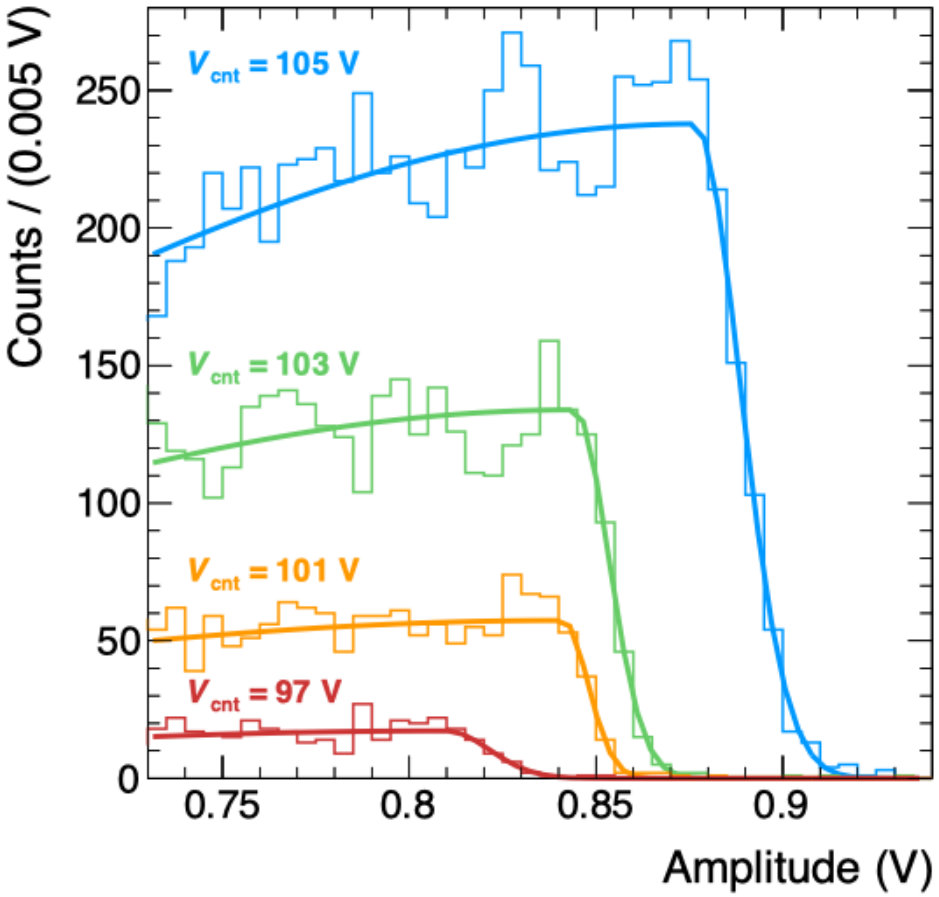


- Fit of the full-absorption peak with **asymmetric Gaussian**:
  - σ_{left} ⇒ partial absorption
  - σ_{right} ⇒ $\sqrt{(\text{energy resolution})^2+(\text{CNT energy spread})^2}$



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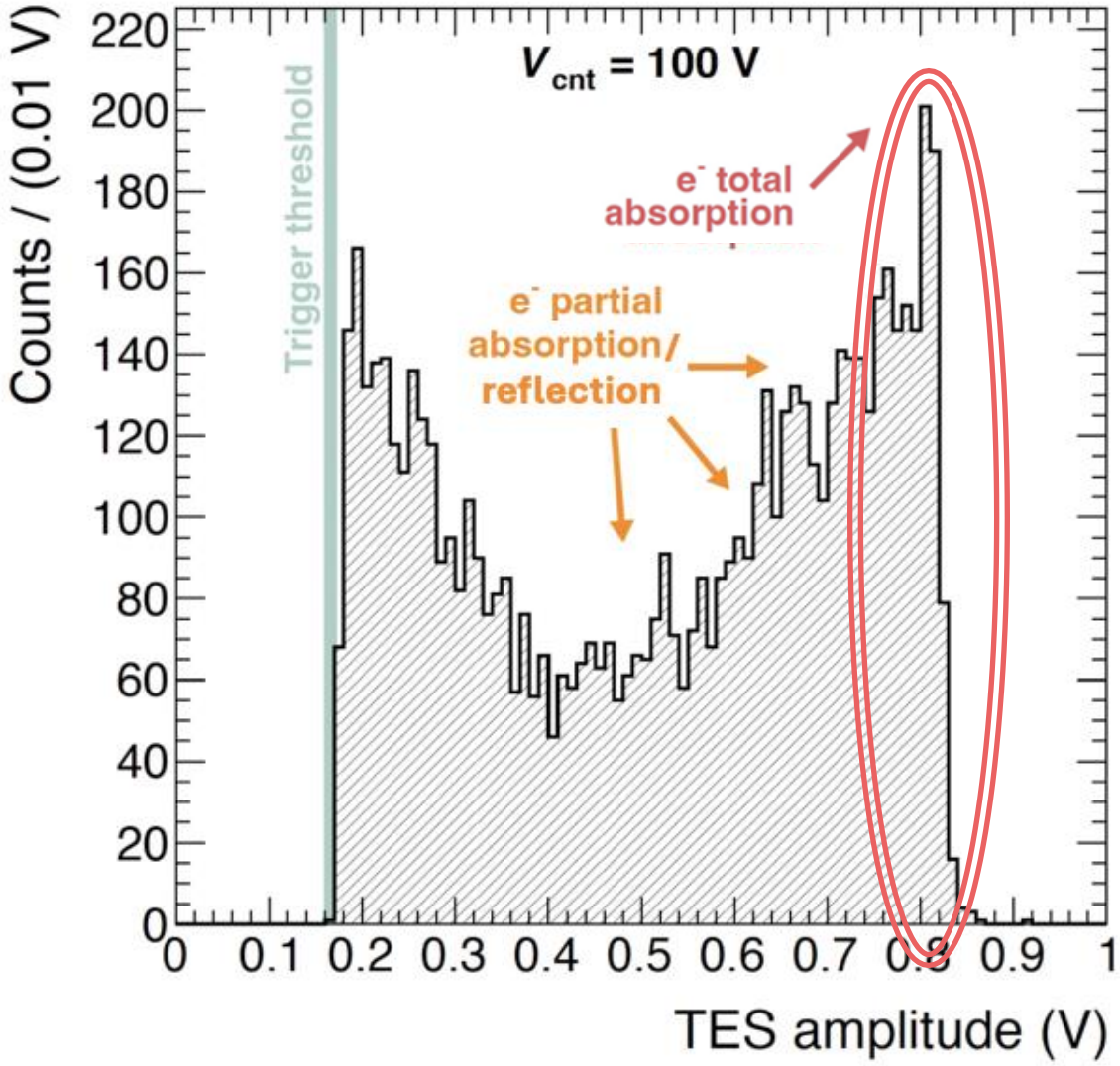

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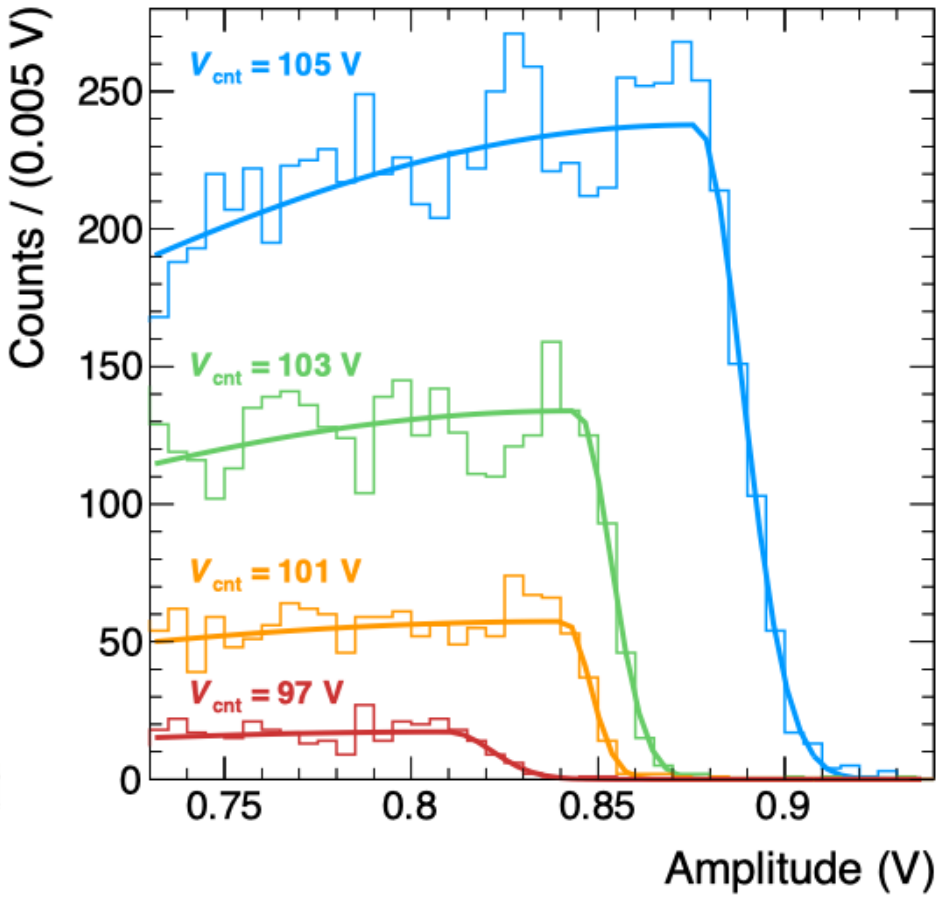
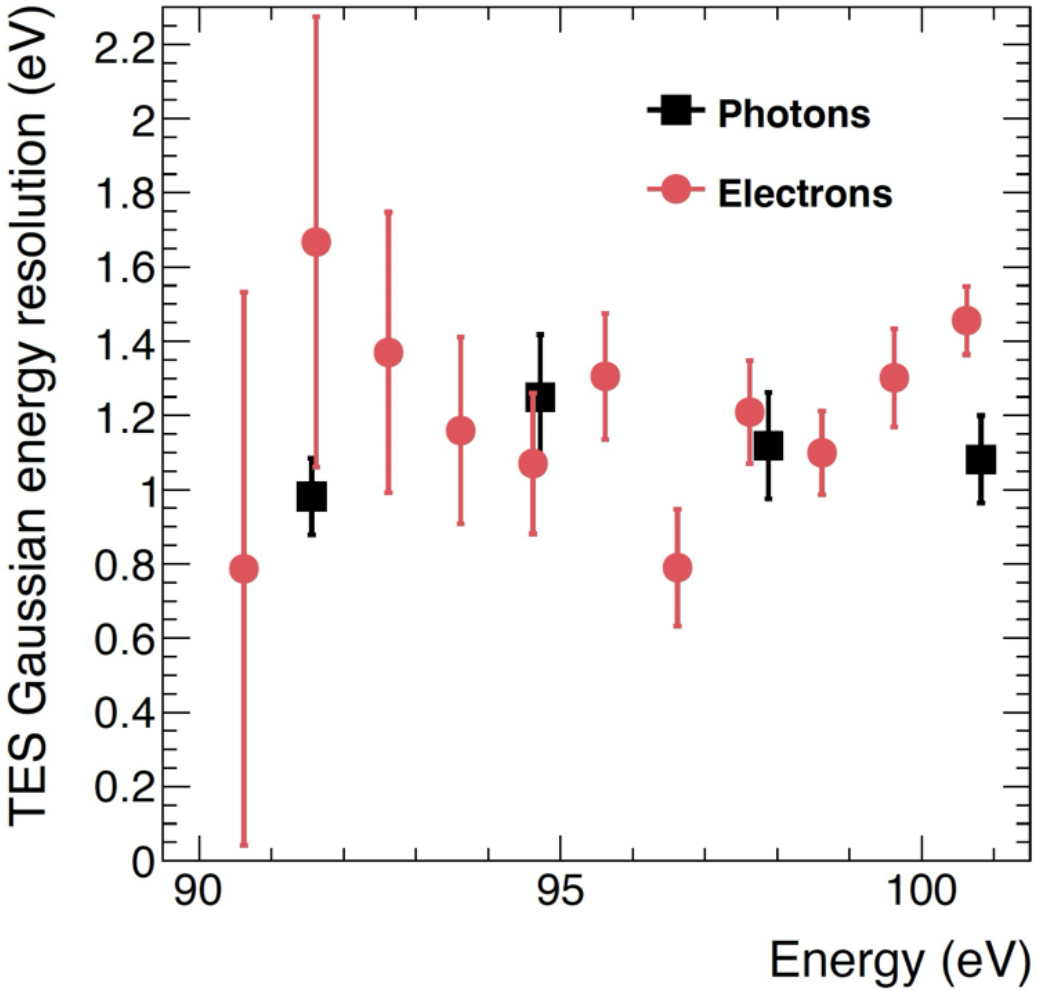


~ 10 μeV

@ $|\vec{E}| = \mathcal{O}(1\ \text{kV/cm})$

@ low temperatures

Electron Resolution Compatible with Photons!



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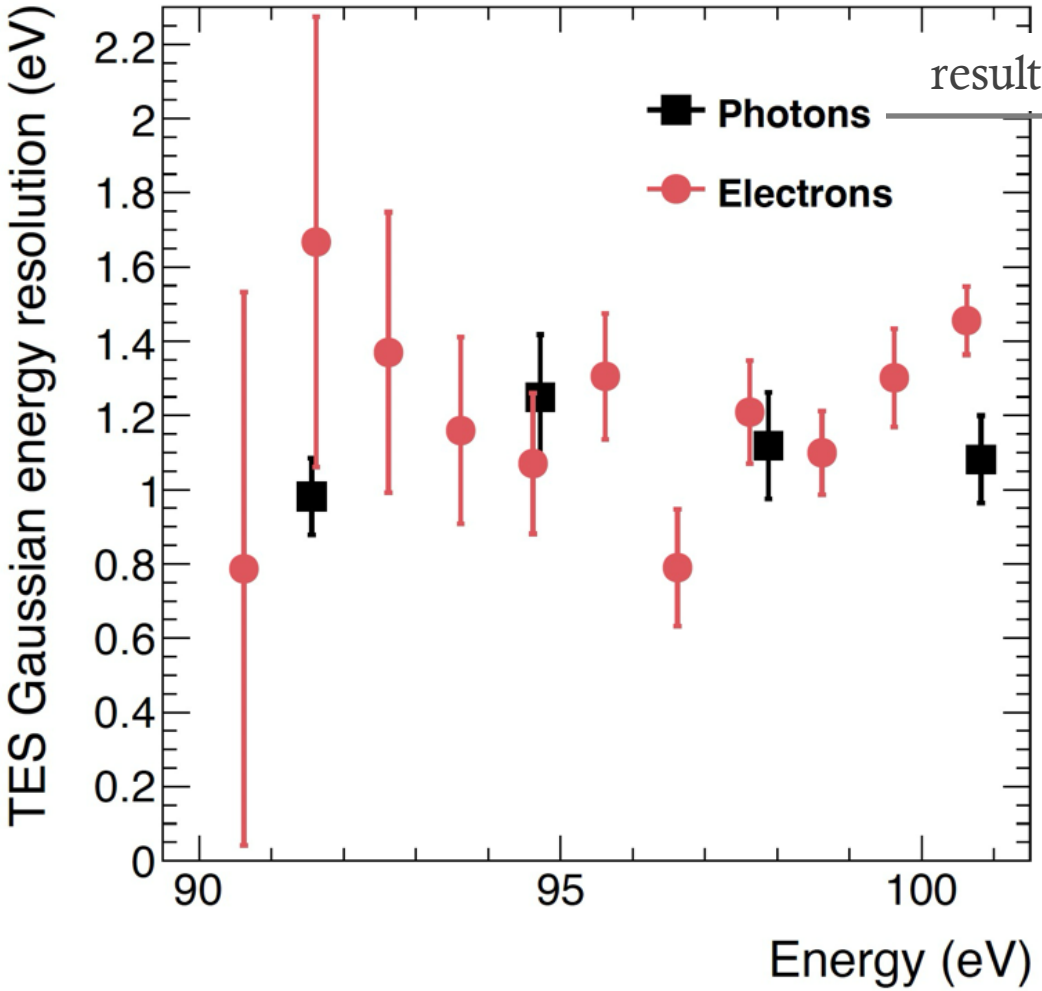
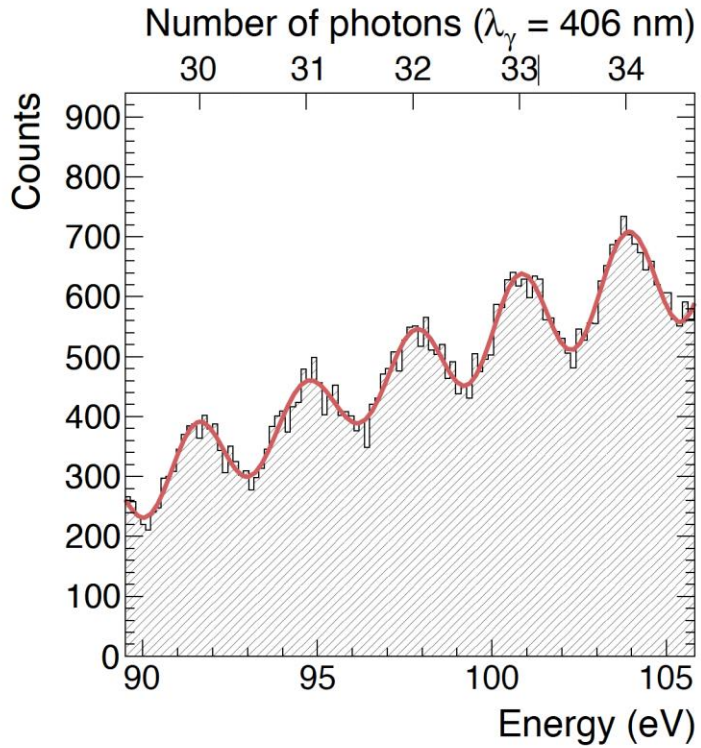


results taken from TES characterization



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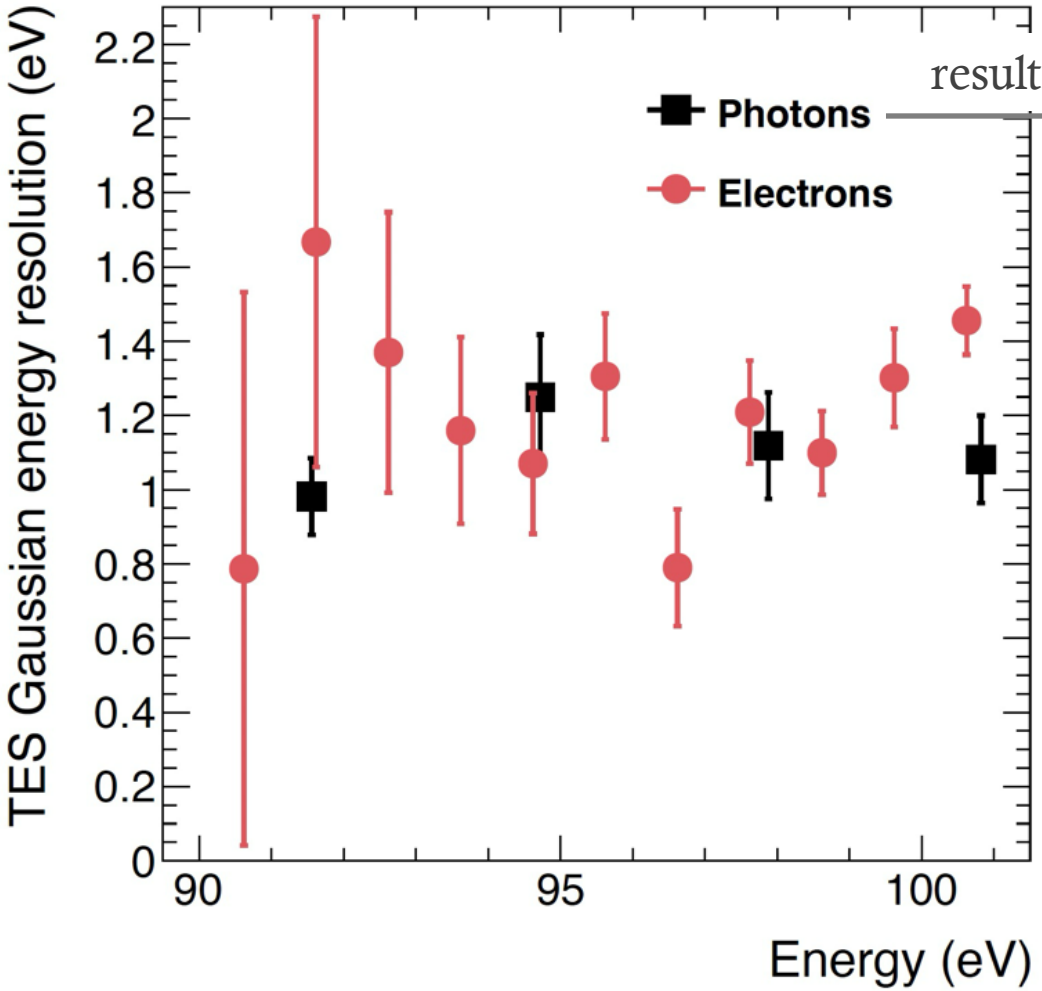

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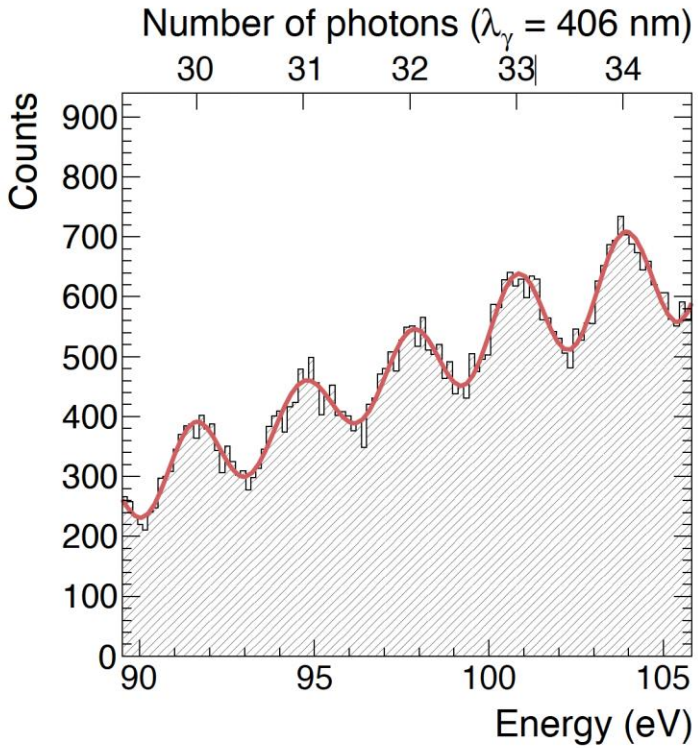

- Electron **energy resolution** defined as:

$$\sigma_e(E) = \frac{\sigma_{right}}{\underbrace{\mu}_{\text{from fits}}} E_e$$

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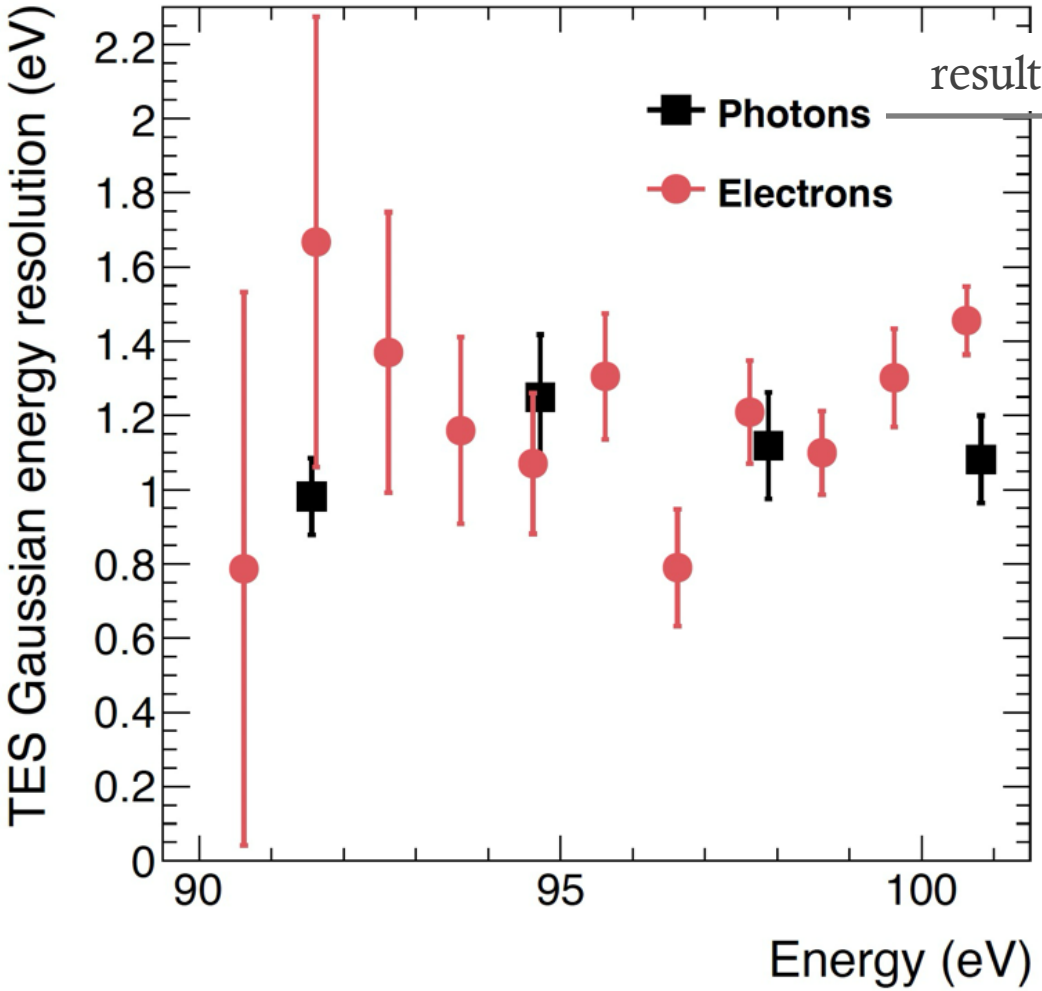

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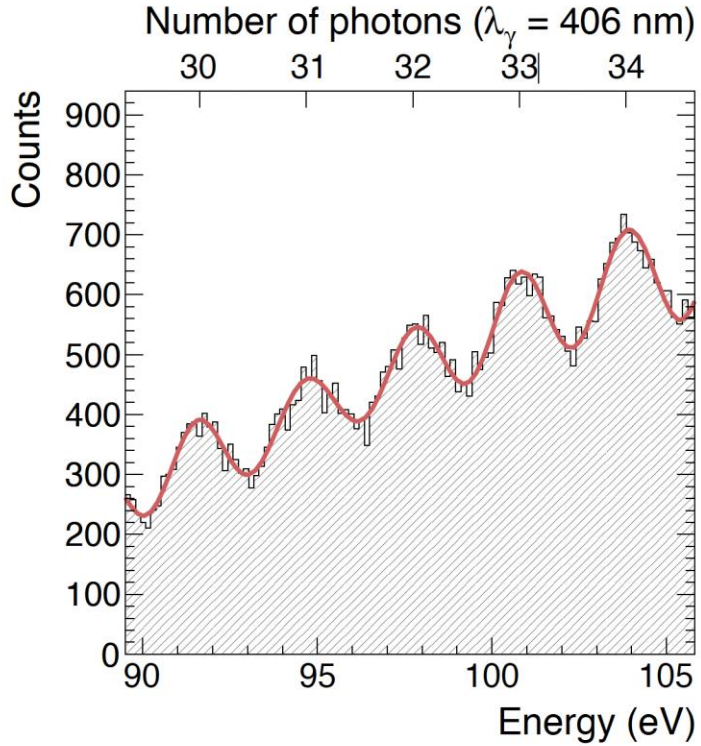

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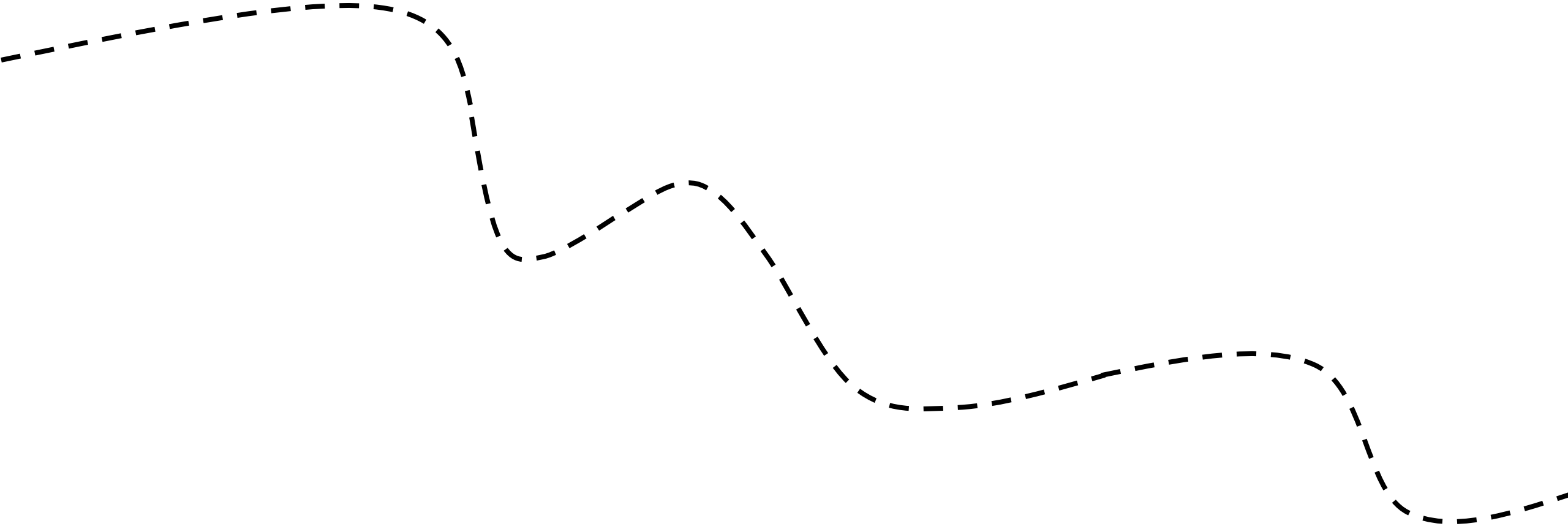
- **Compatible** resolution for electrons and photons!

  ⇒ noteworthy as $e^- \neq \gamma$ at such low energies

  ⇒ same heat absorption mechanism

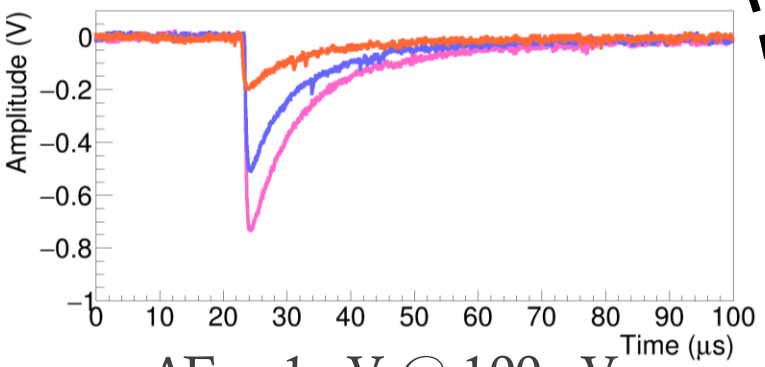
Next Steps Forward



Next Steps Forward

detection of low-energy electrons

WE ARE HERE



ΔE ~ 1 eV @ 100 eV

Phys. Rev. Applied **22**, L041007

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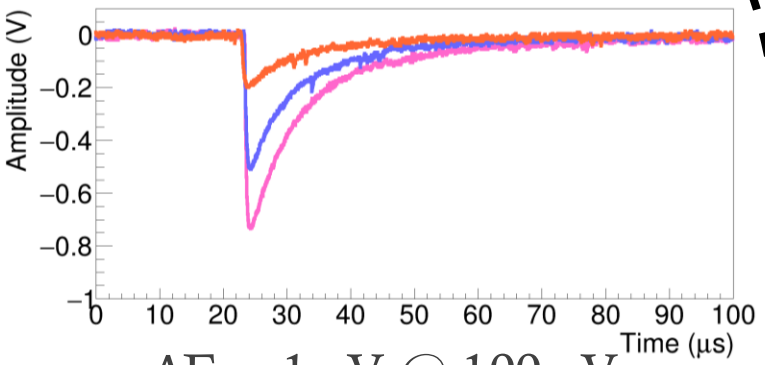

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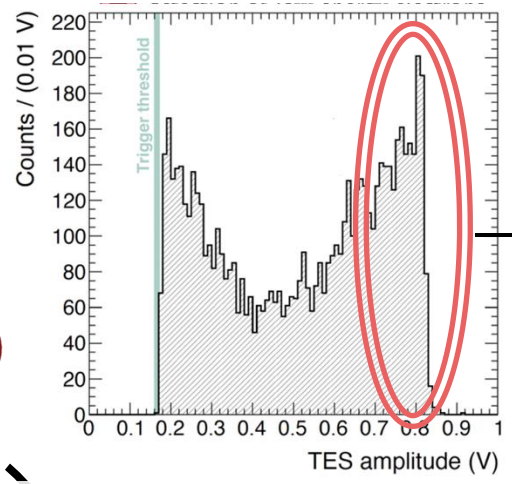

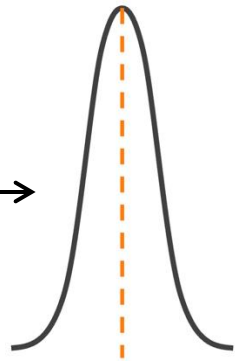

reduce left tail in the histogram of the signal amplitudes

Next Steps Forward

detection of low-energy electrons

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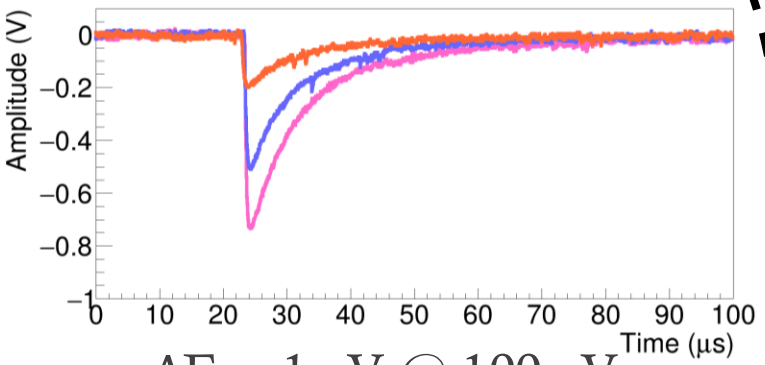

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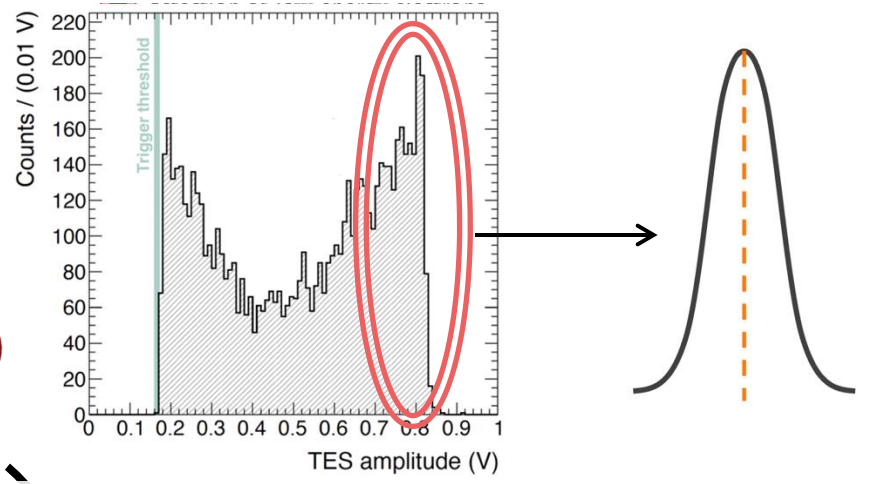

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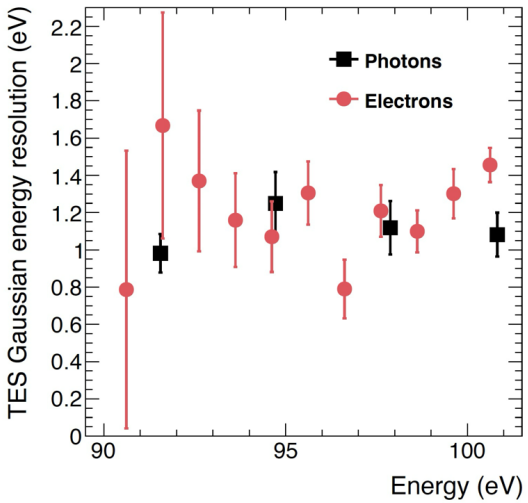


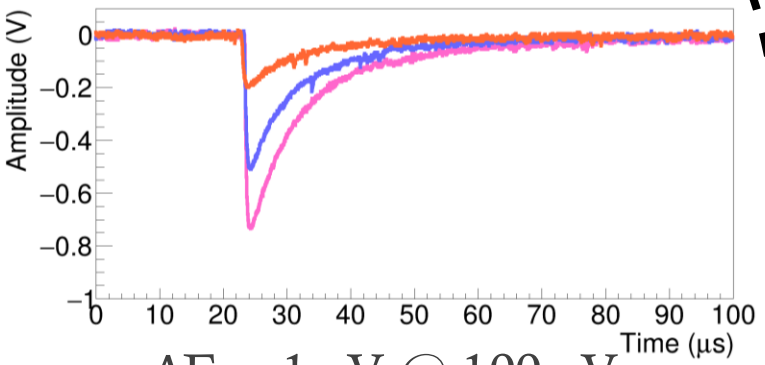
improve energy resolution

ΔE: 1 eV ⇒ 0.05 eV

Next Steps Forward

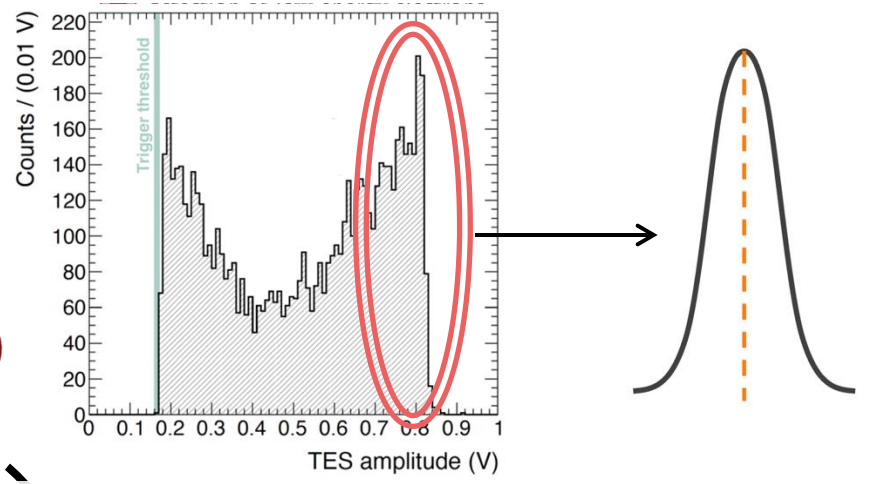
detection of low-energy electrons

WE ARE HERE

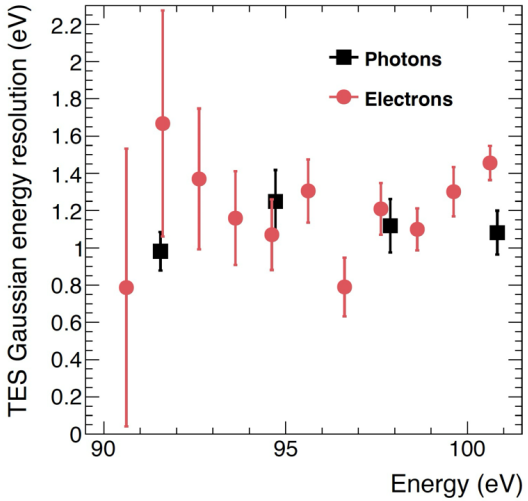


ΔE ~ 1 eV @ 100 eV

Phys. Rev. Applied **22**, L041007



reduce left tail in the histogram of the signal amplitudes



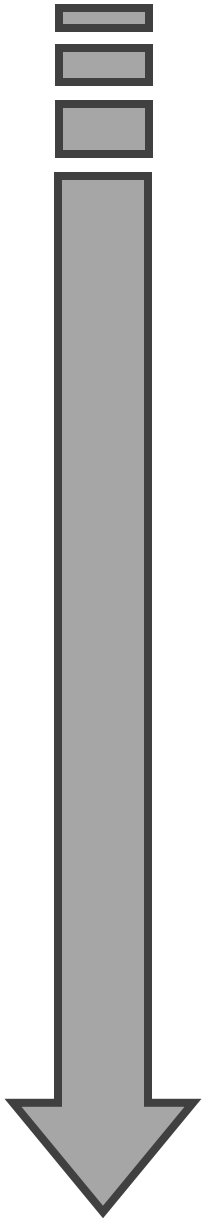
improve energy resolution

ΔE: 1 eV ⇒ 0.05 eV

lower electron energies

E: 100 eV ⇒ 10 eV

What Are We Working on Now?



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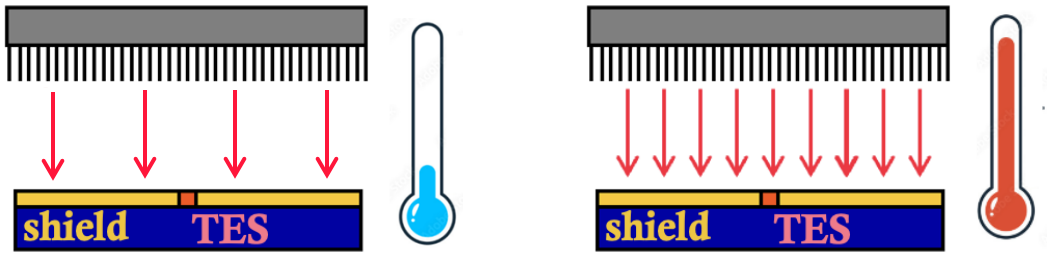

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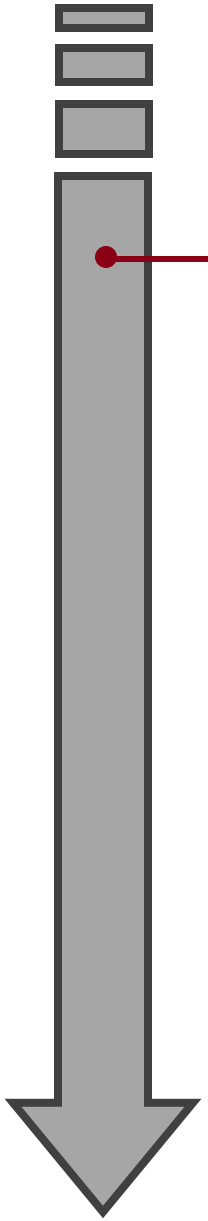

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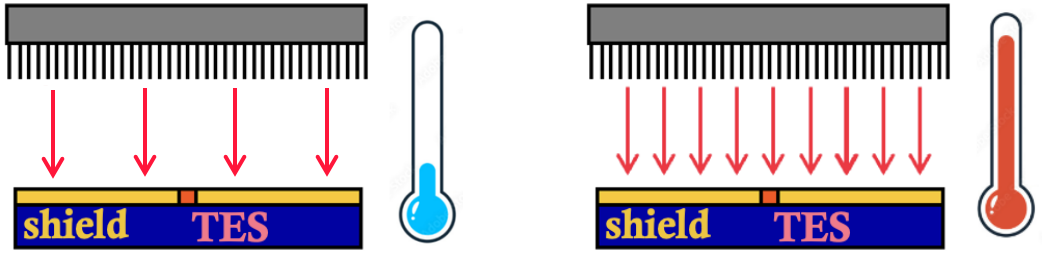
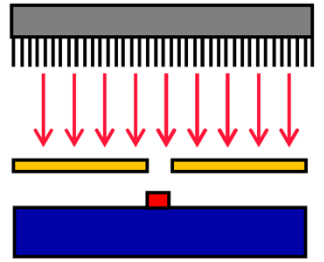


thermal decoupling
TES - shield



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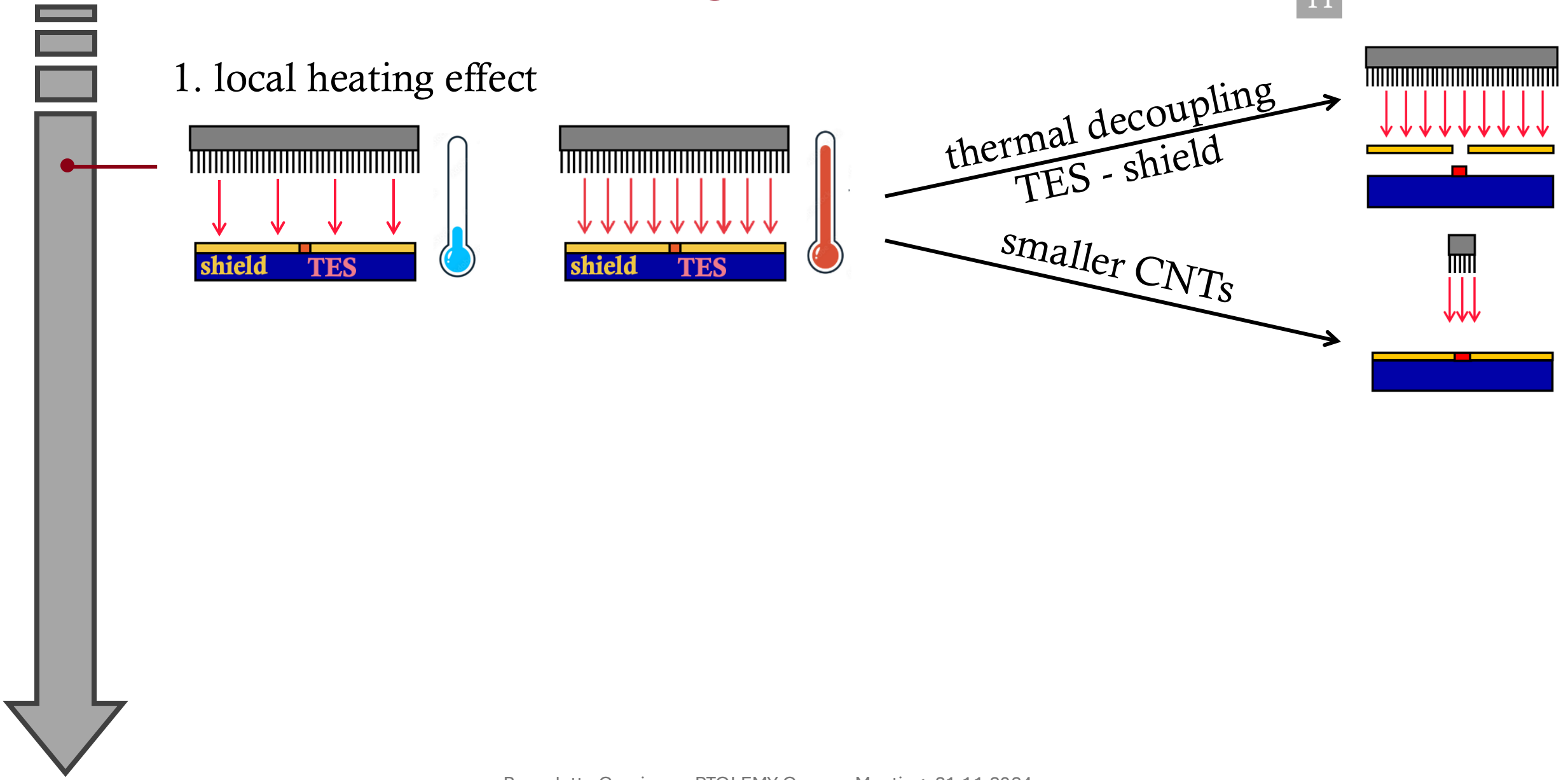

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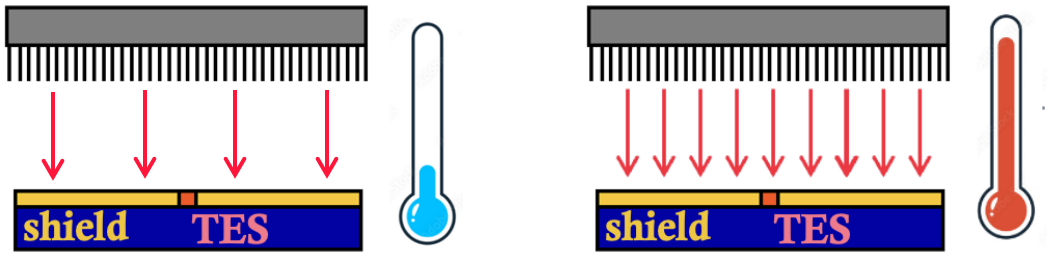
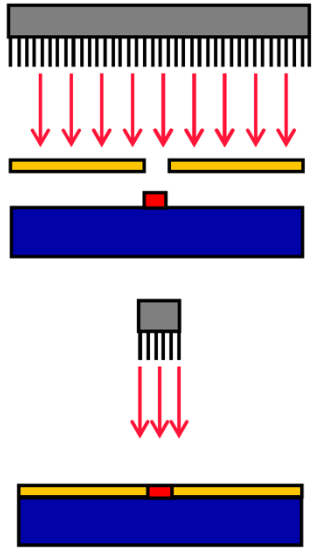


thermal decoupling TES - shield

smaller CNTs



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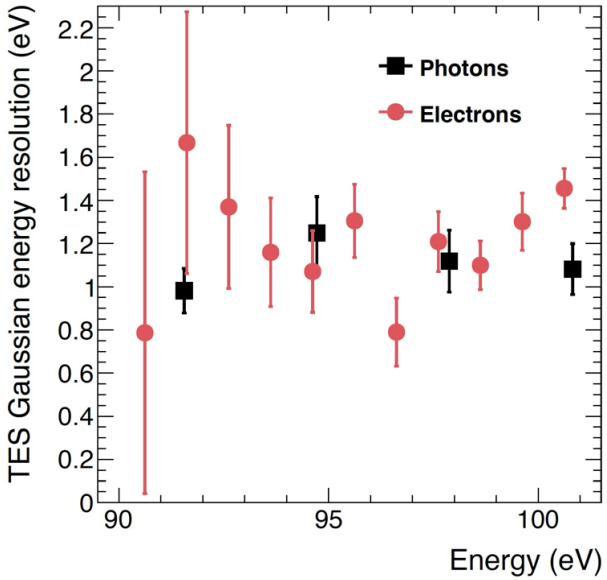

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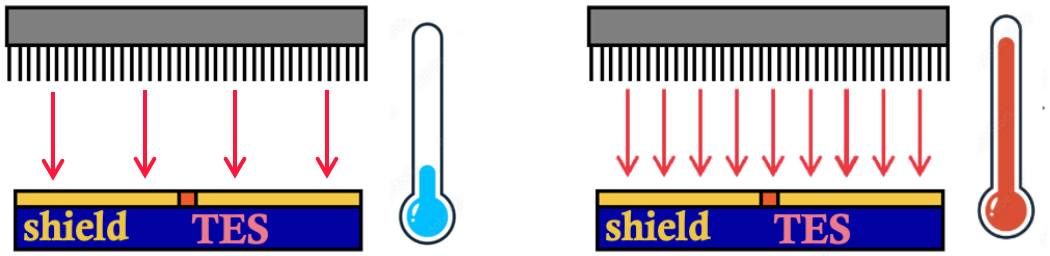

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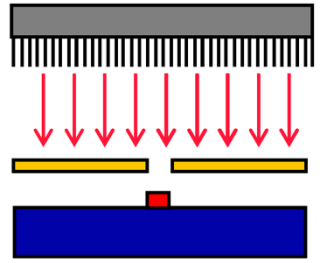

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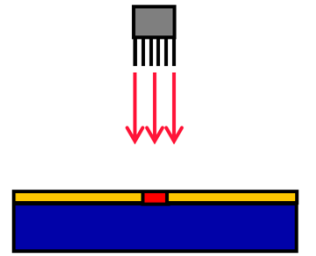

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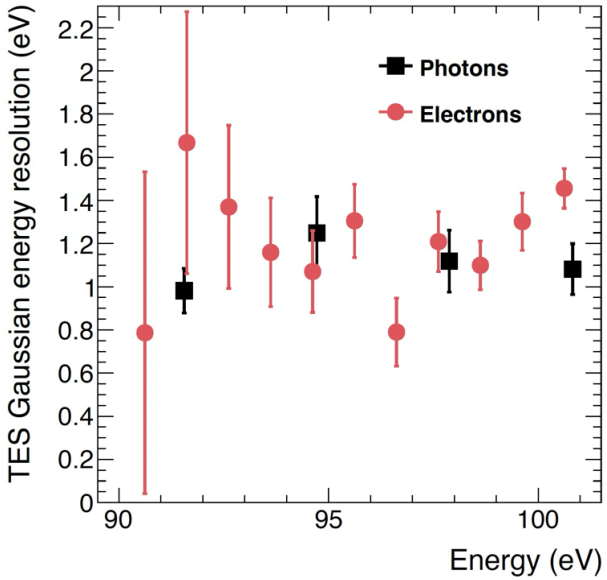

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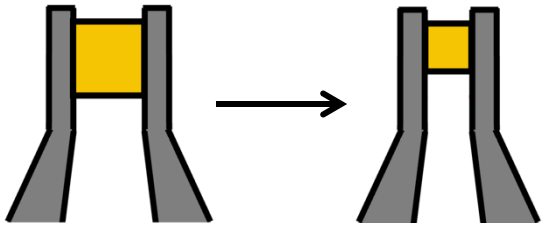

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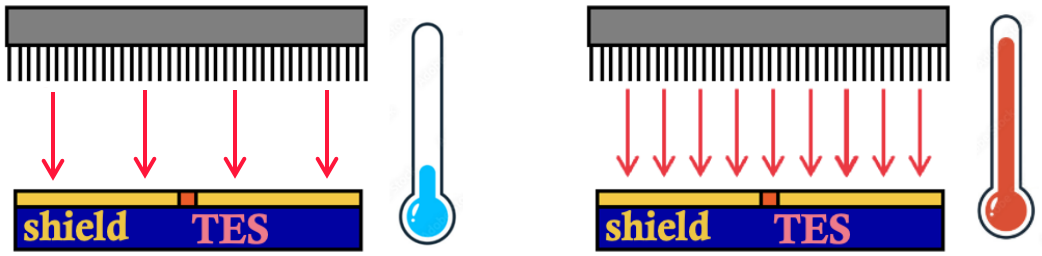

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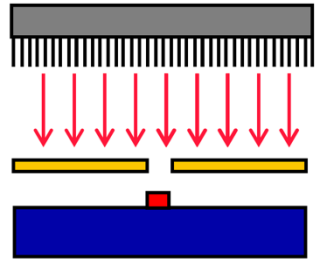

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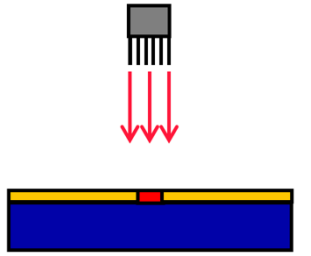

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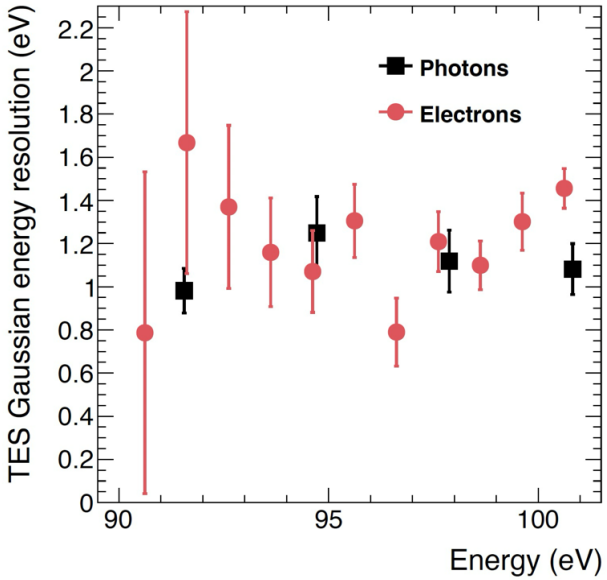

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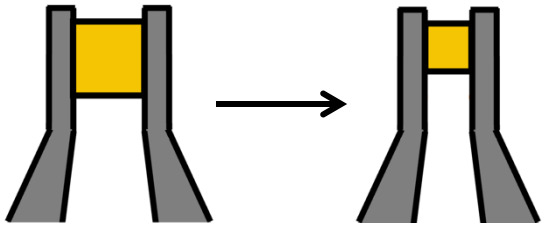
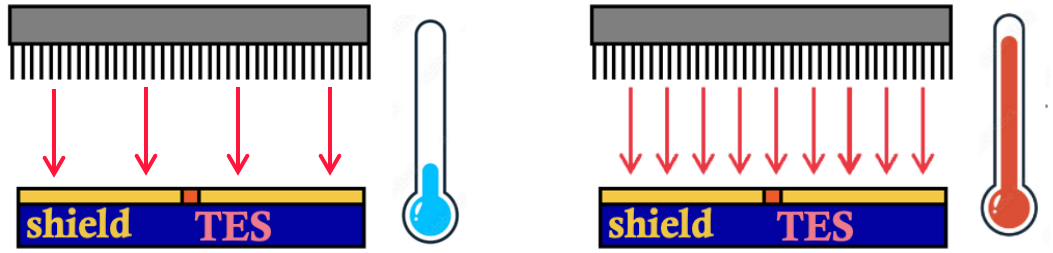


noise reduction

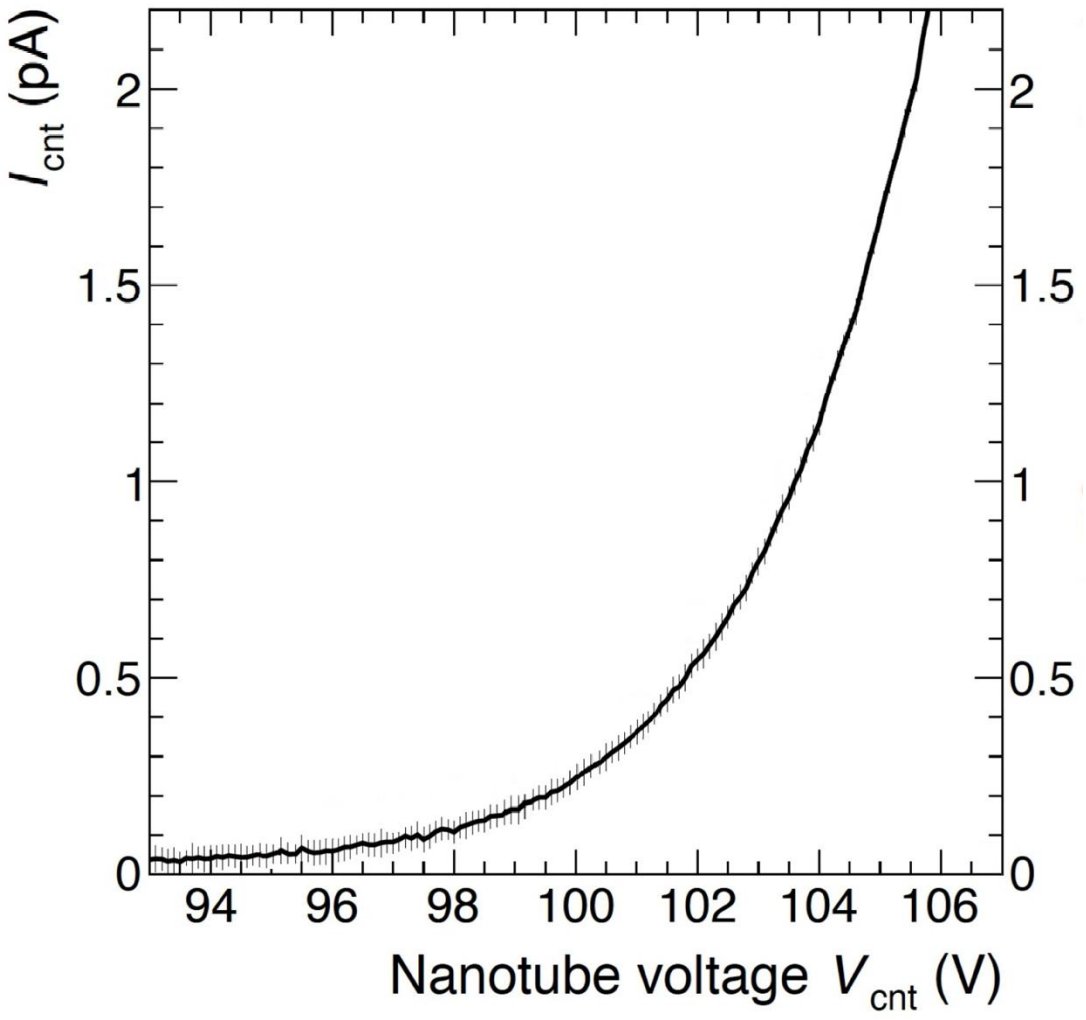
new MiC design

1. Local Heating Effect



Higher Energy ⇒ Higher Temperature

Field-emission current from CNTs



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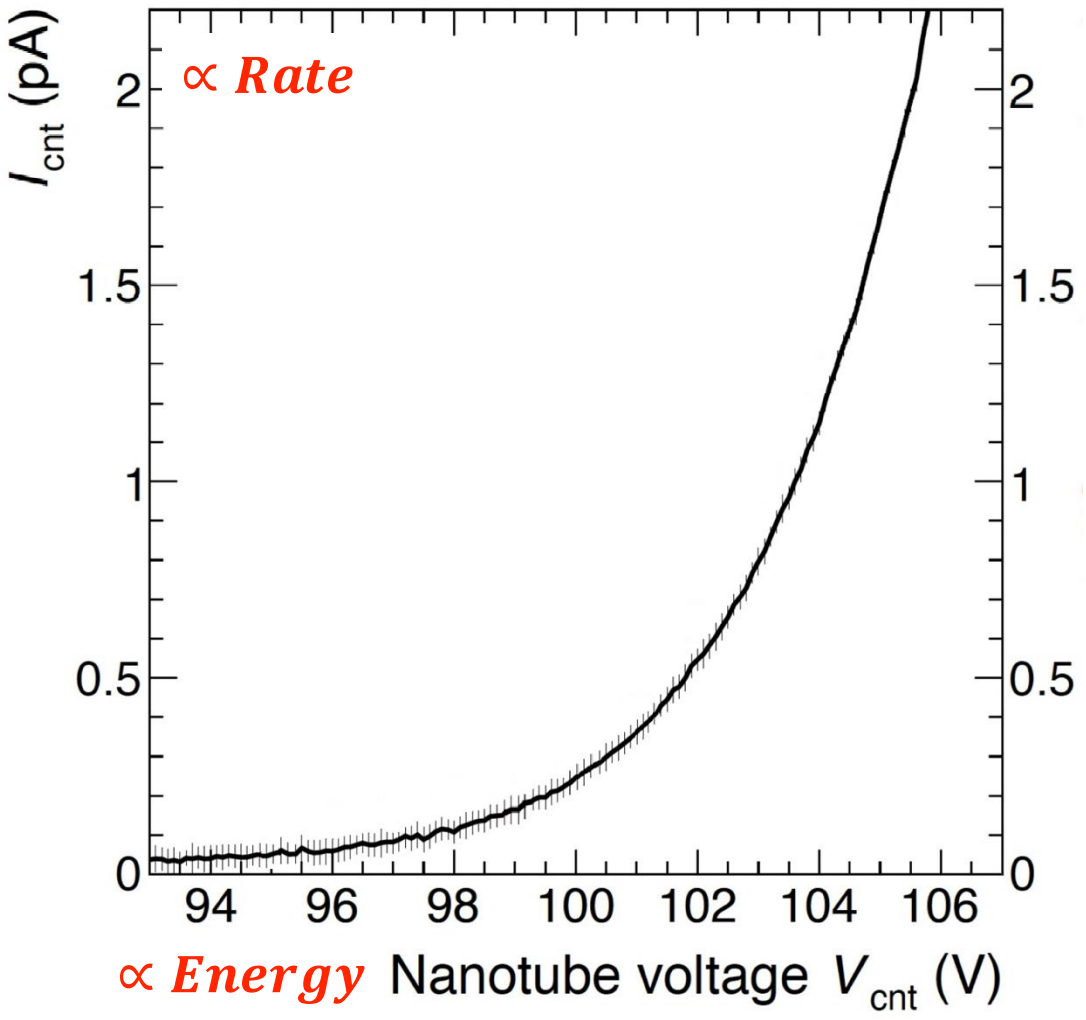

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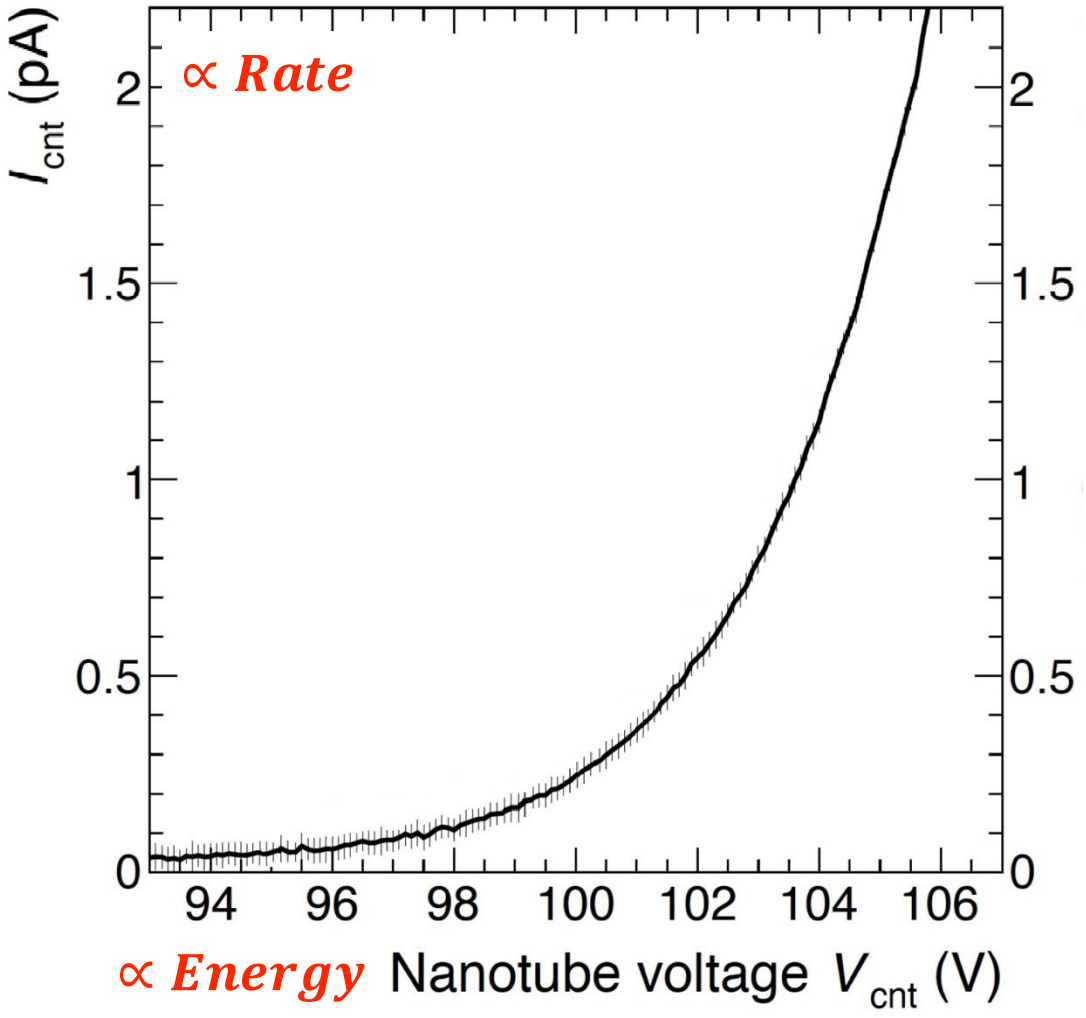
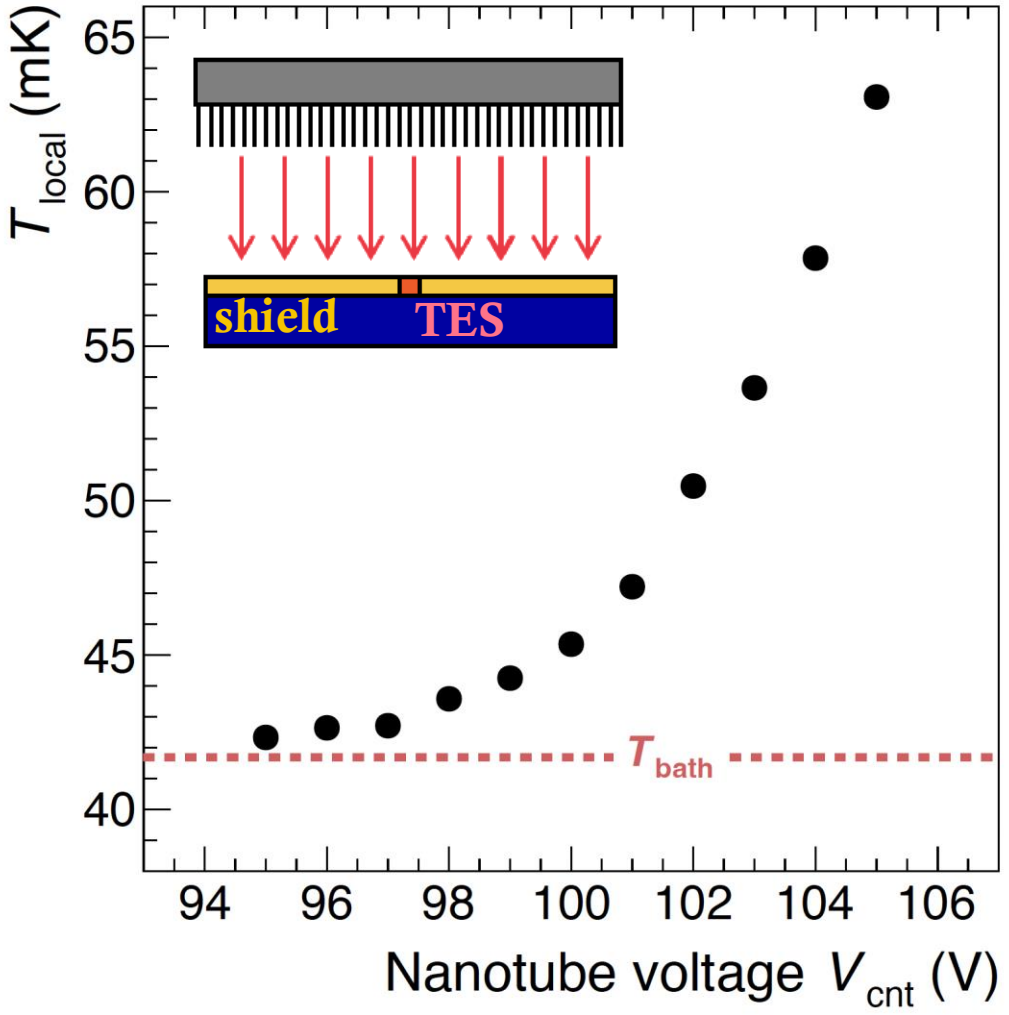
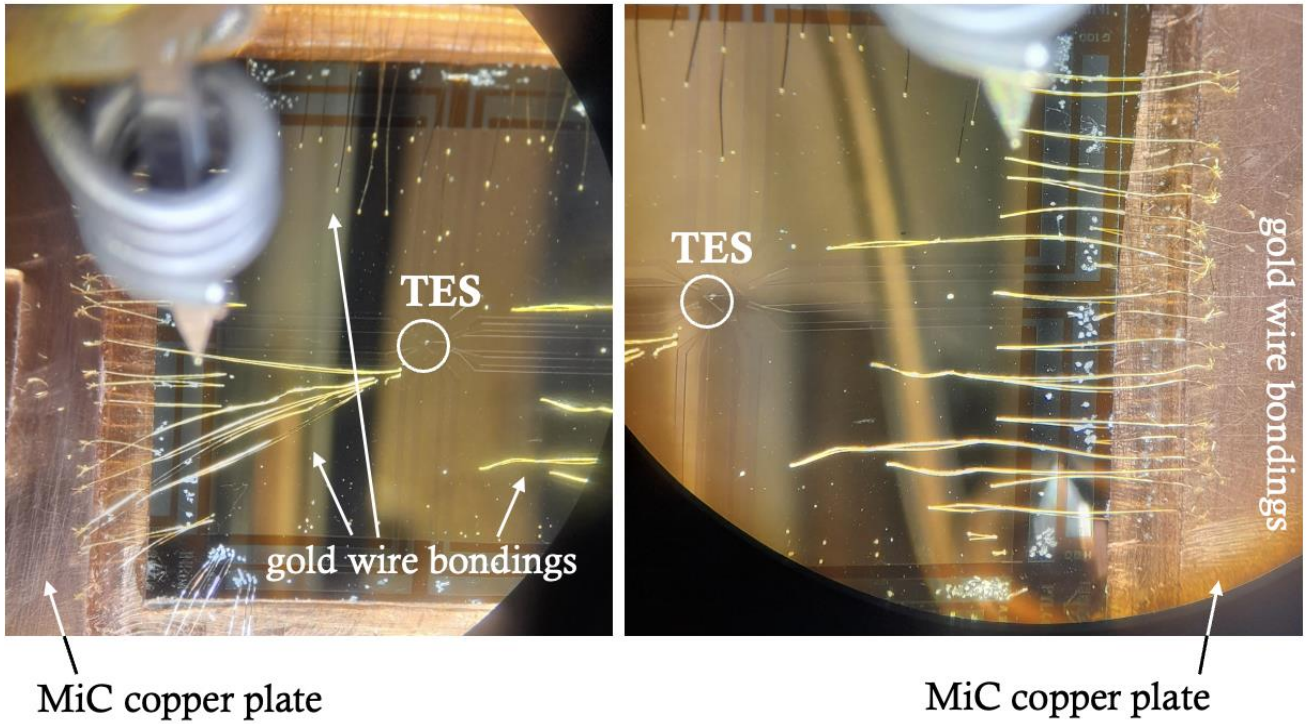


(TES in thermal contact with its gold shield)



14/11/2024: First Attempt

Adding **gold wire bondings** between the shield and the MiC plate seem to facilitate thermalization!



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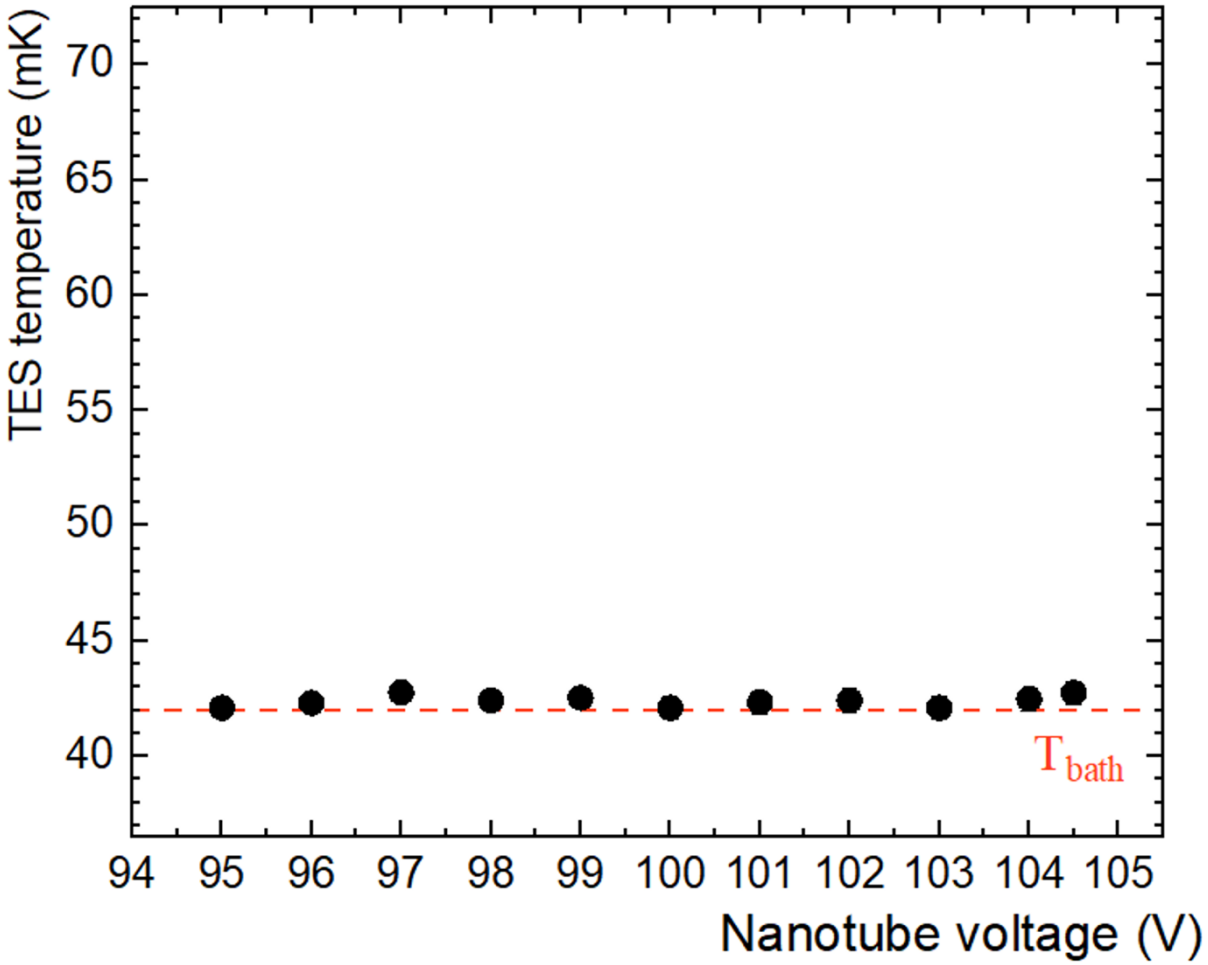

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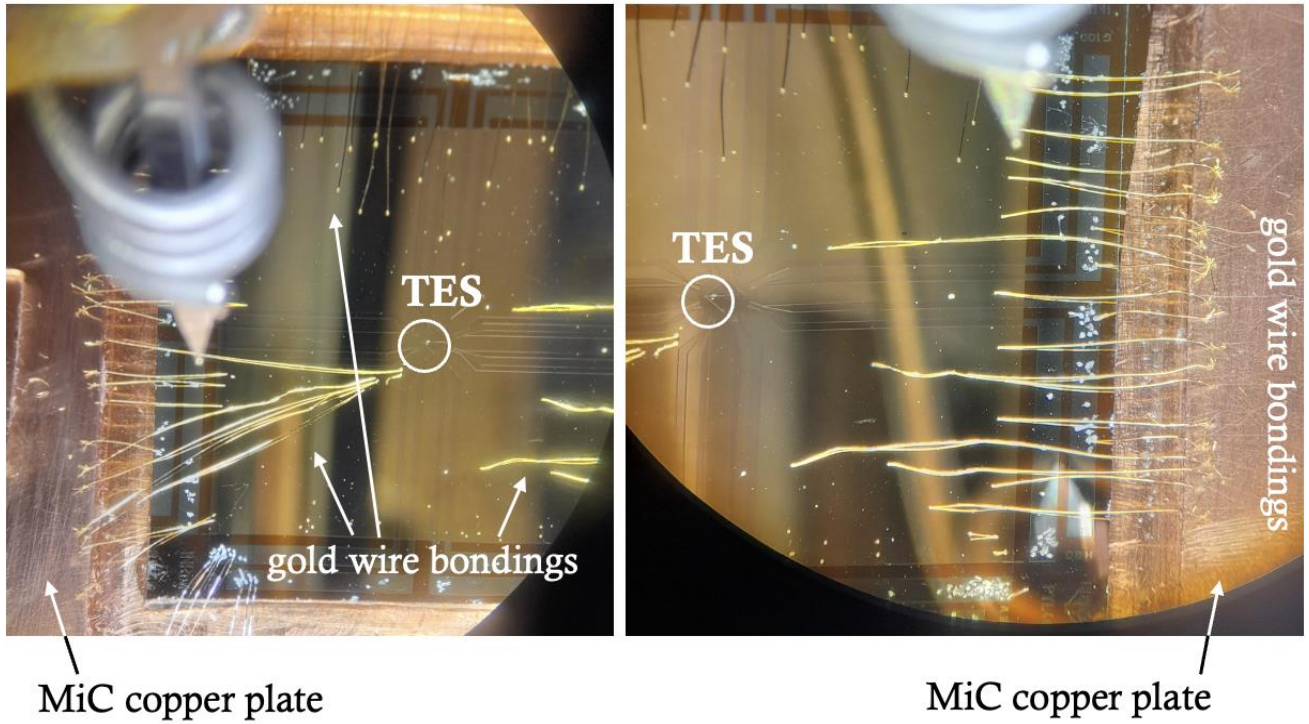

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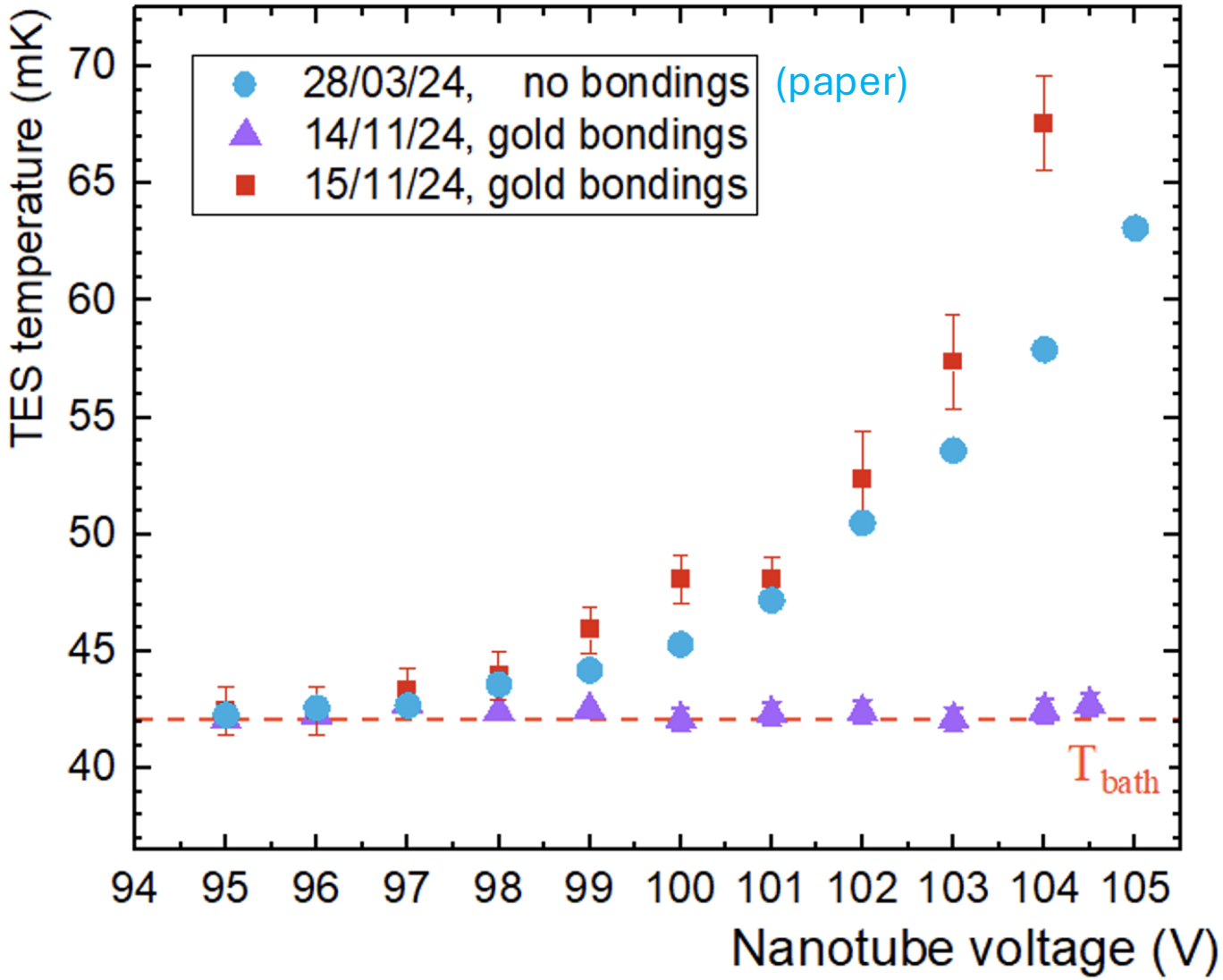

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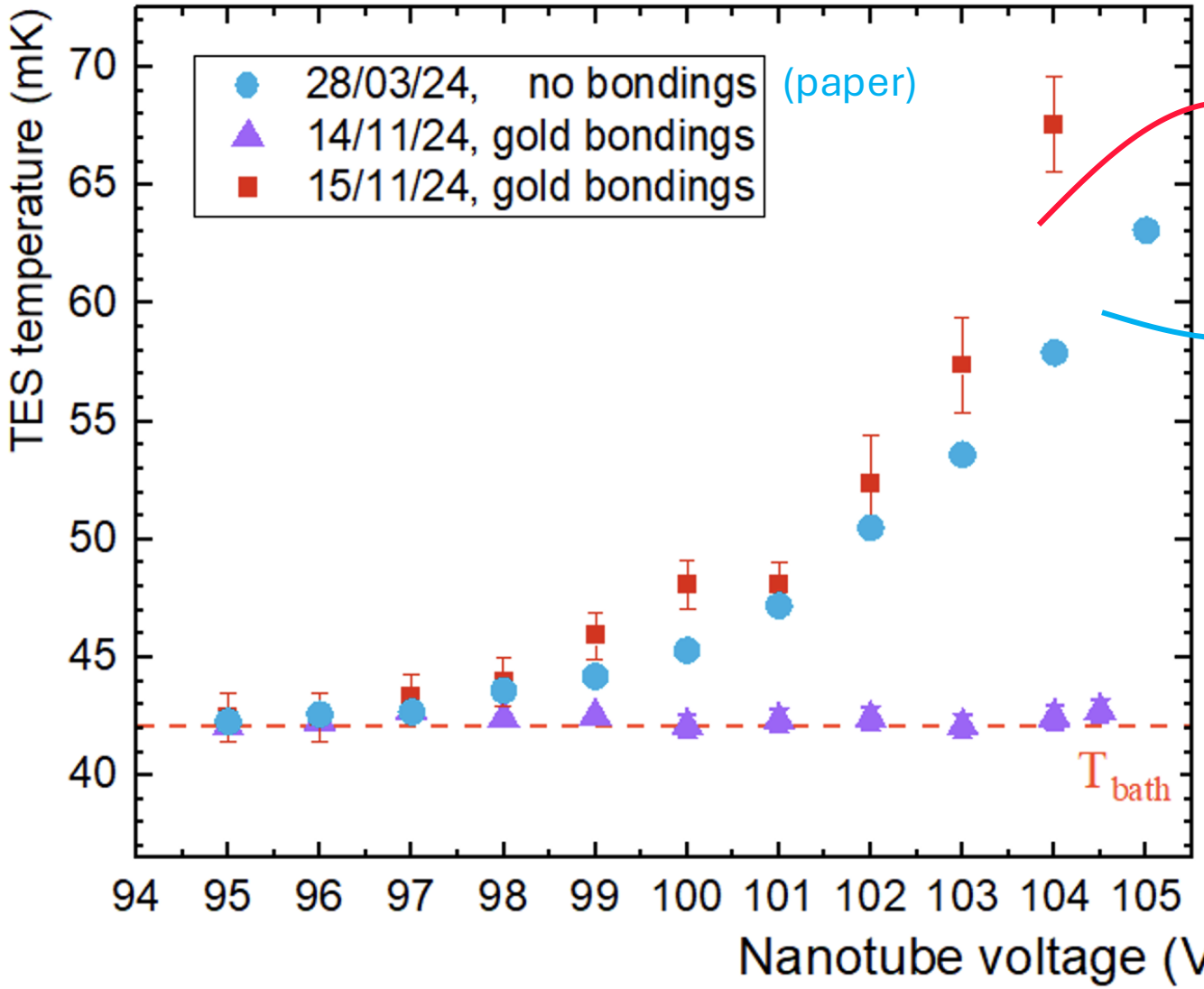

TES working in different conditions

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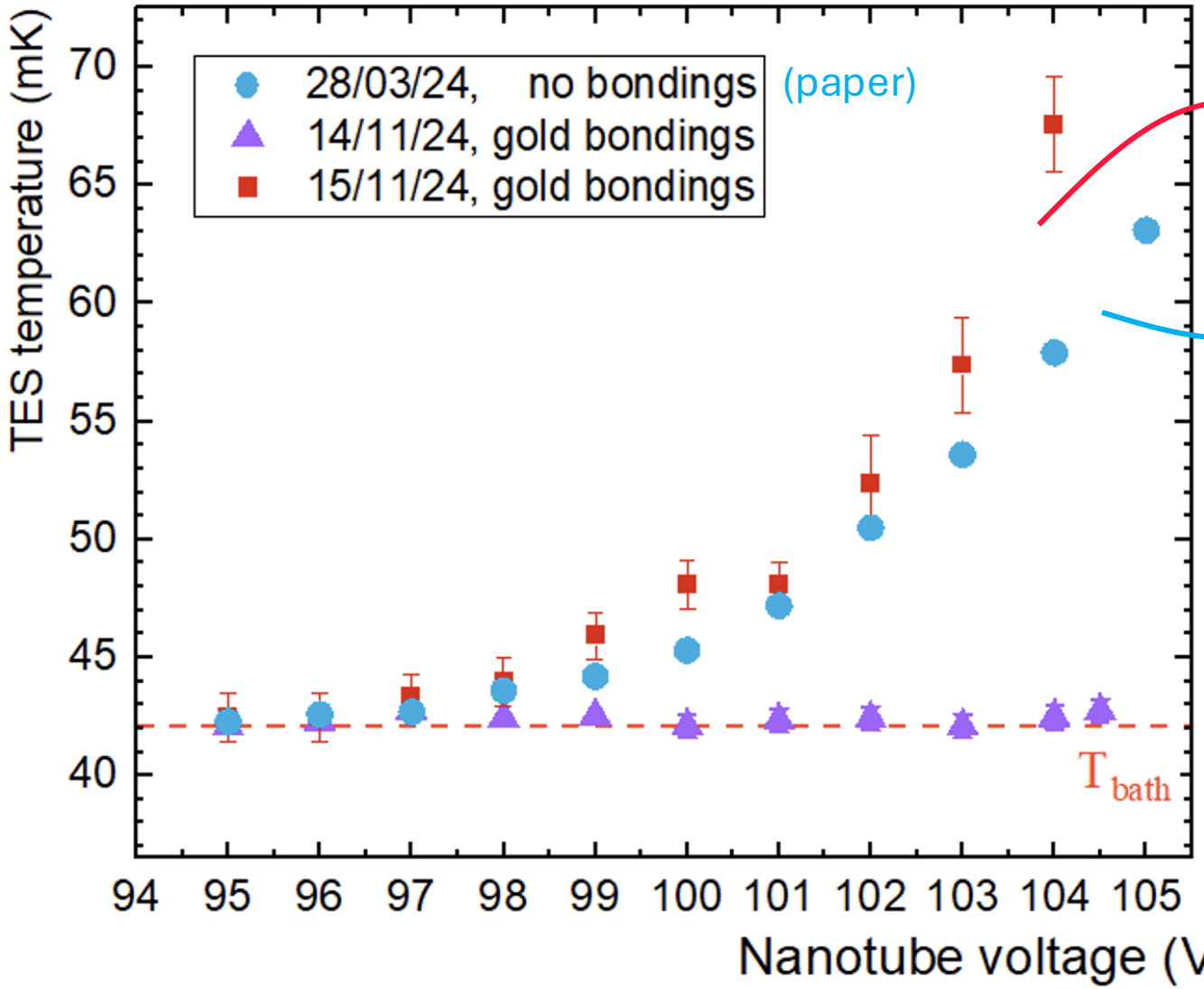

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- performance at different voltages **CANNOT** be compared
- no optical calibration available

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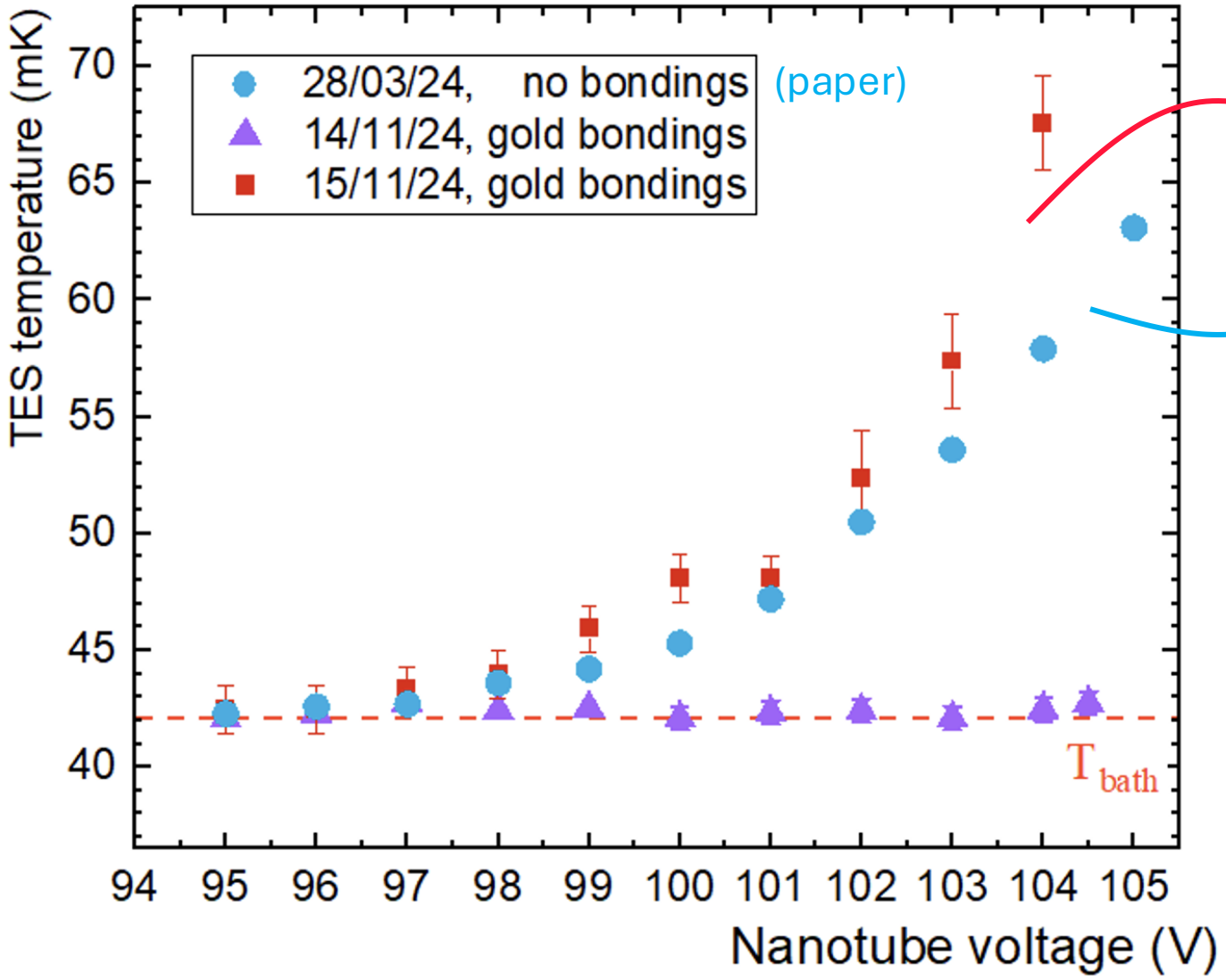

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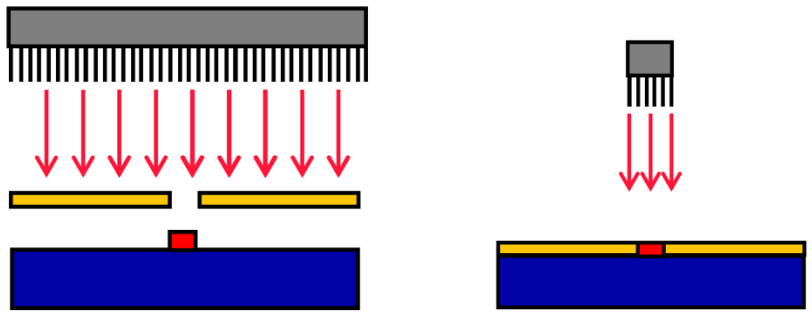
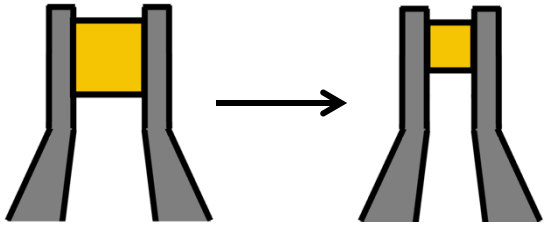
Ideas:



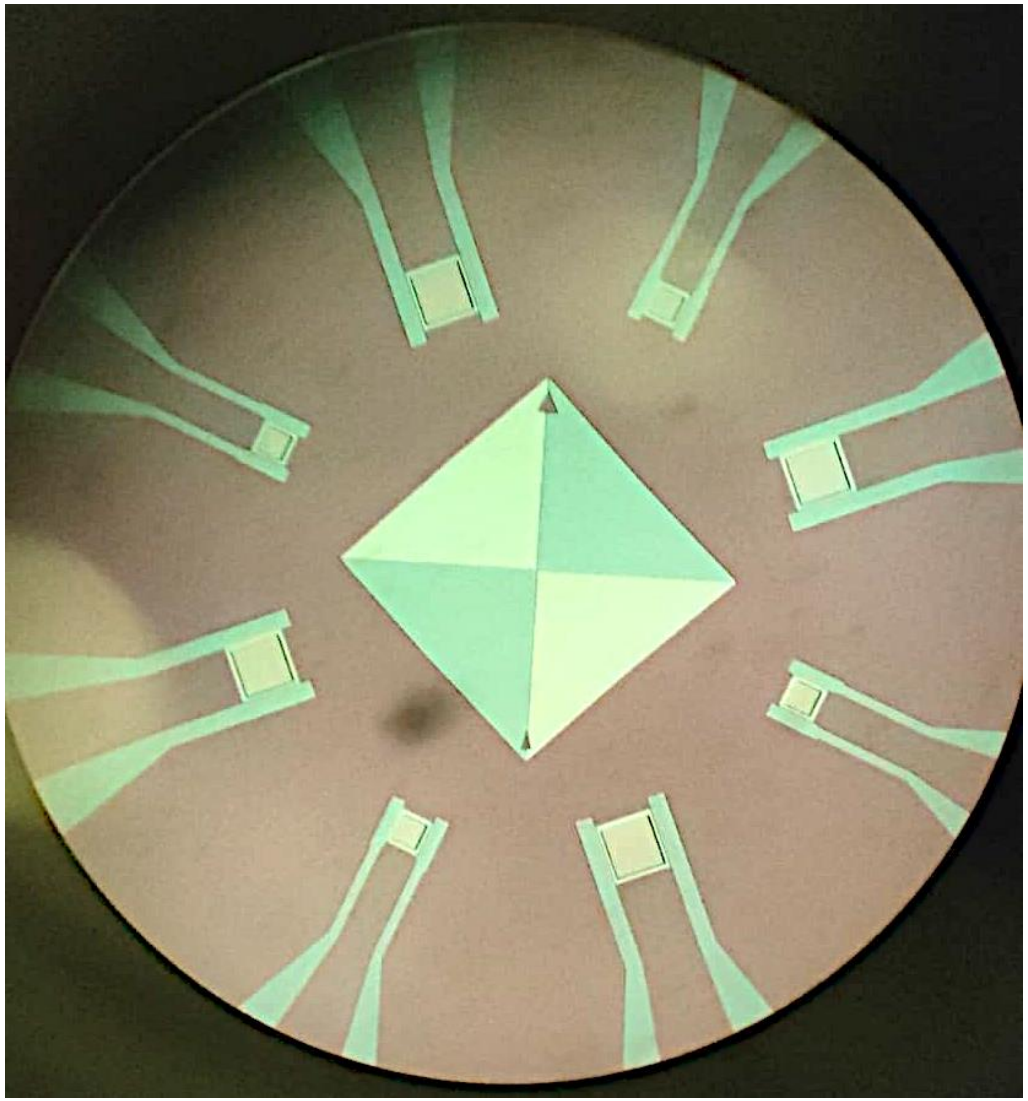
2. Energy Resolution

smaller TES



Smaller TESs Already Available

100 μm x 100 μm & **60 μm x 60 μm**



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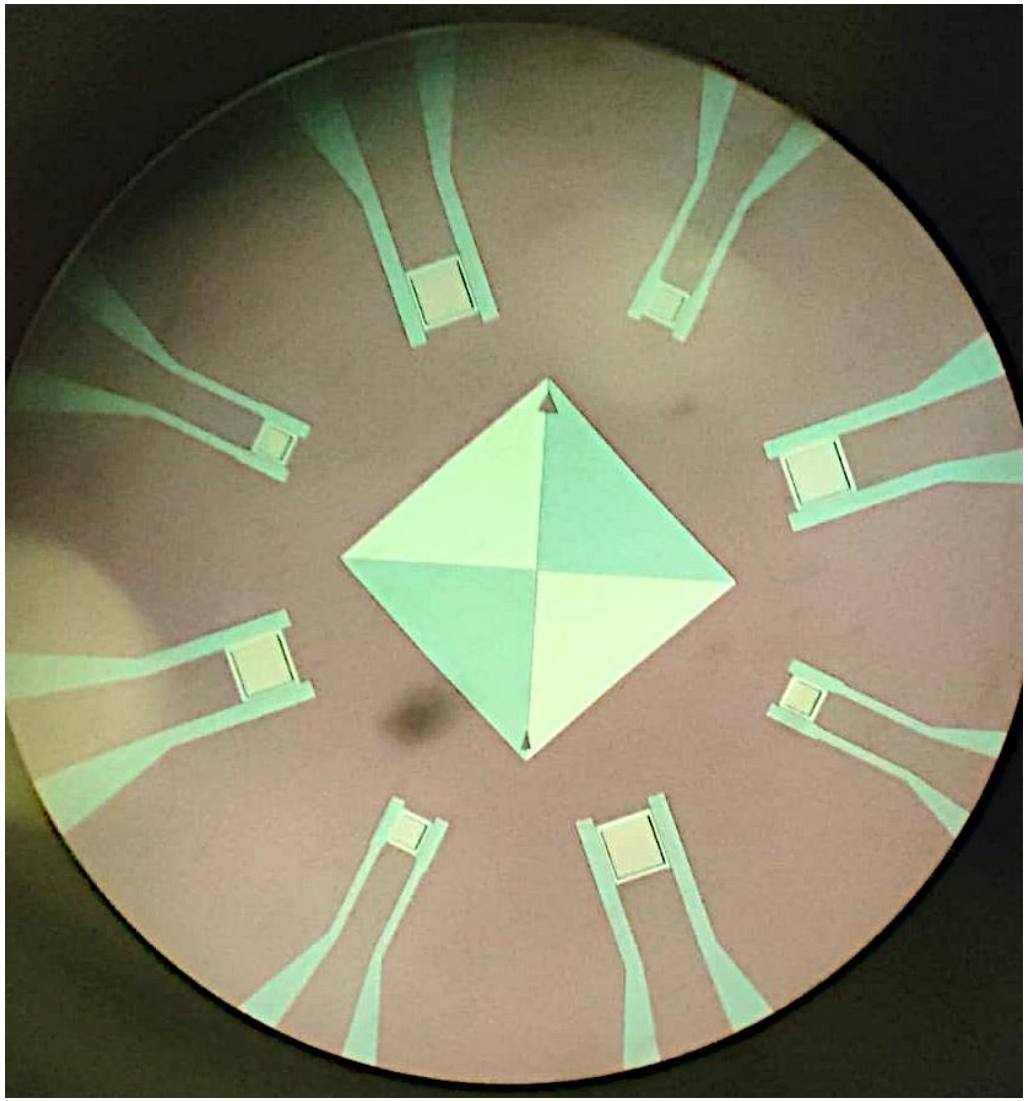

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transition sharpness

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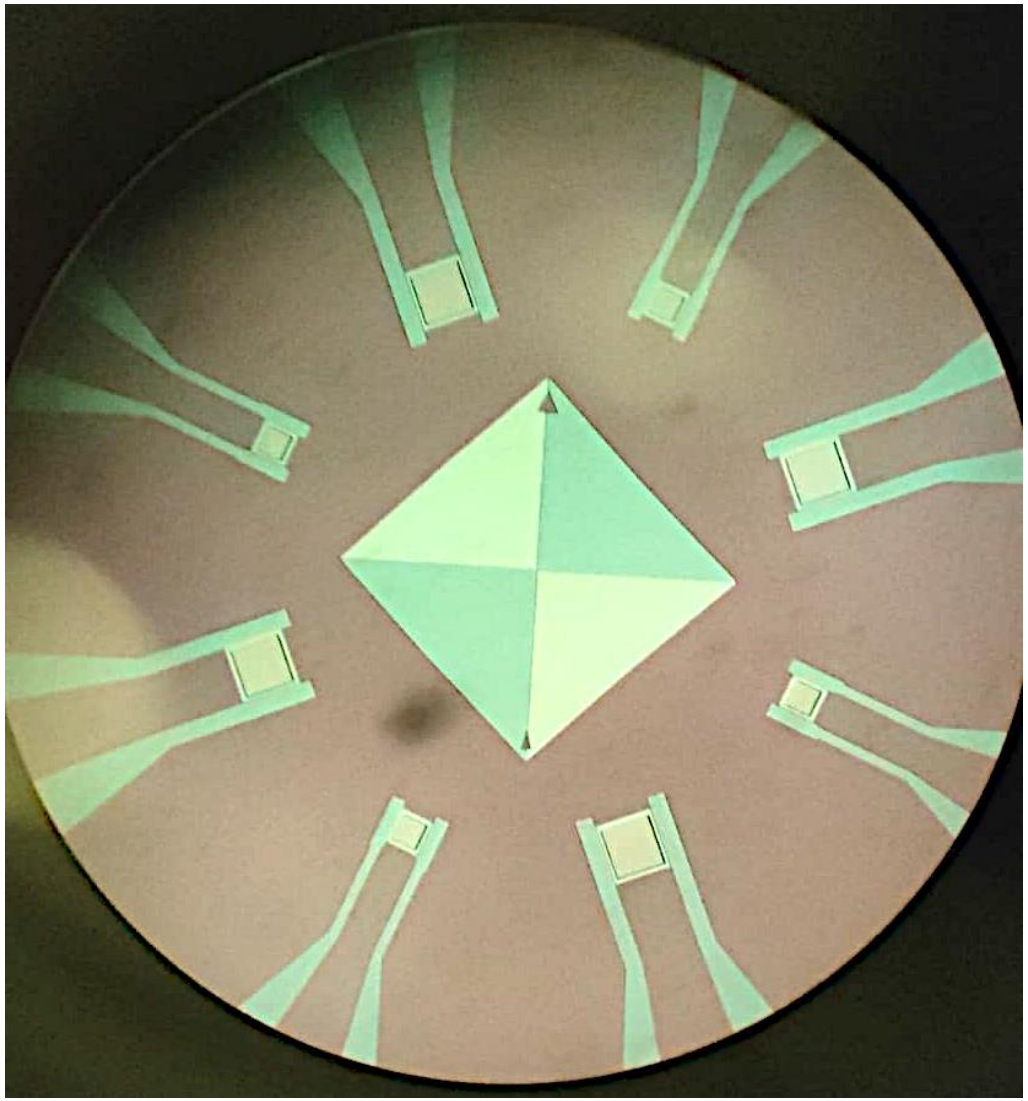

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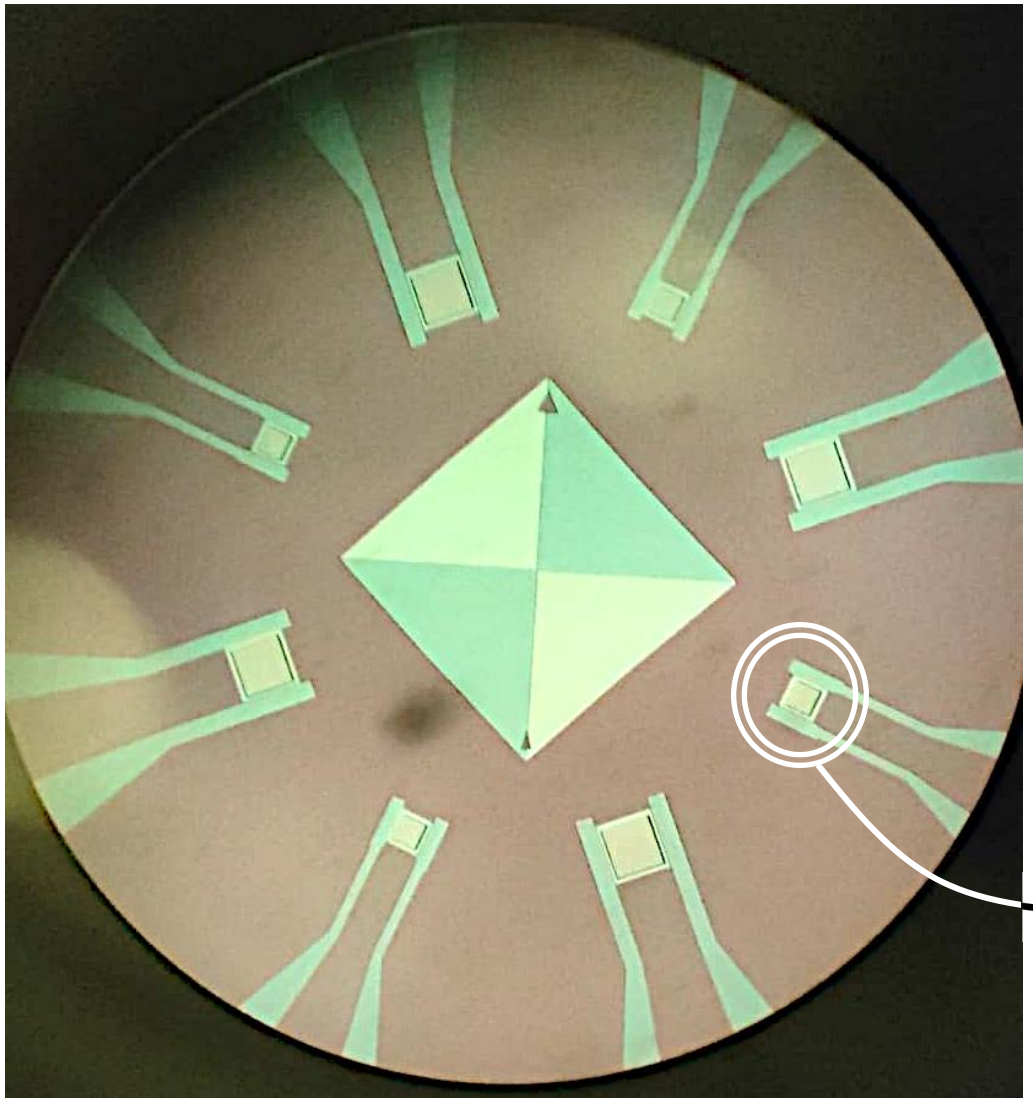

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electrons of 100 eV don't saturate these smaller devices!

3. Energy Resolution

noise reduction

New MiC Setup to Reduce Noise

- Too much noise in the signals: CNT power supply and **'flying wires'** between TES and SQUID
- New MiC 2.0 designed:

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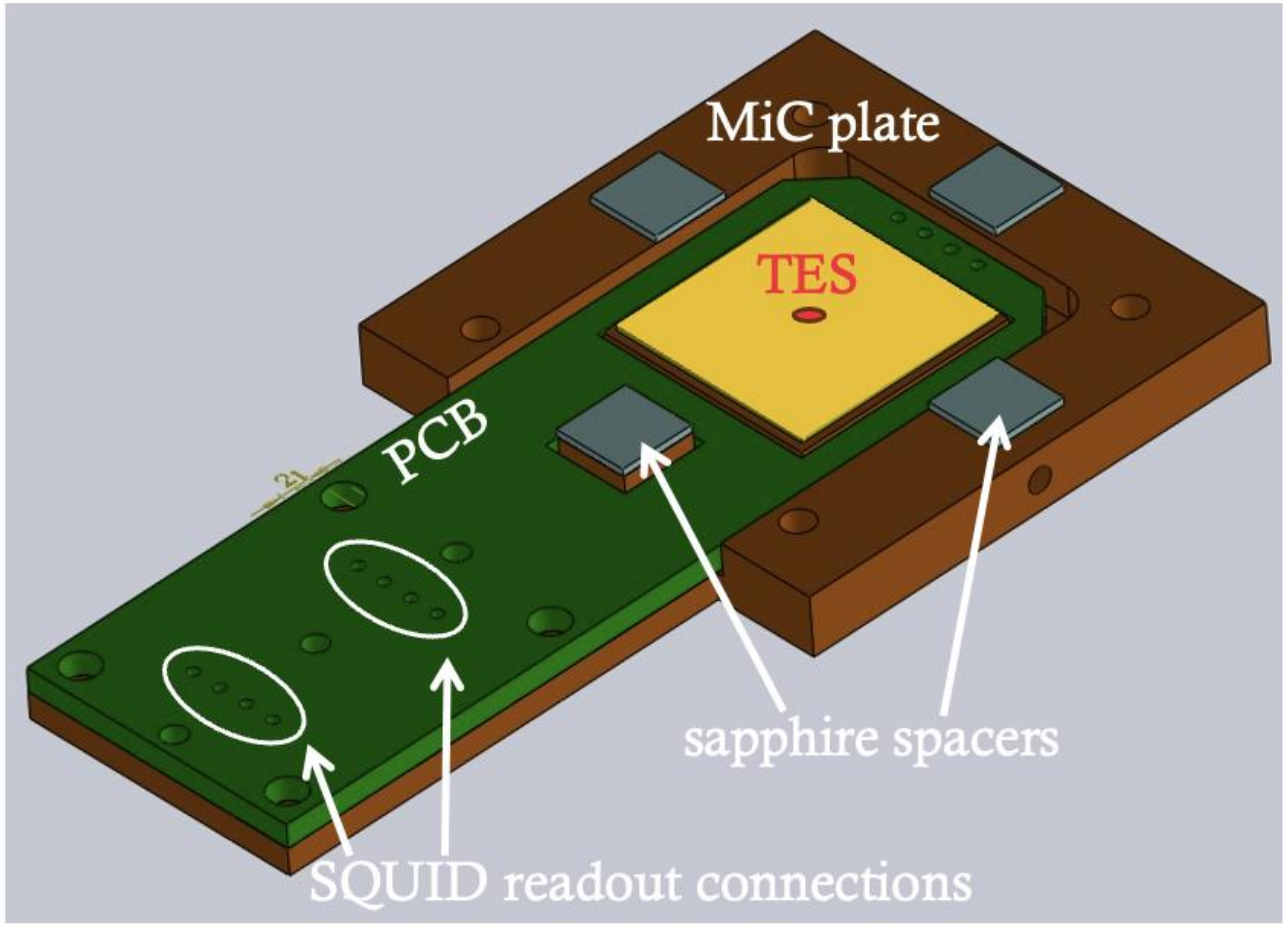

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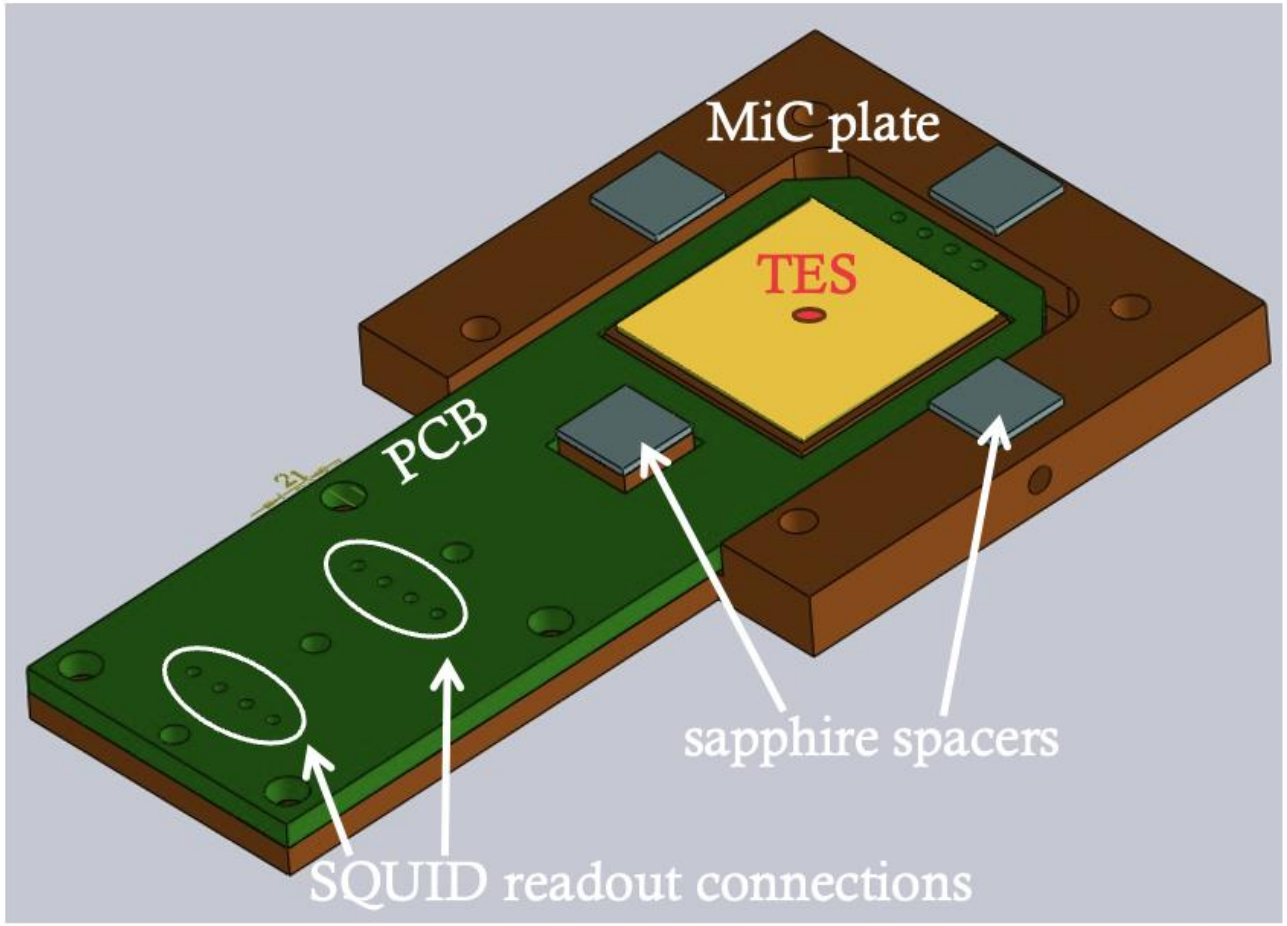
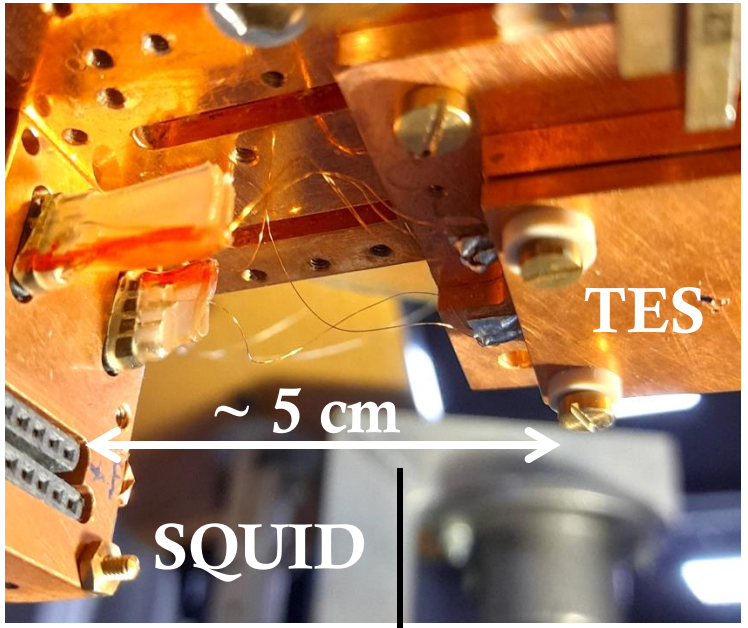
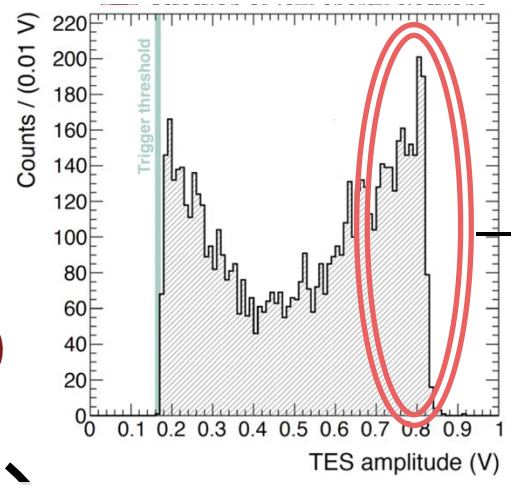


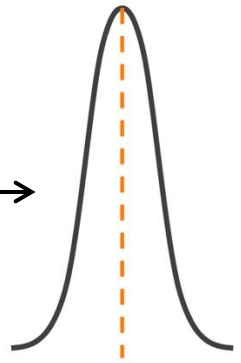


distance between TES and SQUID becomes ~ 0 cm with MiC 2.0!

what happens to electrons?

detection of low-energy electrons





reduce left tail in the histogram of the signal amplitudes

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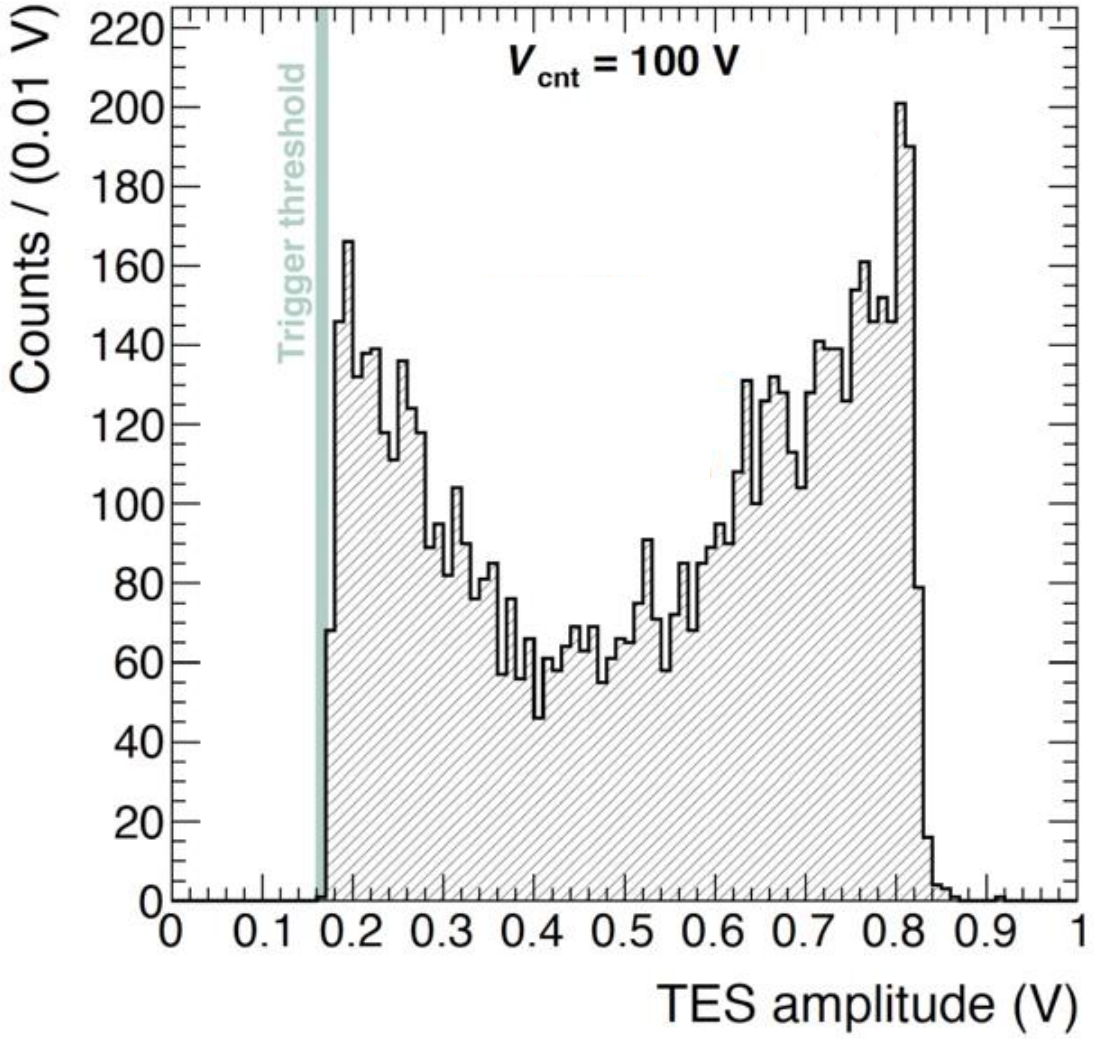

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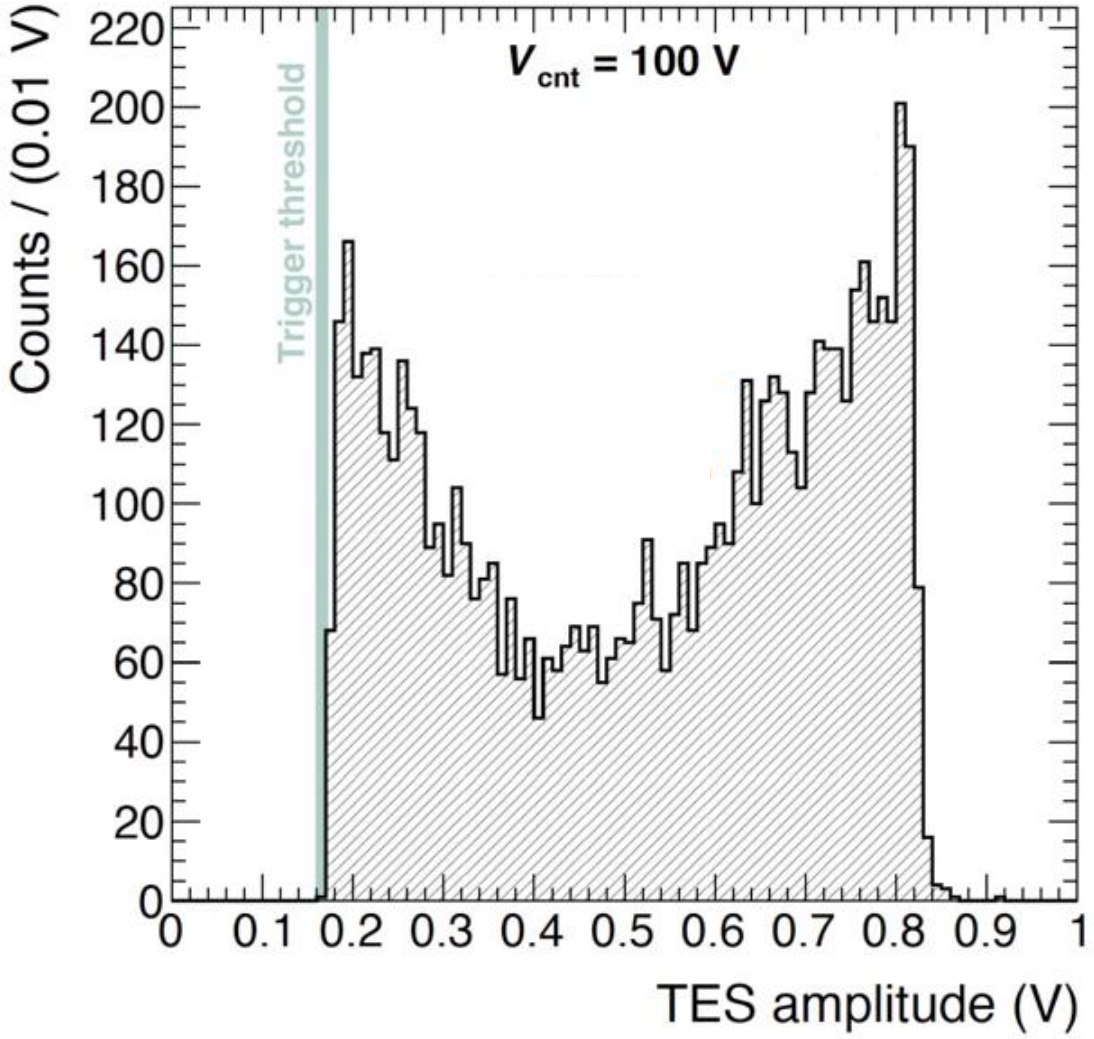

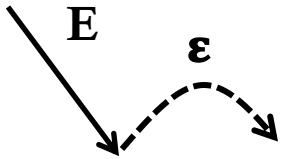

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electron of kinetic energy E produces a secondary electron of kinetic energy **ε < E**
⇒ deposited energy E_{dep} = E - **ε**

What Happens to Electrons?

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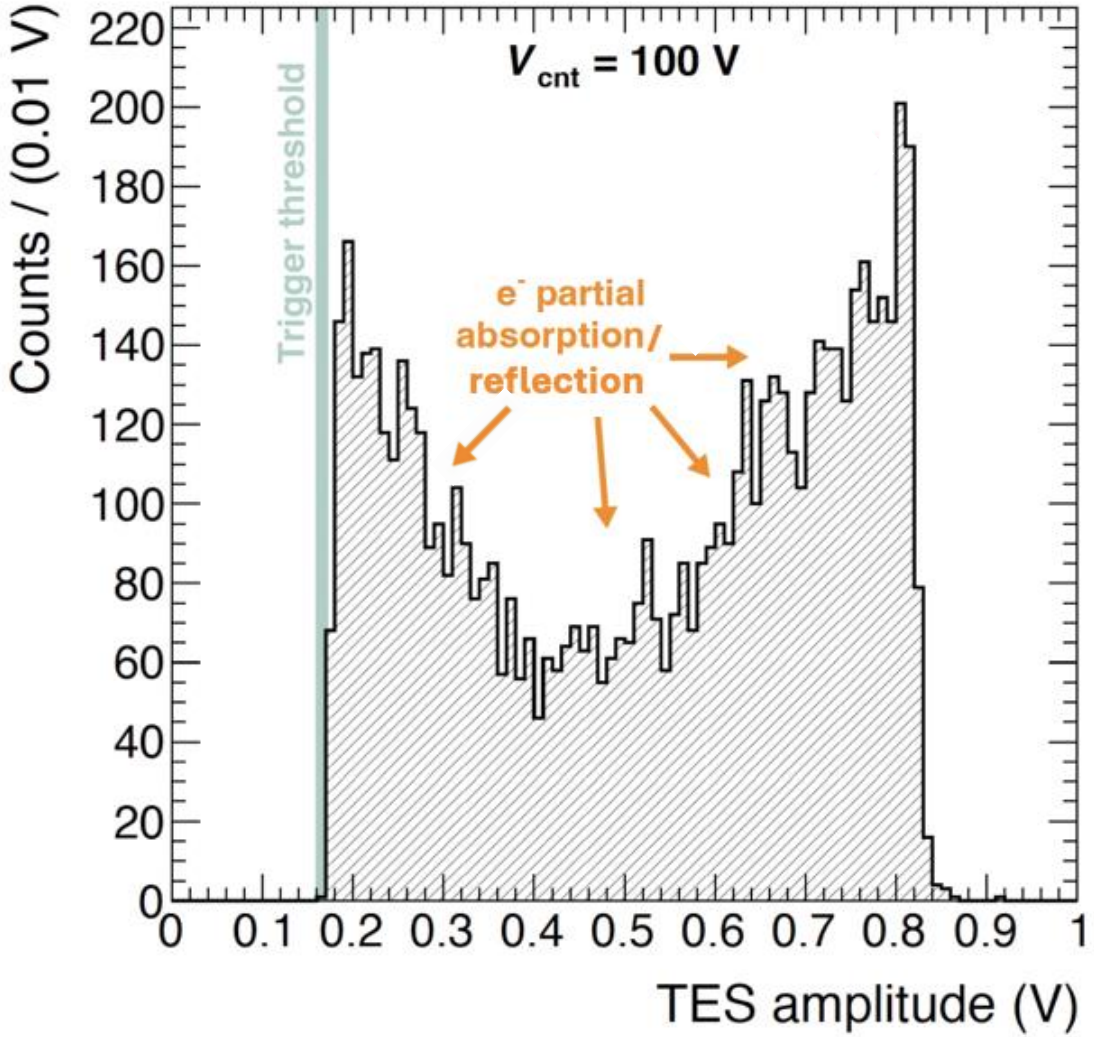

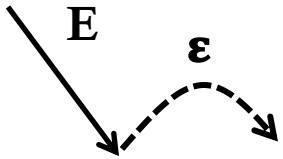

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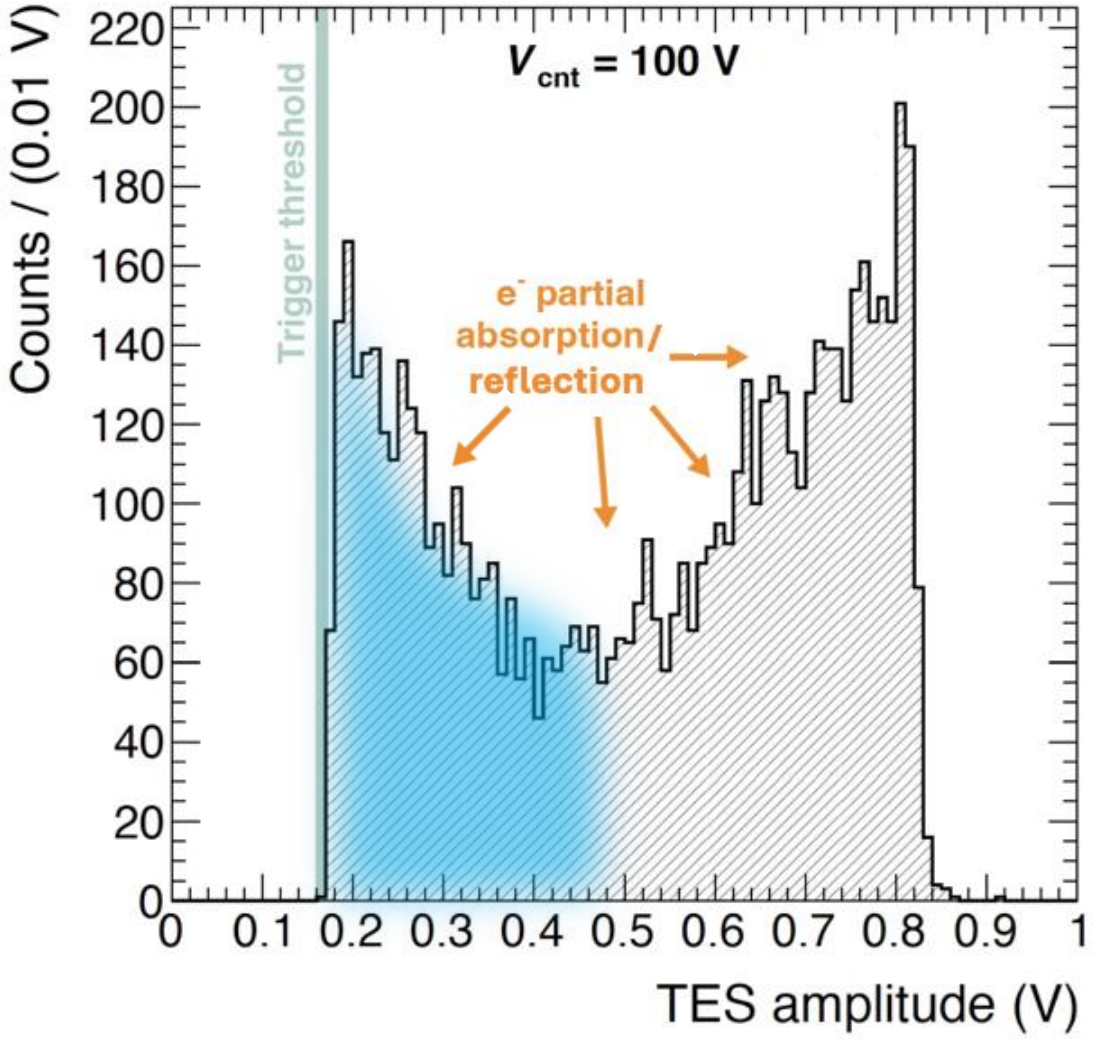

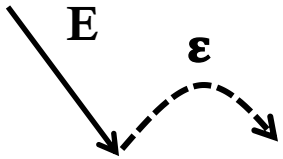

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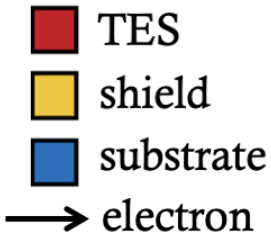
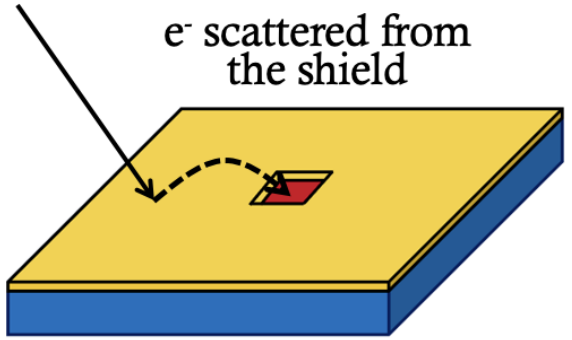
⇒ deposited energy E_{dep} = E - **ε**

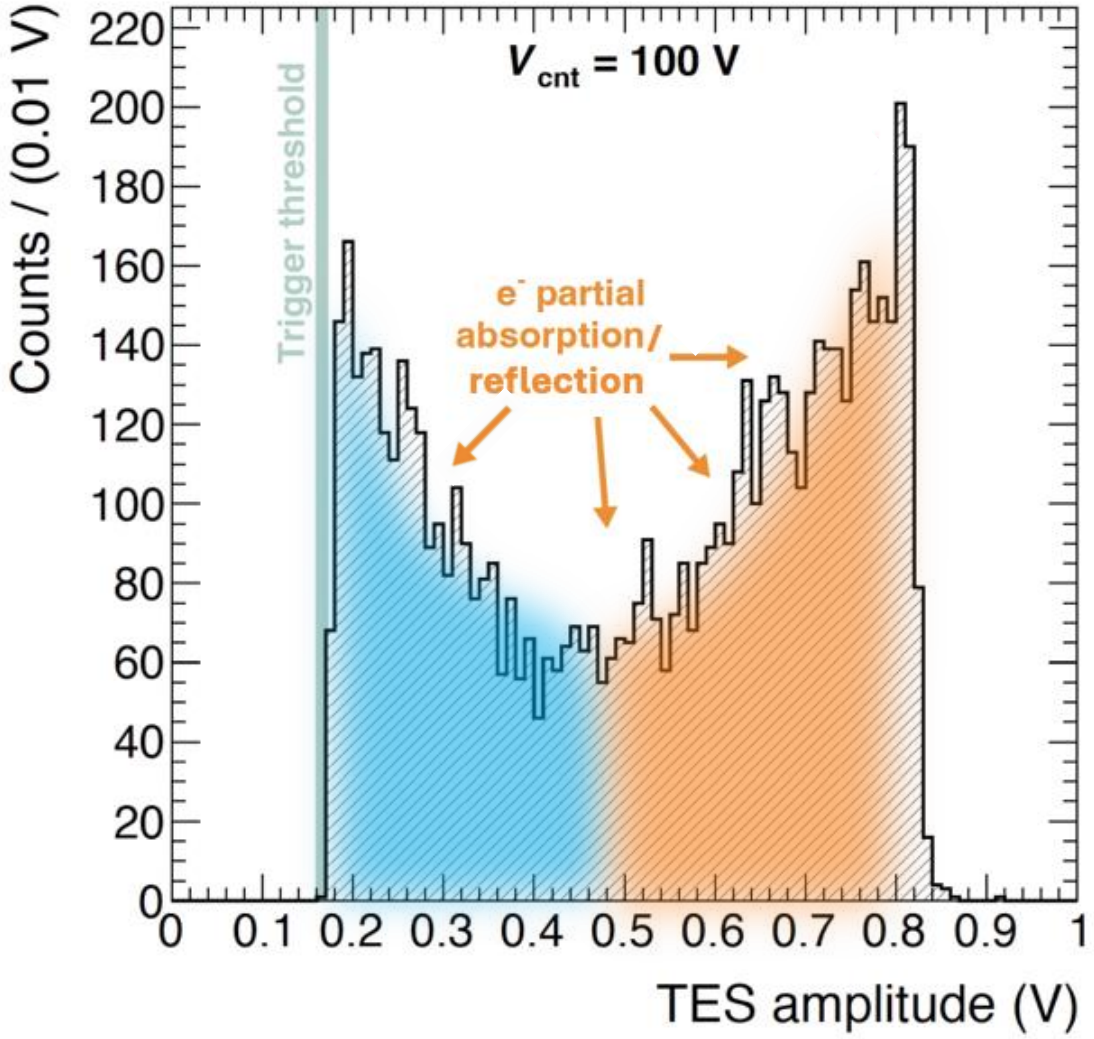


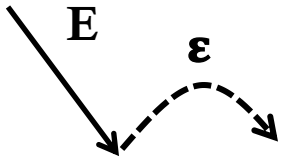


$E_{dep}^{TES} = \varepsilon$

What Happens to Electrons?

Signal amplitude distribution





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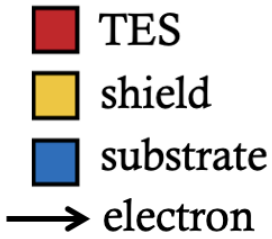

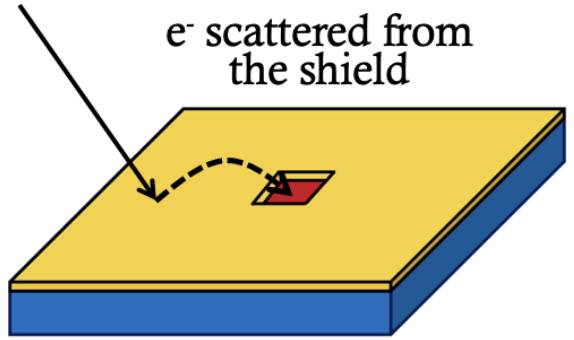

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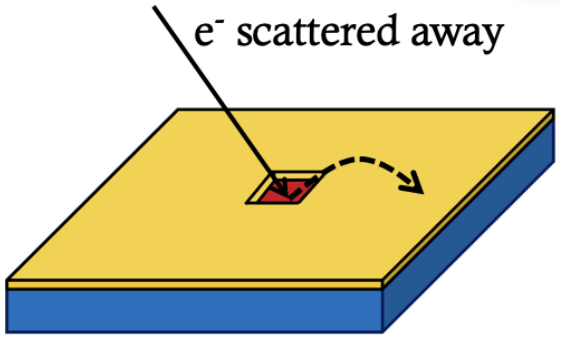

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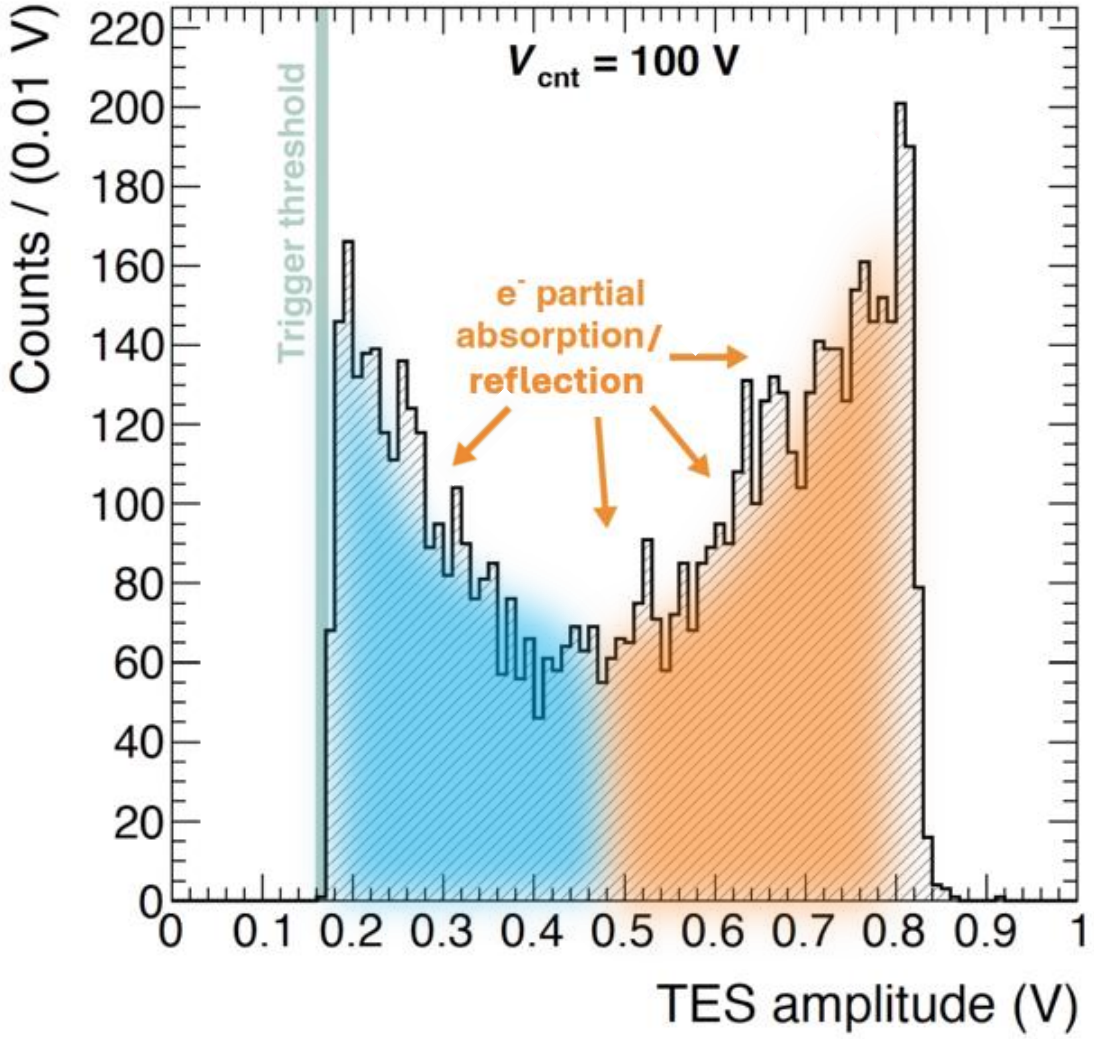
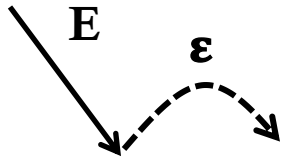
What Happens to Electrons?

Signal amplitude distribution





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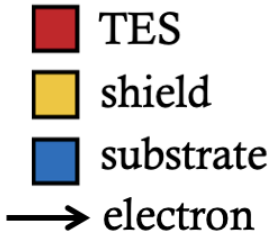
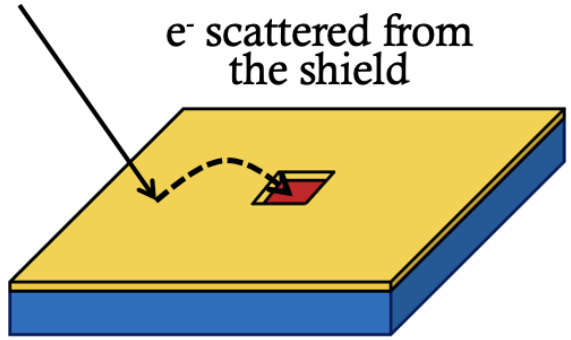
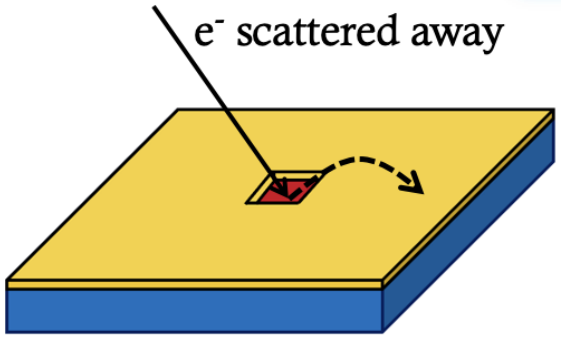
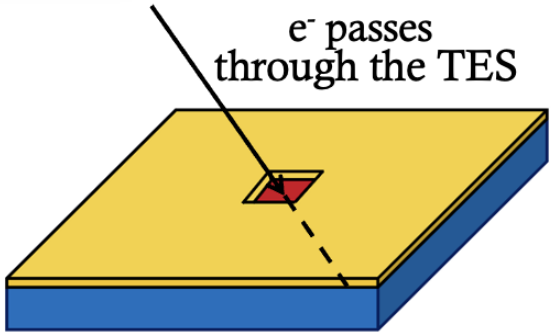




$E_{dep}^{TES} = \varepsilon$



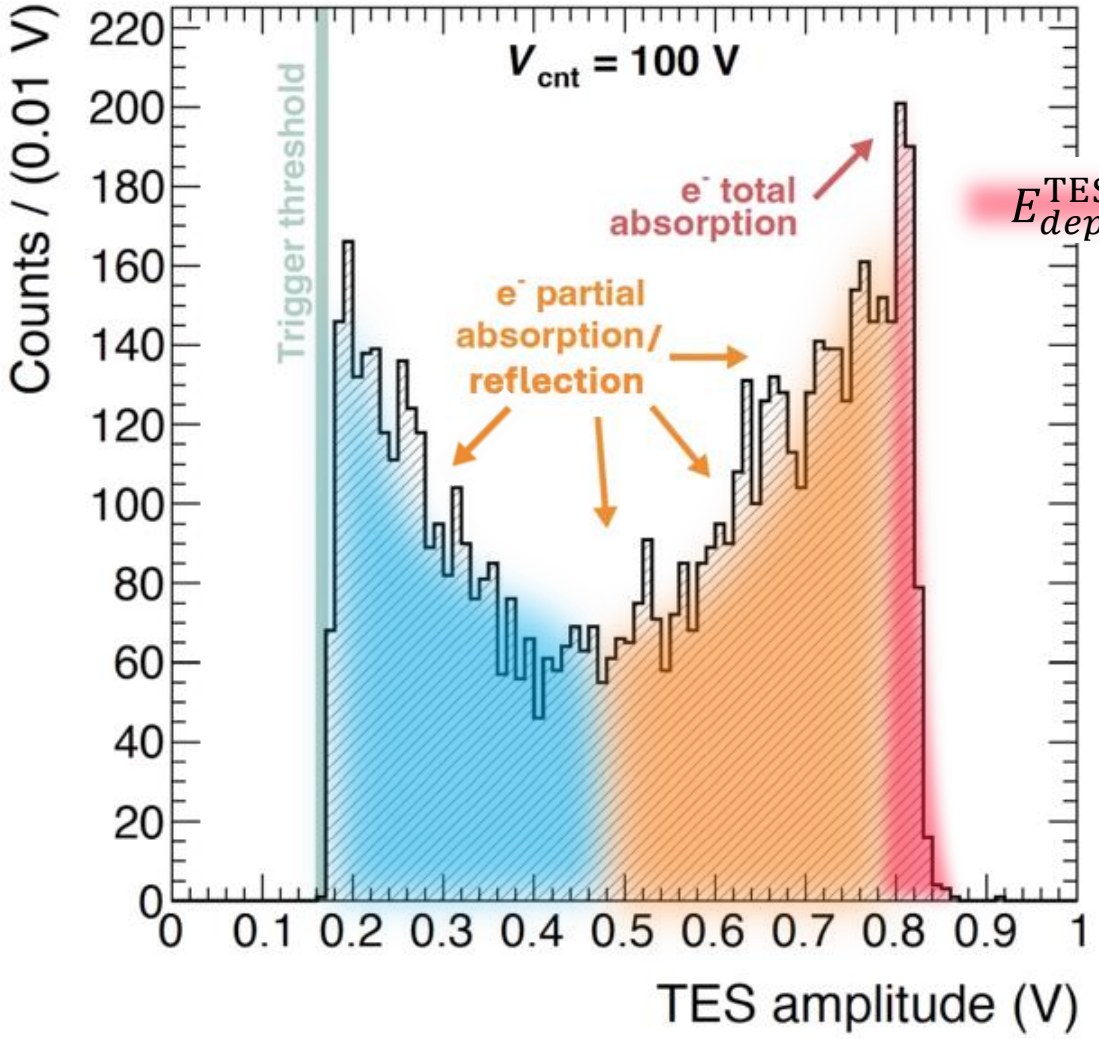
$E_{dep}^{TES} = E - \varepsilon$

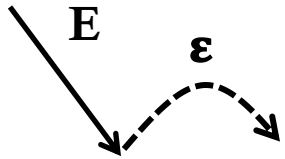


$E_{dep}^{TES} = E - E_{KIN}^{fin}$

What Happens to Electrons?

Signal amplitude distribution





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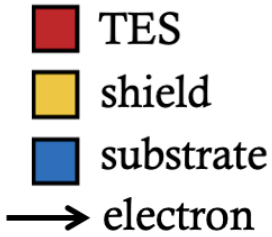
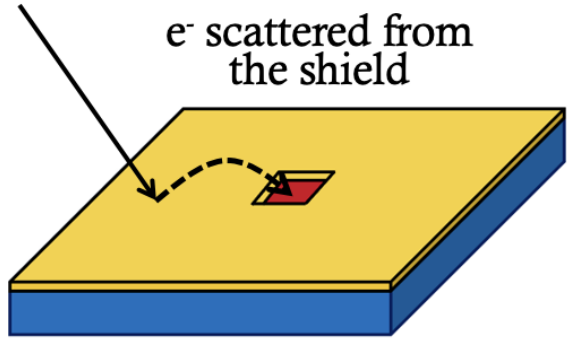
$E_{dep}^{TES} = E$





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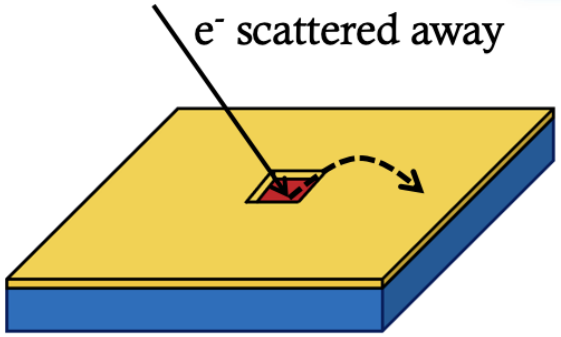

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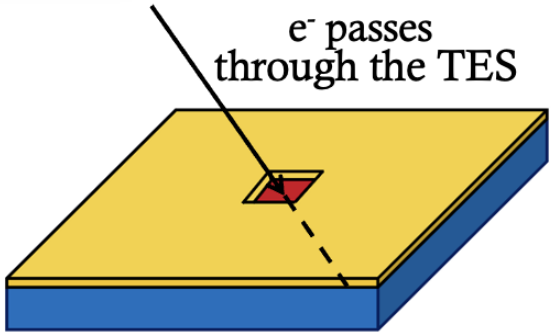
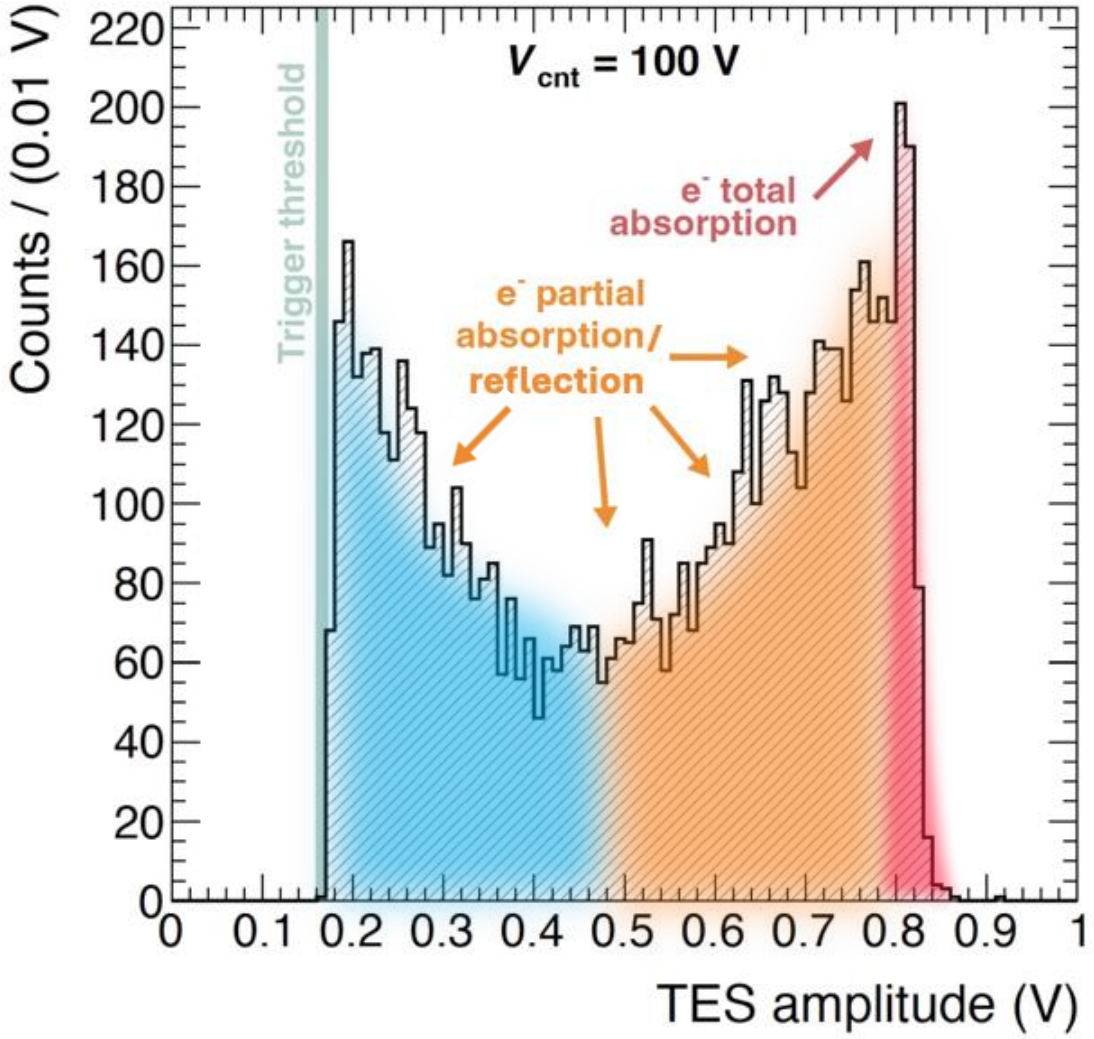


$E_{dep}^{TES} = E - E_{KIN}^{fin}$

What Happens to Electrons?

Signal amplitude distribution



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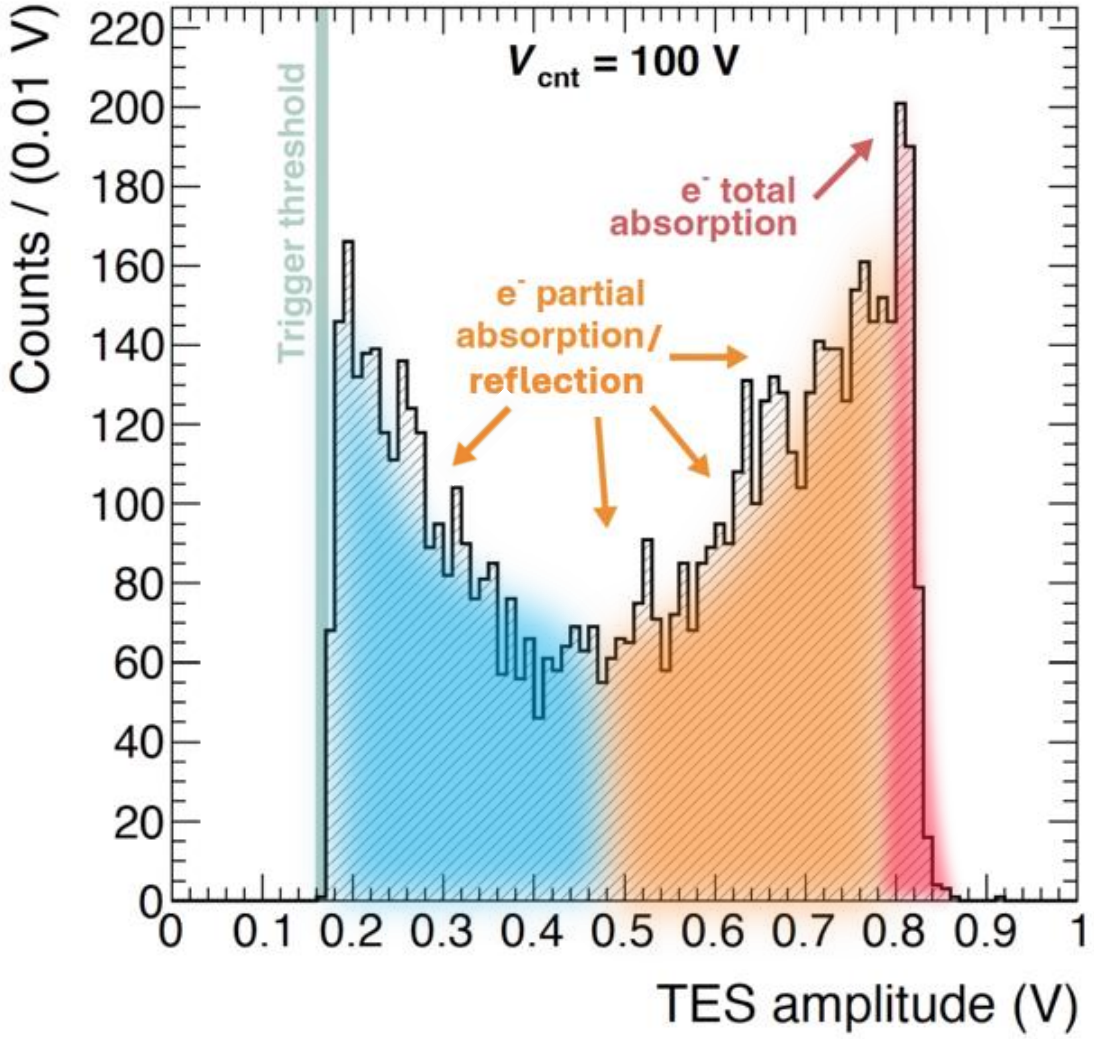
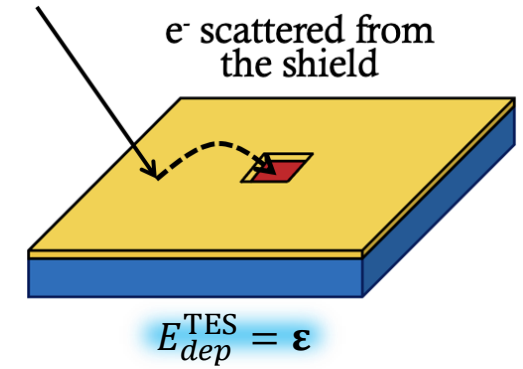
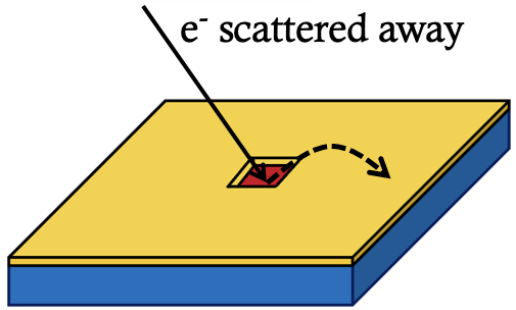




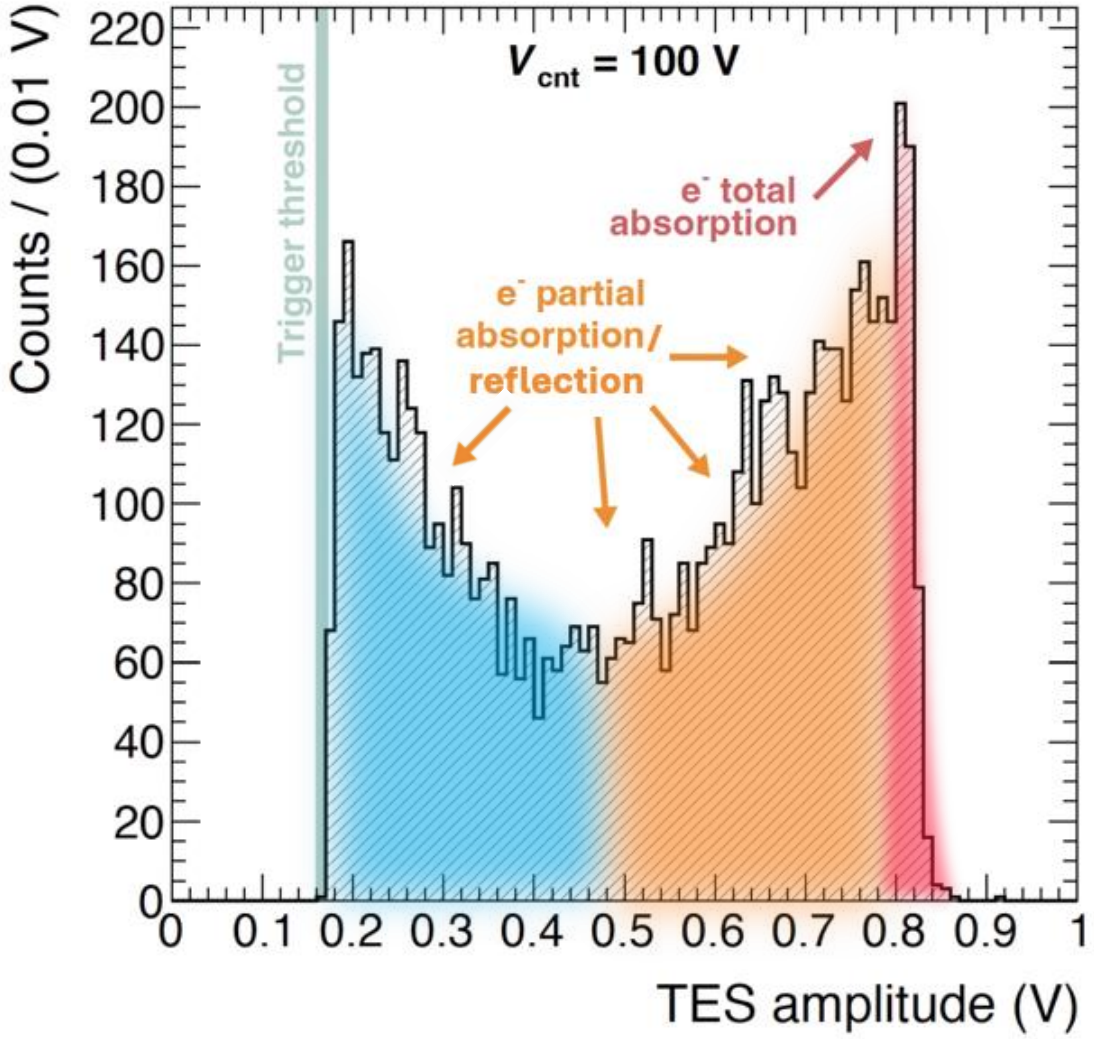
$E_{dep}^{TES} = \boldsymbol{\varepsilon}$

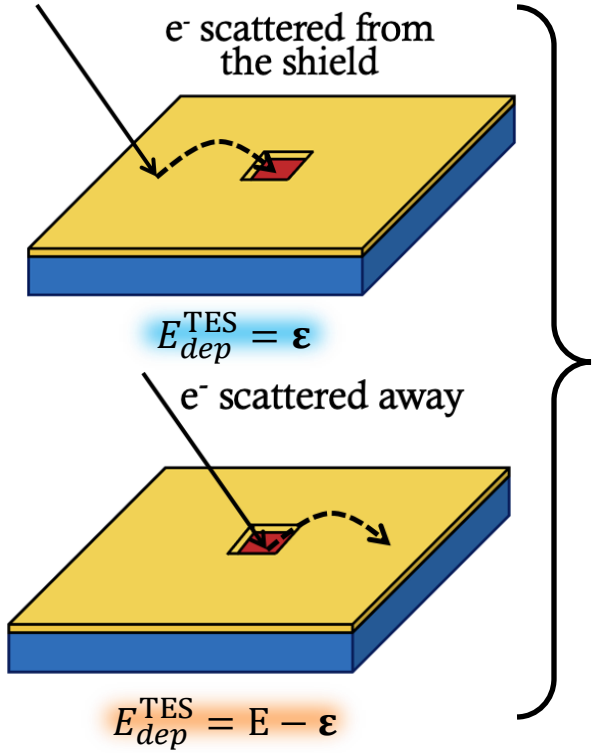


$E_{dep}^{TES} = \mathrm{E} - \boldsymbol{\varepsilon}$

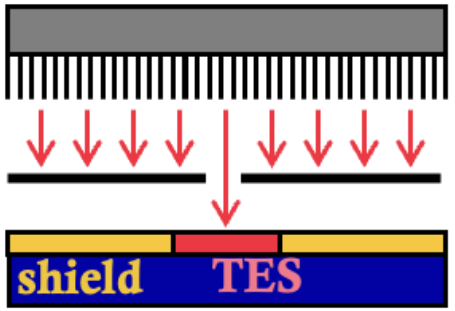
What Happens to Electrons?

Signal amplitude distribution





pinhole smaller than TES



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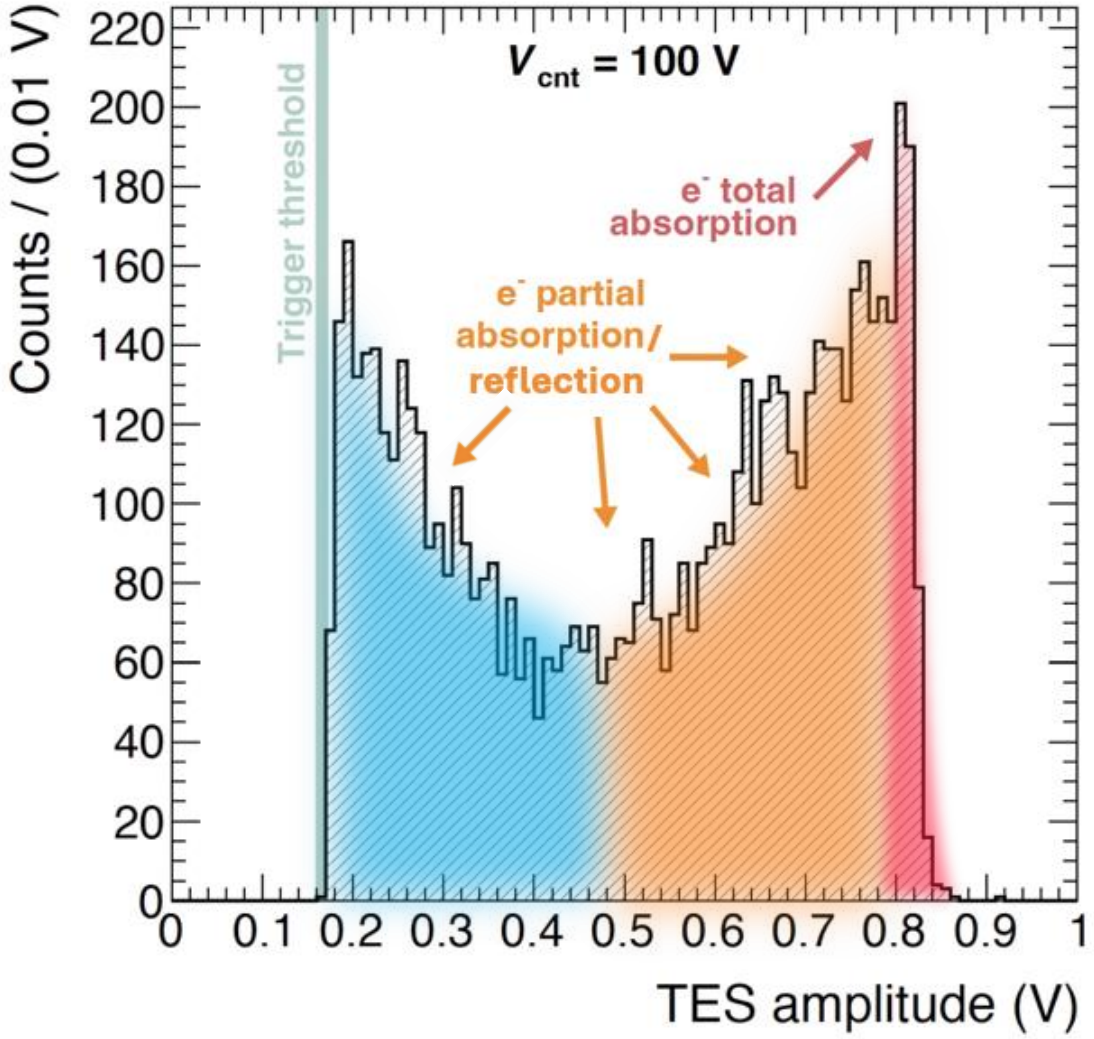

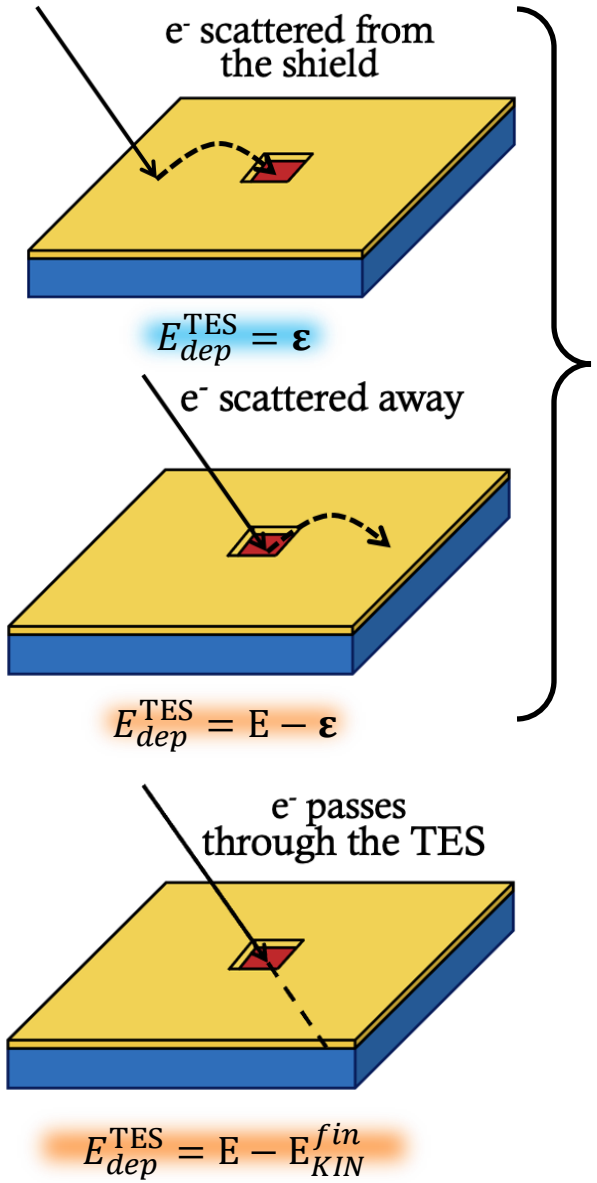

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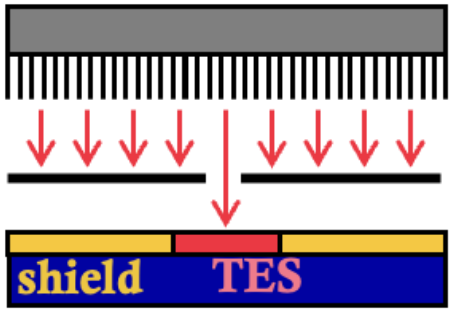

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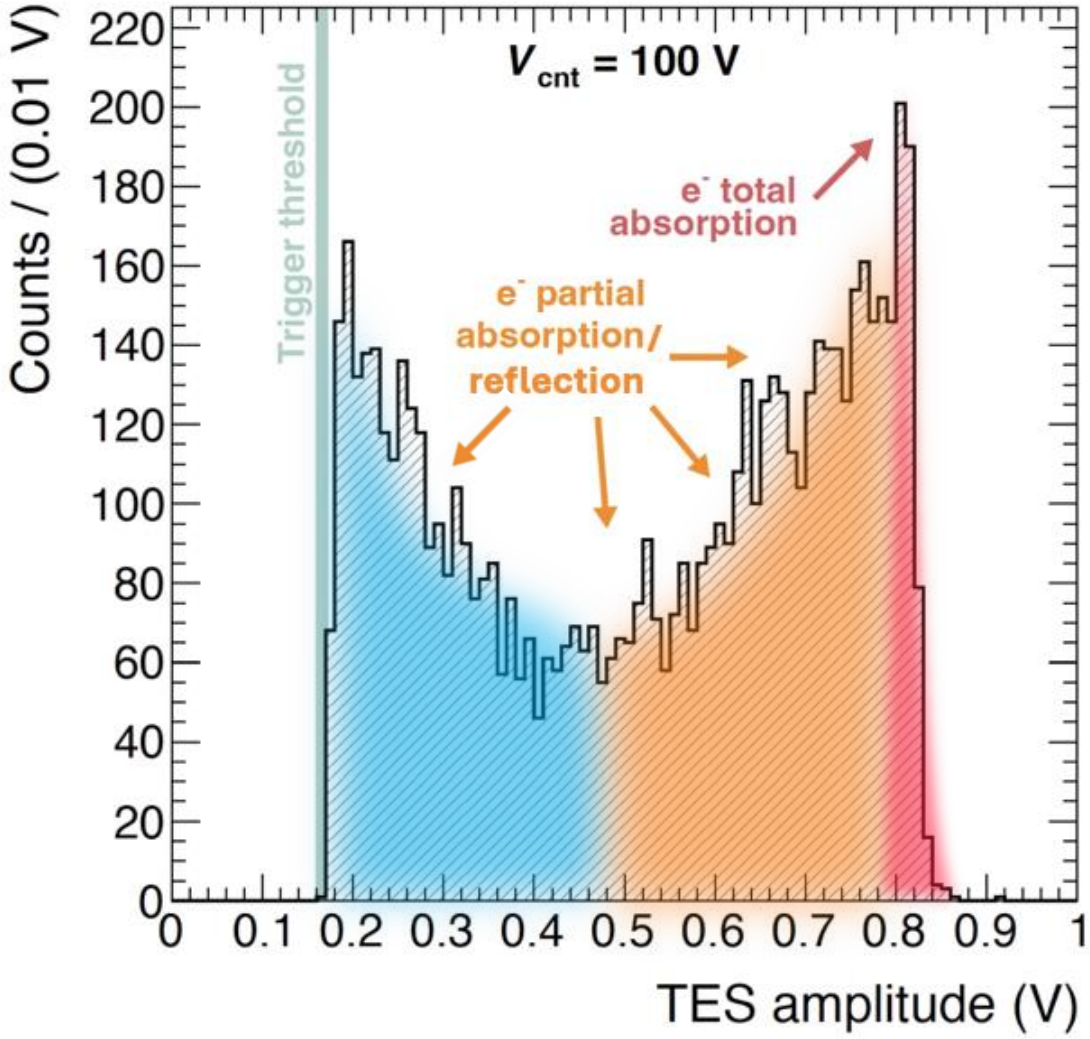

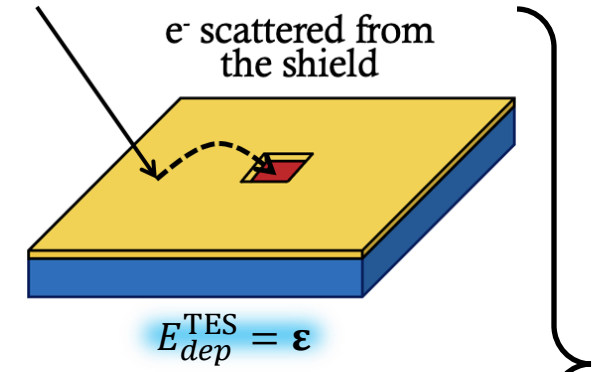

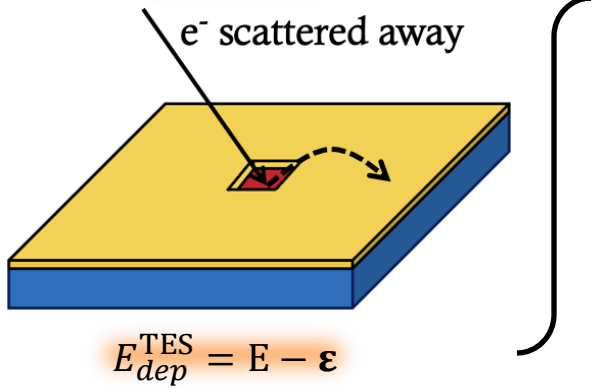

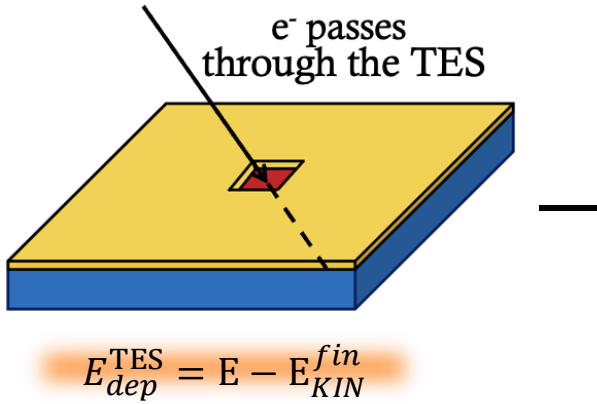

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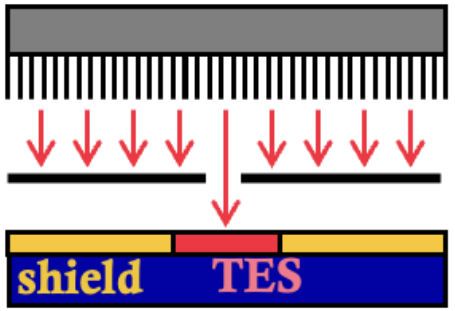
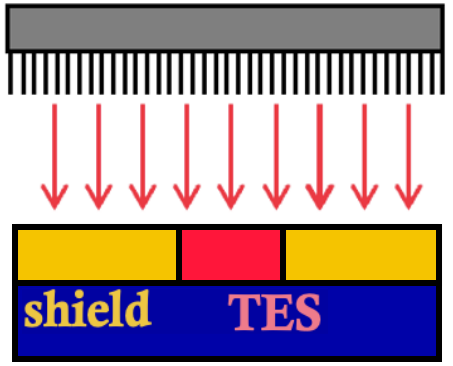


thicker TES



Conclusions

detection of low-energy electrons

reduce left tail in the histogram of the signal amplitudes

improve energy resolution

lower electron energies

Conclusions

detection of low-energy electrons

ΔE ~ 1 eV @ 100 eV

reduce left tail in the histogram of the signal amplitudes

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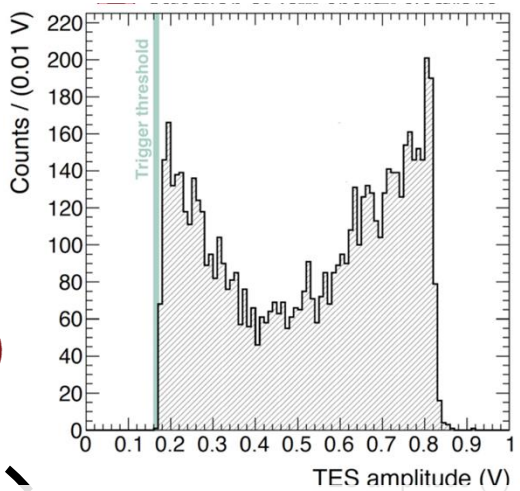
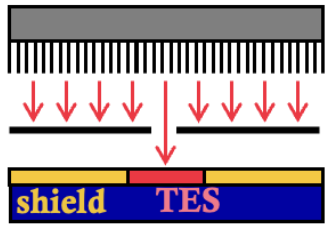
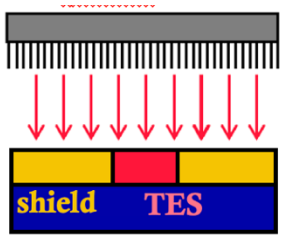


reduce left tail in the histogram of the signal amplitudes

Ideas to study the distribution:

- pinhole in front of the CNTs
- thicker TES





improve energy resolution

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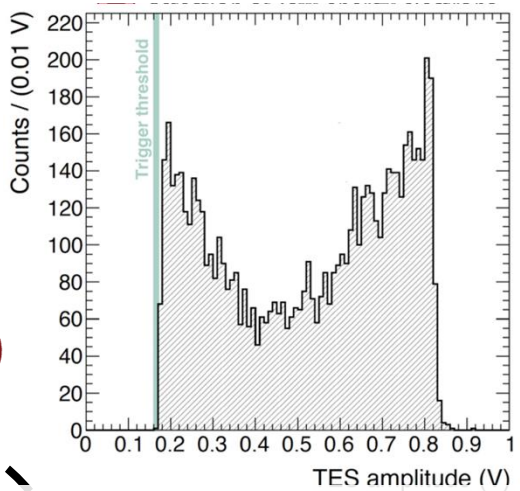

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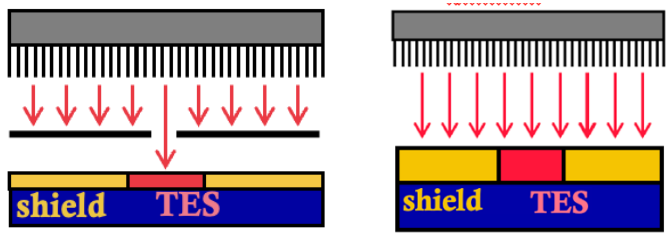

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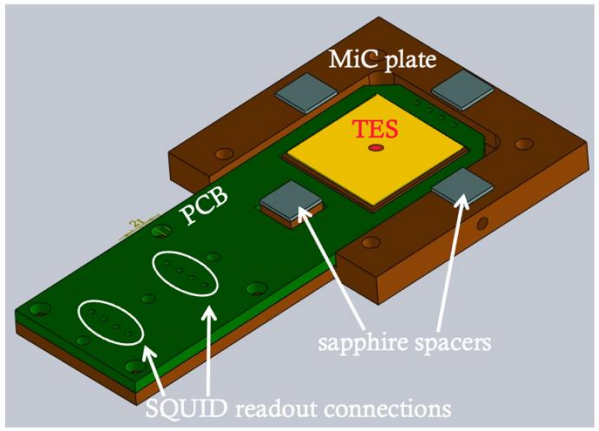
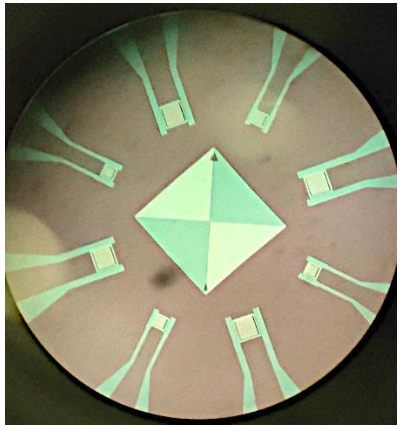




improve energy resolution

ΔE: 1 eV ⇒ 0.05 eV

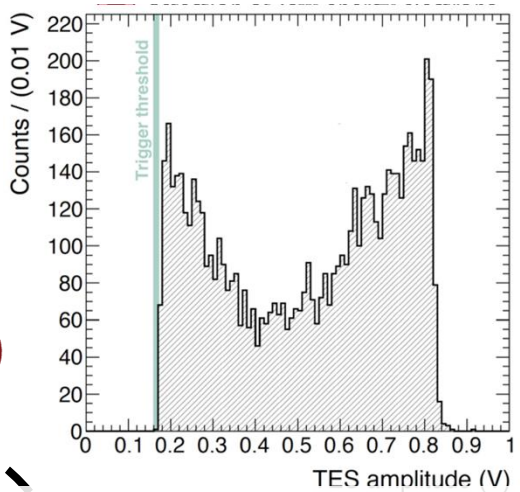
- smaller TES
- reduce noise with MiC 2.0

lower electron energies

Conclusions

detection of low-energy electrons

ΔE ~ 1 eV @ 100 eV



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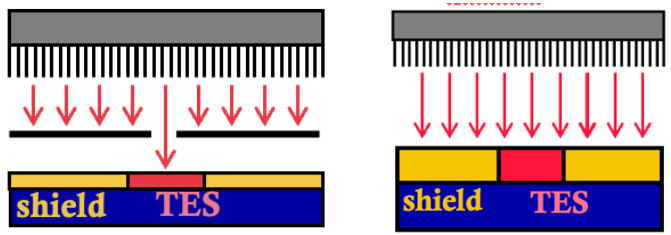
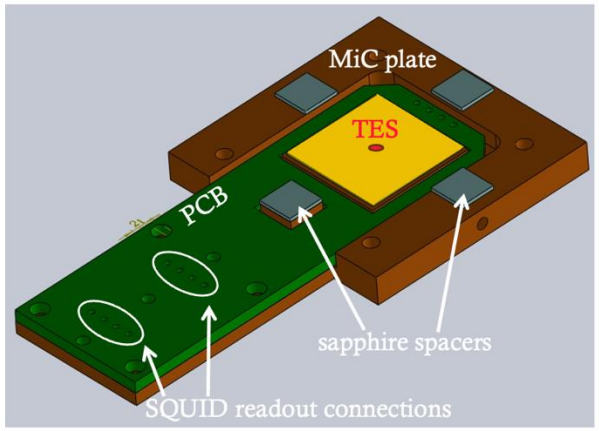
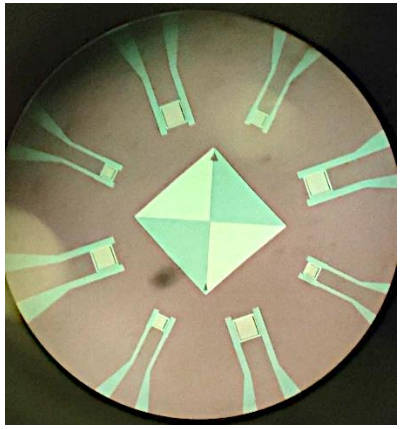


reduce left tail in the histogram of the signal amplitudes





improve energy resolution

ΔE: 1 eV ⇒ 0.05 eV

- smaller TES
- reduce noise with MiC 2.0

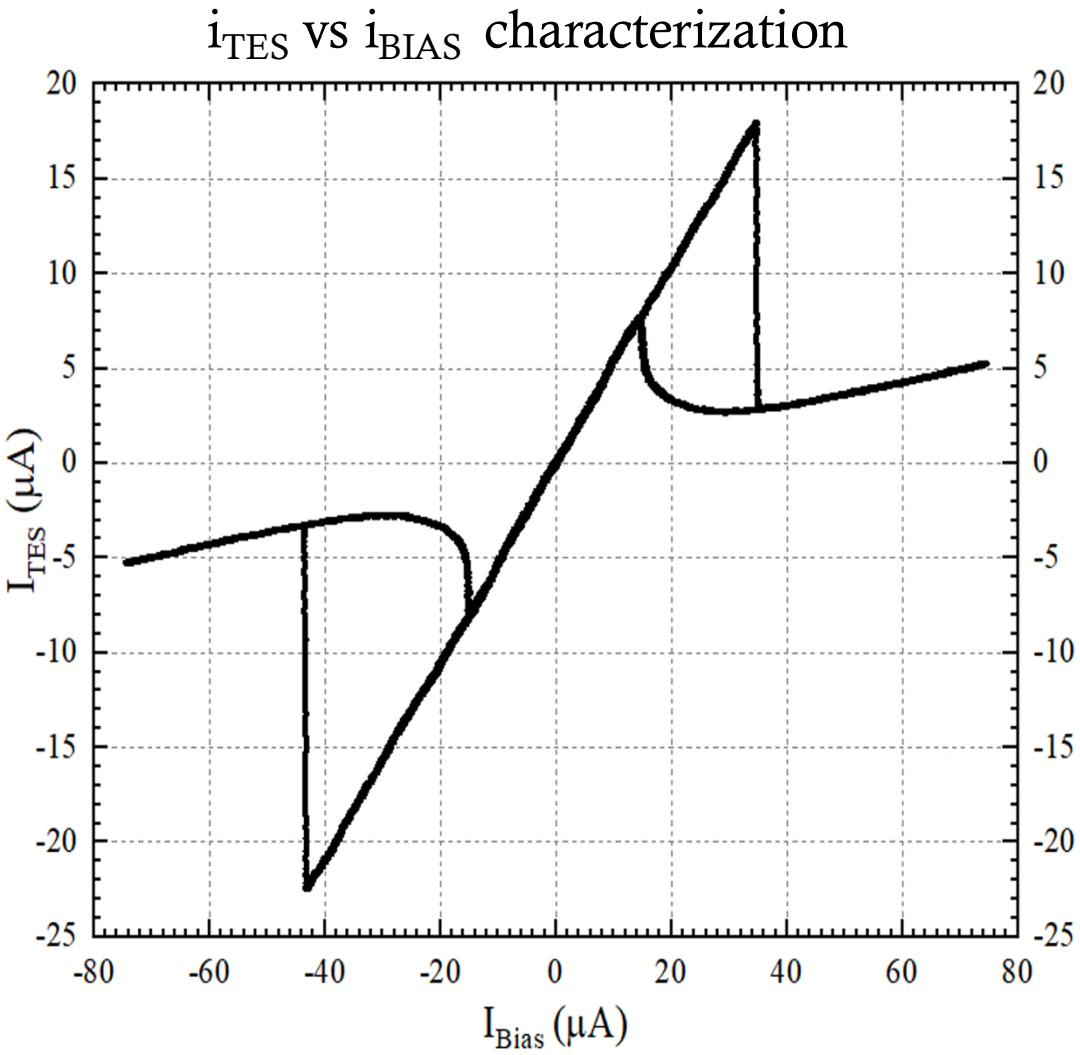
lower electron energies

E: 100 eV ⇒ 10 eV

Backup Slides

TES Characterization Curve

A



TES Characterization Curve

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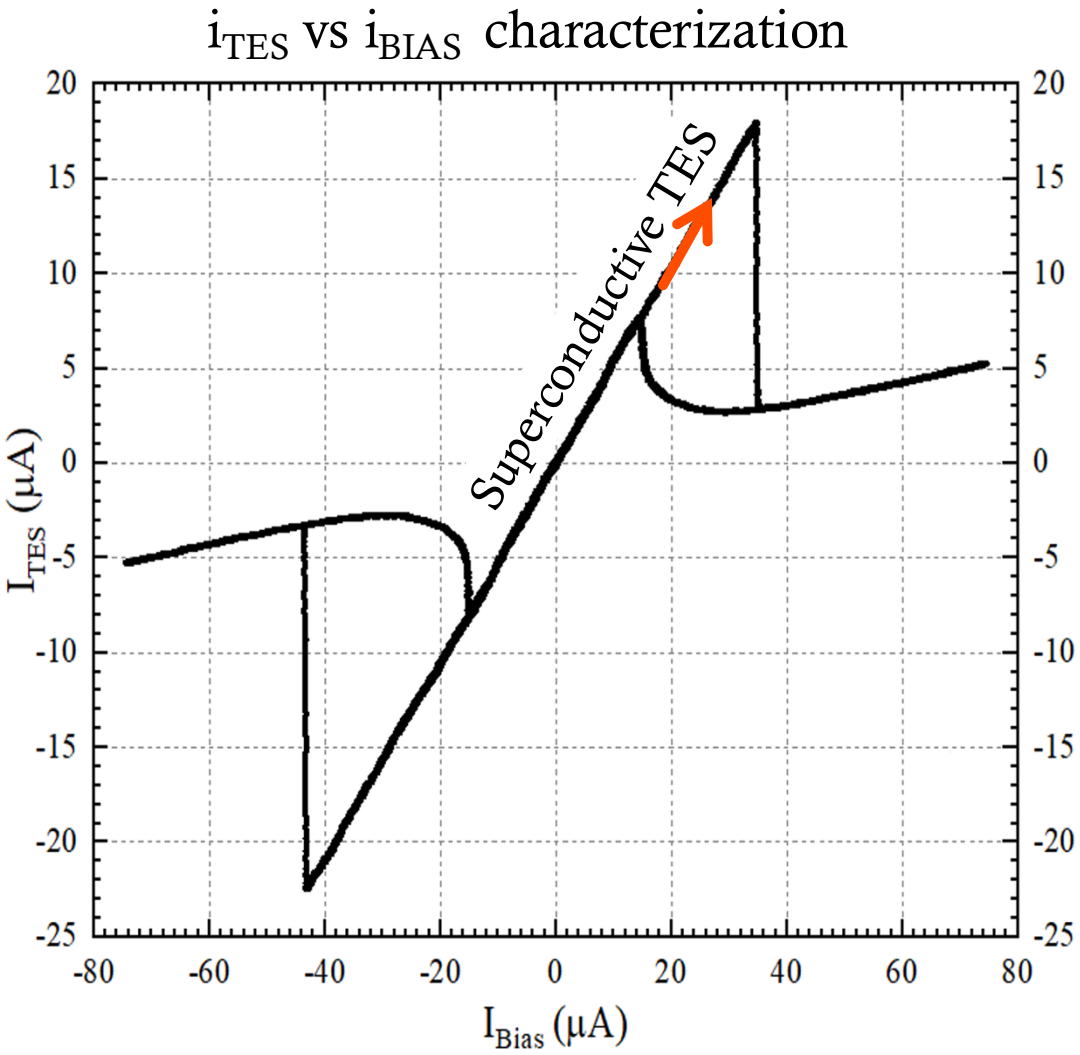
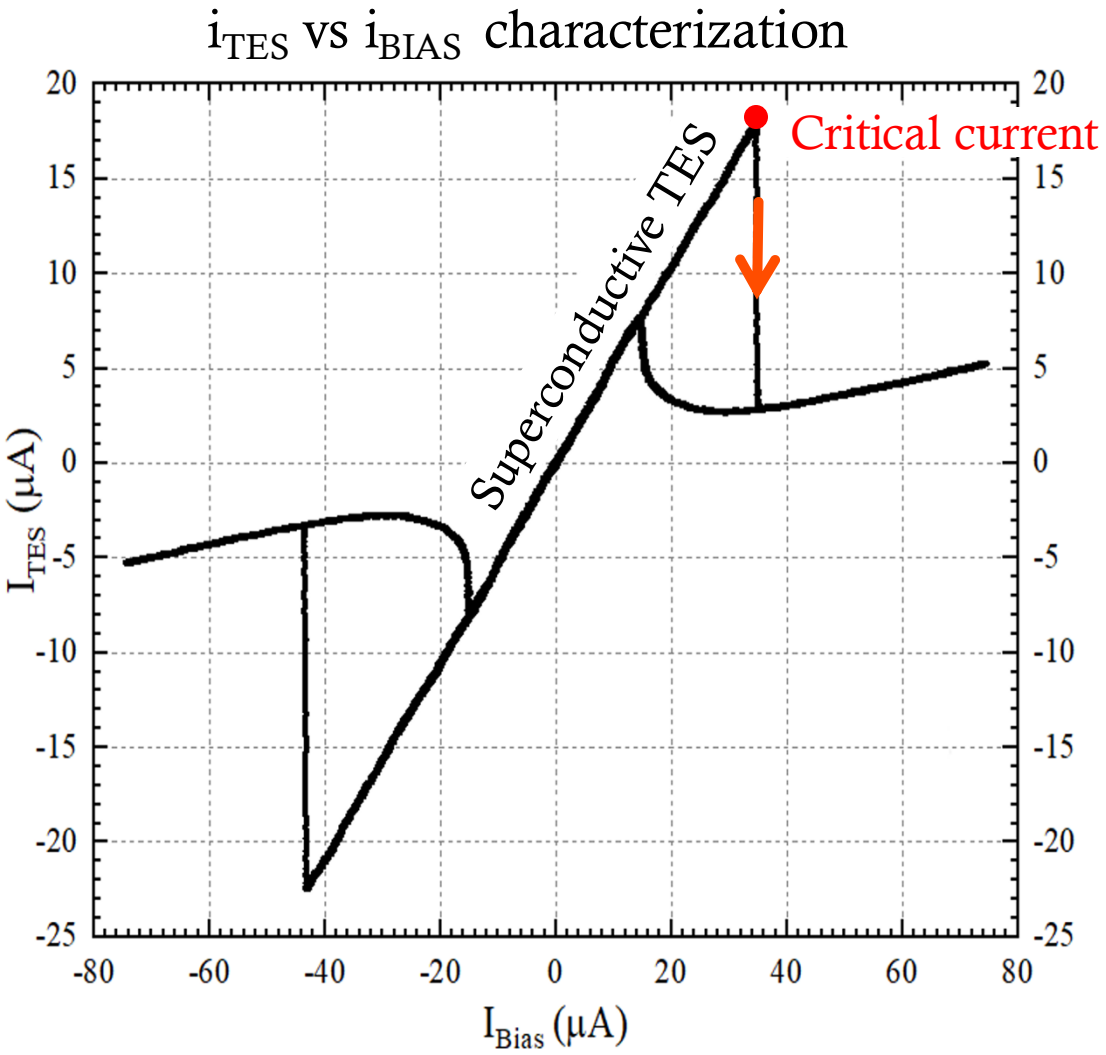
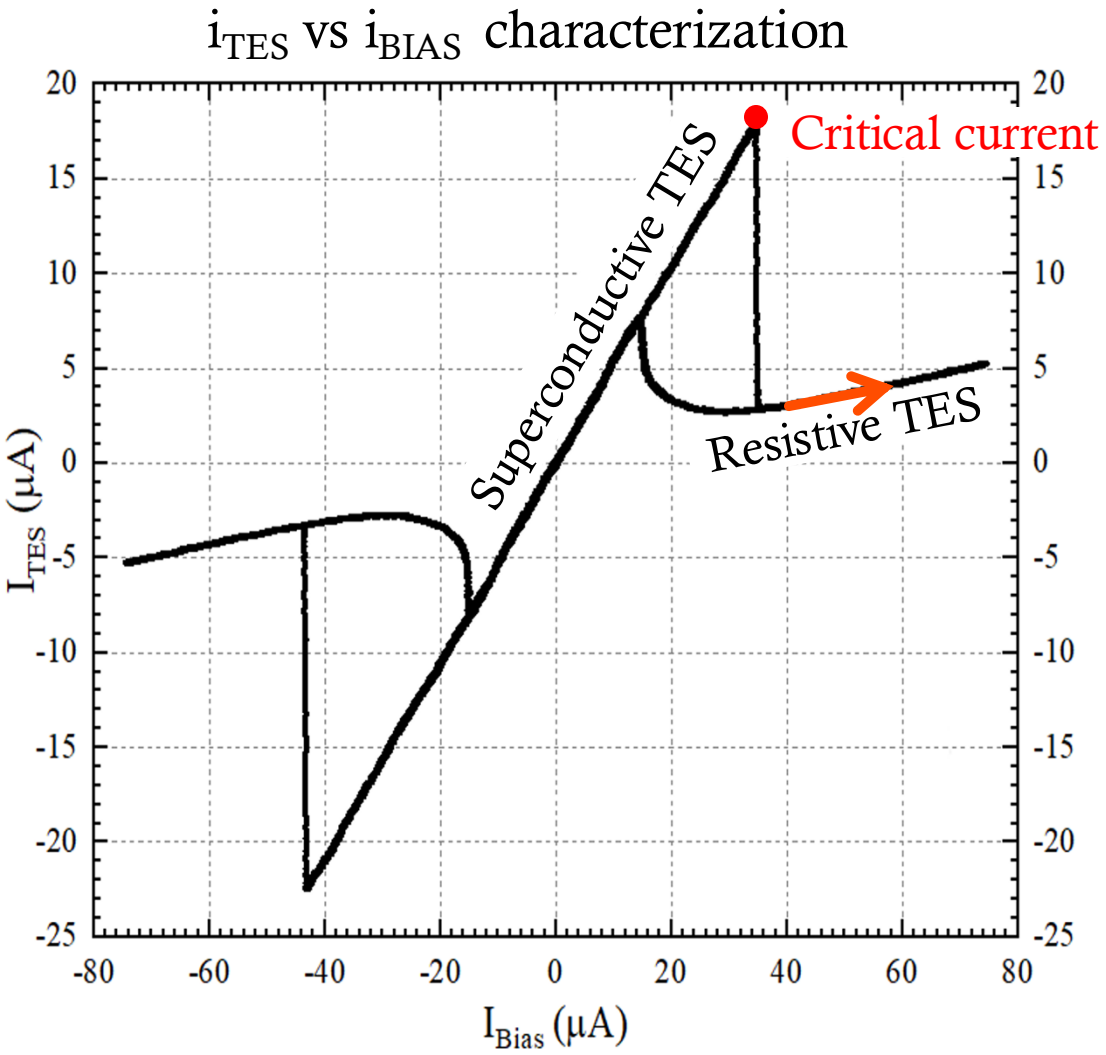


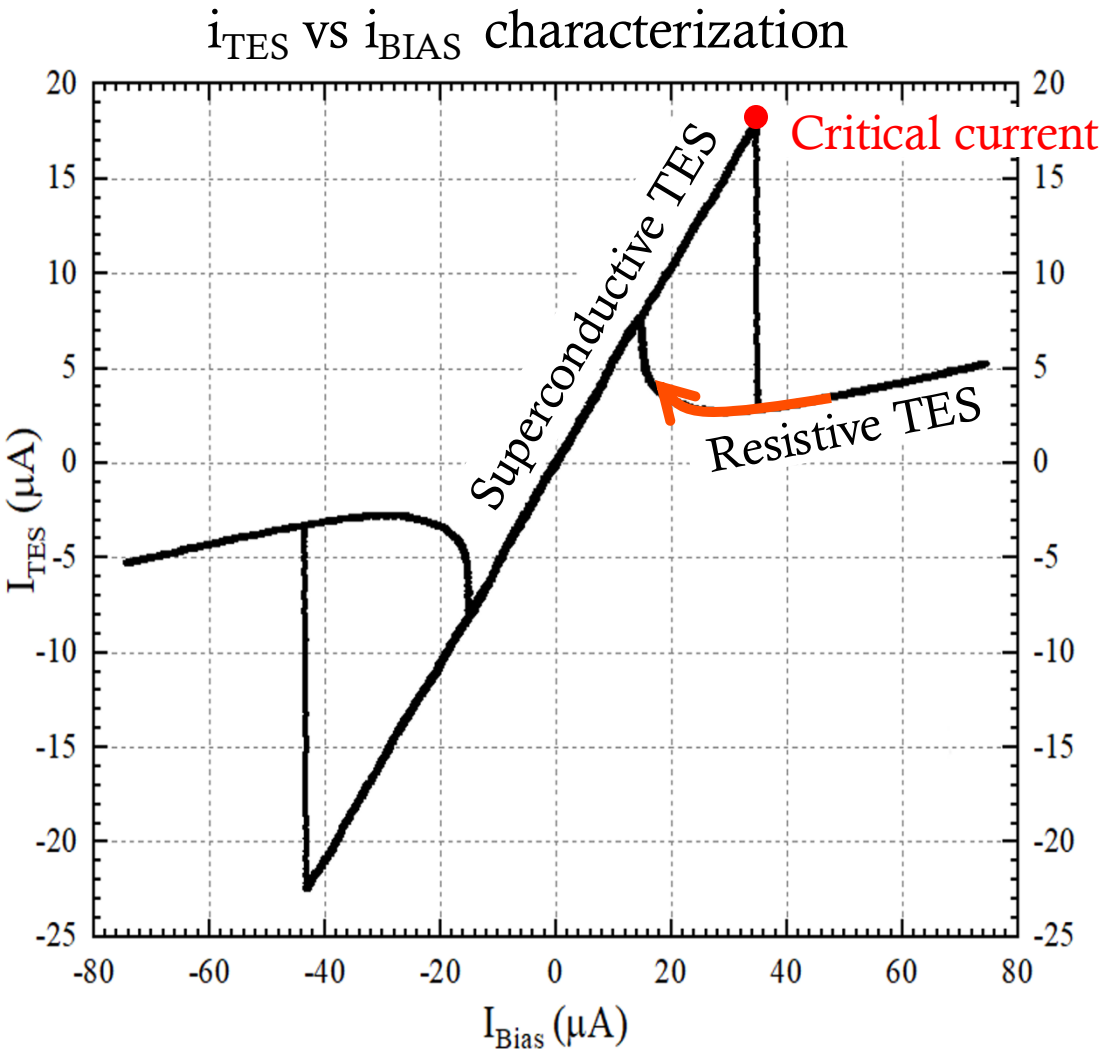
TES Characterization Curve



TES Characterization Curve



TES Characterization Curve



TES Characterization Curve

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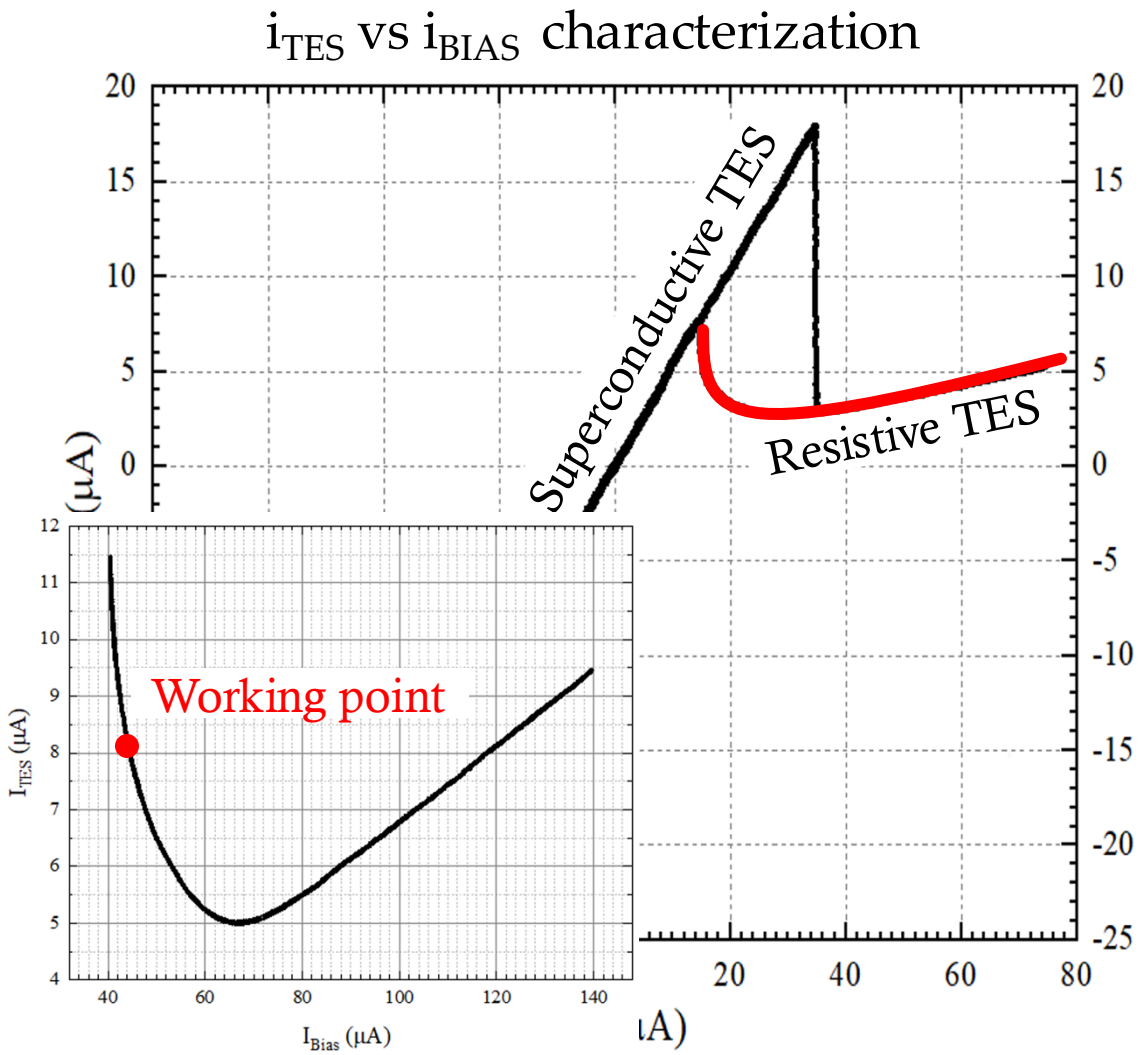
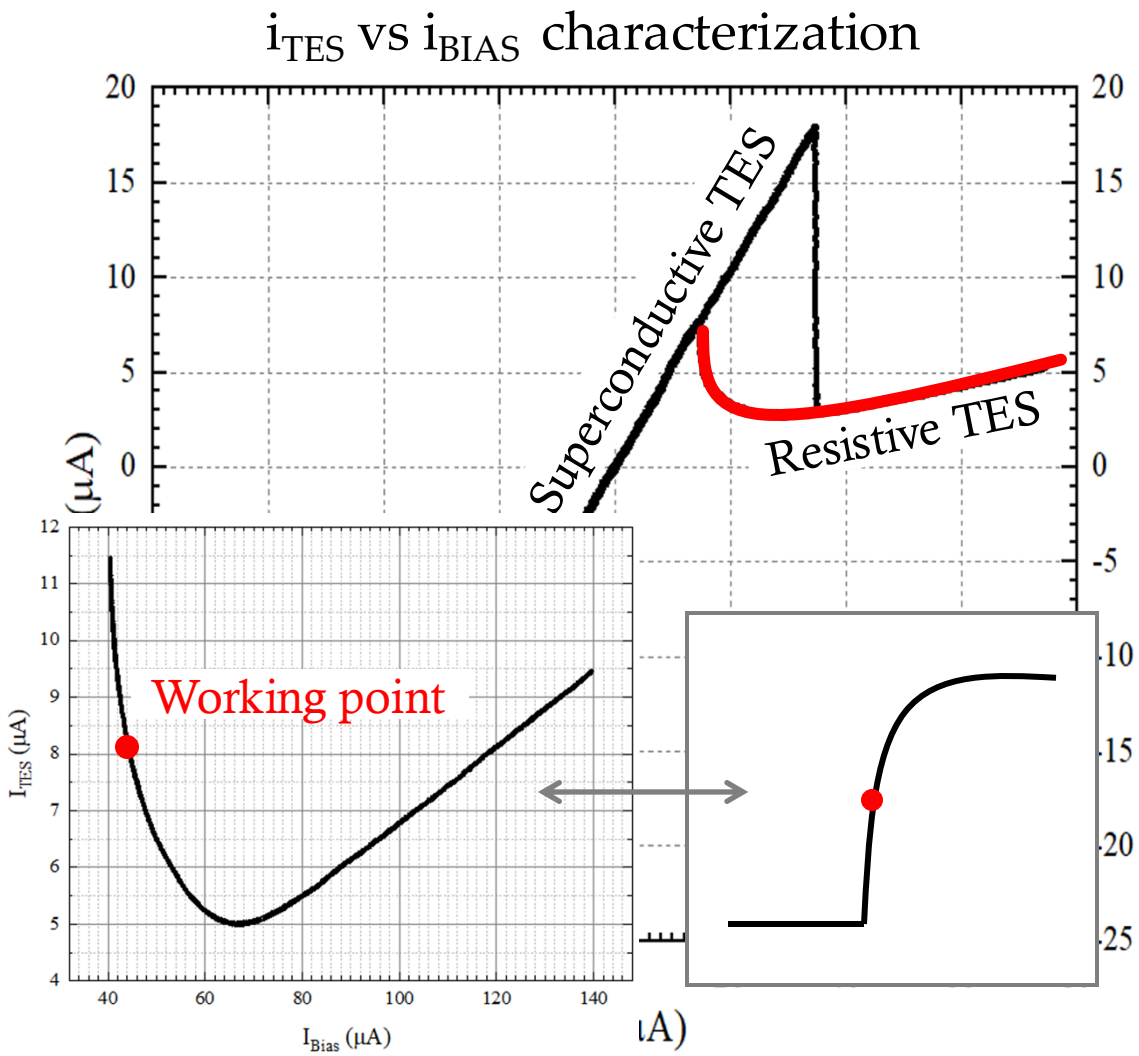


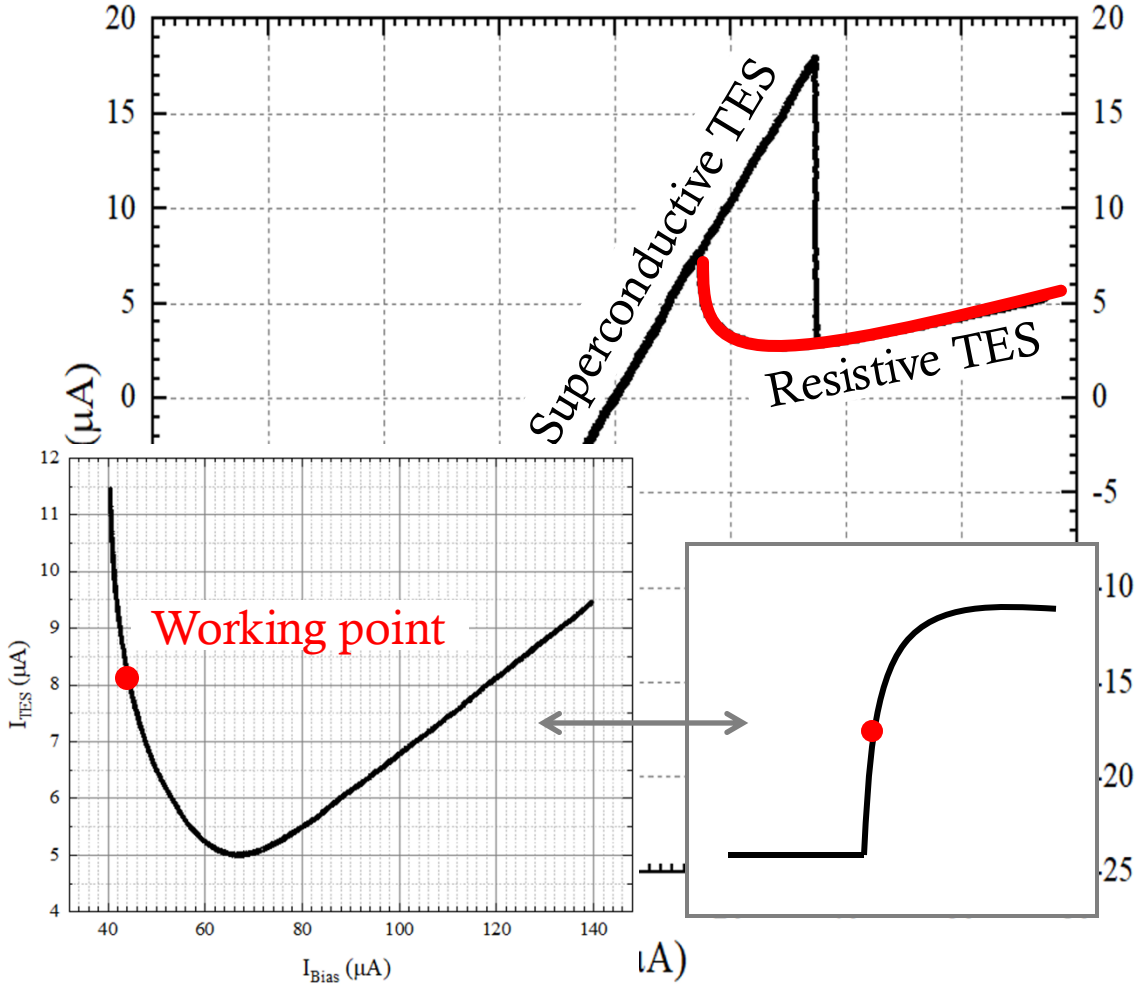
TES Characterization Curve



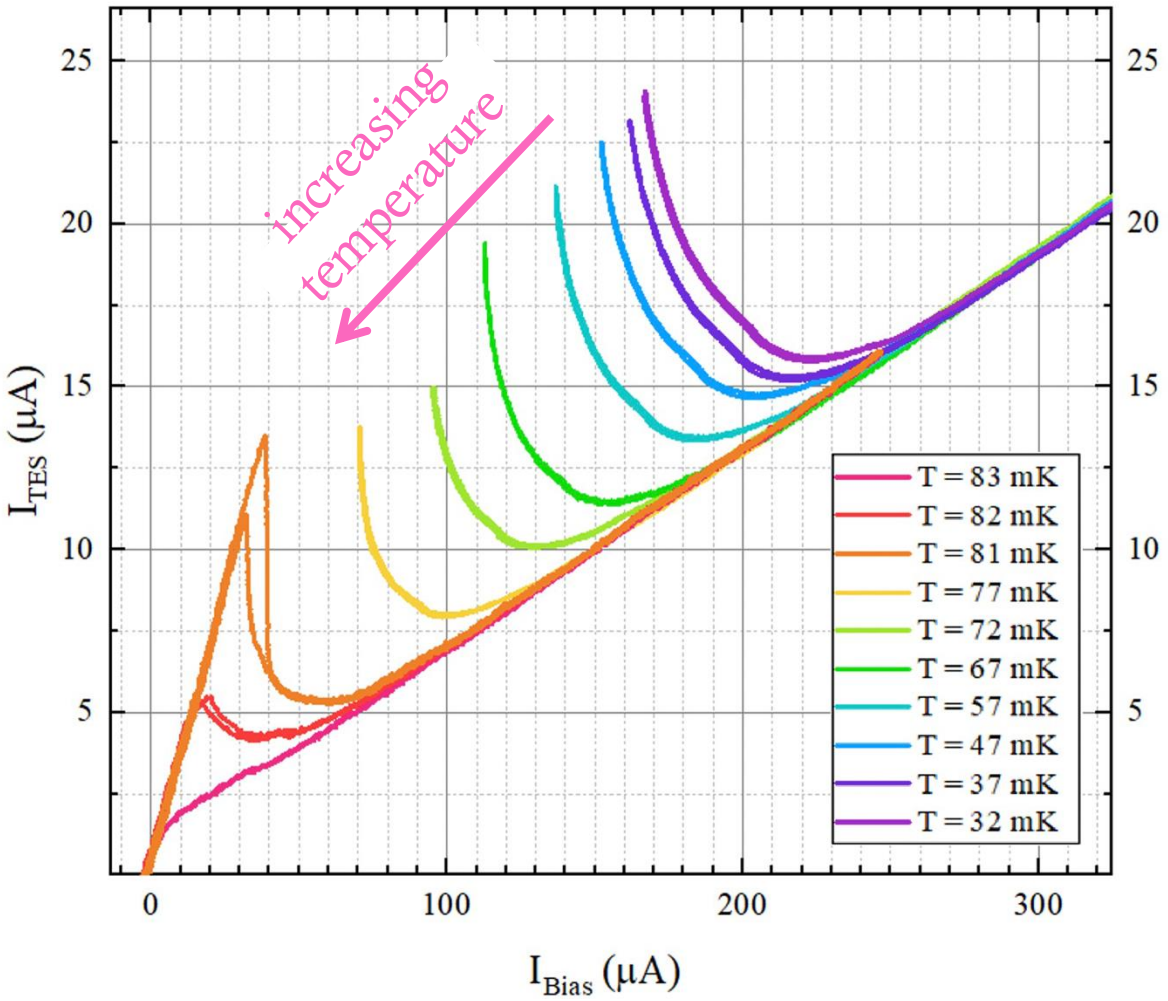
TES Characterization Curve

A

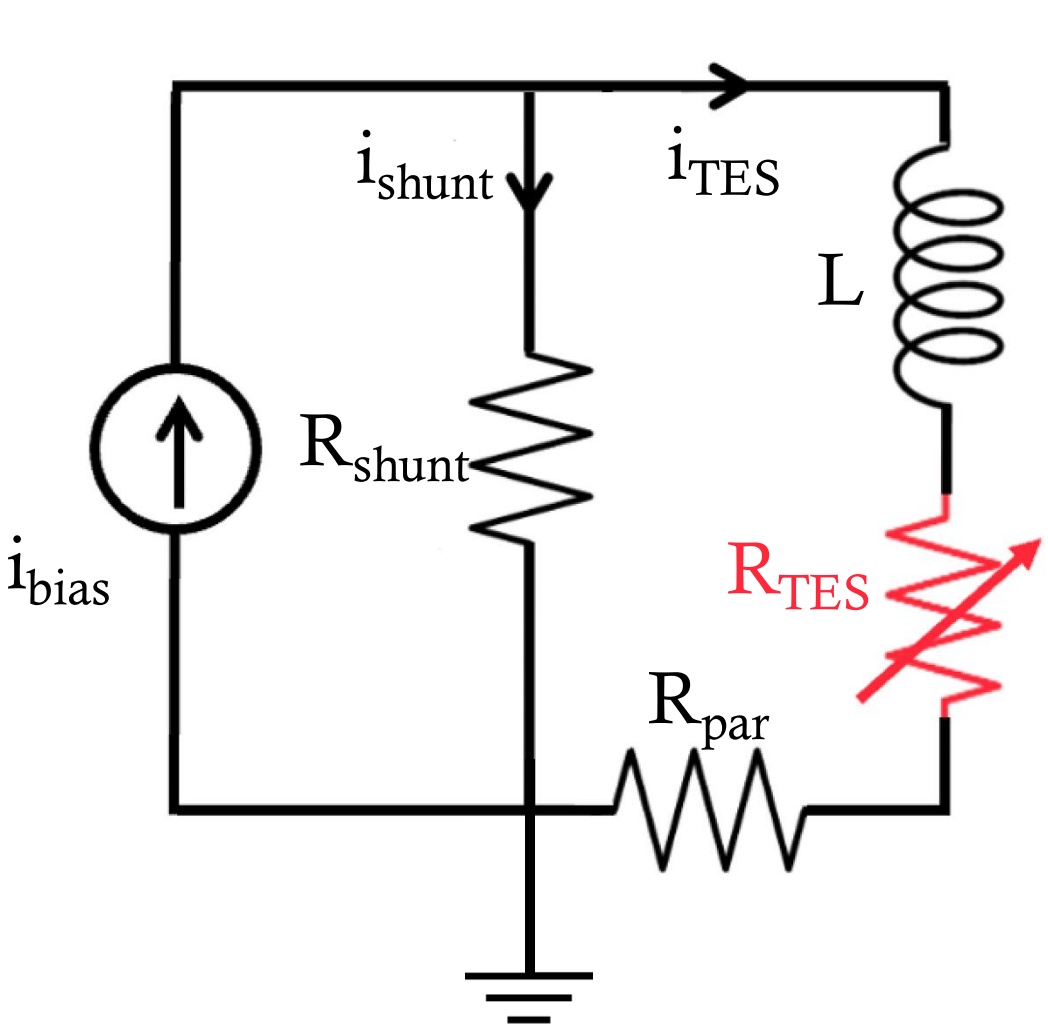
i_{TES} vs i_{BIAS} characterization

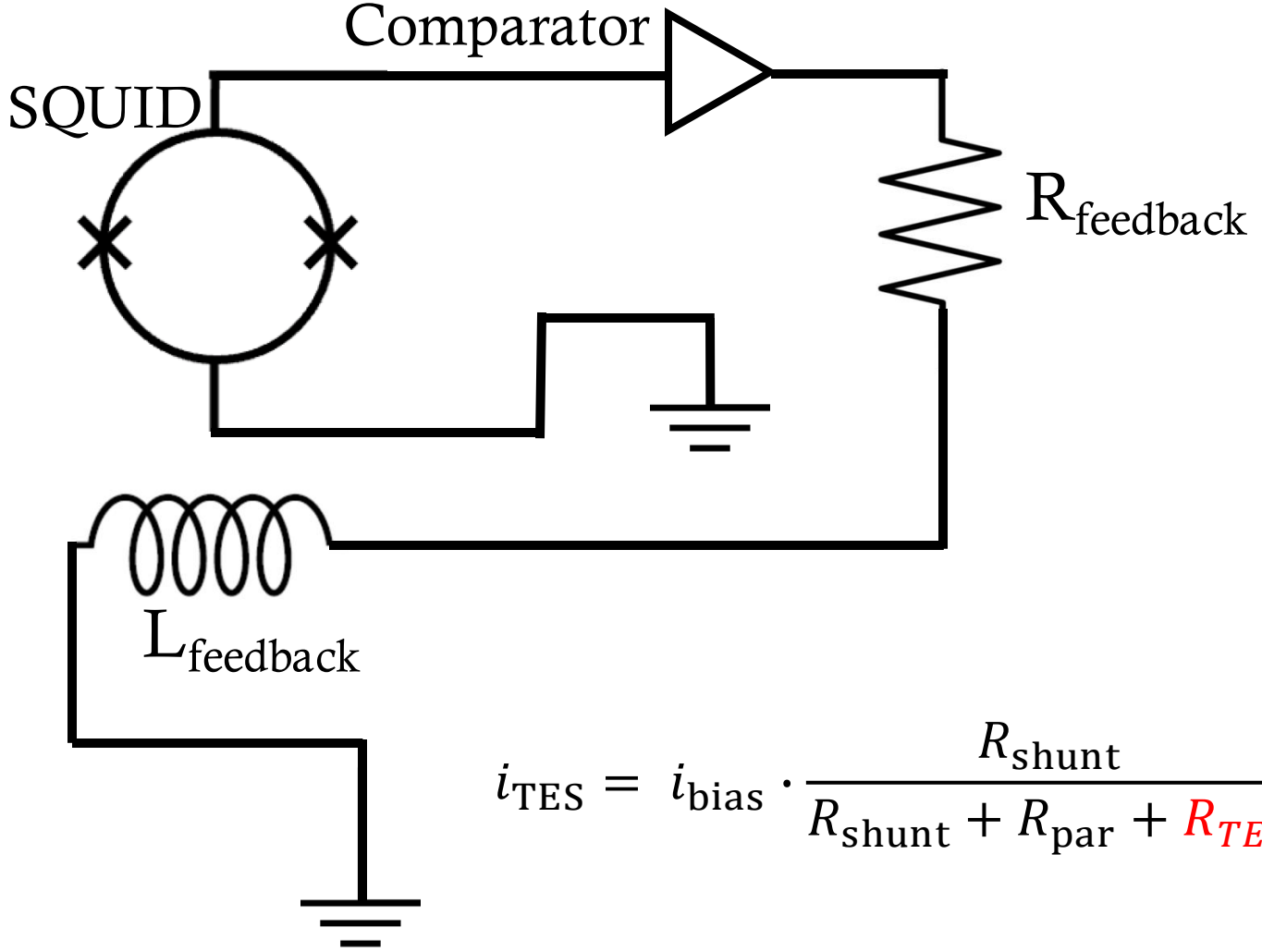


temperature effects



TES Readout Circuit





$$i_{\mathrm{TES}} = i_{\mathrm{bias}} \cdot \frac{R_{\mathrm{shunt}}}{R_{\mathrm{shunt}} + R_{\mathrm{par}} + R_{TES}}$$

TES Detection Performance

C

$$\tau_{eff} = \tau_{th}\left\{1 + \frac{\alpha}{n}\left(1 - \frac{T_{bath}^{n}}{T_c^{n}}\right)\right\}^{-1} \approx \frac{n}{\alpha}\tau_{th} \approx \frac{C}{G} \propto T_c^{-3}$$

effective time response

$$\Delta E_{FWHM} = 2.36\sqrt{4k_B T_c^2 \frac{C}{\alpha}\sqrt{\frac{n}{2}}} \propto T_c^{3/2}$$

energy FWHM

$$E_{sat} = C\Delta T_{sat} = \frac{C}{\alpha}\frac{\Delta R_{sat}}{R}T_c \propto T_c$$

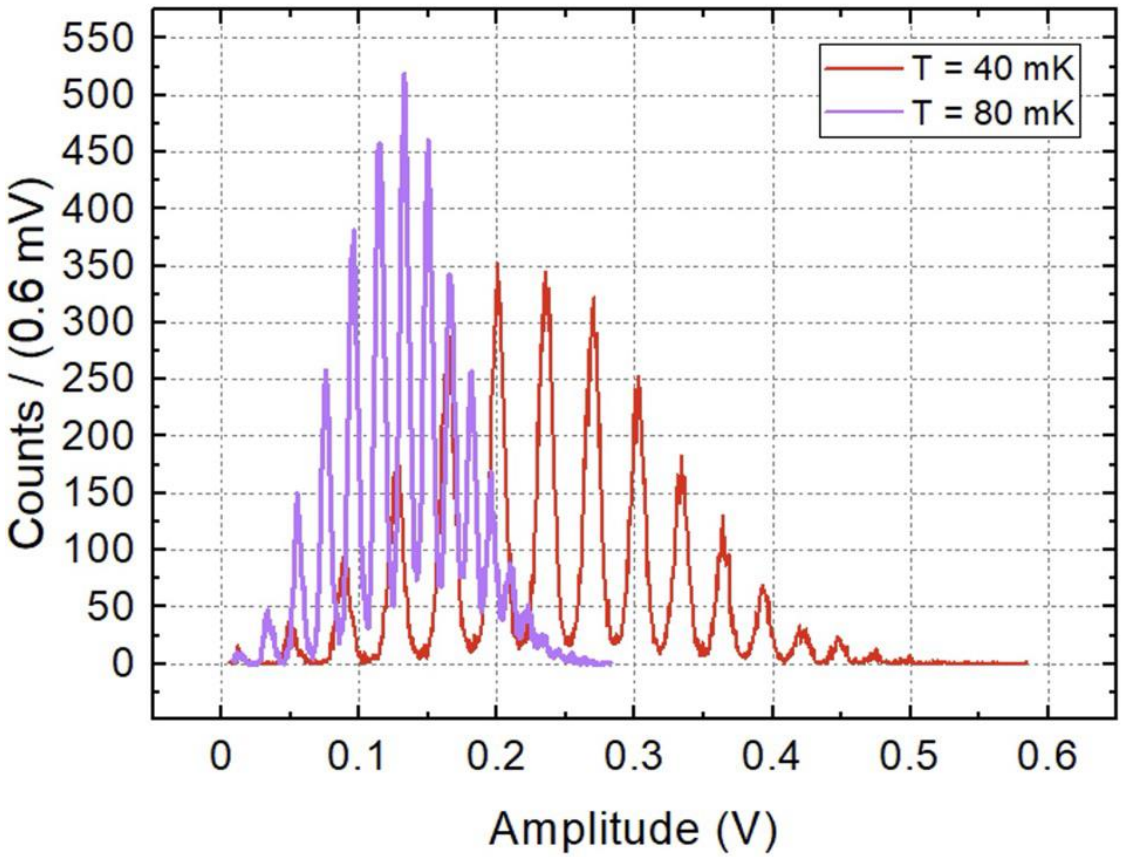
energy saturation

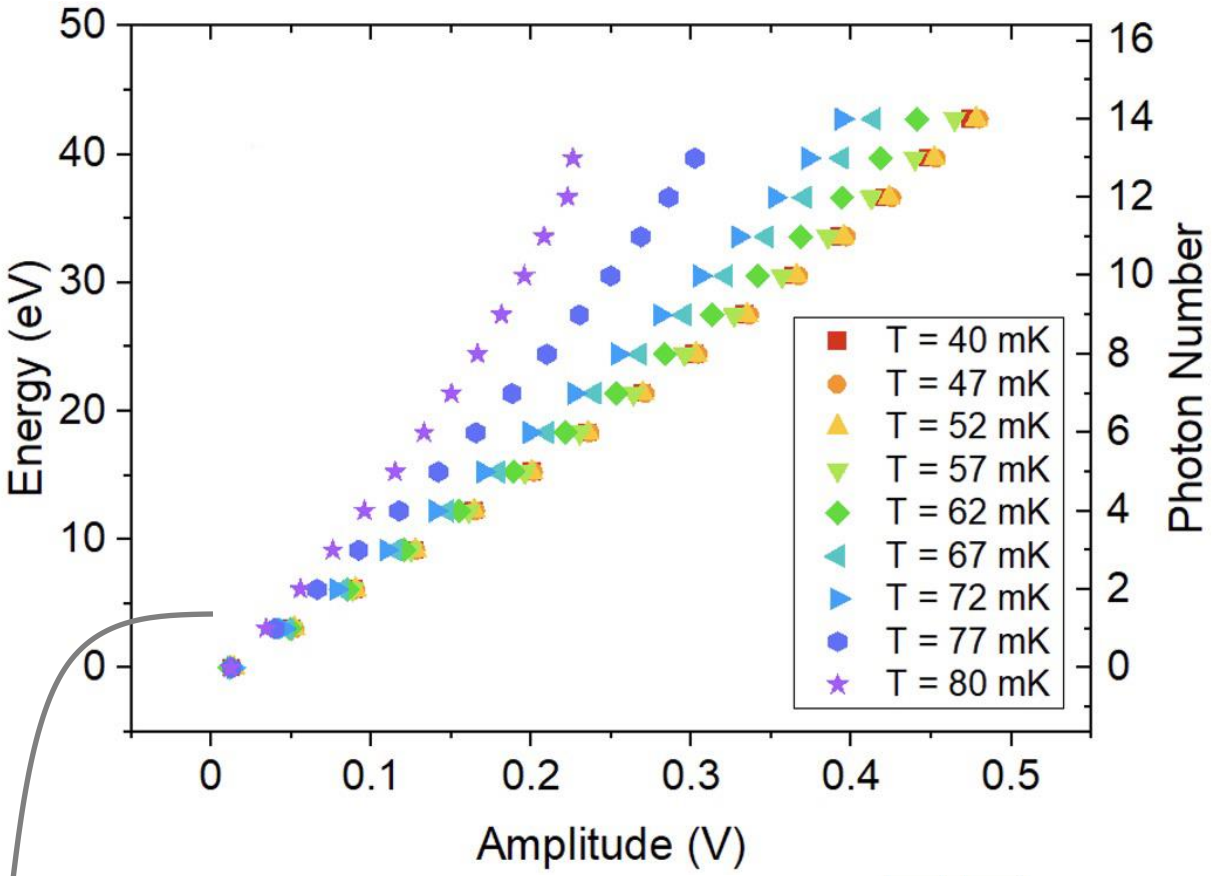
$$\alpha = \frac{T}{R}\frac{dR}{dT}$$

transition sharpness

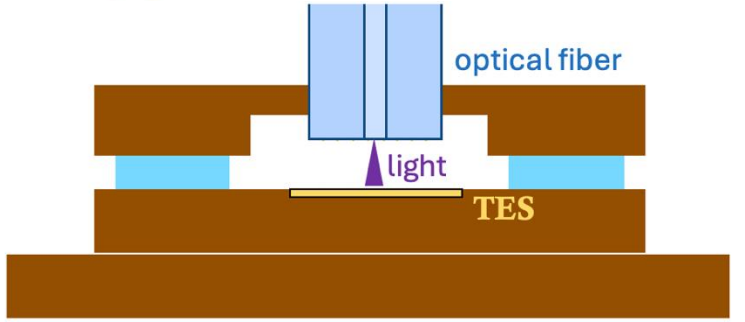
Temperature Effects on Signal Amplitude

D



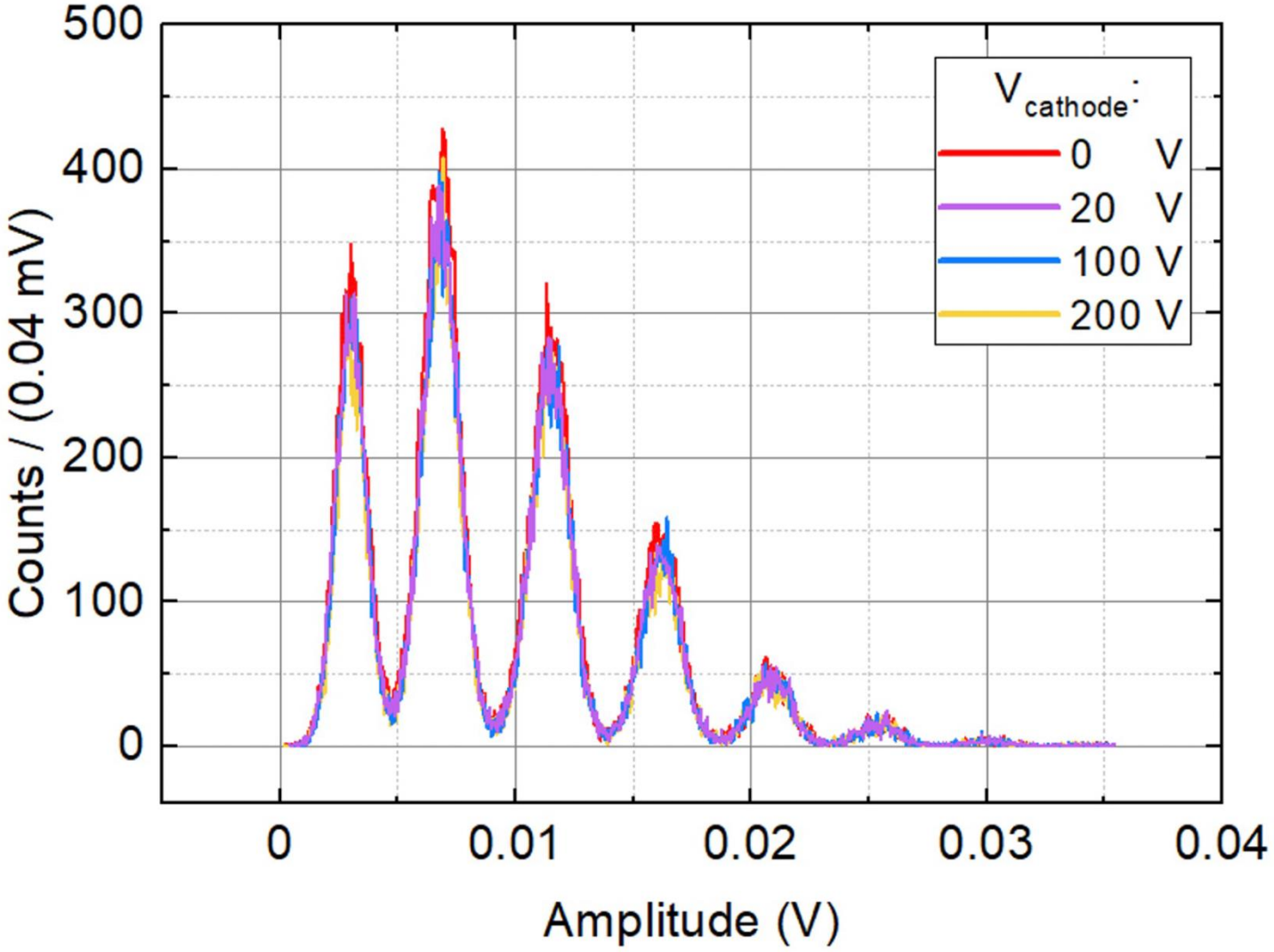


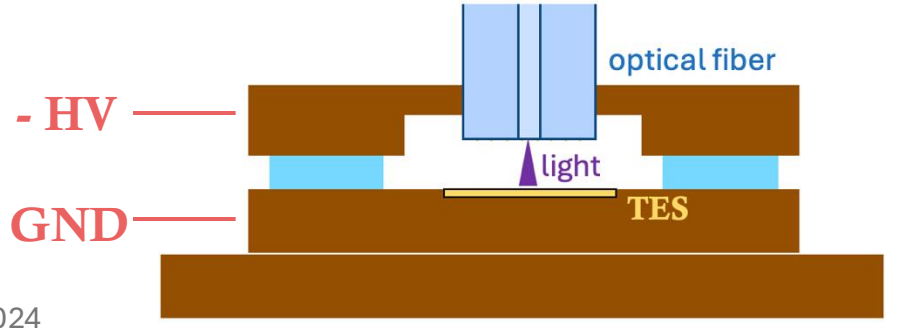
Need for a **different calibration** for each TES
different temperature working condition!



Electric Field does not have any Effect

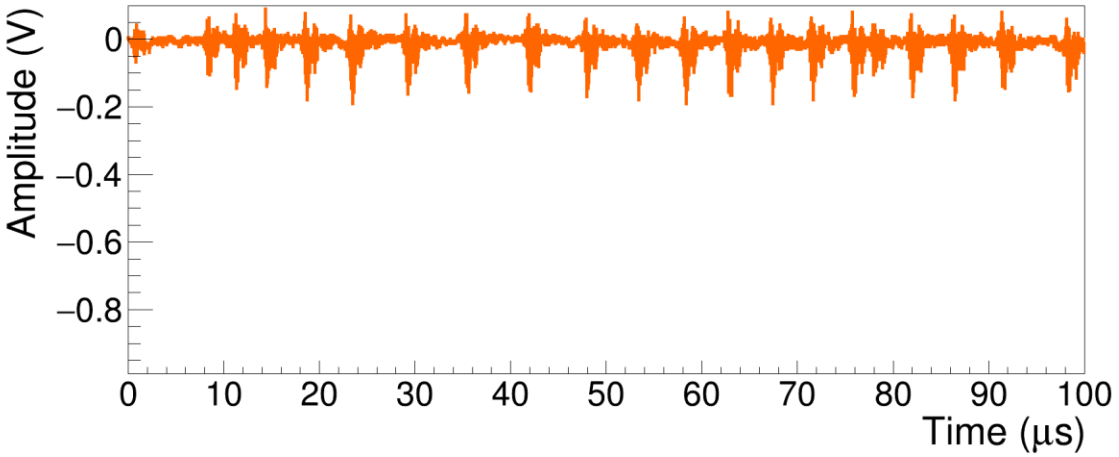
E



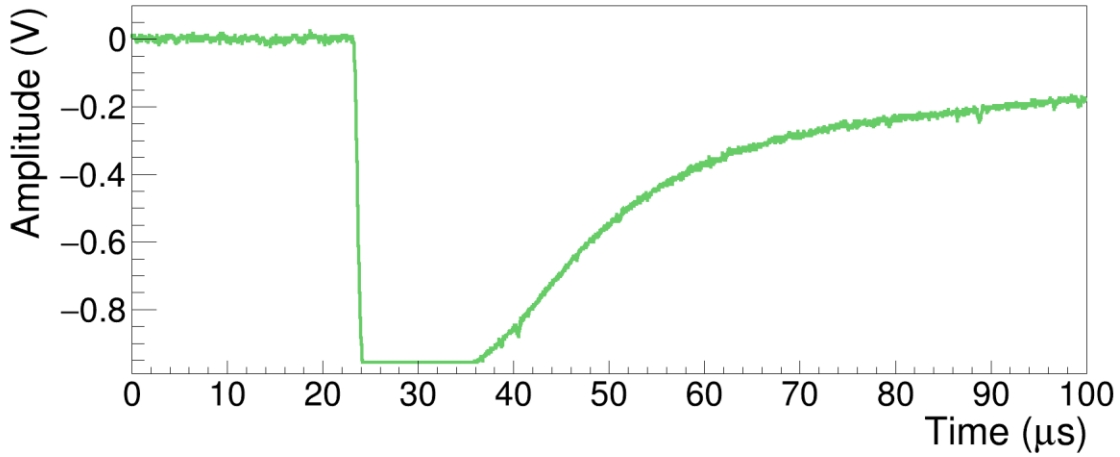


Background Sources

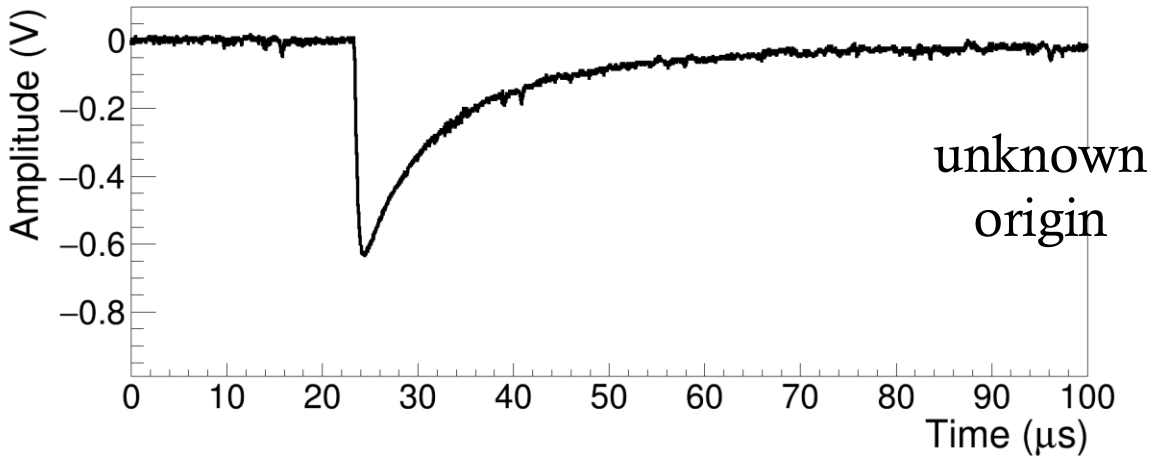
electronic noise



high-energy particles from **cosmic rays**

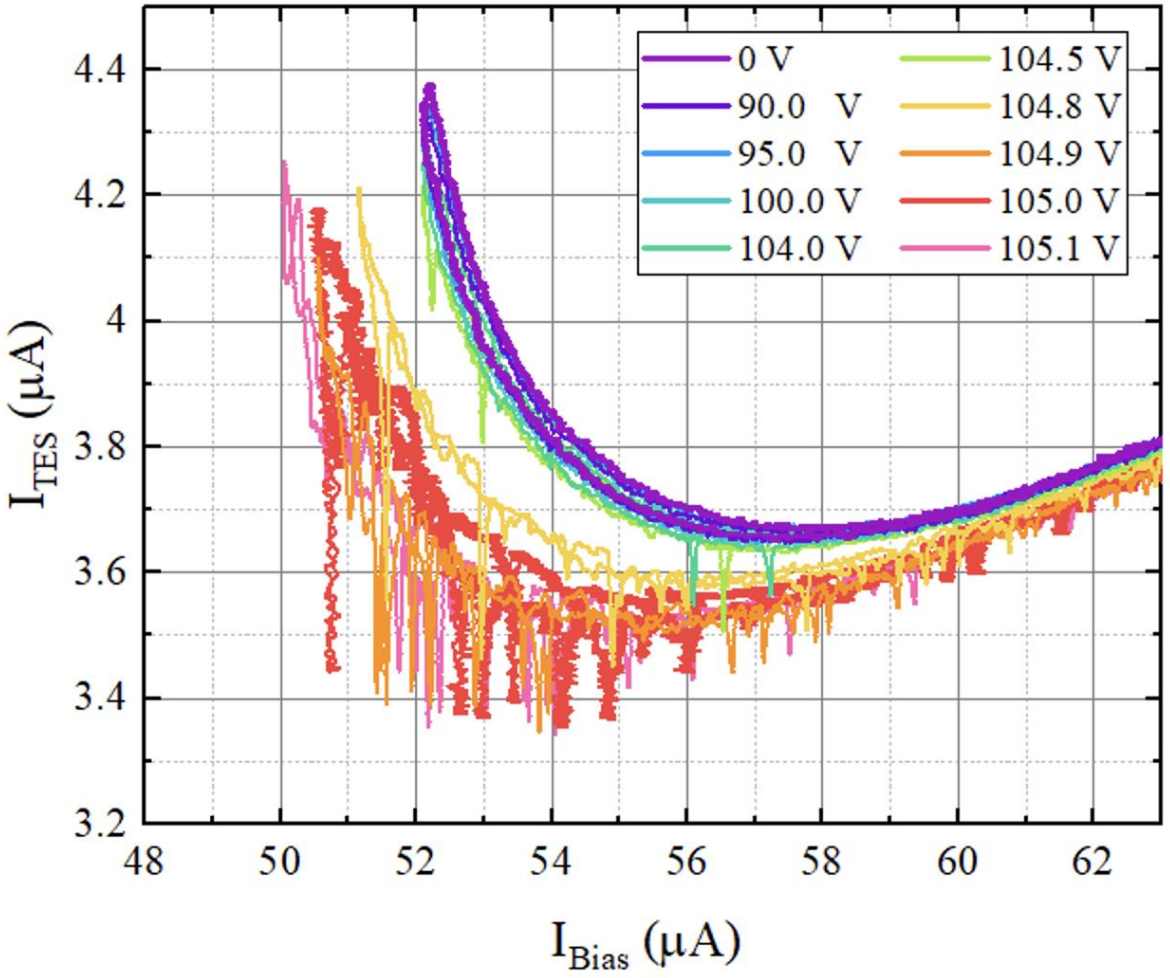


photon-like events

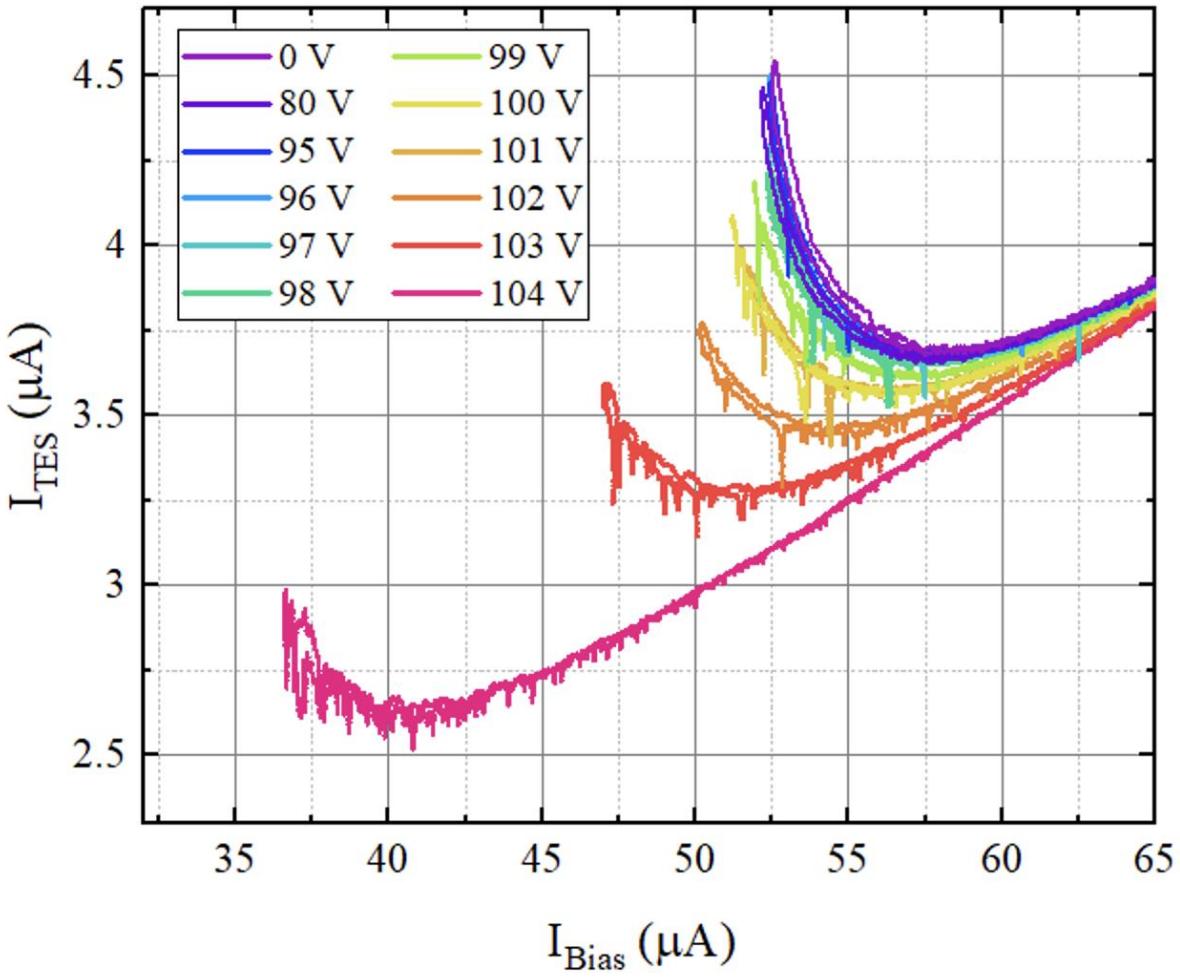


Changes in TES Temperature

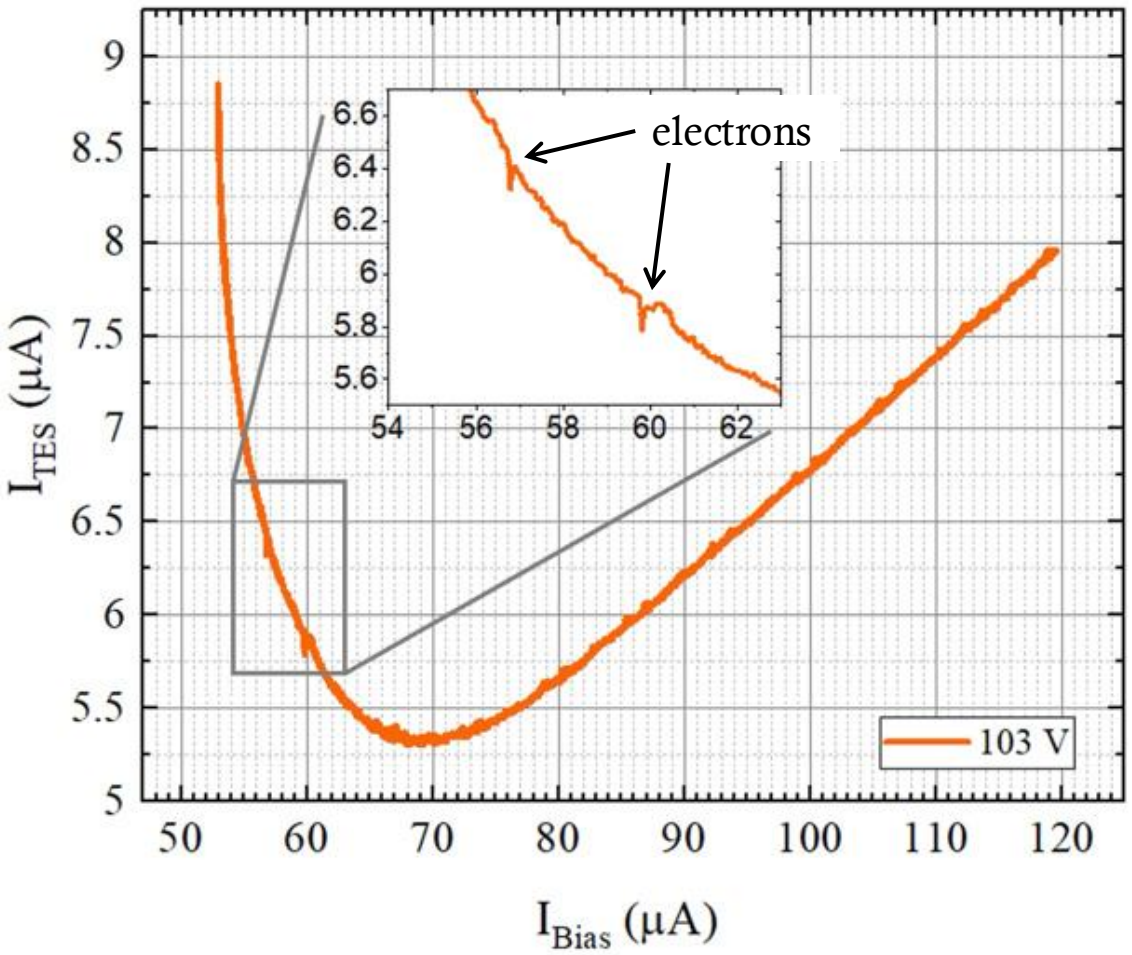
thursday measurement

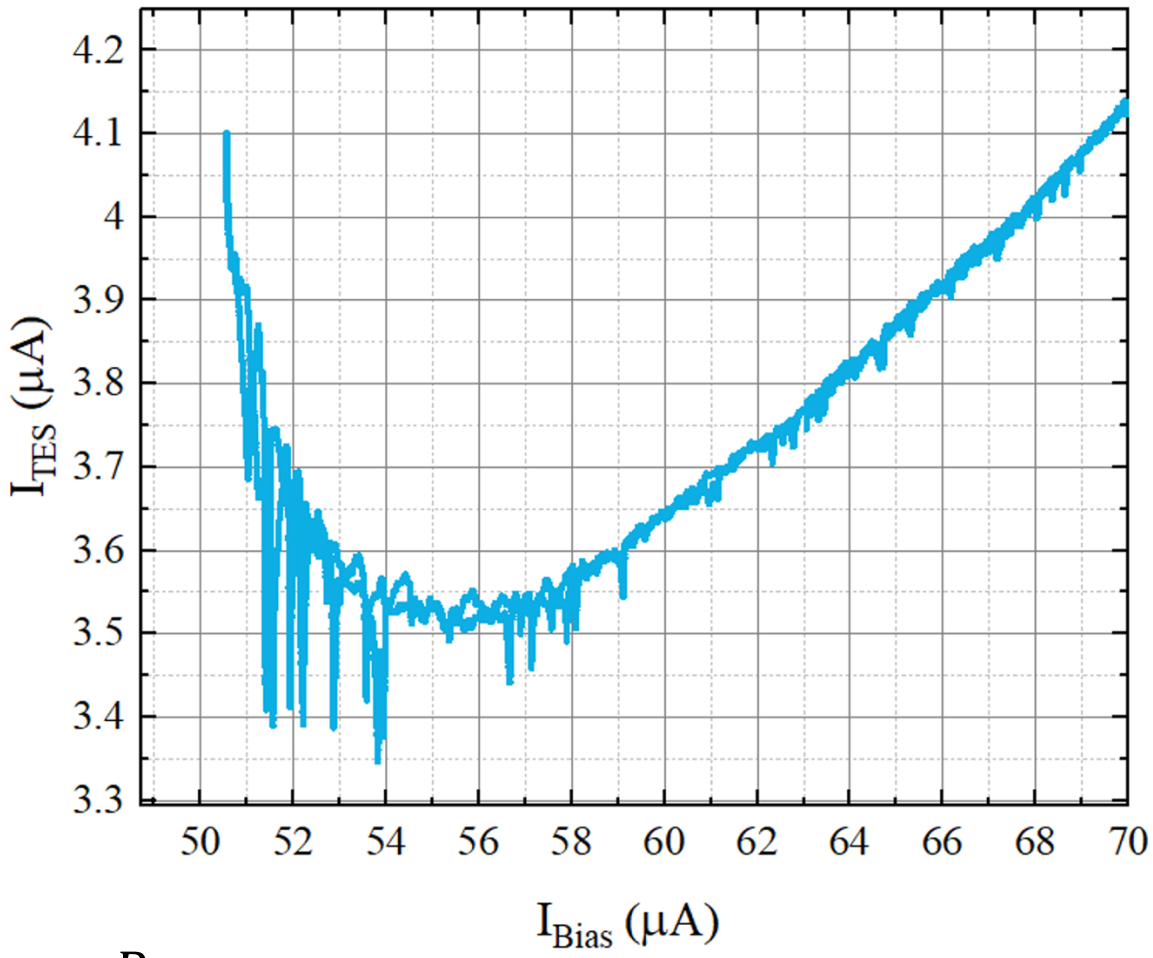


friday measurement



Electrons on Characterization Curve

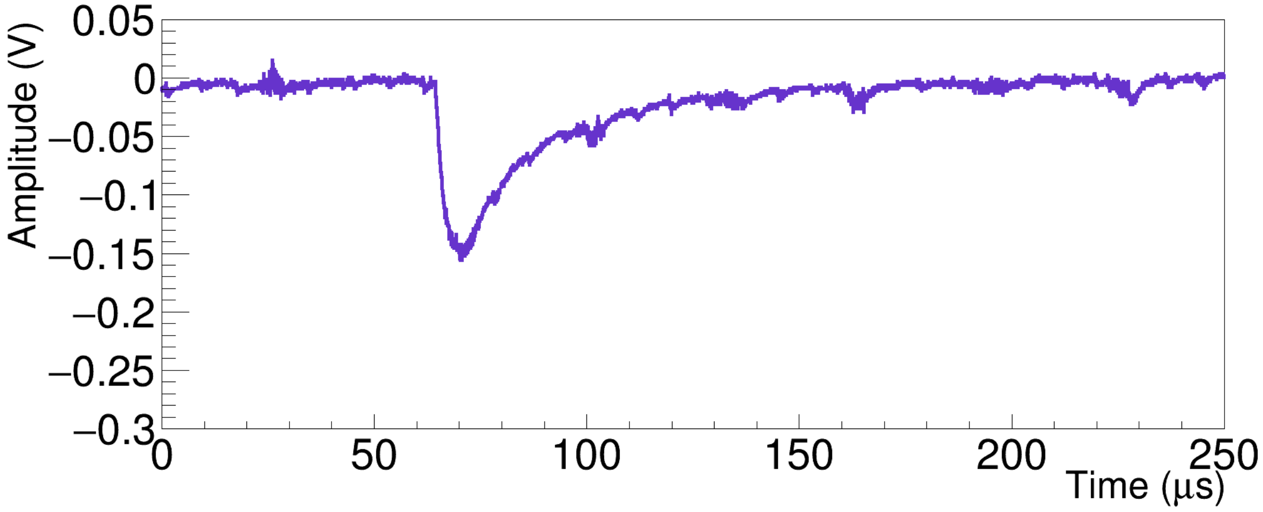


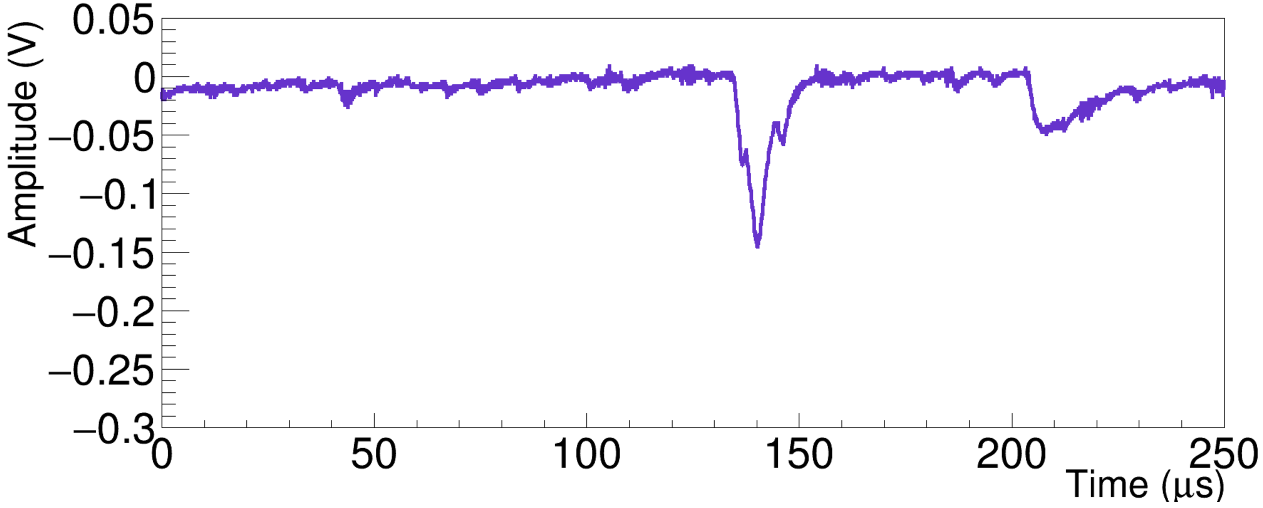


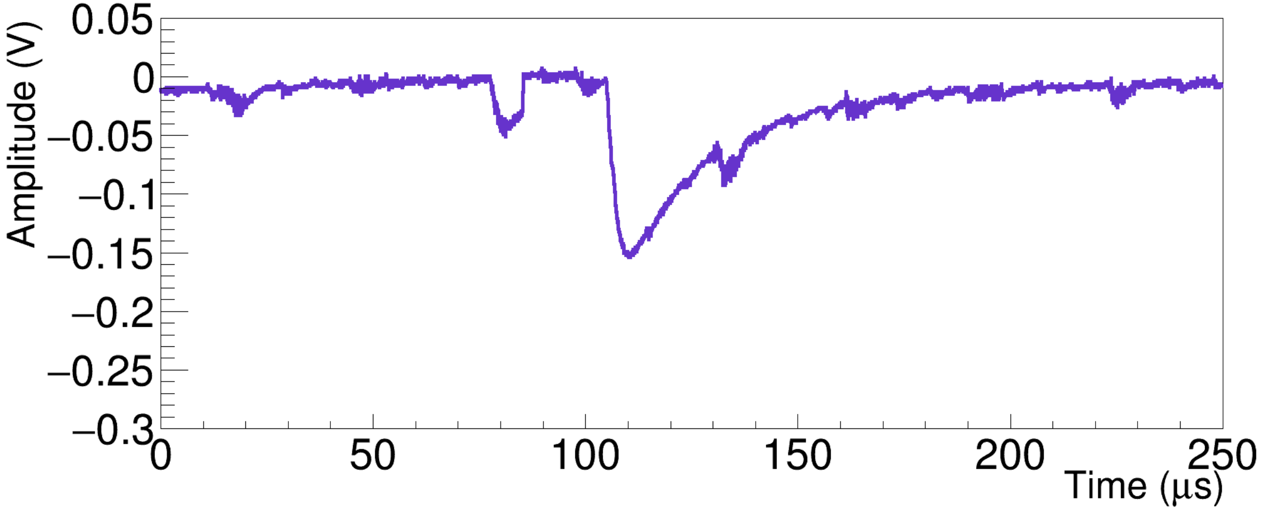
$$i_{\mathrm{TES}} = i_{\mathrm{bias}} \cdot \frac{R_{\mathrm{shunt}}}{R_{\mathrm{shunt}} + R_{\mathrm{par}} + R_{TES}}$$

Excessive Noise on Signals with this Setup

I







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Detection of Low-Energy Electrons with Transition-Edge Sensors

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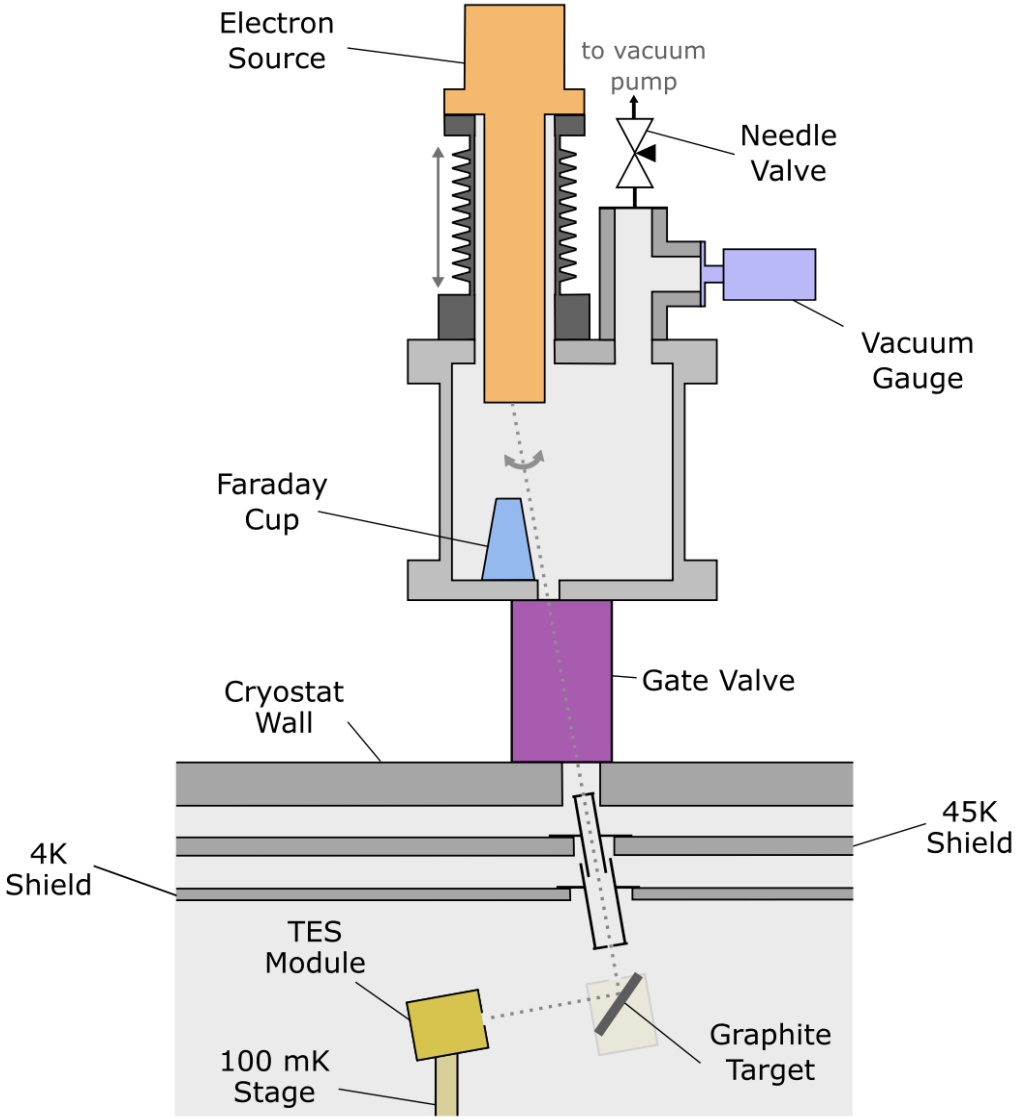
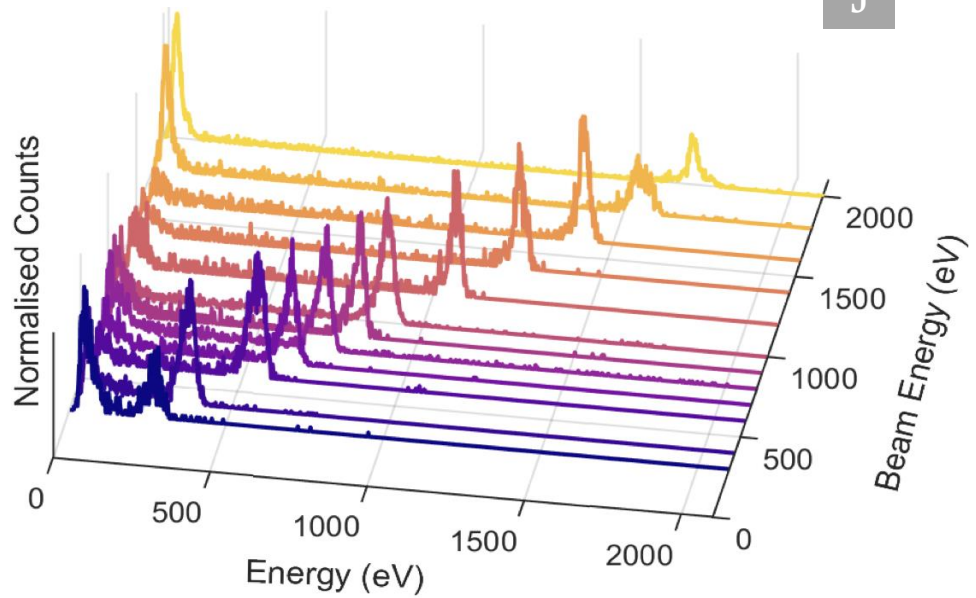
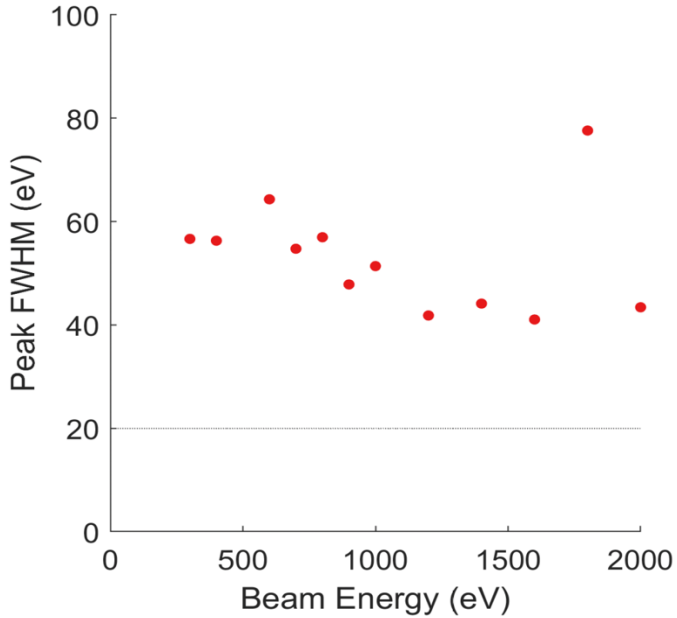
We present the first detection of electrons with kinetic energy in the 100 eV range with transition-edge sensors (TESs). This has been achieved with a (100×100) μm^2 Ti-Au bilayer TES, with a critical temperature of about 84 mK. The electrons are produced directly in the cryostat by an innovative cold source based on field emission from vertically-aligned multiwall carbon nanotubes. We obtain a Gaussian energy resolution between 0.8 and 1.8 eV for fully-absorbed electrons in the $(90 - 101)$ eV energy range, which is found to be compatible with the resolution of this same device for photons in the same energy range. This work opens new possibilities for high-precision energy measurements of low-energy electrons.

Cambridge Results







Energy resolution:

$$\sigma(eV) = \frac{FWHM(eV)}{2.35}$$

→ $\sigma > 17eV$

https://doi.org/10.17863/CAM.104850