Quasiparticle Diffusion in CRESST Light Detectors

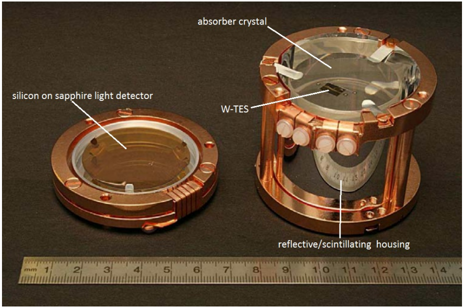
Marc Wüstrich

Max-Planck Institute f. Physics

19.07.2014

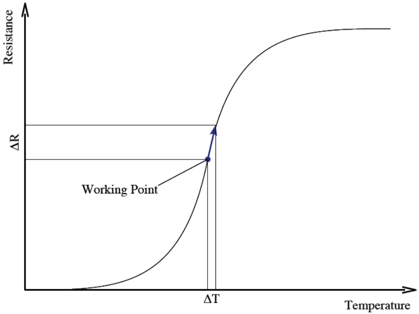
Transition Edge Sensors

- Transition Edge Sensors (TES) common tool to measure precisely energy depositions in a absorber
- TES are sensitive to tiny temperature changes ($\Theta(\mu K)$) in the absorber if operated in the mK scale

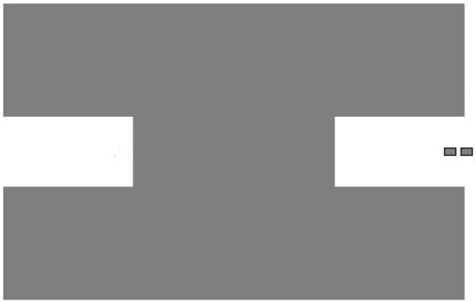


Transition Edge Sensors

- Transition Edge Sensors (TES) common tool to measure precisely energy depositions in a absorber operated in the mK scale
- TES are sensitive to tiny temperature changes ($\Theta(\mu K)$) in the absorber

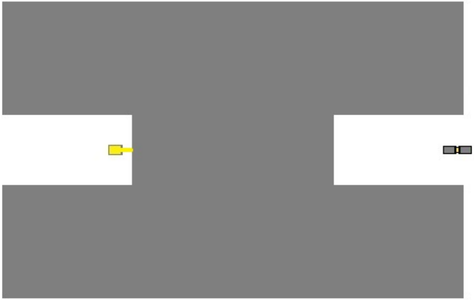


Setup for CRESST TES



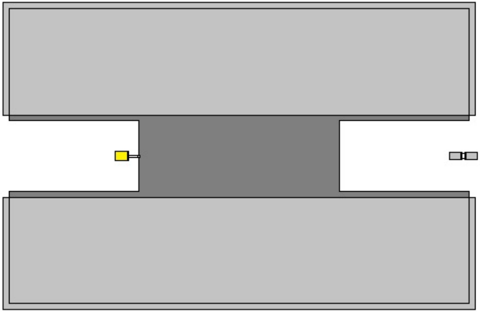
- W layer (100nm-200nm) serving as TES with T_C between 15-20mK

TES setup for CRESST



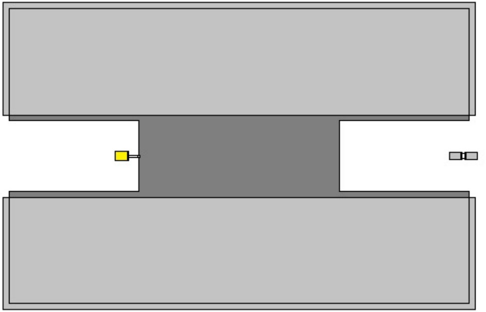
- W layer (100nm-200nm) serving as TES with T_C between 15-20mK
- Au layer serving as thermal link and heater connection

TES setup for CRESST



- W layer (100nm-200nm) serving as TES with T_C between 15-20mK
- Au layer serving as thermal link and heater connection
- supercunducting Al layer covering most of the W serving as phonon collectors (PC) (proximity effect)

TES setup for CRESST



- W layer (100nm-200nm) serving as TES with T_C between 15-20mK
- Au layer serving as thermal link and heater connection
- superconducting Al layer covering most of the W serving as phonon collectors (proximity effect)

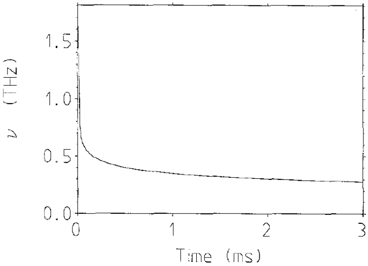
5-6 days of production

Signal evolution in TES systems

1. Energy deposition in the absorber => Phonon production and evolution in the absorber
2. Transmission of the phonons from the absorber into the TES/PC
3. Phonon interactions in the TES
4. Phonon interactions in the PC

Signal evolution in TES systems: Energy deposition in the absorber

- recoils produce high frequency optical phonons with a broad frequency distribution ($\mathcal{O}$ (10 THz))
- within 10 μs the phonons decay rapidly to acoustic phonons with a moderate frequency ($\mathcal{O}$ (0.5 Ghz))
- due to surface scatter and crystal inhomogeneities the absorber is completely populated with non-thermal phonons
- non-thermal phonons have lifetime of some ms and decay very slowly to smaller frequencies



Signal evolution in TES system: Phonon transmission into the TES

- Transmission of the non-thermal phonons into the TES/PC

$$Q_{A \rightarrow T} \propto \frac{1}{2} \cdot \left\langle \frac{E}{V_A} \right\rangle \cdot \left\langle v_{g,\perp} \cdot \alpha \right\rangle$$

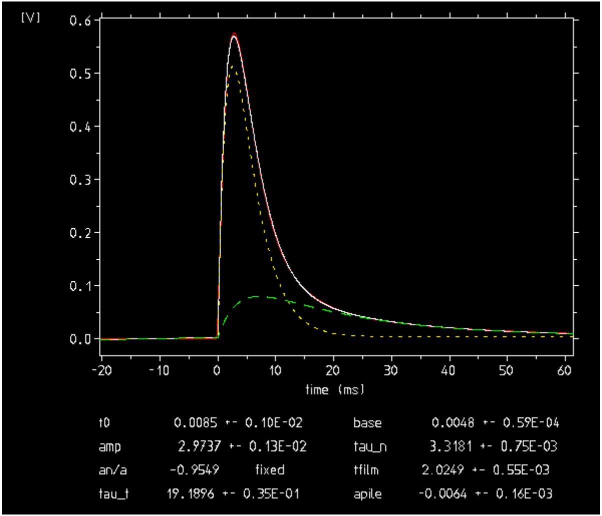
- for the materials used in CRESST LDs the transmission values are between 60%-70%
- inluence of the absorber volume to the transmission explains CRESST strategy towards smaller crystals to lower energy threshold

Signal evolution in TES system

Phonon interaction in the TES

- interaction of thermal phonons is strongly suppressed due to T^5 dependence
- Absorption of transverse phonons $\propto \nu$ => strongly suppressed
- Absorption of longitudinal phonons $\propto \nu^2$ => complete absorption ans strong coupling to the electron system
- strong electron-electron coupling => homogeneous heating of the TES

Signal composition in a TES



$$T(t) = \Theta(t - t_0) \cdot \left(A_n \cdot (e^{-t/\tau_n} - e^{-t/t_{in}}) + A_t \cdot (e^{-t/\tau_t} - e^{-t/t_n})\right)$$

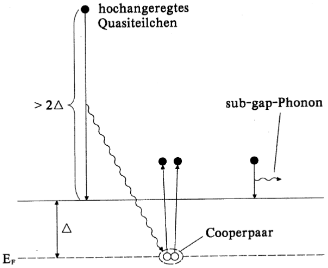
Phonon collectors

- PC are superconducting parts of the TES that reduce the collection time of non-thermal phonons by increasing the collection area
- The heat capacity is not increased by their addition

$$\tau_{col} = \frac{2V_A}{A\langle v_{g\perp} \cdot \alpha \rangle} \qquad C_{TES} \propto A$$

Phonon interaction in the phonon collector

- non-thermal phonons break up Cooper Pairs in free electrons (Quasiparticles)
- as long the energy of the QP is above the band gap, more Cooper Pairs are split up
- QP diffuse thermally in the PC untill the TES is reached where they can interact with the electron system of the TES

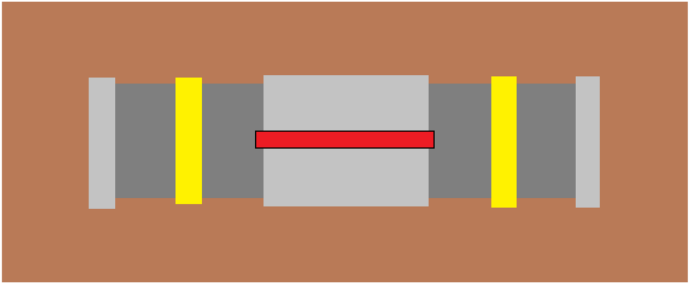


But:

- PCs only influence the TES signal positively if the generated QPs actually reach the TES before their recombination
- The dimensions of the PC have to be adjusted to the diffusion length of the QPs

Measurement

General Setup



- Rad marked area is illuminated by an Fe55 source
- Measurement of the correlated particle signals in the right and left W-TES

Setup

- The number of detected quasiparticles in a detector in a certain distance can be calculated by solving the 1D diffusion equation

$$\frac{\delta n}{\delta t} - D \cdot \frac{\delta^2 n}{\delta x^2} + \frac{n}{\tau_{qp}} = 0 \tag{1}$$

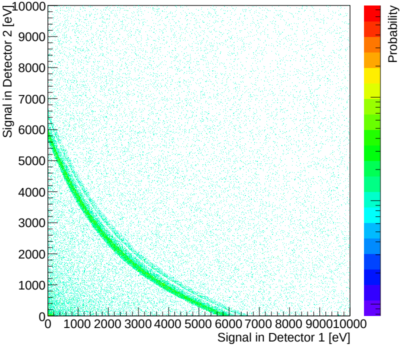
- The solution for the ratio number of detected quasiparticles in one detector is calctulated to be

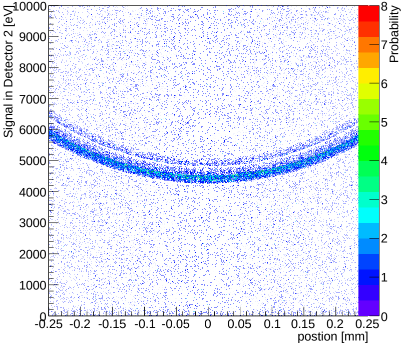
$$n_{1,2}(x_a) = \frac{sinh(\alpha(0.5 \pm \frac{x_a}{L})) + \beta cosh(\alpha(0.5 \pm \frac{x_a}{L}))}{(1+\beta^2)sinh(\alpha) + 2\beta cosh(\alpha)} \tag{2}$$

with $\alpha = \frac{L}{\sqrt{D \cdot \tau_{qp}}}$ and $\beta = \frac{\tau_{tr}}{\tau_{qp}}$

Simulation of the setup

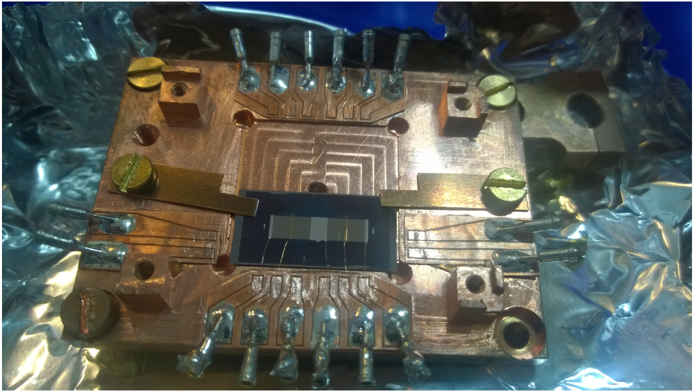
- Simulation of the detector response with a randomly distributed ^{55}Fe spectrum and realistic diffusion parameters





Measurement

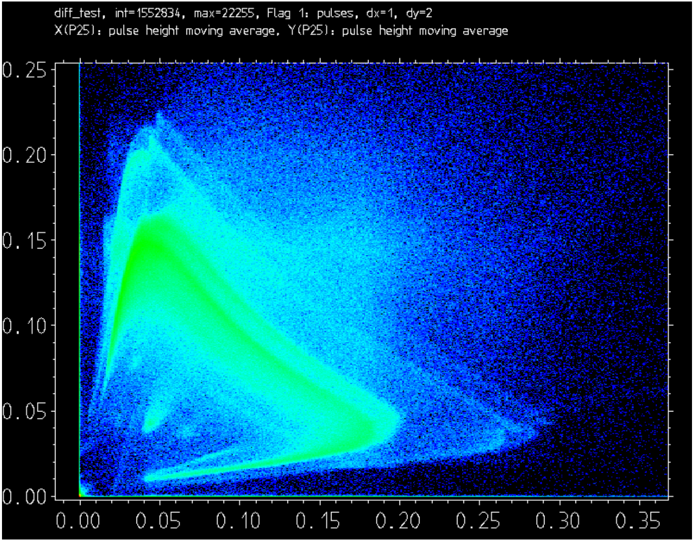
- Si substrate equipped with two TES with the same layer properties like CRESST light detectors



- Setup allows diffusion over a distance of 2mm

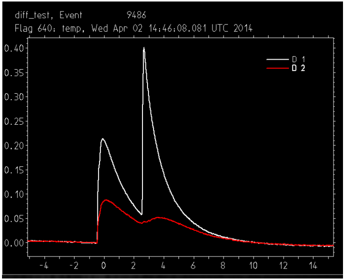
Analysis

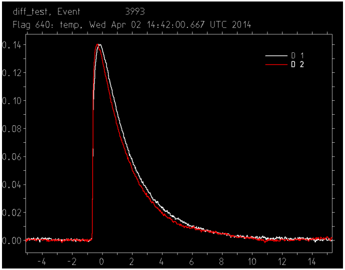
- raw data



Analysis

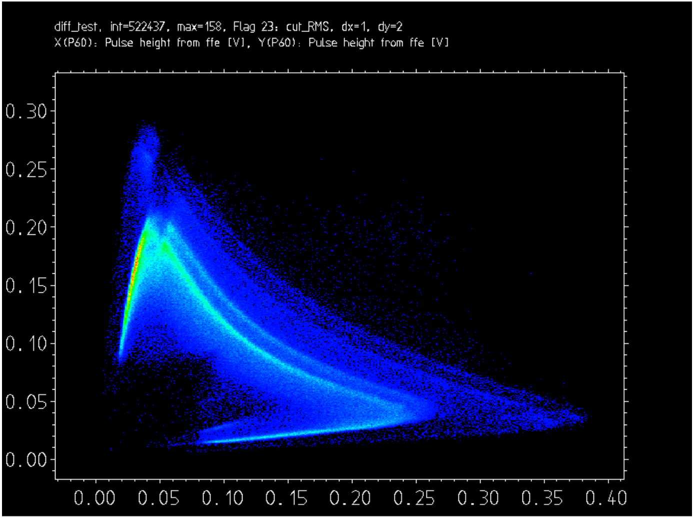
- selection of good pulses (removing pile up events, SQUID artefacts,....)





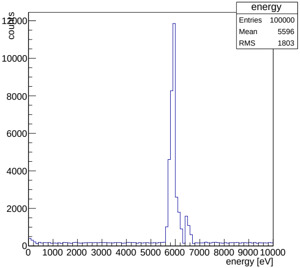
Analysis

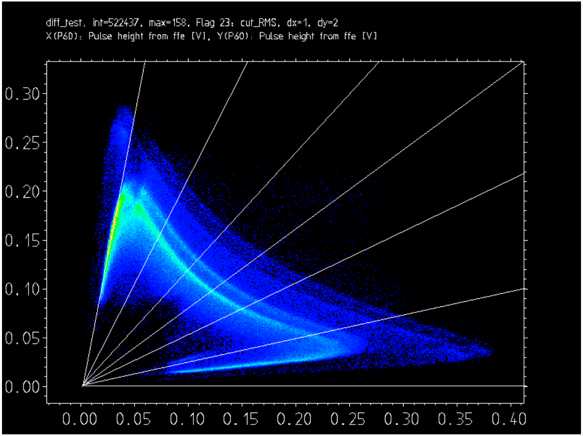
- cutted data (all events poluted with measurement artefacts are removed)



- distinct event classes: substrate hits, PC hits, direct TES hits

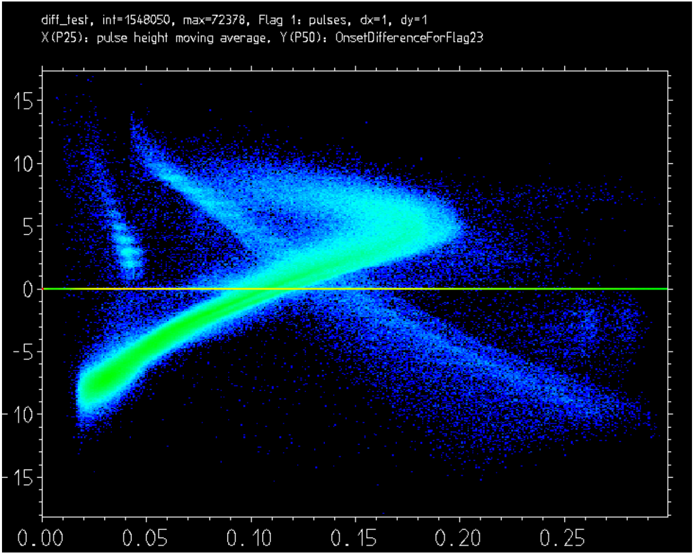
Event selection





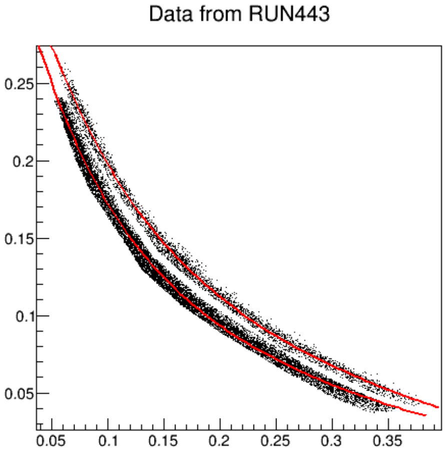
Event discrimination

- separation of PC hits and substrate hits necessary =¿ discrimination possible onset difference



Event discrimination

- after isolating the respective particle populations, fit of the data to determine diffusion parameters

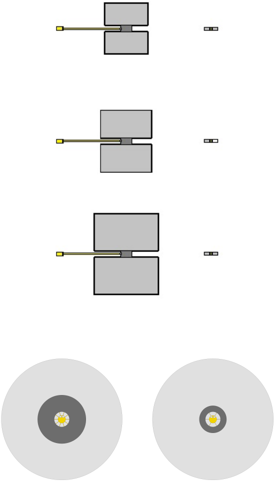


Results

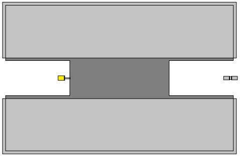
- 4 independent measurements with different substrates reproduced the diffusion parameters
- the measured diffusion length stays between 1-2mm
- the diffusion length is strongly dependent on the quality of the Al phonon collectors (RRR)

=> Diffusion length is much longer than expected

Influence on future CRESST detectors



- in future CRESST detectors the size of the PC is increased relative to the TES size
- first measurements show that 200% more PC area increases the signal height by 30%



Summary

- The efficiency of TES can be increased significantly by the addition of phonon collectors
- The diffusion parameters of the generated Quasiparticles have to be determined for the respective detector setup
- The diffusion length is determining the dimensions of the PC

=> Underestimation of the QP diffusion in CRESST light detectors
=> Next-generation TES are adjusted to the new results by bigger phonon collectors

Thank you!