Particle response of antenna-coupled TES arrays

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Detectors in space

Planck glitch experience

Planck HFI saw frequent ($\sim 1/s/det$) ‘glitches’ in data. The Planck team conclusioned:

- Glitches were caused by particle interactions with some of the surrounding assembly, not just the bolometer.
- Some glitches have long recovery times ($\sim 1$s).

Cleaning data required careful template fitting and subtraction and some excision.

A. Catalano et al. 2014
TES arrays in space

Future space missions (PICO, Lite-BIRD, SPICA, OST and more) will feature larger and more densely populated detector arrays.

- These arrays will have a higher rate of interactions and those interactions may couple to many near-by detectors on the wafer.

- **Multiplexing** may cross-talk glitches across channels.
Modern arrays:
Three telescopes observing at 90GHz and three telescopes observing at 150GHz, totaling more than 2400 TESs.

Multiplexed:
NIST SQUID readout chain and multiplexed by time-division Multi Channel Electronics (MCE) from UBC.

Space-like environment:
16 days floating at ~40km.
SPIDER TES arrays by JPL

Dense wafers, interleaved phased antenna arrays and TES islands

Each grid-square has two interleaved phased antenna array sets of orthogonal polarizations.

Detector NEP $2-4 \times 10^{-17}$ W/rtHz

Photoshop mosaic
Flight expectations

<table>
<thead>
<tr>
<th>TES island</th>
<th>Wafer</th>
</tr>
</thead>
<tbody>
<tr>
<td>dimensions</td>
<td>300(\mu m) (\times) 150(\mu m) (\times) 1(\mu m)</td>
</tr>
<tr>
<td>rate</td>
<td>(\sim 1/10) min</td>
</tr>
<tr>
<td>deposition</td>
<td>250 eV</td>
</tr>
</tbody>
</table>
Flight results

- **Glitch rate:** $\sim 1/3 \text{min/det}$.  
  - Each glitch lasts $< 0.1 \text{s}$.  
  - $\Rightarrow < 1\%$ of data is excised because of cosmic rays!

### Coincidence rates (averaged)

- $\frac{N_{\text{dets} > 1}}{N_{\text{events}}}$: $5.3\%$  
- $\frac{N_{\text{dets} = 2}}{N_{\text{events}}}$: $\sim 90\%$

### Coincidence pattern

<table>
<thead>
<tr>
<th></th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB partner</td>
<td>$&lt; 0.5%$</td>
<td>$7.4%$</td>
</tr>
<tr>
<td>Adj. mux row</td>
<td>$&lt; 0.5%$</td>
<td>$0.6%$</td>
</tr>
</tbody>
</table>
Lab setup
Constructed and run at UIUC

Custom FPU built from all flight systems:
- A recovered SPIDER flight TES wafer
- Recovered SPIDER flight SQUIDs
- A recovered SPIDER flight telescope base
  - incl. the sub-kelvin fridge
- Flight-like multiplexer
Lab set-up: $5\,MeV\ \alpha$s from $^{241}\text{Am}$

- Two sources are placed directly over TES islands, we expect a few $\alpha$ interactions per min, depositing $100\,keV$ to $1\,MeV$ into each island.
- Two sources are placed over antenna patches, each providing hundreds of $\alpha$s/s interactions depositing $5\,MeV$ into the wafer.
Lab set-up: 5MeV $\alpha$s from $^{241}$Am

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- Two sources are placed over antenna patches, each providing hundreds of $\alpha$s/s interactions depositing 5MeV into the wafer.
Lab rates

Lab agrees with flight:

- Detector sensitivity is localized to near the TES island.
Lab coincidences

For a glitch on **Primary**, what is the probability of a glitch on cross-talkers?

- AB partner: 9.8%
- Next mux row: 8.8%

Expected Poisson coincidence < 0.5% in AB pair.

Some cross-talk mechanisms evident:

- **AB pair correlated:**
  - \( \Rightarrow \) Could be either wafer propagation or cross talk.

- **Next mux row correlated:**
  - Adj. mux row cross-talk visible in lab, not in flight. Possibly because of lab’s high energy depositions.
Lab coincidences

For a glitch on **Primary**, what is the probability of a glitch on 
cross-talkers?

<p>| | |</p>
<table>
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<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AB partner</td>
<td>13.7%</td>
</tr>
<tr>
<td>next mux row</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Some cross-talk mechanisms evident:

- **AB pair correlated:**
  - ⇒ Could be either wafer propagation or cross-talk.

- **Next mux row correlated:**
  - ○ Adj. mux row cross-talk visible in lab, not in flight. Possibly because of lab’s high energy depositions.
Lab glitch shapes at 15.2kHz

- Some glitches saturate (expected!) at this TES bias.
- Diverse rising and falling time constants (notice trace crossings!).
  - Diverse falling time constant could come from where the energy is deposited in the island or along the legs (modeling work by JPF).
- Very fast rise and fall times only occur in low energy glitches.
Flux slips

There are flux slips on the rising edges of very big glitches. Causing the readout system to recover one SQUID flux period away from where it should.

At SPIDER 1’s sampling rate, these shapes have no information about the underlying glitch.

In SPIDER these happen about 1/hour/det.
Take-aways and looking forward

- The detectors are **not sensitive to large areas** of the wafer, sparing them of a significant analysis glitch impact.
  - The detectors are **probably sensitive to depositions on the legs**, increasing the area of sensitivity and causing ‘rounded’ glitch shapes.
- Multiplexing is responsible for some cross-talk, but we now know **SQUID periodicity is responsible for converting big glitches into flux-slips**.
- Repeating the tests at 100$mK$.
- Further modeling work:
  - flux-slip mitigation.
  - particle-leg interactions.
  - energy calibrating non-linear / non-ideal glitches.
This work is supported by NASA Strategic Astrophysics Technology (SAT) program, and the SPIDER collaboration.
Adding multiplexing to readout

Showing time division with SQUID amplifier chain
Need to include:

- Fractional transfer of energy from legs.
- Glitch → step cut-off.
- Energy calibration for non-linear/non-ideal glitches.
SPIDER flight cosmic ray spectrum for X1

$dN/dE$ [count/min/keV/det]

$E$ [eV] (est.)

- Tile 1
- Tile 2
- Tile 3
- Tile 4
- Planck long
- Planck short

Flight Spectrum 1/6
SPIDER flight cosmic ray spectrum for X3

The graph shows the differential number of counts per minute per kiloelectron volt per detector ($\frac{dN}{dE}$) as a function of energy ($E$) in electron volts (eV). The x-axis represents the energy range from 100 eV to 50 keV, and the y-axis represents the number of counts ranging from $10^{-6}$ to $10^3$. The graph includes data for different tiles (Tile 1, Tile 2, Tile 3, Tile 4) and comparison with Planck long and short models.
SPIDER flight cosmic ray spectrum for X5

$dN/dE [\text{count/minute/keV/det}]$

$E [\text{eV}] (\text{est.})$

- Tile 1
- Tile 2
- Tile 3
- Tile 4
- Planck long
- Planck short
SPIDER flight cosmic ray spectrum for X6

$dN/dE [\text{counts}/\text{min}/\text{keV/det}]$

$E[\text{eV}](\text{est.})$

- Tile 1
- Tile 2
- Tile 3
- Tile 4
- Planck long
- Planck short

Flight Spectrum 6/6
Flux slips explained: In simulation 1/3

Tracing a 10 keV deposition

Tracing a 25 keV deposition
Flux slips explained: In simulation 2/3

Tracing a 10 keV deposition

Tracing a 25 keV deposition
Flux slips explained: In simulation 3/3
Effects of bias on flux slips

Flux slips can be prevented in tuning or TES design.

Simulation: TES responds to instantaneous $E_{dep}$
TES biased at $R = 0.5R_N$

Biased at $R_{TES} = 1/2 \, R_n$

Simulation: TES responds to instantaneous $E_{dep}$
TES biased at $R = 0.75R_N$

Biased at $R_{TES} = 3/4 \, R_n$

Simulation: TES responds to instantaneous $E_{dep}$
After MCE readout, filtering and decimation

Biased at $R_{TES} = 1/2 \, R_n$

Simulation: TES responds to instantaneous $E_{dep}$
After MCE readout, filtering and decimation

Biased at $R_{TES} = 3/4 \, R_n$
More details on SPIDER flight coincidences

<table>
<thead>
<tr>
<th>FPU</th>
<th>$N_{\text{events}}^{dets&gt;1} / N_{\text{events}}$</th>
<th>$N_{\text{events}}^{dets\leq2} / N_{\text{events}}^{dets&gt;1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>7.7%</td>
<td>87.4%</td>
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<tr>
<td>X2</td>
<td>3.7%</td>
<td>91.3%</td>
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<tr>
<td>X3</td>
<td>4.0%</td>
<td>89.0%</td>
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<tr>
<td>X4</td>
<td>2.5%</td>
<td>93.7%</td>
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<tr>
<td>X5</td>
<td>9.0%</td>
<td>83.0%</td>
</tr>
<tr>
<td>X6</td>
<td>4.9%</td>
<td>90.5%</td>
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</table>
More details on SPIDER flight coincidences
SPIDER 150GHz simulation parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>$I_c$</td>
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<tr>
<td>$C$</td>
<td>$1pJ/K$ at $450mK$</td>
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<tr>
<td>$G$</td>
<td>$20pW/K$ at $450mK$</td>
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<td>$L$</td>
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<tr>
<td>$R_{sh}$</td>
<td>$3mΩ$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>1096Ω</td>
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<tr>
<td>$P_{opt}$</td>
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