The Coordinating Panel for Advanced Detectors: CPAD 2022

# Performance of Highly Irradiated SiPMs

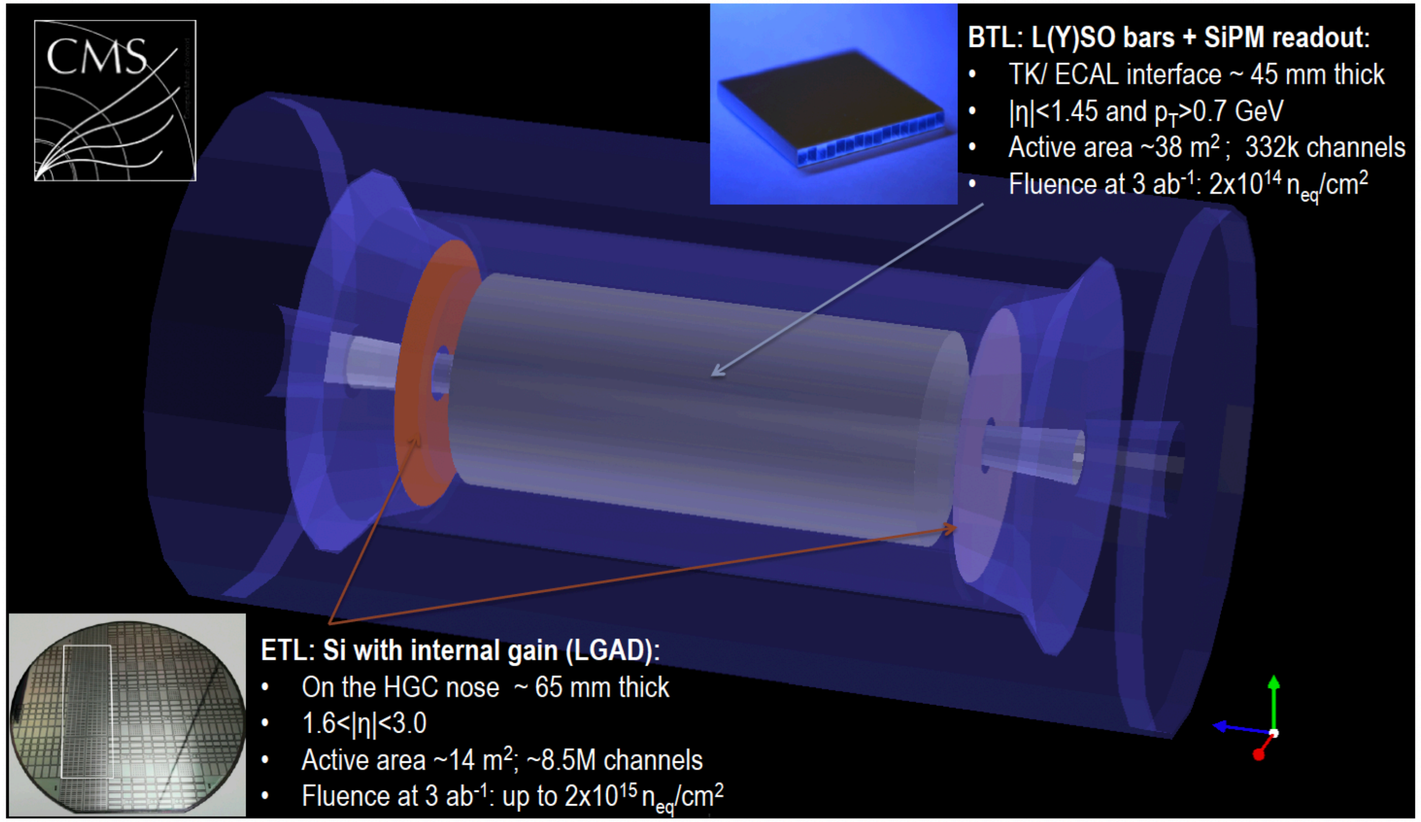
**Coupled to LYSO:Ce Crystals for the CMS MTD Barrel Timing Layer**

Carlos E. Pérez Lara

- University of Virginia -

for the CMS collaboration

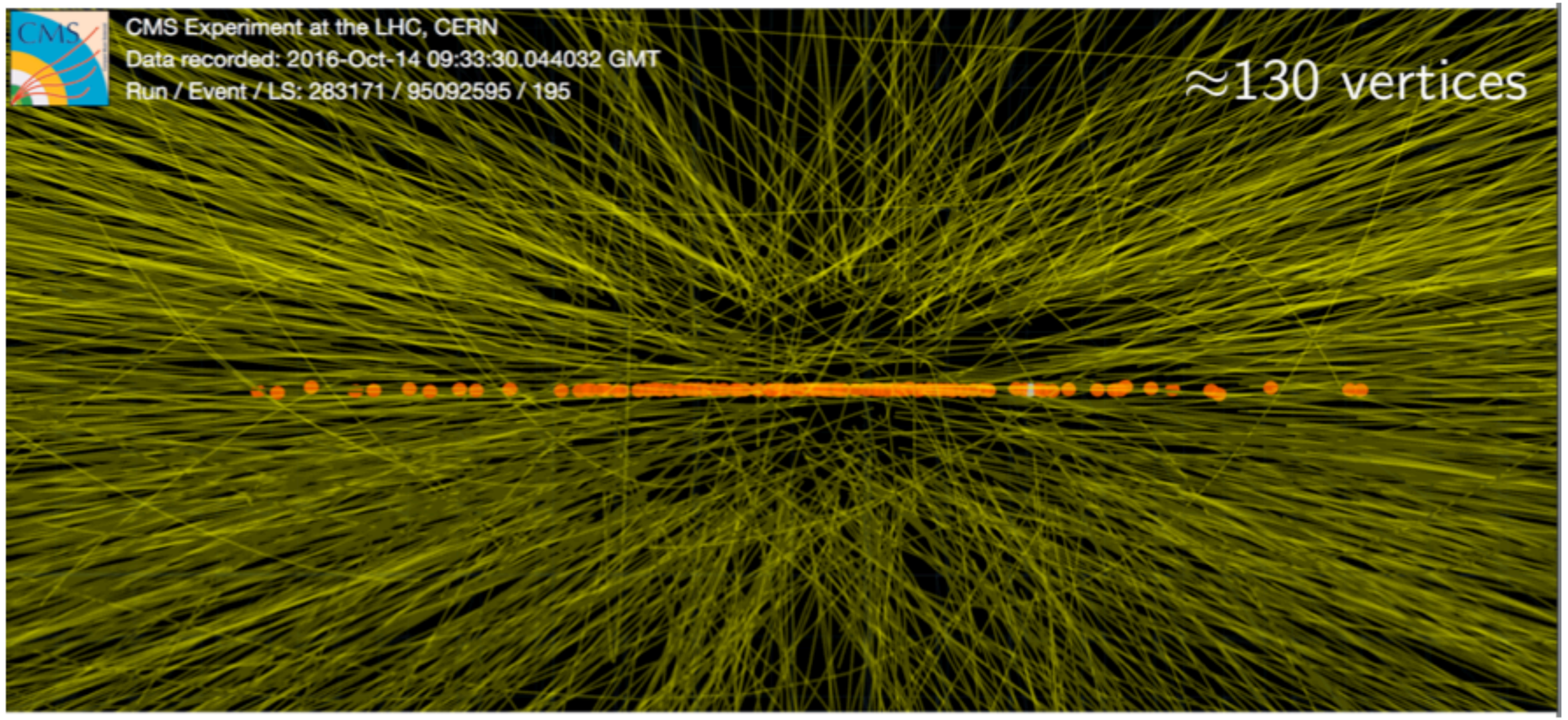
on behalf of the MTD group



# The Barrel Timing Layer Detector

CMS phase 2 upgrade program => High Luminosity LHC era

- We expect pile-up of 200 events per bunch crossing
  - Challenging to disentangle vertexes and to do tracking without upgrade



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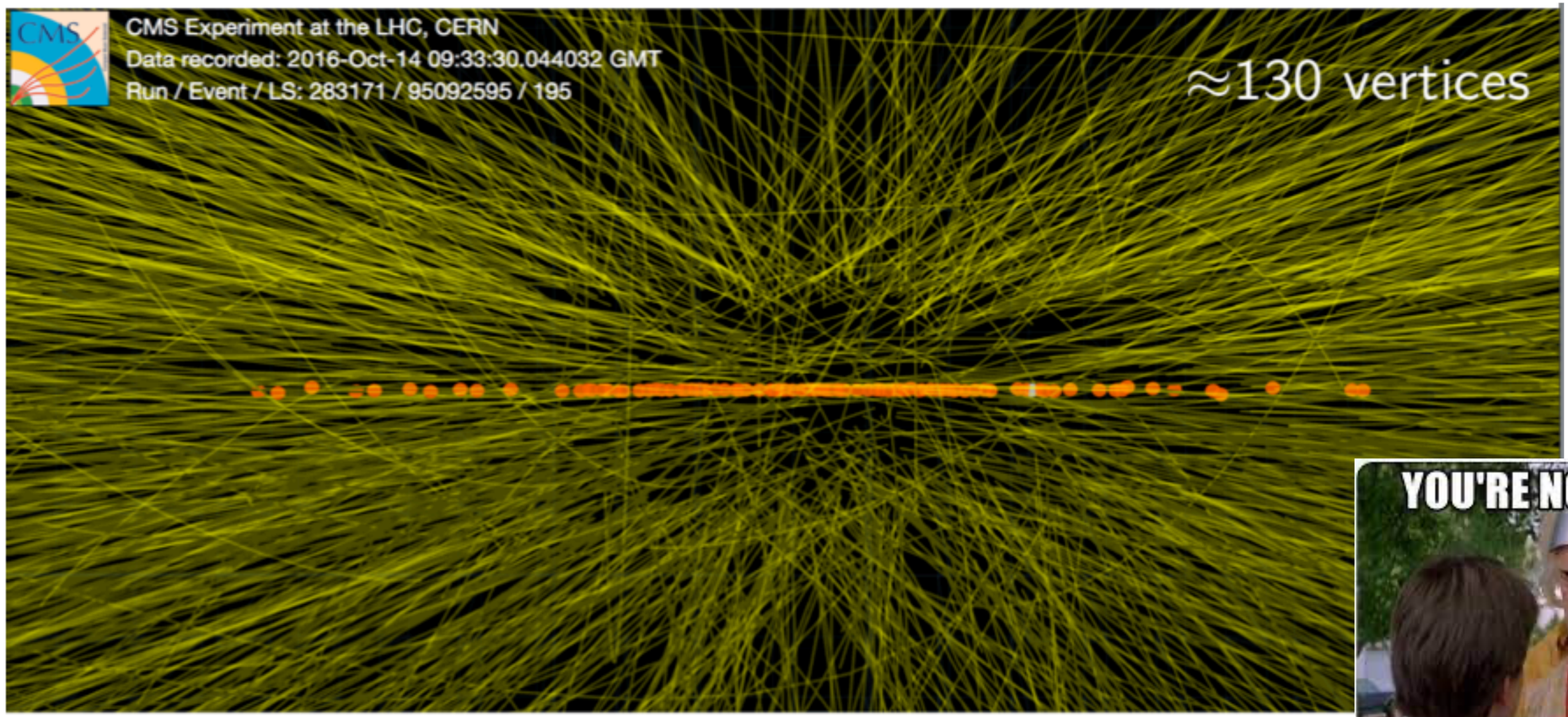


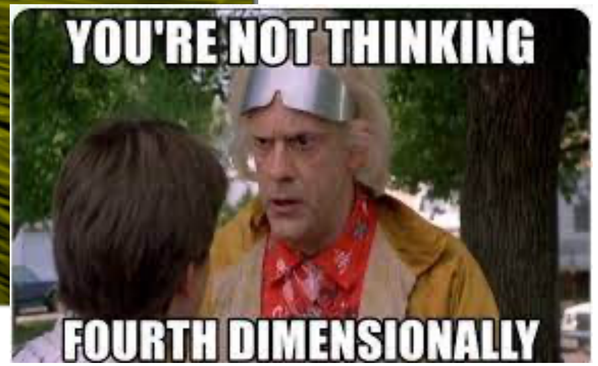

# The Barrel Timing Layer Detector

CMS phase 2 upgrade program => High Luminosity LHC era

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**MIP Timing Detector** - Improve vertex ID and aid tracking

Timing resolution from 30-40 ps to 50-60 ps

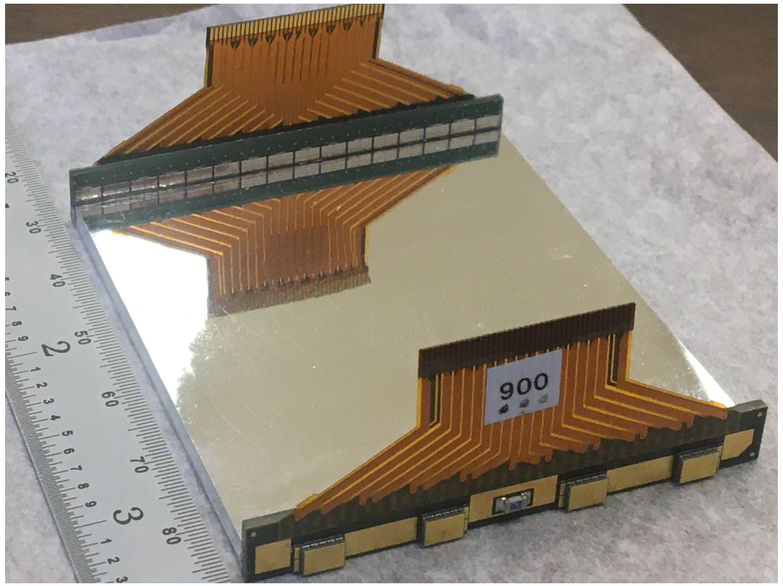
- Barrel Timing Layer : LYSO+SiPM

  Cylindrical coverage: 5.2 m length, 1.15 m radius

  - 10368 modules (each about 5.3x5.3 $cm^2$)
  - 1 module = 16 crystals, 32 SiPMs, 8 TECs, 1 ASIC

Effects from radiation damage currently under study

Crystal and SiPM array



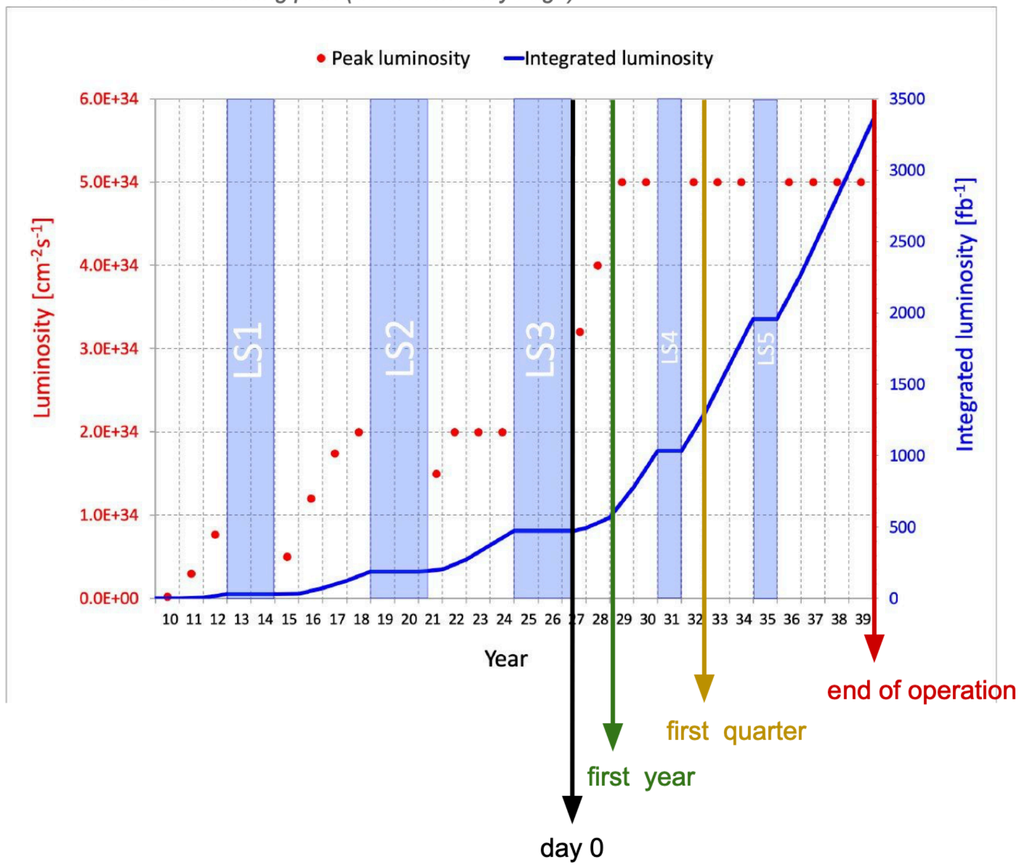

**SiPM's pros:**

- Insensitive to magnetic fields
- Good uniformity
- Compact size (3x3mm^2)
- Small pixel (15um)
- PDE > 20%
- Fast recovery time < 10ns
- Radiation tolerant*

# Expected Radiation Damage [>10 years operation]

## BTL life snapshots considered

*Nominal HL-LHC running plan (as of some days ago)*




- Consider three snapshots along the BTL lifetime
  - **First year (<200 fb$^{-1}$):**
    - PU ~ 100
    - integrated fluence 1e13 1MeV neq/cm²
    - OV ~ 3.0 V
  - **First quarter of operation (750 fb$^{-1}$):**
    - PU~140
    - integrated radiation 5e13 1MeV neq/cm²
    - OV ~ 1.8 V
  - **End of operation (3000 fb$^{-1}$):**
    - PU~140
    - integrated radiation 2e14 1MeV neq/cm²
    - OV ~ 1.0 V

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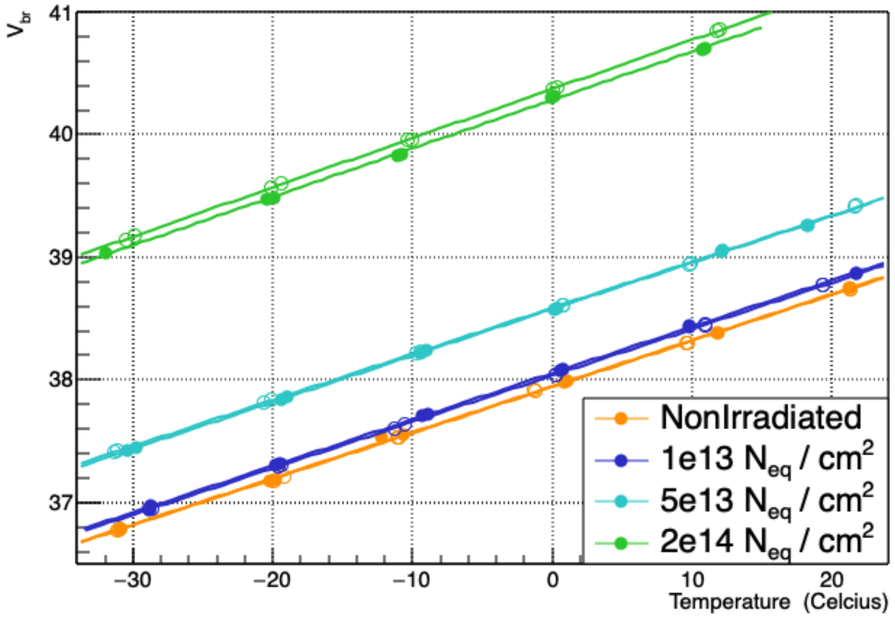
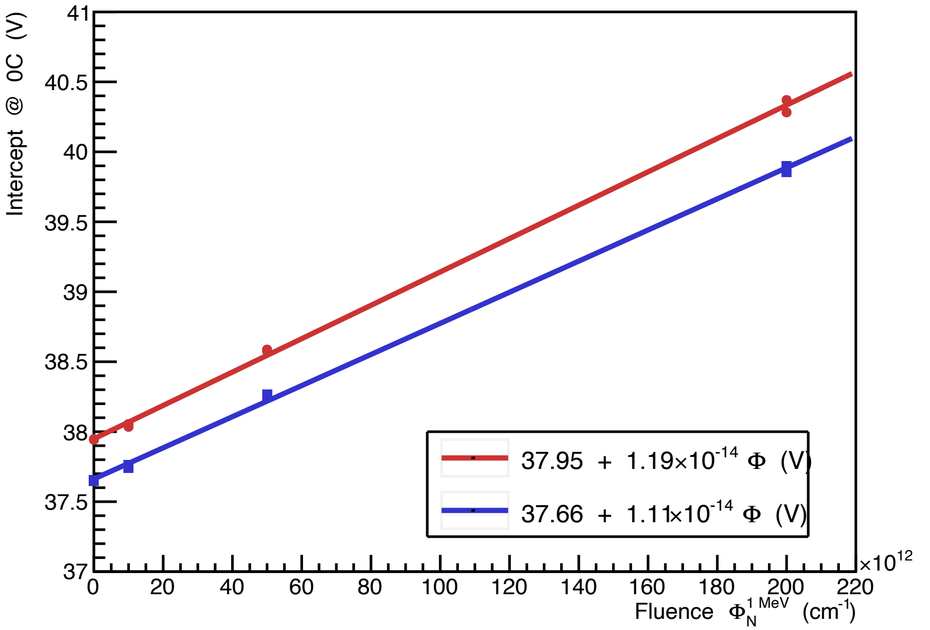
# Breakdown Voltage ($V_{br}$) as function of Temperature

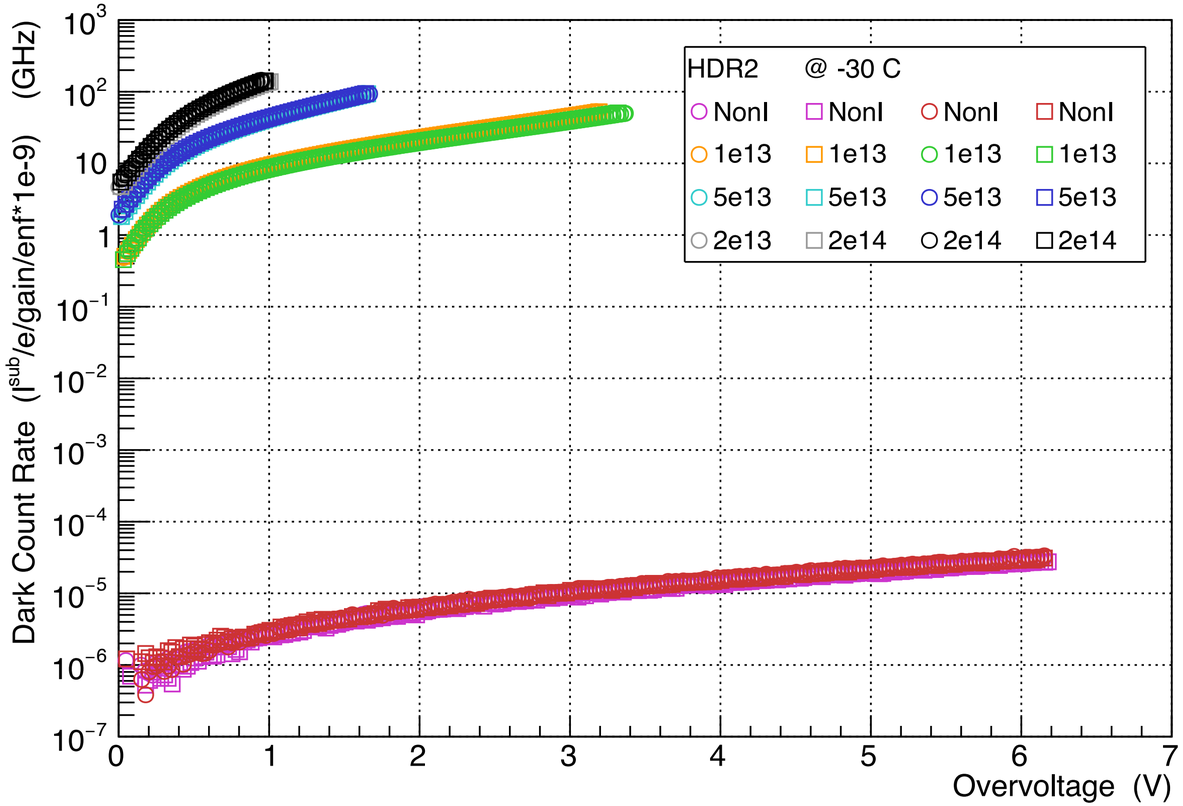
- IV curves are measured for each HDR2s at various temperatures
- $V_{br}$ is computed from inflection point after HDR2 enters into geiger mode domain
- Linear dependence with Temp found for all HDR2s. Similar slope ~37mV/deg
- Strong linear increase of intercept with fluence found in data

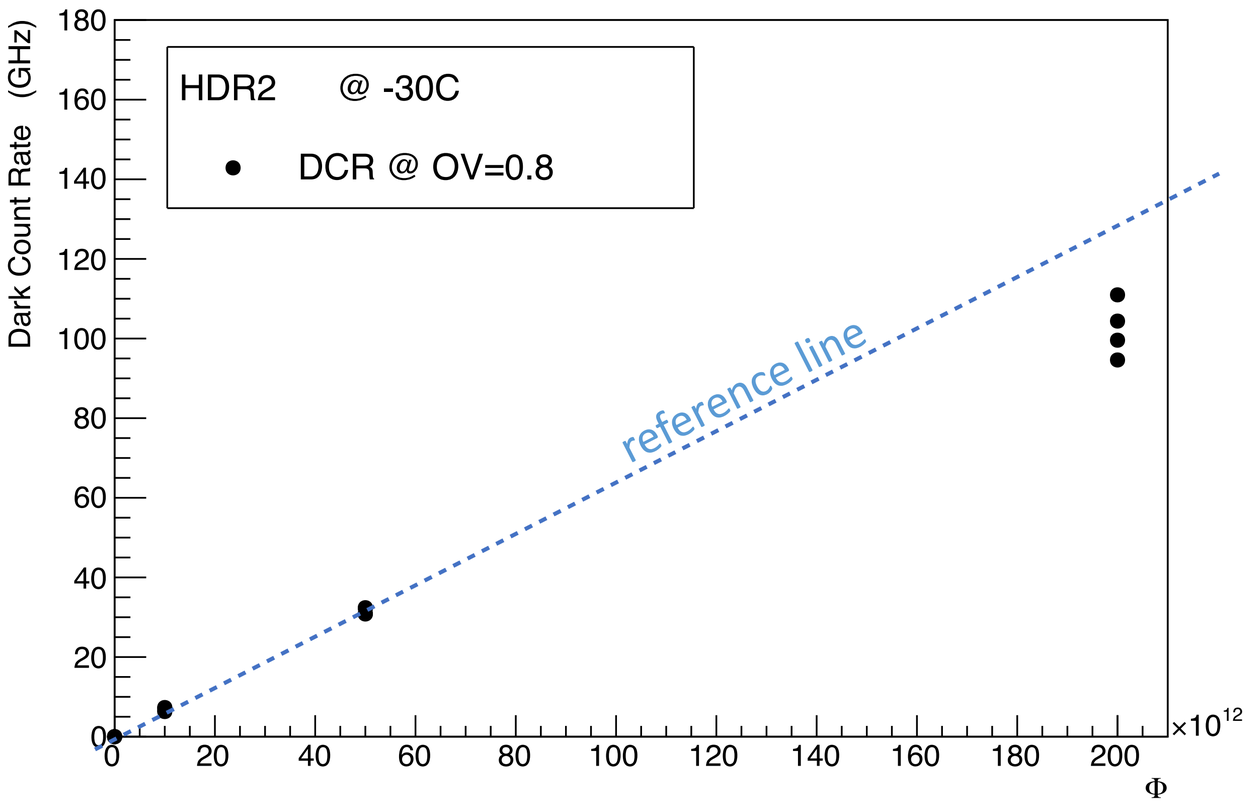



Vbr as function of temperature for HDR2 with different levels of radiation damage



# Dark Count Rate (DCR) as function of OverVoltage



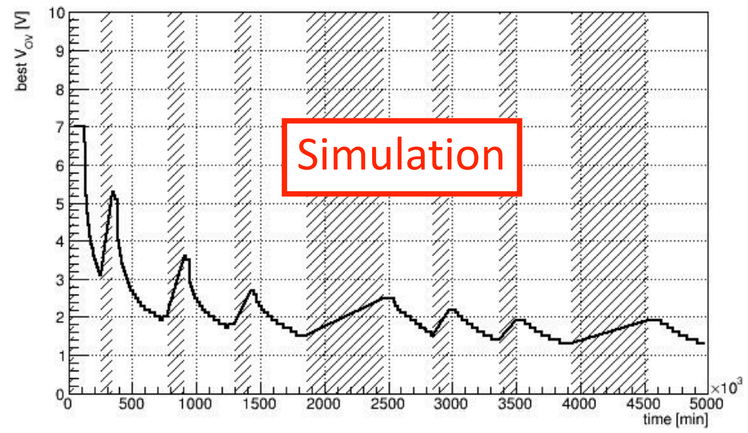



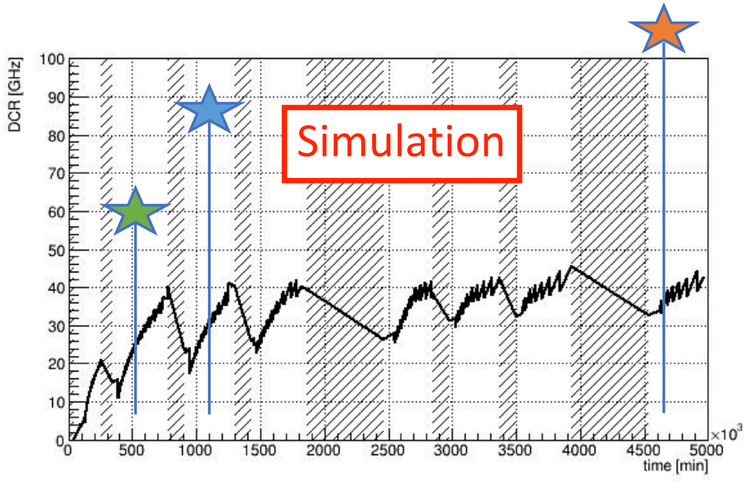

- DCR increases very rapidly with radiation damage!
- At -30C and 0.8 OV rise from 5 kHz to 100 GHz depending on radiation damage

# Extrapolation of Performance for a Ten Year Scenario

## Results for $T_{op}$ = -45° C, $T_{ann}$ = 40° C

- $T_{ann}$ = 40° C throughout the whole duration of Technical Stops / Long Shutdowns




- Silicon recovers most of its properties by heat treatment: annealing
- Thermal motion reduces structural defects and stress caused by radiation
- Periods of annealing are foreseen for BTL during LHC shutdowns as depicted by the gray bands in the plots
- To obtain DCR levels at the TB operational temperature, comparable to what we expect in BTL at the end of life, we subjected four SiPMs to a high-temperature annealing procedure

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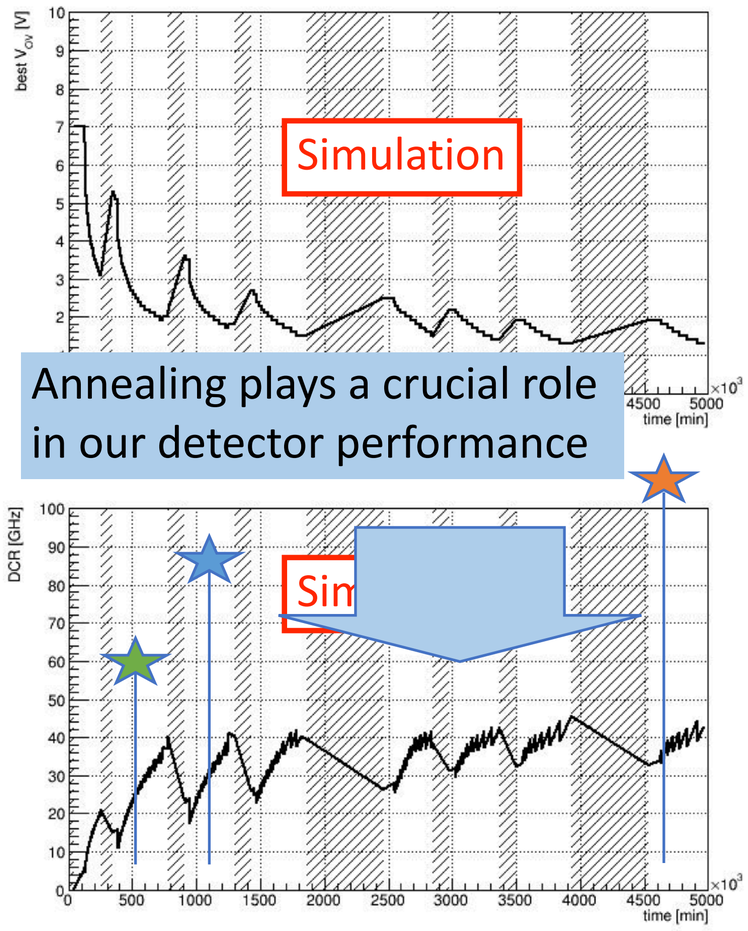


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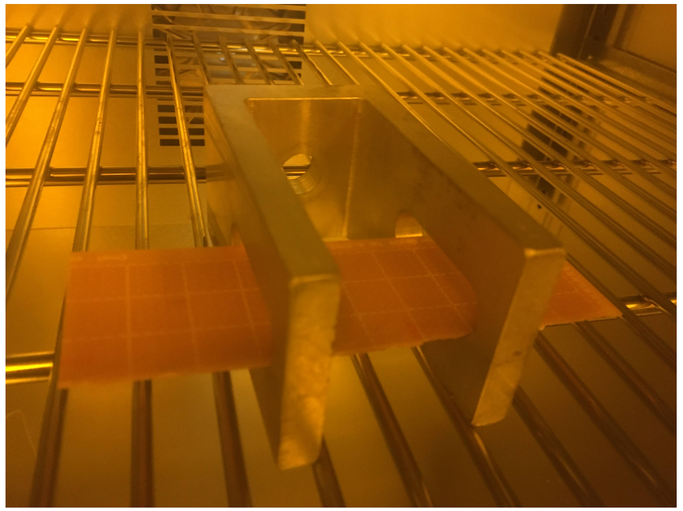
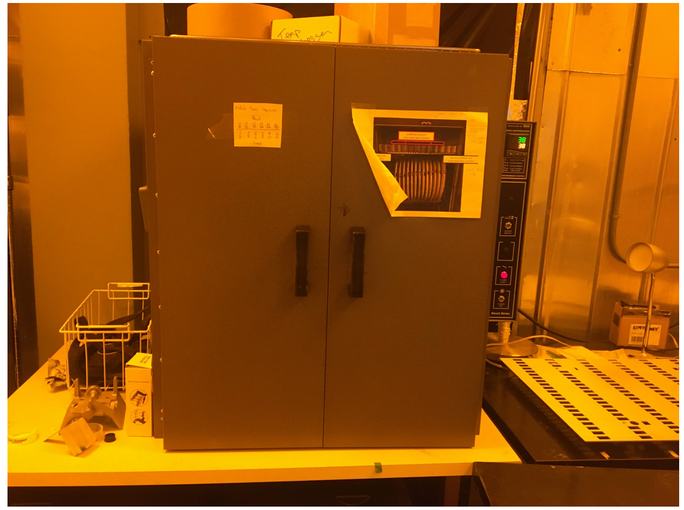
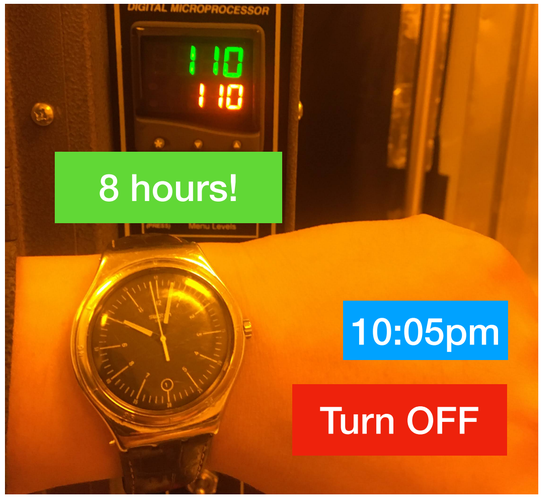
# High Temperature Annealing

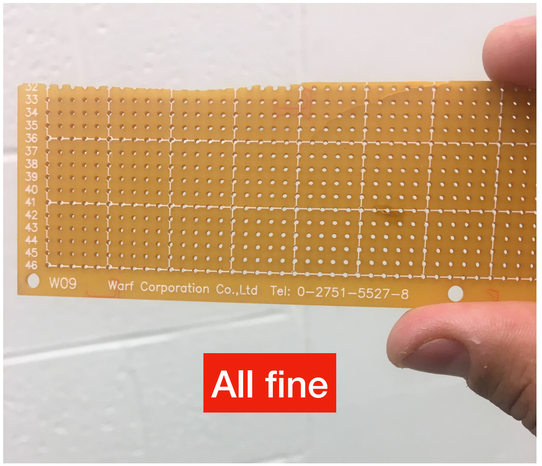


**It was shown by T. TSang [2018 JINST 13 P10019] that SiPMs can withstand high temperature annealing procedure up to 250 C (also HPK although with epoxy resin)**

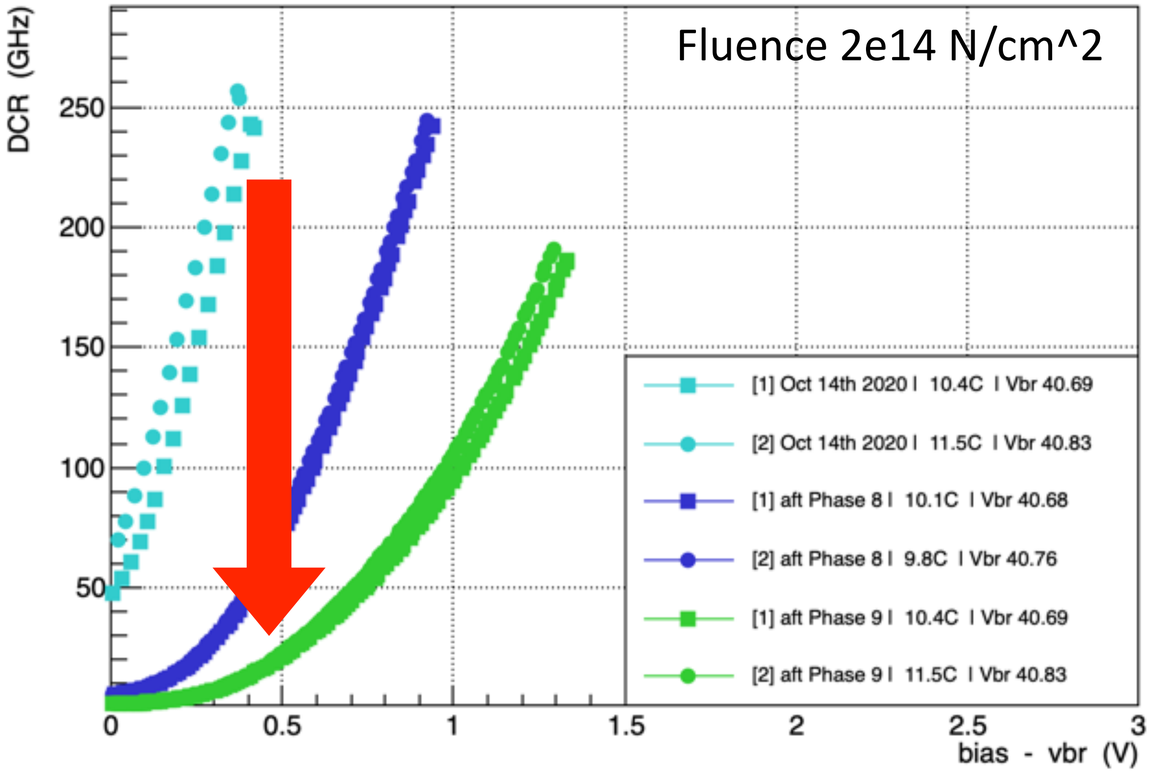


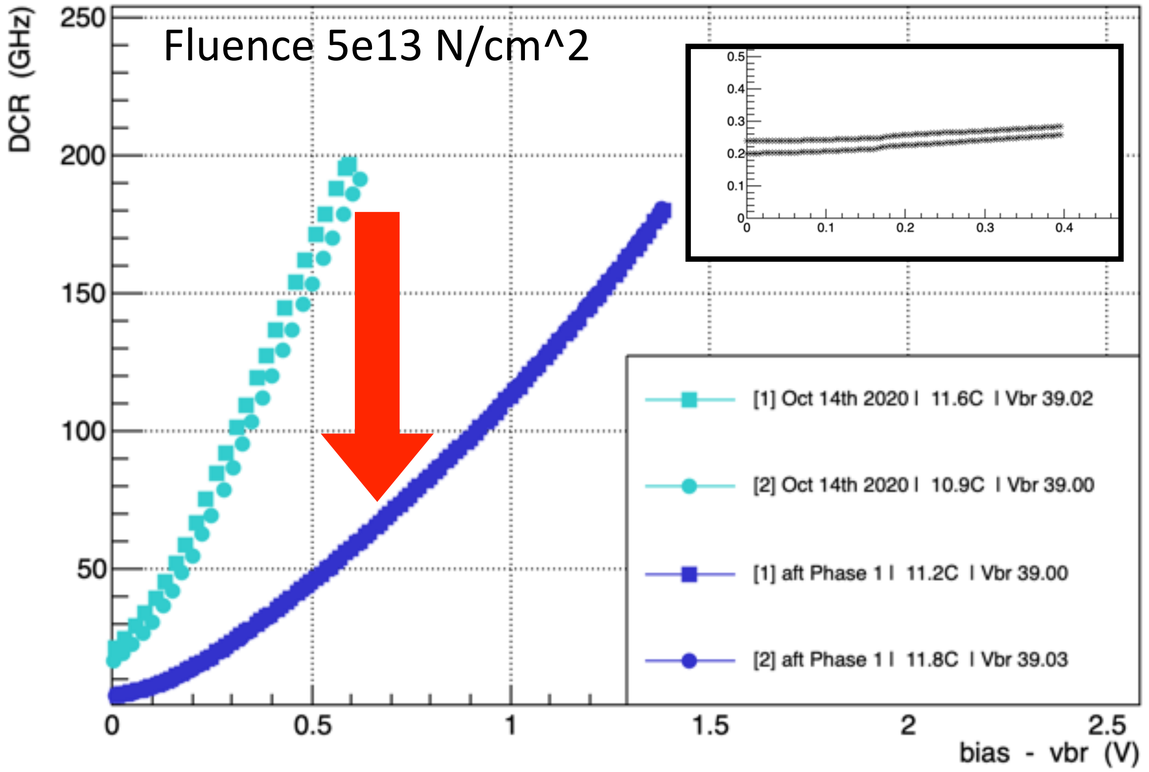




# Annealing Performance in the Lab



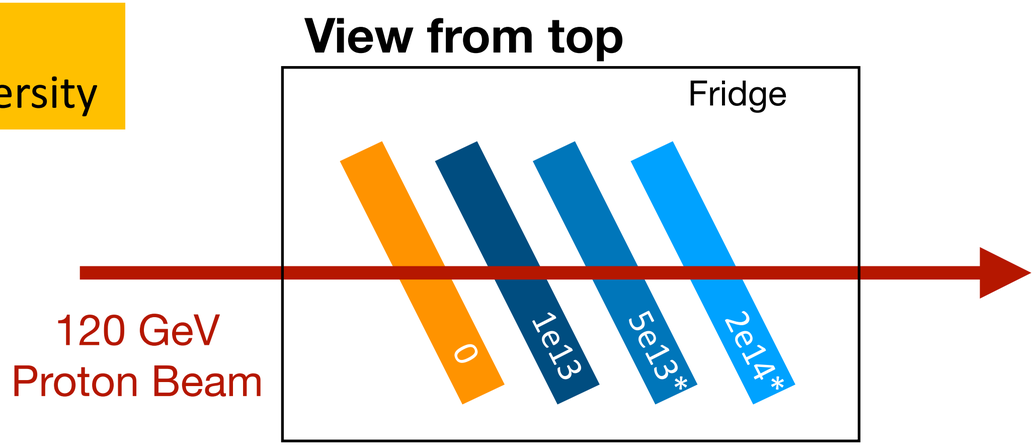

- **Phase 8**: 2 hours at 110C
  Storing at 10 deg
- **Phase 9**: 4 days at 120C

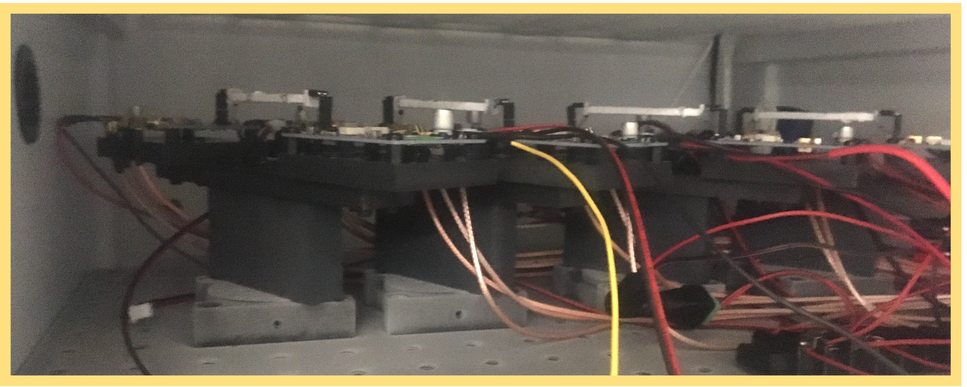
- **Phase 1**: 2 days at 90C  Factor 5!

- Worth mentioning here: The full detector will have an active thermal layer between the SiPMs and cooling to locally anneal SiPMs only (more on this later)

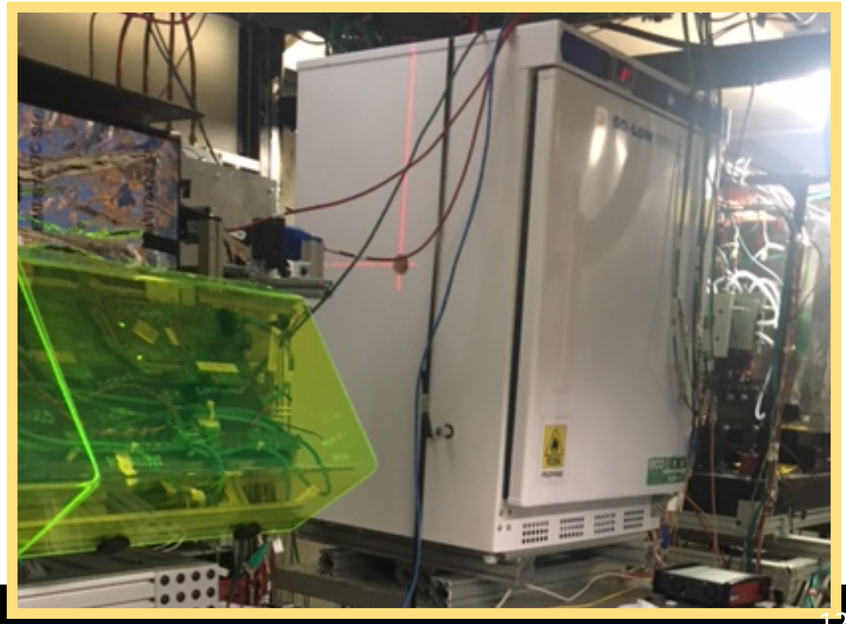
# May’21 Testbeam: Prototype Perf. w/Irrad SiPMs

PhD students from NorthEastern University



- Four BTL prototypes with different levels of radiation simultaneously exposed to a 120 GeV proton beam
  - 0, 1e13, 5e13*, 2e14* (Neq/cm$^2$)
- Setup allowed to rotate bars wrt beam - up to 52 deg
- Temperature was monitored at each HDR2 via thermistors
- HDR2 signals read via two-gain amplification board; digitized by DRS4 chip
  - Attempt to complement and diagnosed part of BTL ASIC

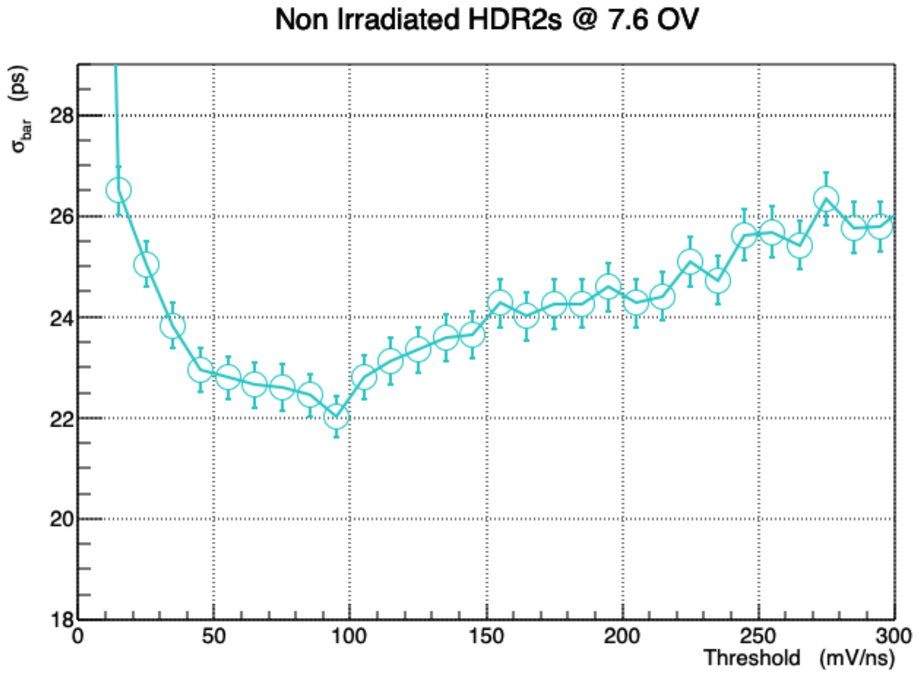


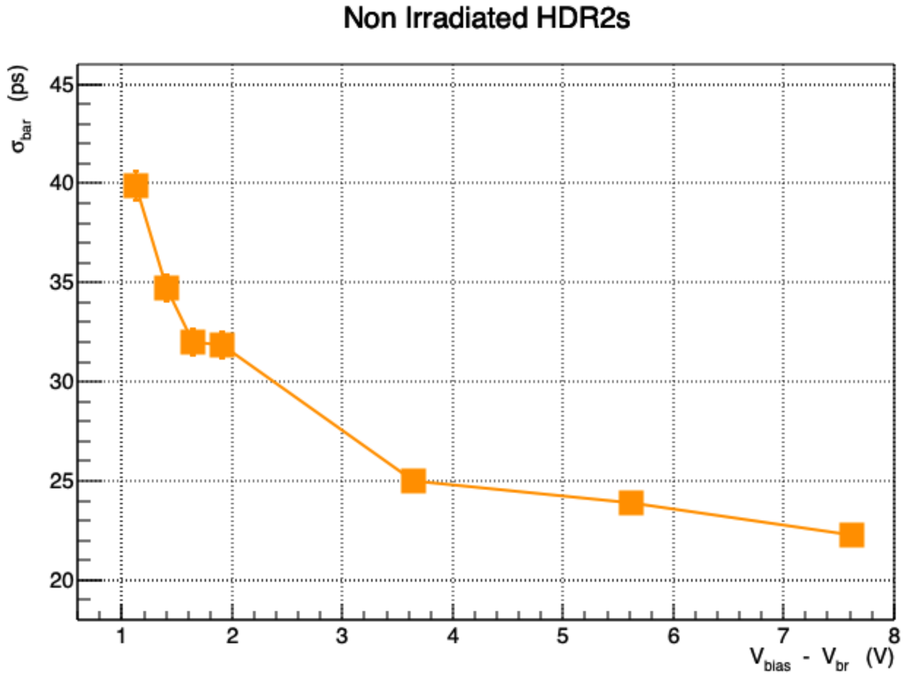
# Timing Resolution for NonIrradiated Prototype

- Response to MIP was found to be within expectations [1]
- Depending on $V_{op}$, HDR2+LYSO are demonstrated to achieve better than 23 ps resolution
- Threshold optimization for $V_{op}$ is essential and part of BTL's ASIC configuration
- Optimization has to be fine-tuned as radiation effects take place

[1] Test beam characterization of sensor prototypes for there CMS Barrel MIP Timing Detector. 2021 JINST 16 P07023

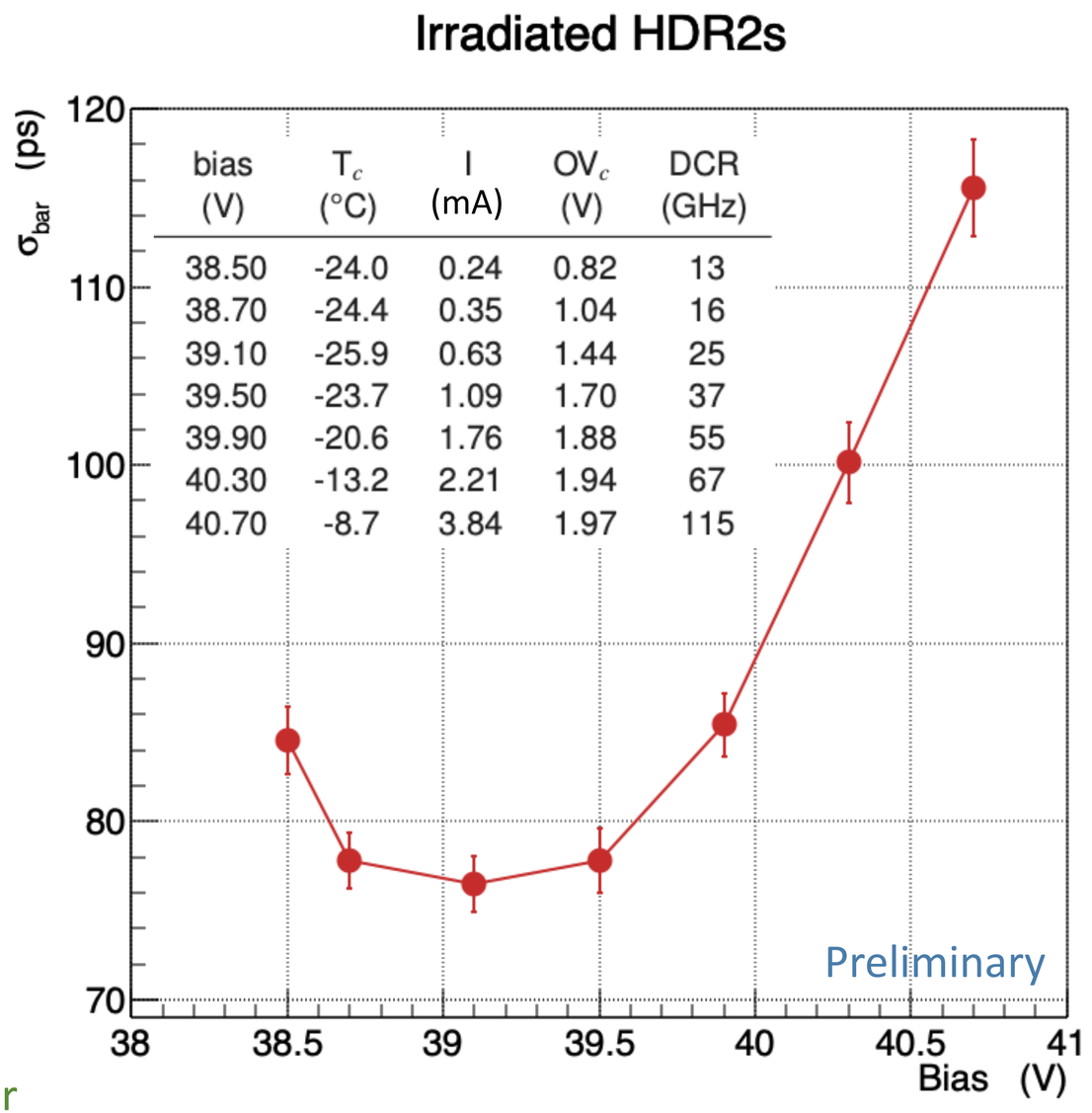
Results presented in IEEE2021 last October



# Timing Resolution for Prototype with Irradiated HDR2

- Procedure to estimate OverVoltage (OV) based on deviation of MPV/PDE/GAIN was applied
- Internal temperature was computed based on $V_{br}(T_c)$
- DCR was scaled from $I_{SiPM}$ using gain curves from nonirradiated HDR2
- Optimal time resolution for different $V_{op}$ and internal temperatures are presented
- Temperatures no further down than -25C were explored, due to lack of TEC units in prototype single-bar detector
- Worth mentioning here: The full detector will be working at a temperature of -45C, after annealing we expect a DCR of 40 GHz at EndOfLife

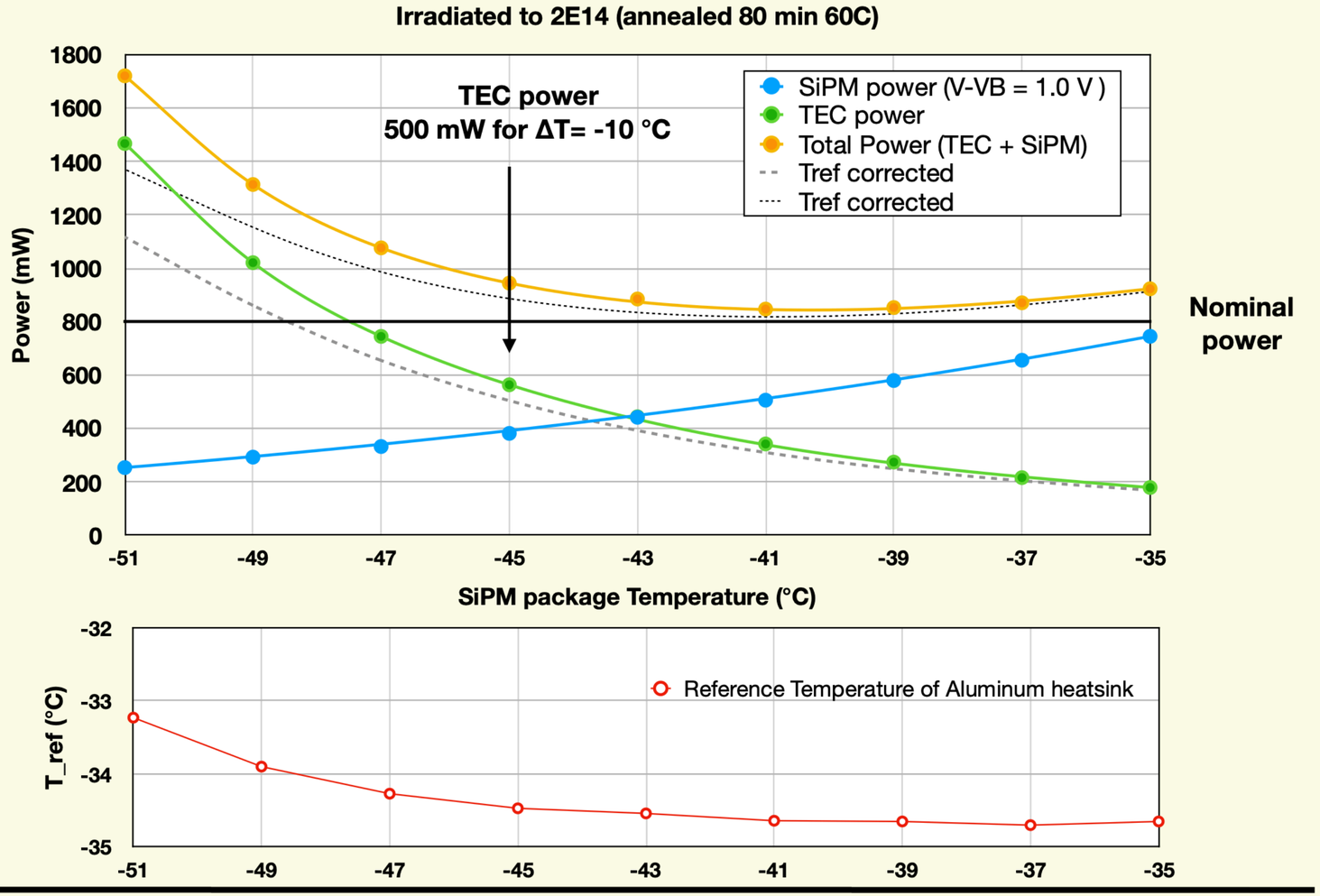



| bias (V) | $T_c$ (°C) | I (mA) | $OV_c$ (V) | DCR (GHz) |
|---|---|---|---|---|
| 38.50 | -24.0 | 0.24 | 0.82 | 13 |
| 38.70 | -24.4 | 0.35 | 1.04 | 16 |
| 39.10 | -25.9 | 0.63 | 1.44 | 25 |
| 39.50 | -23.7 | 1.09 | 1.70 | 37 |
| 39.90 | -20.6 | 1.76 | 1.88 | 55 |
| 40.30 | -13.2 | 2.21 | 1.94 | 67 |
| 40.70 | -8.7 | 3.84 | 1.97 | 115 |

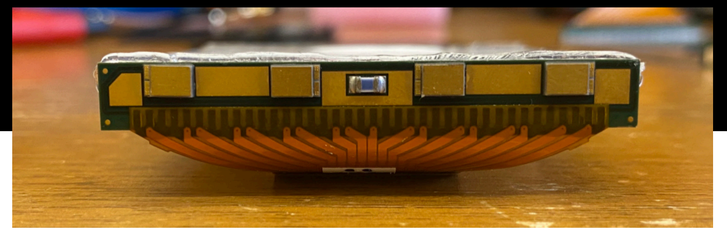
Results presented in IEEE2021 last October

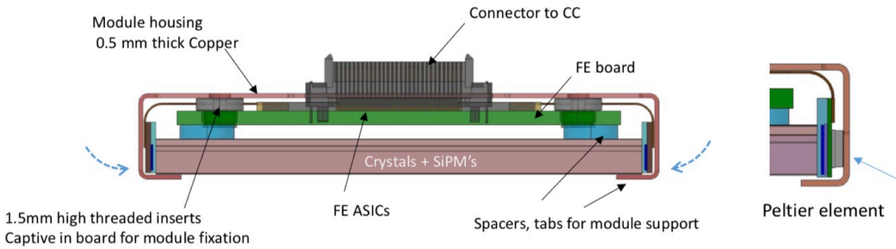
# Reducing DCR by Design

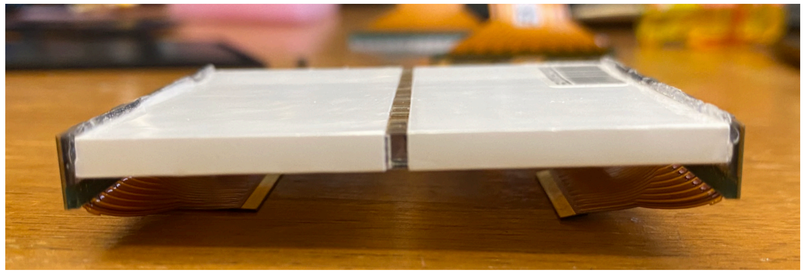
## Total power consumption for full array at 1 V over voltage




Nominal power



March 18, **CPAD 2021 Stony Brook, NY**

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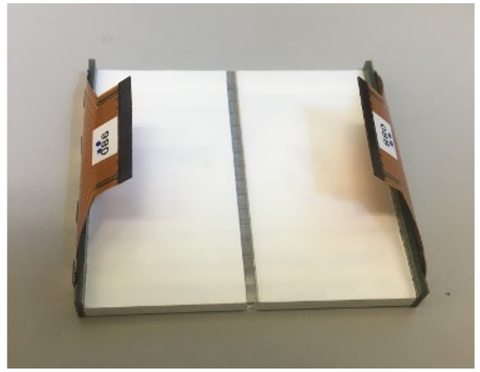
# Modules Under Study

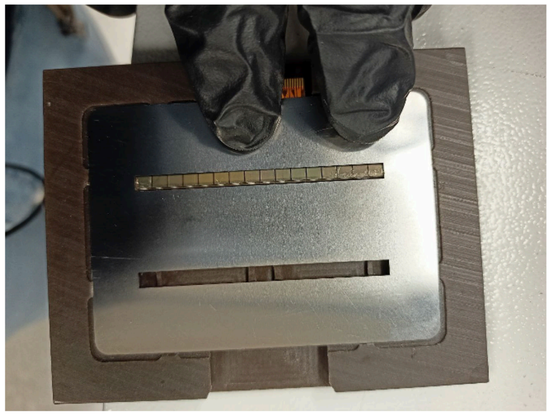
- Module 1
  - LYSO 33300060000739
    - Length 55.25 mm
    - Width 51.66 mm
  - 2-102 HPK S15408-32TC (ES1)
  - 2-98 HPK S15408-32TC (ES1)

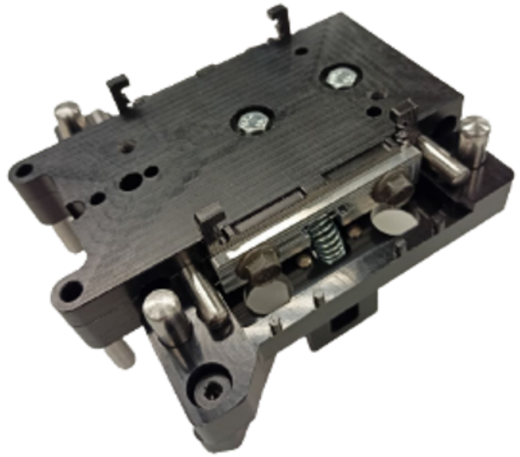
- Module 2
  - LYSO 33300060000738
    - Length 55.22 mm
    - Width 51.95 mm
  - 2-39 HPK S15408-32TC (ES1)
  - 2-104 HPK S15408-32TC (ES1)

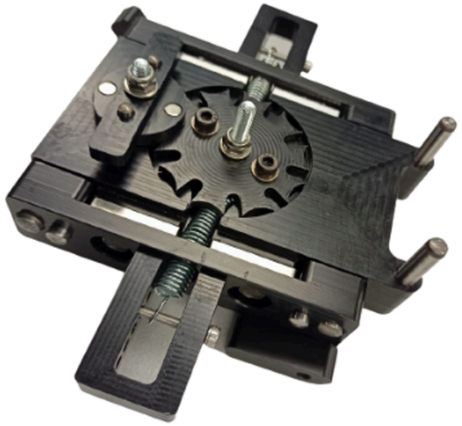
- Module 3
  - LYSO 33300060000763
    - Length X mm
    - Width X mm
  - 2-86 HPK S15408-32TC (ES1)
  - 2-88 HPK S15408-32TC (ES1)



Three modules were assembled at UVA for testing

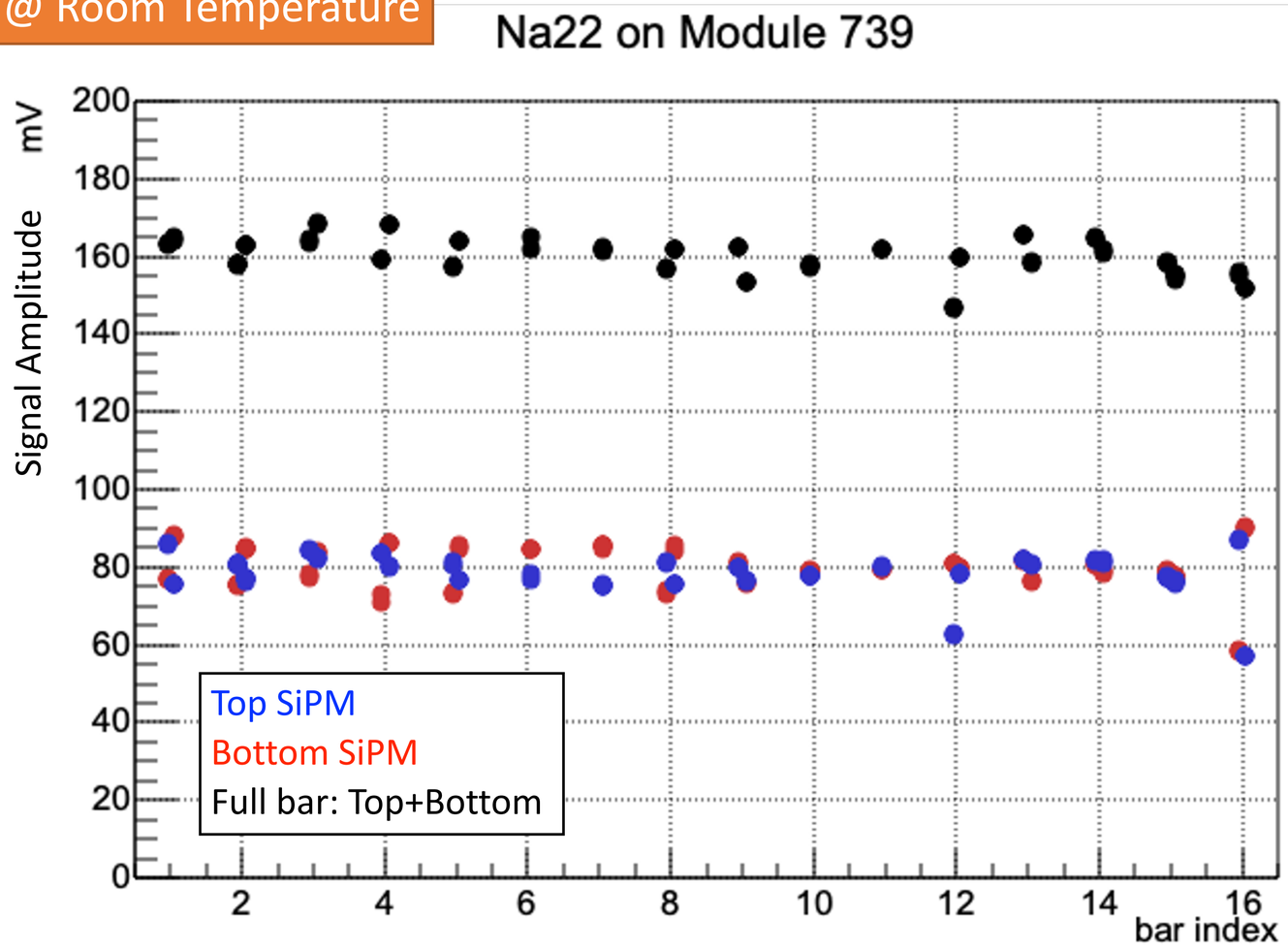


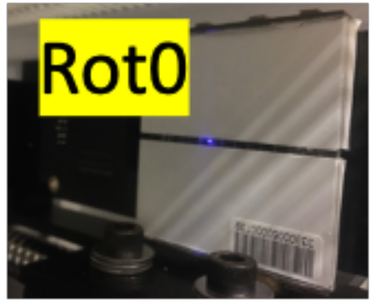


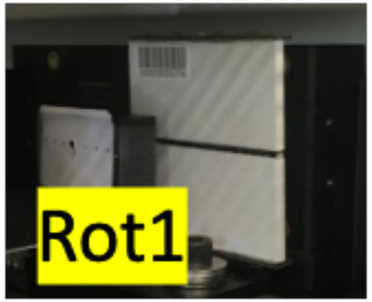


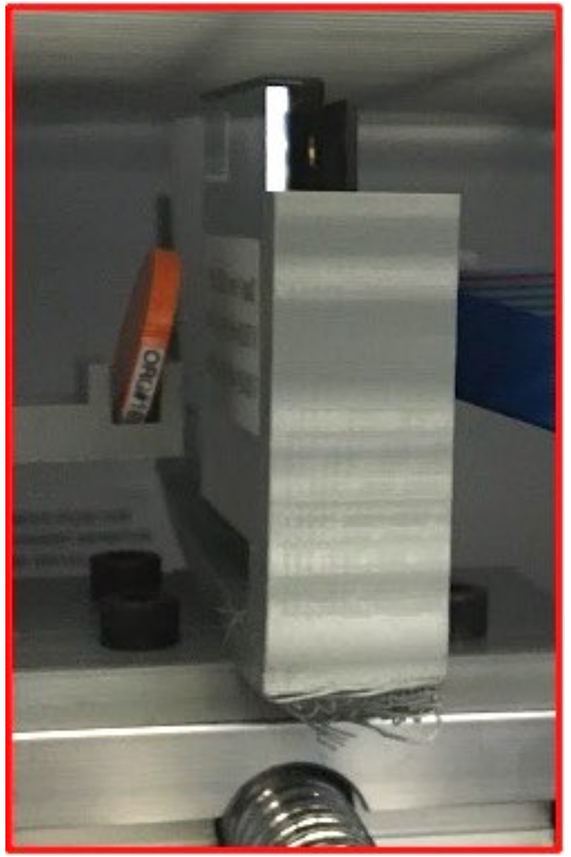
# Na22 Test

Vop=7 OV @ Room Temperature



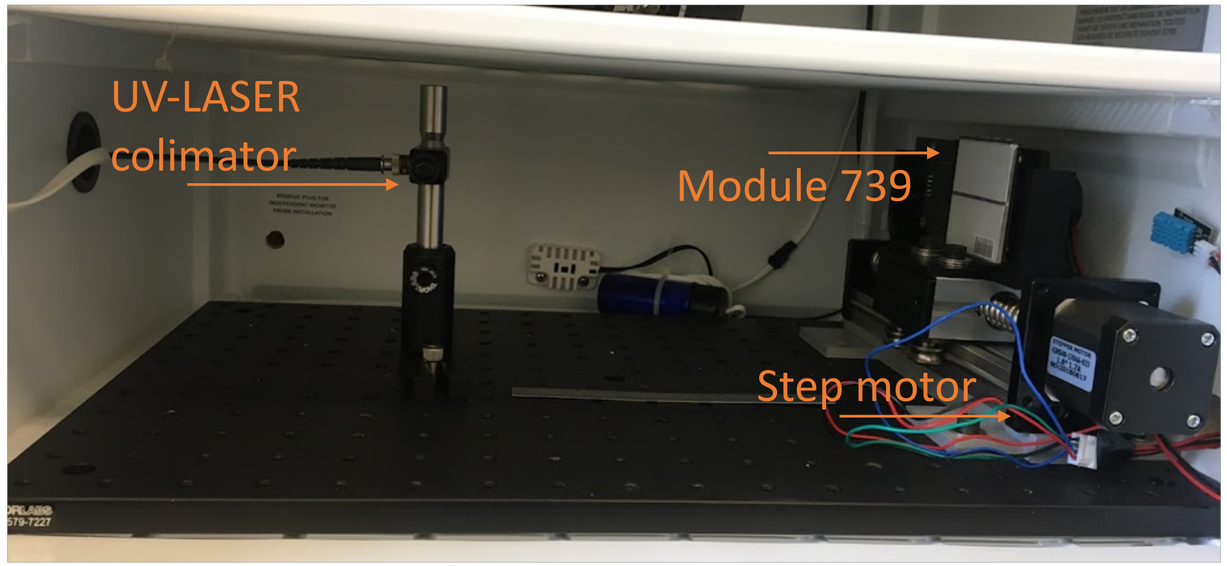



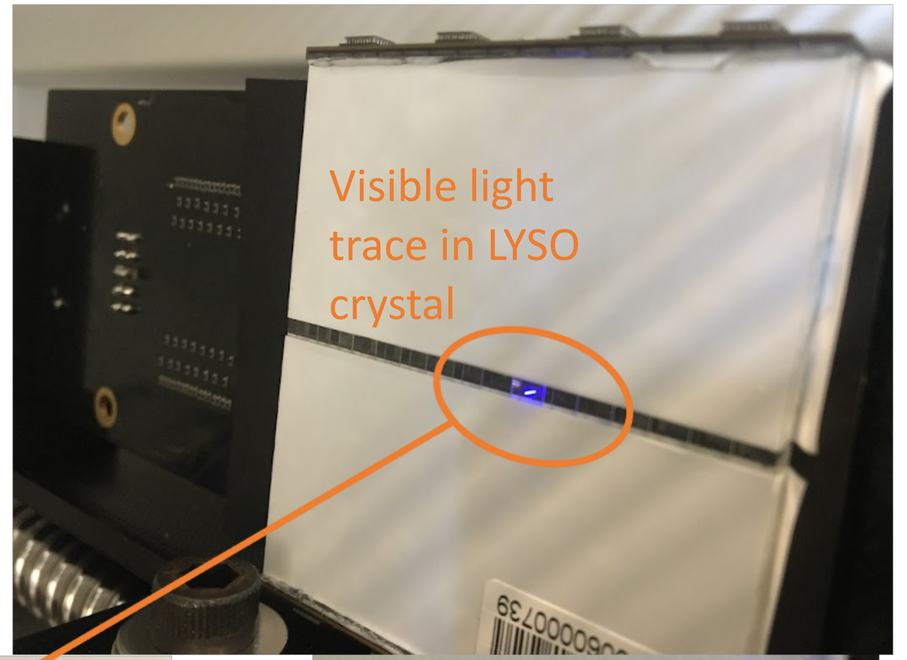



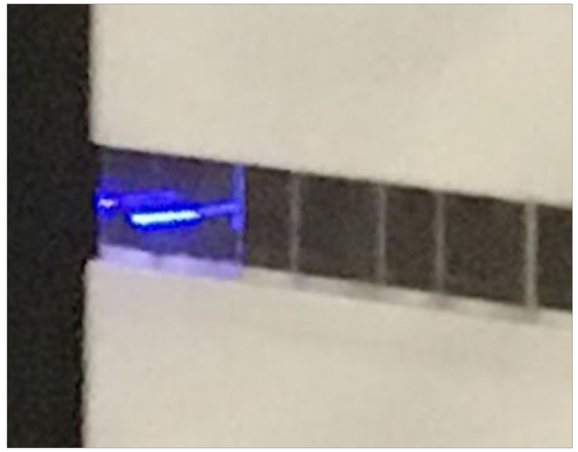



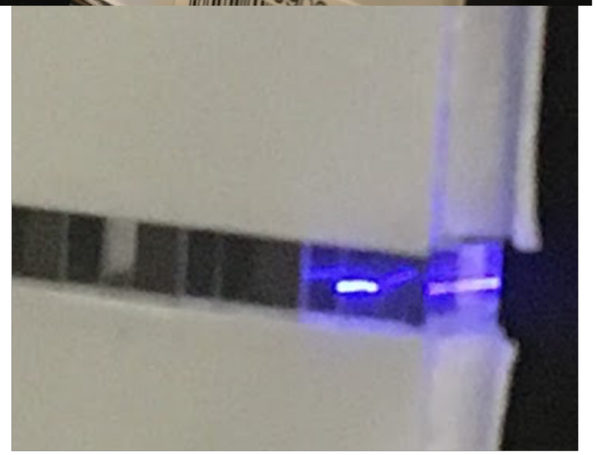
- Energy calibration of electronics while scanning across bars in prototype module also shows module homogeneity

# UV-Laser Scan Tests



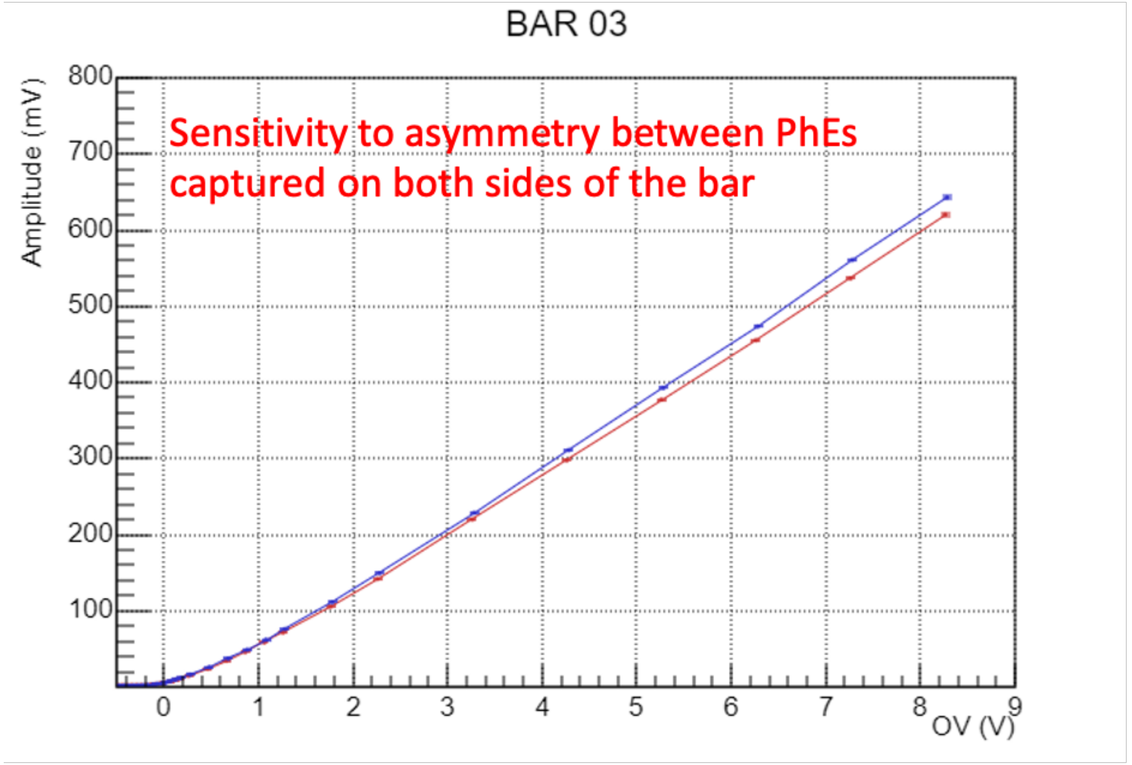



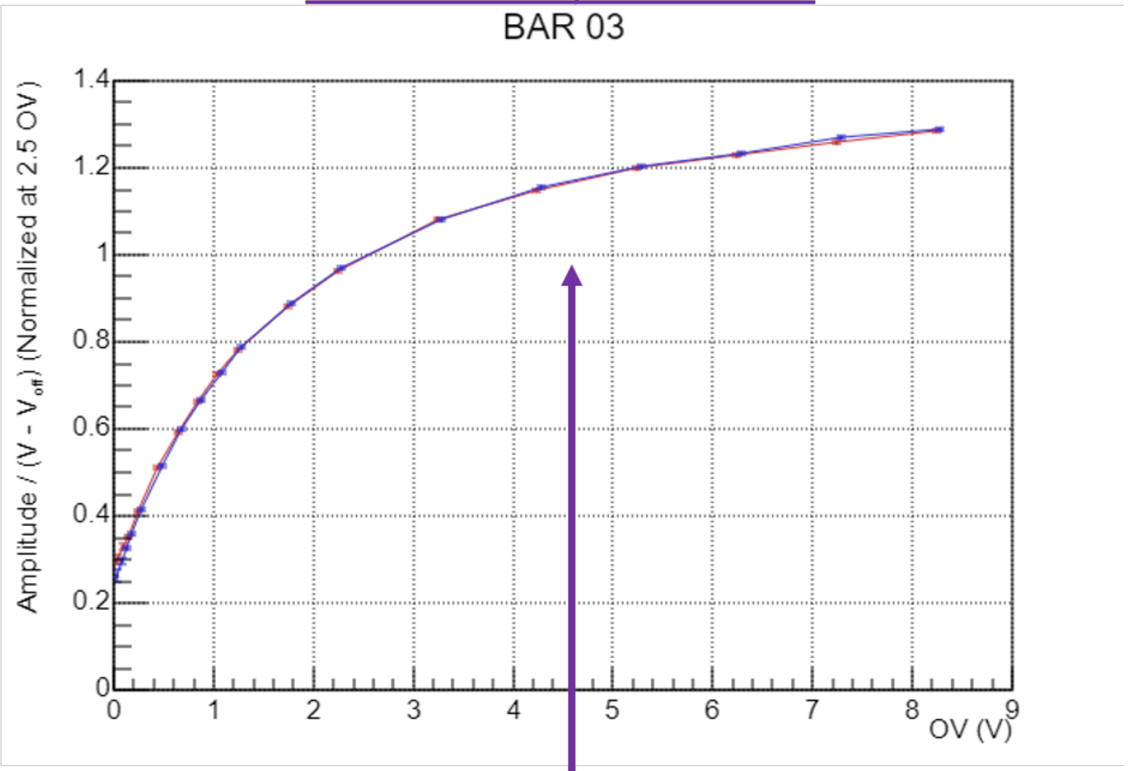


# UV Laser on Module 739

UV source centered on bar 03
T approx. +19C
Intensity to 8.0 (approx. ~2.9 MeV)




Sensitive mainly to SiPM PDE




Amplitude is proportional to Npe * Gain * PDE * XTalk*ndf

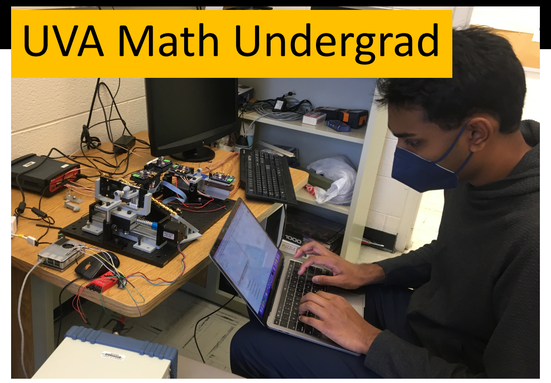
Linear with (V-V$_{off}$)

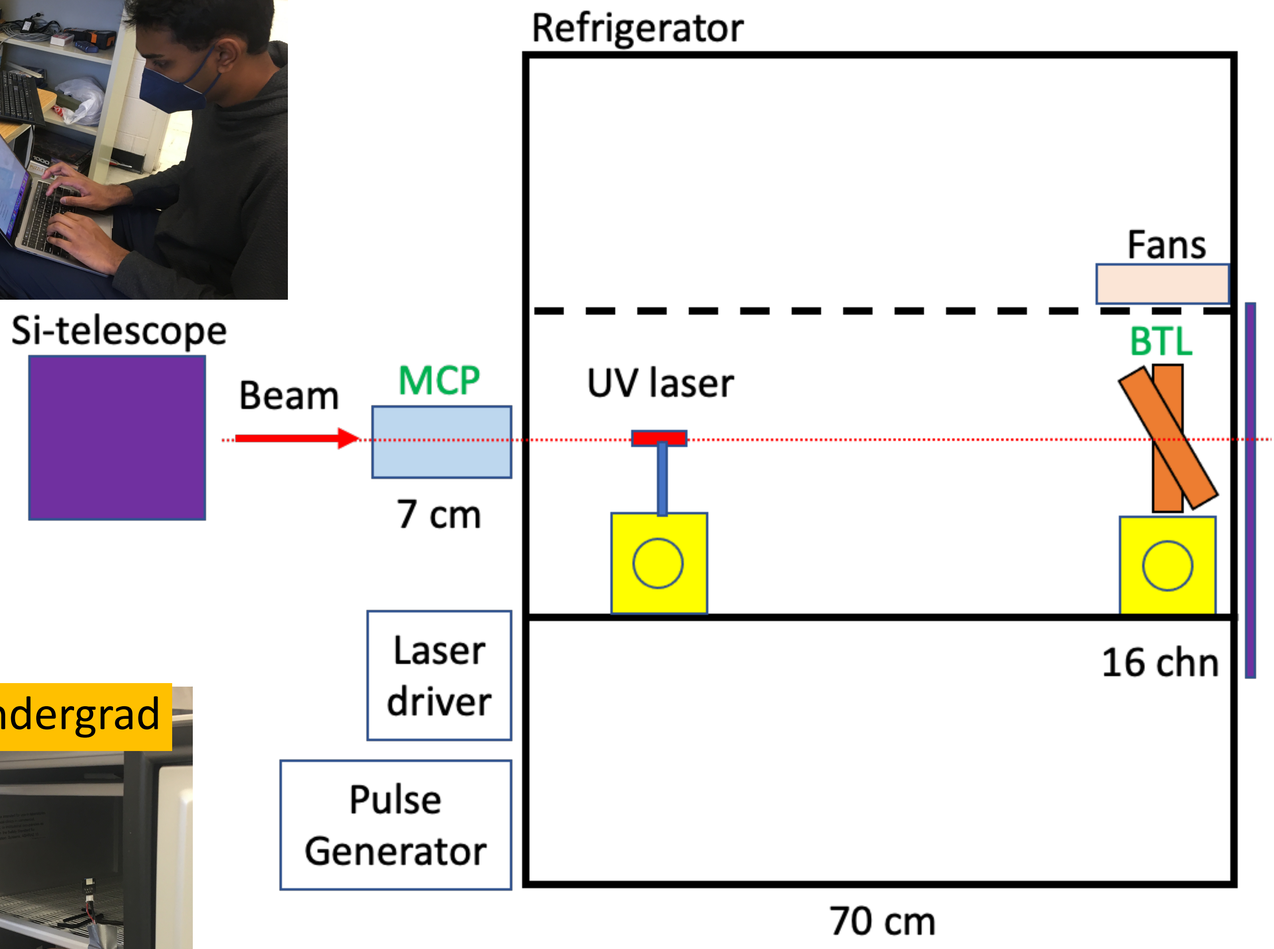
Dominated by Shape of PDE(OV)

Voff approx. as Vbr - 0.4

# Testbeam Jun'22: Protons and Electrons on Full Module

UVA Math Undergrad





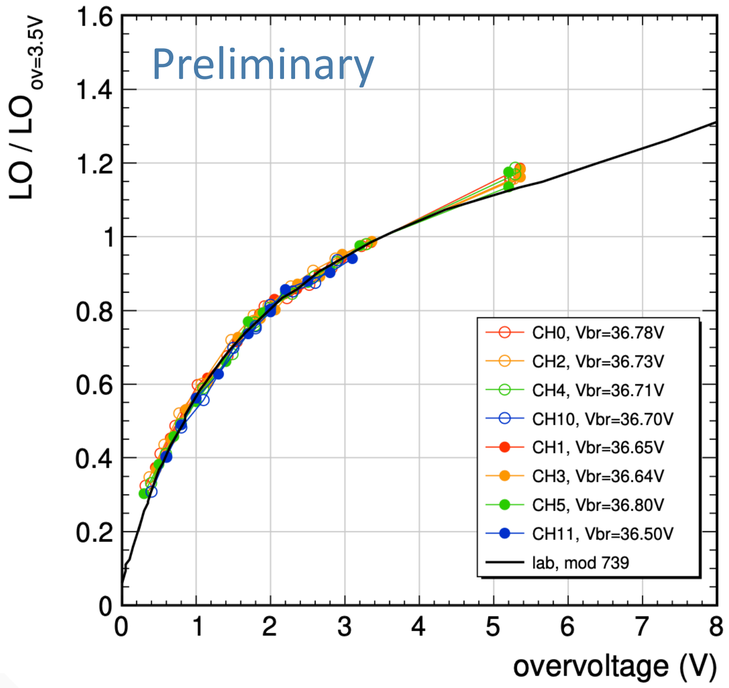

NotreDame PhD Student

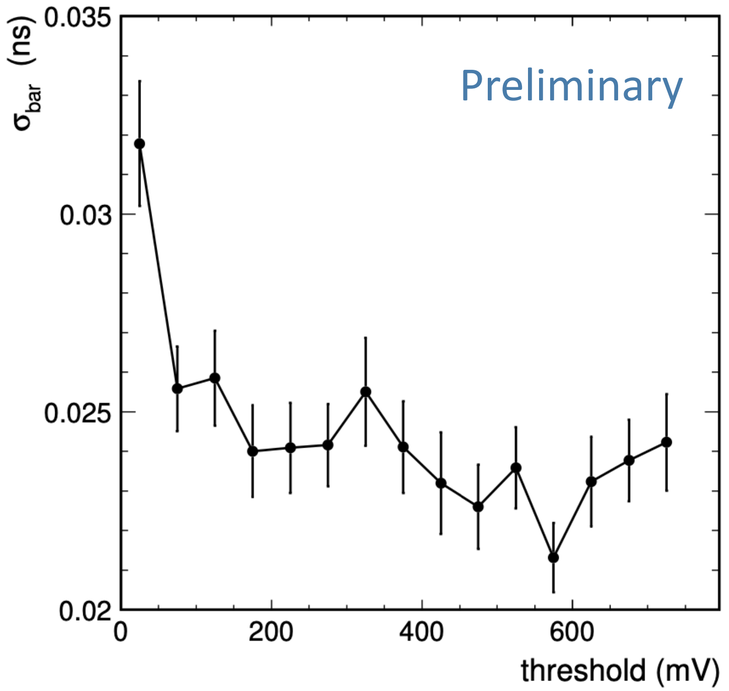
UVA Phy Undergrad

- Temperature was monitored at each HDR2 via thermistors
- HDR2 signals read via two-gain amplification board; digitized by DRS4 chip

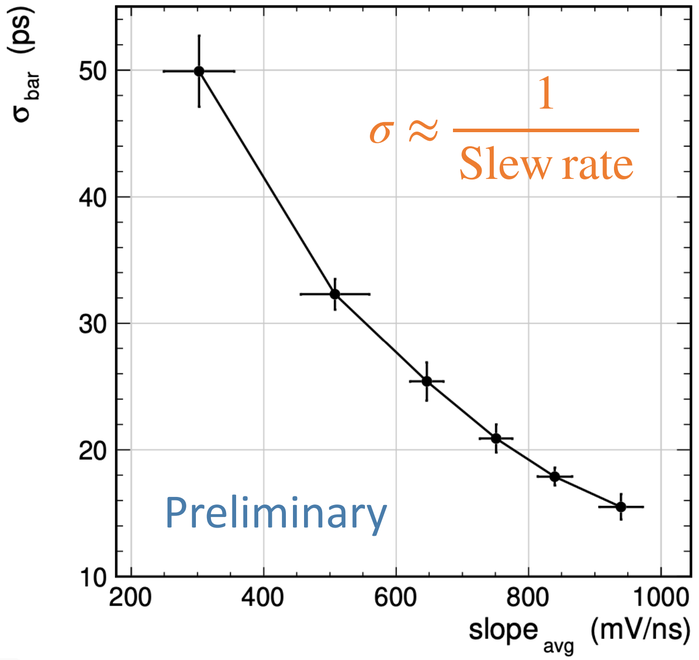
# Preliminary Results (28 GeV Electrons on Full Module)

Relative Light Output (LO) measure with proton beam compared to laser measurements



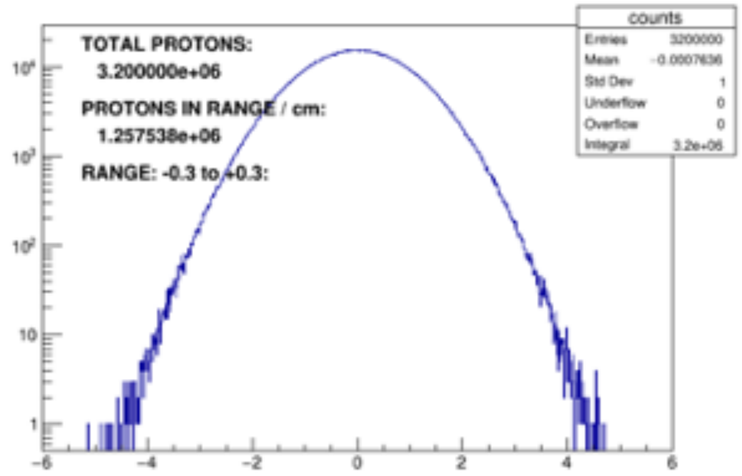

Time Resolution as a function of slew rate




Time Resolution (slew rate > 500 mV/ns) measured with protons on full module. Compatible with measurements obtained on Single-Bar-Protoype

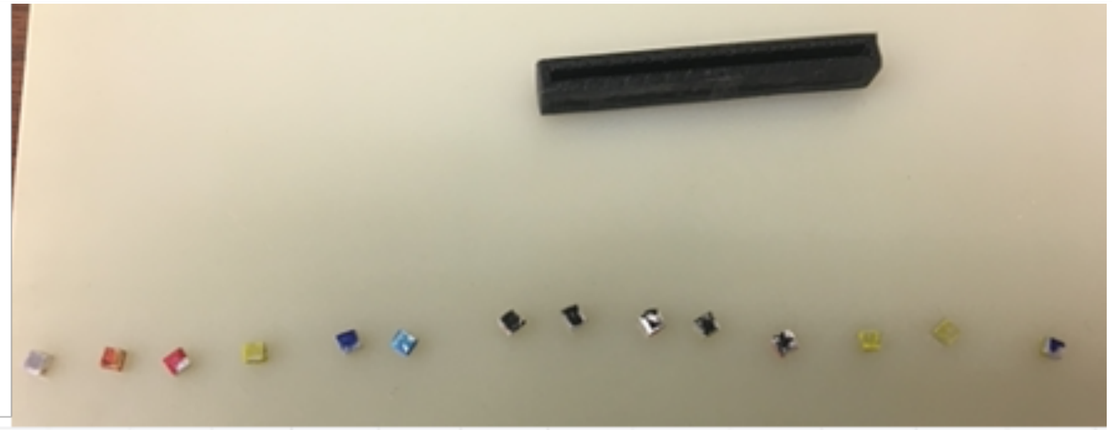
# Full Module to Fermilab ITA

## ASKING FOR 3.2e14 protons delivered



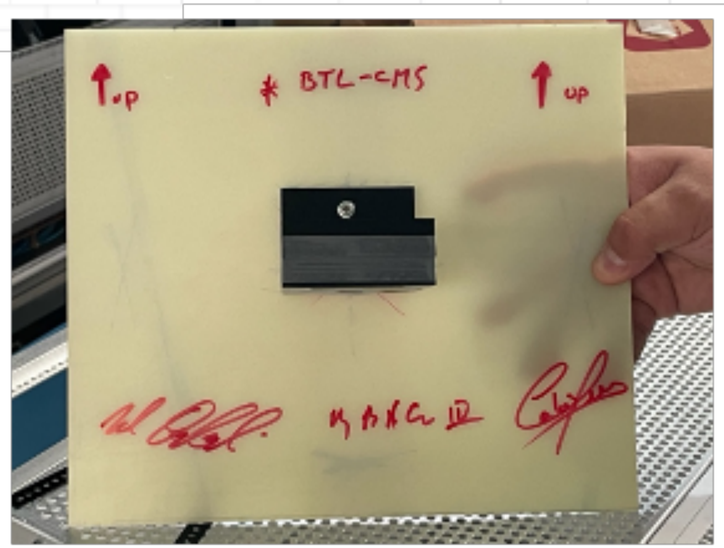

**3.20E+14 PROTONS**
1.26E+14 PROTONS PER CM

0.8 NIEL (400MeV PROTON) / NIEL (1 MeV NEUTRON)
**1.01E+14 EQ 1MeV NEUTRONS PER CM**



**Aluminum dots setup**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| I - II | 0 / 0 | R / R | R / 0 | Y / 0 | Bk / 0 | LB / 0 | Bk / Bu | Bk / Bk | Bk / R | Bk / Y | LB / R | Y / R | Y / Y | Bu / Y | Y / R | Bu / R |
| III - IV | Bu / R | Y / Bu | R / Y | R / LB | Y / Y | R / Bk | Y / Bk | Bk / LB | Bk / Bk | Bk / 0 | LB / 0 | Bu / 0 | Y / 0 | R / R | R / 0 | 0 / 0 |




# Summary

- Preliminary results for $V_{br}$ and DCR for various temperatures and various levels of radiation damage on HDR2s were presented
- Various waveform analysis methods were studied to complement ASIC (based on TOFHIR design) configuration
- Results presented here further improve our understanding radiation damage effects on detector performance
  - Once radiation damage effects are fully understood, we will optimized our ASIC configuration to get optimal resolution at every time
- Uniformity of response of full module was assessed with Na-22, laser and protons.
- Timing response of full module measured with electrons was found to be better than 30ps
- Full module has been irradiated to check integrity of the whole assembly and test overall resolution
- We plan to test this newly irradiated module on January'23 with protons at Fermilab

Thanks!

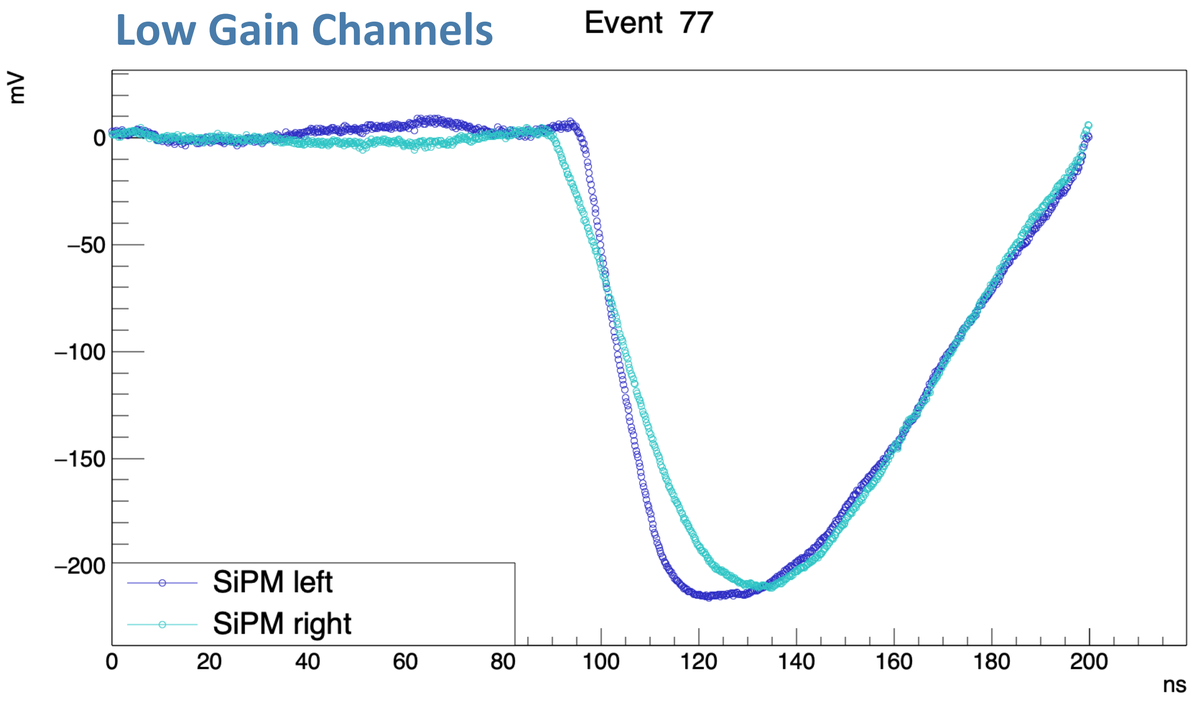
# Backup

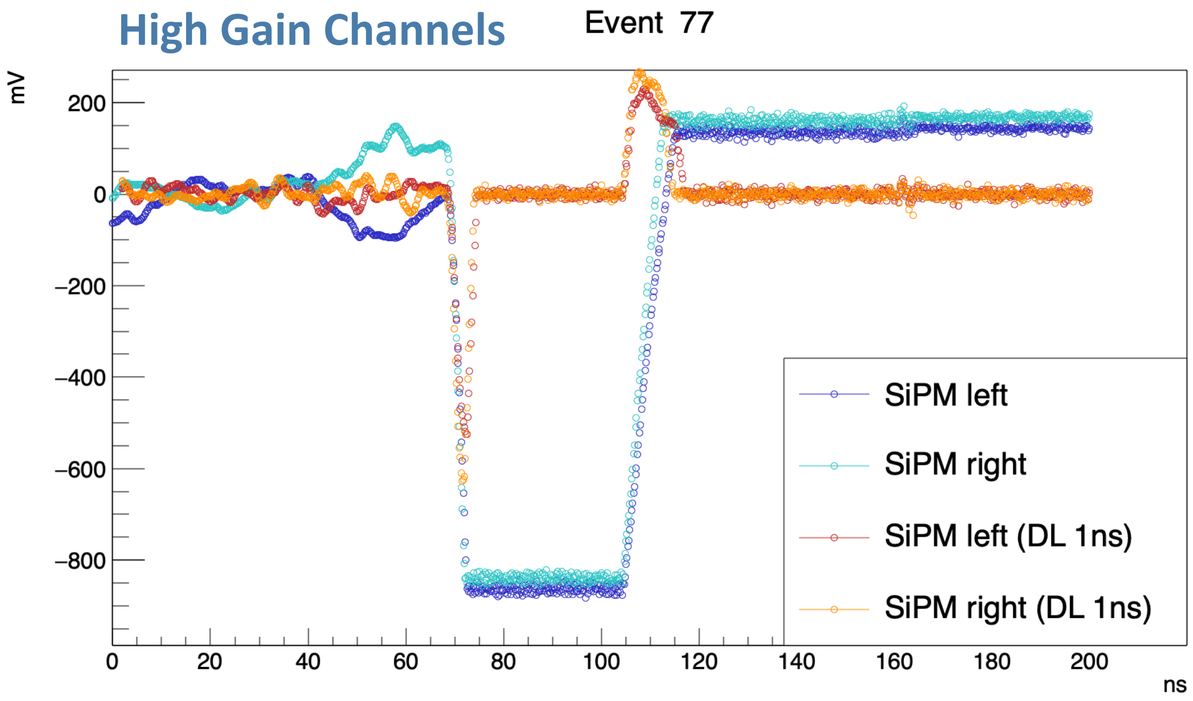
# Event display for Irradiated HDR2s

- Data taken at 52 deg inclination with respect to the crystal's normal to surface

(To mimic average energy deposition of 4.2 MeV which is the average expectancy in BTL detector)

- Signal digitized using CAEN DT5742 - DRS4 chip 5GS/s Switched Capacitor Array



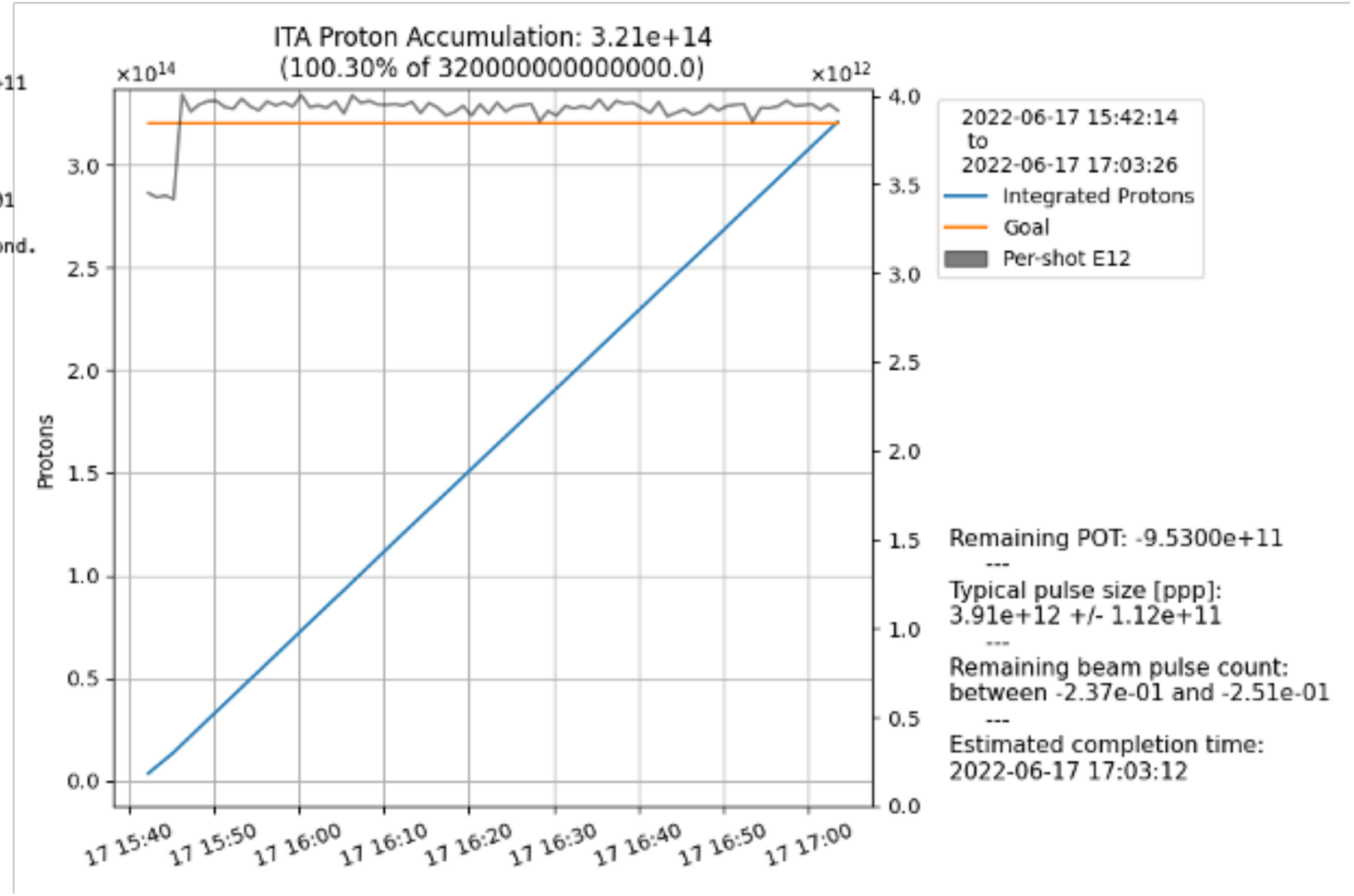



# ITA Delivery of Protons to Module

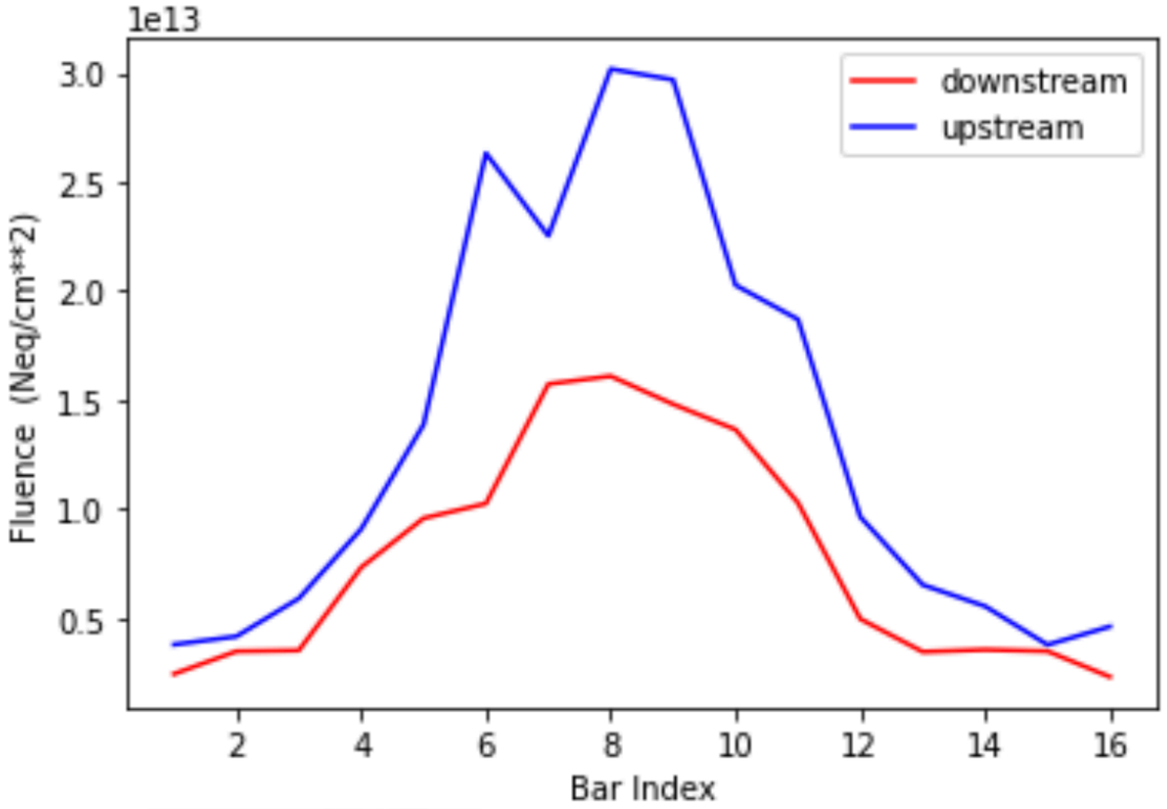
```
83 total measurements found.
Integrated protons at ITA:
17-Jun-2022-10:00:00 to 17-Jun-2022-17:06:39: 3.21e+14
  100.30% of goal 320000000000000.0.
Shots so far:83
Count size range (excluding outliers): 3.9141e+12 +/- 1.1244e+11
Accumulated POT: 3.2095e+14
Remaining POT: -9.5300e+11


Remaining beam pulse count: Between -2.3668e-01 and -2.5068e-01
Elapsed time in seconds since first beam: 4872.0
   Approx. time-averaged beam rate: 6.588e+10 protons per second.
   Approx. time-averaged shot interval 5.870e+01 s


  Rough guess is 2022-06-17 17:03:11.707951
```

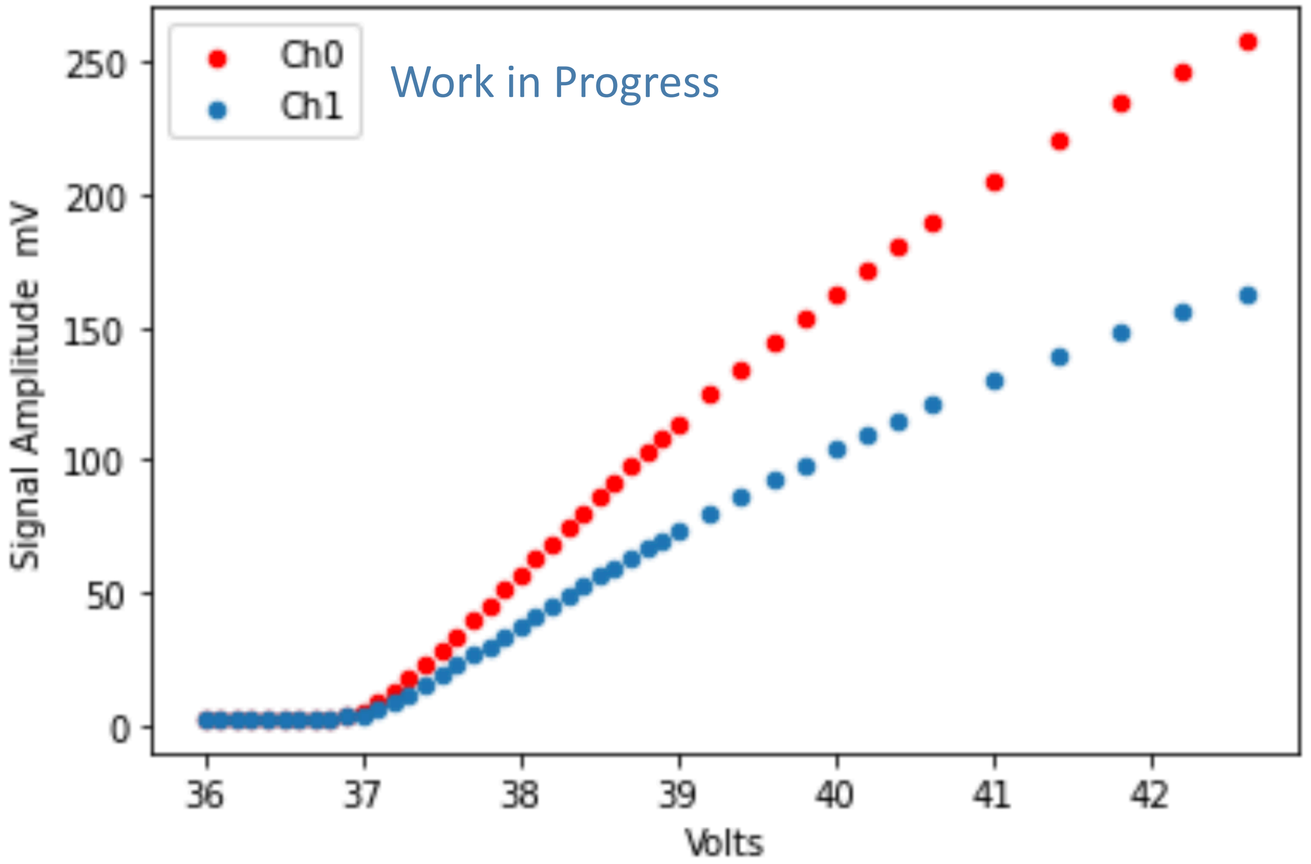


# First Tests of Irradiated Module





Bar index 9




Zeroth Test of UV-laser on bar
Mounted inside the fridge:
Including boards, stand and rotation table
One bar setup for the moment

The values of the theoretical "average" trigger rate, computed upon the given formulas, are reported in the following tables for $N_S$ = 1024 samples.

| $N_G$ | TR Not Digitized | TR Digitized |
|---|---|---|
| 1 | 6.813 kHz | 6.058 kHz |
| 2 | 3.409 kHz | 3.030 kHz |

**Tab. 7.3:** Theoretical "average" trigger rate values for the Optical Link

| $N_G$ | TR Not Digitized | TR Digitized |
|---|---|---|
| 1 | 2.556 kHz | 2.272 kHz |
| 2 | 1.278 kHz | 1.136 kHz |

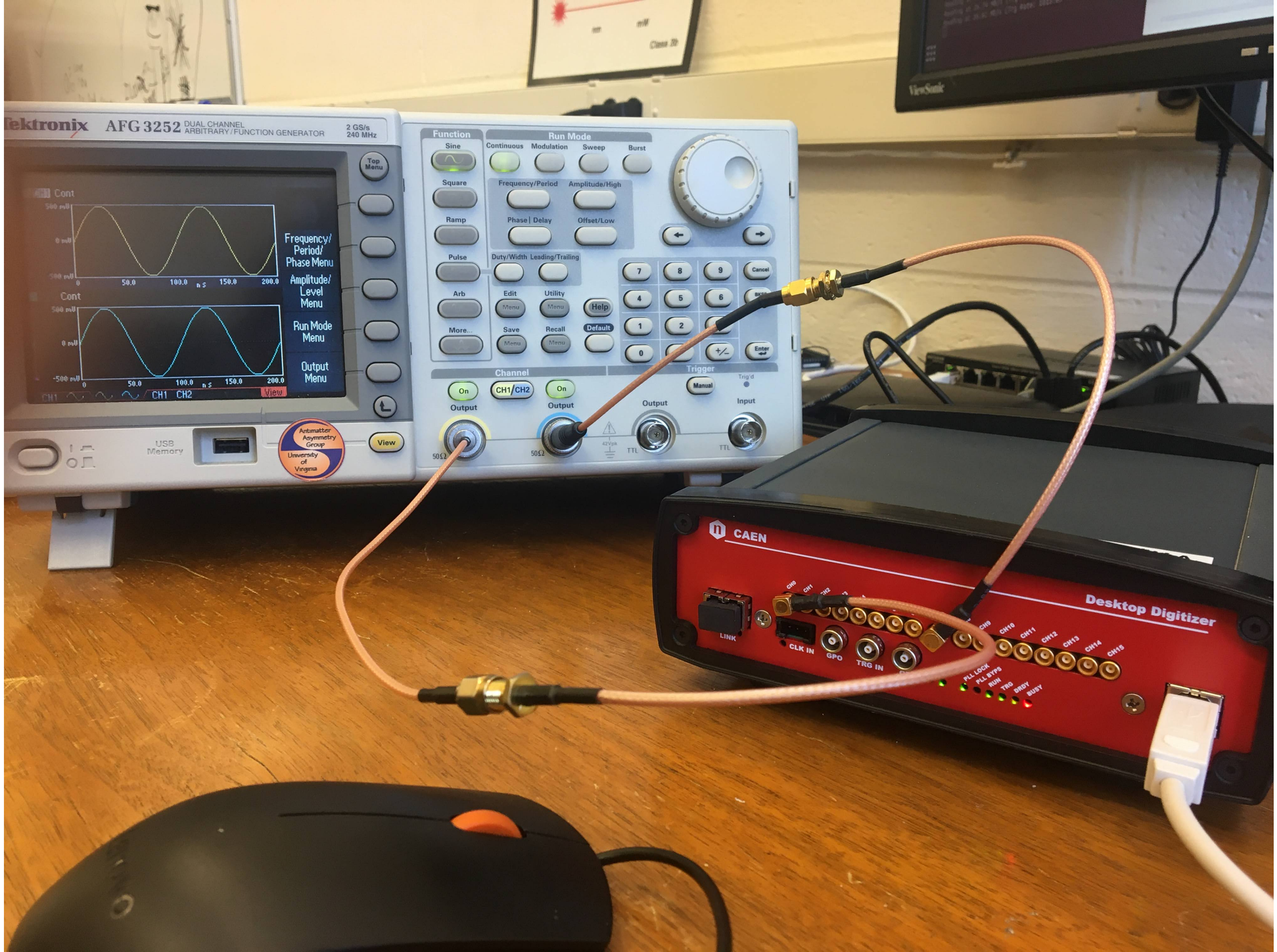
**Tab. 7.4:** Theoretical "average" trigger rate values for the USB Link

So theoretically for our use 16CH + TR0 digitized we will get

USB 1.136 kHz

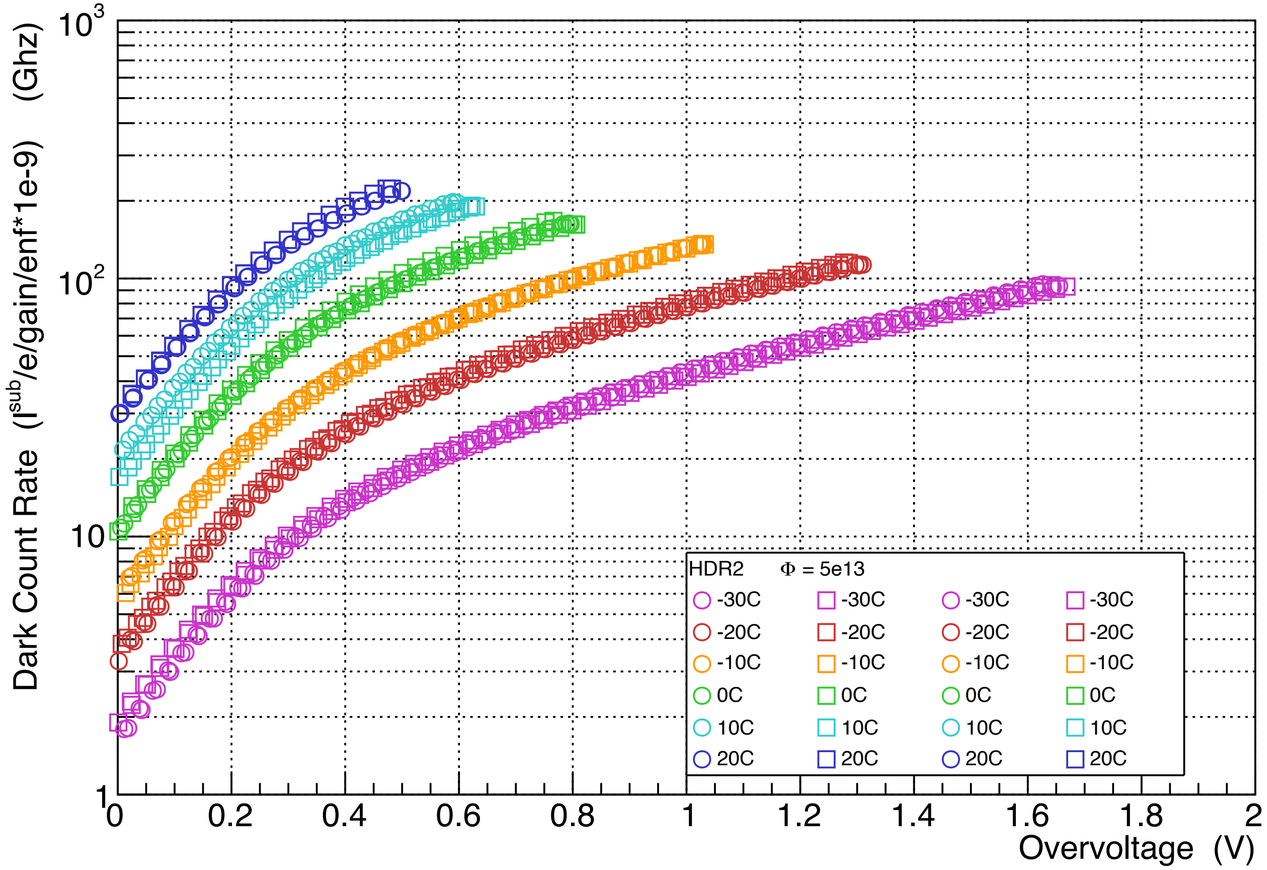
PCI 3.030 kHz

**50k MIPS in** **13 min** **4 min**

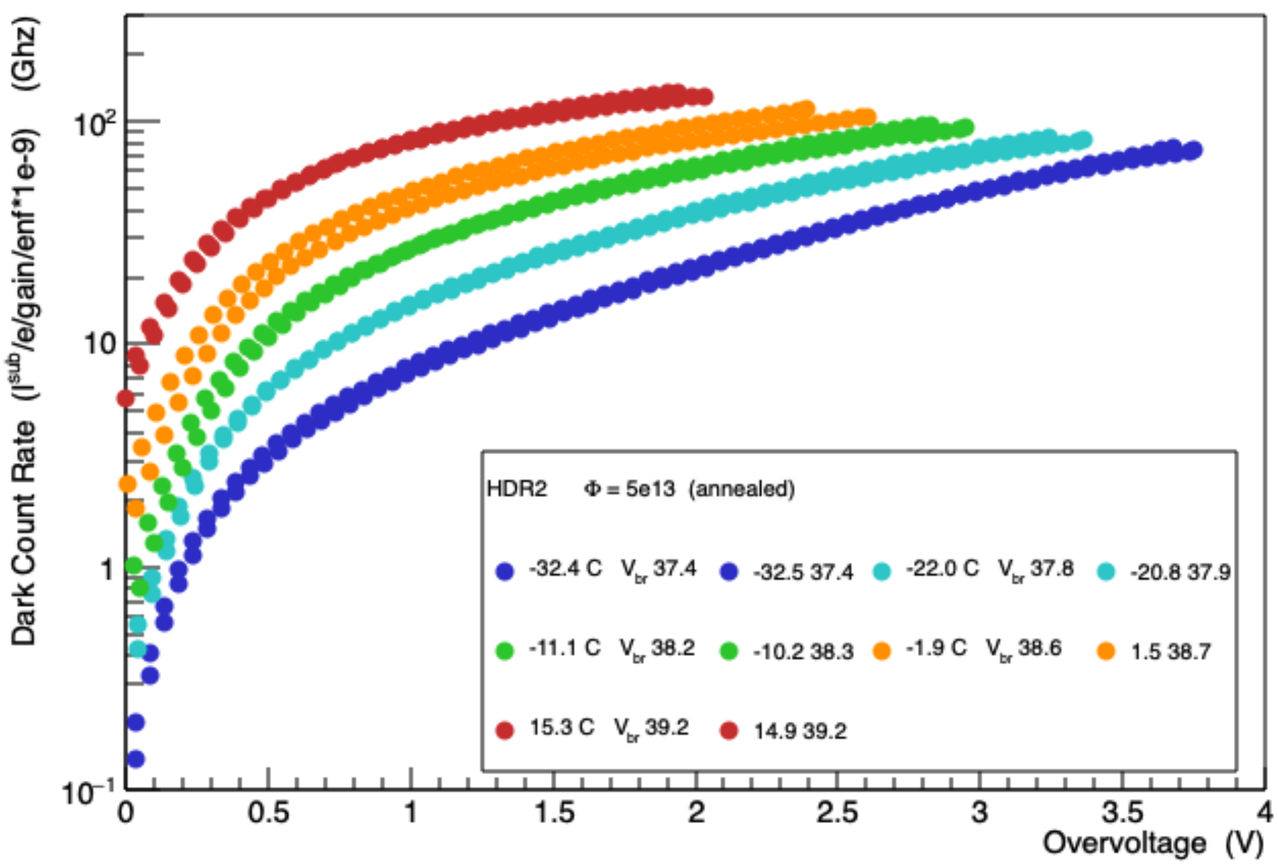

Tektronix AFG 3252 DUAL CHANNEL ARBITRARY/FUNCTION GENERATOR
2 GS/s
240 MHz
Function
Sine
Square
Ramp
Pulse
Arb
More...
Run Mode
Continuous
Modulation
Sweep
Burst
Frequency/Period
Amplitude/High
Phase| Delay
Offset/Low
Duty/Width
Leading/Trailing
Edit
Utility
Save
Recall
Help
Default
Menu
Top Menu
Frequency/ Period/ Phase Menu
Amplitude/ Level Menu
Run Mode Menu
Output Menu
View
USB Memory
Antimatter Asymmetry Group
University of Virginia
Channel
Trigger
On
CH1/CH2
Output
Manual
Trig'd
Input
50Ω
TTL
CAEN
Desktop Digitizer
LINK
CLK IN
GPO
TRG IN
CH9
CH10
CH11
CH12
CH13
CH14
CH15
PLL LOCK
PLL BYPS
RUN
TRG
RDY
BUSY

# Comparison of DCR for 5e13 SiPMs before and after annealing

Oct 2020




Mar 2021

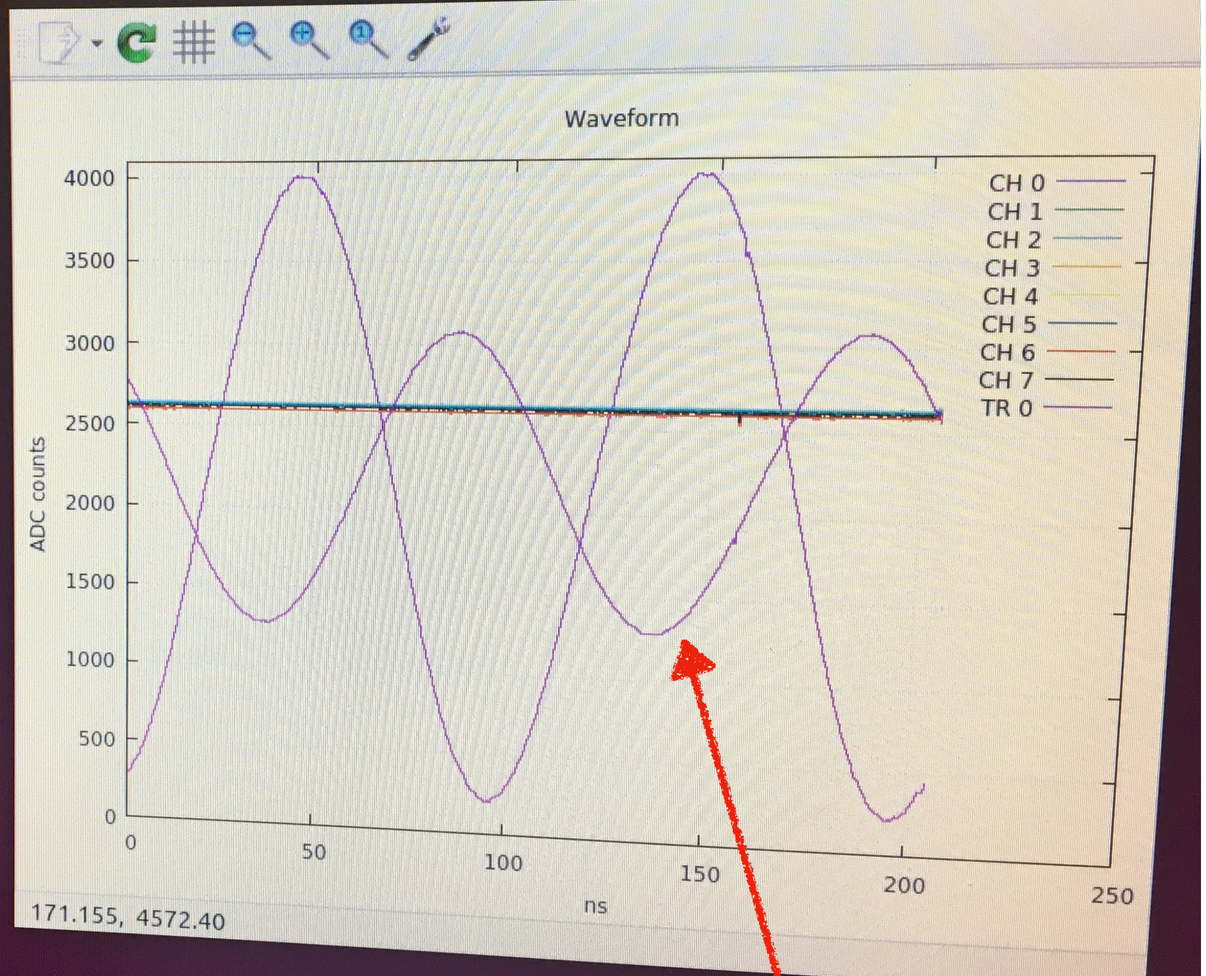



After leakage current correction, all IV curves were scaled to the same gain(OV) and enf(OV), measured by Youri/Marco in 2020

```
Reading at 26.55 MB/s (Trg Rate: 1005.90 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Plot group set to 0
Reading at 26.79 MB/s (Trg Rate: 1014.88 Hz)
Reading at 26.58 MB/s (Trg Rate: 1006.89 Hz)
Reading at 26.61 MB/s (Trg Rate: 1007.88 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 27.00 MB/s (Trg Rate: 1023.00 Hz)
Reading at 26.66 MB/s (Trg Rate: 1009.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.66 MB/s (Trg Rate: 1009.87 Hz)
Reading at 26.98 MB/s (Trg Rate: 1021.98 Hz)
Reading at 26.76 MB/s (Trg Rate: 1013.88 Hz)
Reading at 26.74 MB/s (Trg Rate: 1012.87 Hz)
Reading at 26.84 MB/s (Trg Rate: 1016.90 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.82 MB/s (Trg Rate: 1015.89 Hz)
Reading at 26.84 MB/s (Trg Rate: 1016.90 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.79 MB/s (Trg Rate: 1014.88 Hz)
Reading at 26.68 MB/s (Trg Rate: 1010.87 Hz)
Reading at 26.40 MB/s (Trg Rate: 1000.00 Hz)
Reading at 23.54 MB/s (Trg Rate: 891.89 Hz)
Reading at 26.19 MB/s (Trg Rate: 992.24 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.02 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.92 MB/s (Trg Rate: 1019.94 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.68 MB/s (Trg Rate: 1010.87 Hz)
Reading at 26.66 MB/s (Trg Rate: 1009.87 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.76 MB/s (Trg Rate: 1013.88 Hz)
Reading at 26.79 MB/s (Trg Rate: 1014.88 Hz)
Reading at 26.74 MB/s (Trg Rate: 1012.87 Hz)
```

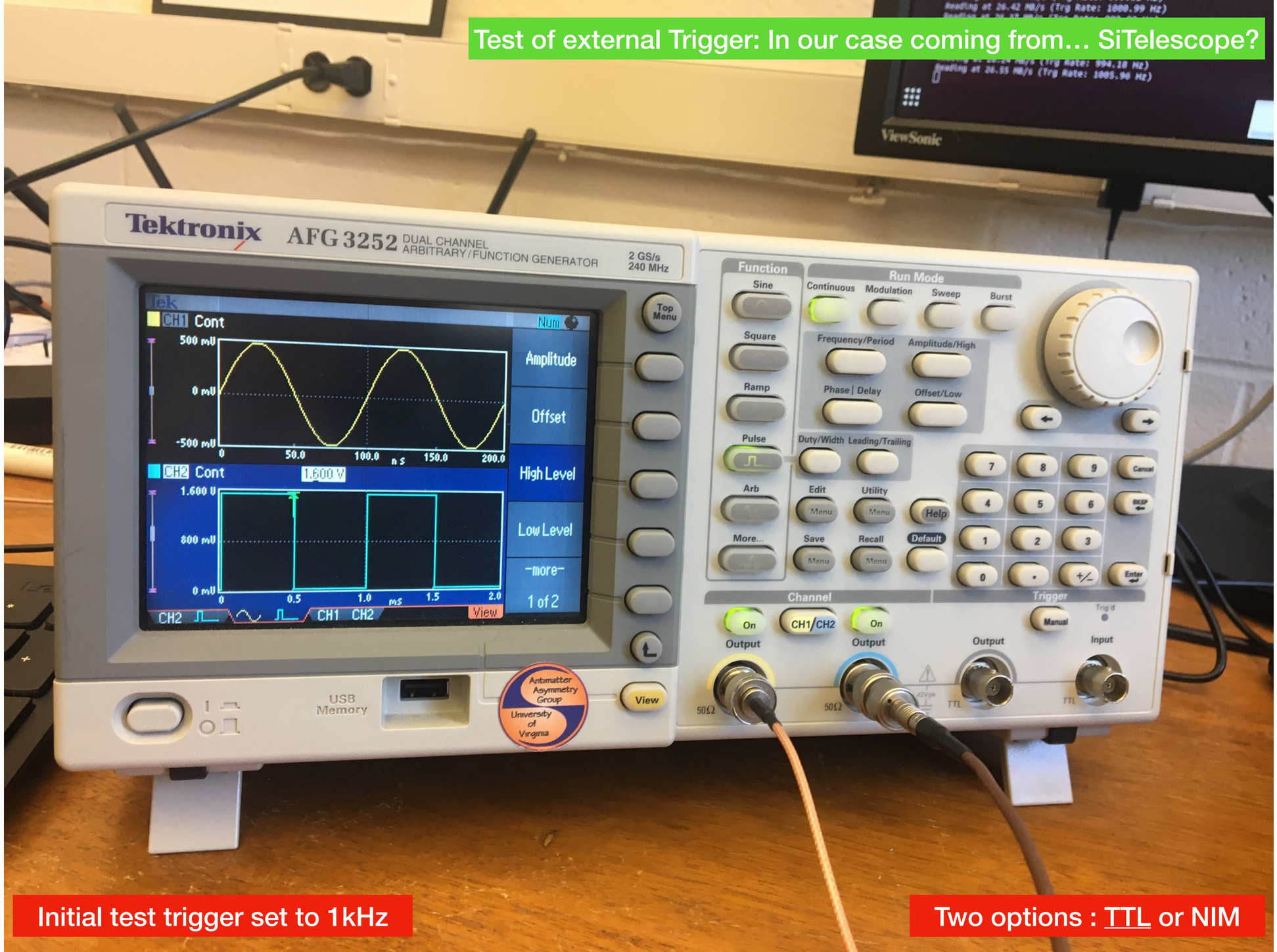
Using CAEN's tool wavedump

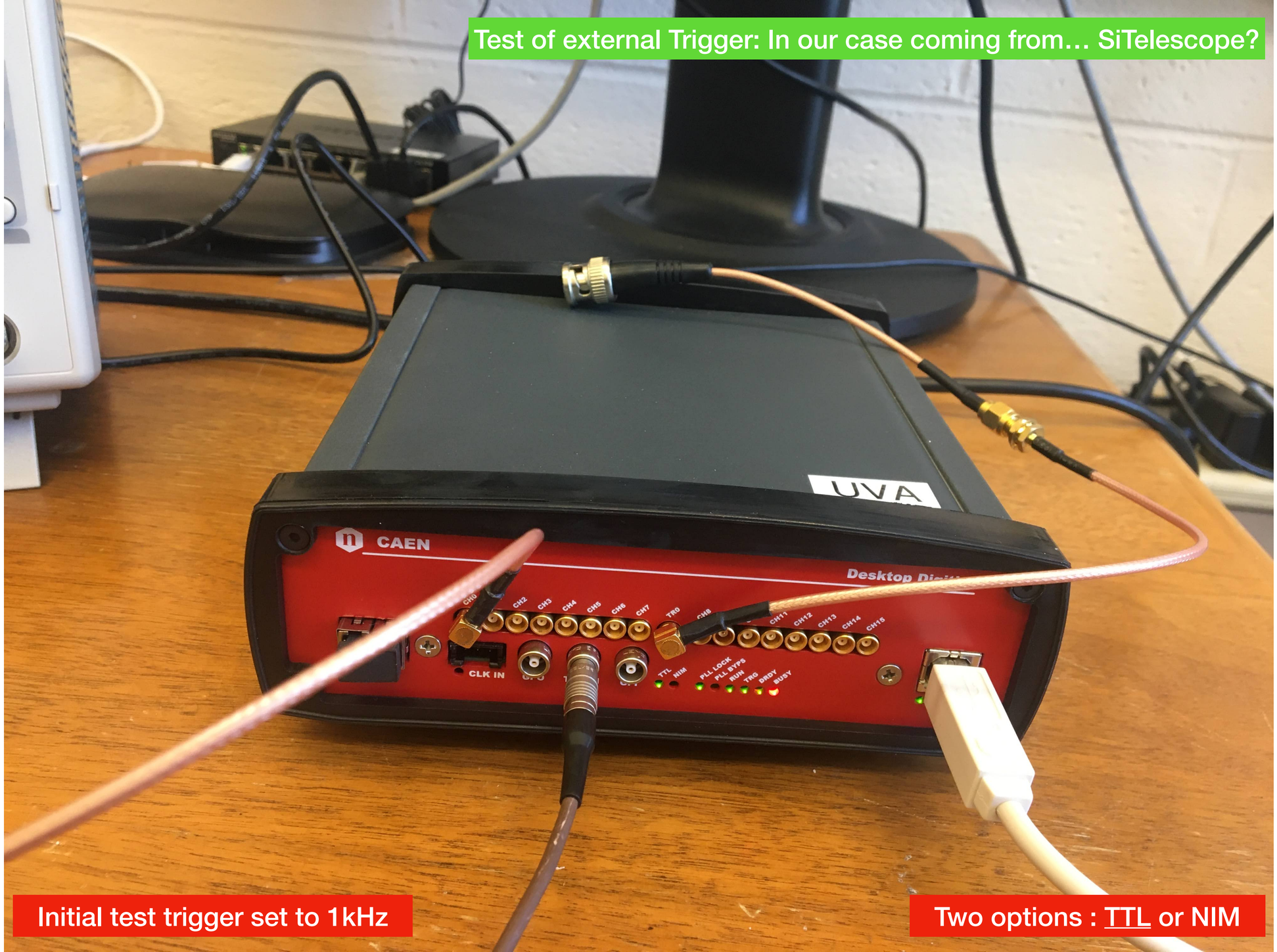
Gnuplot window 0

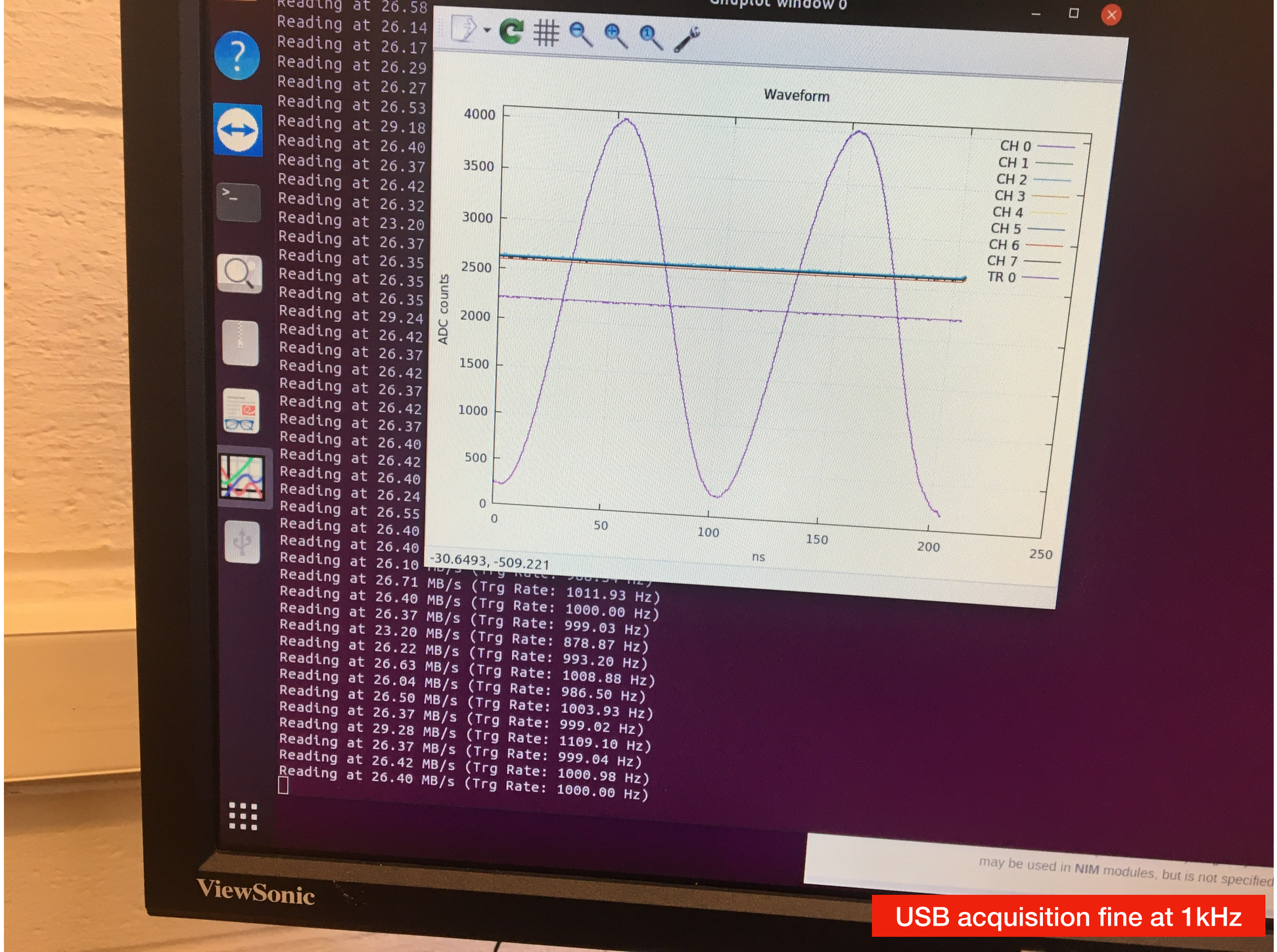



TR0 capable to digitize up to 2V

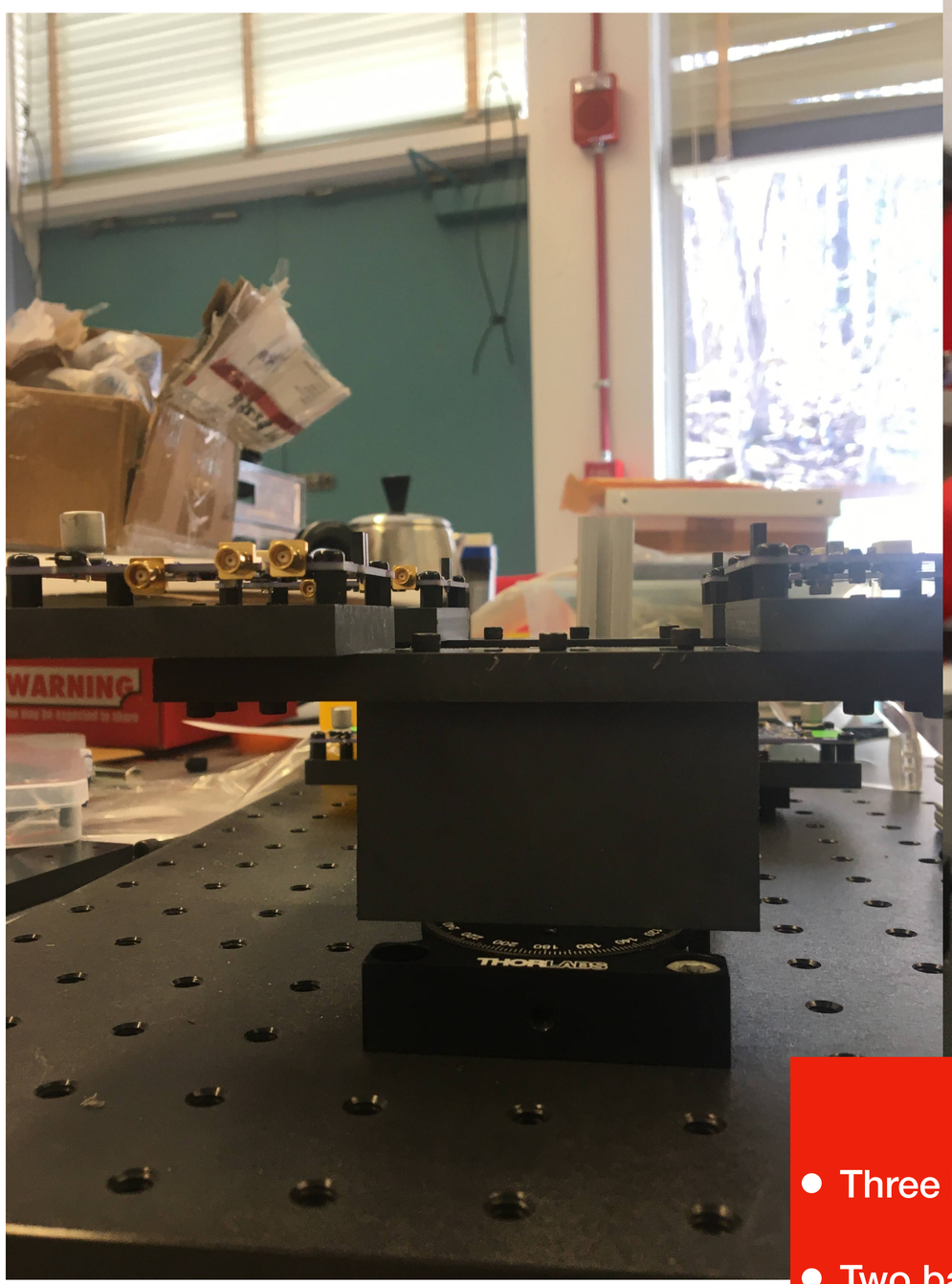
ViewSonic

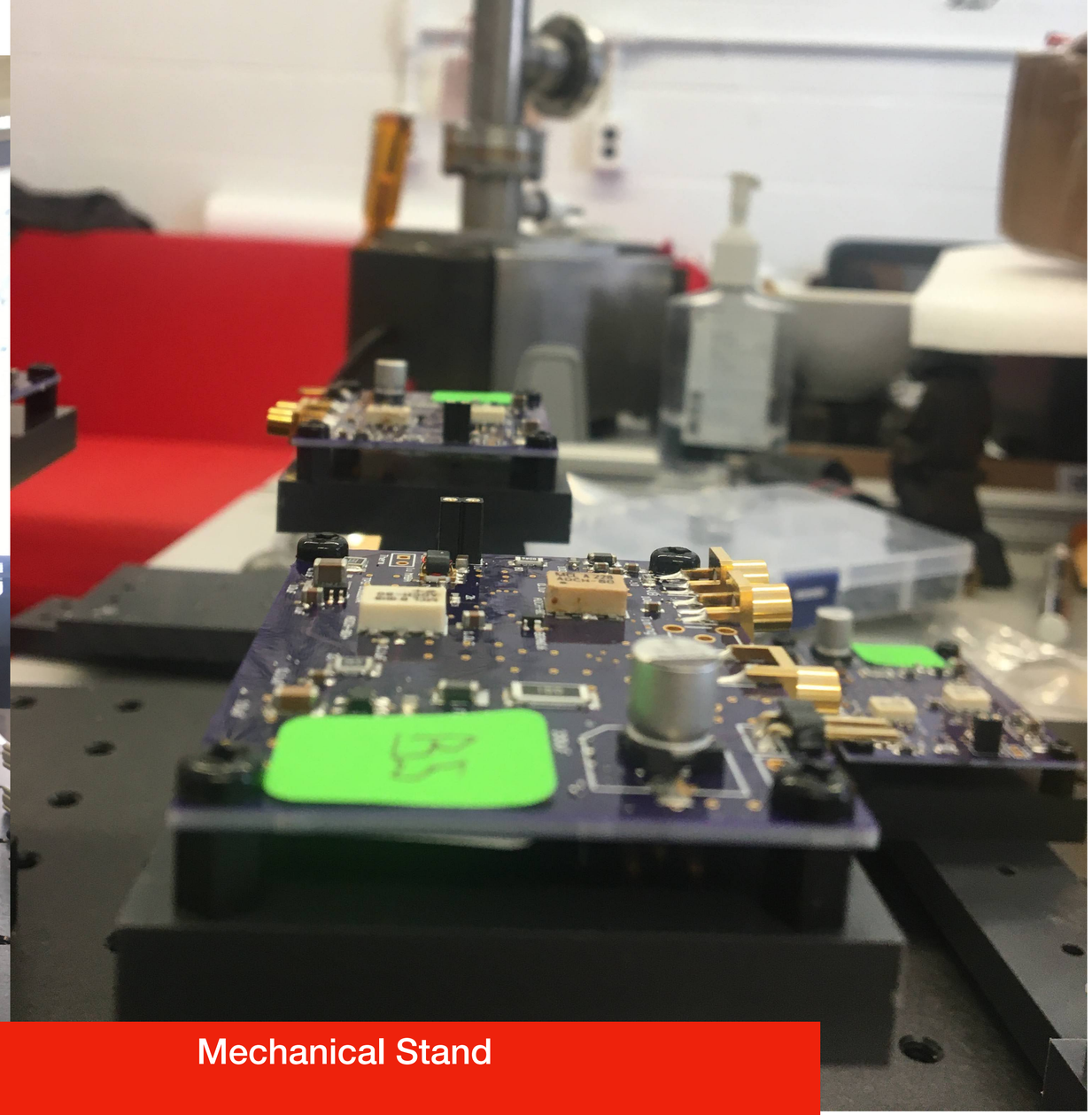

Test of external Trigger: In our case coming from… SiTelescope?
Tektronix AFG 3252 DUAL CHANNEL ARBITRARY/FUNCTION GENERATOR 2 GS/s 240 MHz
CH1 Cont
CH2 Cont
Amplitude
Offset
High Level
Low Level
-more-
1 of 2
Function
Run Mode
Channel
Trigger
Antimatter Asymmetry Group
University of Virginia
USB Memory
ViewSonic
Initial test trigger set to 1kHz
Two options : TTL or NIM


Test of external Trigger: In our case coming from… SiTelescope?
UVA
CAEN
CLK IN
Initial test trigger set to 1kHz
Two options : TTL or NIM


Gnuplot window 0
Waveform
ADC counts
ns
CH 0
CH 1
CH 2
CH 3
CH 4
CH 5
CH 6
CH 7
TR 0
-30.6493, -509.221
Reading at 26.58
Reading at 26.14
Reading at 26.17
Reading at 26.29
Reading at 26.27
Reading at 26.53
Reading at 29.18
Reading at 26.40
Reading at 26.37
Reading at 26.42
Reading at 26.32
Reading at 23.20
Reading at 26.37
Reading at 26.35
Reading at 26.35
Reading at 26.35
Reading at 29.24
Reading at 26.42
Reading at 26.37
Reading at 26.42
Reading at 26.37
Reading at 26.42
Reading at 26.37
Reading at 26.40
Reading at 26.42
Reading at 26.40
Reading at 26.24
Reading at 26.55
Reading at 26.40
Reading at 26.40
Reading at 26.10
Reading at 26.71 MB/s (Trg Rate: 1011.93 Hz)
Reading at 26.40 MB/s (Trg Rate: 1000.00 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.03 Hz)
Reading at 23.20 MB/s (Trg Rate: 878.87 Hz)
Reading at 26.22 MB/s (Trg Rate: 993.20 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.04 MB/s (Trg Rate: 986.50 Hz)
Reading at 26.50 MB/s (Trg Rate: 1003.93 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.02 Hz)
Reading at 29.28 MB/s (Trg Rate: 1109.10 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.04 Hz)
Reading at 26.42 MB/s (Trg Rate: 1000.98 Hz)
Reading at 26.40 MB/s (Trg Rate: 1000.00 Hz)
may be used in NIM modules, but is not specified
ViewSonic
USB acquisition fine at 1kHz

# Electronic Board
# And Mechanical Assembly

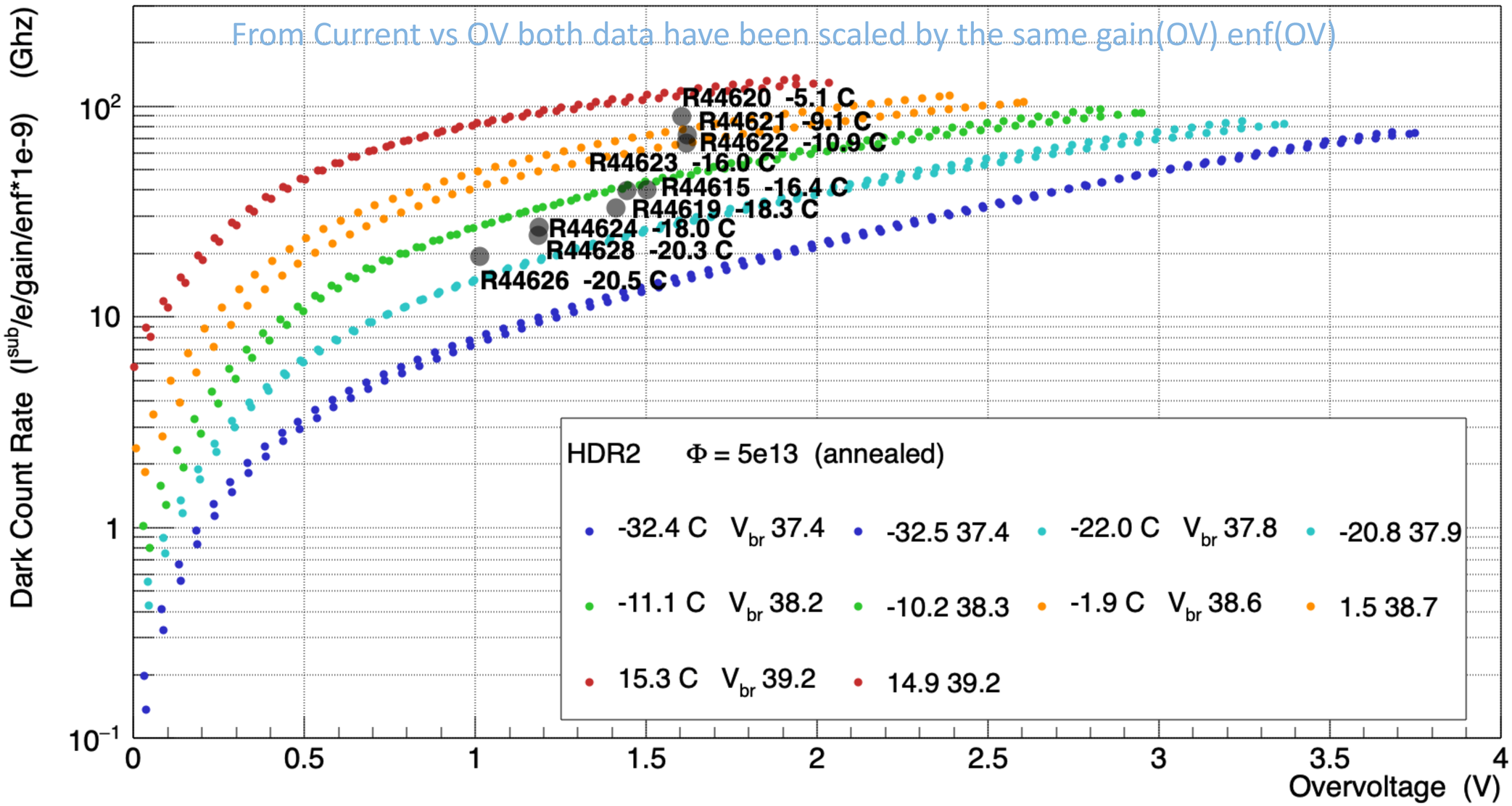


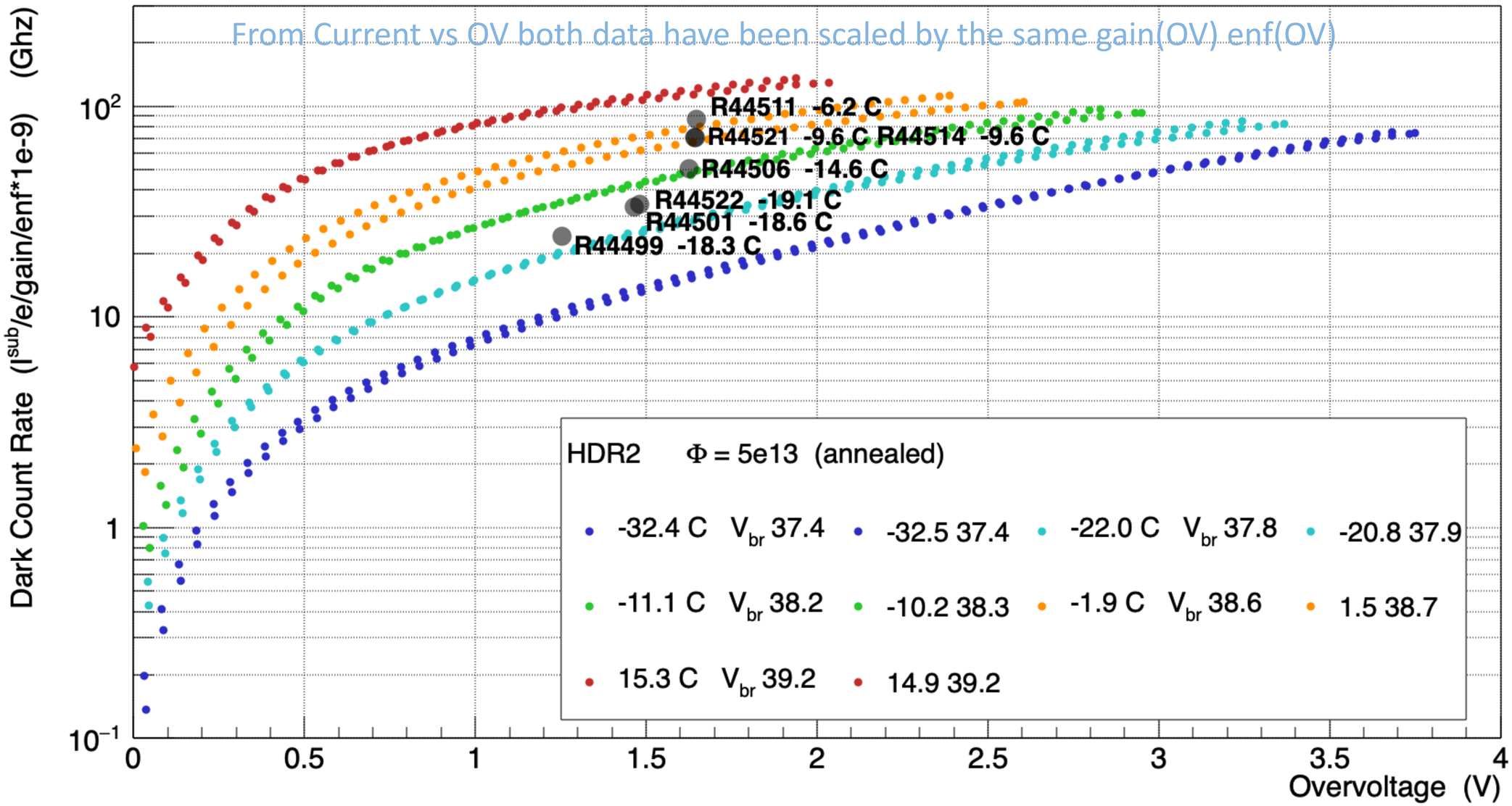
## Mechanical Stand

- Three bars with 2 boards each aligned
- Two bars mounted in rotation table and align wrt beam

# DCR Map for bars @ 40 deg inclination.



# DCR Map for bars @ 0 deg inclination.




@ 52 deg

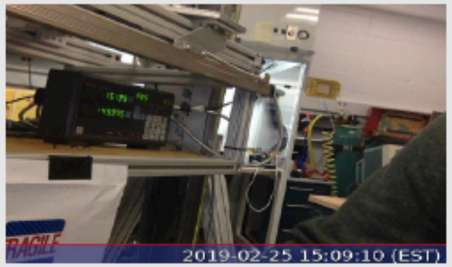
# Run Control
# and Data Monitor

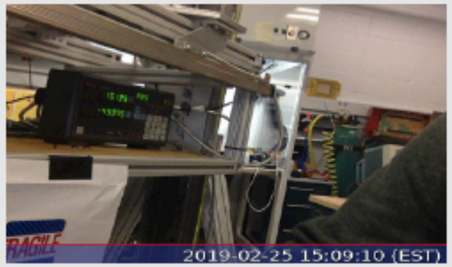
Run Control

DAQ Control

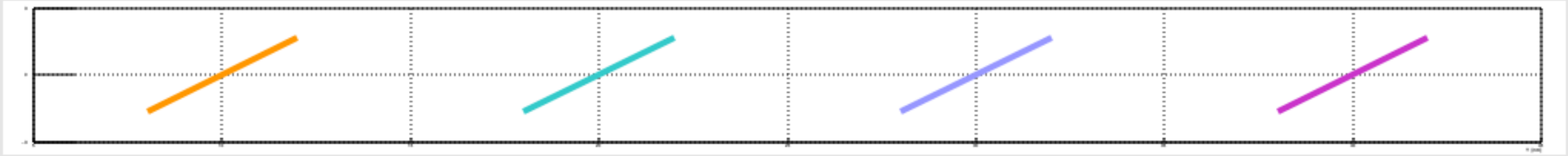
Master Controler

Angle0: 50.0 deg  Angle1: 50.0 deg  Angle2: 50.0 deg  Angle3: 50.0 deg






| | Bar0 H0 | Bar1 H0 | Bar2 H0 | Bar3 H0 |
|---|---|---|---|---|
| V_bdown: | 36.80 | 36.90 | 37.40 | 39.00 |
| OverVolt: | 0.50 | 0.50 | 0.50 | 0.50 |
| Voltage: | 37.30 V | 37.40 V | 37.90 V | 39.50 V |



| | Bar0 H1 | Bar1 H1 | Bar2 H1 | Bar3 H1 |
|---|---|---|---|---|
| Voltage: | 37.30 V | 37.40 V | 37.90 V | 39.50 V |
| V_bdown: | 36.80 | 36.90 | 37.40 | 39.00 |
| OverVolt: | 0.50 | 0.50 | 0.50 | 0.50 |

Unlock  Set & Lock

Last ConfigFile

```
00031
    50.0          50.0          50.0          50.0
38.50  0.50   39.20  0.50   39.80  0.50   40.00  0.50
38.50  0.50   39.20  0.50   39.80  0.50   40.00  0.50
 --.- degC     --.- degC     --.- degC     --.- degC
 --.- degC     --.- degC     --.- degC     --.- degC
 ----.- mA     ----.- mA     ----.- mA     ----.- mA
 ----.- mA     ----.- mA     ----.- mA     ----.- mA
```

Run Number: 00032

Start Run

STOP

| | Bar0 H0: | Bar0 H1: | Bar1 H0: | Bar1 H1: | Bar2 H0: | Bar2 H1: | Bar3 H0: | Bar3 H1: |
|---|---|---|---|---|---|---|---|---|
| | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC |
| | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA |

# Data Quality Monitoring

Bar selector

One Run

Persistent WF

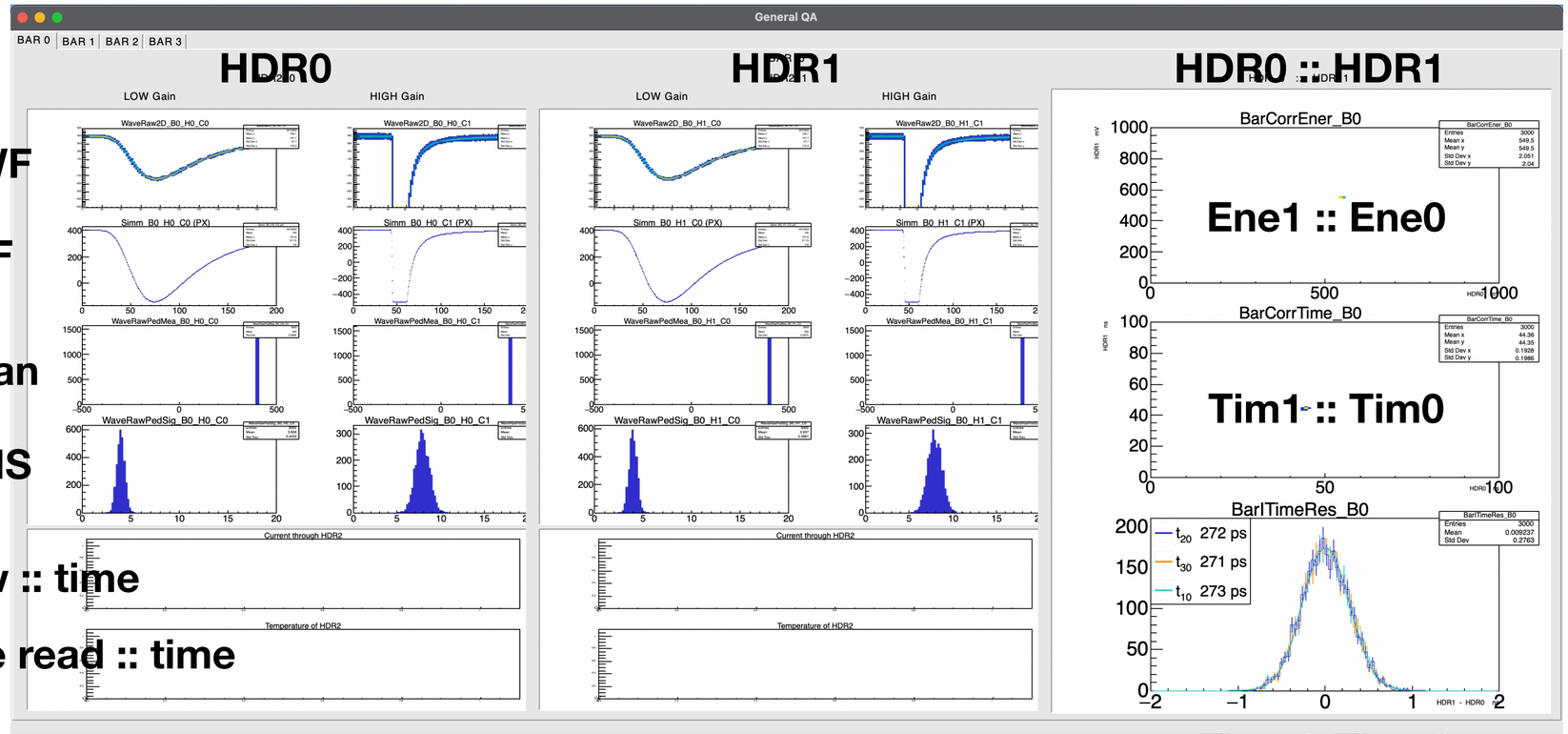
Average WF

Baseline Mean

Baseline RMS

Current draw :: time

Temperature read :: time

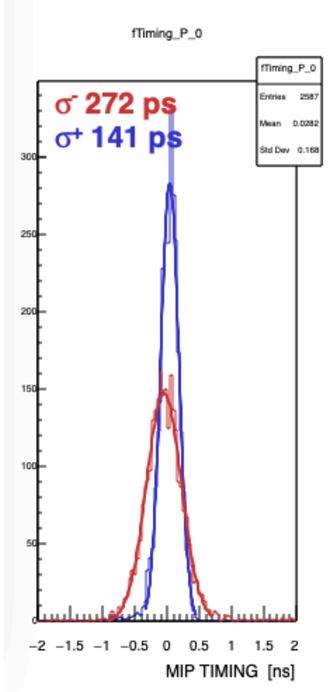



Time1-Time0

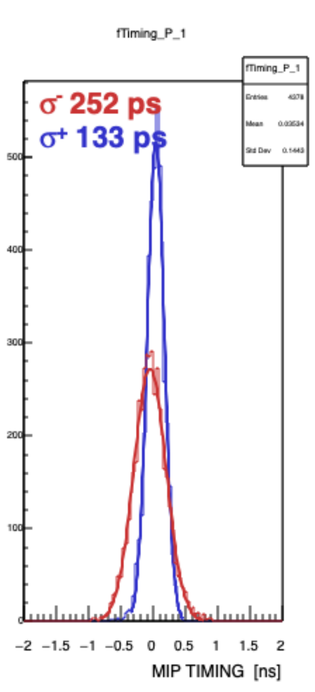
Fake MC signals

# MIP Timing [ns] for different thresholds

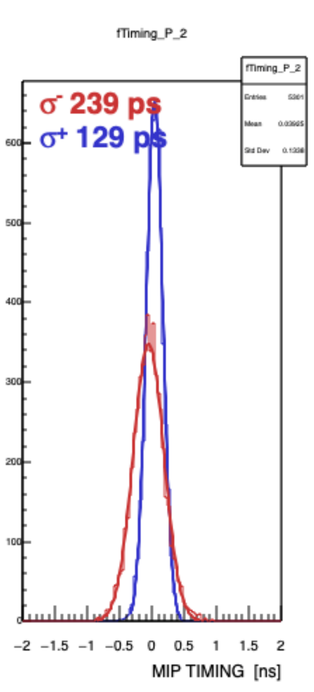
Thr -50 mV



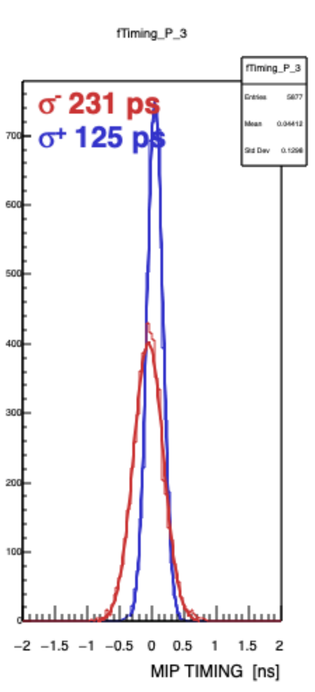

Thr -60 mV



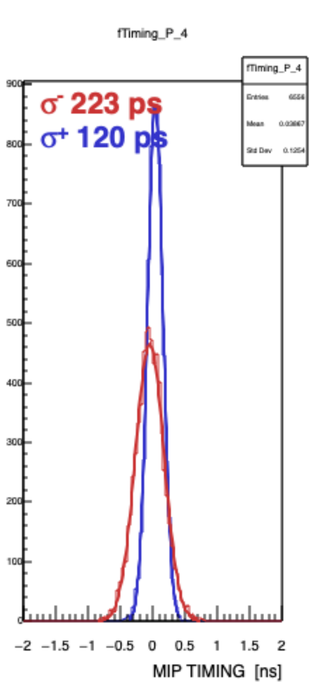

Thr -70 mV



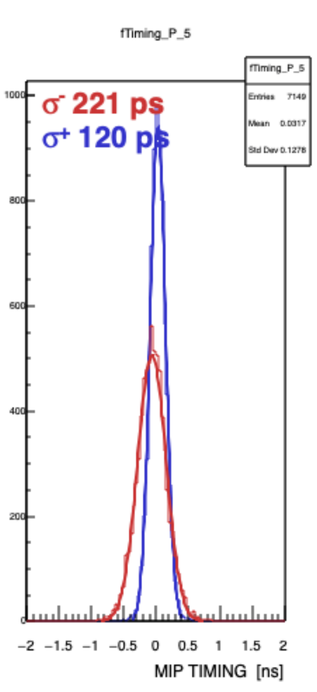

Thr -80 mV



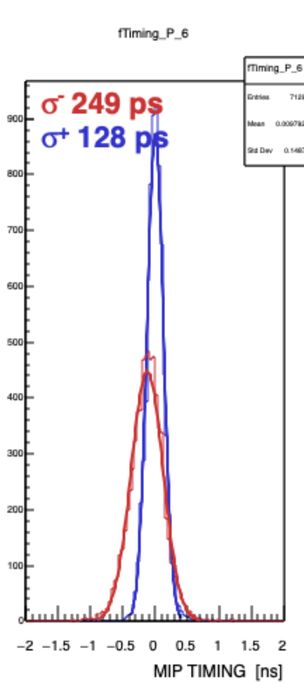

Thr -100 mV




Thr -150 mV



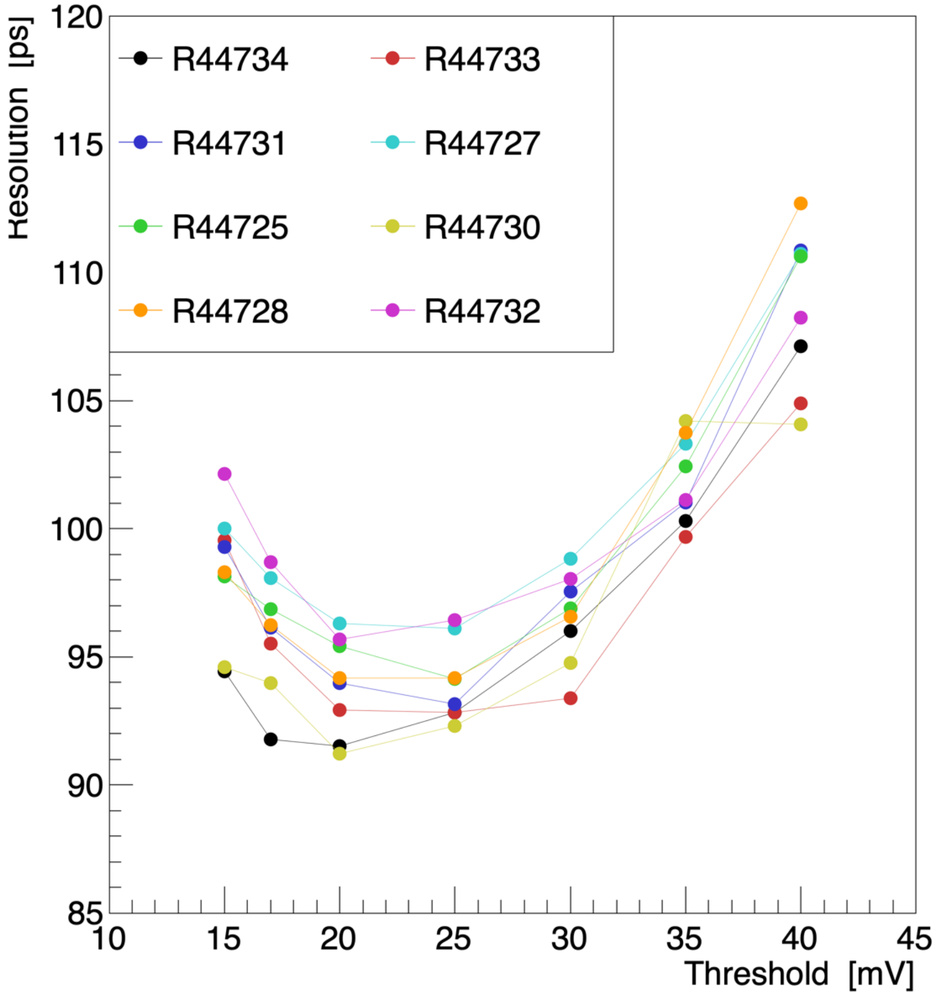

Thr -200 mV



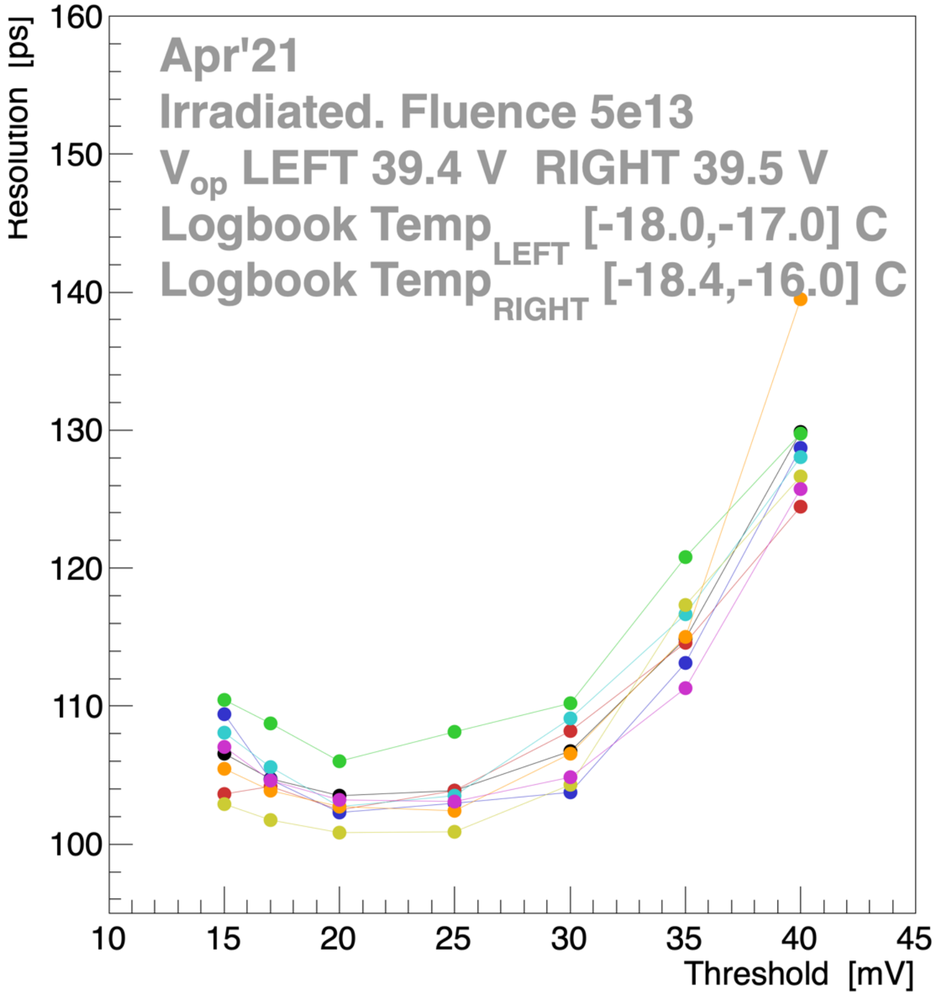

Resolutions achieved for Delay-line = 2ns

# Performance of runs taken during last shift (similar conditions)

$\sigma_{BAR} = \sigma^{-} / 2$




$\sigma^{+} = \sqrt{\sigma^2_{BAR} + \sigma^2_{MCP}}$

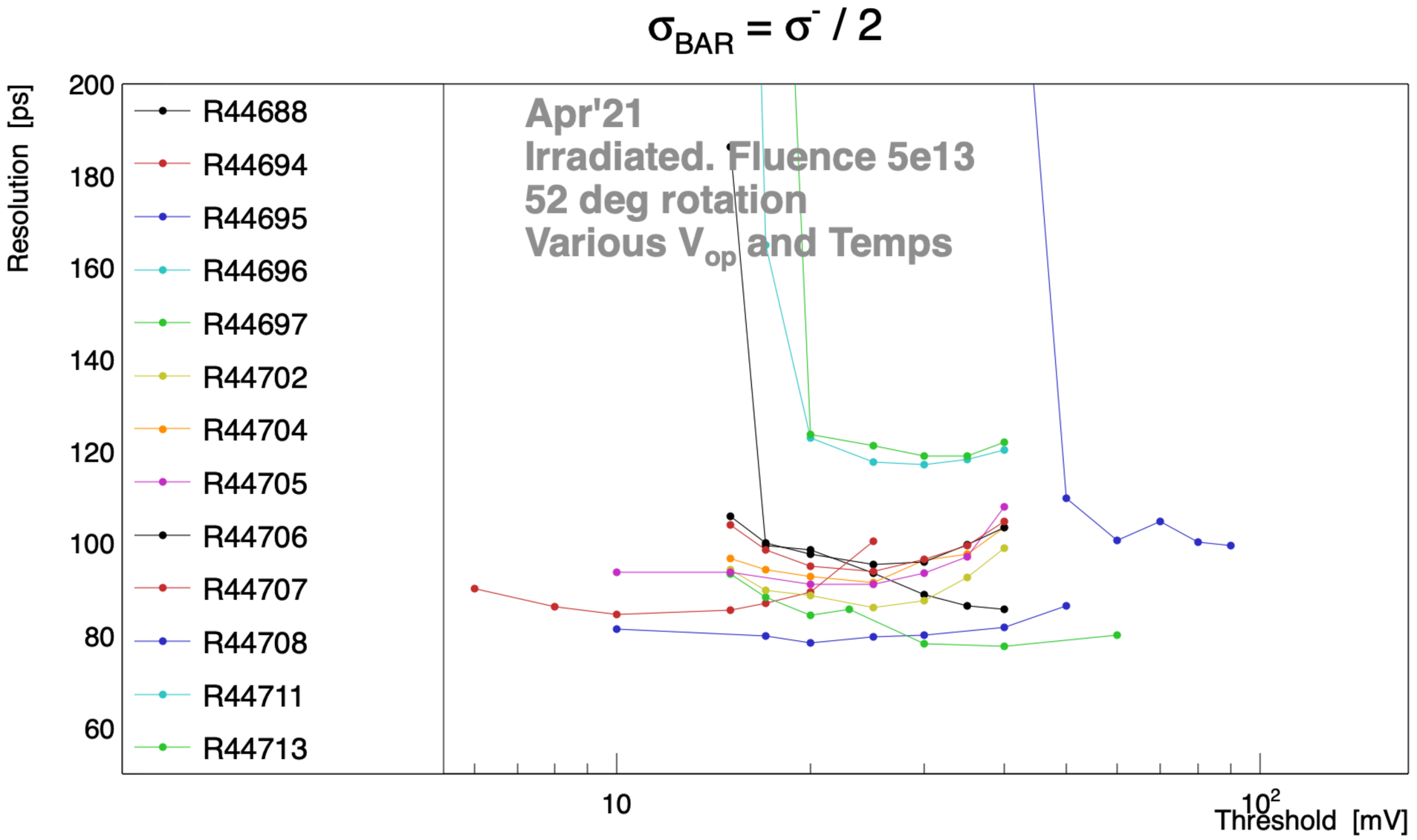



Optimal resolutions within 91 to 96 ns

Optimal thresholds within 15 and 30 mV

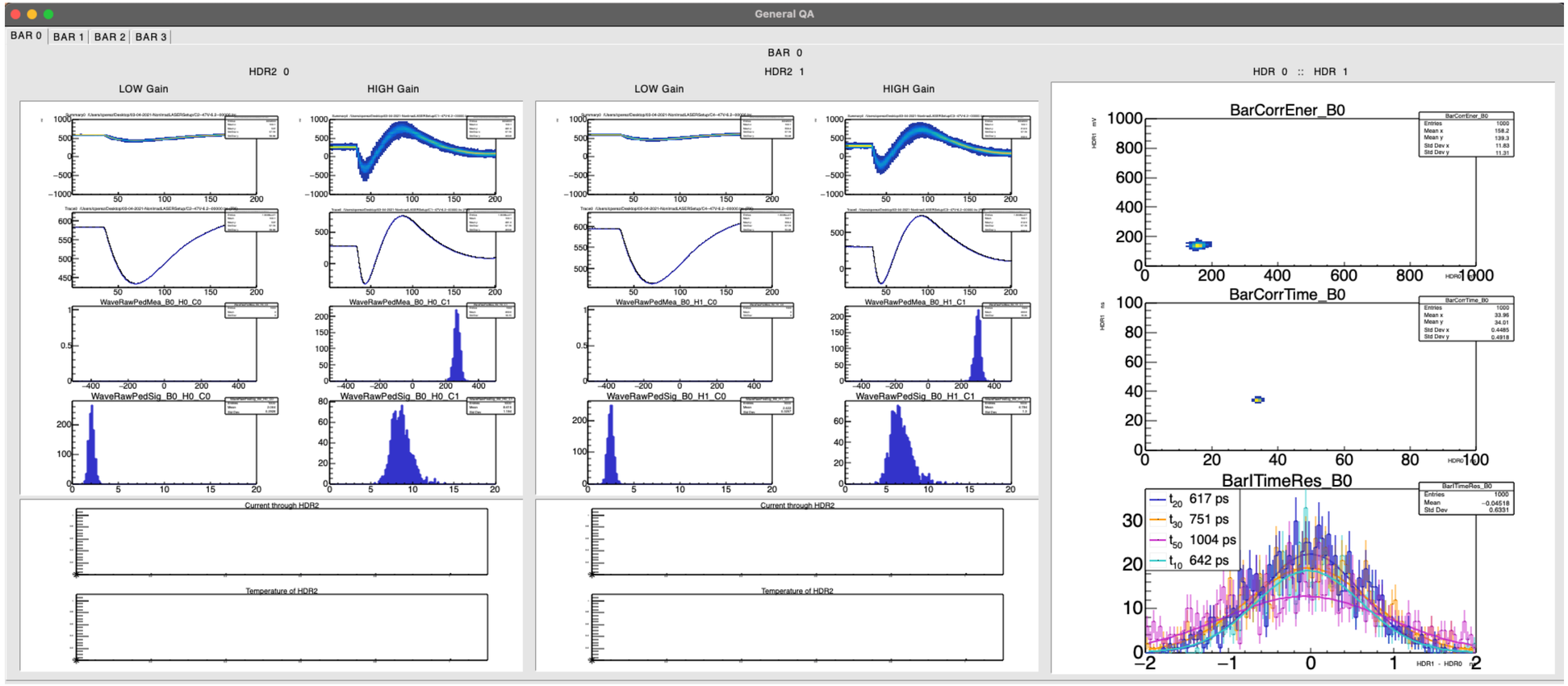
Sigma_plus suffers from the 50ps jitter from DRS

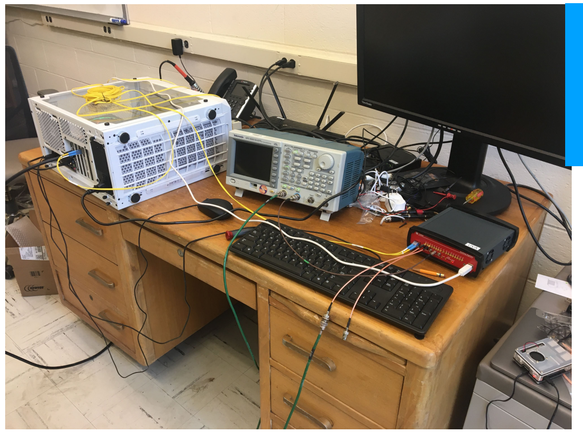
# Performance of runs Wed evening (OV / Temp scan)



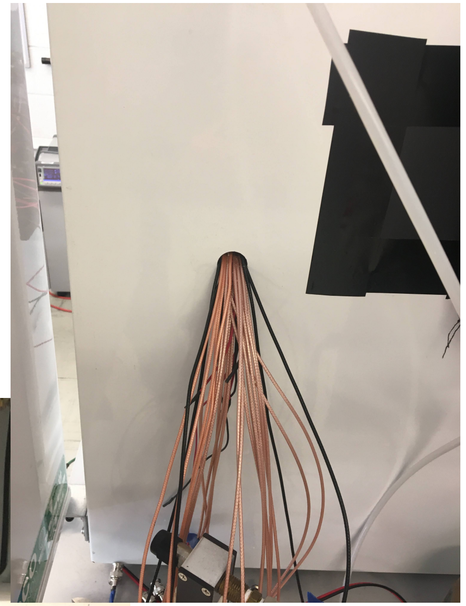
# Real response of UV-laser on LYSO + HDR2 + FEElectronics

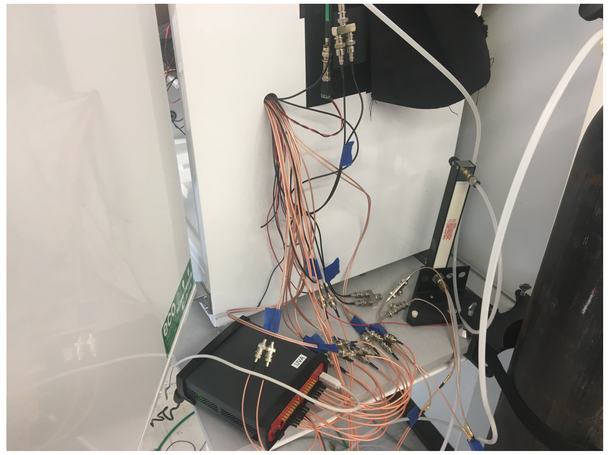
```
TString base = "47V-6.2--00000.trc";
```



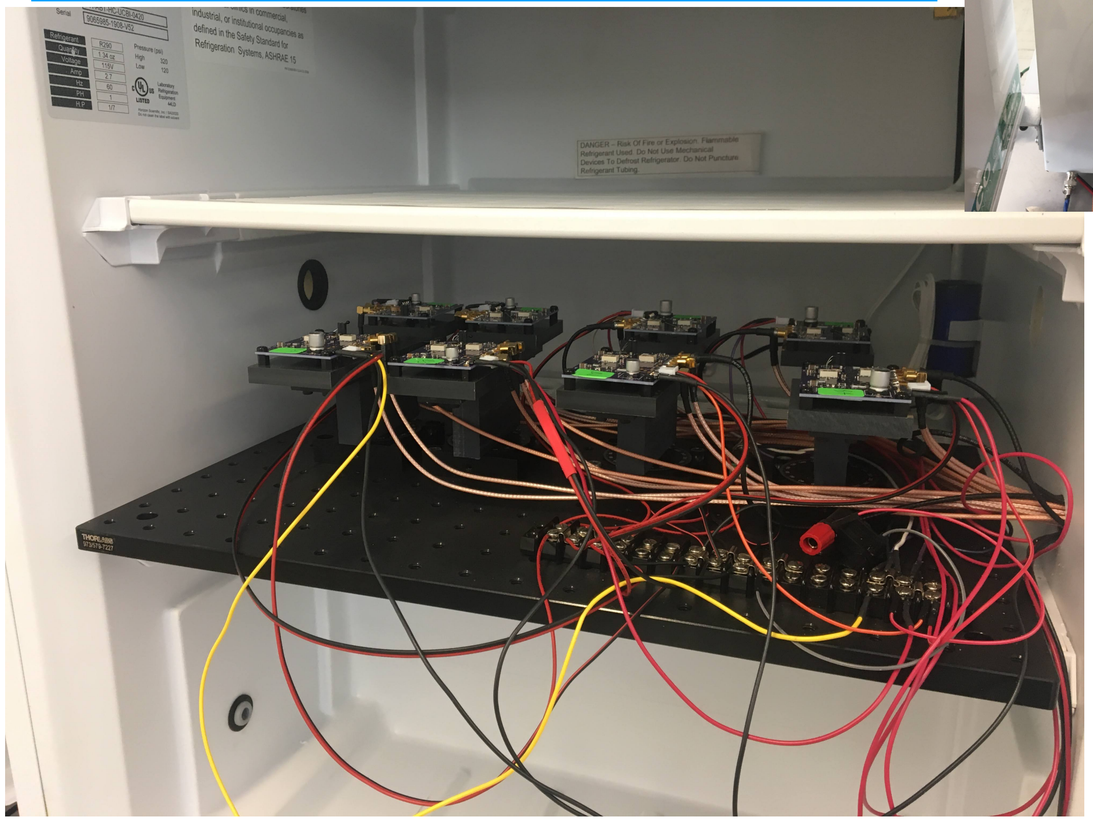


New DAQ Machine running fedora and talking to DRS at top speed. All software installed and ready. Need to work on channel mapping and few tweaks once in fnal





4-bar setup complete. Last cables arrived yesterday. All cables fit through fridge's hole





All channels show normal waveforms. Measured with DRS

# HDR2 Annealing

Notes on the annealing procedure taken for most irradiated SiPMs

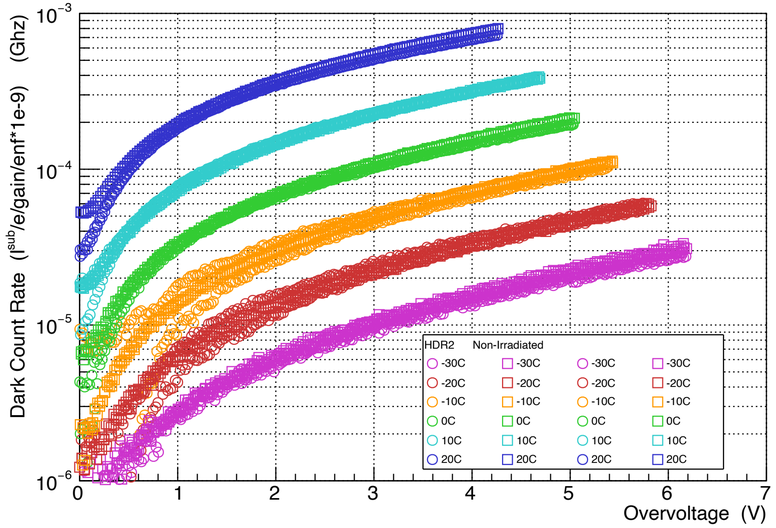
T. Anderson, B. Cox, M. Joyce, A. Ledovskoy, C. Pérez Lara, S. White

Big thanks to: M.Lucchini, A. Benaglia, A. Heering, I. Musienko

# Context

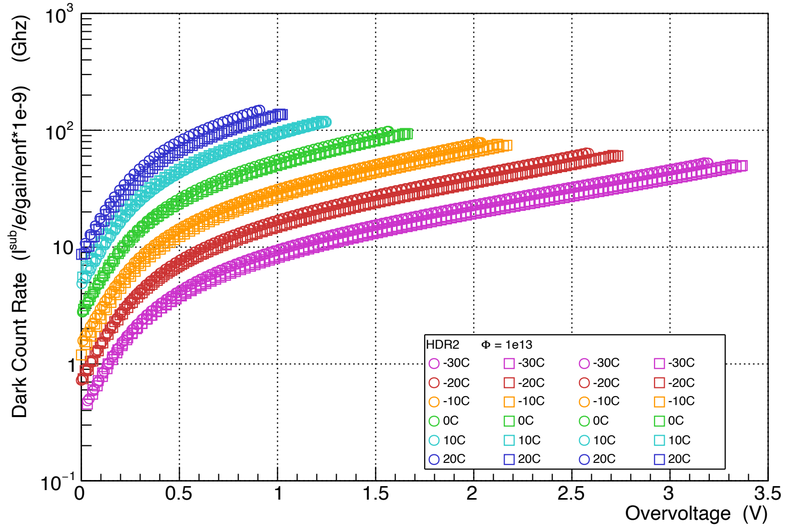
# DCR HDR2 measured on Oct 2020

Non-irradiated



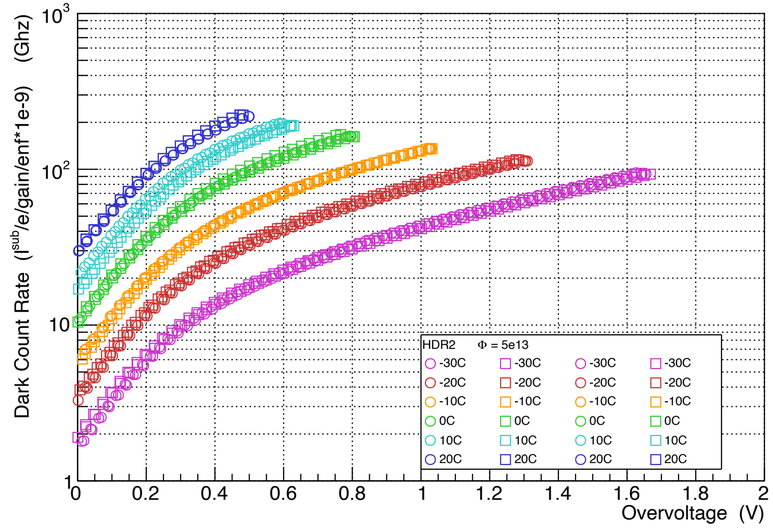

1 MHz

Fluence 1e13



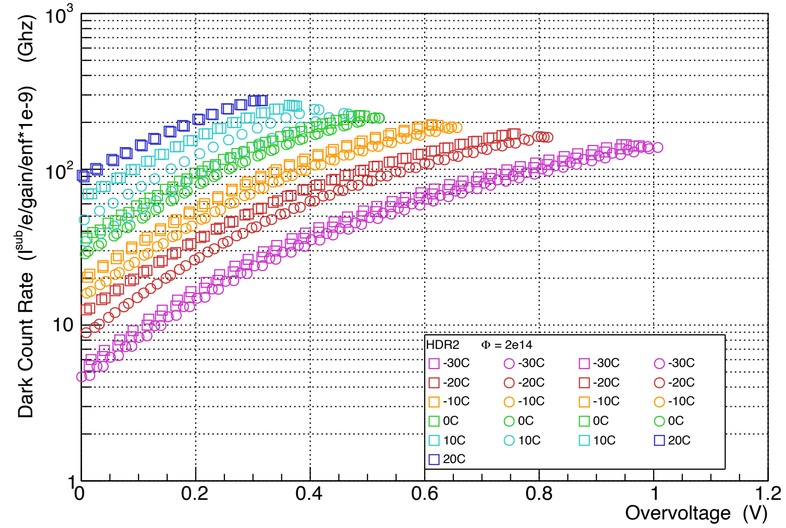

100 GHz

Fluence 5e13




100 GHz

Fluence 2e14




100 GHz

# Meeting March 18th 2021

Attended by people listed in first slide. Minutes:

Hi,
just a quick recap and action items from our meeting. Please correct mistakes:
1) the goal of the annealing is to achieve a **SiPM condition representative of the end of life BTL conditions** (including PDE and gain loss in the SiPM) under the assumption of an optimistic annealing scenario and test it on beam. Thus:
+ the SiPM irradiated to 2e14 should be annealed to the level of 30GHz at 1.5V OV @ -25°C
+ the SiPM irradiated to 5e13 should be annealed to have the same DCR as of the 2e14 SiPMs (thus also 30 GHz at 1.5V OV @ -25°C)
- it will be possible to span higher DCR levels by raising the environmental temperature in the test beam box
- to achieve the desired annealing of about a factor 10 a high temperature annealing is required (Sasha working on the exact numbers, T and time)
2) As annealing to temperatures higher than 85°C (for relatively long time) may imply some risk for the SiPM performance (anomalous dark current behavior observed by Yuri or epoxy aging) it is agreed to start ASAP by annealing the samples at 85°C and monitor every ~2 days the DCR level (and if possible the response to a calibrated LED source).
3) In the meantime Arjan will inquire with HPK if they consider safe to anneal at higher temperatures and for how long. Marco will also try to make some high temperature annealing on silicone resin samples from HPK to see if any degradation in optical transparency occurs.
4) In about one week from now, and depending on the outcome of 3), we could consider to further raise the annealing temperature if this is deemed necessary to achieve the DCR level desired for the test beam.
cheers,
Marco

# How long will it take to anneal?

5e13
---- **@1 OV**

Measured DCR for 5e13 SiPM is 43GHz at -30C.
Target DCR is 30GHz at -25C or 23.4GHz at -30C. The annealing factor is 43/23.4 = 1.84
Estimated annealing time at different temperatures:

| Temp | Time |
|---|---|
| 20 | 202 days 21 hours 2 min |
| 30 | 42 days 7 hours 22 min |
| 40 | 9 days 17 hours 42 min |
| 50 | 2 days 10 hours 52 min |
| 60 | 0 days 16 hours 12 min |
| 70 | 0 days 4 hours 52 min |

2e14 **@1 OV**
-----

The annealing factor is x4 of 5e13 or 4 * 1.84 = 7.36
Estimated annealing time at different temperatures:

| Temp | Time |
|---|---|
| 70 | 745 days 0 hours 12 min |
| 80 | 234 days 7 hours 52 min |
| 90 | 78 days 10 hours 52 min |
| 100 | 27 days 19 hours 42 min |
| 110 | 10 days 9 hours 42 min |
| 120 | 4 days 2 hours 2 min |
| 130 | 1 days 16 hours 22 min |

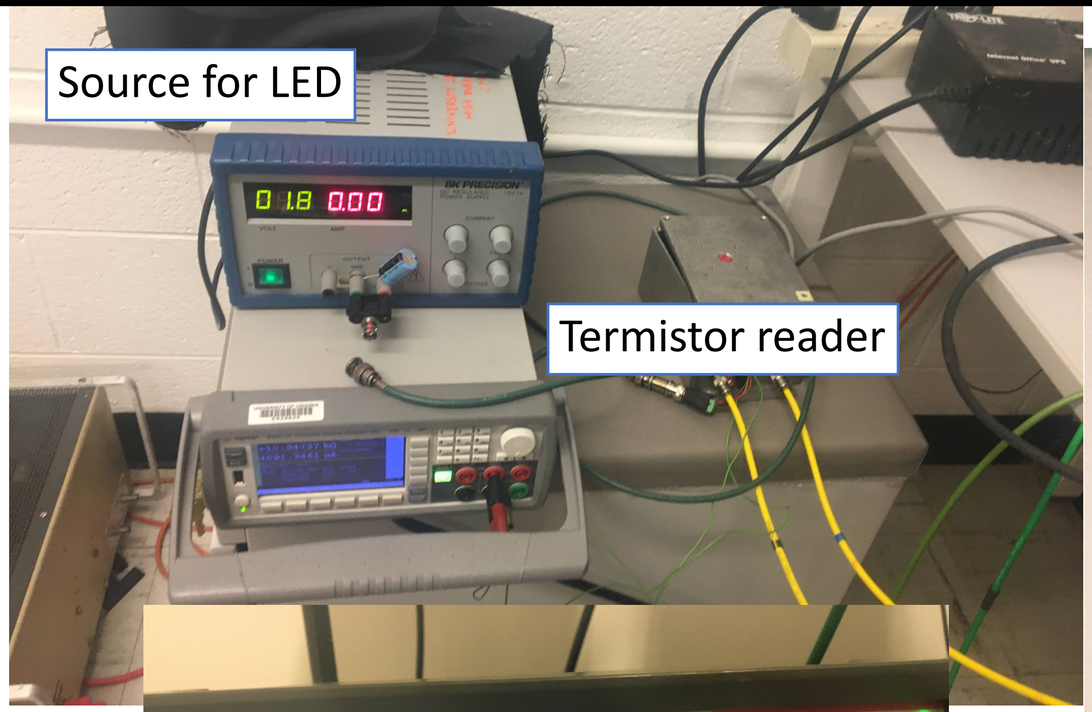
**If we anneal at 80C we would need several months to reach such levels**

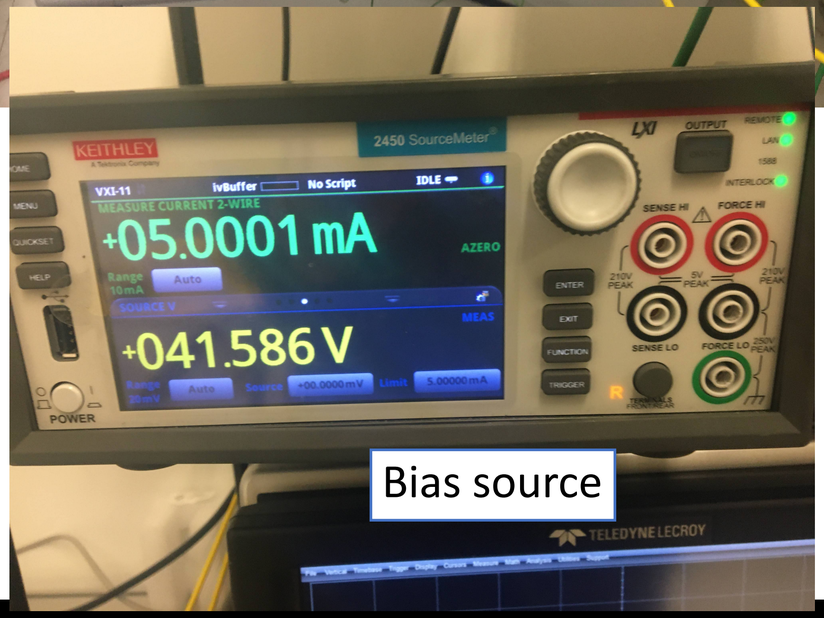
**If we anneal at this temperature, what do we chose as time intervals?**

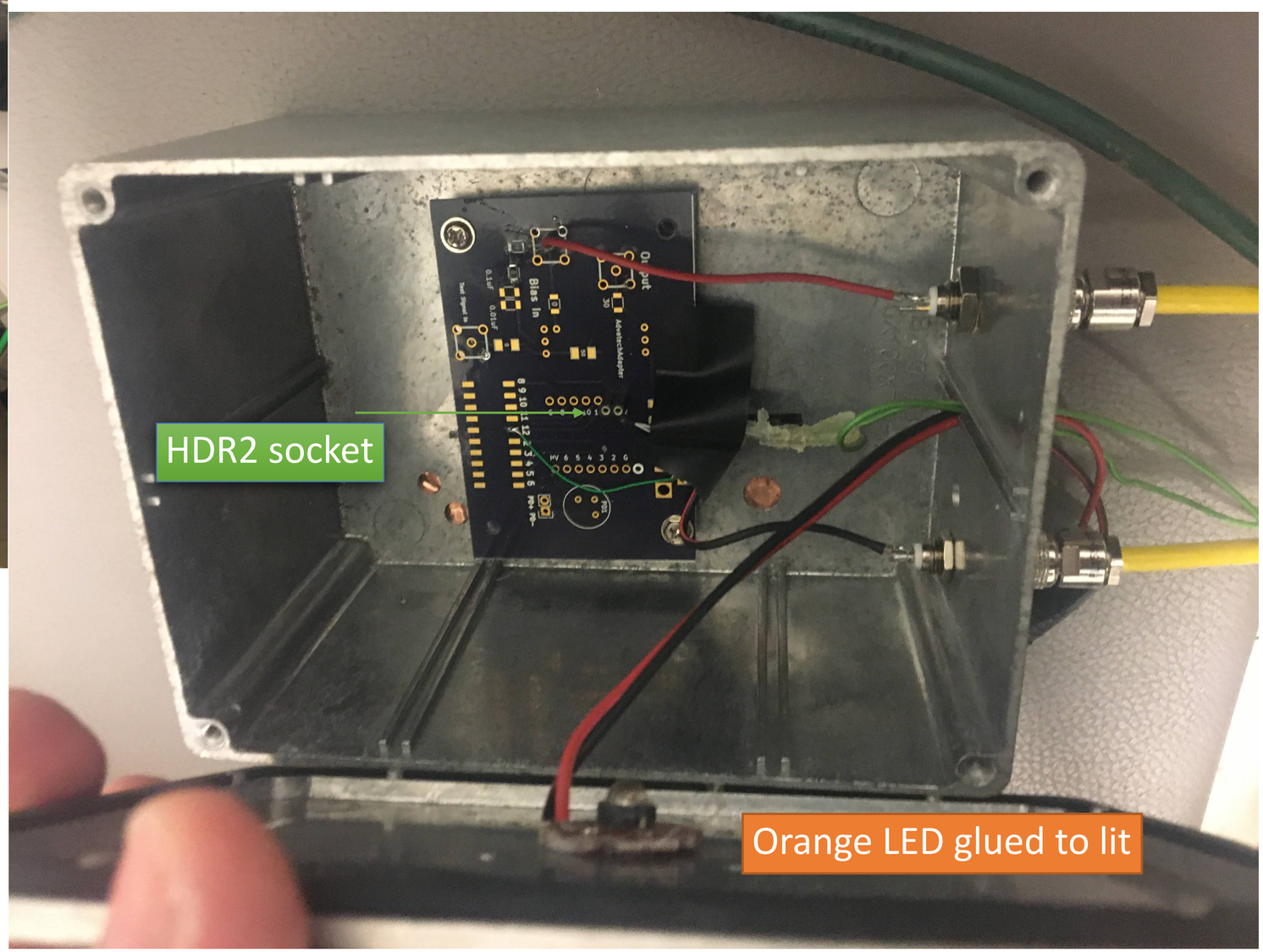
**Still we need to hear from Hamamatsu if we can go to 110C**

# Initial Setup

# IV-Setup


Source for LED
Termistor reader


KEITHLEY
2450 SourceMeter
+05.0001 mA
+041.586 V
Bias source
TELEDYNE LECROY


HDR2 socket
Orange LED glued to lit

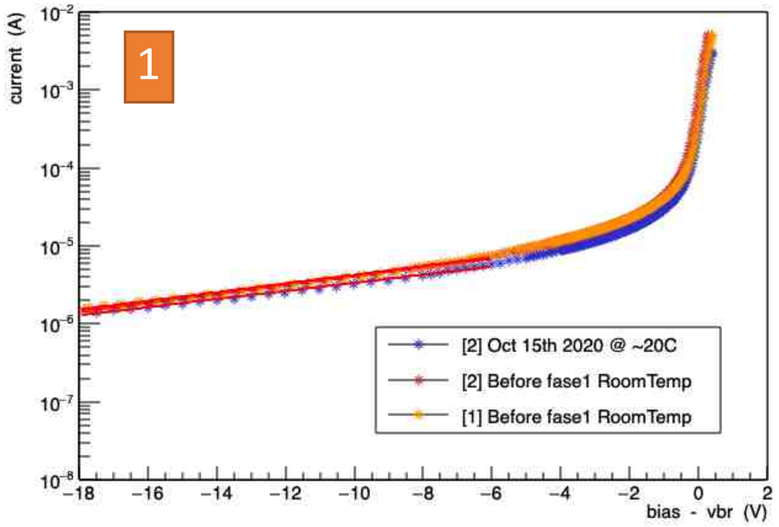
# Take one

Annealing for 2 hours

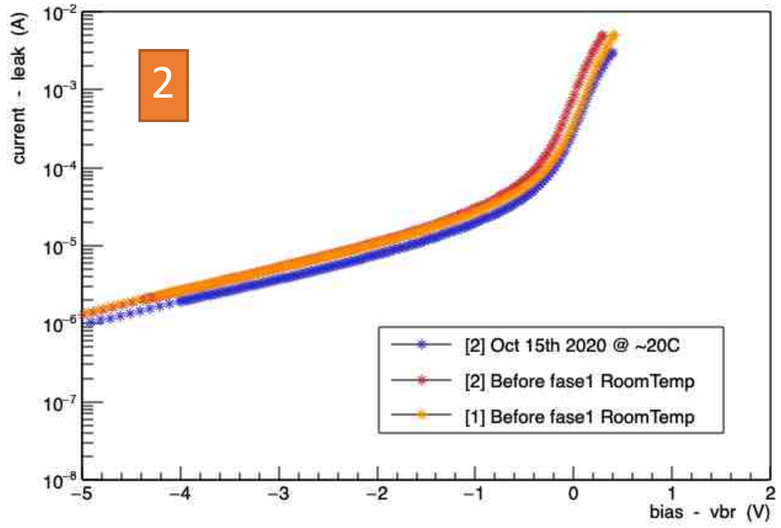
at 80C

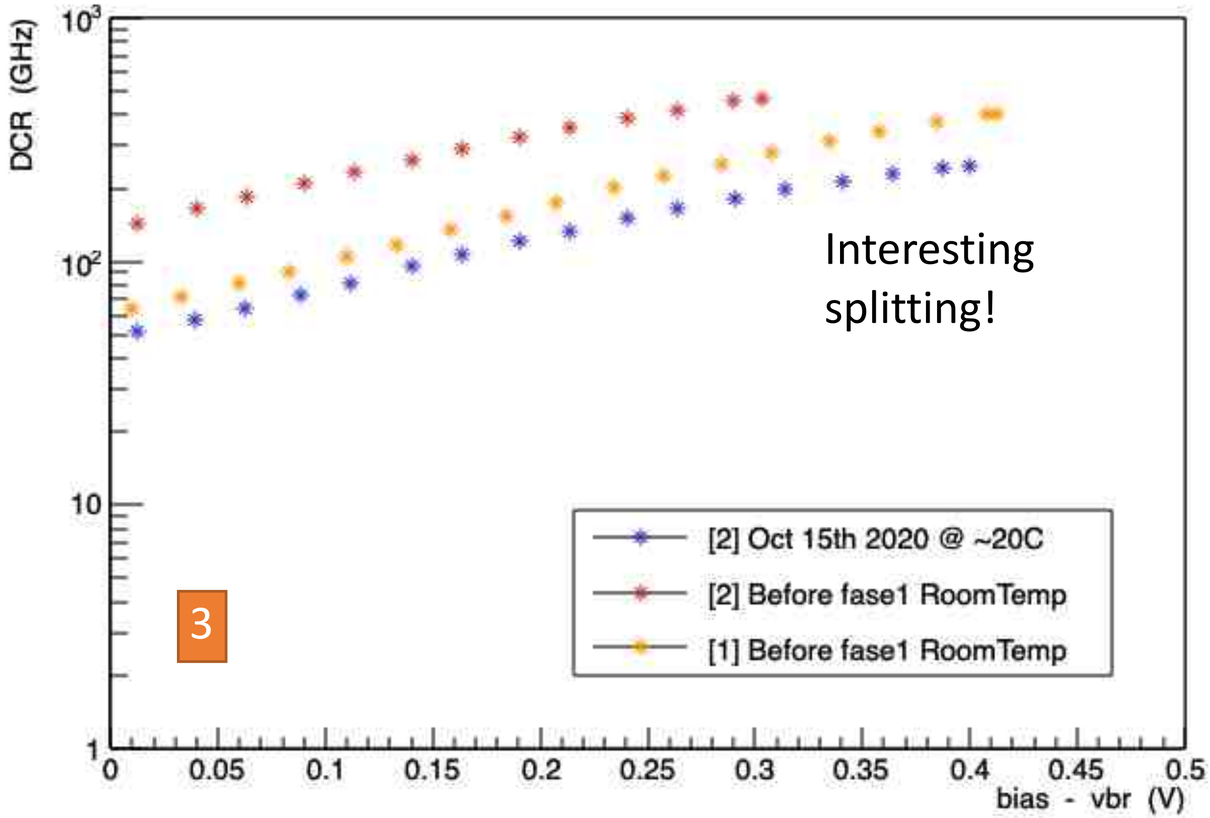
# Measurements before first annealing interval

- Once Vbr was determined via DARK/LED procedure, we compute DCR



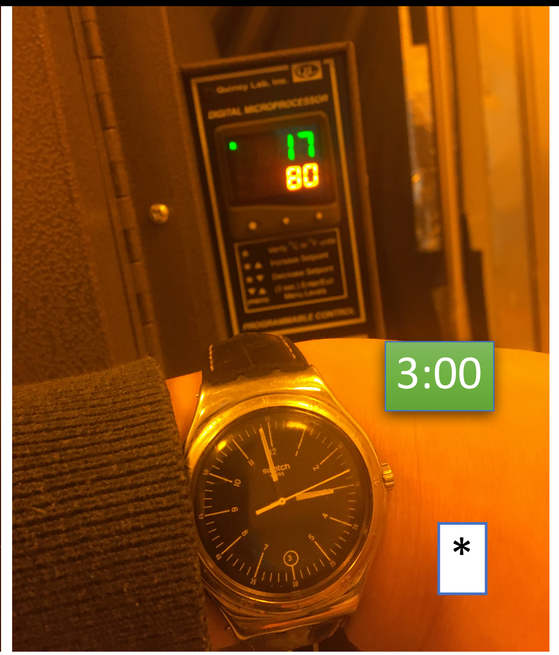

Similar leakage current

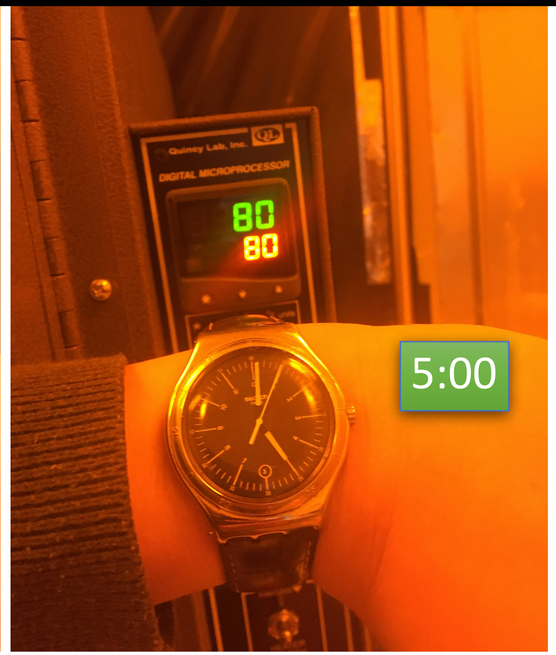


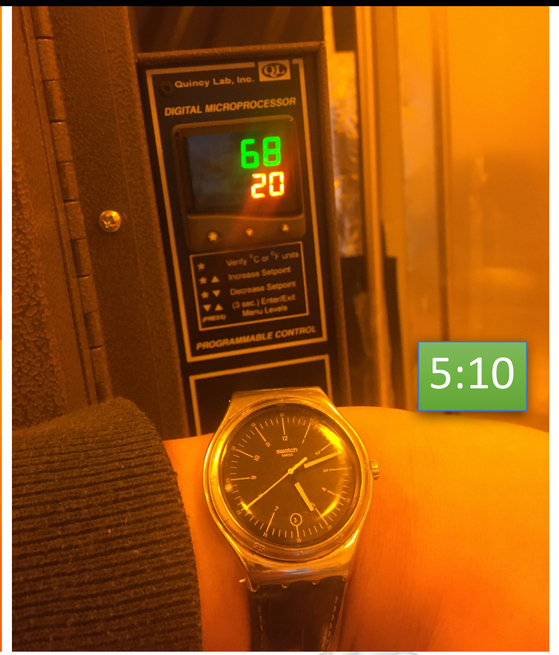



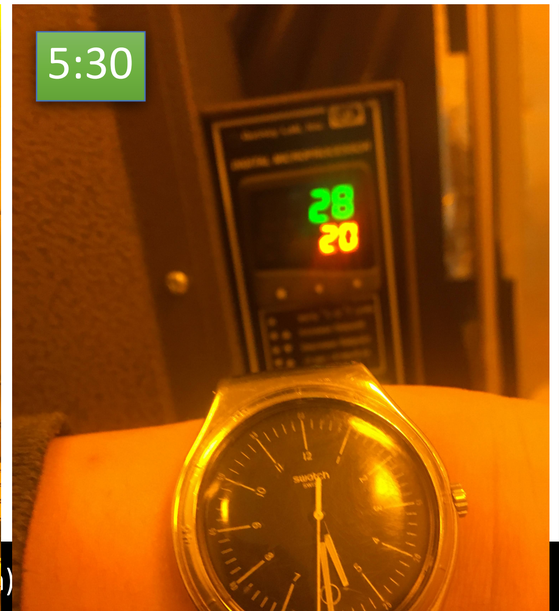

Interesting splitting!

# Cooking HDR2 2e14

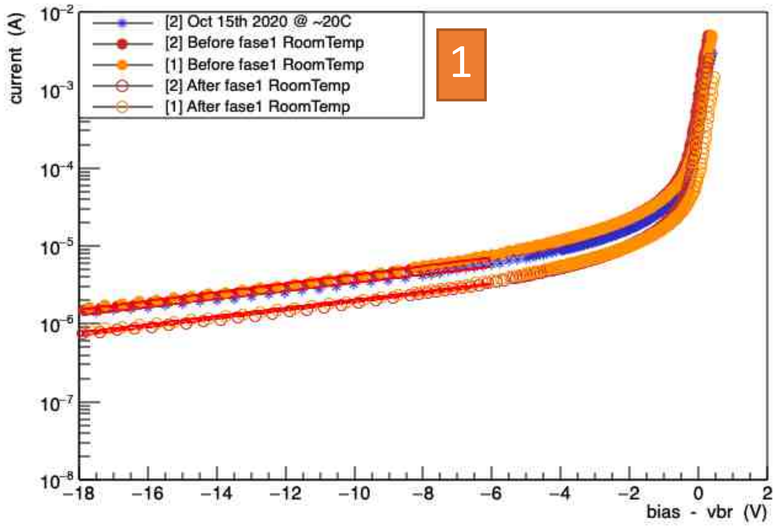





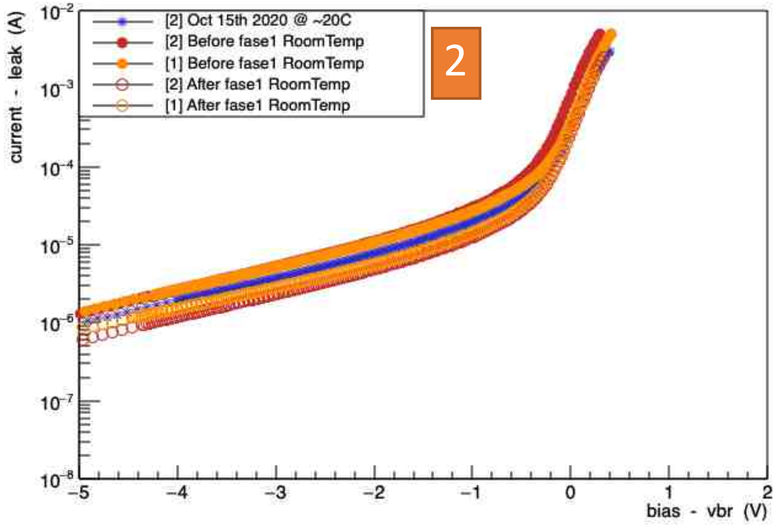
*Lost the picture, but checked that after 10 minutes we reached 80C

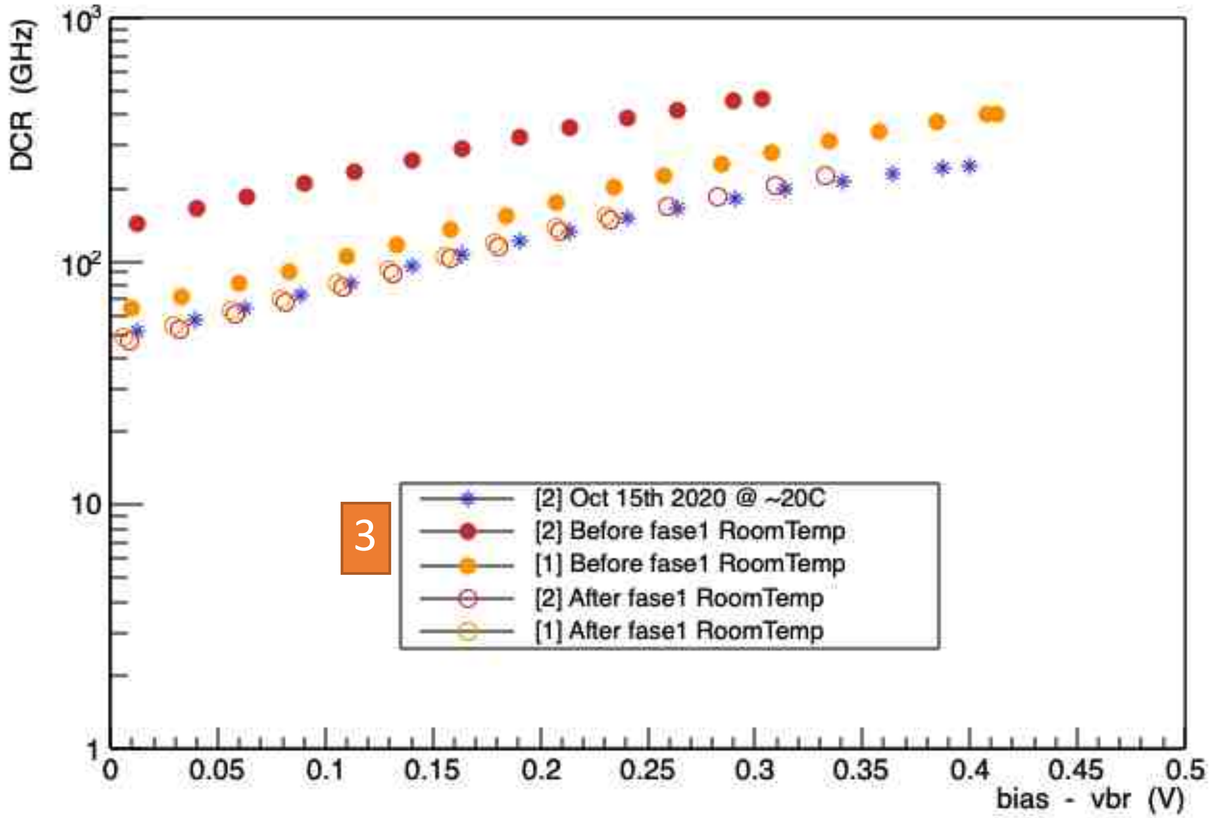
# Measurements after first annealing interval

- Once Vbr was determined via DARK/LED procedure, we compute DCR




Leakage significantly smaller (~20%)



# Take two

Annealing for 3.5 hours

at 85C

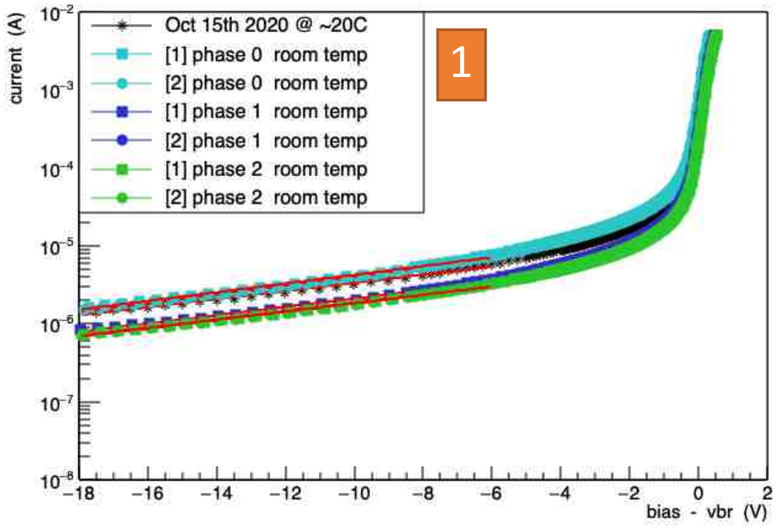
# Cooking HDR2 2e14



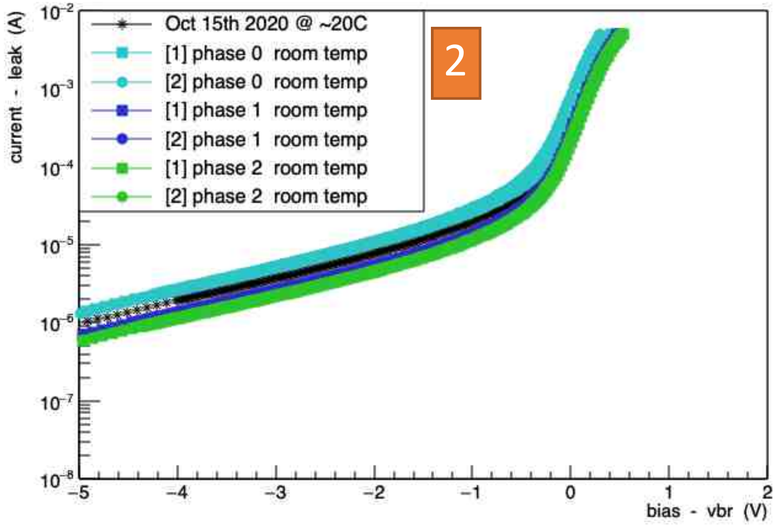

Cooking for around 4h 20m at 85C

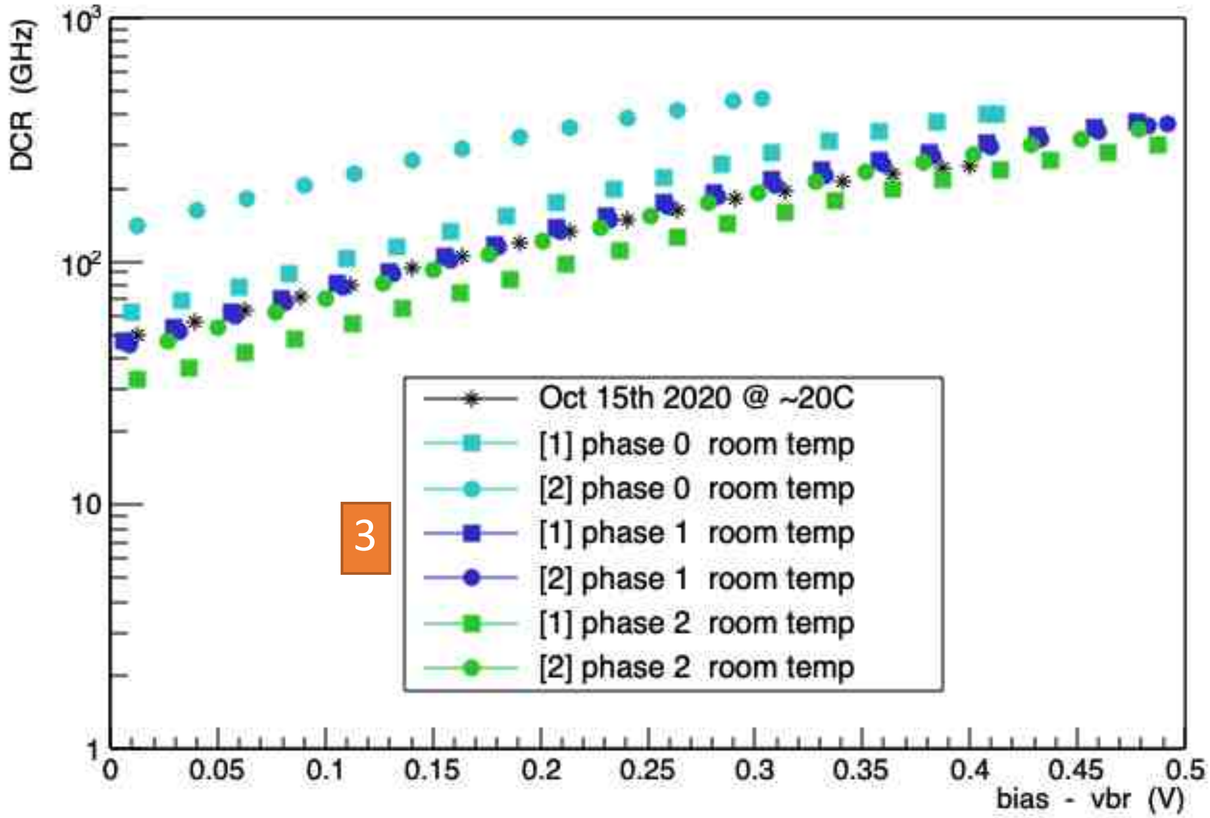
# Measurements after first annealing interval

- Once Vbr was determined via DARK/LED procedure, we compute DCR




Leakage even smaller



# Take four

Annealing for 8.3 hours

at 85C

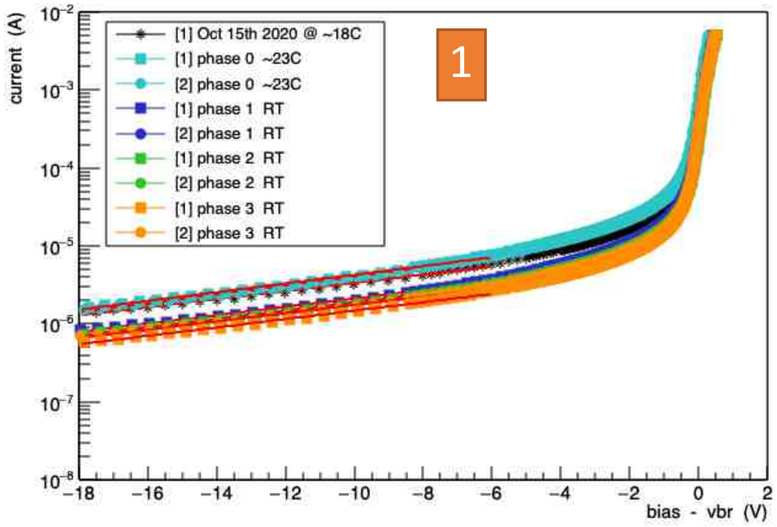
# Cooking HDR2 2e14

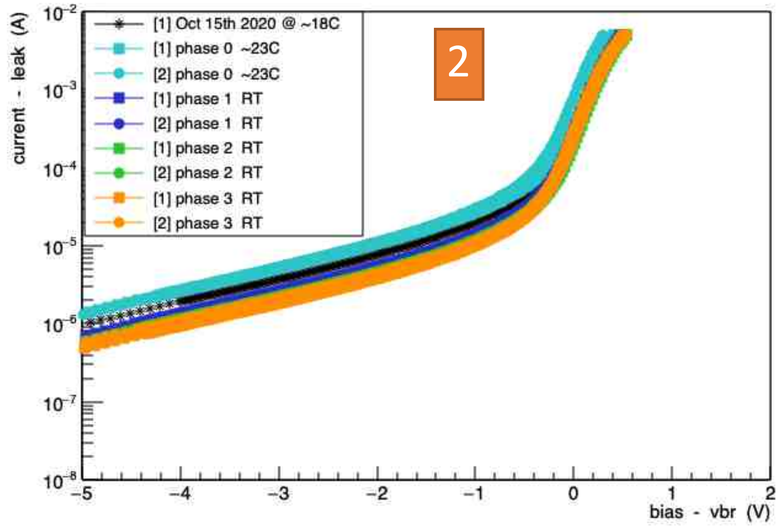


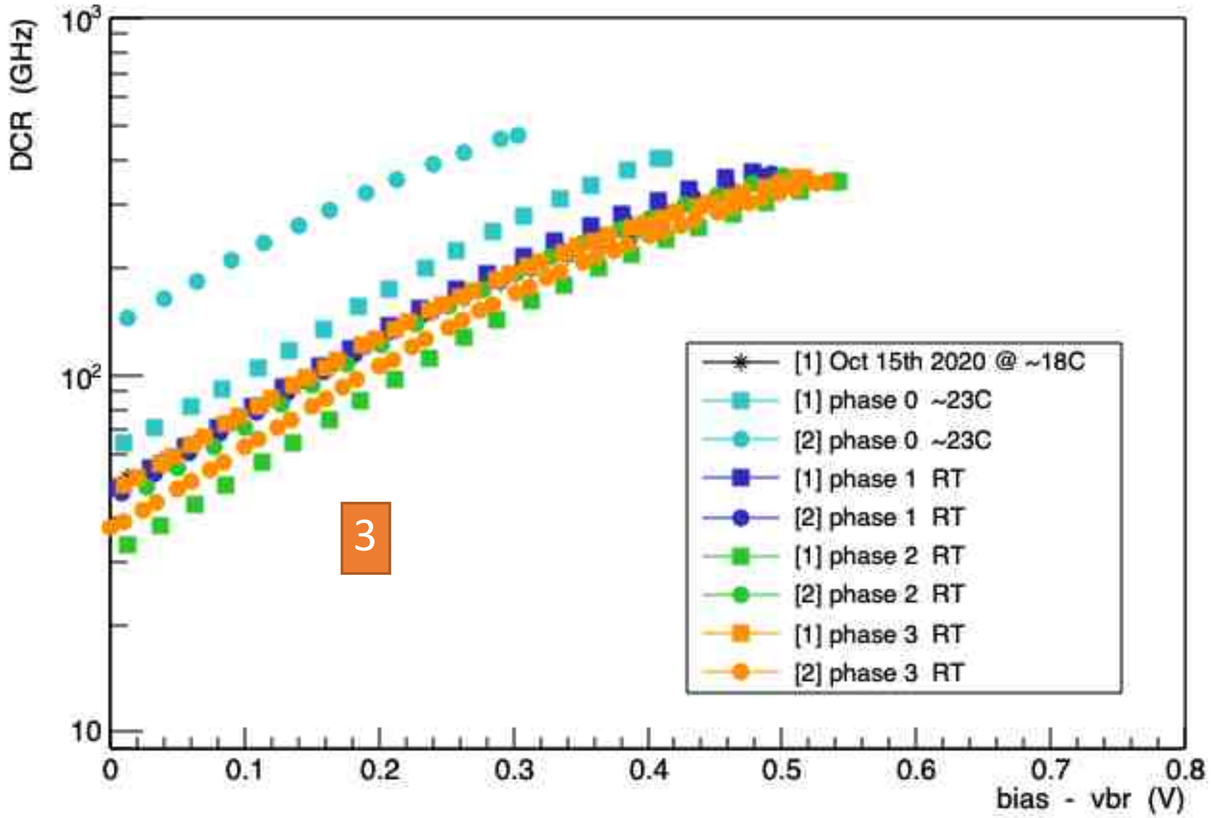
Cooking for around 8h 20m at 85C

# Measurements after first annealing interval

- Once Vbr was determined via DARK/LED procedure, we compute DCR



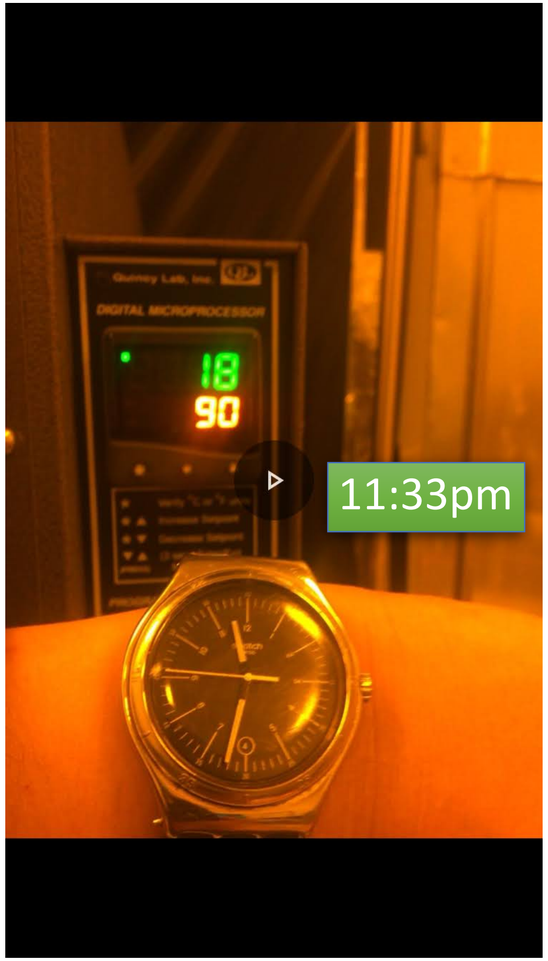



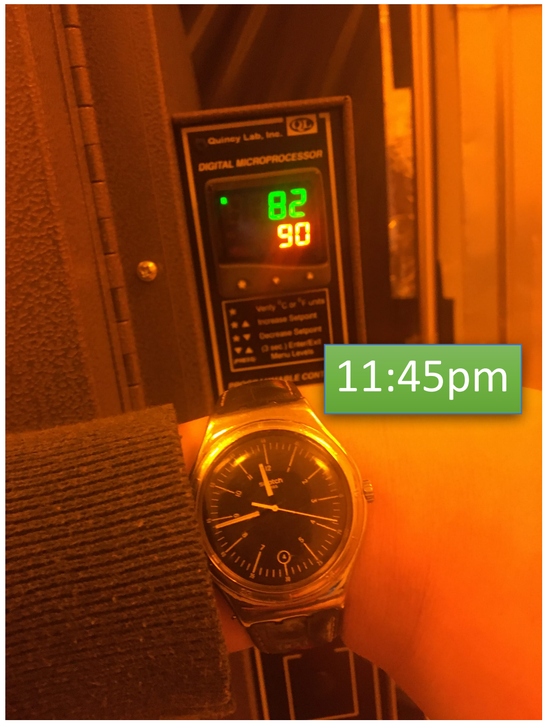
# Take five

Annealing for 2.0 hours

at 90C

# Cooking HDR2 2e14



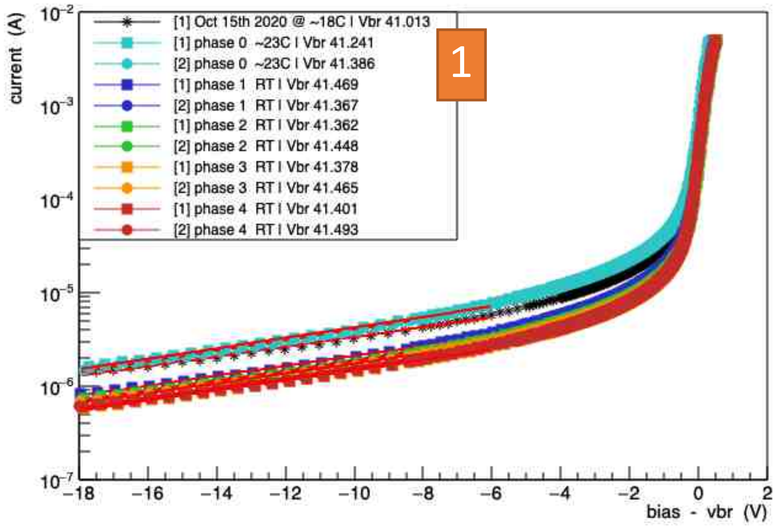



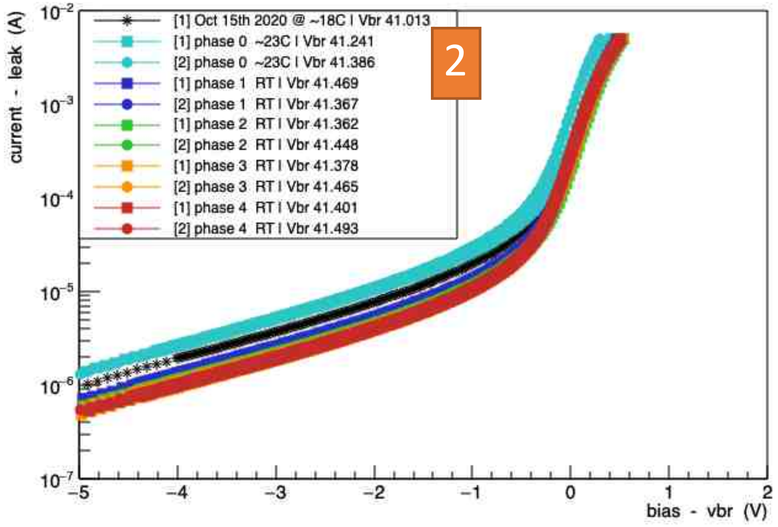


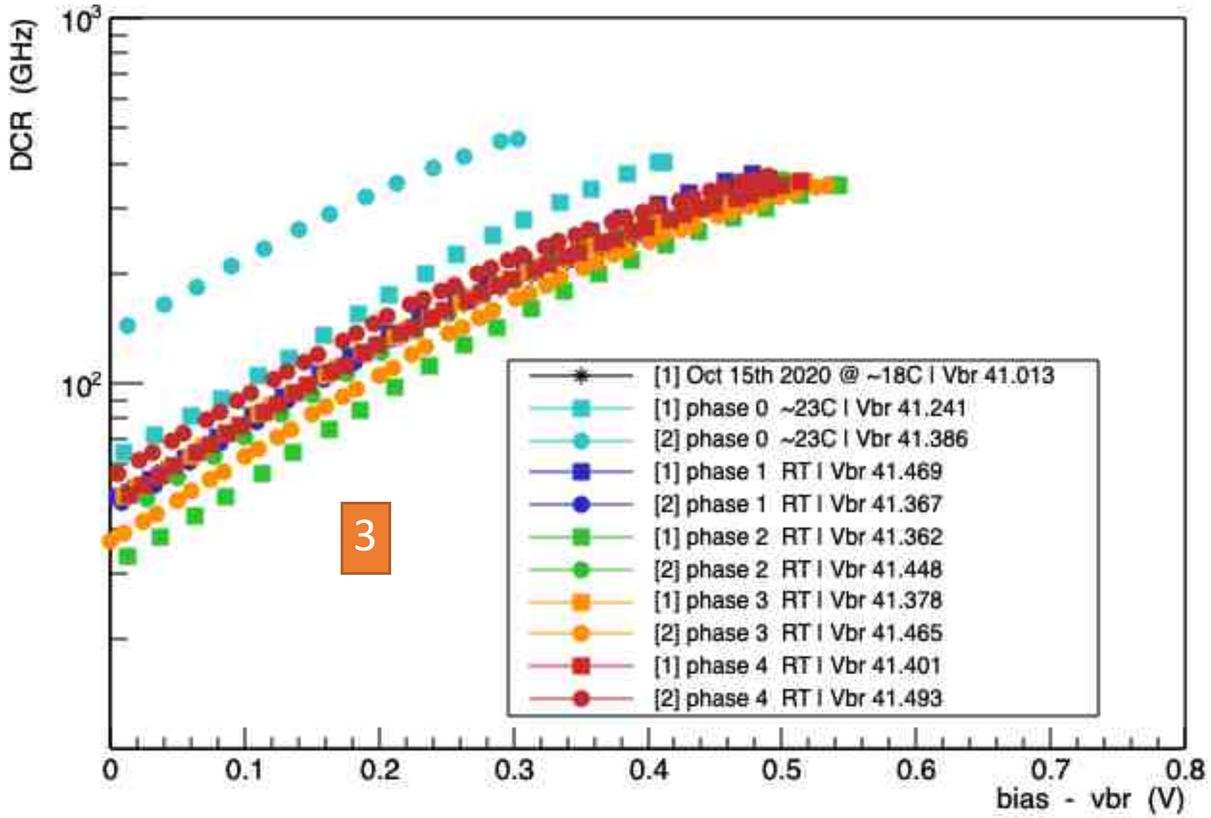

Cooking for around 2h at 90C

# Measurements after first annealing interval

- Once Vbr was determined via DARK/LED procedure, we compute DCR



# Cooking HDR2 2e14

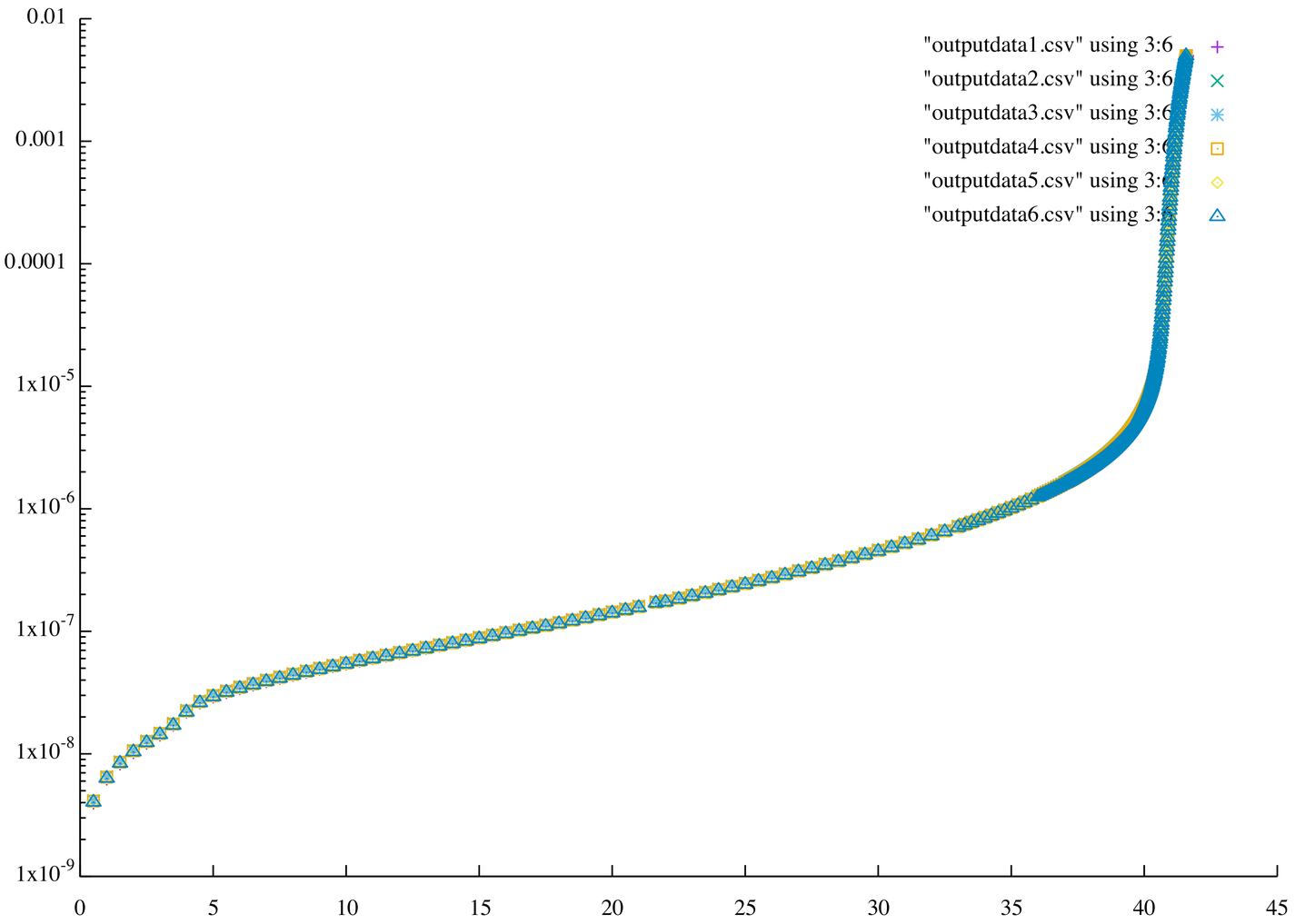
Fri 1:40pm - Sat2:20 at RT => 11 hours
Sat 2:20pm - Sat 6:55pm at 90C => 2.5 hours
Sat 7pm - Mon 7:45am at RT => 36 hours
Move to cold storage

ROOM TEMP



ROOM TEMP

# Fase5 stability




6 consecutive runs of ~40 secs each

UNIVERSITY of VIRGINIA

# Hamamatsu HDR2 5e13

Study of HDR2s timing resolution

Based on data taken during Apr’21, May’21 TB and Jul’21 bench-test

T. Anderson, B. Cox, J.P. Dervan, M. Joyce, A. Krishna,

A. Ledovskoy, C. Pérez Lara, S. White

Still work in progress

# April Results

# Setup at FNAL Testbeam (Apr'21)

## Data available

**Four bars**

- ~~NI~~, 1e13, 5e13, 2e14
- 0 deg and 40 deg
- Several temperatures

**Three bars:**

- NI, 5e13, 2e14
- 52 deg
- Several temperatures

# Setup at FNAL Testbeam (Apr'21)

## Data available

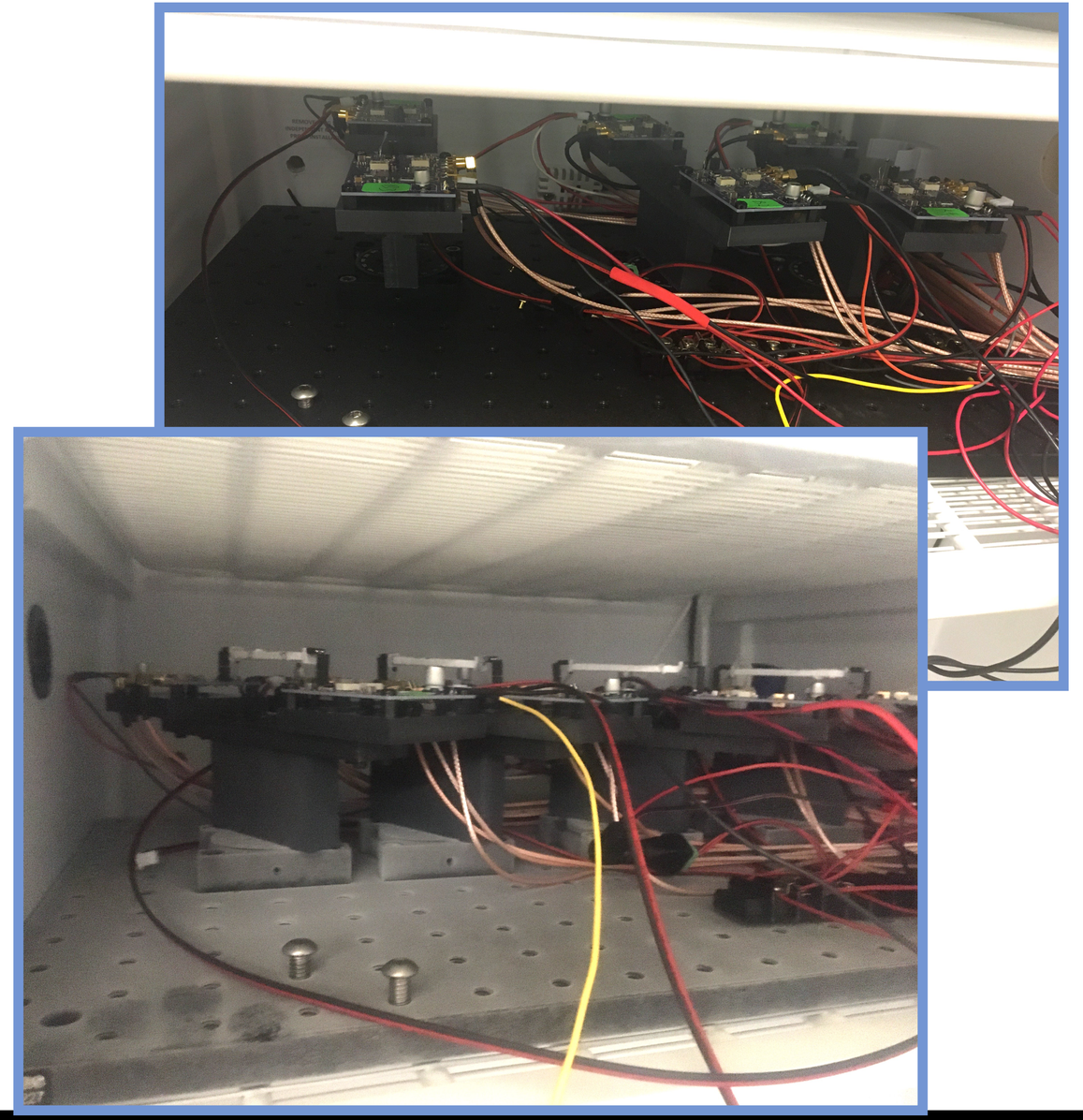
**Four bars**

- ~~Nl~~, 1e13, 5e13, 2e14
- 0 deg and 40 deg
- Several temperatures

**Three bars:**

- Nl, 5e13, 2e14
- 52 deg
- Several temperatures

This presentation:
Only looked a fraction of this data set



# Data available

**Apr’21**

**Wed Apr 21st @ -19 C , 52 deg**
**44725, 44728, 44730, 44731,**
**44732, 44733, 44734, 447435**
Vop = 39.4 V (left)  39.5 V (right)

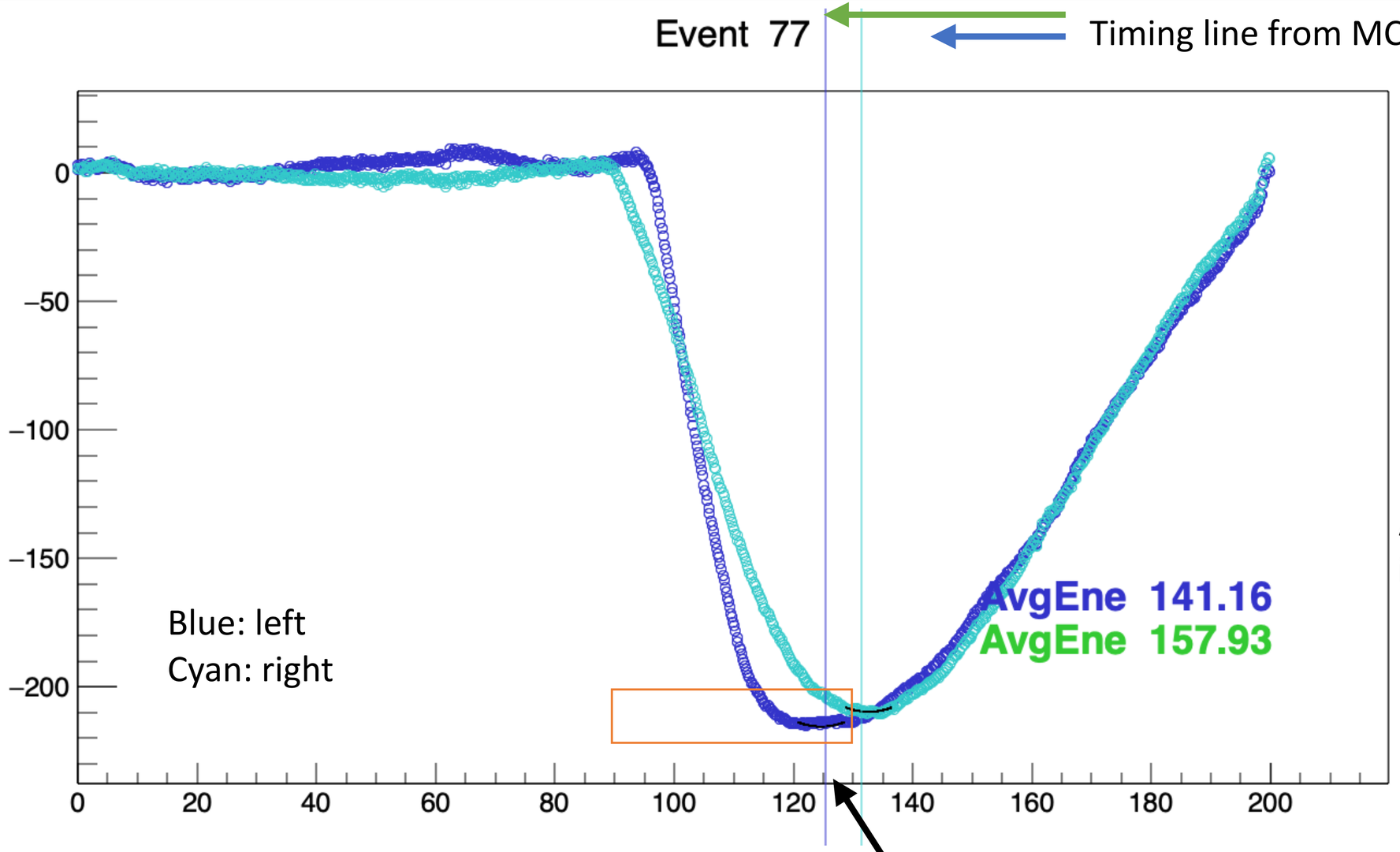
| | |
|---|---|
| SiPM5 | DRS CHN 4, 12 |
| SiPM6 | DRS CHN 5, 13 |

Length of LYSO : 56.5 mm

X-Projection at 52 deg = 34.8 mm

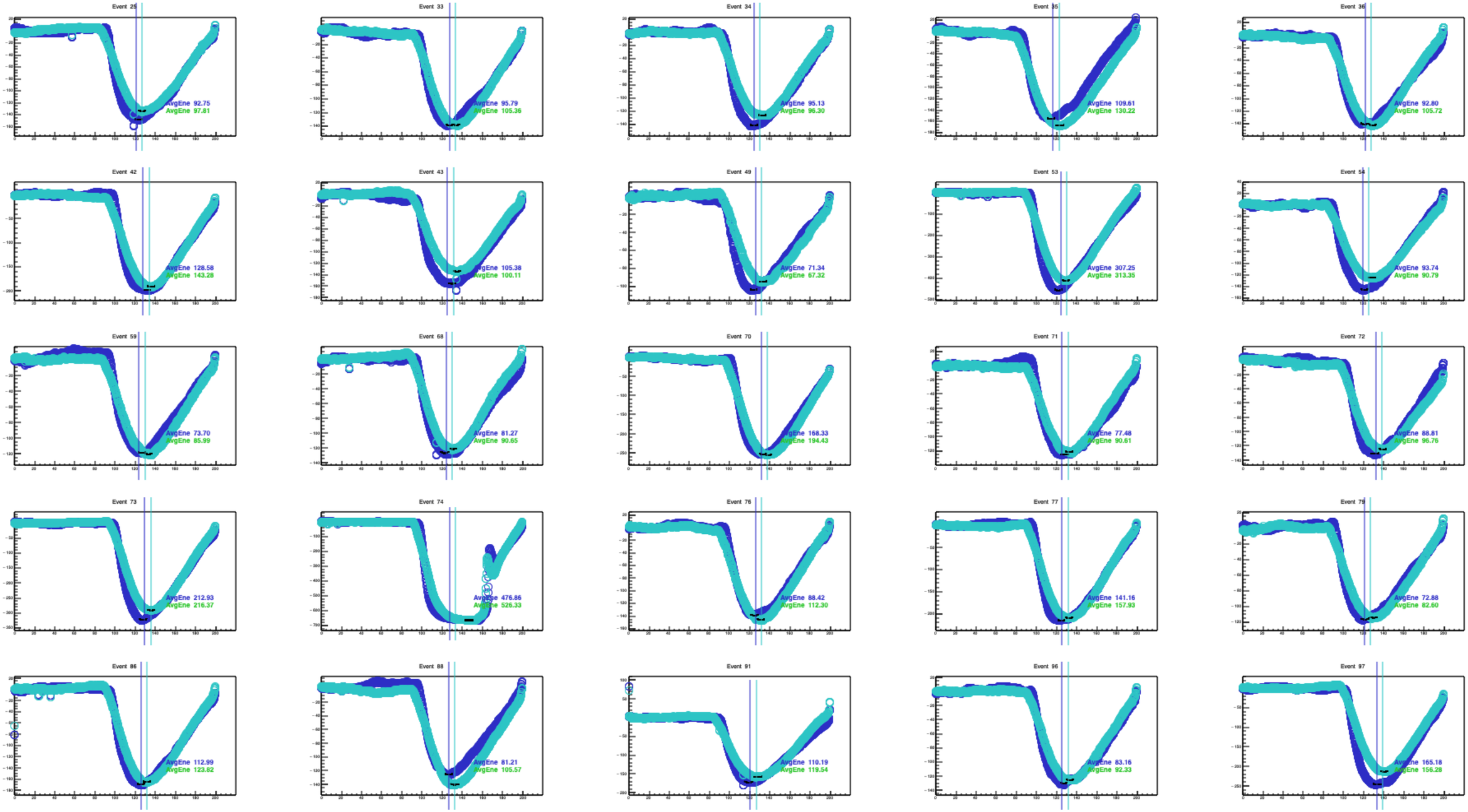
# Example of one event [Energy Channel]

Run 44734



# First 25 Events selected [Energy Channel]

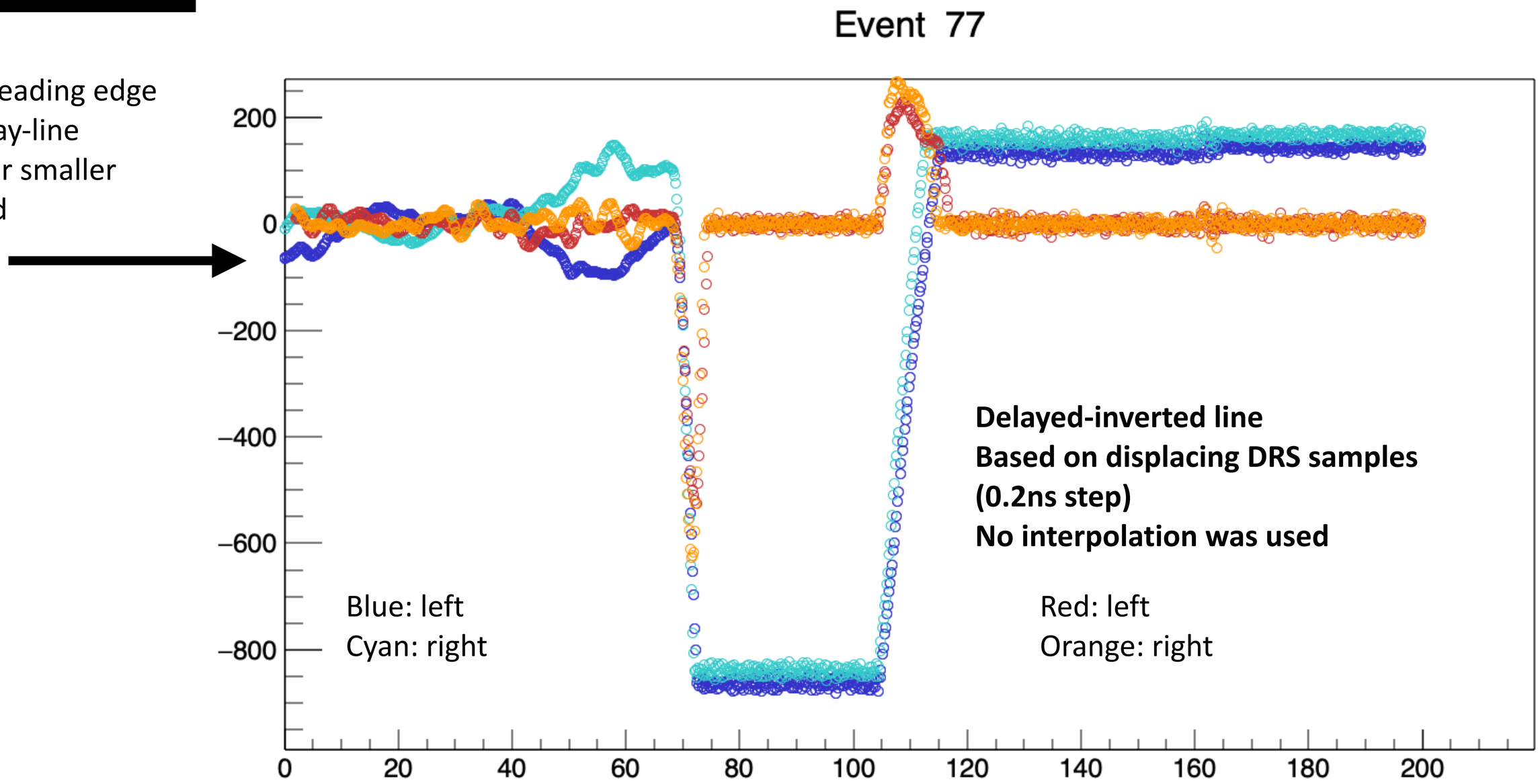
Run 44734



# Example of one event [Timing Channel]

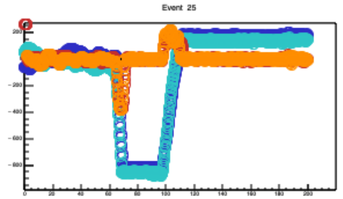
Run 44734

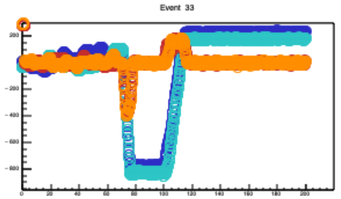
Cleaner leading edge
after delay-line
Allows for smaller
threshold

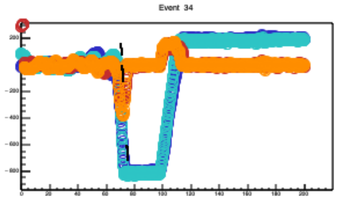


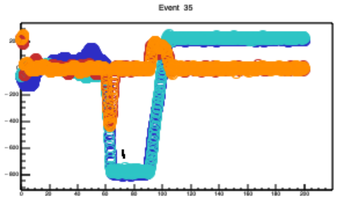
# First 25 Events selected [Timing Channel]

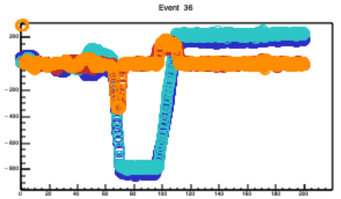
Run 44734

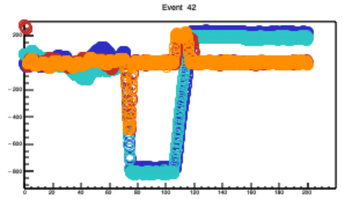


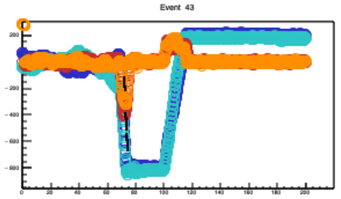


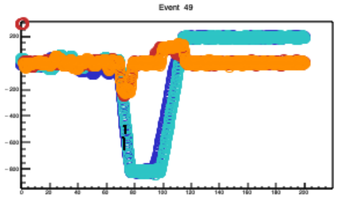


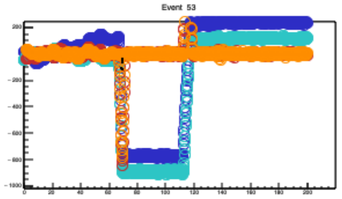


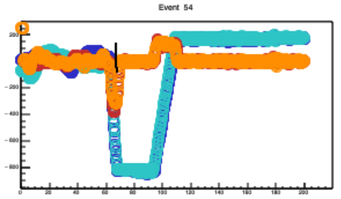


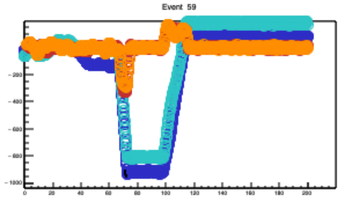


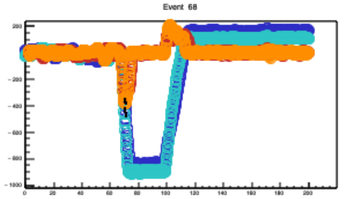


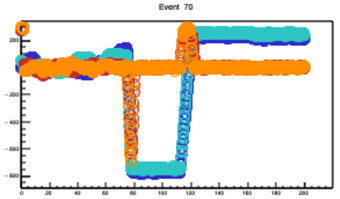


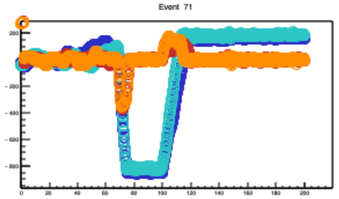


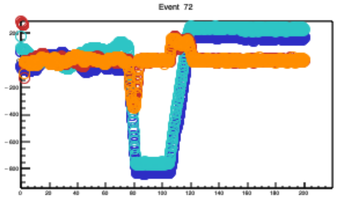


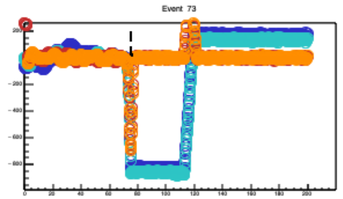


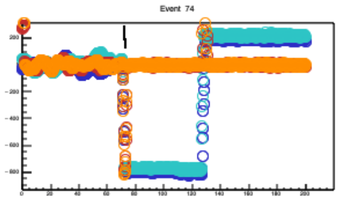


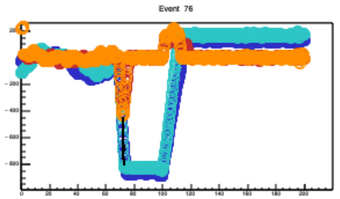


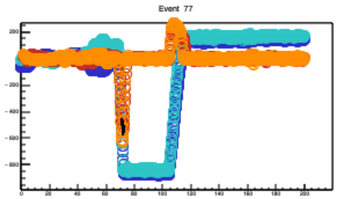


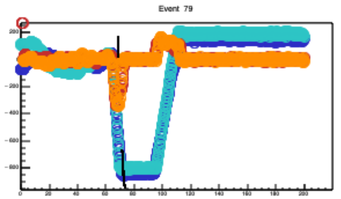


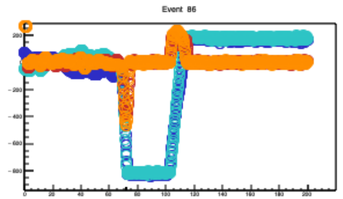


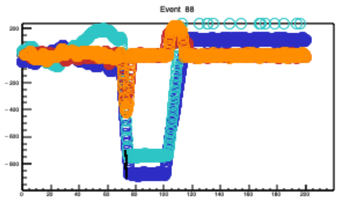


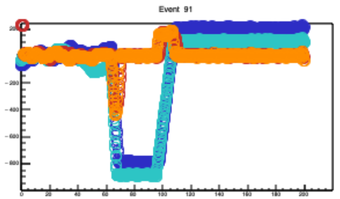


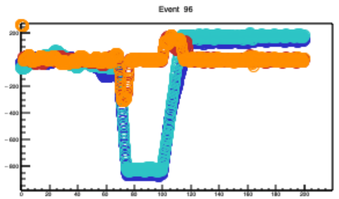


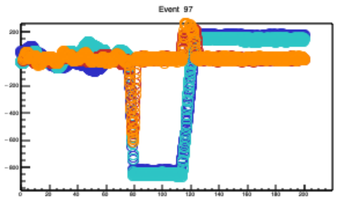




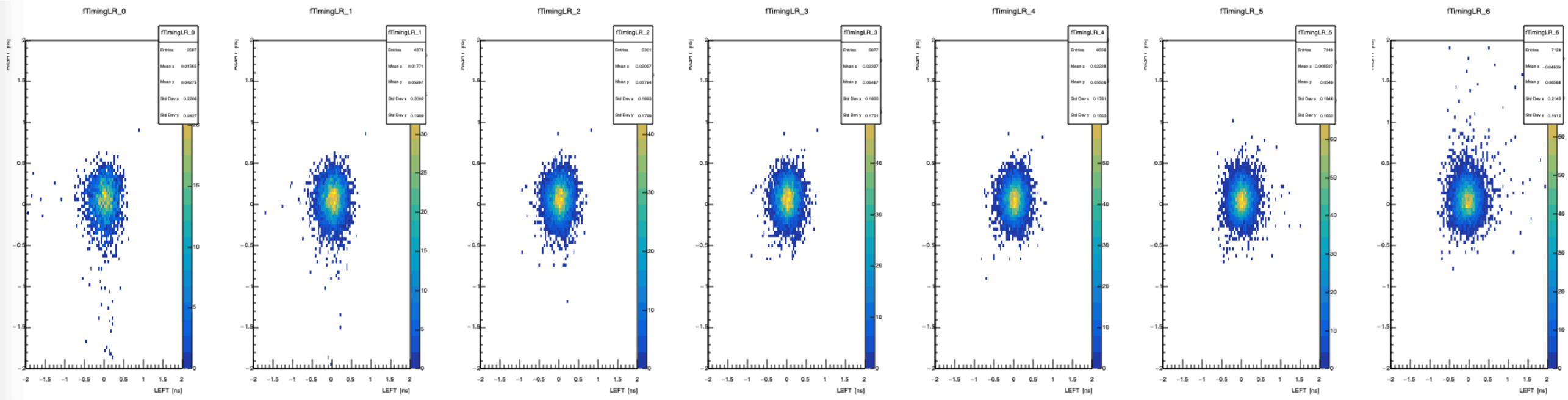






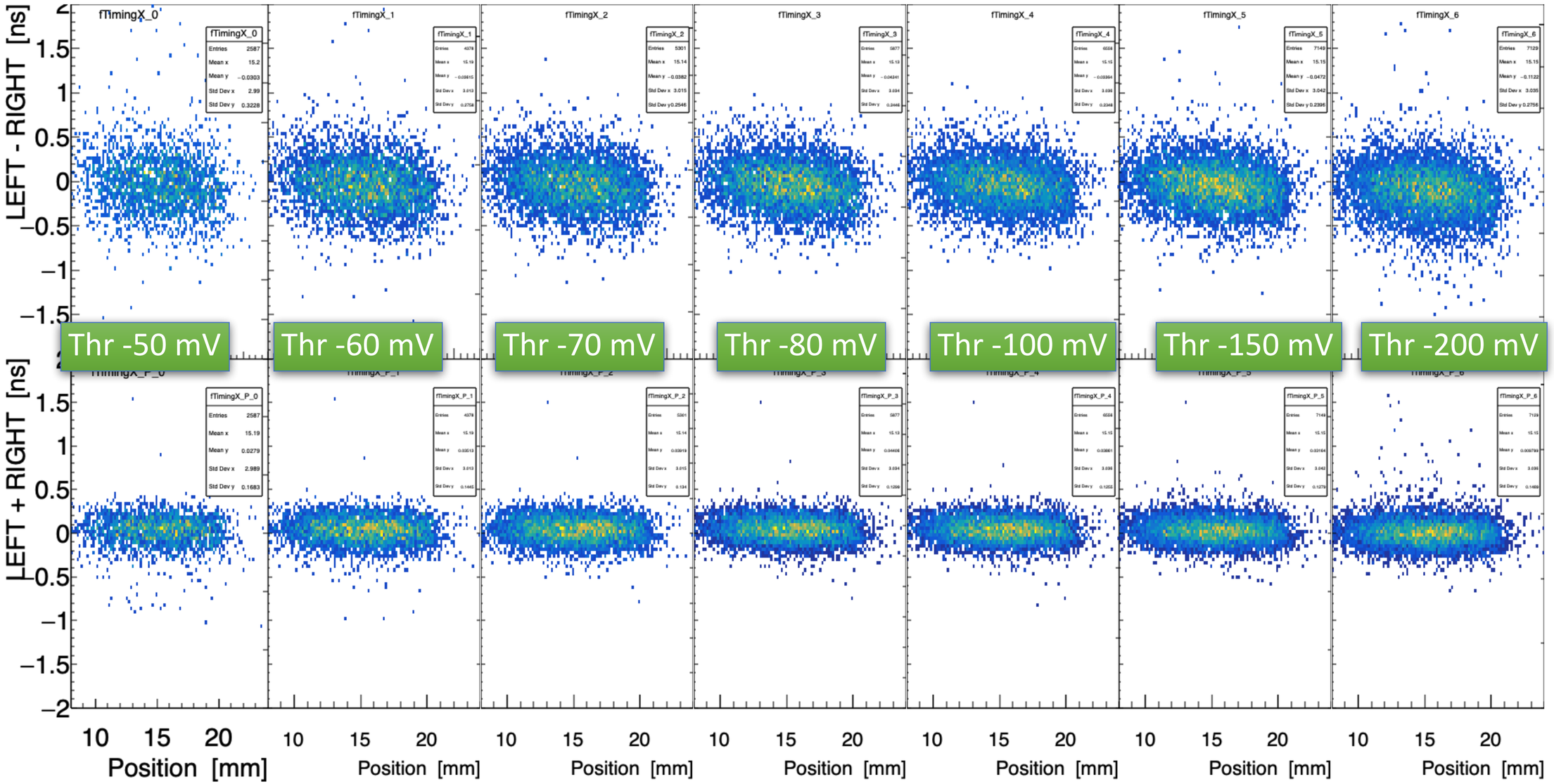


# LEFT [ns] vs RIGHT [ns]

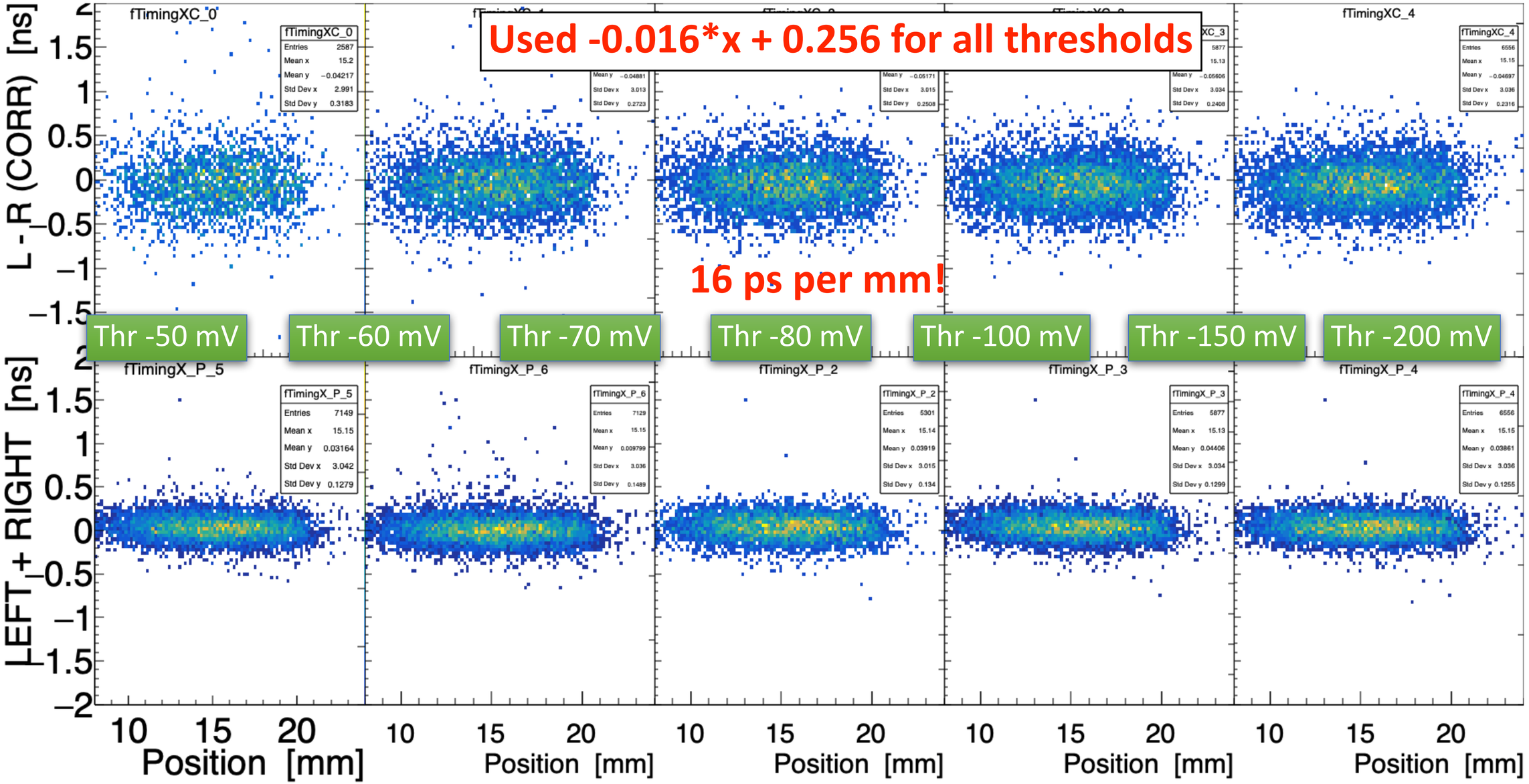



Thr -50 mV | Thr -60 mV | Thr -70 mV | Thr -80 mV | Thr -100 mV | Thr -150 mV | Thr -200 mV

# Time offset with X-along the bar



# Time offset with X-along the bar



# DT5742

16+1 Channel 12 bit 5 GS/s Switched Capacitor Digitizer


**GROUP0** **GROUP1**

**CH [0 - 7]** **TR0** **CH [8-15]**

2 Bars
4 HDR2s
8 Channels

MCP

2 Bars
4 HDR2s
8 Channels

Each group is composed by 8 channels (GROUP 0 = CHANNEL 0 – 7, GROUP 1 = CHANNEL 8 – 15, etc.) and by the special channel TRn: such signal is common to two groups; it can be used as Local Trigger or "digitized" and stored with the data for high resolution timing analysis between the ADC channels and the TRn itself (refer to **Sec. TR0 and TR1 Inputs**).

The values of the theoretical "average" trigger rate, computed upon the given formulas, are reported in the following tables for $N_S$ = 1024 samples.

| $N_G$ | TR Not Digitized | TR Digitized |
|---|---|---|
| 1 | 6.813 kHz | 6.058 kHz |
| 2 | 3.409 kHz | 3.030 kHz |

**Tab. 7.3:** Theoretical "average" trigger rate values for the Optical Link

| $N_G$ | TR Not Digitized | TR Digitized |
|---|---|---|
| 1 | 2.556 kHz | 2.272 kHz |
| 2 | 1.278 kHz | 1.136 kHz |

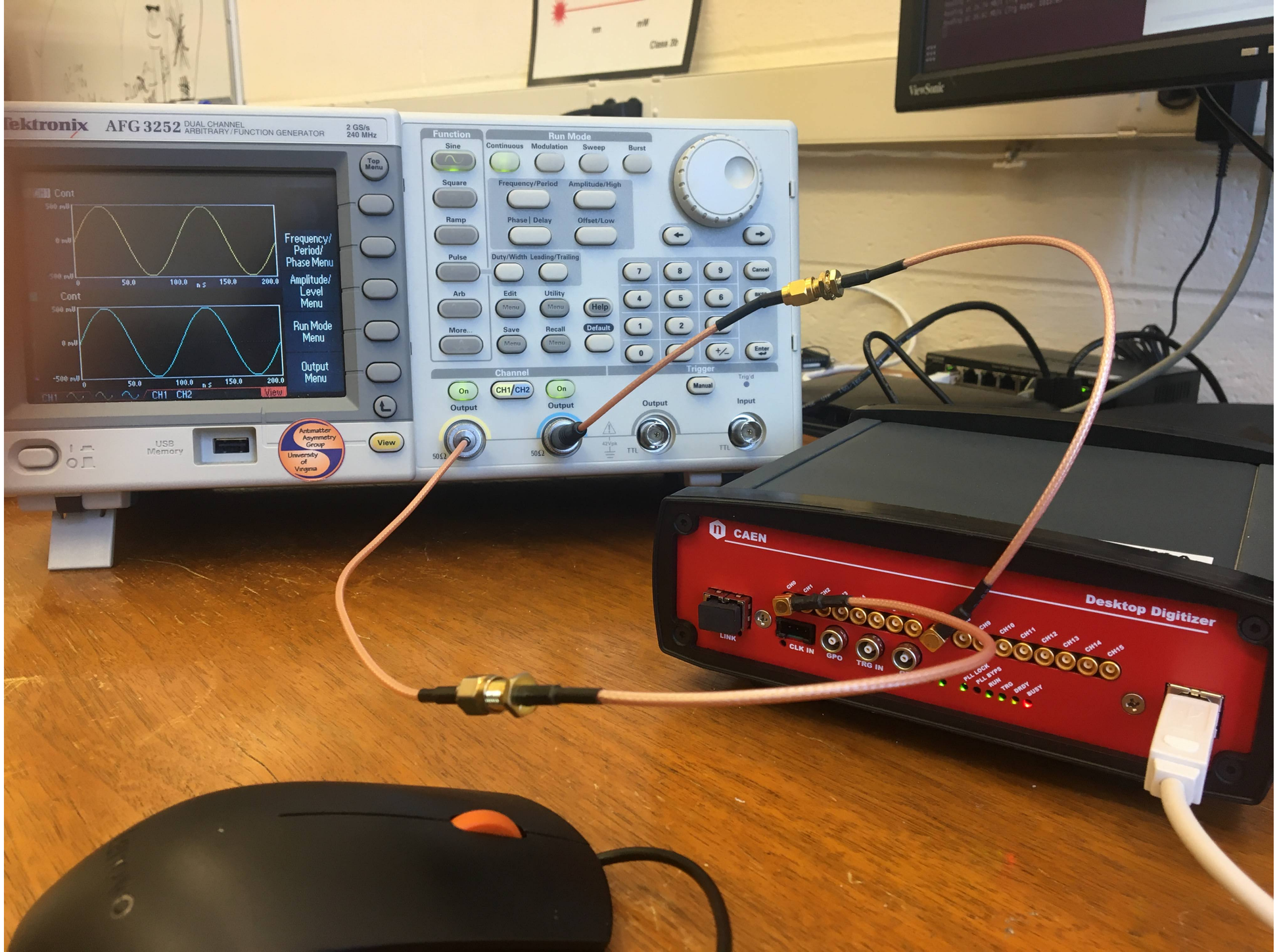
**Tab. 7.4:** Theoretical "average" trigger rate values for the USB Link

So theoretically for our use 16CH + TR0 digitized we will get

USB 1.136 kHz

PCI 3.030 kHz

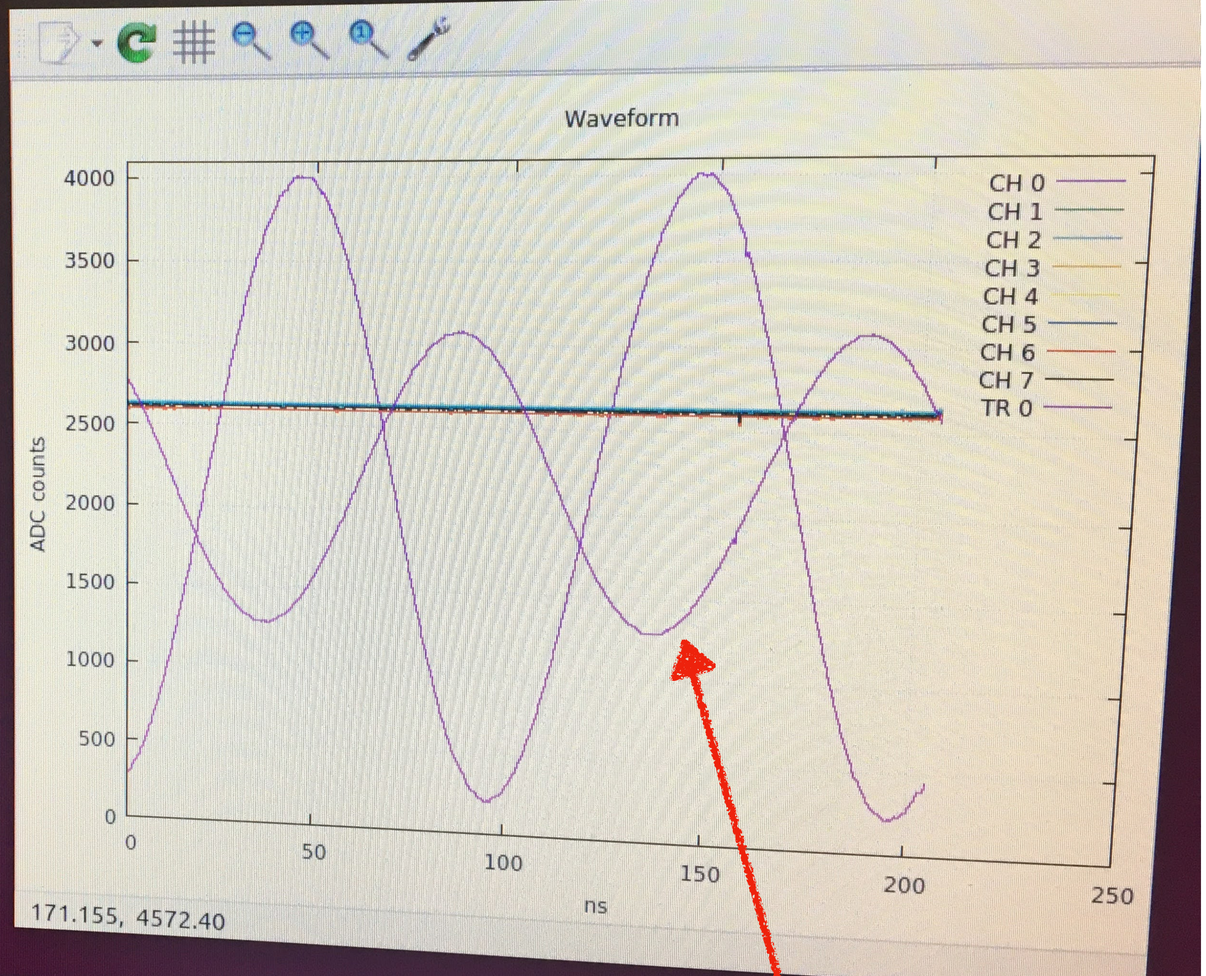
**50k MIPS in** **13 min** **4 min**


Tektronix AFG 3252 DUAL CHANNEL ARBITRARY/FUNCTION GENERATOR
2 GS/s
240 MHz
Function
Sine
Square
Ramp
Pulse
Arb
More...
Run Mode
Continuous
Modulation
Sweep
Burst
Frequency/Period
Amplitude/High
Phase| Delay
Offset/Low
Duty/Width
Leading/Trailing
Edit
Utility
Save
Recall
Help
Default
Menu
Top Menu
Frequency/ Period/ Phase Menu
Amplitude/ Level Menu
Run Mode Menu
Output Menu
View
USB Memory
Antimatter Asymmetry Group
University of Virginia
Channel
Trigger
On
CH1/CH2
Output
Manual
Trig'd
Input
50Ω
TTL
CAEN
Desktop Digitizer
LINK
CLK IN
GPO
TRG IN
CH9
CH10
CH11
CH12
CH13
CH14
CH15
PLL LOCK
PLL BYPS
RUN
TRG
RDY
BUSY

```
Reading at 26.55 MB/s (Trg Rate: 1005.90 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Plot group set to 0
Reading at 26.79 MB/s (Trg Rate: 1014.88 Hz)
Reading at 26.58 MB/s (Trg Rate: 1006.89 Hz)
Reading at 26.61 MB/s (Trg Rate: 1007.88 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 27.00 MB/s (Trg Rate: 1023.00 Hz)
Reading at 26.66 MB/s (Trg Rate: 1009.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.66 MB/s (Trg Rate: 1009.87 Hz)
Reading at 26.98 MB/s (Trg Rate: 1021.98 Hz)
Reading at 26.76 MB/s (Trg Rate: 1013.88 Hz)
Reading at 26.74 MB/s (Trg Rate: 1012.87 Hz)
Reading at 26.84 MB/s (Trg Rate: 1016.90 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.82 MB/s (Trg Rate: 1015.89 Hz)
Reading at 26.84 MB/s (Trg Rate: 1016.90 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.79 MB/s (Trg Rate: 1014.88 Hz)
Reading at 26.68 MB/s (Trg Rate: 1010.87 Hz)
Reading at 26.40 MB/s (Trg Rate: 1000.00 Hz)
Reading at 23.54 MB/s (Trg Rate: 891.89 Hz)
Reading at 26.19 MB/s (Trg Rate: 992.24 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.02 Hz)
Reading at 26.90 MB/s (Trg Rate: 1018.92 Hz)
Reading at 26.92 MB/s (Trg Rate: 1019.94 Hz)
Reading at 26.71 MB/s (Trg Rate: 1011.87 Hz)
Reading at 26.68 MB/s (Trg Rate: 1010.87 Hz)
Reading at 26.66 MB/s (Trg Rate: 1009.87 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.76 MB/s (Trg Rate: 1013.88 Hz)
Reading at 26.79 MB/s (Trg Rate: 1014.88 Hz)
Reading at 26.74 MB/s (Trg Rate: 1012.87 Hz)
```

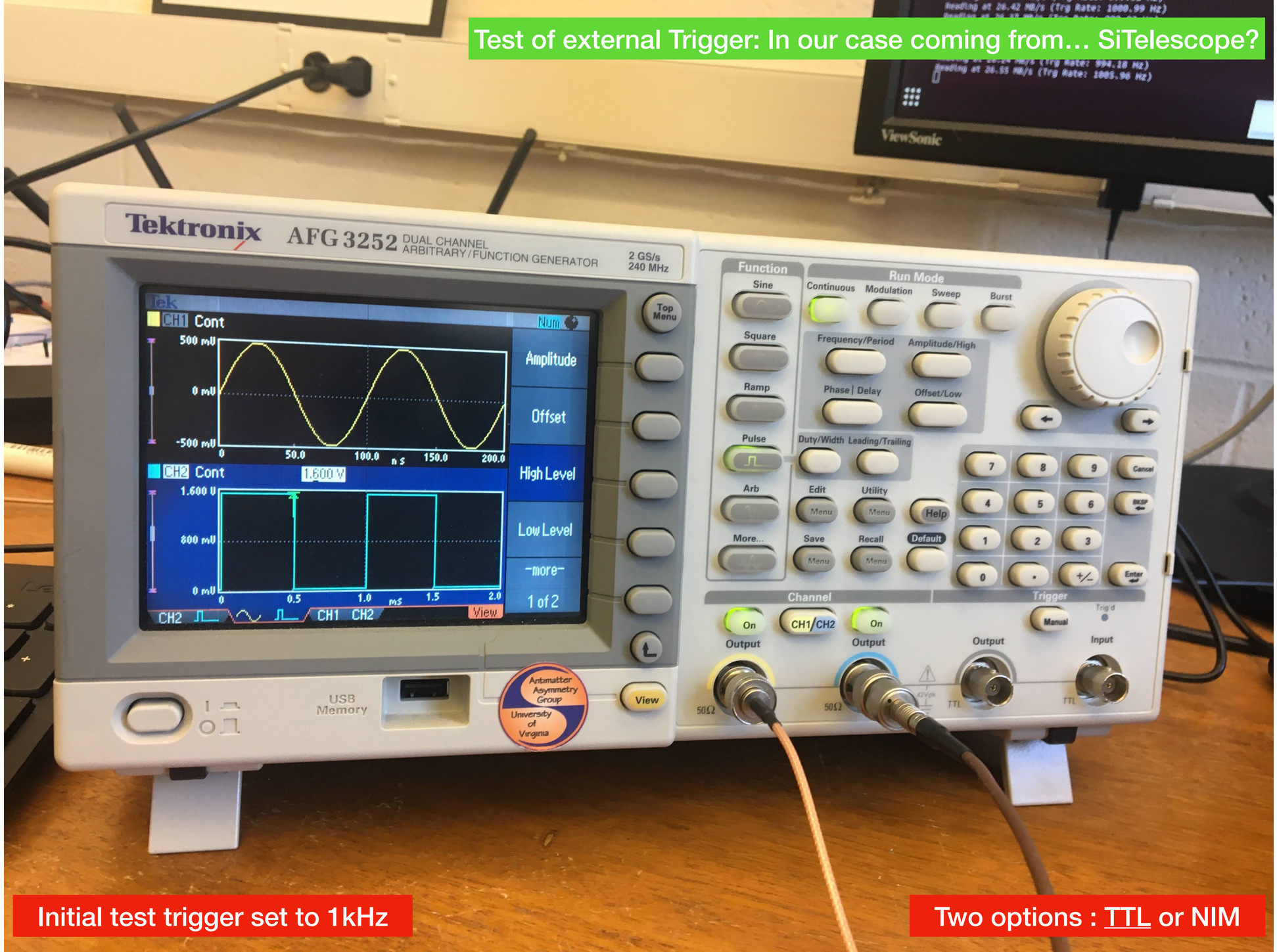
Using CAEN's tool wavedump

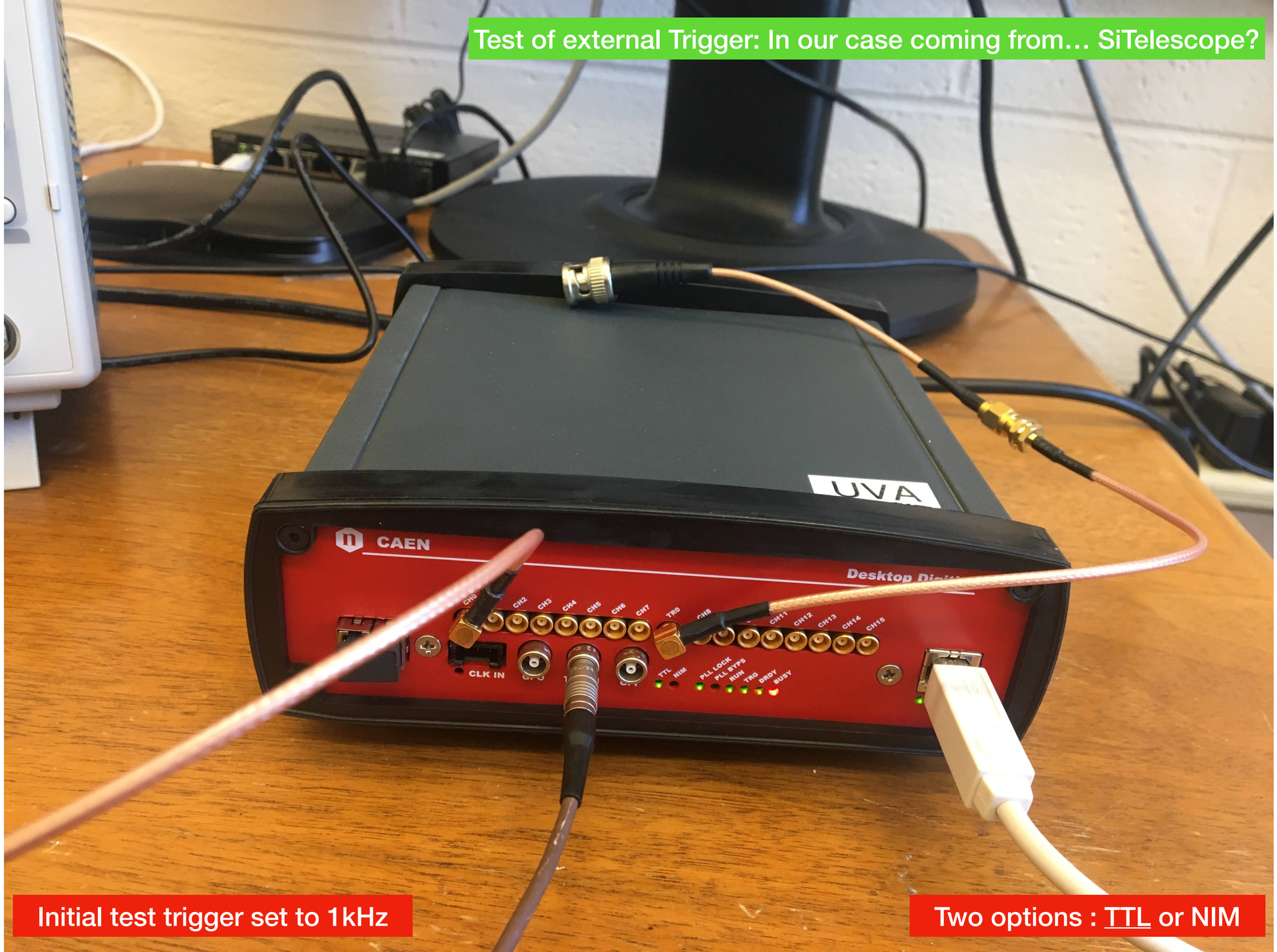
Gnuplot window 0

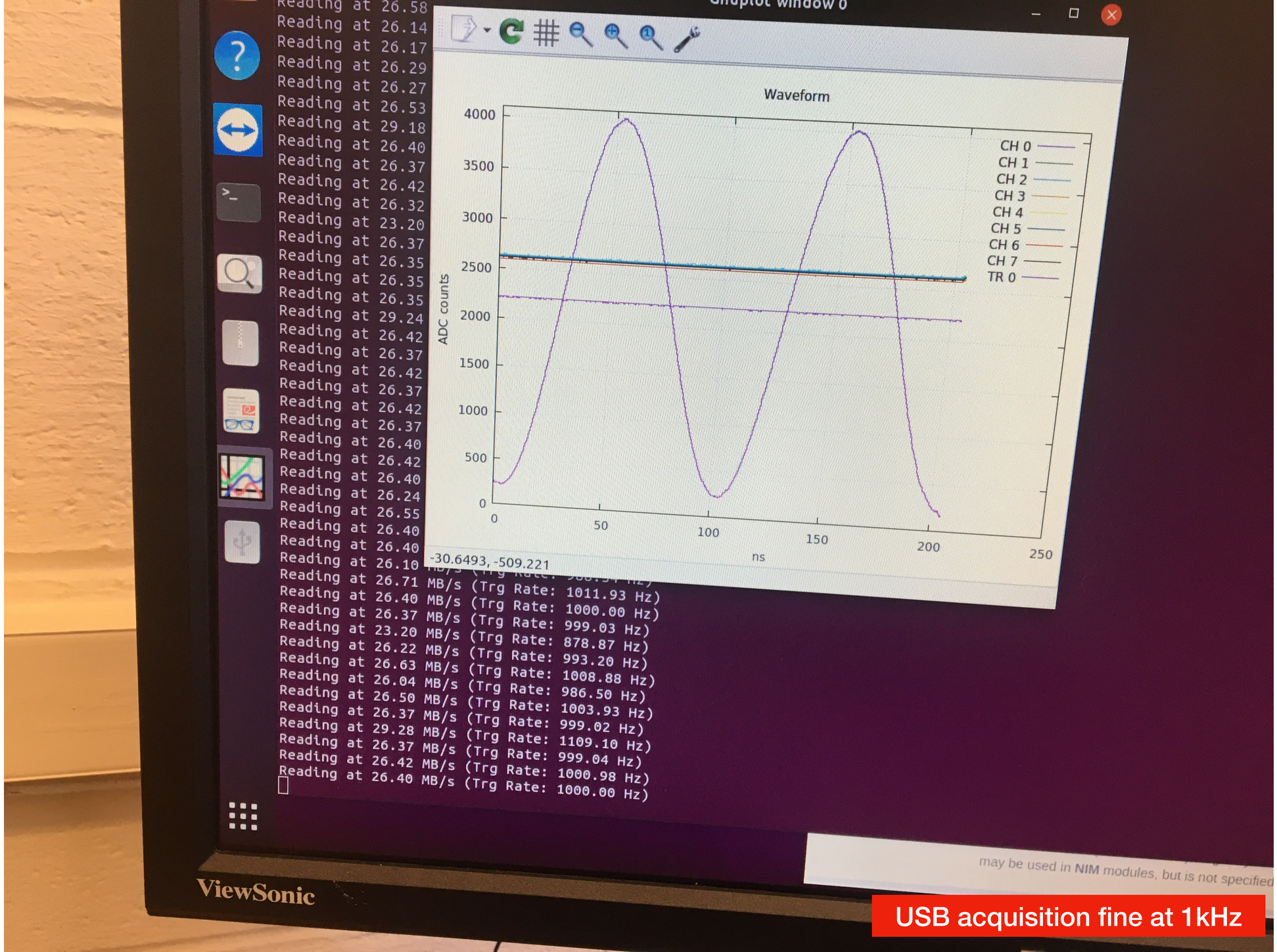



TR0 capable to digitize up to 2V

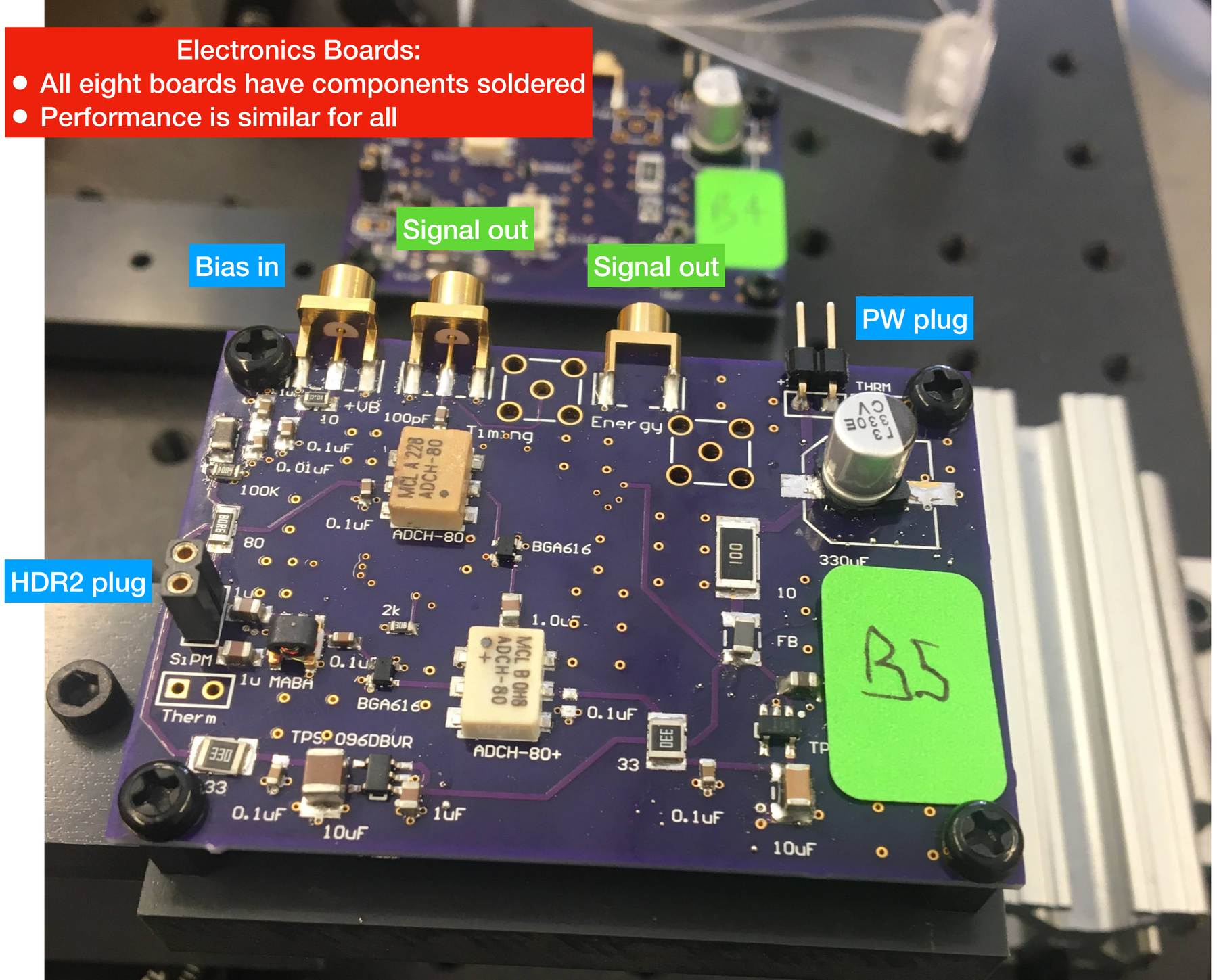
ViewSonic


Test of external Trigger: In our case coming from… SiTelescope?
Tektronix AFG 3252 DUAL CHANNEL ARBITRARY/FUNCTION GENERATOR 2 GS/s 240 MHz
CH1 Cont
CH2 Cont
Amplitude
Offset
High Level
Low Level
-more-
1 of 2
Function
Run Mode
Channel
Trigger
Antimatter Asymmetry Group
University of Virginia
USB Memory
ViewSonic
Initial test trigger set to 1kHz
Two options : TTL or NIM


Test of external Trigger: In our case coming from… SiTelescope?
UVA
CAEN
CLK IN
Initial test trigger set to 1kHz
Two options : TTL or NIM

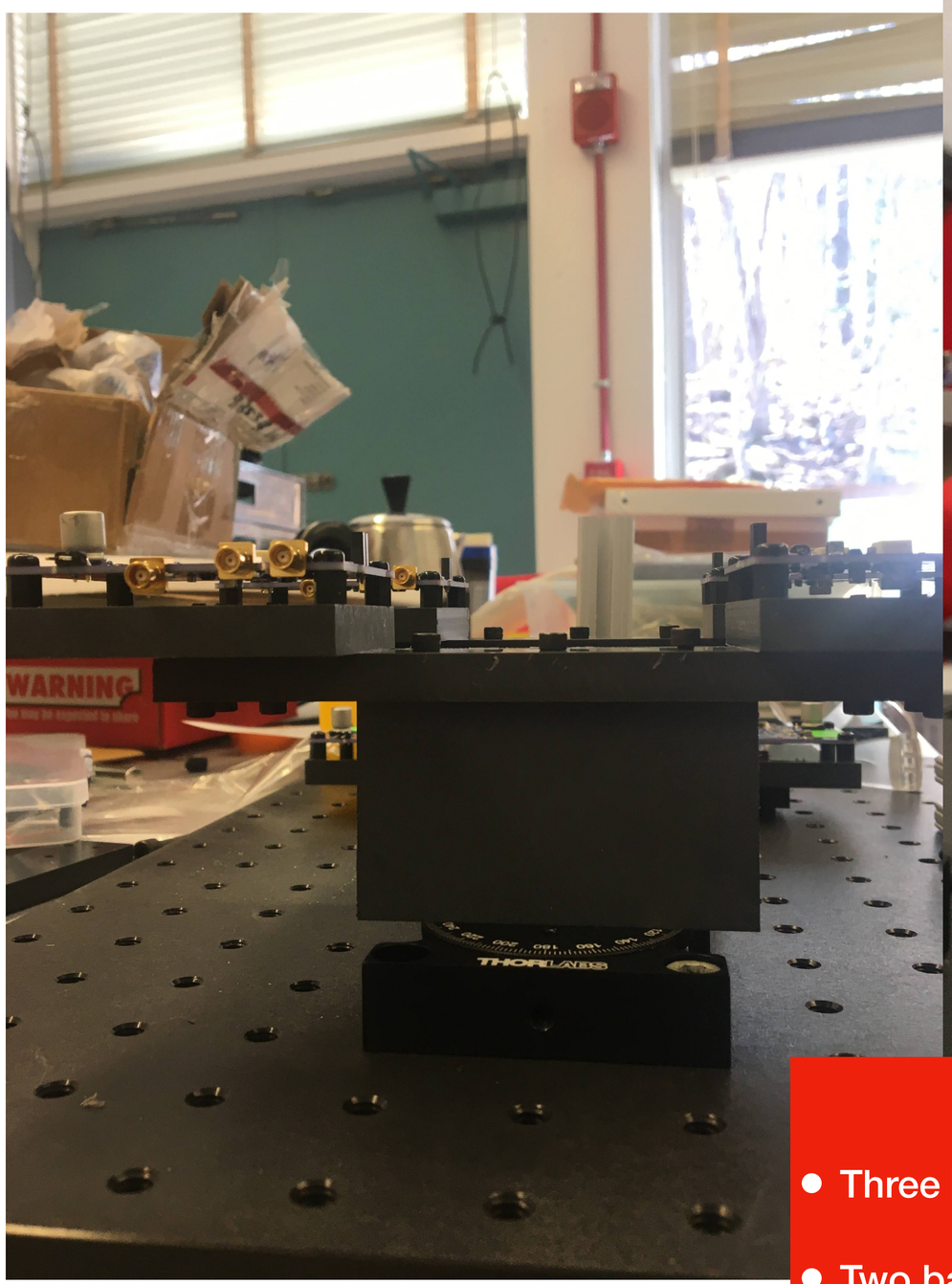

Gnuplot window 0
Waveform
ADC counts
ns
CH 0
CH 1
CH 2
CH 3
CH 4
CH 5
CH 6
CH 7
TR 0
-30.6493, -509.221
Reading at 26.58
Reading at 26.14
Reading at 26.17
Reading at 26.29
Reading at 26.27
Reading at 26.53
Reading at 29.18
Reading at 26.40
Reading at 26.37
Reading at 26.42
Reading at 26.32
Reading at 23.20
Reading at 26.37
Reading at 26.35
Reading at 26.35
Reading at 26.35
Reading at 29.24
Reading at 26.42
Reading at 26.37
Reading at 26.42
Reading at 26.37
Reading at 26.42
Reading at 26.37
Reading at 26.40
Reading at 26.42
Reading at 26.40
Reading at 26.24
Reading at 26.55
Reading at 26.40
Reading at 26.40
Reading at 26.10
Reading at 26.71 MB/s (Trg Rate: 1011.93 Hz)
Reading at 26.40 MB/s (Trg Rate: 1000.00 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.03 Hz)
Reading at 23.20 MB/s (Trg Rate: 878.87 Hz)
Reading at 26.22 MB/s (Trg Rate: 993.20 Hz)
Reading at 26.63 MB/s (Trg Rate: 1008.88 Hz)
Reading at 26.04 MB/s (Trg Rate: 986.50 Hz)
Reading at 26.50 MB/s (Trg Rate: 1003.93 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.02 Hz)
Reading at 29.28 MB/s (Trg Rate: 1109.10 Hz)
Reading at 26.37 MB/s (Trg Rate: 999.04 Hz)
Reading at 26.42 MB/s (Trg Rate: 1000.98 Hz)
Reading at 26.40 MB/s (Trg Rate: 1000.00 Hz)
may be used in NIM modules, but is not specified
ViewSonic
USB acquisition fine at 1kHz

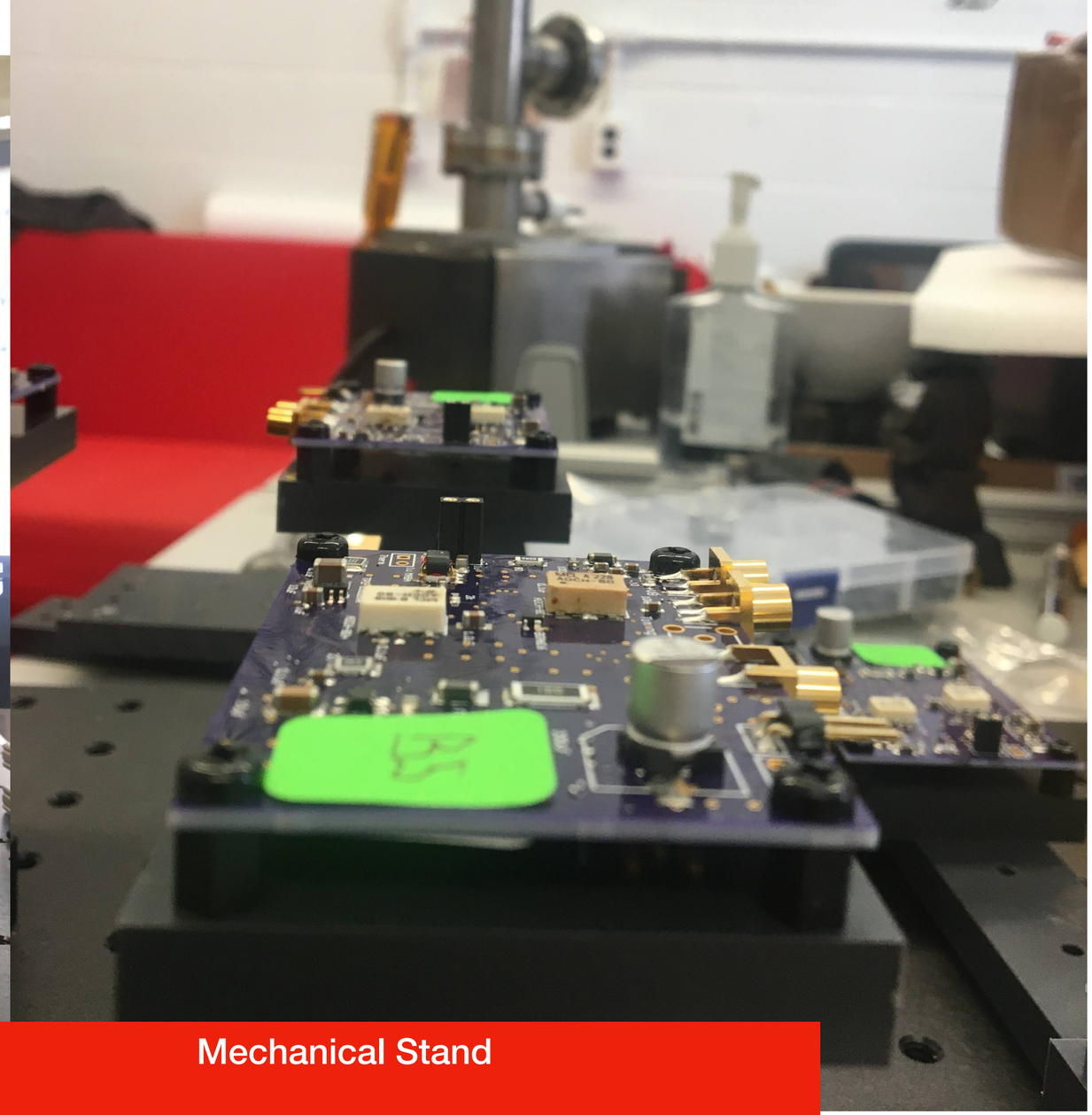
# Electronic Board
# And Mechanical Assembly


Electronics Boards:
All eight boards have components soldered
Performance is similar for all
Signal out
Signal out
Bias in
PW plug
HDR2 plug
B4
B5
+VB
100pF
Timing
Energy
THRM
330uF
100K
0.1uF
0.01uF
ADCH-80
BGA616
80
2k
1.0uF
SiPM
1u MABA
Therm
TPS 096DBVR
ADCH-80+
33
10uF
FB
TP


## Mechanical Stand

- Three bars with 2 boards each aligned
- Two bars mounted in rotation table and align wrt beam
- aligned



## Mechanical Stand

- Three bars with 2 boards each aligned
- Two bars mounted in rotation table and align wrt beam


@ 52 deg

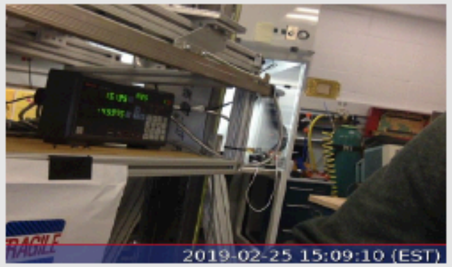
# Run Control
# and Data Monitor

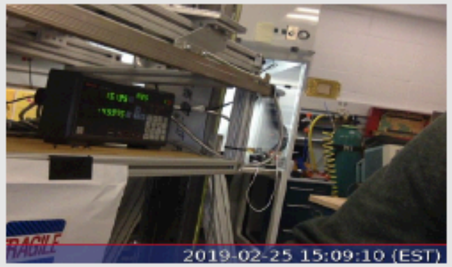
Run Control

DAQ Control

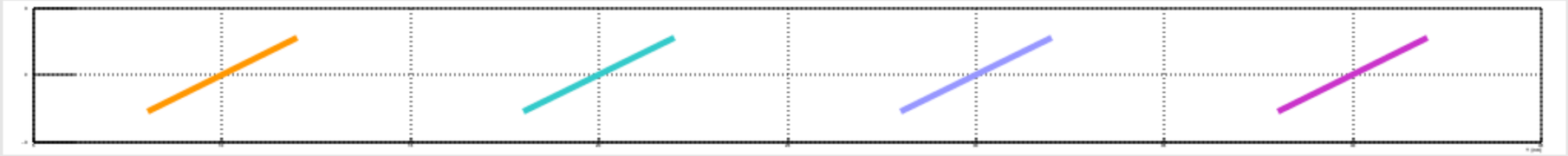
Master Controler

Angle0: 50.0 deg  Angle1: 50.0 deg  Angle2: 50.0 deg  Angle3: 50.0 deg






| | Bar0 H0 | Bar1 H0 | Bar2 H0 | Bar3 H0 |
|---|---|---|---|---|
| V_bdown: | 36.80 | 36.90 | 37.40 | 39.00 |
| OverVolt: | 0.50 | 0.50 | 0.50 | 0.50 |
| Voltage: | 37.30 V | 37.40 V | 37.90 V | 39.50 V |



| | Bar0 H1 | Bar1 H1 | Bar2 H1 | Bar3 H1 |
|---|---|---|---|---|
| Voltage: | 37.30 V | 37.40 V | 37.90 V | 39.50 V |
| V_bdown: | 36.80 | 36.90 | 37.40 | 39.00 |
| OverVolt: | 0.50 | 0.50 | 0.50 | 0.50 |

Unlock  Set & Lock

Last ConfigFile

```
00031
    50.0          50.0          50.0          50.0
38.50  0.50   39.20  0.50   39.80  0.50   40.00  0.50
38.50  0.50   39.20  0.50   39.80  0.50   40.00  0.50
 --.- degC     --.- degC     --.- degC     --.- degC
 --.- degC     --.- degC     --.- degC     --.- degC
 ----.- mA     ----.- mA     ----.- mA     ----.- mA
 ----.- mA     ----.- mA     ----.- mA     ----.- mA
```

Run Number: 00032

Start Run

STOP

| | Bar0 H0: | Bar0 H1: | Bar1 H0: | Bar1 H1: | Bar2 H0: | Bar2 H1: | Bar3 H0: | Bar3 H1: |
|---|---|---|---|---|---|---|---|---|
| | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC | --.- degC |
| | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA | ----.- mA |

# Data Quality Monitoring

Bar selector

One Run

Persistent WF

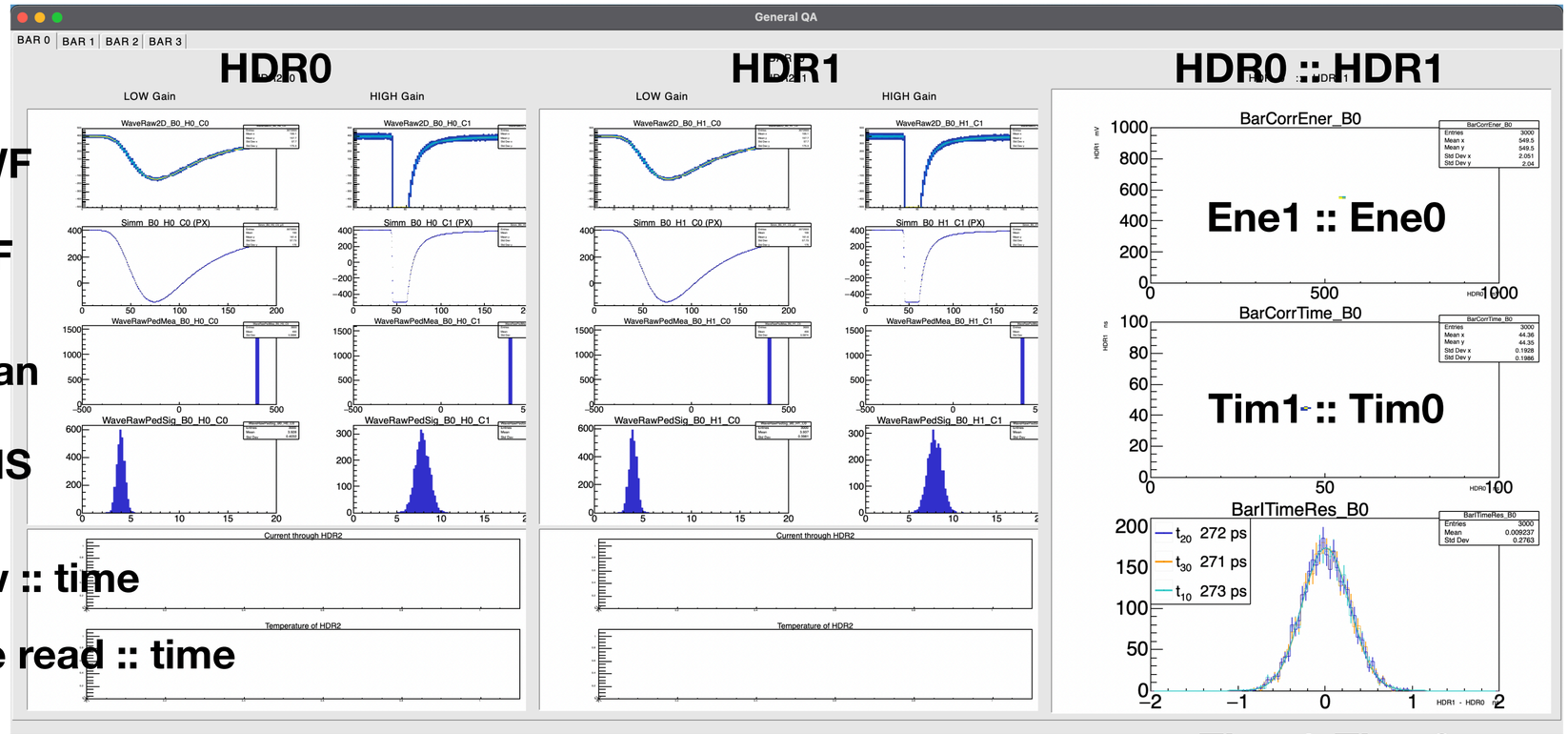
Average WF

Baseline Mean

Baseline RMS

Current draw :: time

Temperature read :: time



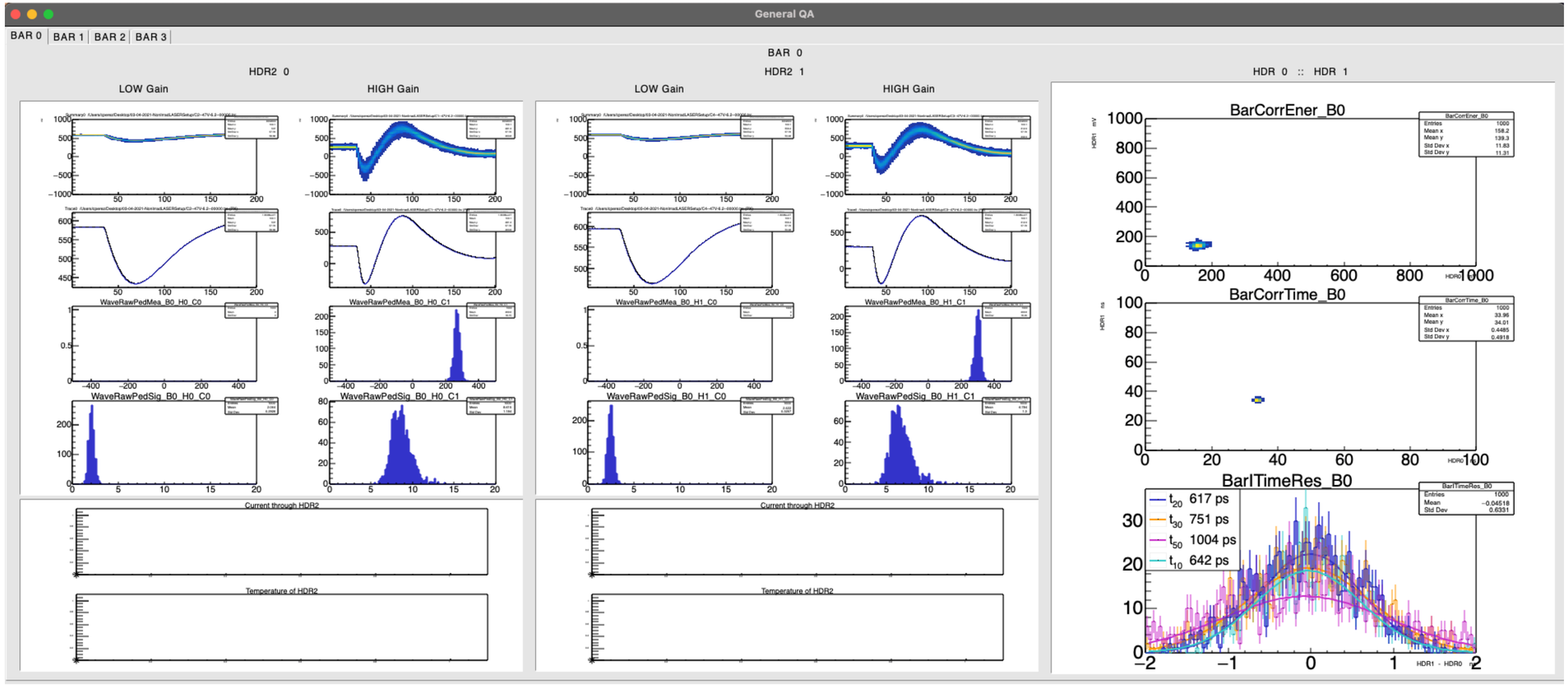

Time1-Time0

Fake MC signals

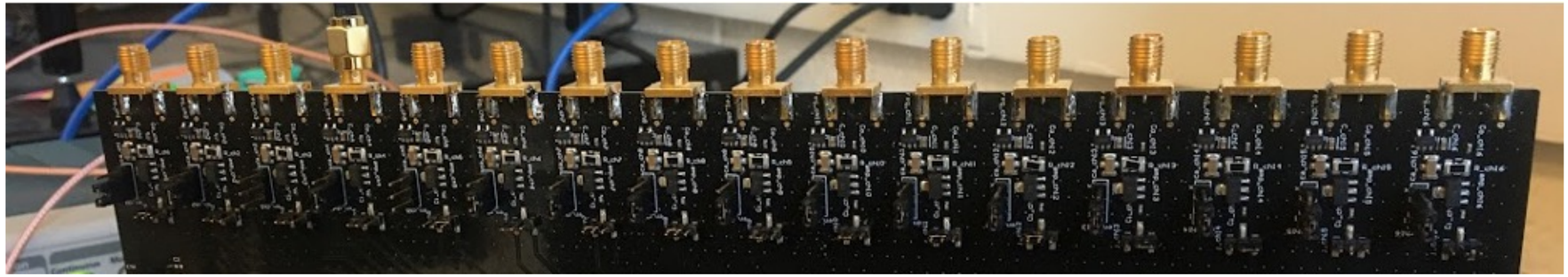

Zeroth Test of UV-laser on bar
Mounted inside the fridge:
Including boards, stand and rotation table
One bar setup for the moment

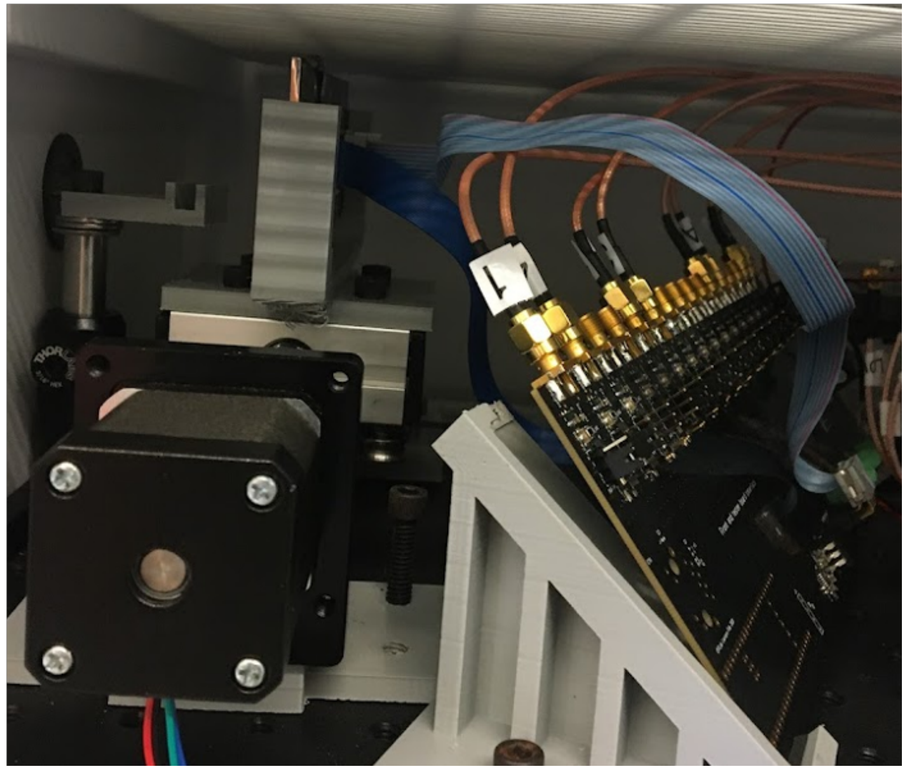
# Real response of UV-laser on LYSO + HDR2 + FEElectronics

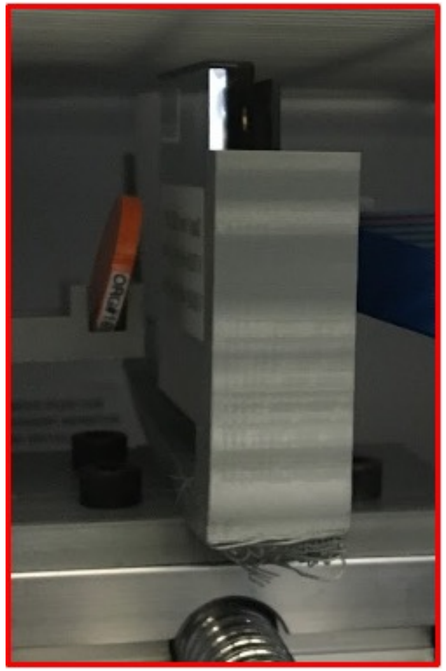
```
TString base = "47V-6.2--00000.trc";
```



# EBoard allows reading 8 bars at a time







Testing board developed at Caltech using a x5 amplifie

Provides a bridge between flex connector and

# How long will it take to anneal?

5e13
---- **@1 OV**

Measured DCR for 5e13 SiPM is 43GHz at -30C.
Target DCR is 30GHz at -25C or 23.4GHz at -30C. The annealing factor is 43/23.4 = 1.84
Estimated annealing time at different temperatures:

| Temp | Time |
|---|---|
| 20 | 202 days 21 hours 2 min |
| 30 | 42 days 7 hours 22 min |
| 40 | 9 days 17 hours 42 min |
| 50 | 2 days 10 hours 52 min |
| 60 | 0 days 16 hours 12 min |
| 70 | 0 days 4 hours 52 min |

2e14 **@1 OV**
-----

The annealing factor is x4 of 5e13 or 4 * 1.84 = 7.36
Estimated annealing time at different temperatures:

| Temp | Time |
|---|---|
| 70 | 745 days 0 hours 12 min |
| 80 | 234 days 7 hours 52 min |
| 90 | 78 days 10 hours 52 min |
| 100 | 27 days 19 hours 42 min |
| 110 | 10 days 9 hours 42 min |
| 120 | 4 days 2 hours 2 min |
| 130 | 1 days 16 hours 22 min |

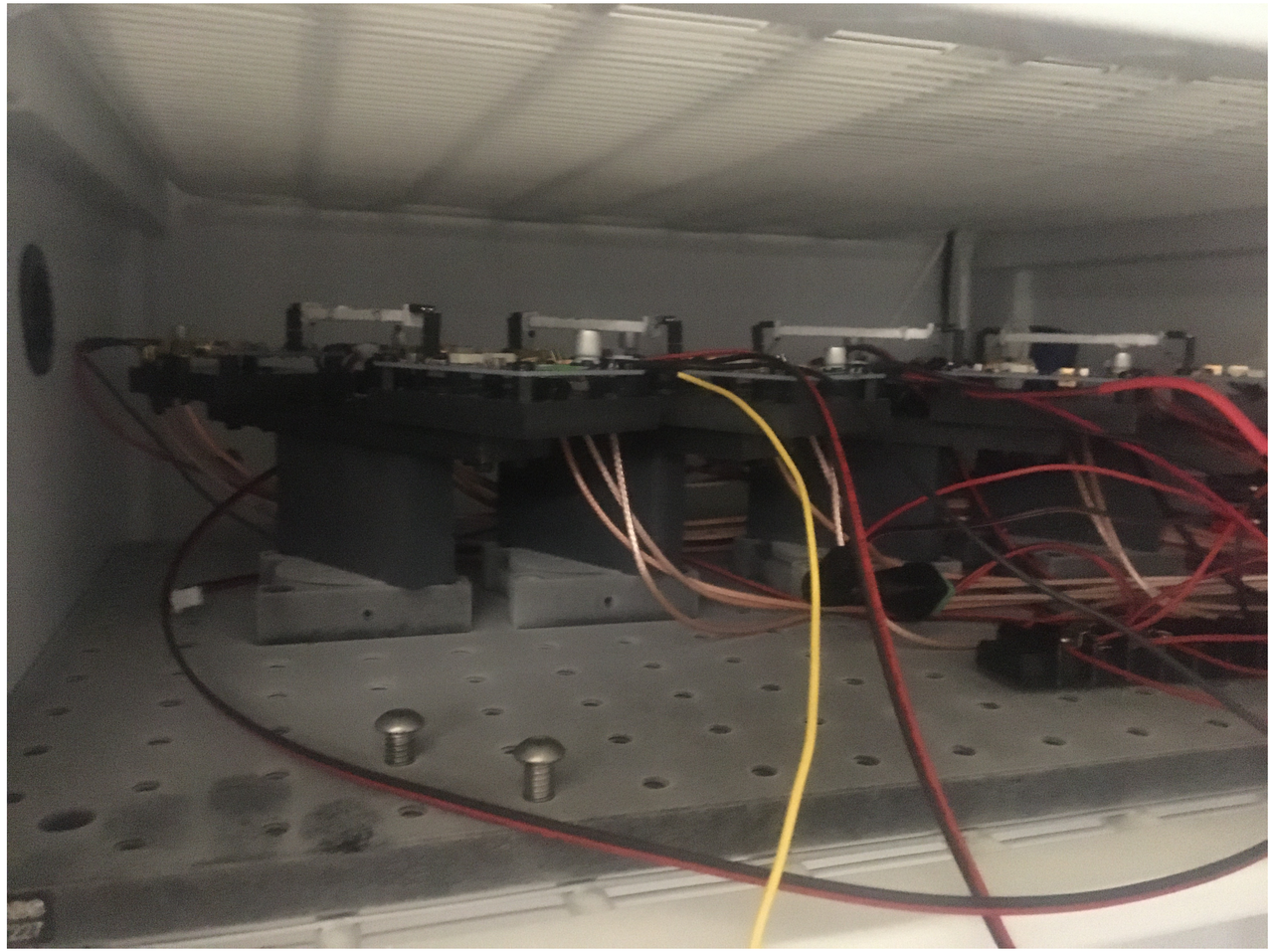
**If we anneal at 80C we would need several months to reach such levels**

**If we anneal at this temperature, what do we chose as time intervals?**

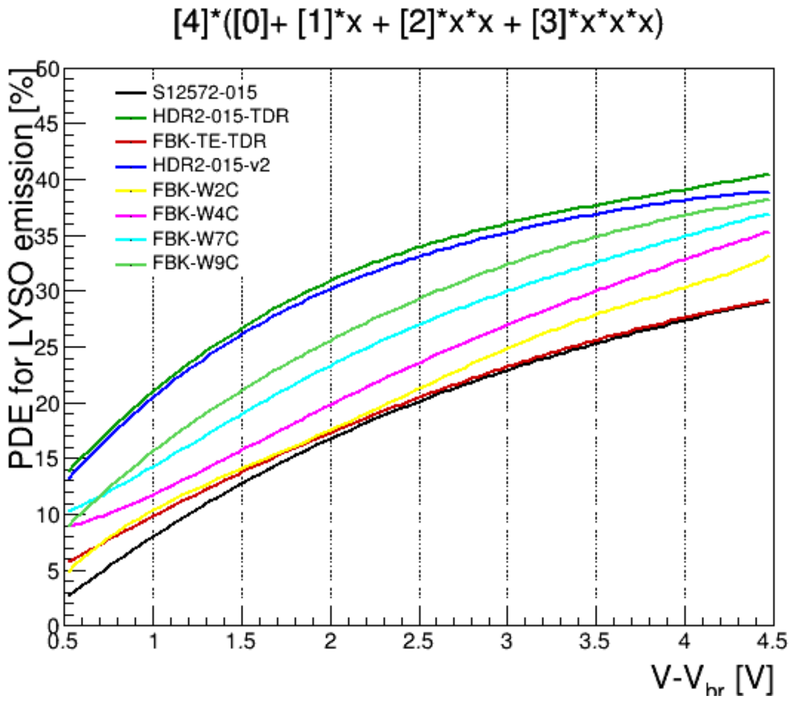
**Still we need to hear from Hamamatsu if we can go to 110C**

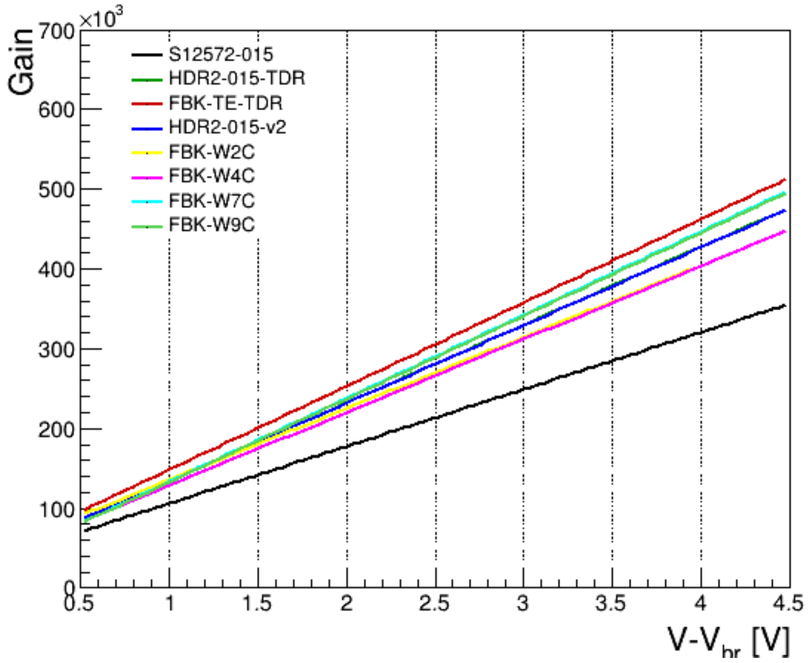
# Running at -30 C

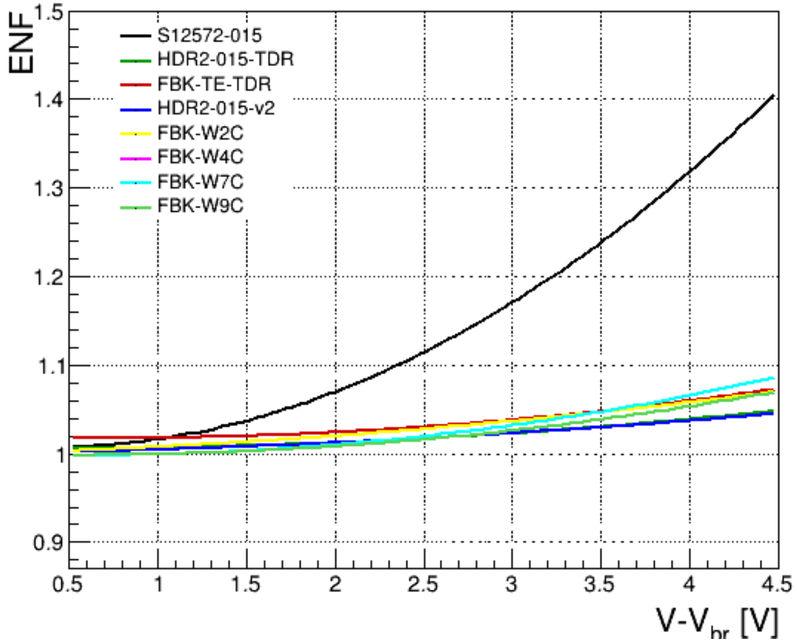
Push nitrogen and installed se



# Some HDR2-015-v2 Parameters



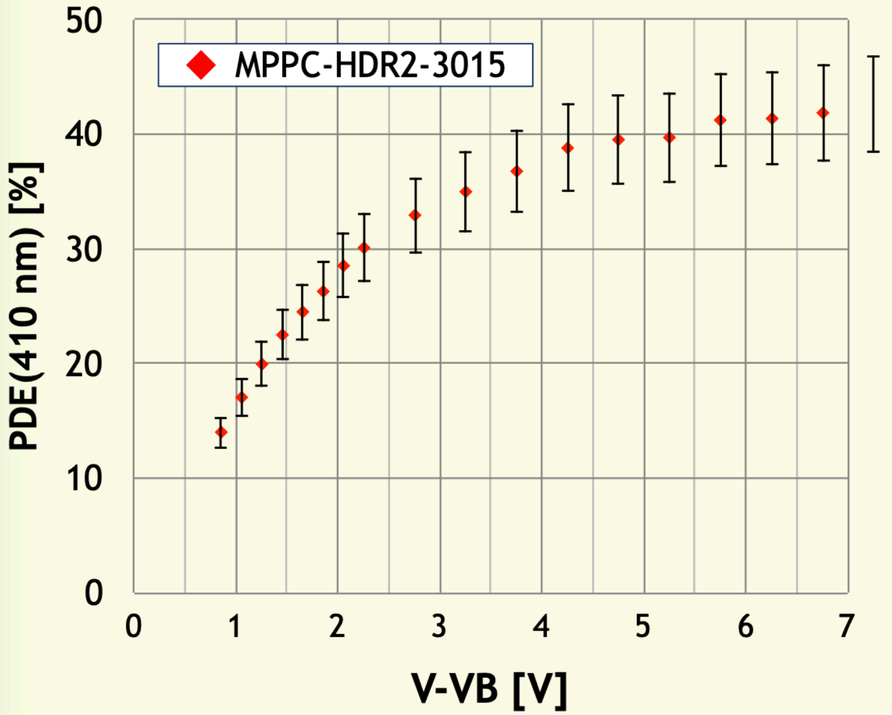



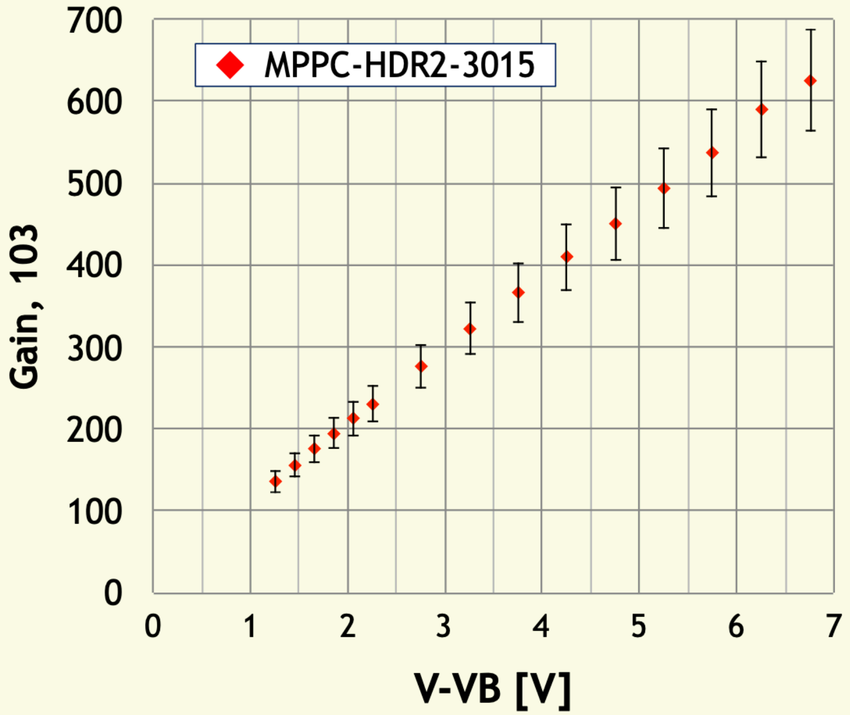

https://twiki.cern.ch/twiki/bin/viewauth/CMS/BTLSensors

https://twiki.cern.ch/twiki/pub/CMS/BTLSensors/sipm_spec_input_HDR2-015-v2-1e13.root

# SiPM parameters

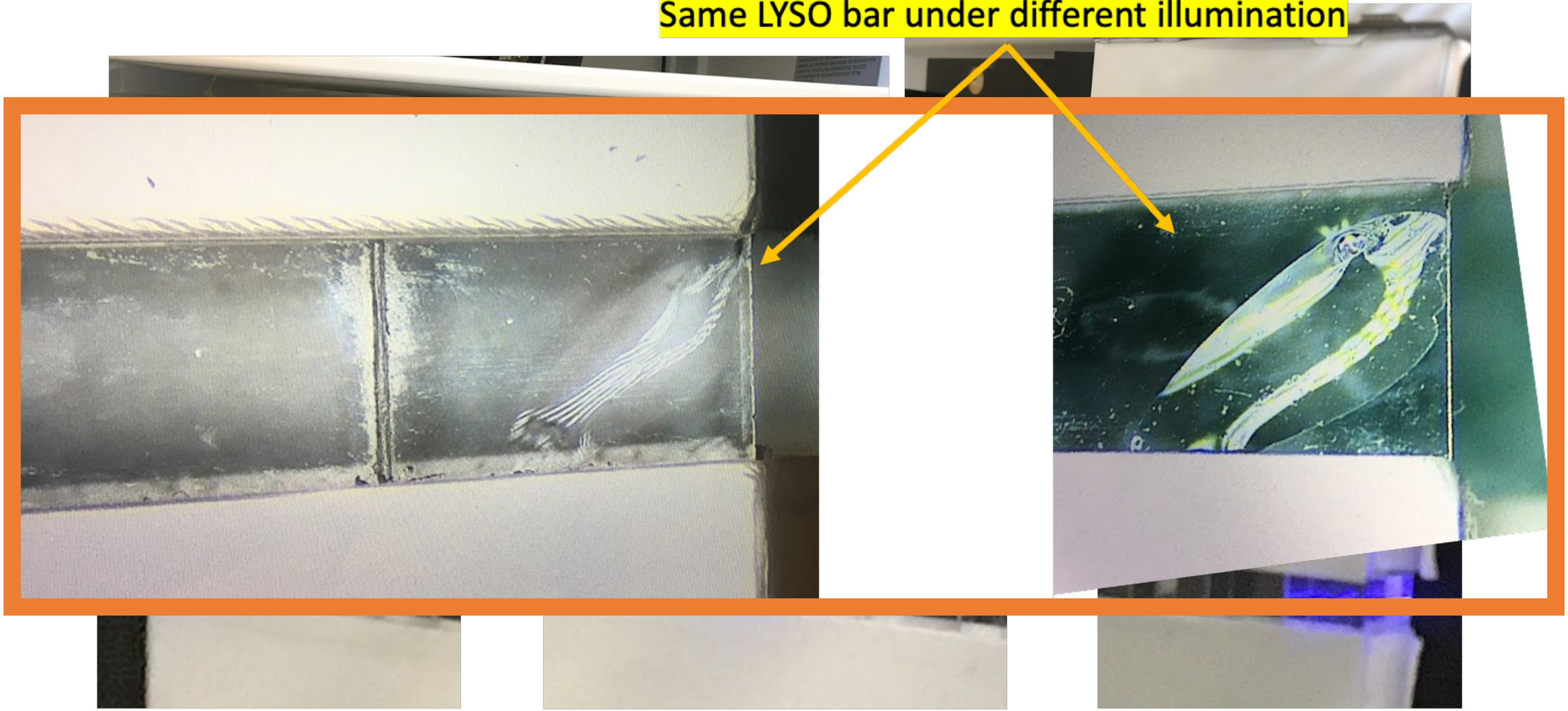
We work with multiple SiPM vendors in the BTL but for this TEC R&D we used the Hamamatsu 3x3 mm HDR2 SiPM



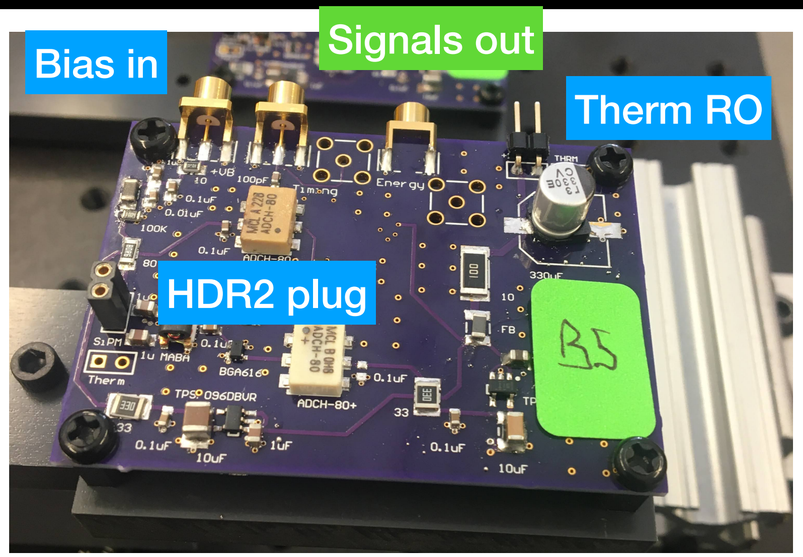



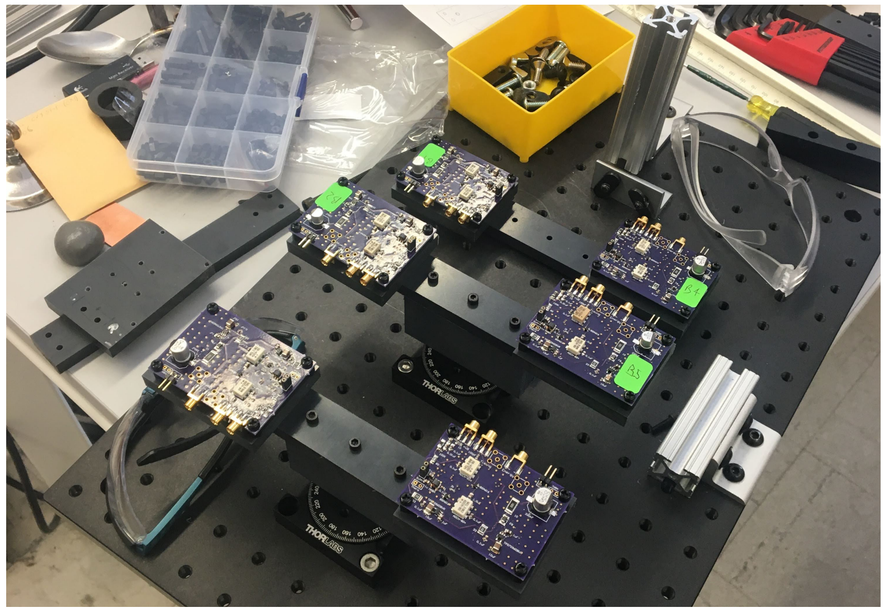

Due to the fast rising PDE data shows that these HDR2 SiPMs have optimum S/N after high irradiation at 1 to 1.5V over voltage (V-Vb)

# UV-Laser Scan Tests - bubble in bar 16



# May'21 TestBeam



PhD students from NorthEastern University

DT5742


GROUP0 GROUP1

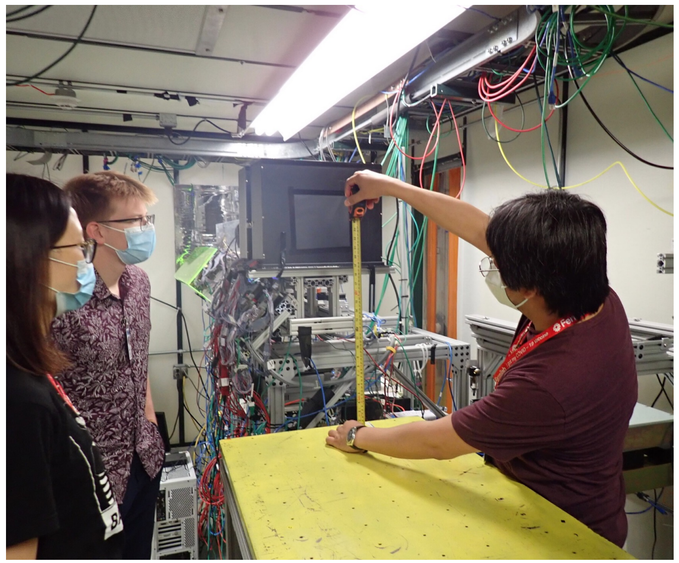
CH [0 - 7] TR0 CH [8-15]

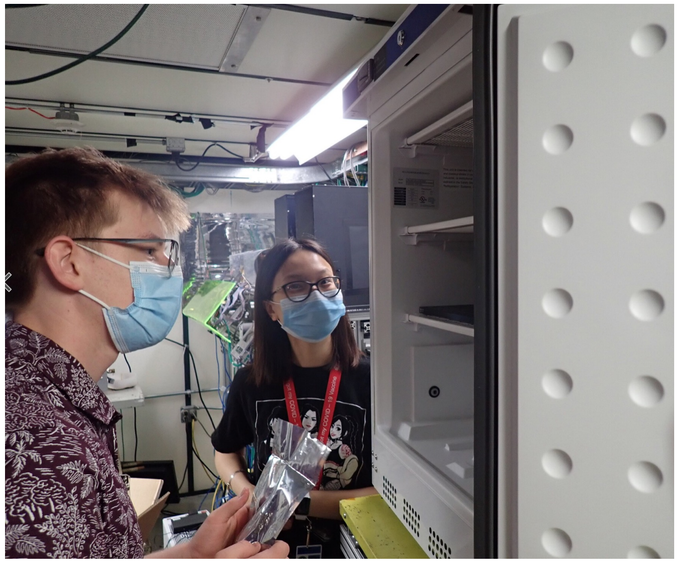
2 Bars
4 HDR2s
8 Channels

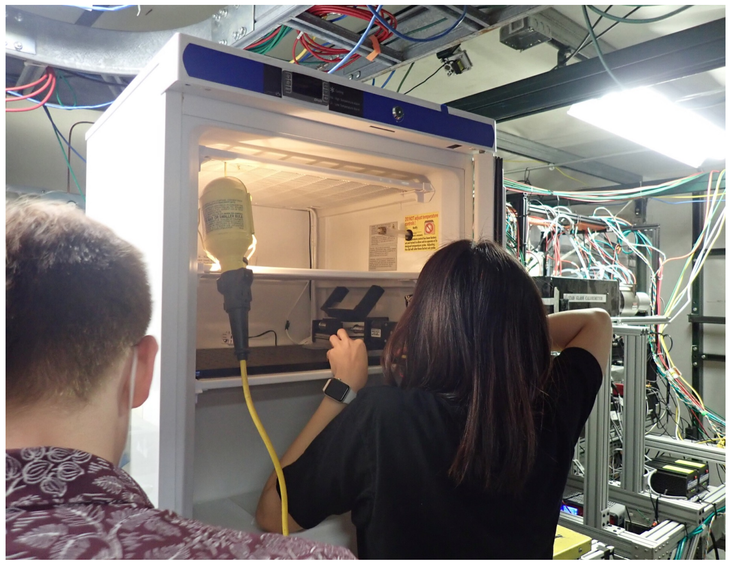
MCP

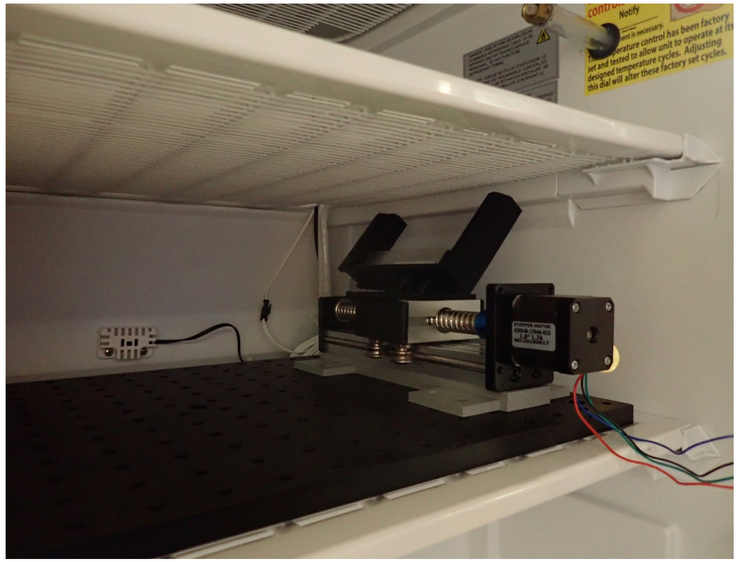
2 Bars
4 HDR2s
8 Channels

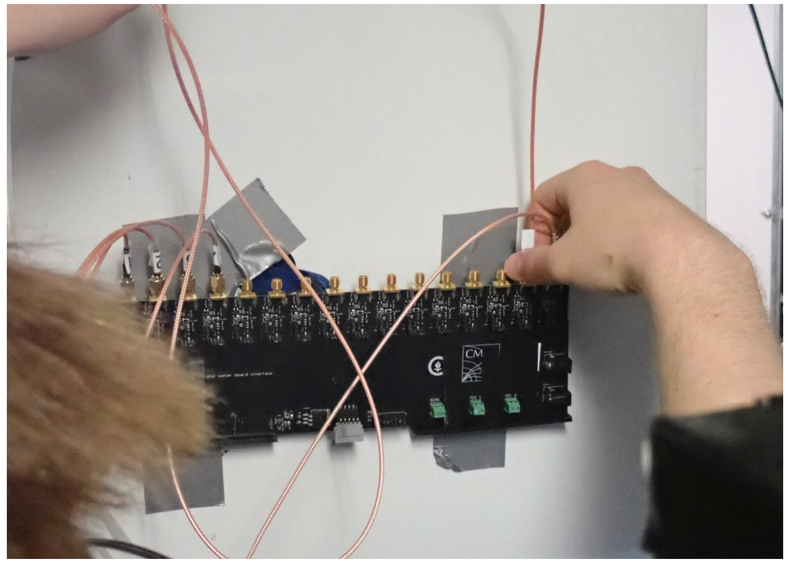
# June’22 Testbeam



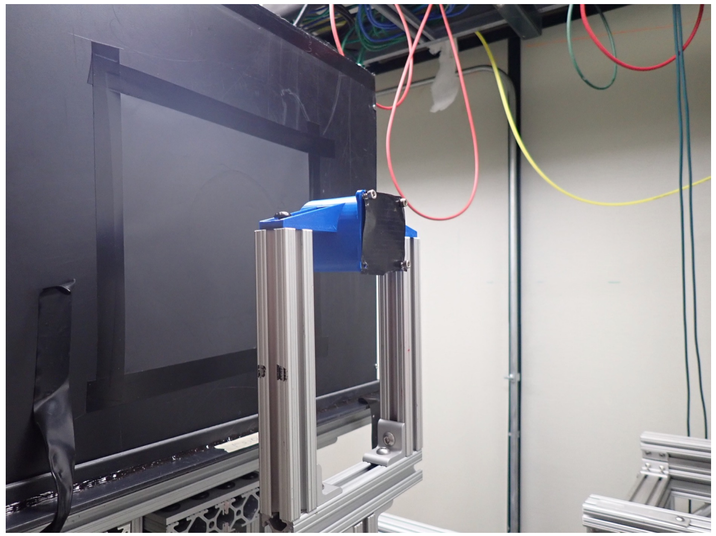


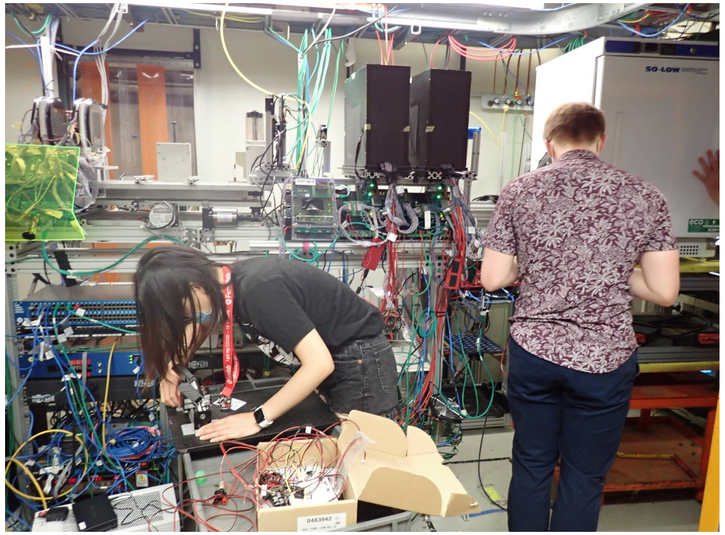


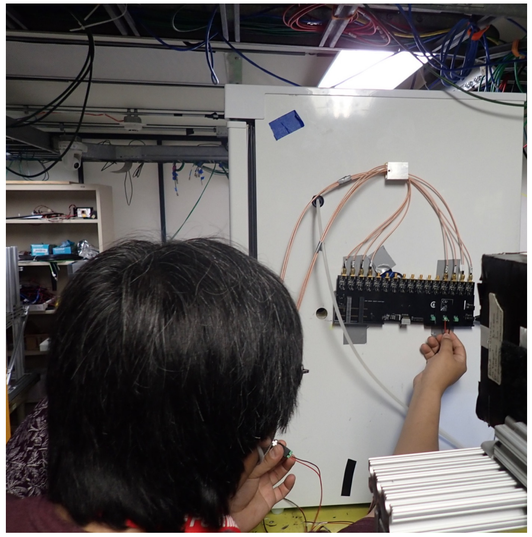





# June’22 Testbeam

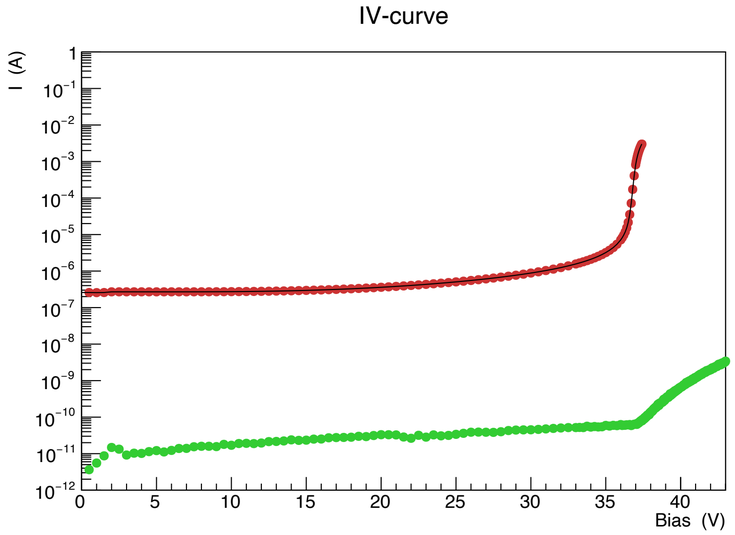




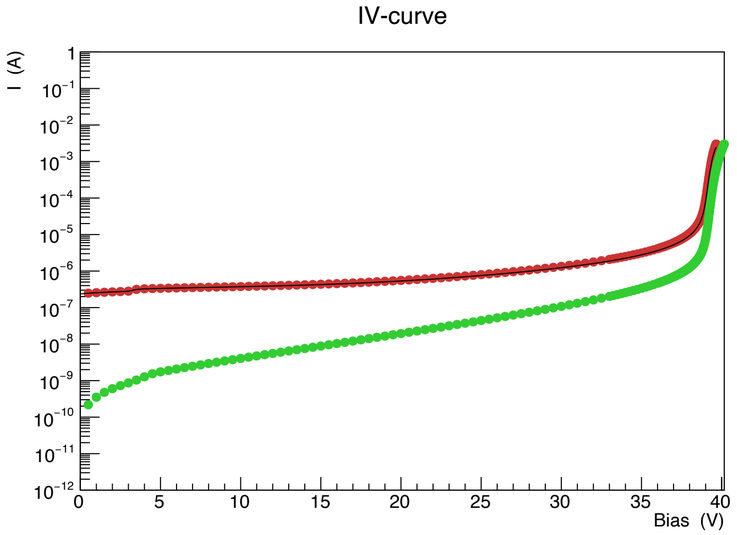

# Measuring Radiation Damage on SiPMs at UVA

- We tested eight Hamamatsu HDR2 SiPMs (S14160-3015PS, S15408-02-singl, S15408-01-singl)
  - Three pairs were irradiated to an equivalent fluence of: 1e13, 5e13 and 2e14 $N_{eq}/cm^2$
  - One pair was left un-irradiated (benchmark)

- HDR2 IV-curves were measured at different temperatures from 20 degC to -30 degC
  - Orange LED diode on and off to asses dark current component
  - System place inside a refrigerator
  - Temperature controlled within few degrees and read at the HDR2's ceramic package with thermistors




Example of NonIrradiated (left) and Irradiated (right) HDR2 IV curve response. Green points are $I_{dark}$, red points are $I_{LED}$ and black curve is the difference ($I_{photon}$).

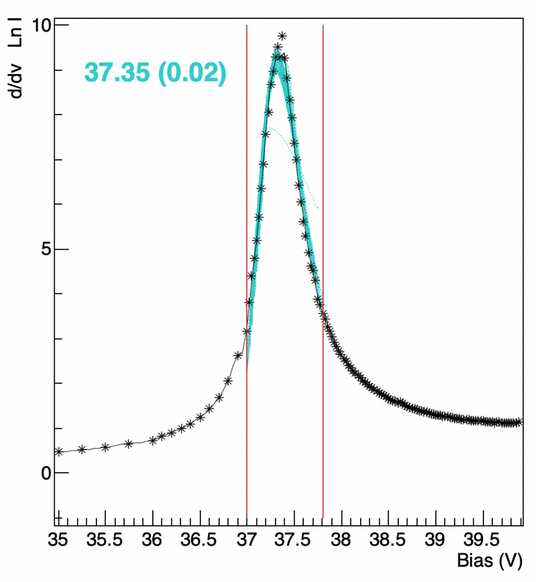


# Breakdown Voltage ($V_{br}$) as function of Temperature

- There are several methods to compute the Vbr of a SiPM [CITE]
- Here I use two methods

**Method A:**

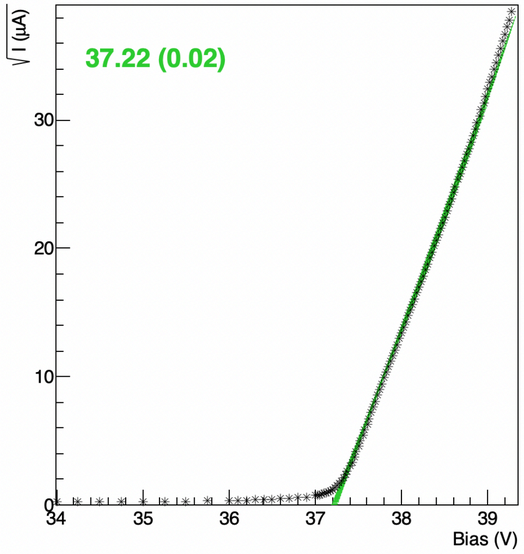
- Computes inflection point from IV-curve during rise when in overvoltage
- Method has been widely used before by different groups
- Assumption is that Vbr == InflectionPointX




**Method B:**

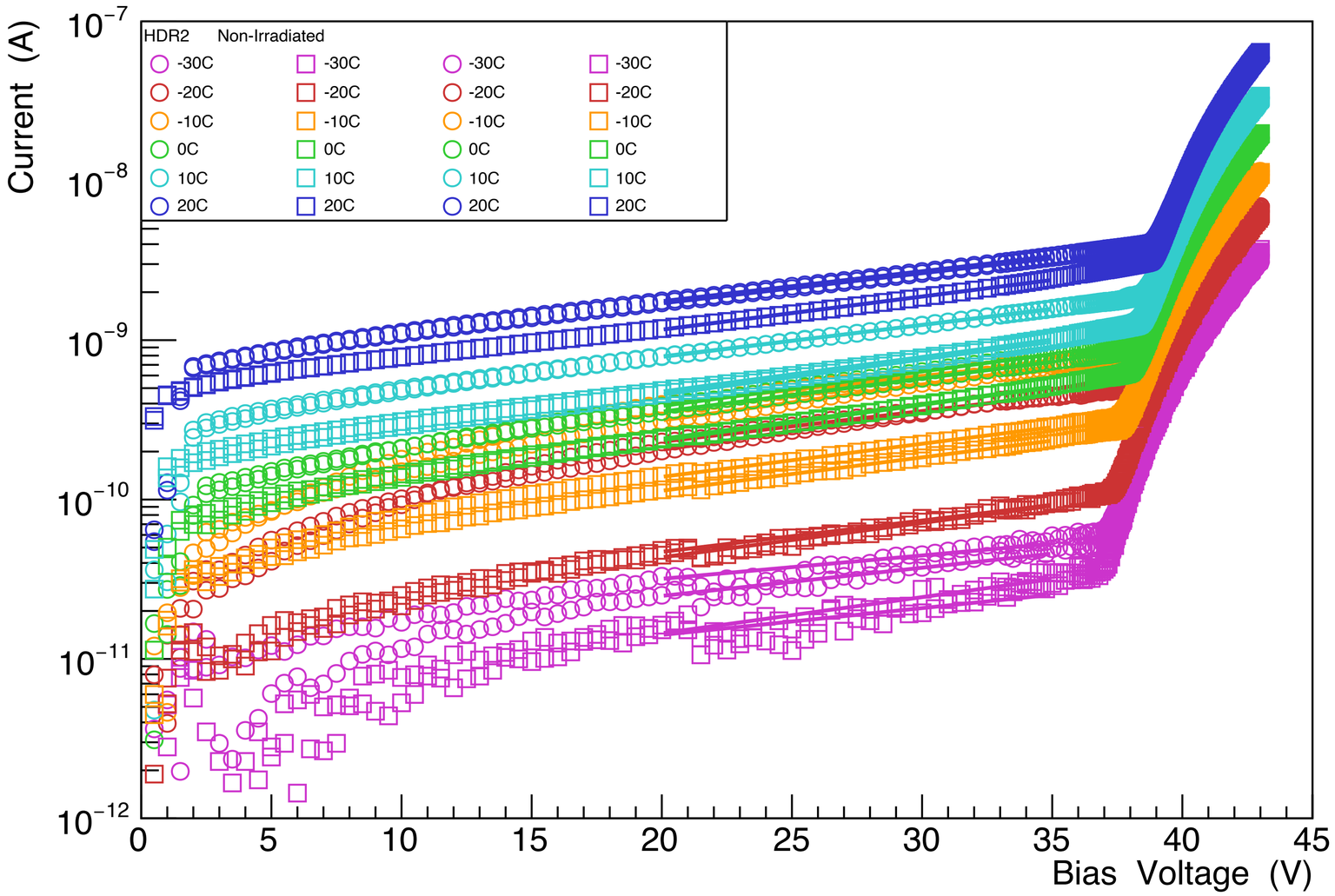
Based on technical note from SensL devices: link here

- Based on linearity of sqrt(I) when in overvoltage
- Method is promising and as will be seen does a good job in reproducing manufacturer nominal value
- However may present large systematics since for HDR2 the kink is not so sharp




Example of IV curve for HDR2 1e13 at -20C

# DCR HDR2 NonIrradiated

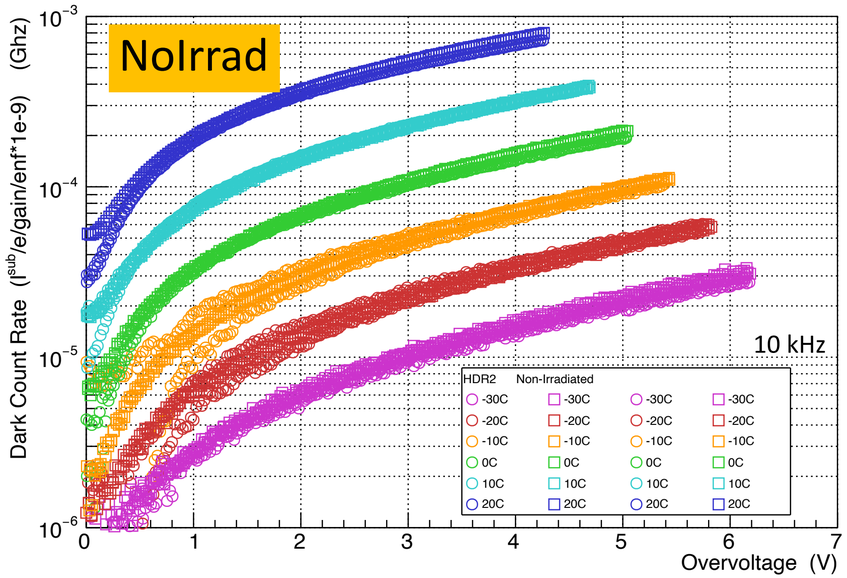


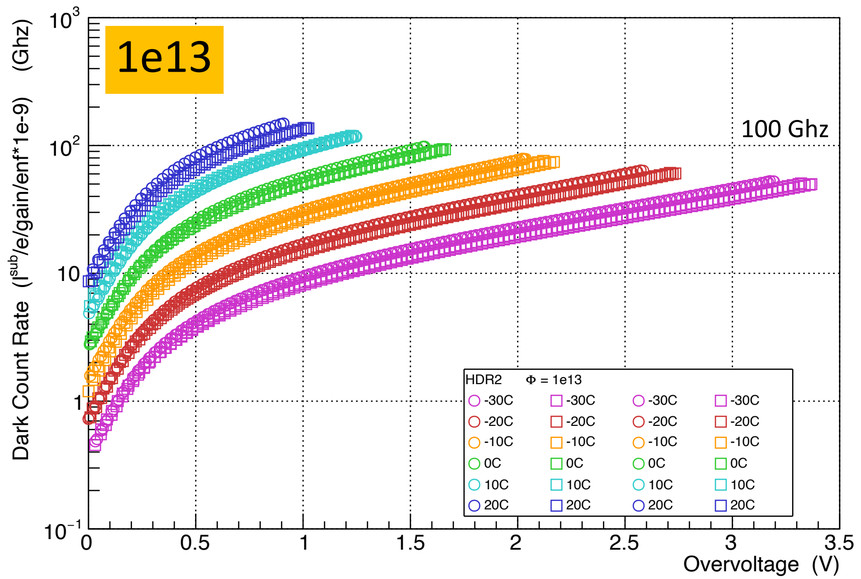

$CR_{pe}$ e gain = I - $I_{leak}$ = y

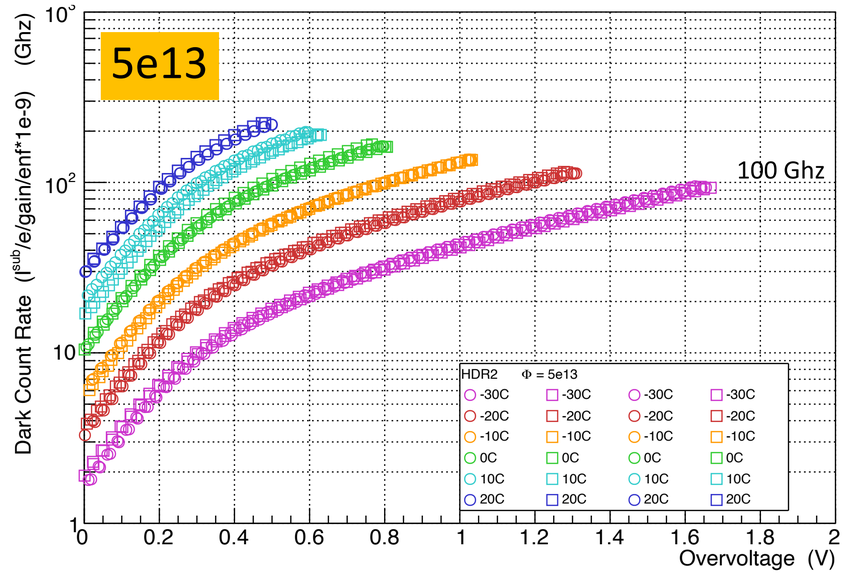
- $I_{leak}$ is estimated from fit to IV-curve in the range of 20-35 (see figure)
- $V_{br}$ obtained from MethodA (MaxdLnI)

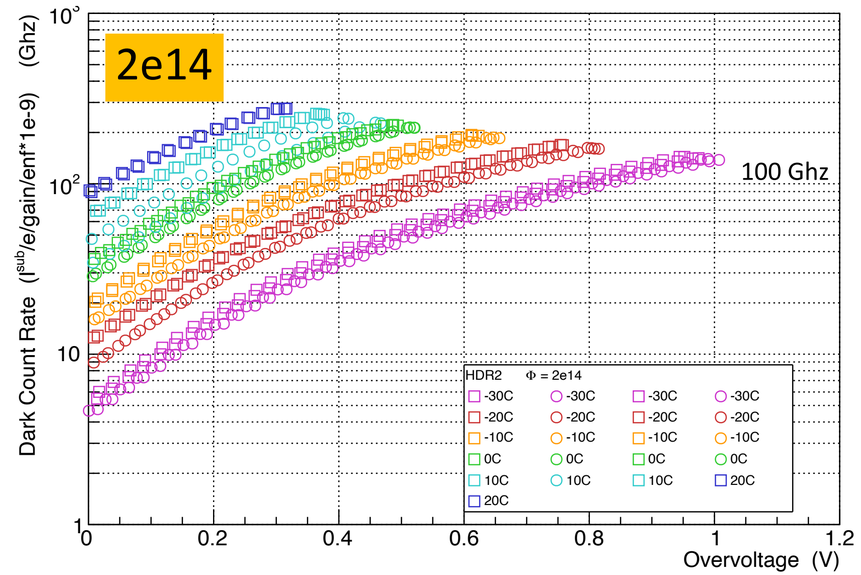
x -> x - $V_{br}$
y -> y/e/gain(OV)/ENF(OV)

# Dark Count Rate (DCR) as function of OverVoltage



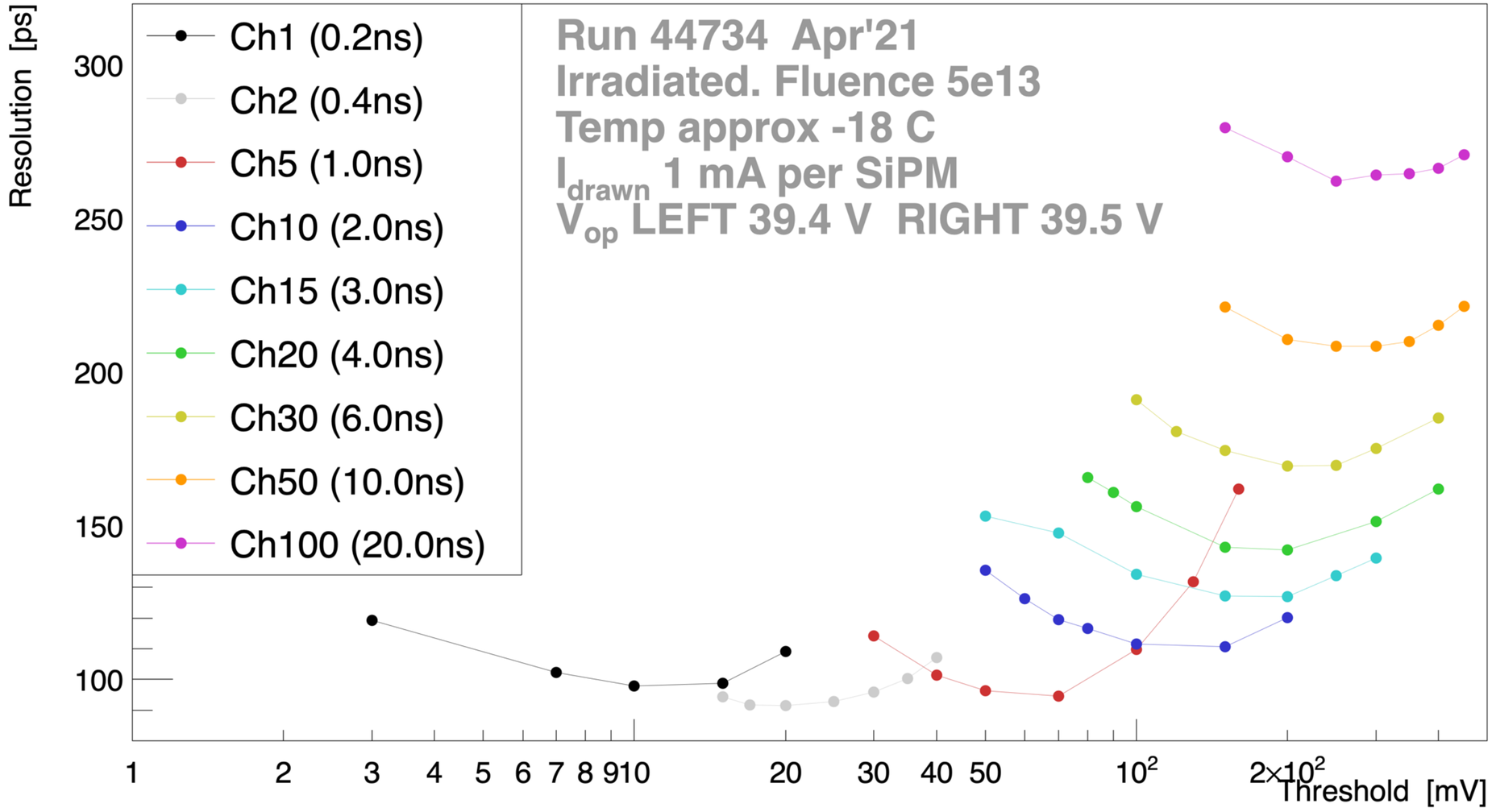



# Delay Line Shaping Analysis

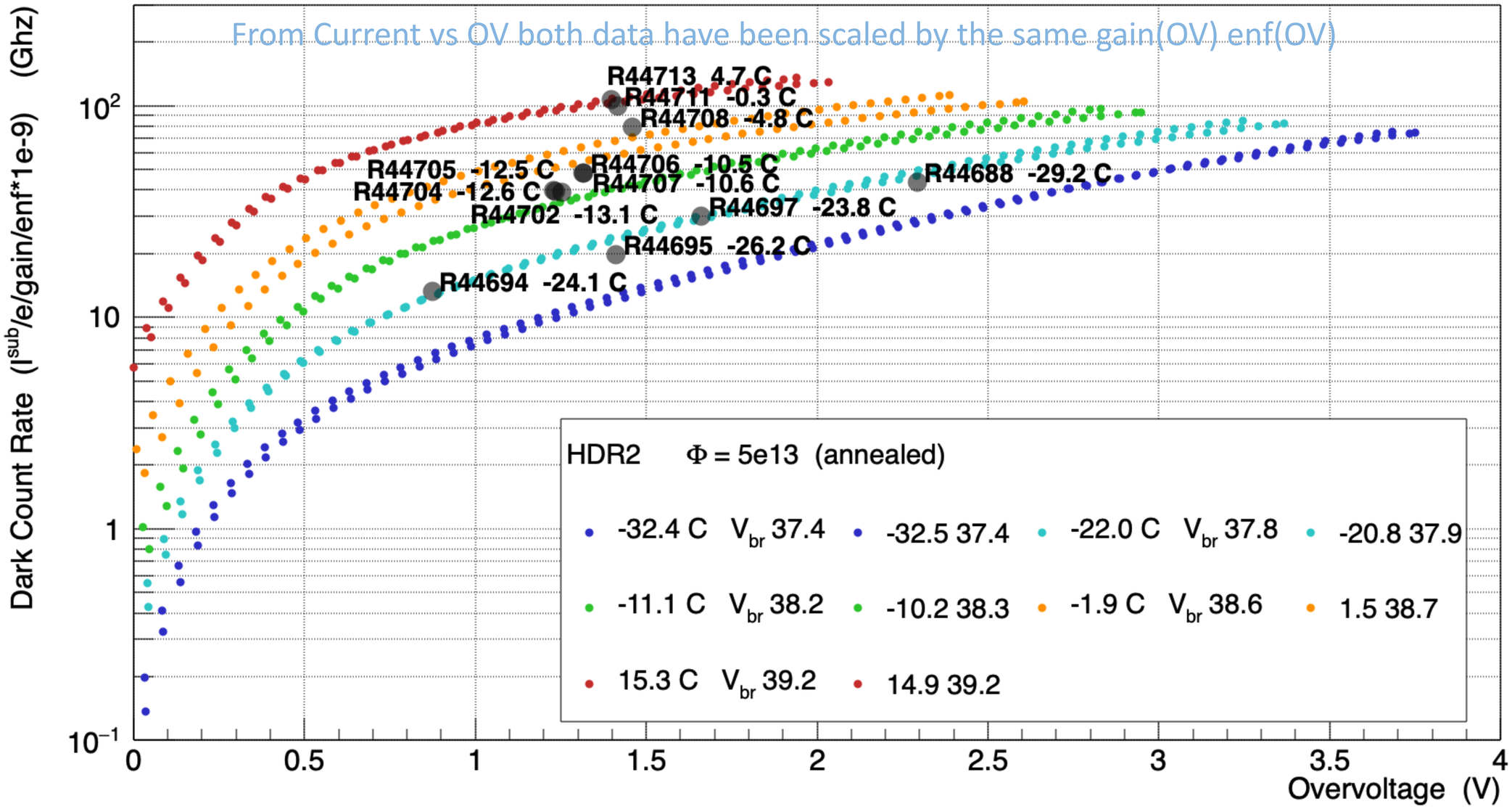
$\sigma_{BAR} = \sigma^{-} / 2$




Tested different signal delay line chain lengths

- Anything below 1 ns is fine
- There seems to be some optimal close to 0.4 ns for this run

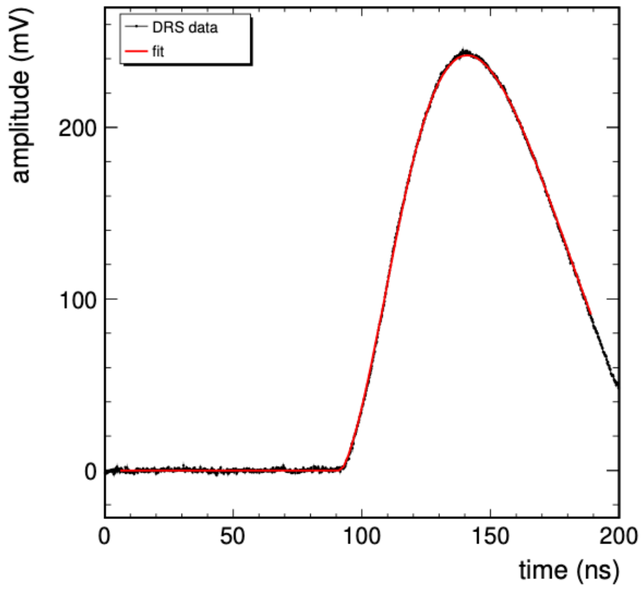
# DCR Map for bars @ 52 deg inclination.



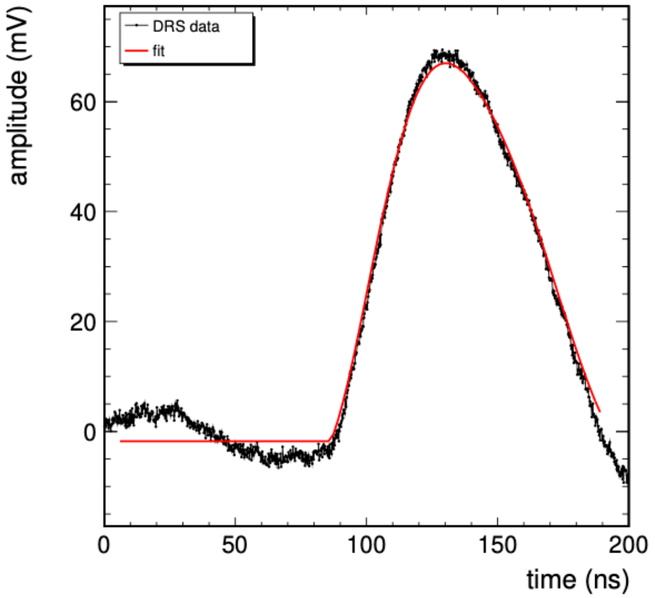
# Energy and Time Reconstruction

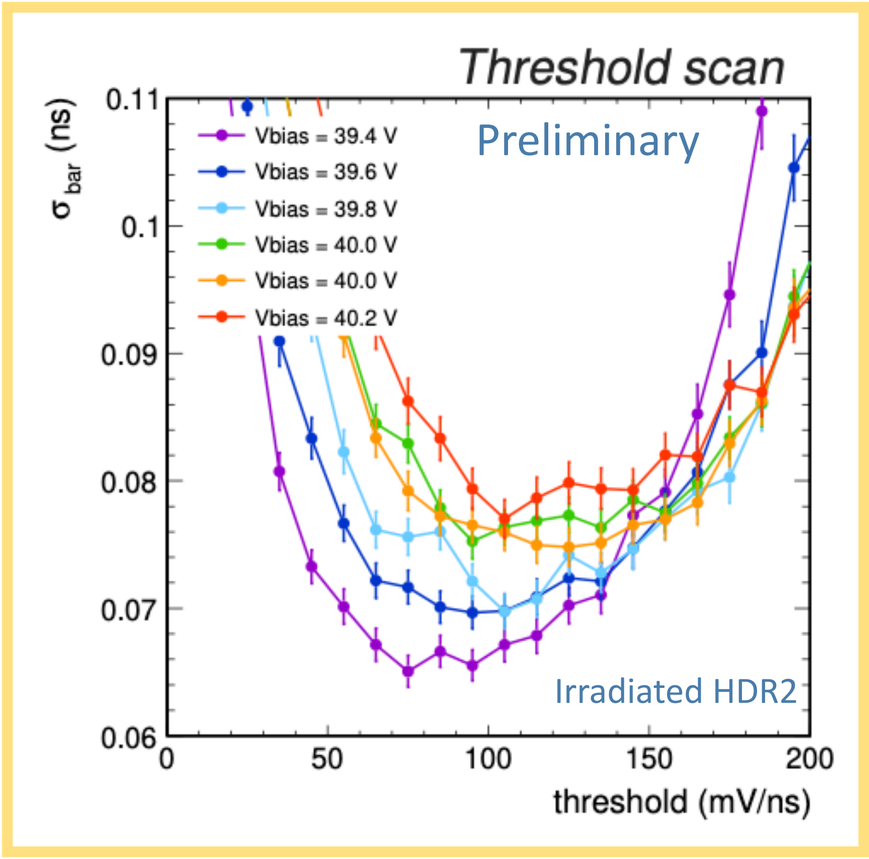
- For the energy channel, a template fit to the pulse was used for each HDR2
- For the timing channel, a single delay line shaping was applied in order to mitigate DCR (+noise)
- Threshold optimization based on OverVoltage

Example of NonIrradiated HDR2 waveform (low gain) fit to template




Example of Irradiated HDR2 waveform (low gain) fit to template



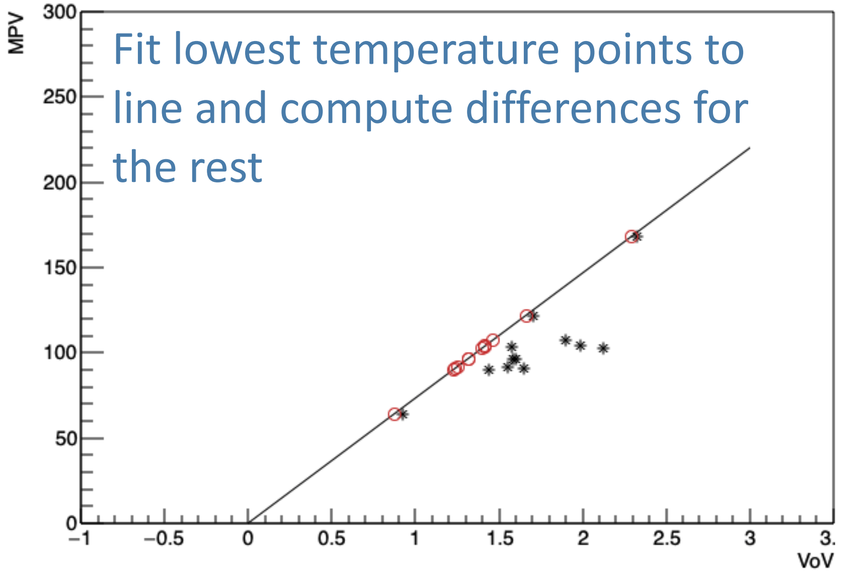



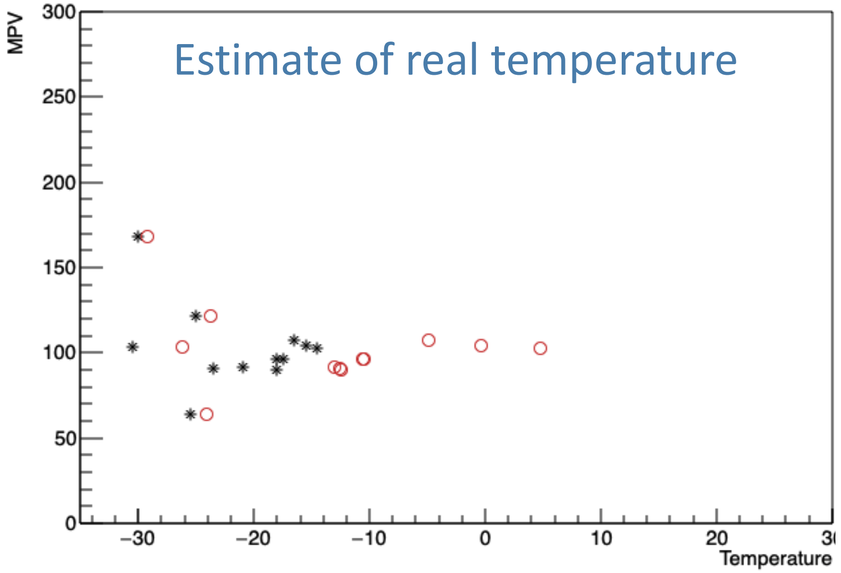
# Computing OV correction based on MPV scaling

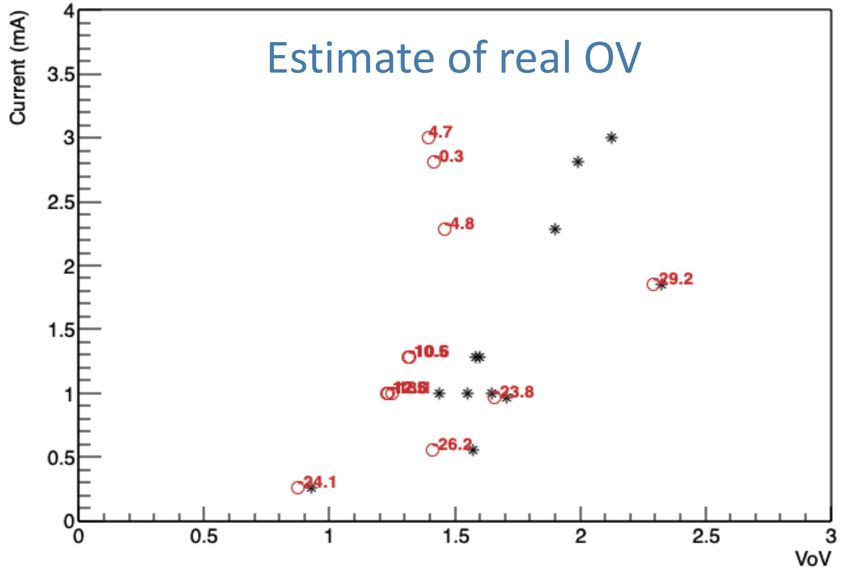
MPV vs OV

MPV vs Temperature

Current vs OV

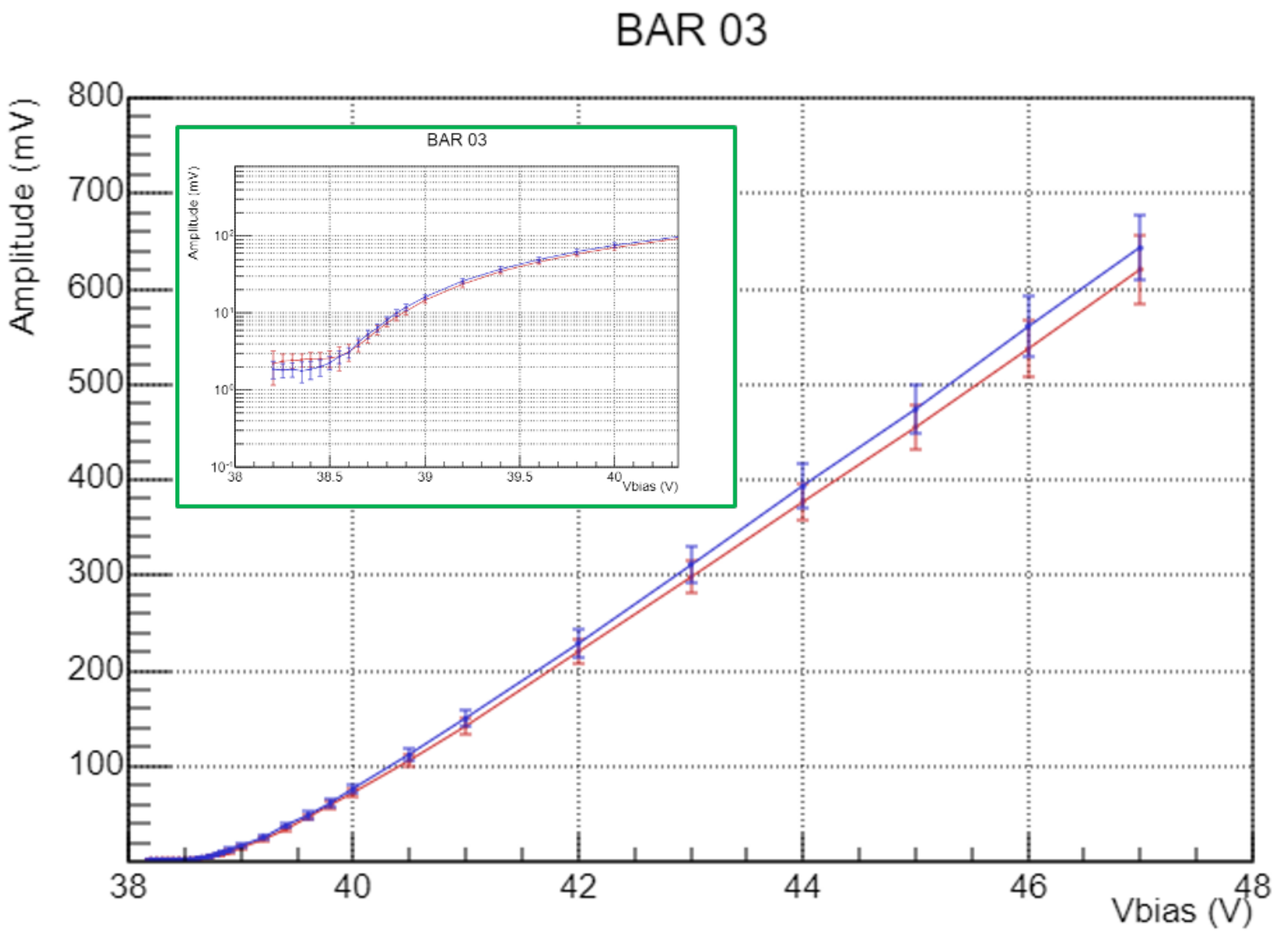


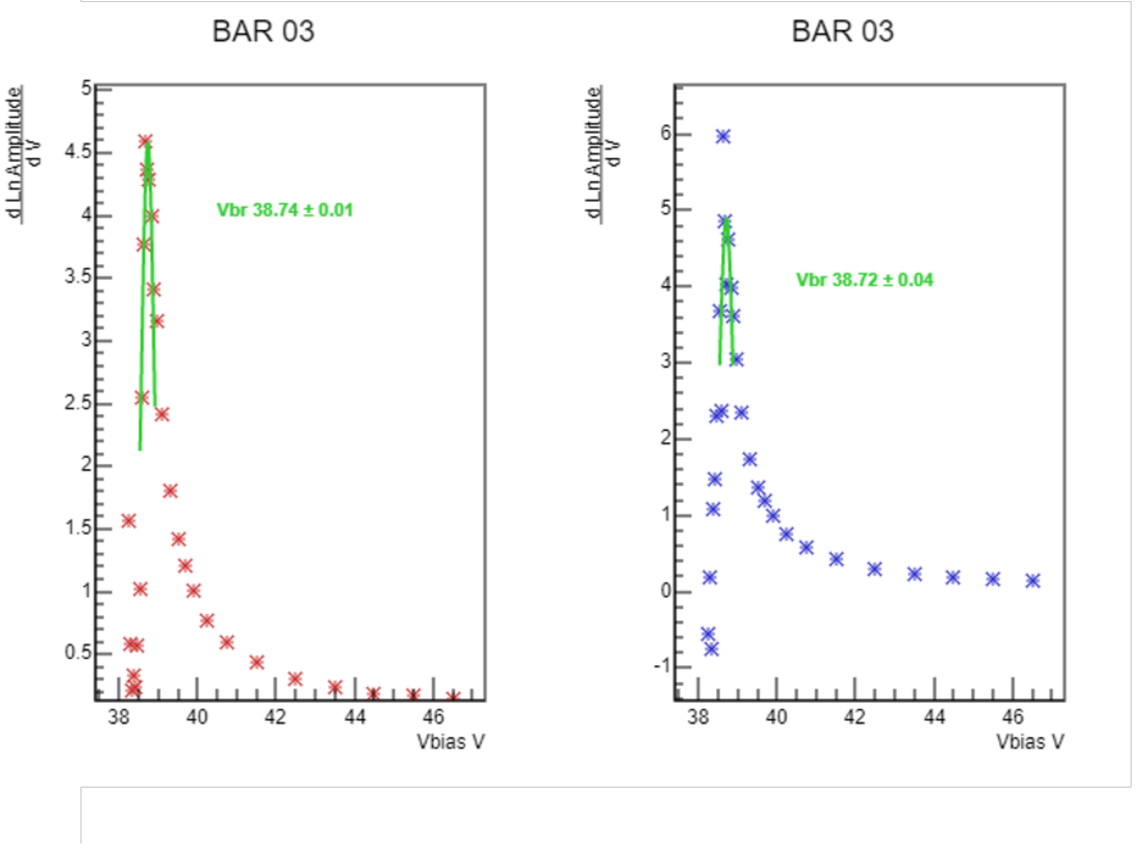



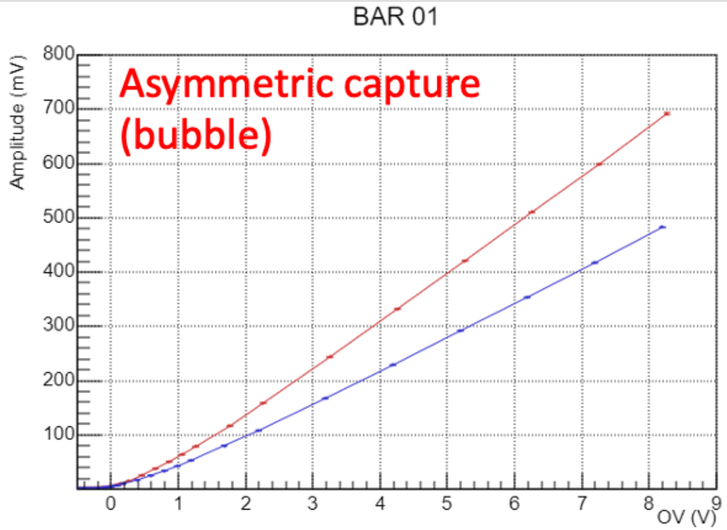
# UV Laser on Module 739

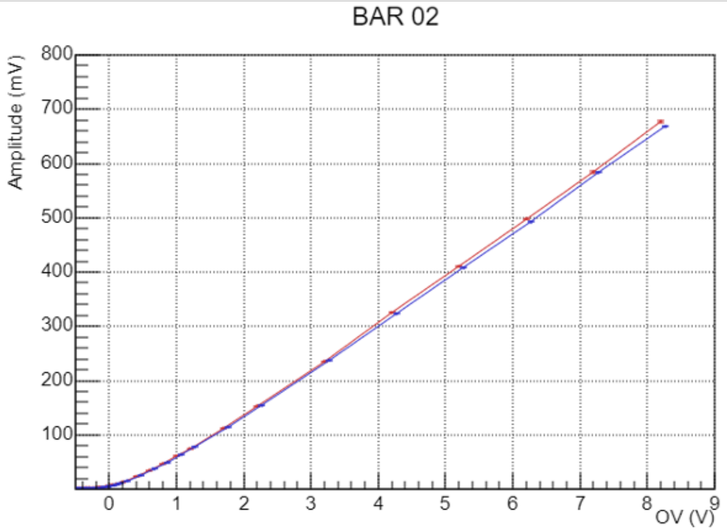
UV source centered on bar 03
T approx. +19C
Intensity to 8.0 (approx. ~2.9 MeV)

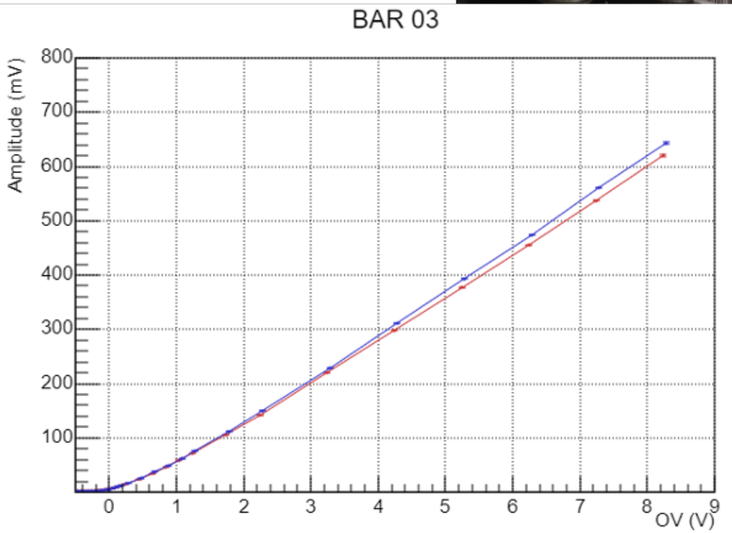


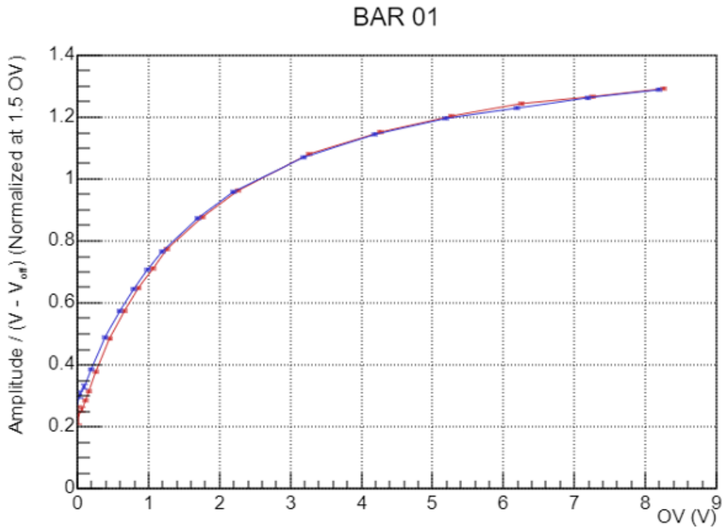



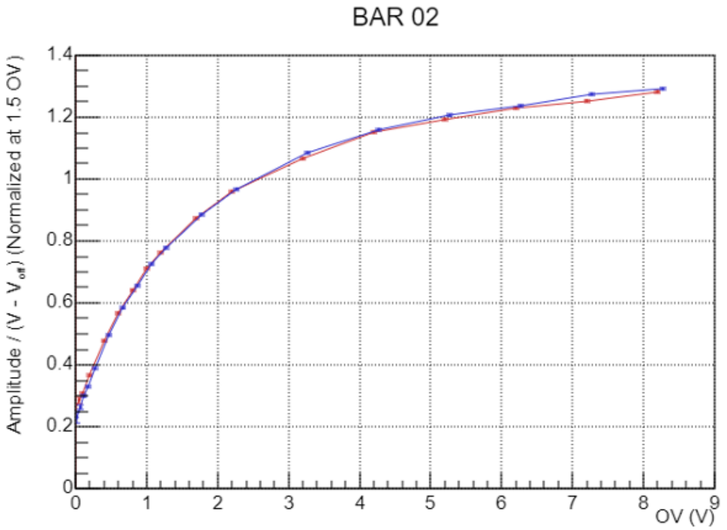
# UV Laser on Module 739

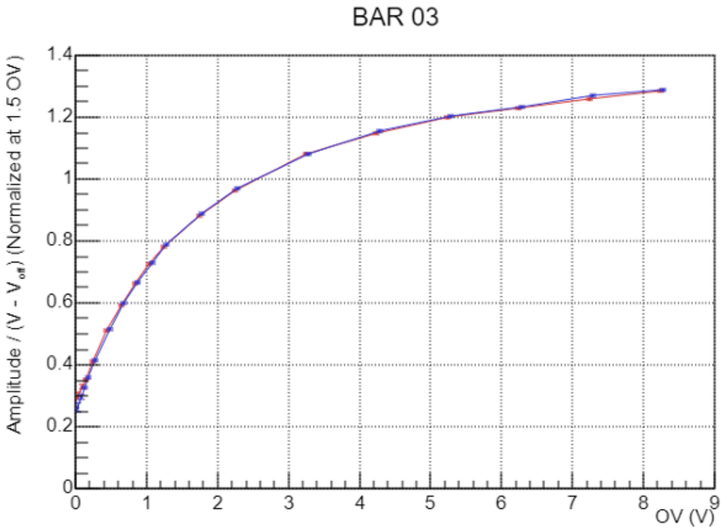


# Radiation Damage to SiPM Response

- Displacement of silicon atoms in the crystal lattice [G. Landstrom - NIM A 512 (2003) 30]

  Crystal defects create additional energy levels in the band gap and facilitate thermal generation of electron-hole pairs which…

  - increase the SiPM dark count rate and dark current

- Change of effective doping density in silicon [A. Heering - NIM A 824 (2016) 111]
  - change the SiPM breakdown voltage

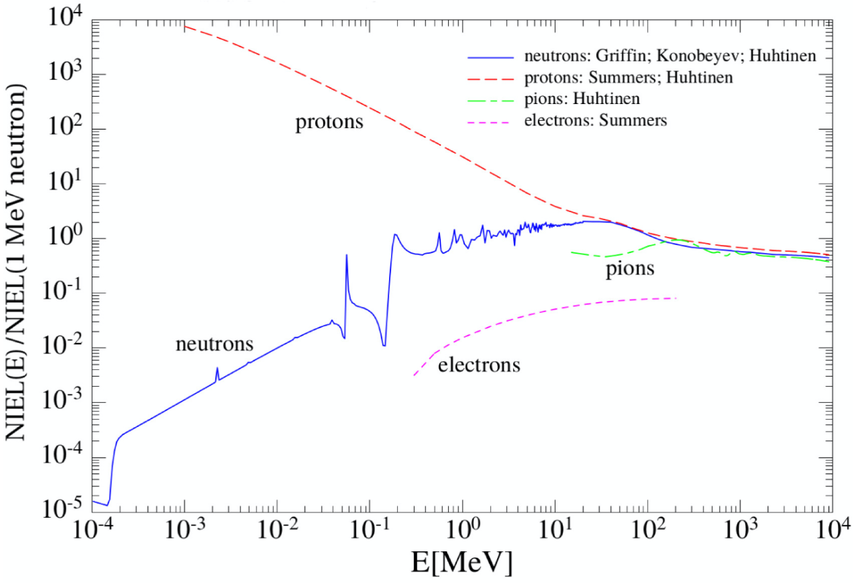
- Ionizing damage in the $SiO_2$ layer which covers the surface of the silicon and insulates it from the bias lines and quench resistors [C. Xu - NIM A 762 (2014) p.149]

  Surface-generated current which significantly….

  - increases the SiPM total leakage current below the breakdown voltage

  If a fraction of the surface-generated charge carriers reach the amplification region, then also an…

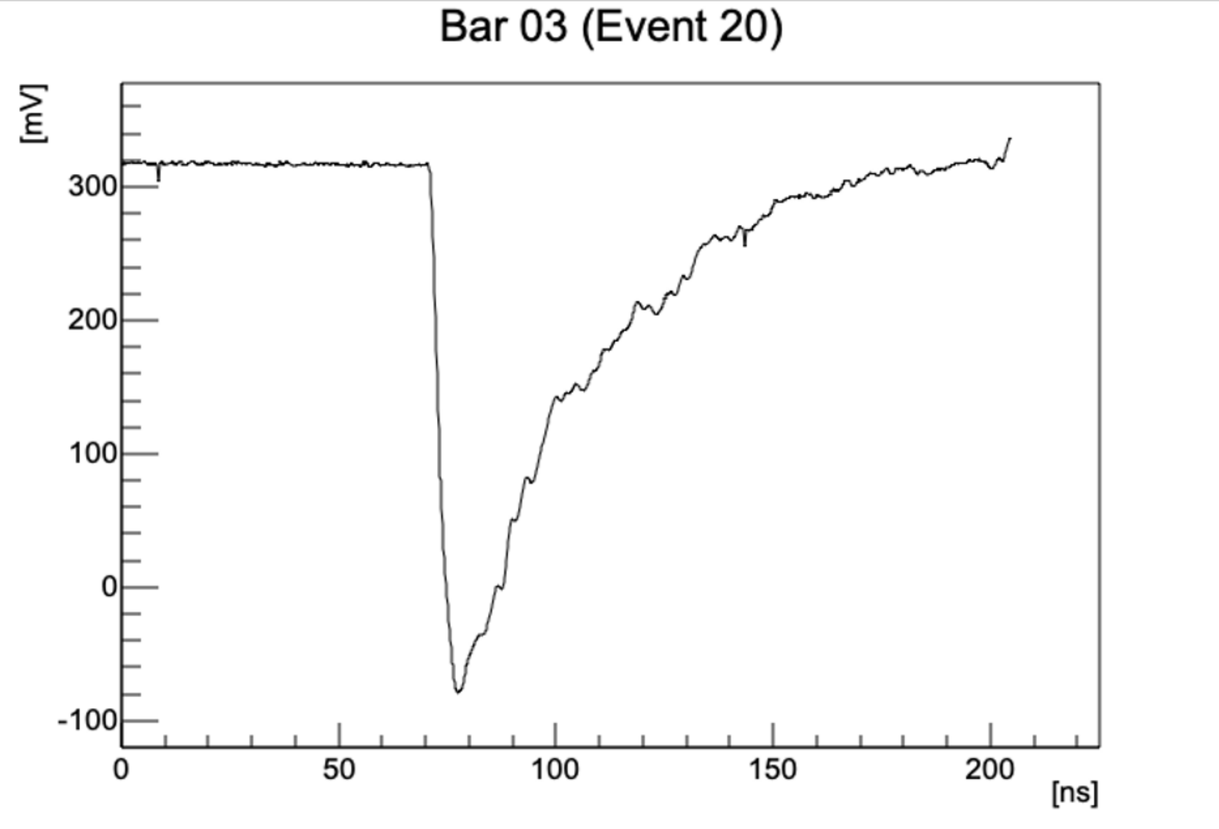
  - increase of dark count rate and dark current above the breakdown voltage may occur

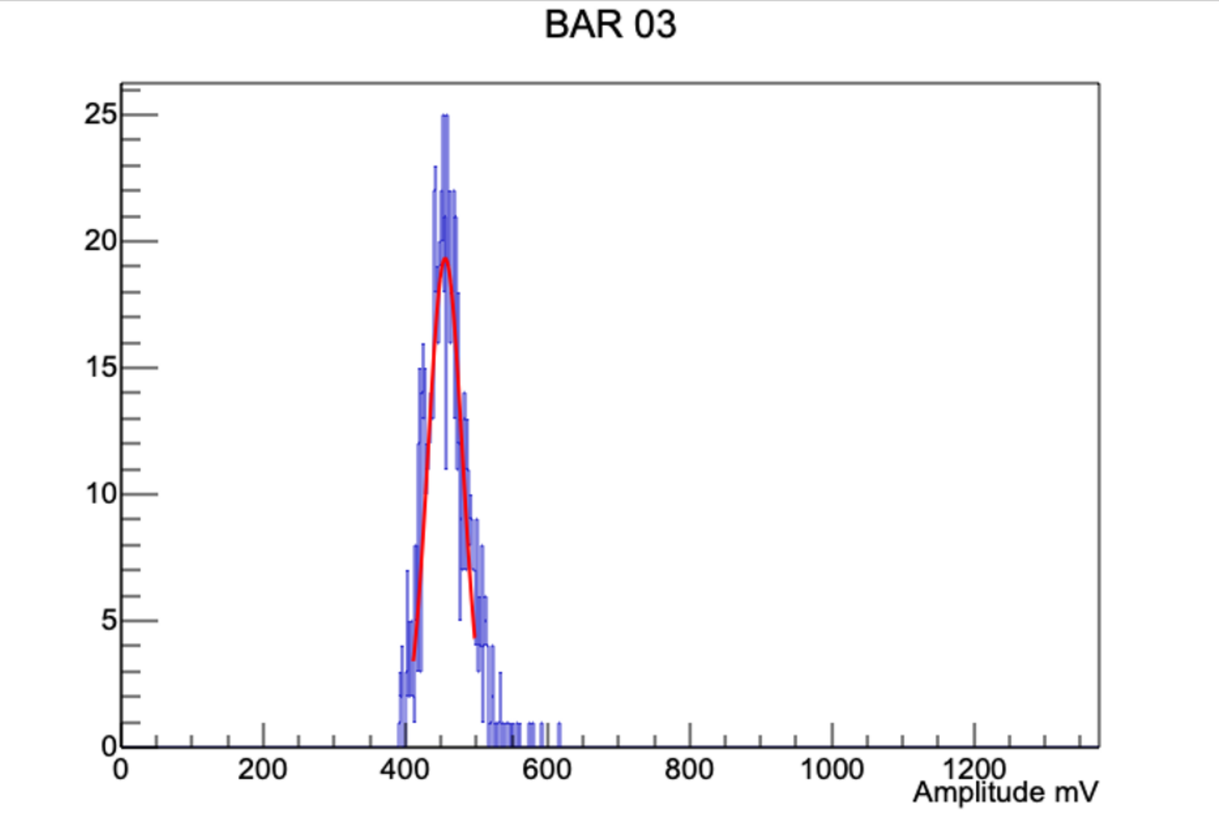



Non-ionizing energy loss (NIEL) in silicon for different particles relative to 1 MeV neutrons. [A. Ulyanov - NIM A 976 (2020) 164203]

# UV Laser on Module 739

UV source centered on bar 03
T approx. +19C
Intensity to 8.0 (approx. ~2.9 MeV)
Bias 45 V

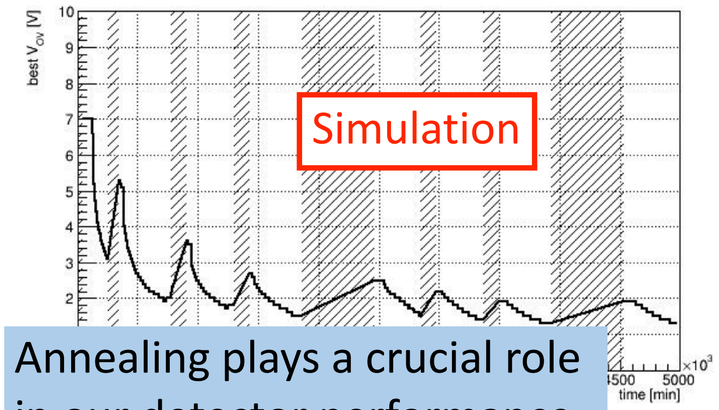


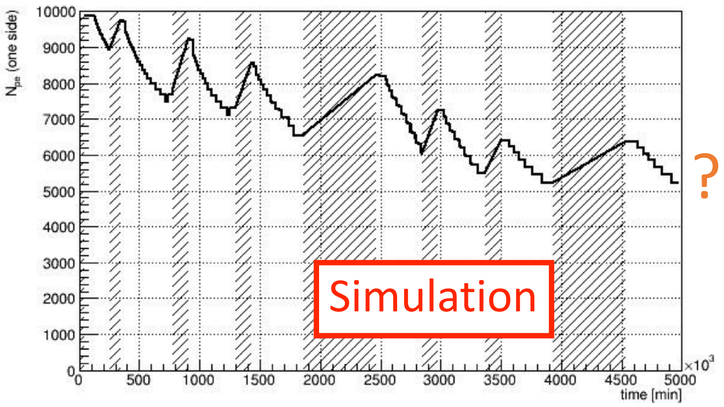
# Extrapolation of Performance for a Ten Year Scenario

## Results for $T_{op}$ = -45° C, $T_{ann}$ = 40° C

- $T_{ann}$ = 40° C throughout the whole duration of Technical Stops / Long Shutdowns




Annealing plays a crucial role in our detector performance

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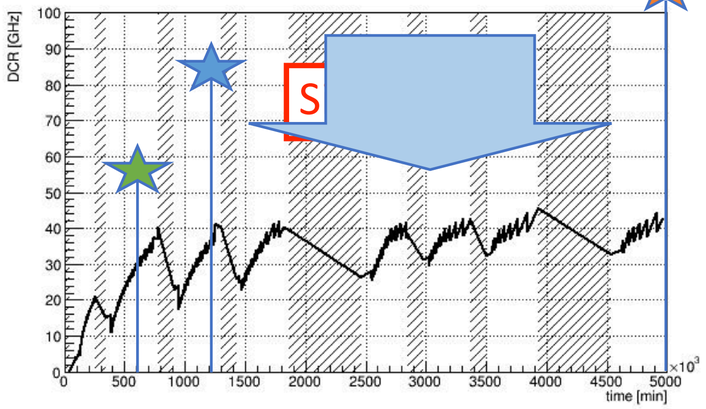


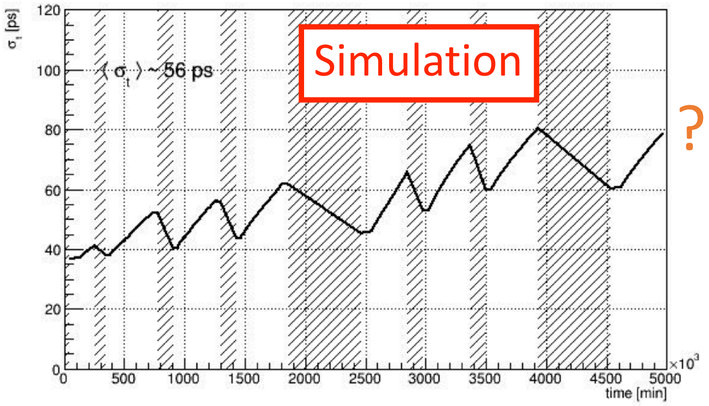


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- Silicon recovers most of its properties by heat treatment: annealing
- Periods of annealing are foreseen for BTL during LHC shutdowns
- To obtain DCR levels at the TB operational temperature, comparable to what we expect in BTL at the end of life, we subjected four SiPMs to a high-temperature annealing procedure