SiPMs for calorimeters. Discussion 02/04/2022 O.Tsai (UCLA).

Disclaimer: materials have not been discussed within ATHENA calorimetry group, some results were shown in previous EIC generic R&D meetings/reports.

Questions:

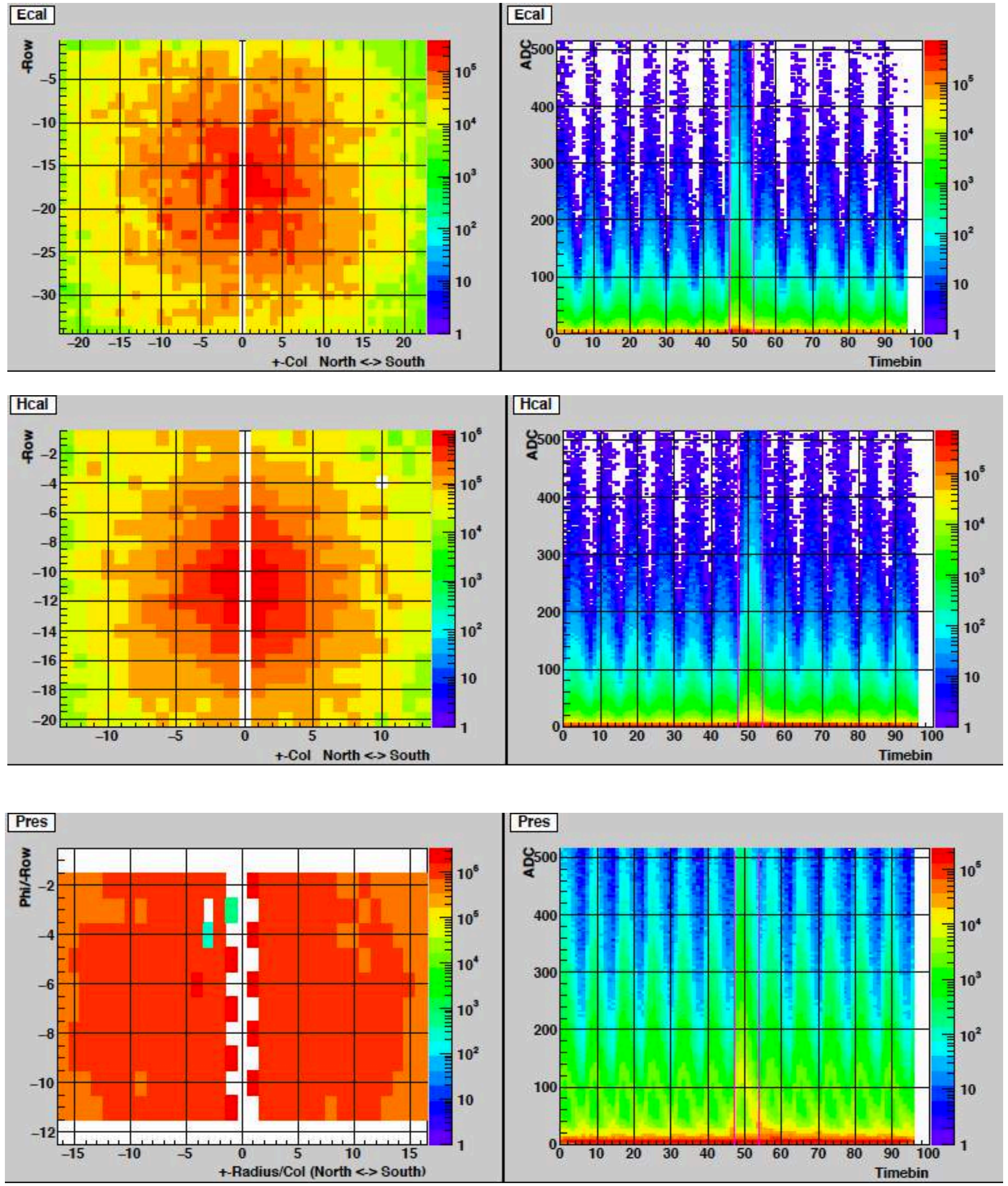
- where we are? – we are using SiPMs for STAR detector (R&Ds and real detectors) for past 10 years or so
- where the technology has to improve? - current sensors can be used for EIC calorimetry applications as is*
- what the prospects are? – I don't expect breakthrough developments**, incremental improvements probably possible
- where we can benefit from synergies? - little overlap with PID due to different requirements
- what we need to focus on? – better define requirements/justifications, continue R&D (eRD105, eRD106, eRD107,eRD110)

*Related to 'requirements' for nECal and pECal

**SiPM noise due to radiation damages

- Main concern is increase in noise with radiation.
- Minor to No degradation of response due to rad damages. (backup slides)

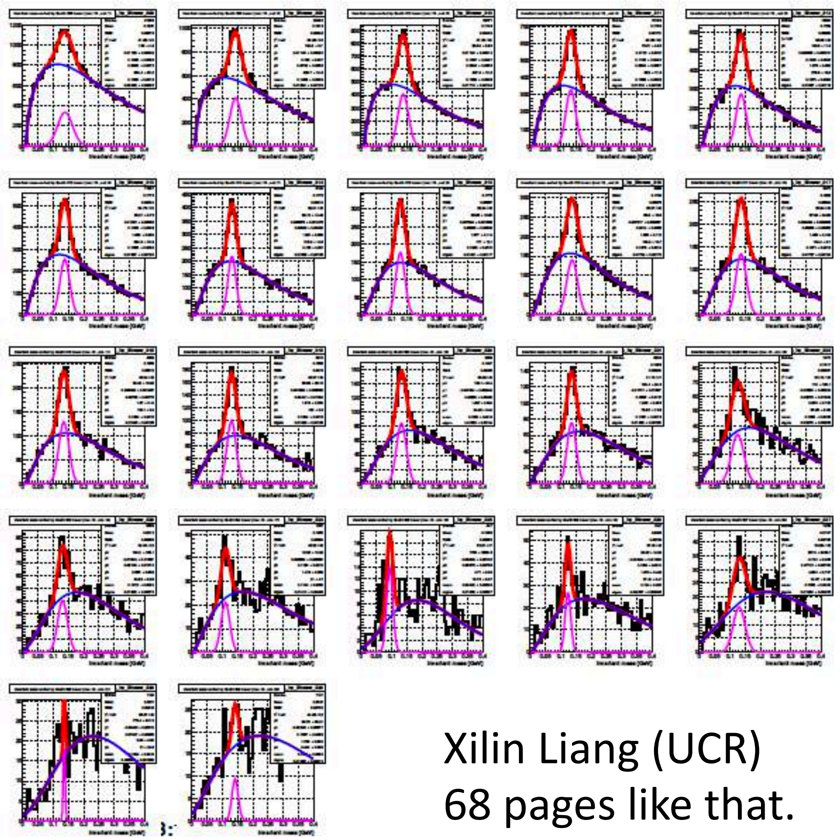
Where we are ?



FCS On-line plots Feb 3. 2022 RHIC/STAR Run 22

SiPMs are wonderful photosensors!

SiPM developments in past ~decade made STAR FCS possible.
STAR constrains precludes other sensors.
Simplicity in integration makes possible to build >2k channels Ecal+Hcal system in two years. NSF grant – Nov 2019. Jan 2021 commissioning with beam at RHIC BES II Run.
Run 22, pp 500 GeV, 5-6 MHz collision rate. 18 production FCS triggers (combinations of Emcal+Hcal+Preshower)



Xilin Liang (UCR)
68 pages like that.

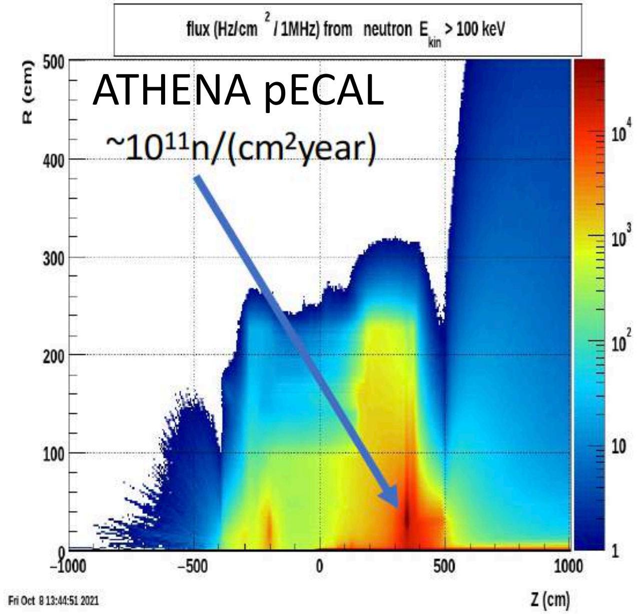
Iteration 1, Jan. 7 2022
Calibration run.

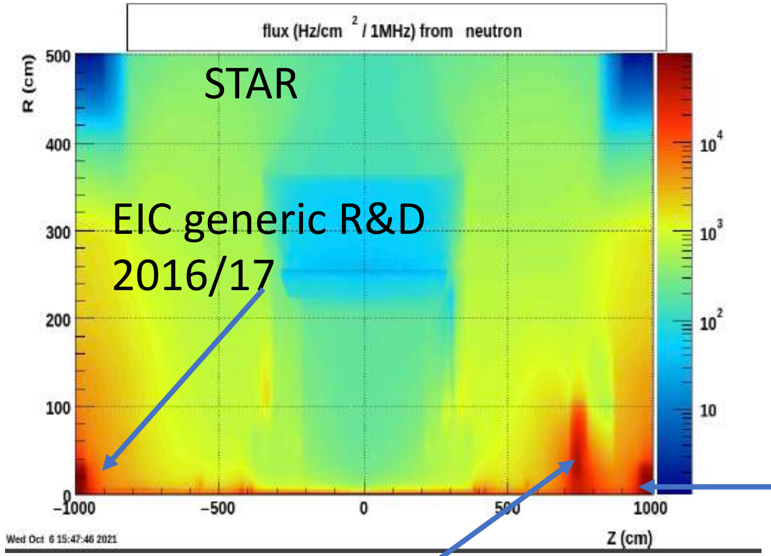
Good pi0 peak in all Ecal towers

Detector was uniform +-10% from the box.

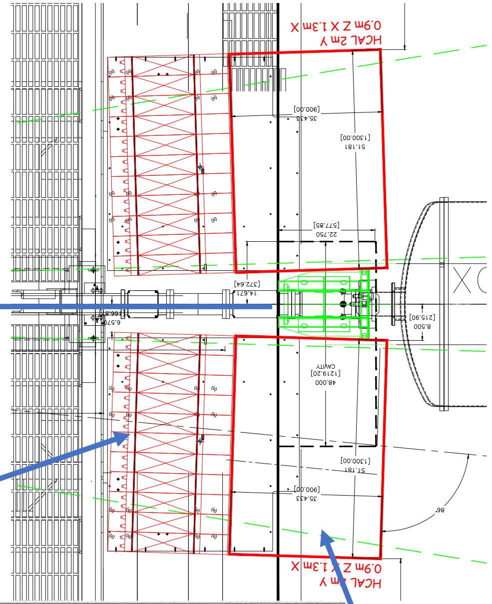
It is so much easier to do everything with SiPMs compare to PMTs.

But, SiPMs and neutrons are not friends ☹

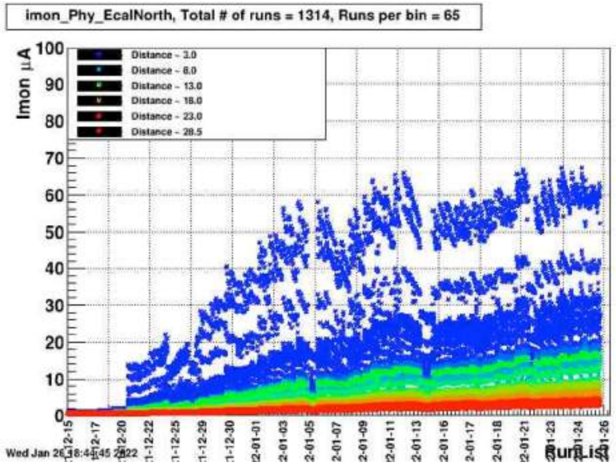




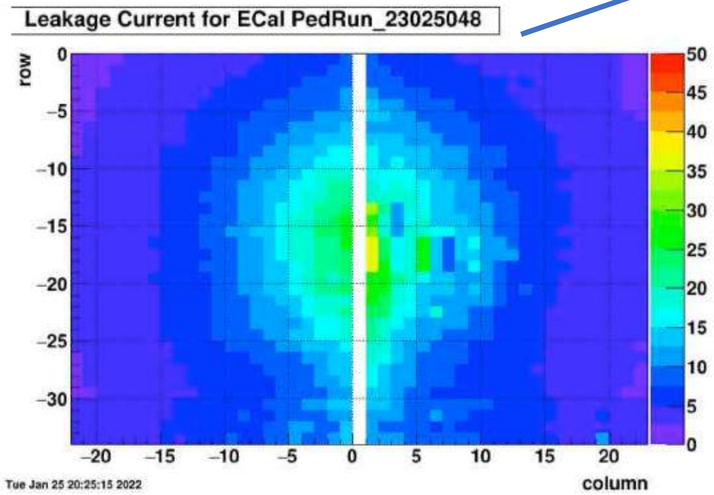
FCS uses more than 10k SiPMs
mostly S12572 -15 um pixels
some are S14160-3015PS
No cooling. 23 C in HCAL, 28 C in Ecal

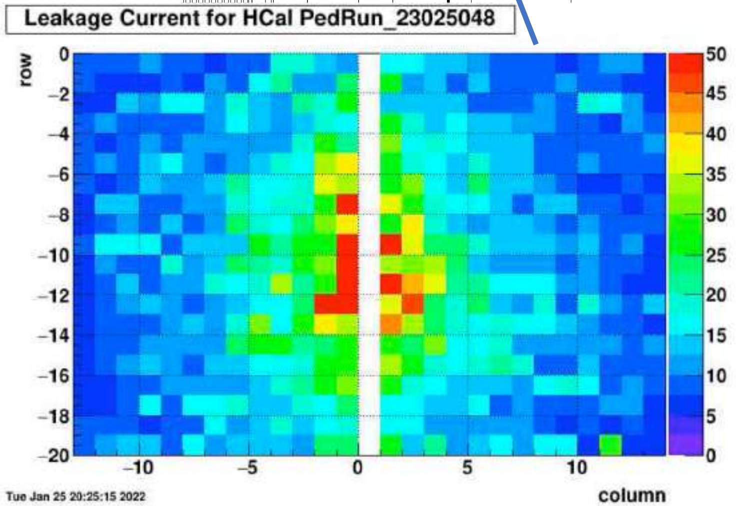


ATHENA, pEndCap high lumi n fluxes close to STAR pp 500 GeV for Forward Calorimeter System
EIC collision rate 500 kHz eP, vs STAR 5-6 MHz pp, but STAR FCS is ~ 7m from IP compare to EIC at 3.5 m
ATHENA n,bECal (Hcal) ~ 10^9 n(cm²year) (Plots from Y. Fisyak (BNL))



Physics Runs



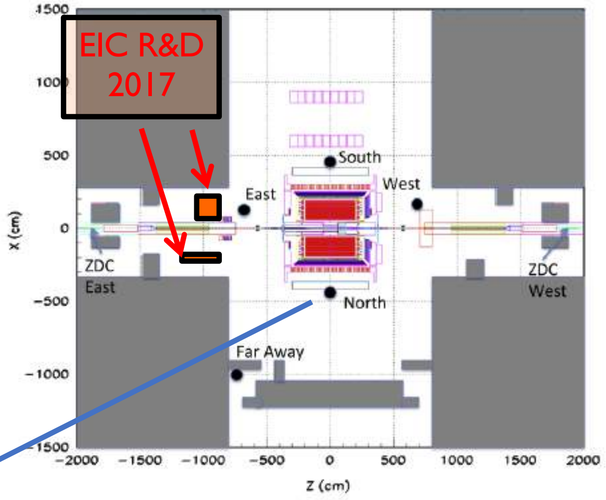


2m

Pedestal Run

6m

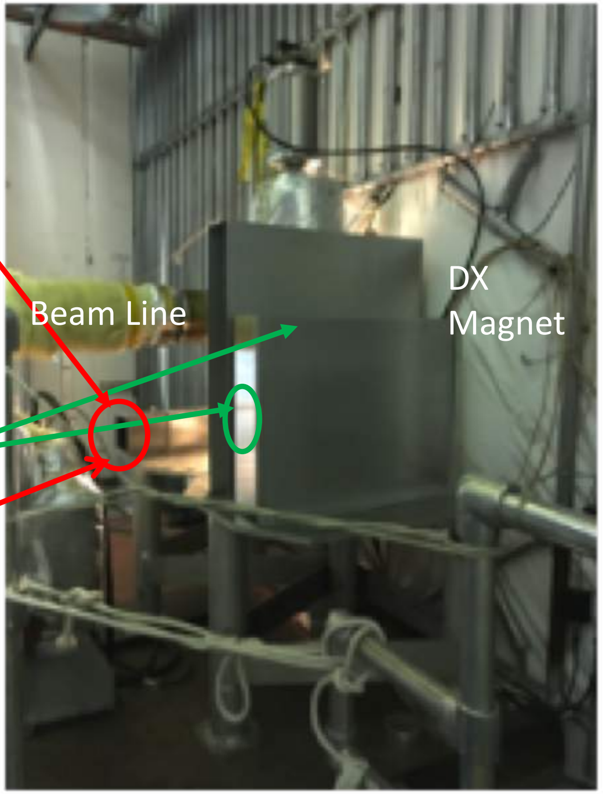
Large sample of SiPMs exposed in Run17 at RHIC STAR IP

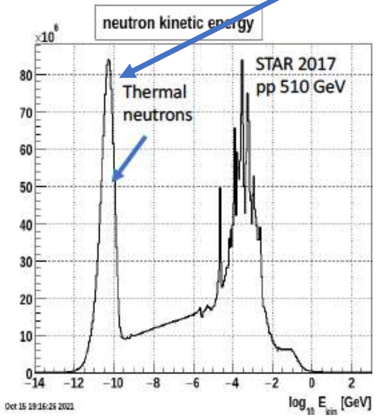


Y.Fisyak, et.al NIM A756

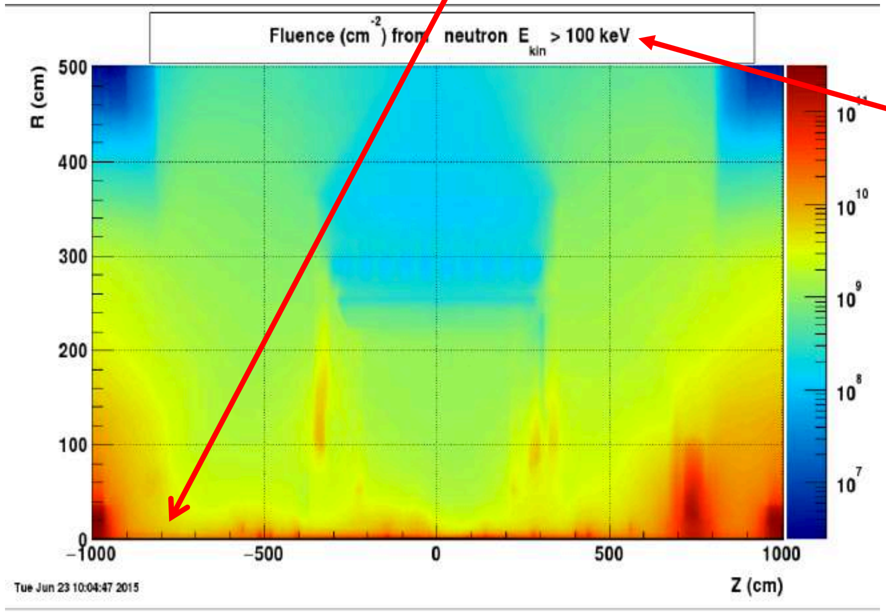
EIC, Run 17 STAR IP:

- 152 SiPM at ~135 cm (since Feb.) . All in Volume 10 x 10 x 2.5cm^3
- 26 SiPMs at ~45 cm (since April)
- APDs at ~45 cm, (since April)

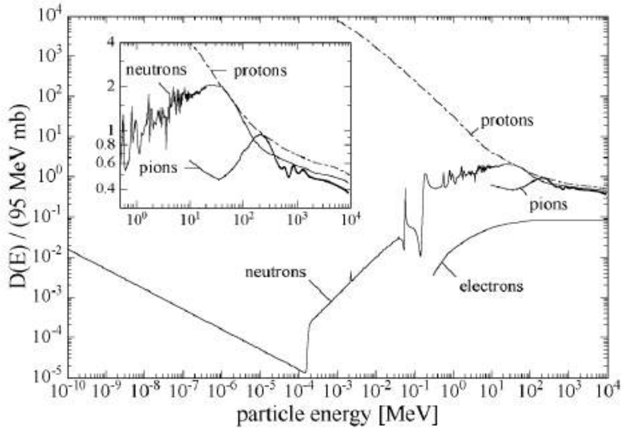


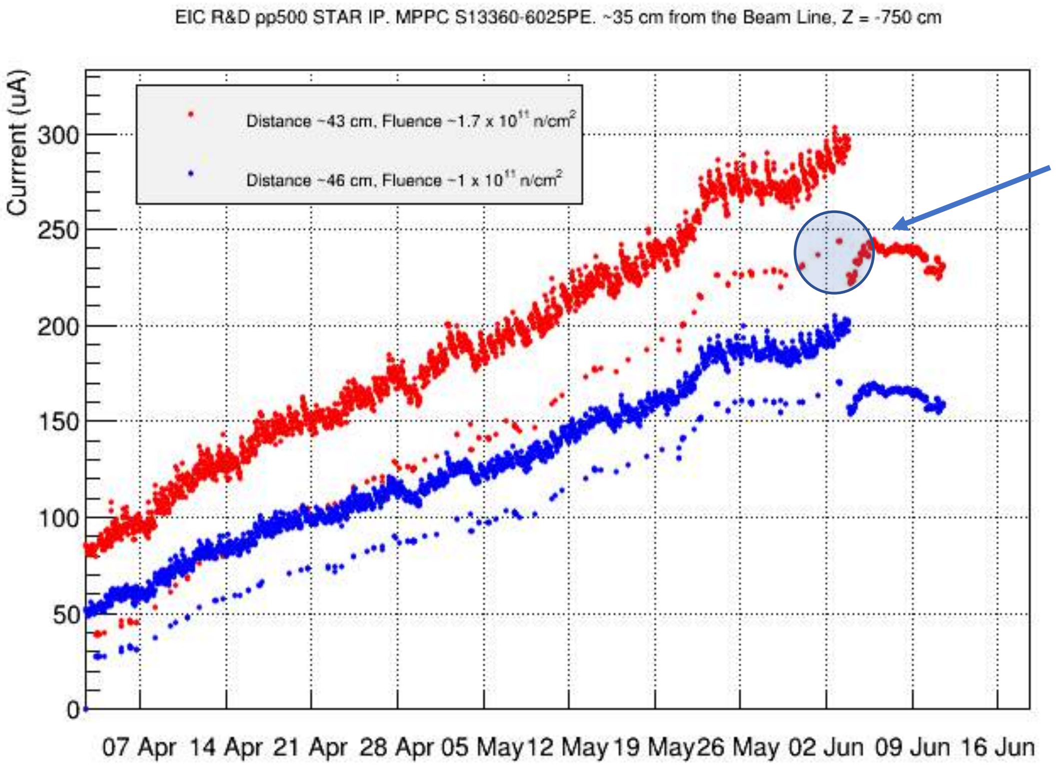


FEMC Run16, Run17

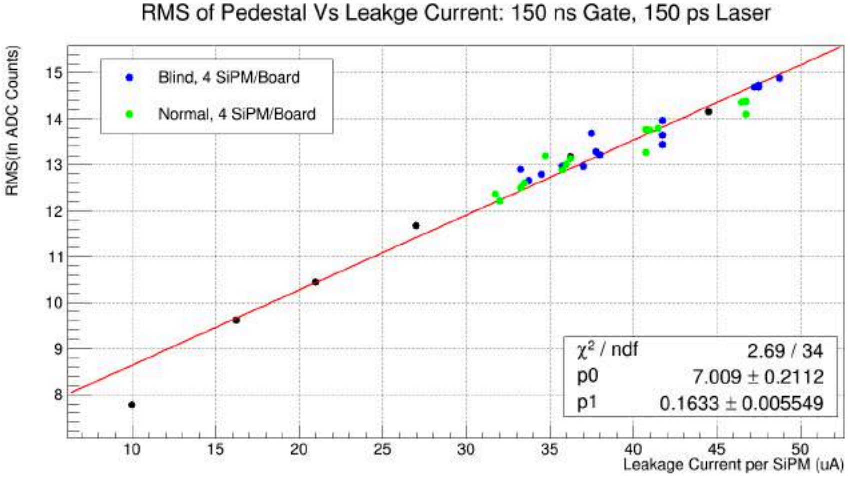


To accurately calculate damages this is probably not enough. Damage function for protons, pions etc. had to be included.

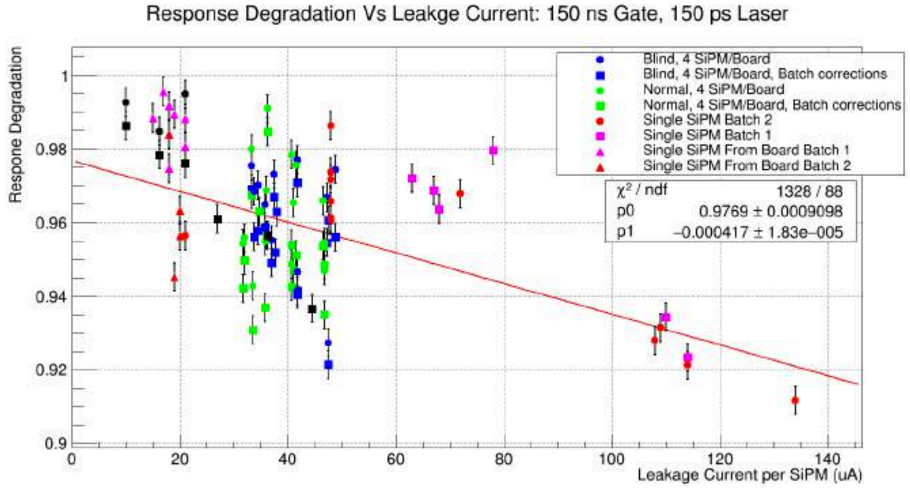




Defects accumulates -> Leakage current grows, roughly ~ delivered lumi.
Annealing at room temperature (~ 27 C) between pp and AuAu running

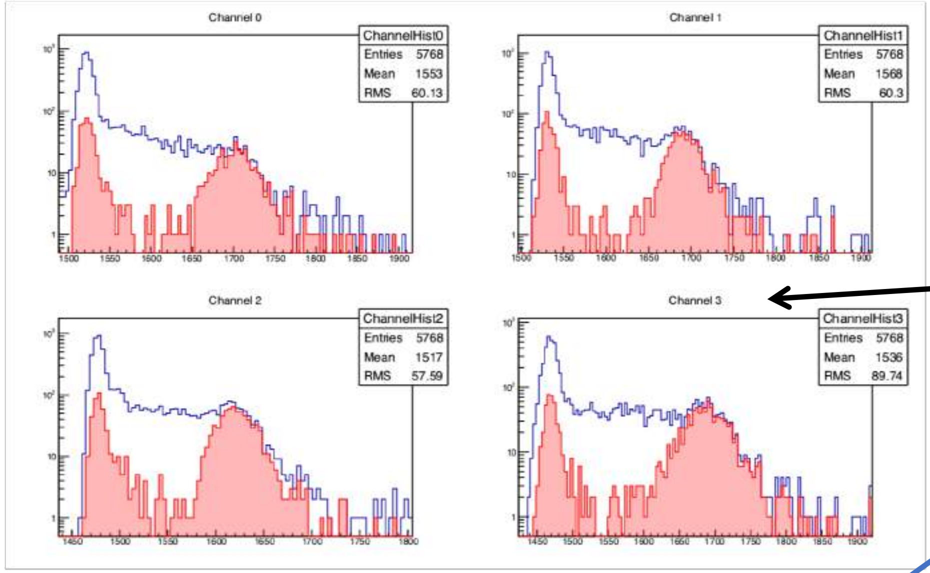


Noise grows linearly with leakage current



Very concerning observation that SiPMs under same irradiation (leakage current) degraded differently. The exact mechanism wasn't clear, worrying for **triggering** primarily and effect on **constant term**. Later investigation pointed to heating (very localized) of avalanche region by leakage current. Led to simple **requirement for FCS to keep current per SiPM below 100 uA.** (Backup slides)

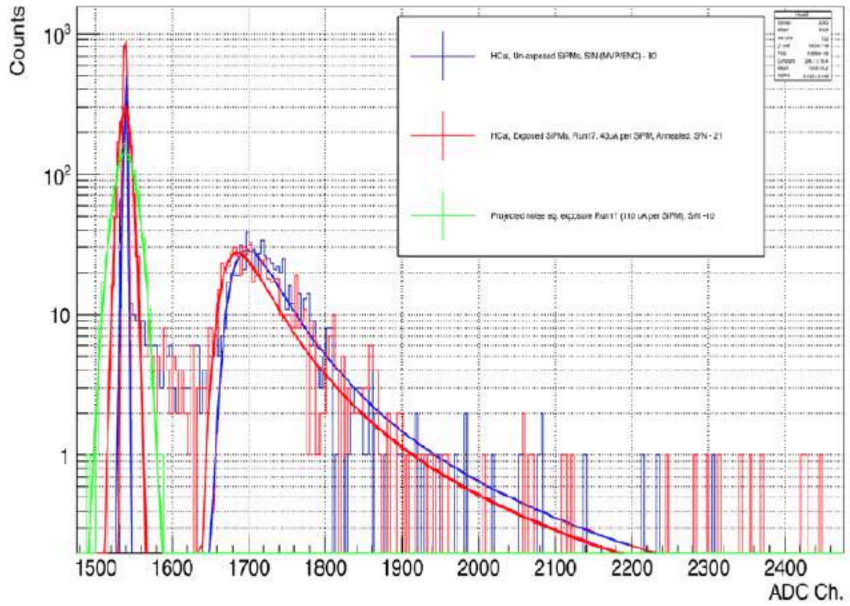
Back to main concern, Noise. R&D 2017, Shashlyk S12572-15 four 3x3 mm SiPMs per tower.



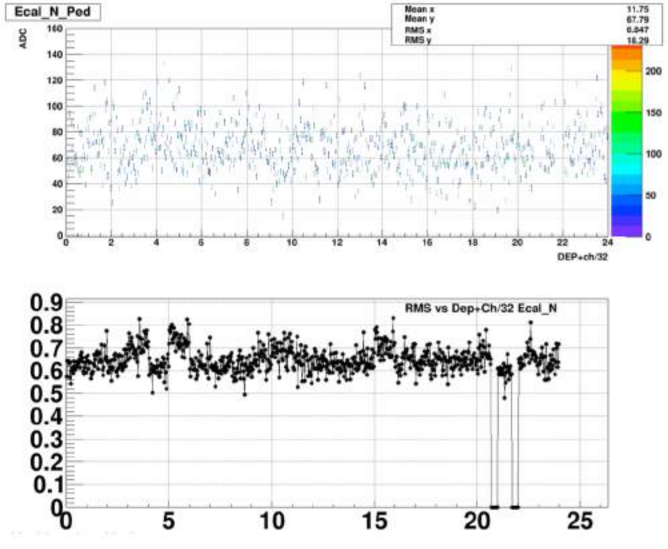
Cosmic Muons with un-exposed SiPMs ENF ~ 1.7 MeV

- SiPMs Degrade with exposure (details later in talk).
- 500 GeV pp (Run 17) was the worst case in terms of exposure.
- Cosmic Muons with exposed (Run17) SiPMs, ENF – 10 MeV/tower
- Hcal (6 SiPMs/tower) noise after exposure ~ 100 MeV (100 uA per SiPM)

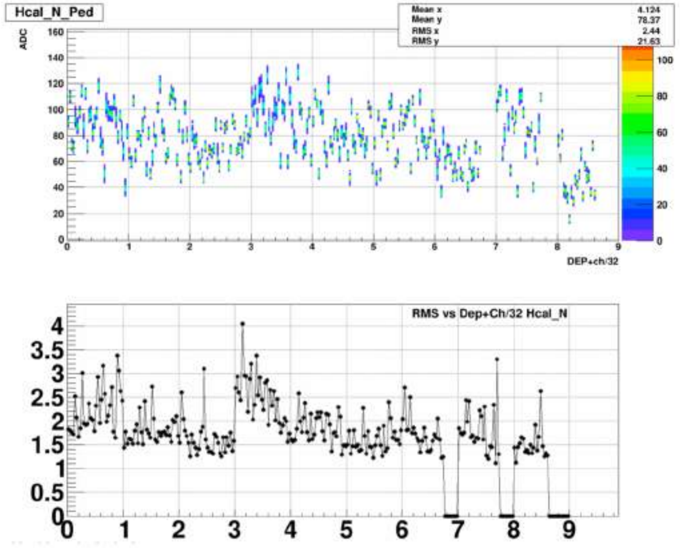
N.B. S/N depends on over bias!



FCS 2022, pp 500 GeV. Feb. 3 2022 (~ 1/3 lumi delivered)



Ecal Noise ~ 3 MeV



HCal Noise ~ 16 MeV

How that related to EIC?

Some requirements in YR looks tough,

Sub-system	Readout Unit	Minimal Energy YR Table 10.6	Minimal Practical	Maximum Energy YR Inclusive	Signal Range
n-EMCal PWO	Tower	50 MeV	2.5 MeV	20 GeV	5-100k pixels
n-EMCal SC Glass	Tower	50 MeV	2.5 MeV	20 GeV	5-100k pixels
n-Hcal (KLM type) (10 layers)	Scint. Tile (individual tile)	500 MeV	0.1 MeV	20 GeV	10-200 pixels
p-EMCal	Tower (sum all fibers)	100 MeV	5 MeV	100 GeV	5-60k pixels
p-Hcal	Tower (sum 51 tiles)	500 MeV	300 MeV	100 GeV	50-20k pixels
b-Hcal (KLM Type) (5 layers)	Scint. Tile (individual tile)	500 MeV	0.1 MeV	10 GeV	10-200 pixels
b-Ecal (ScFI part)	Sub-Layer (one light guide)	50 MeV	2.5 MeV	50 GeV	90-40k pixels
b-Ecal (Si layers)	Pixel	50 MeV	2.5 MeV		

eRD 105

eRD 106

Is it justified?

Table 10.6 YR – requirements table. pEMcal – min. energy 100 MeV. EM cluster – side tower 5 MeV

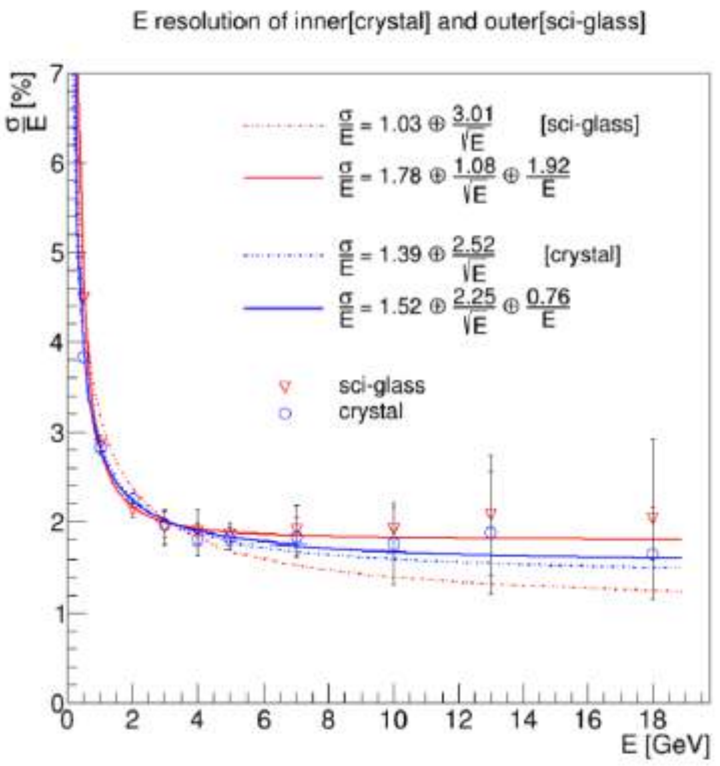
For many reasons we want to keep S_F in pECal (WScFi) at ~ 2.8% and not at 12%

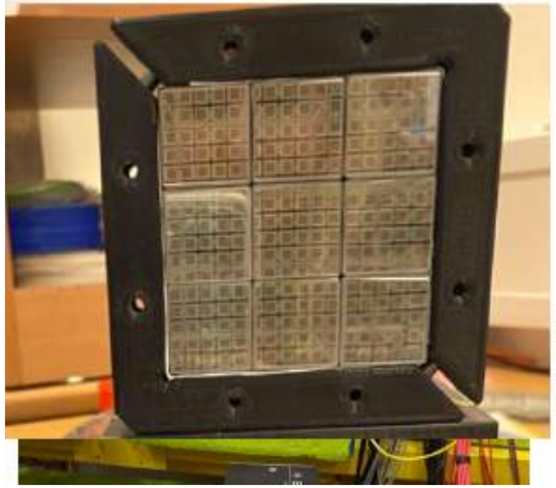
Light Yield at 1000 p.e./GeV is possible with SiPMs (that will be close to previous example), BUT we need to move from 3x3 SiPMs to 6x6 SiPMs -> Noise may reach 2 x 10 MeV = 20 MeV Unless one start to cool SiPMs S/N what is listed in 10.6 not reachable.

And during discussions at ATHENA calor meetings it was not clear at all what is justification for 100 MeV minimal energy in pECal?

eRD106 is for pECal (tied with eRD107 pHCal).

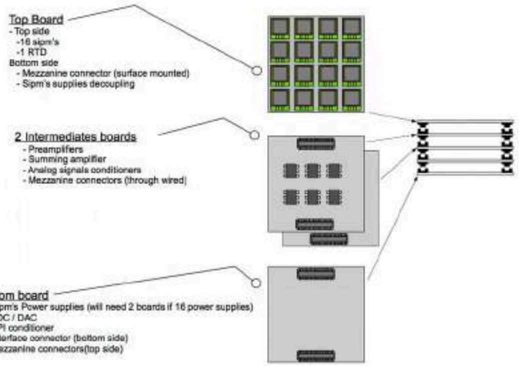
EEEMCAL Consortia. PWO + SciGalss eRD105
High resolution Emcal with SiPM readout.

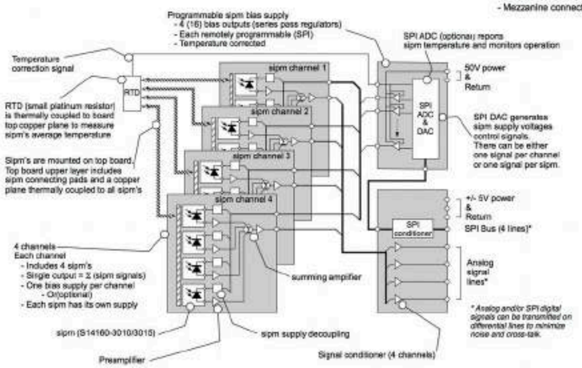




Goal of the tests: Optimize and test SiPM matrix readout chain with new generation PWO crystals

- CRYTUR USA concept
- 9 CRYTUR crystals
- 16 SiPMs per crystal
- 3x3 mm^2 SiPMs
- ~90k cells per SiPM
- Plug-n-play prototype
- First working RO version for EIC





- Direct performance comparison with 3x3 PMT version, INFN SiPM version
- Energy resolution studies
- Noise studies
- Light collection studies
- Linearity studies
- Threshold studies

20

N	Layout	Photosensor	GlueX Run	Energy, GeV	ER, % raw	ER,% calib
1	PWO+PMT	PMT Hamamatsu R4125-01	81386	4.698+-0.013	2.1%	1.8%
2	PWO+SiPM (INFN RO)	SIPM Hamamatsu S13360-6025CS	81518	4.698+-0.013	2.3%	2.1%
3	PWO+SiPM (CRYTUR RO)	SIPM Hamamatsu	81704	5.504+-0.013	-	-

https://indico.bnl.gov/event/14655/contributions/59753/attachments/39598/65689/Berdnikov_EEEMCAL.pdf

In process of testing both PWO and SciGlass with SiPM matrix, single 6x6 SiPM at 4.6 GeV shows good result,
Going to 20 GeV requires 4x4 matrix of 3 x 3 15 um SiPMs.
Roughly to keep stochastic term at 2% probably need to ~ 10k pixels/GeV light collection efficiency, with such LY and lower n fluxes (10^9) compare to hadron endcap area, noise due to rad damages does not look like a big concern. Concern about constant term, i.e. calibration of 4 channels per tower.

SiPMs for calorimetry in eRD110 proposal.

In FY22 plan was to develop needed FEEs for pECal for 6x6 SiPMs, and 16 ch board to match EMcal superblock (eRD106). Production of these boards was assumed in FY23 (eRD106).

As part of eRD110 plan was to submit request in FY23 to buy needed SiPMs. Produce SiPM curry boards, get them exposed. (possible to expose sensors only, then make boards, but as we learned with standard reflow soldering annealing is about 50%)
After that compare response of detector with fresh and exposed boards (same approach used for FCS).

All needed information (S/N) can be obtained with cosmics, no need to get to a test run. Although it was also planned a test Run late in FY23, where irradiated boards can be used as well.

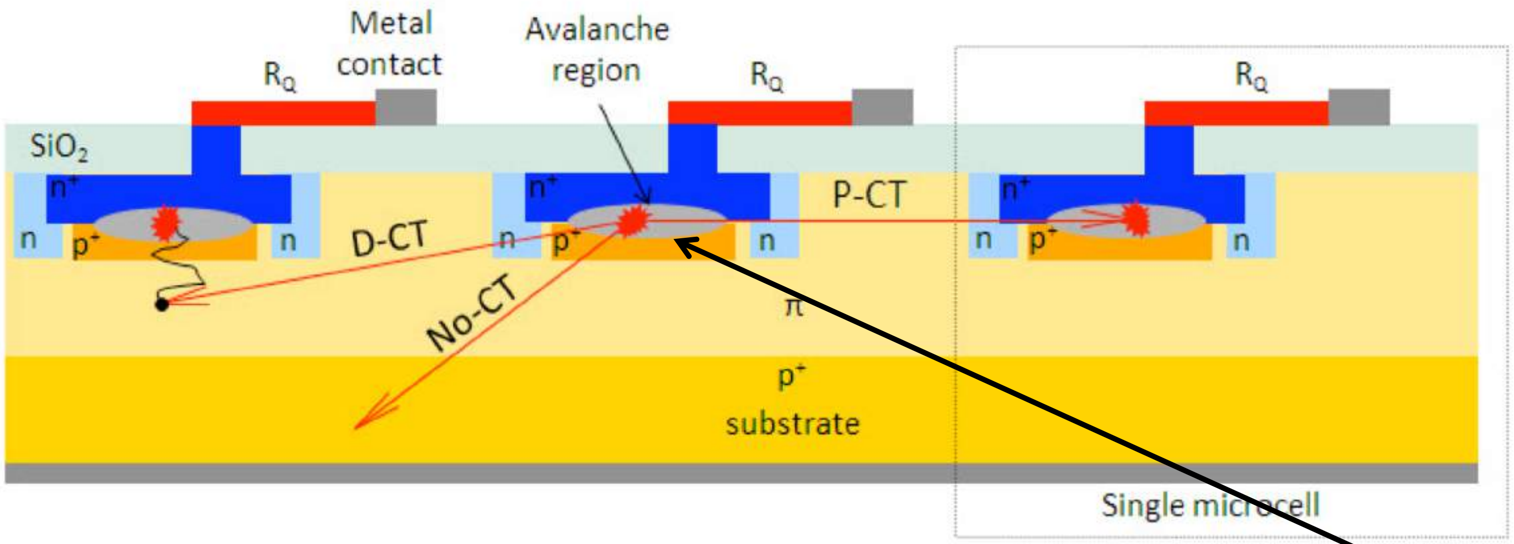
- We used RHIC/STAR to do SiPM/APD/calorimetry studies in 2016/17, which was very useful for both EIC and STAR FCS.
- East side of STAR has plenty of space to do such studies until 2025.
- STAR management was very supportive in the past and I expect if needed we can count on this in future.

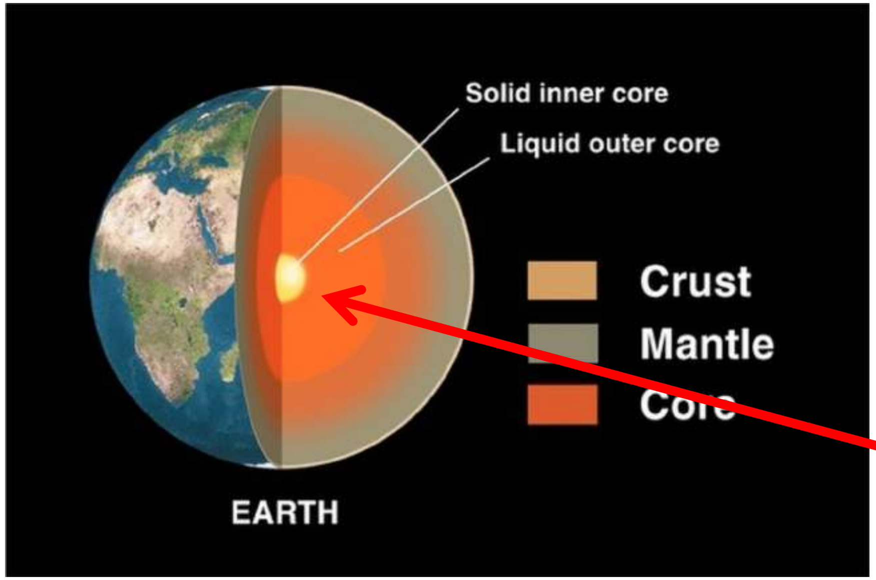
Summary (2018) eRD1 EIC generic R&D

Effects of degradation of SiPMs observed during Run17 have been understood:

- Combination of leakage current (due to radiation damages) and signal current from calorimeter light heats junction of the sensors, which leads to increase in Vbd, which leads to degradation of response.
- Differential degradation (variation from sensors to sensors) probably is due to different overvoltage required to achieve same response.
- **New HPK sensors are superior to previous versions. Degradation of response for these sensors due to irradiation at forward rapidities at EIC will be very small (~1% level) for Forward Calorimeter.**
- There is a hope that this can be improved in future, for example, SensL SiPMs has even lower T dependence, lower operation voltage as well. And seemingly HPK is moving in this directions (last three generation of SiPMs).

Backup Slides



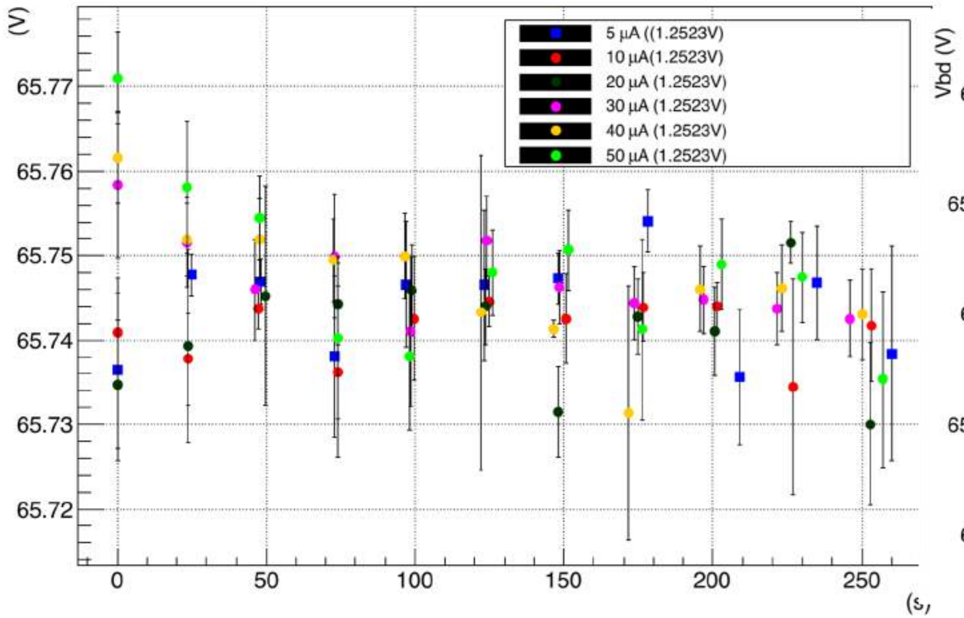


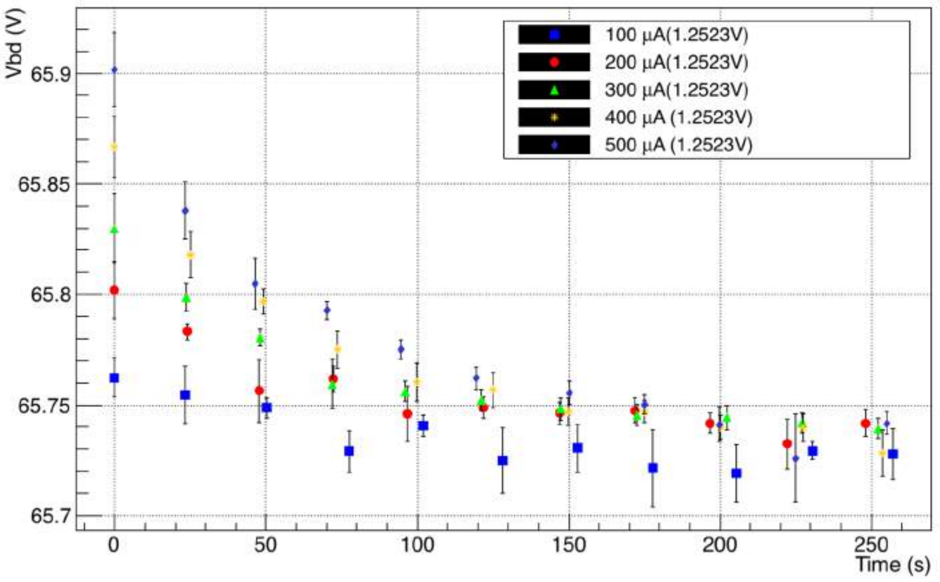
What is T over there at experimental conditions? (exposure + signal current)

Estimated T ~ 6000 C

Estimated @10 MHz dark noise, 5 um thick layer, 5V overvoltage, no heat dissipation. T rises ~1 deg/sec

Vbd vs Time. Cool down Starts at 0.

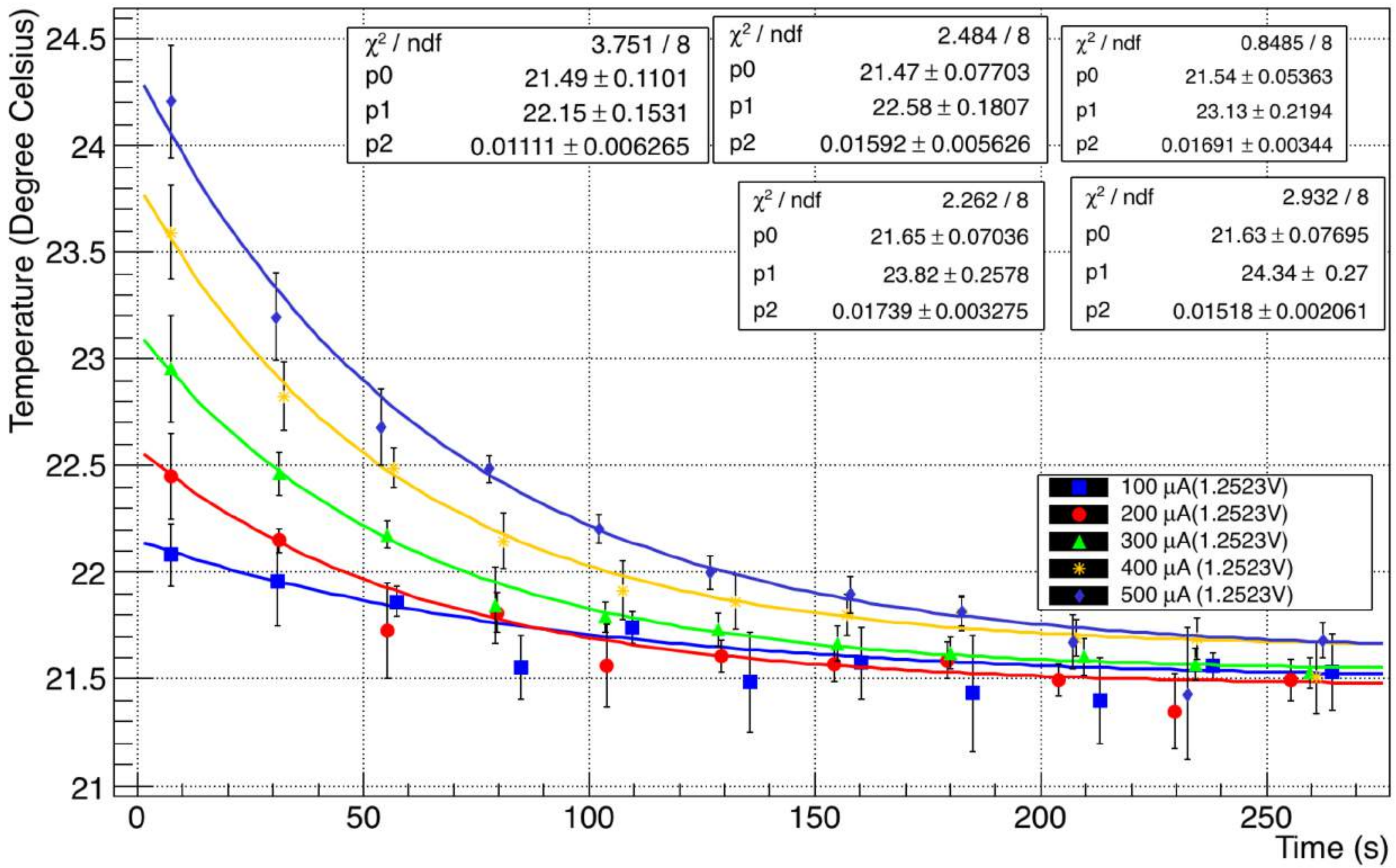




SiPM kept 5 min at highets over votage for IV scan (1.25V) with specified current, then series of IV scans taken.

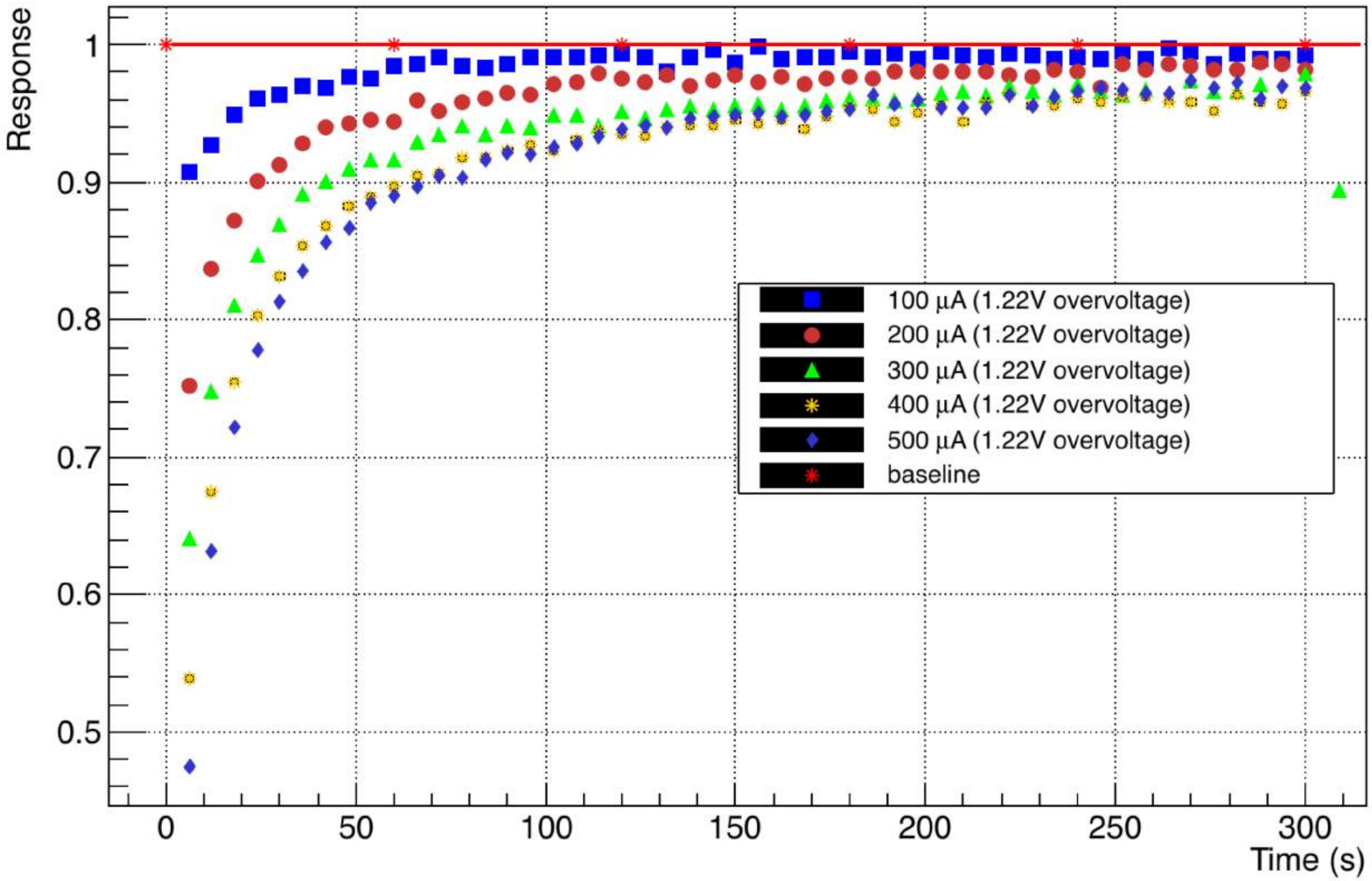
'Preheating' with 30-40 uA current – already shows hints that Vbd changes.

- SiPM kept 5 min at highest over voltage for IV scan (1.25V) with specified current. HeatUp
- IV scans taken with 20uA highest current. Cooldown.



- Knowing Vbd vs T (slide 4) we can calculate T in junction vs time.
- Fit with Newton's law of cooling (p1 – junction temperature at t=0, p0- ambient temperature. t=0 - time when LED intensity switched to low for IV scans)
- Example, for 100 uA steady current at experiment, T on junction increases ~ 0.6 degrees C above ambient 21.5 C.

- Another approach, measure response. Same method, preheat with LED, switch LED Off, measure response with very low intensity laser. (N.B. different setup, electronics)



SiPMs un-pleasant properties:

a) Response degrades with increased current flowing through SiPM (dark noise due to rad damages + from primary interaction (light from calorimeter), which heats junction). Expect up to 10% change for EIC Forward.

b) It may be large variations across forward calorimeter surface.

c) Possibly, each SiPM will degrade differently.

T compensation in Vbias does not handle this!

T on junction depends on current, which depends on

- location
- luminosity time profile
- integrated exposure
- ambient temperature
- overvoltage SiPM operates at

Partial hardware solutions for S12572 type:

a) Switch to 15 um sensors will help (lower gain)

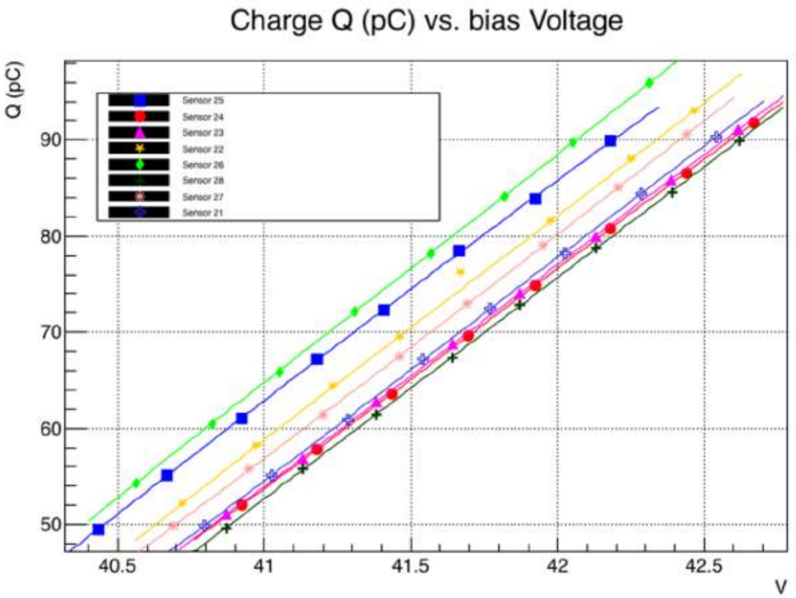
b) Carefully chose operation bias. (Depends on LY in calorimeter, S/N).

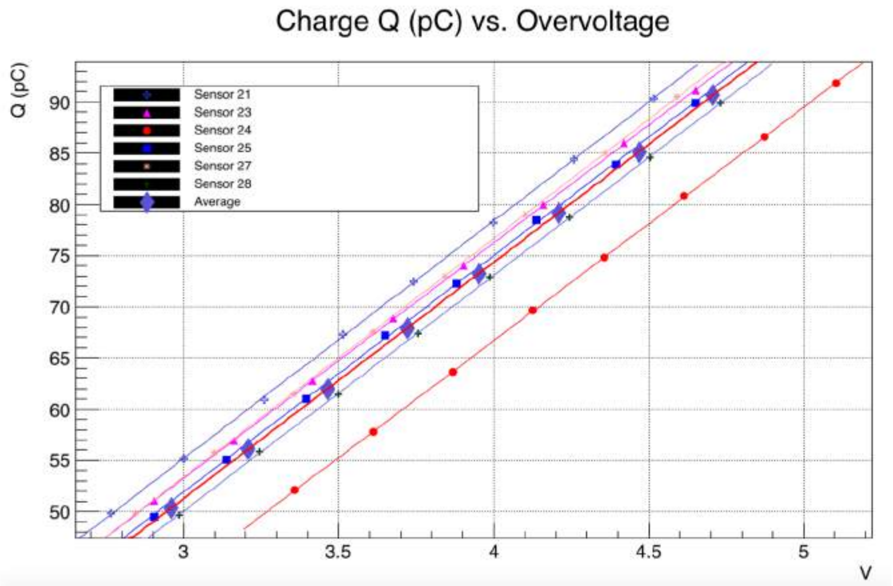
c) Make sure, monitoring (interleaved with data, had to be taken at same average current flowing), i.e. LED runs between fills may not work well).

Efficient cooling for SiPMs, keep delta T (junction ambient) high, reduce leakage current etc. -> lots of complications with integration on the detector.

New HPK sensors, **HDR2-3x3mm-15um** got 8 sensors for tests early summer.
Characterized:

- response vs bias (before/after irradiation)
- Vbd, Vbd vs temperature
- Run similar tests as for S12572-025P, heating with LED – relaxation.

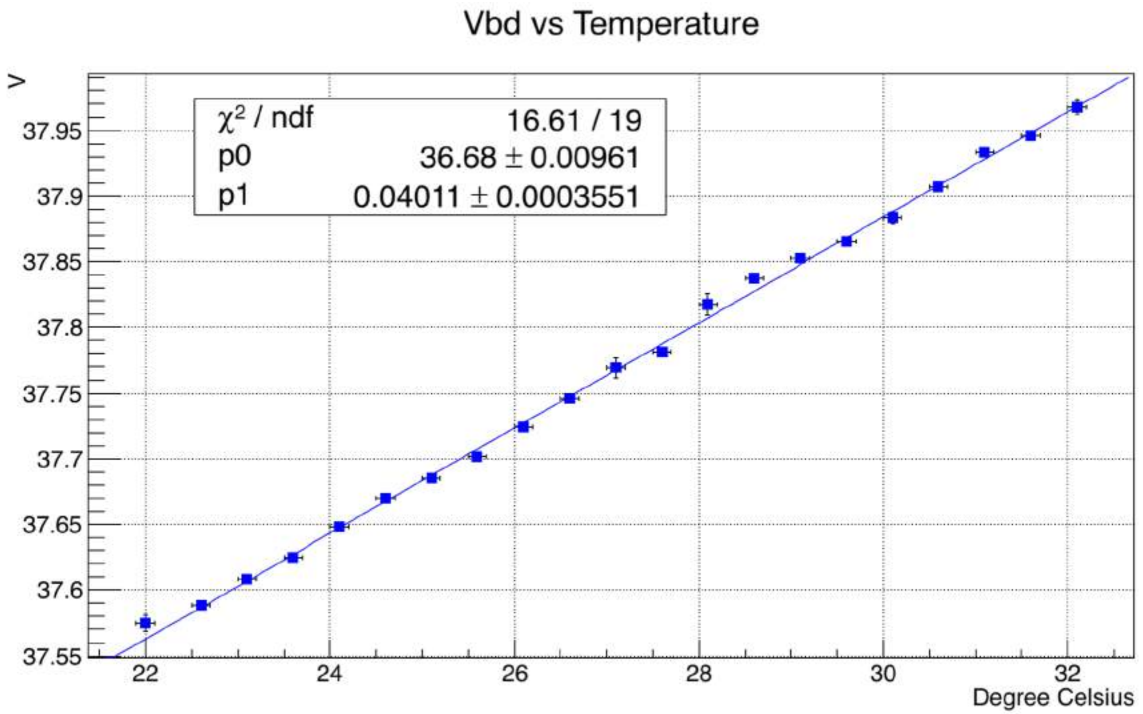




Compare to Old SiPMS:

- Vop is ~20V lower
- Spread from sensor to sensor (overvoltage) to get same response for laser is about the same as for old devices (GlueX has large statistics).
- N.B. this spread possibly is a reason for differential response degradation in Run17 (sensors with same leakage current degrades differently, Slide 3).

- New HPK senasors, HDR2-3x3mm-15um, Vbd vs T – Improved!



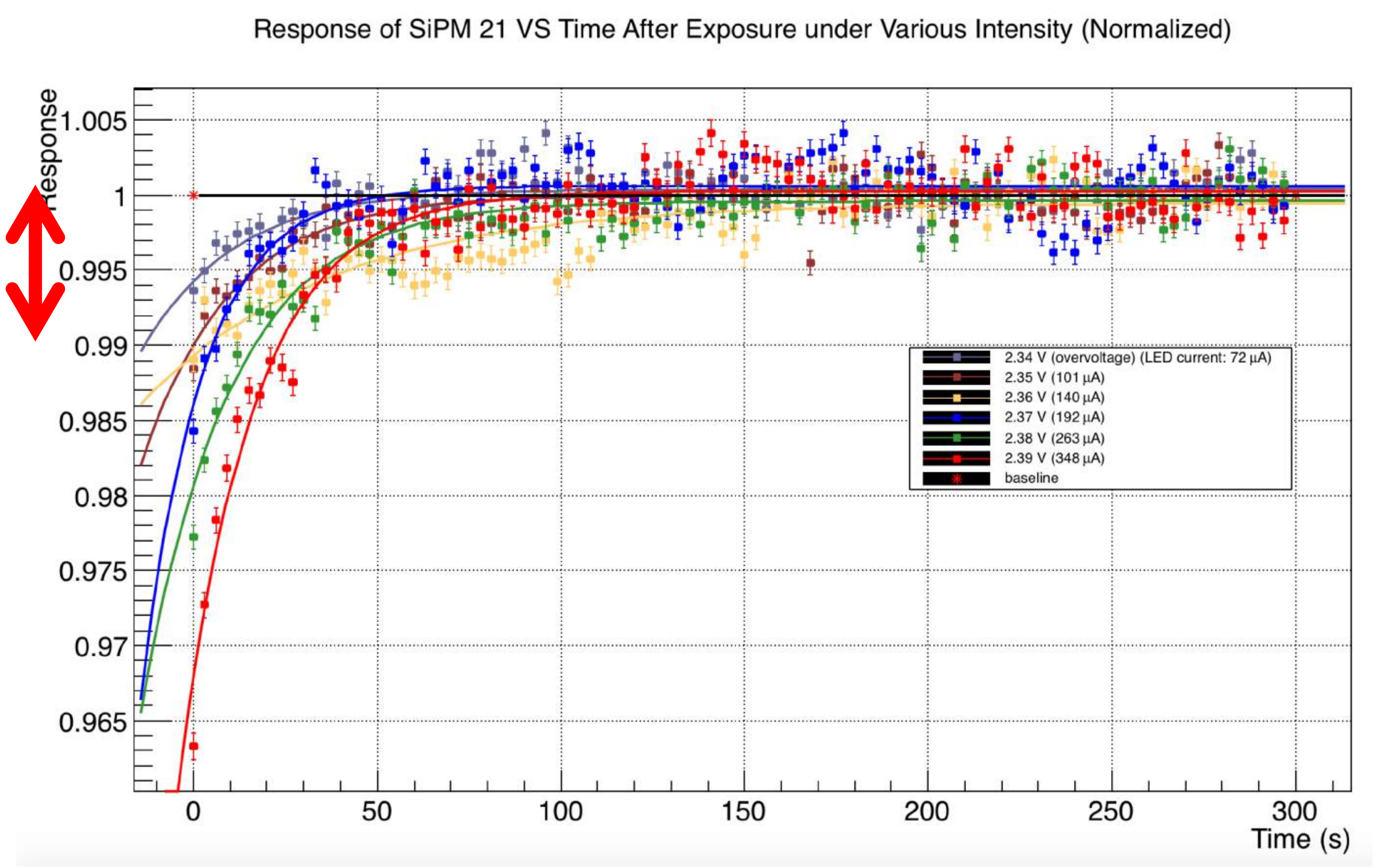
■ Electrical and optical characteristics

(Typ. T = 25 deg. C, Vr = Vop unless otherwise noted)

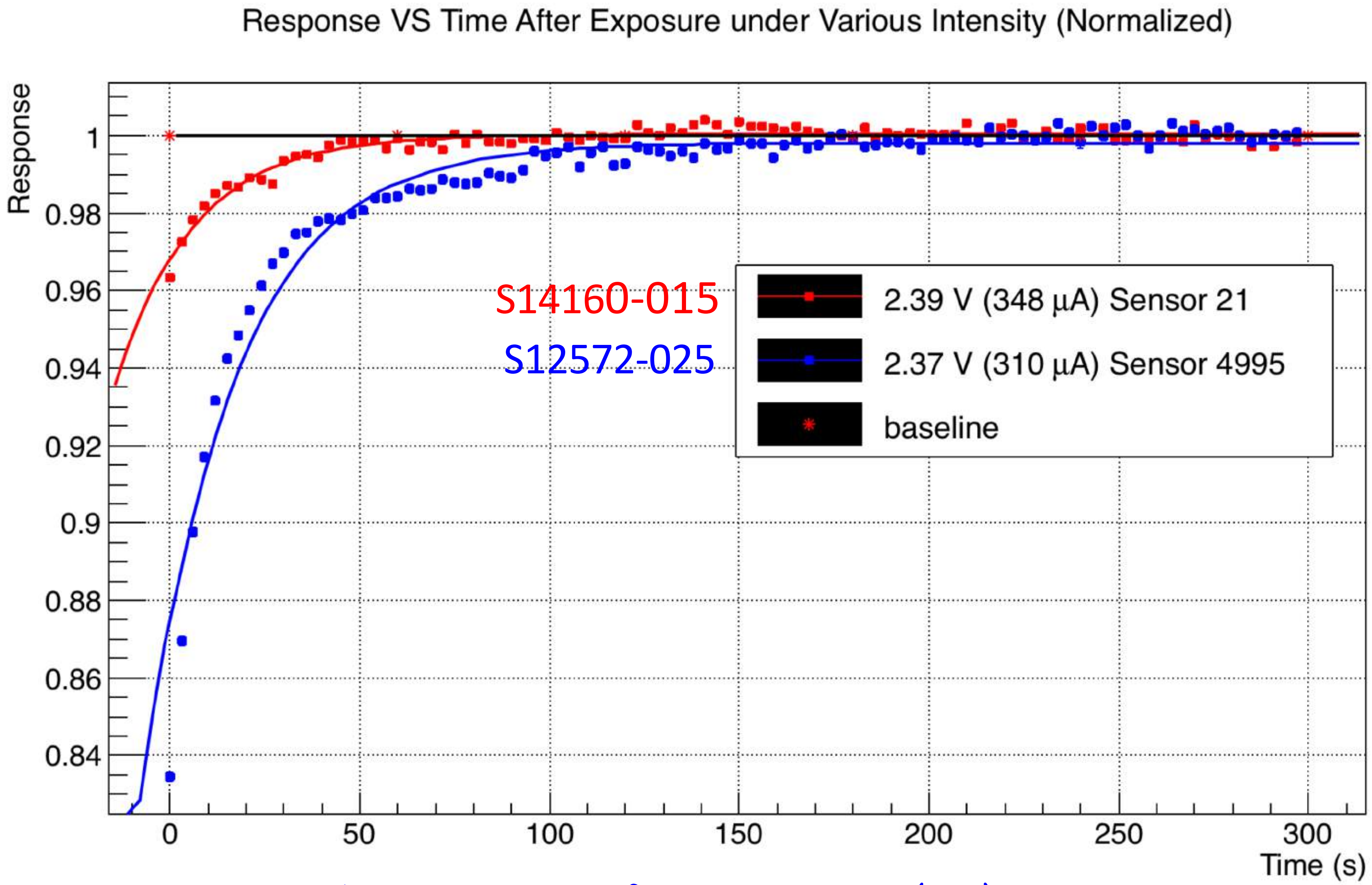
Parameters	Symbol	S14160 (typ.)				Unit
		-1310PS	-3010PS	-1315PS	-3015PS	
Spectral response range	λ	290 to 900				nm
Peak sensitivity wavelength	λp	460				nm
Photon detection efficiency at λp *3	PDE	18		32		%
Breakdown voltage *4	Vbr	38				V
Recommended operating voltage *4	Vop	Vbr + 5		Vbr + 4		V
Dark count rate	DCR	120	700	120	700	kcps
Direct Crosstalk probability	Pct	< 1				%
Terminal capacitance at Vop	Ct	100	530	100	530	pF
Gain	M	1.8×10^5		3.6×10^5		-
Temperature coefficient of Vop	Δ TVop	34				mV/deg C

*3 : Photon detection efficiency does not include crosstalk and after pulse.

- HPK released ref. data sheet on Oct 9.
- T dependence is consistent with our measurements.



- Same tests as shown in Slide 8. Much better performance.
- Changes in response due to irradiation relative to EIC forward will be within 1%



Another example, direct comparison of new S141160-015 (#21) vs old S12572_025 (#4995).