Neutron Radiation & recovery studies of SiPMs

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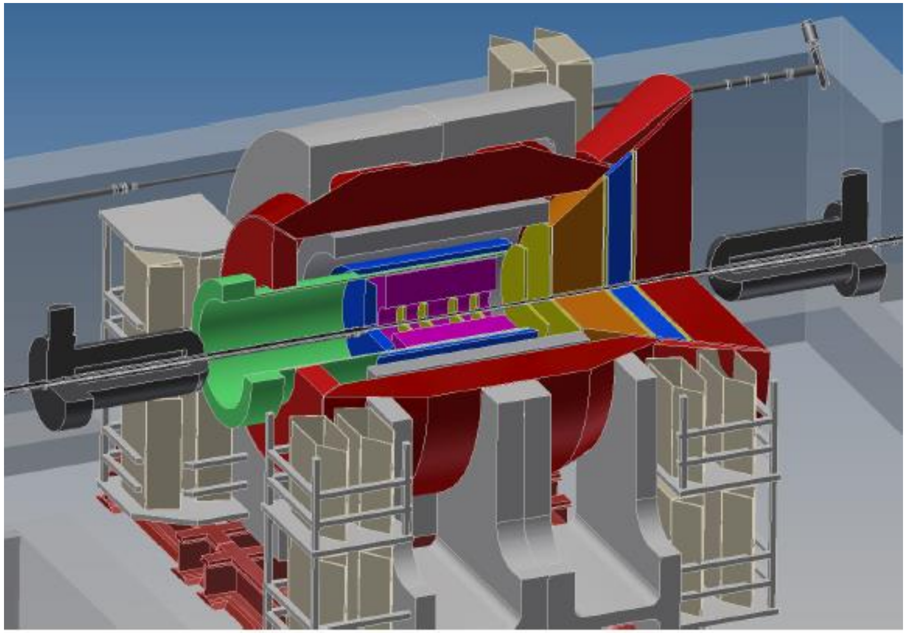
Outline

1. Main effect of neutron radiation
2. Charactization techniques:
   IV & photon-counting & PNR
1. SiPMs performance with increasing dosage
2. Recovery: thermal anneal with +I bias
3. Irradiation in LN2

SiPM in neutron radiation environment

ePHENIX

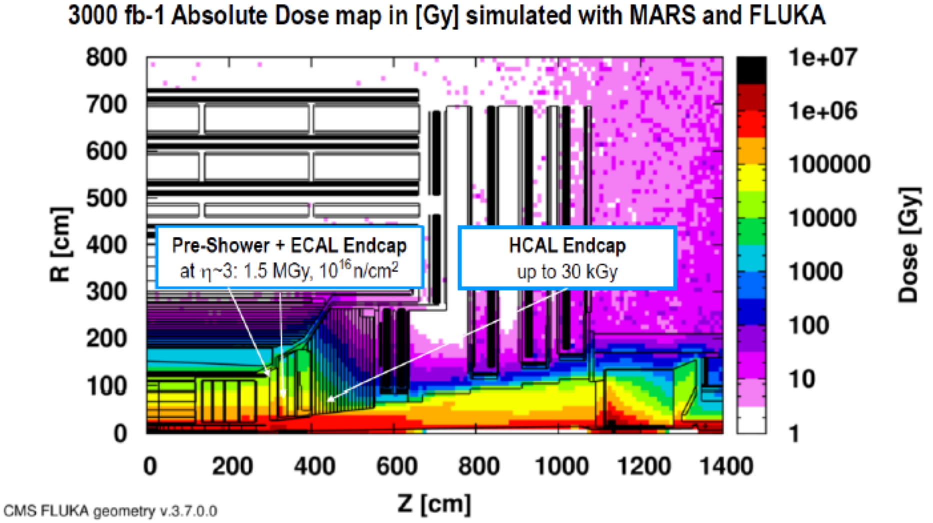


Estimates for 2013 run (L=526 pb^{-1}):

R= 3-8 cm, |Z| < 10 cm : $\Phi_{eq} \sim 8\times10^{10}$ n/cm^2

R= 100 cm, Z = 675 cm : $\Phi_{eq} \sim 2.2\times10^{10}$ n/cm^2

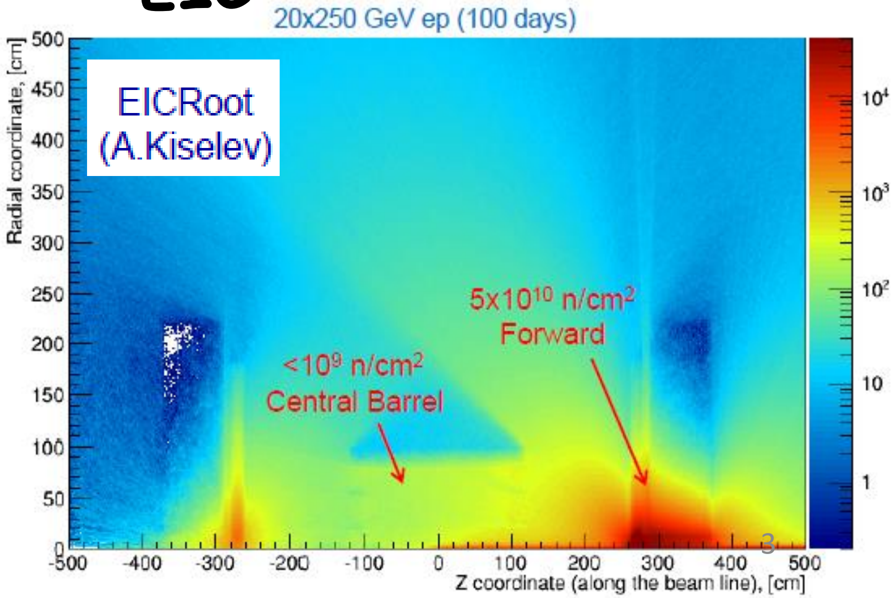
CMS



CMS FLUKA geometry v.3.7.0.0

EIC

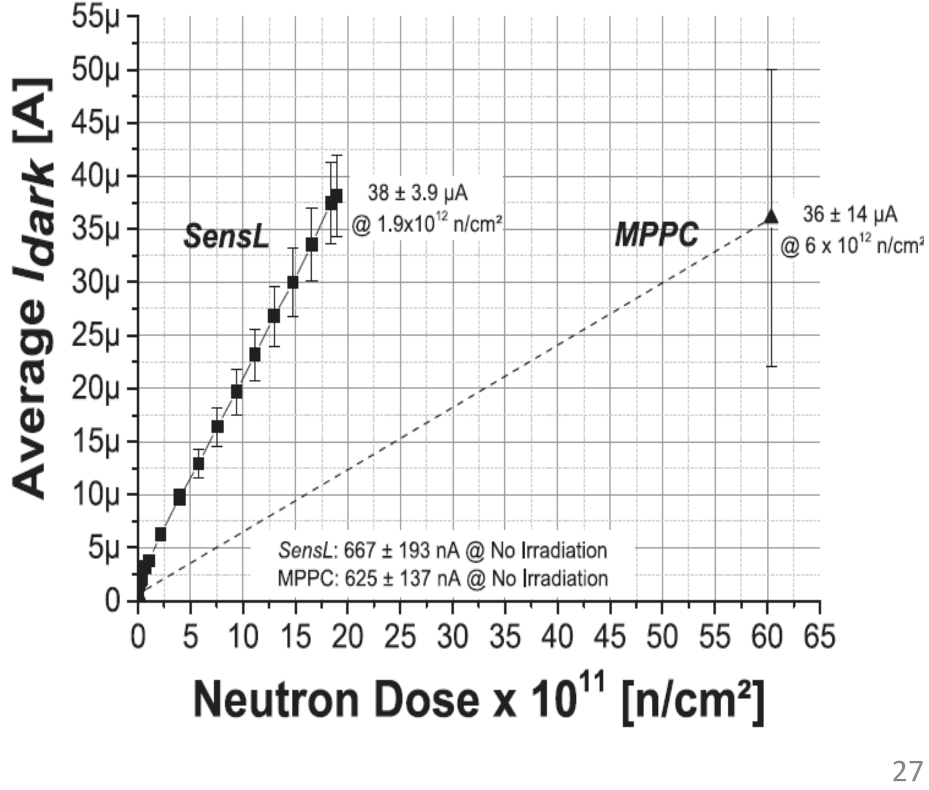
C. Ochando CALOR 2016



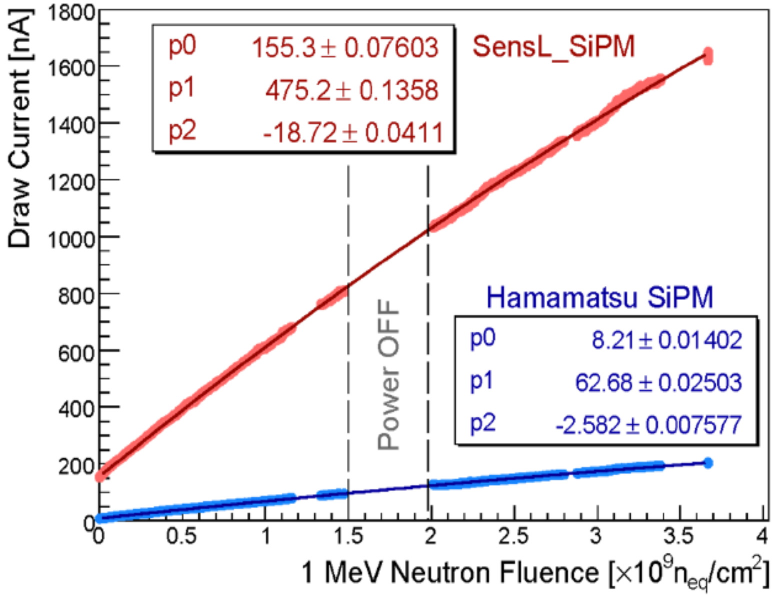
The main effect of radiation

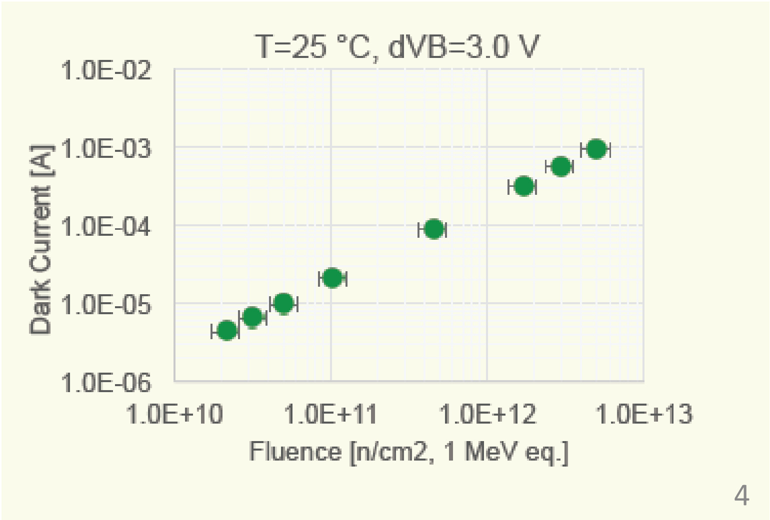
Linear increase of dark current with radiation dose.

D.Durini et.al., NIM A835, Vol 1 (2016) 99-109



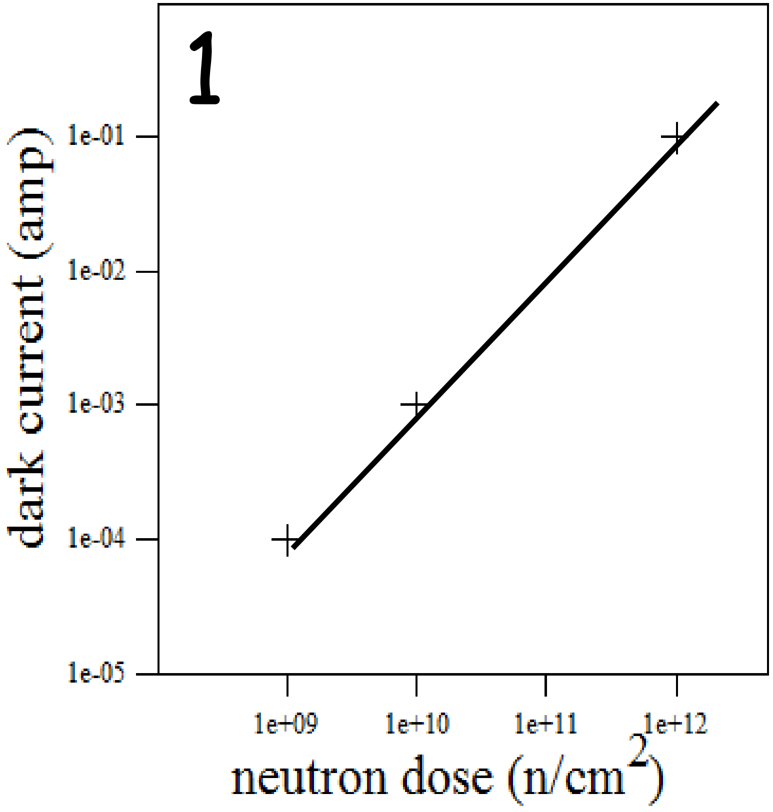
Yi Qiang. JLab





The main effect of radiation

1. Increase of dark current (Linear with dose)
2. Loss of single-photoelectron detection capability



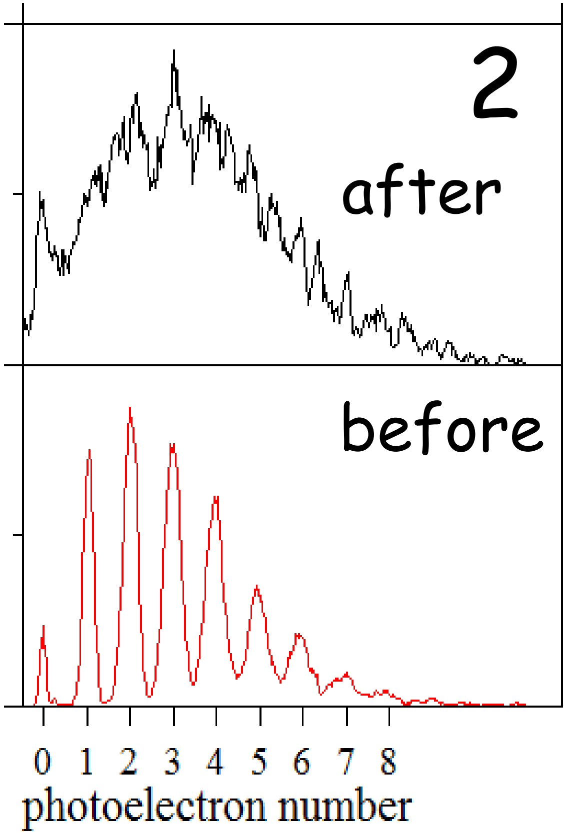
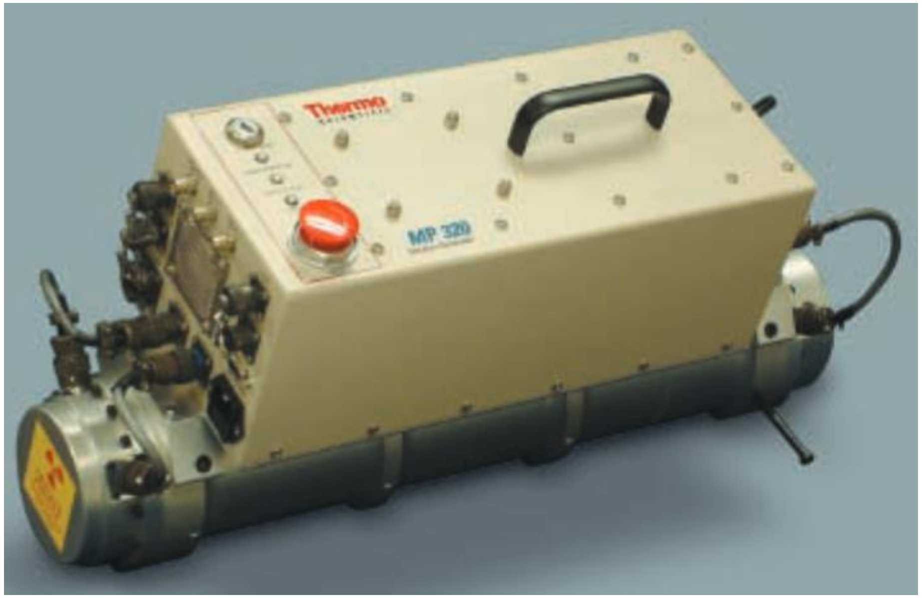


Figure of merit on SiPM are:
1. **Lowering of dark current**
2. **Goodness of p.e. spectrum and resolution**

Neutron sources

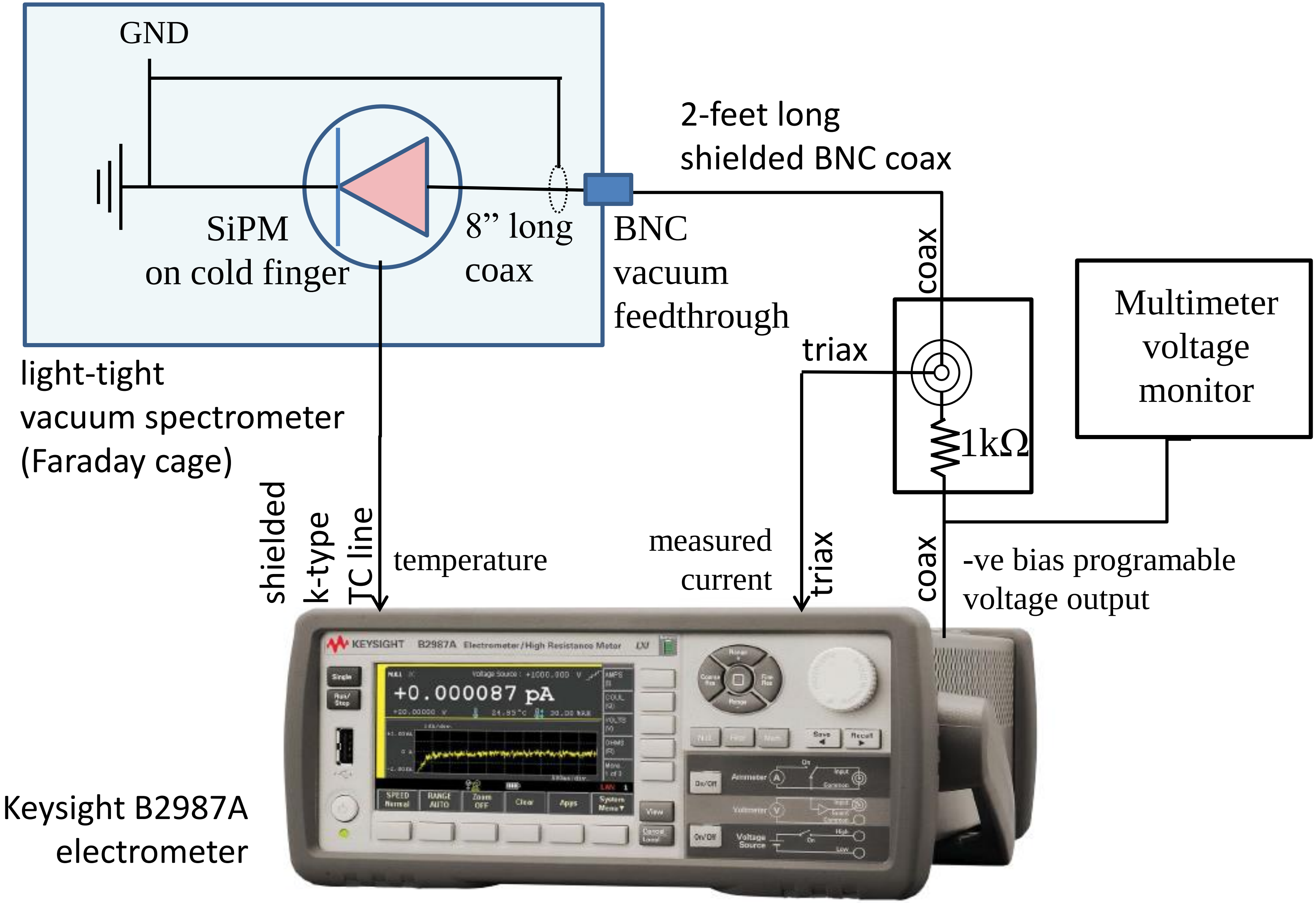
BNL Phenix detector IR region
Primarily radiation
Neutrons: 10-20 MeV



Thermo Scientific MP 320
Portable Neutron Generator
Deuterium-Tritium tube.
Neutrons: 14 MeV
(flux 10^5 neutrons/cm^2/sec)

All SiPMs are irradiated at room temperature

IV measurement setup



GND

SiPM
on cold finger

8” long
coax

BNC
vacuum
feedthrough

2-feet long
shielded BNC coax

light-tight
vacuum spectrometer
(Faraday cage)

coax

triax

1kΩ

Multimeter
voltage
monitor

shielded
k-type
TC line

temperature

measured
current

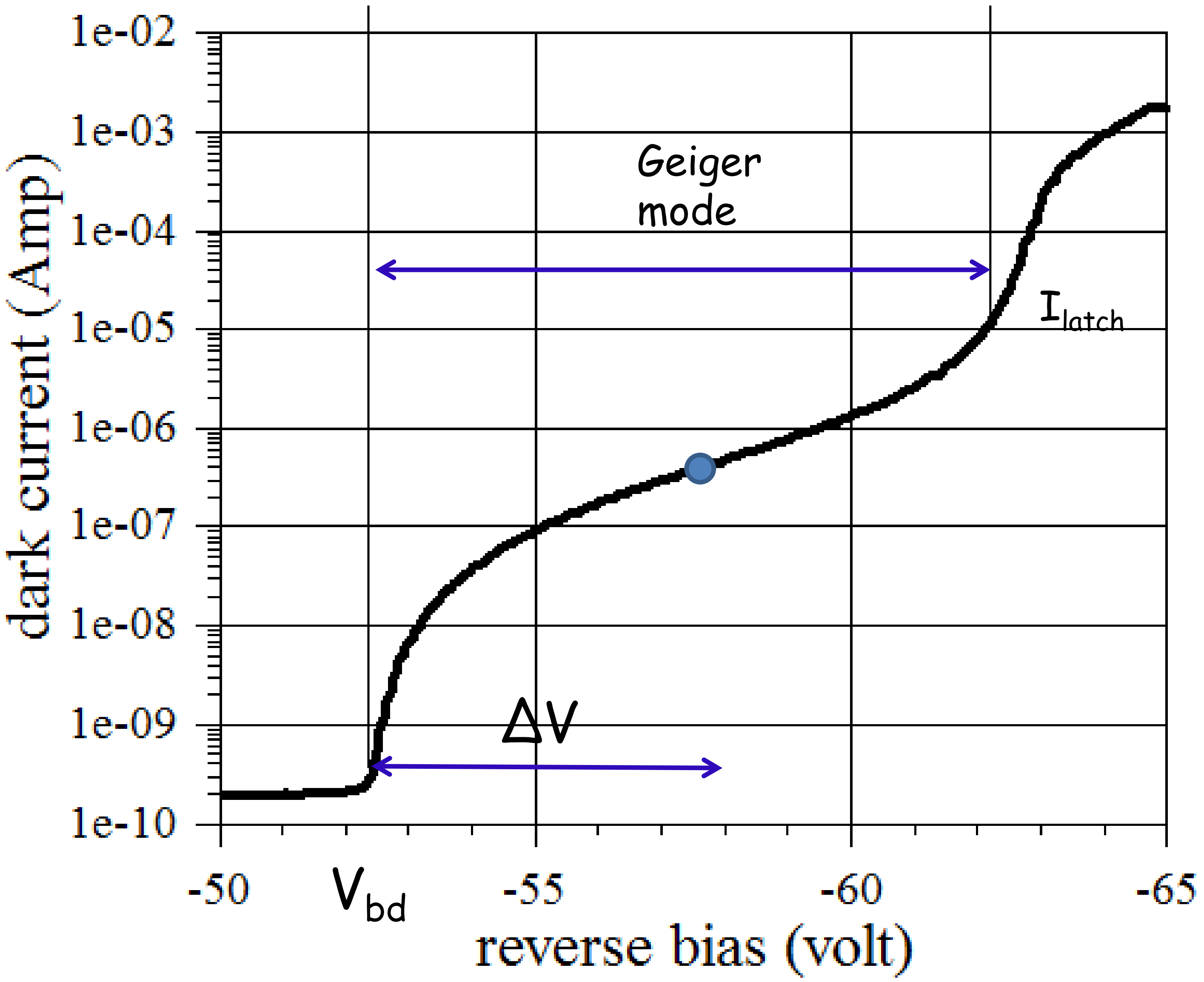
triax

coax

-ve bias programable
voltage output

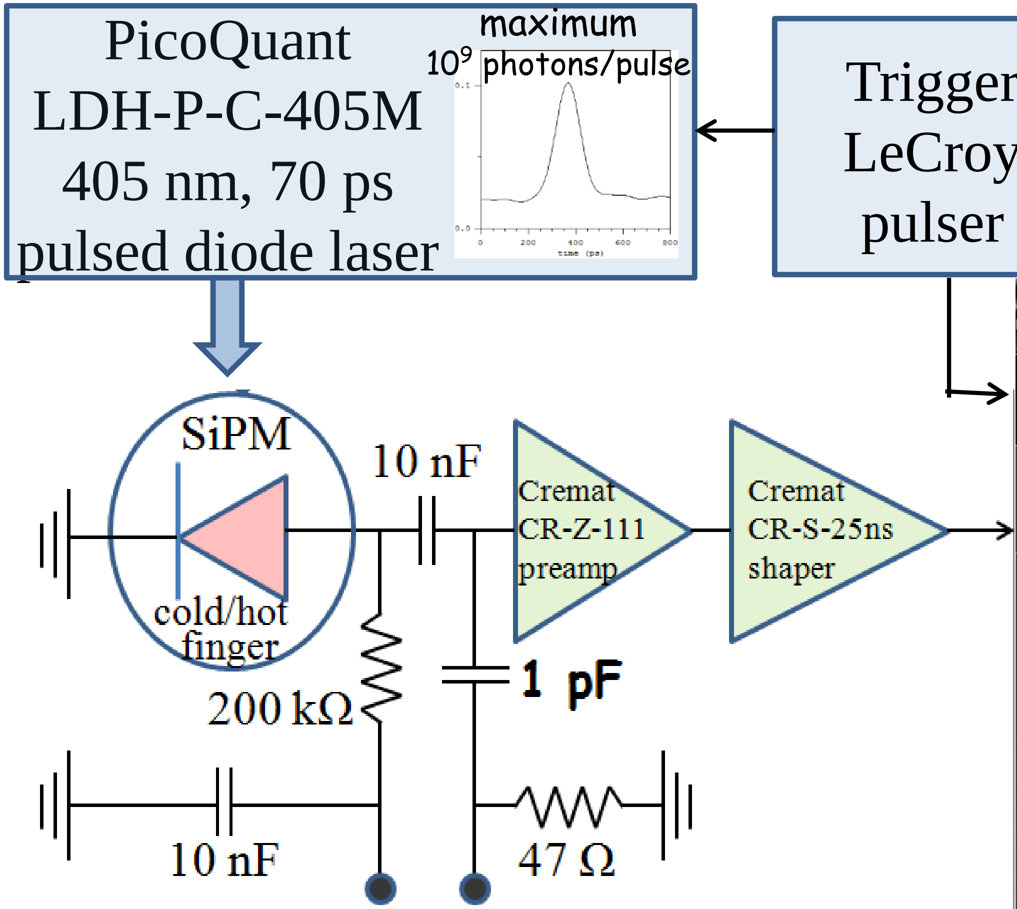
Keysight B2987A
electrometer

Expermental: reverse IV characterization

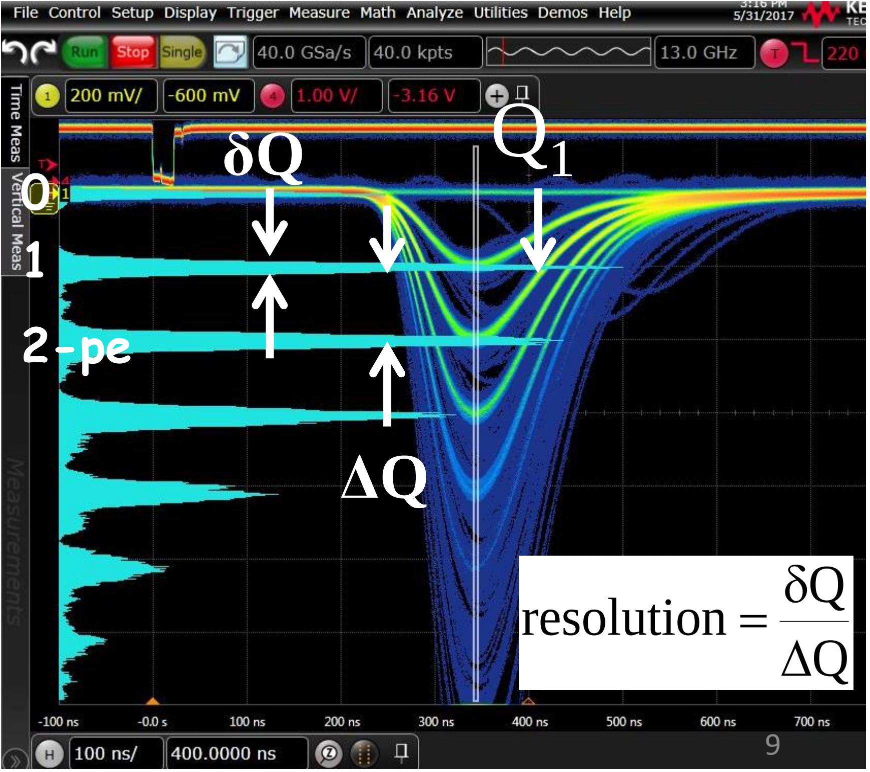


27

Experimental: Photo-response time-gated single-photoelectron spectrum



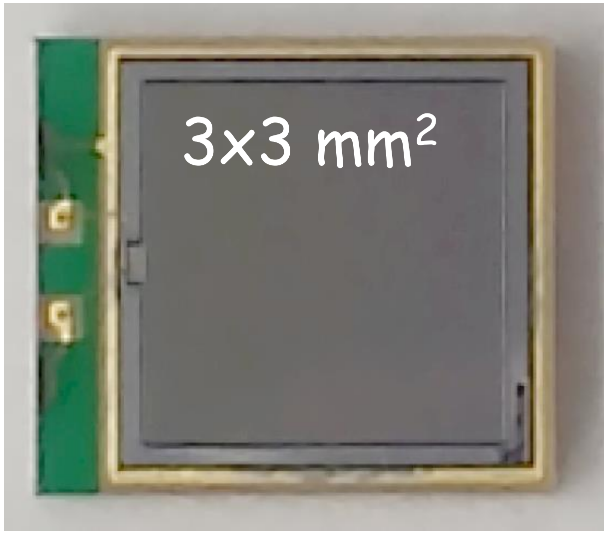
charge calibration
0.1 to 0.4 volt injection

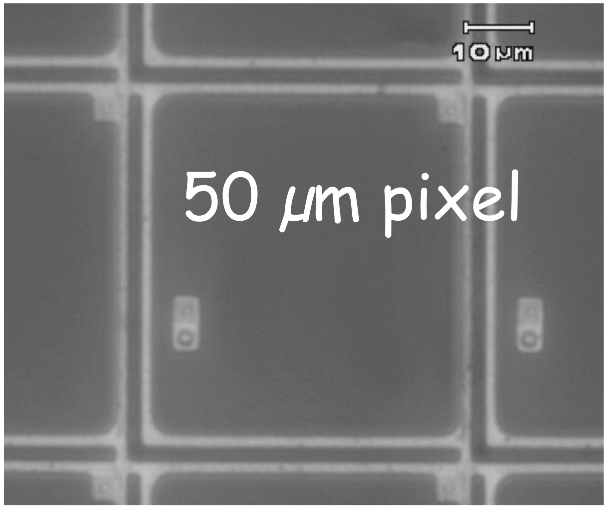


$$\text{resolution} = \frac{\delta Q}{\Delta Q}$$

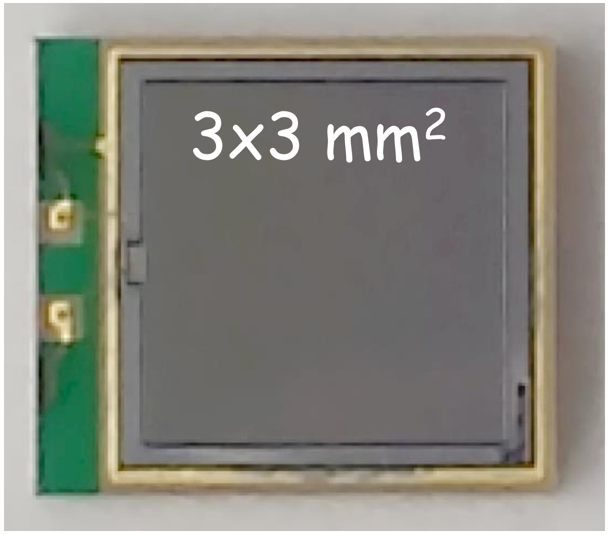
SiPMs

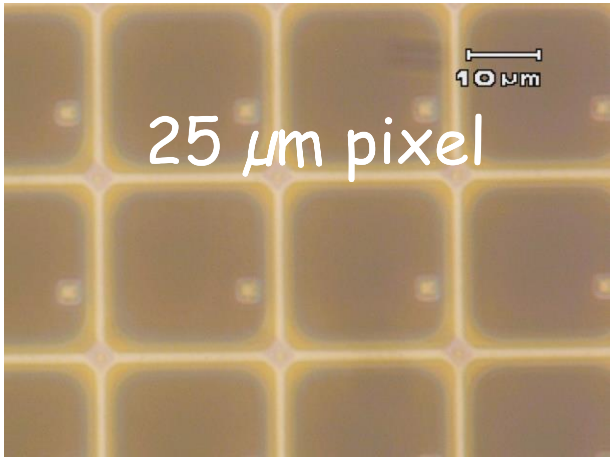
HPK S13360
3600 pixels



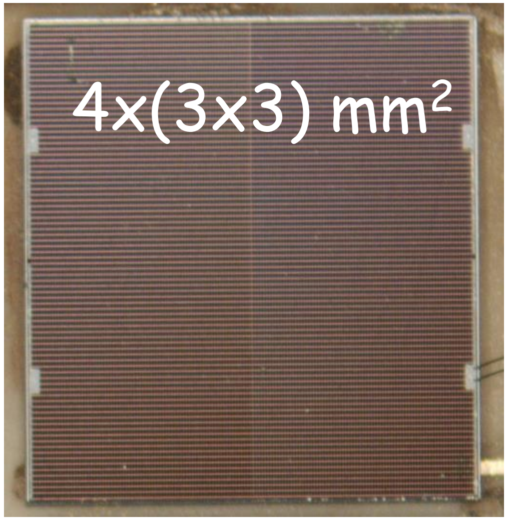


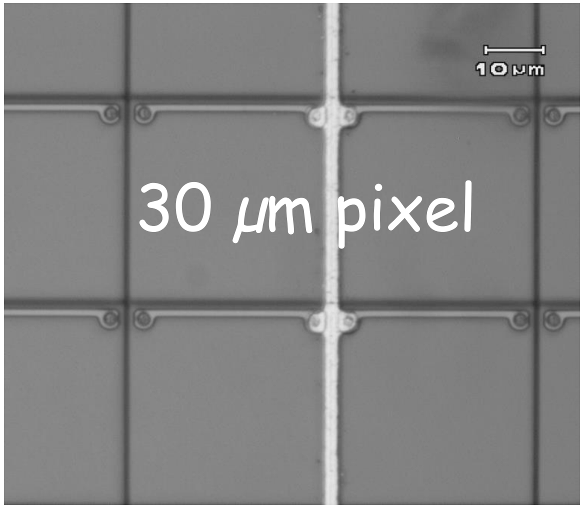
HPK S12572-25P
14400 pixels





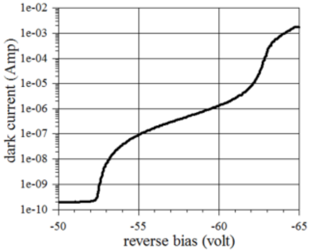
FBK HD-LF
4x(3x3) mm
4x6367 pixels

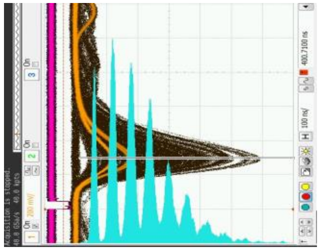




Experimental

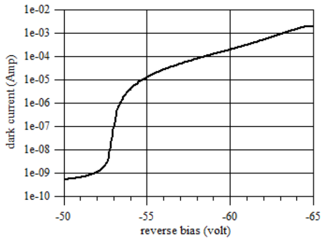
1. Evaluate **before irradiation**
   room & cold: IV & PNR

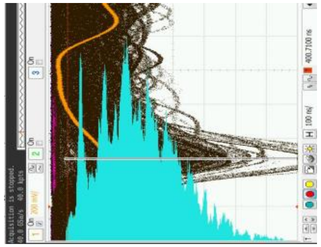




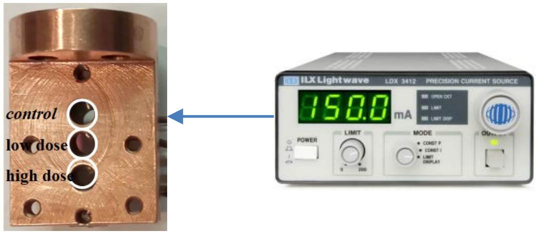
2. Neutron irradiation
   room/LN2, unbias

3. Evaluate **after irradiation**
   room & cold: IV & PNR

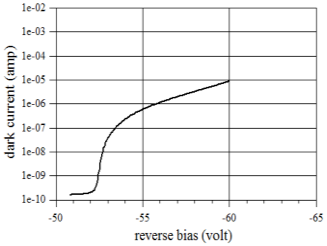


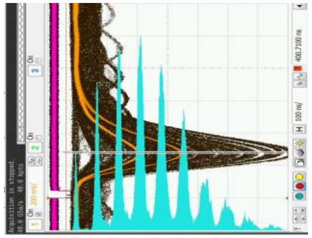


4. Thermal anneal
   ~250°C, bias +10mA

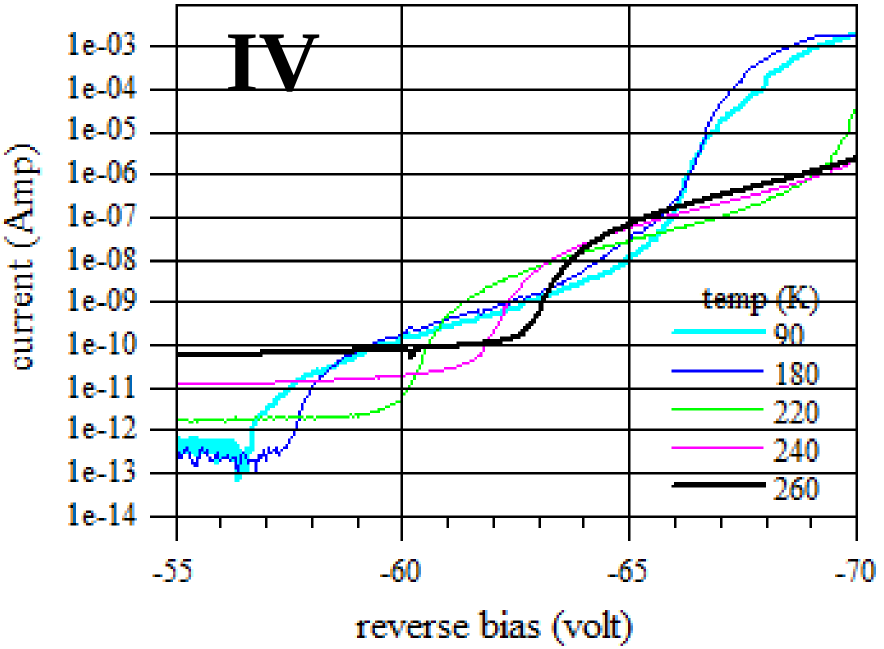


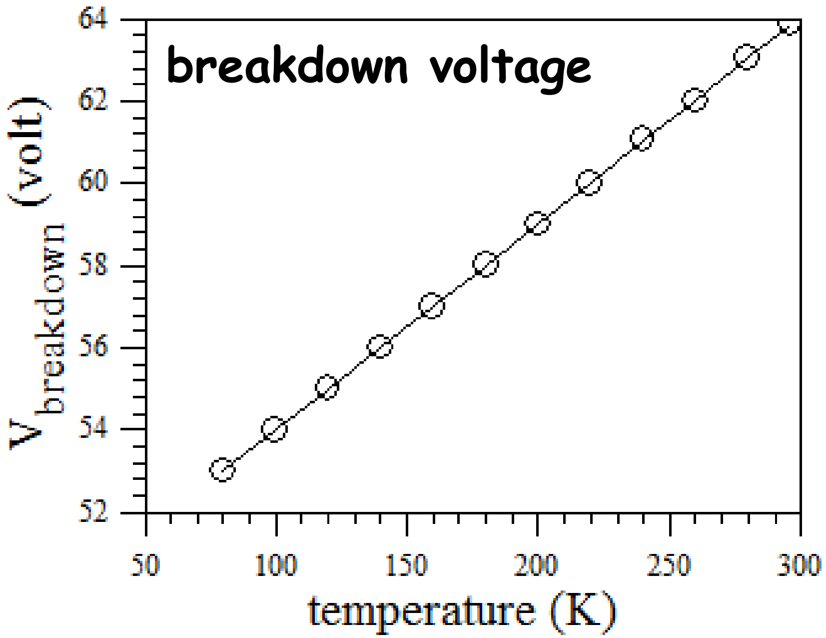
5. Evaluate **after annealing**
   room & cold





-IV plot: V_{bd} temperature dependence

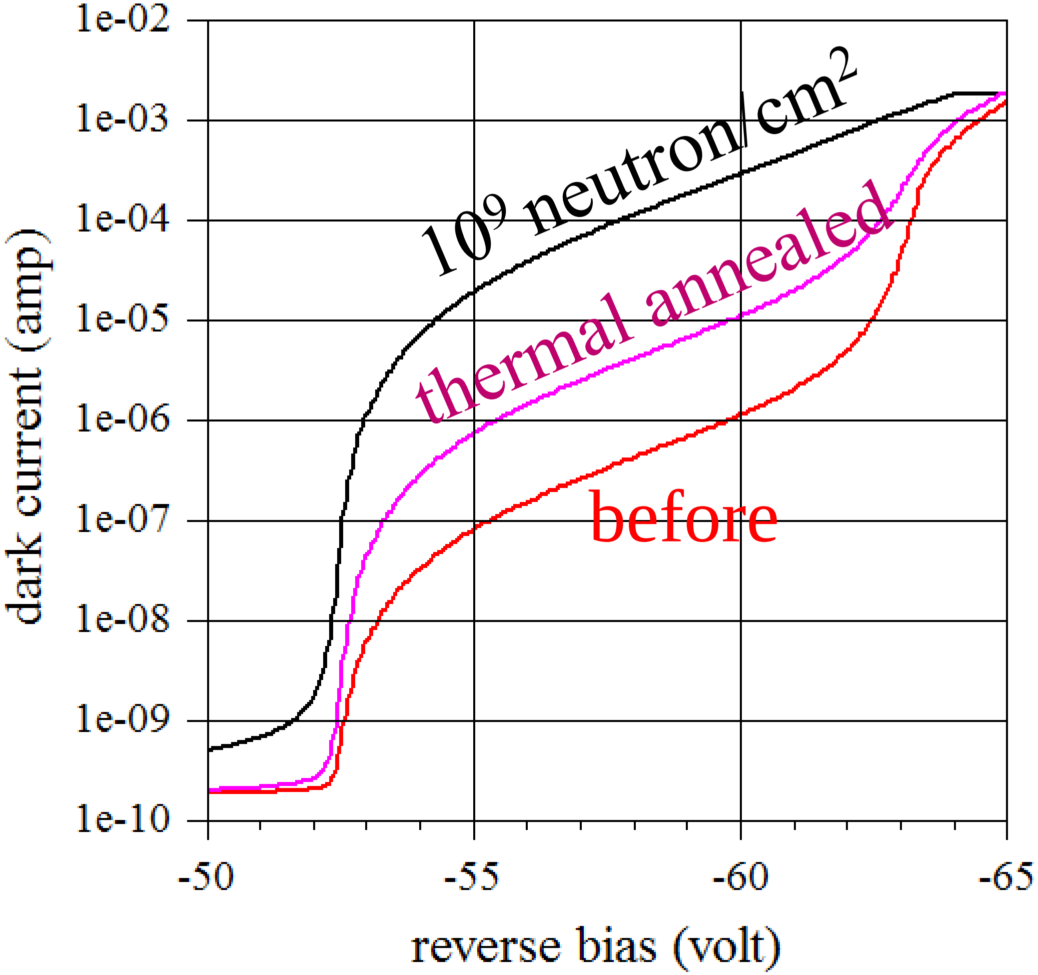


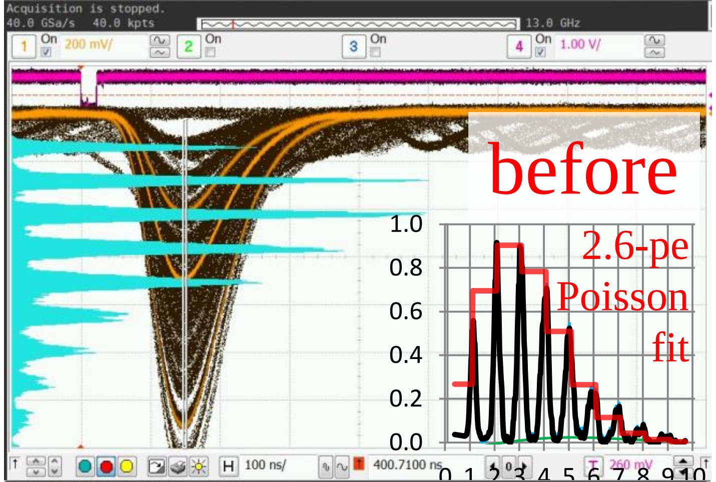


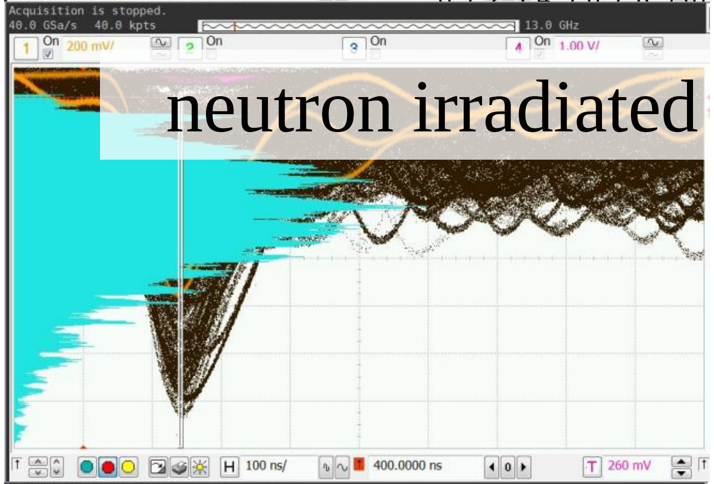
Temp. coefficient	
HPK	~54 mV/^{o}K
FBK	~27 mV/^{o}K

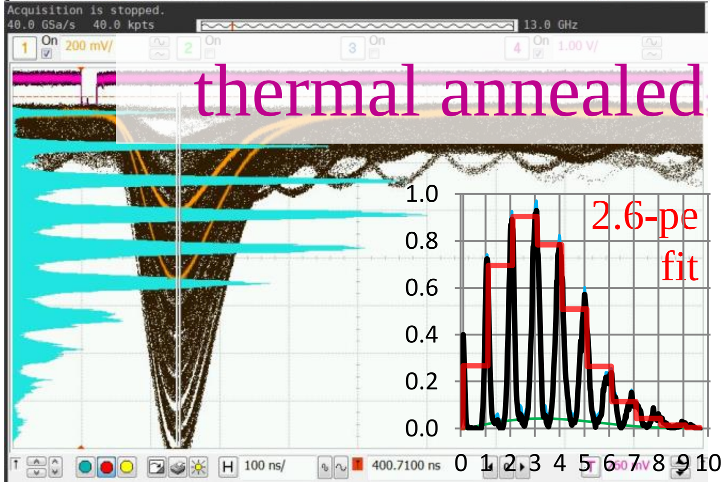
$V_{breakdown}$ strongly dependent on temperature

reverse I-V
room temperature





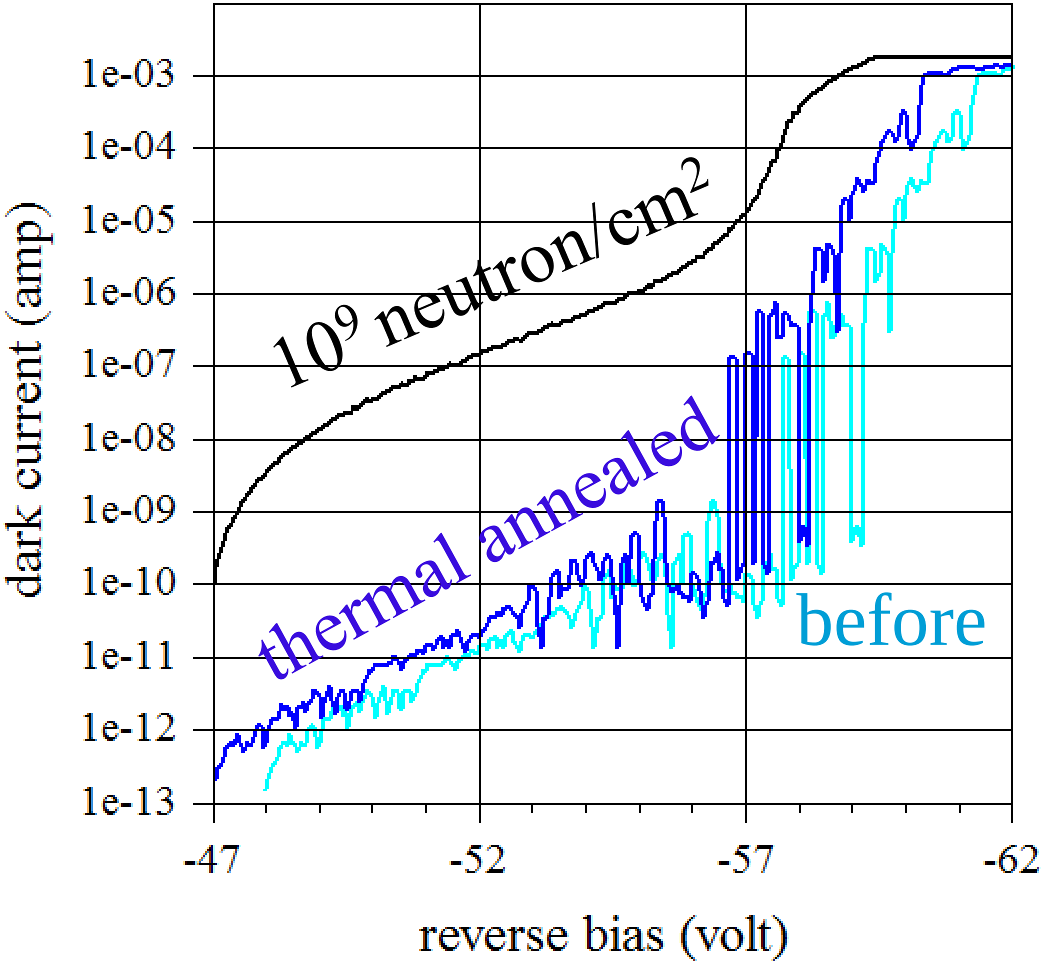


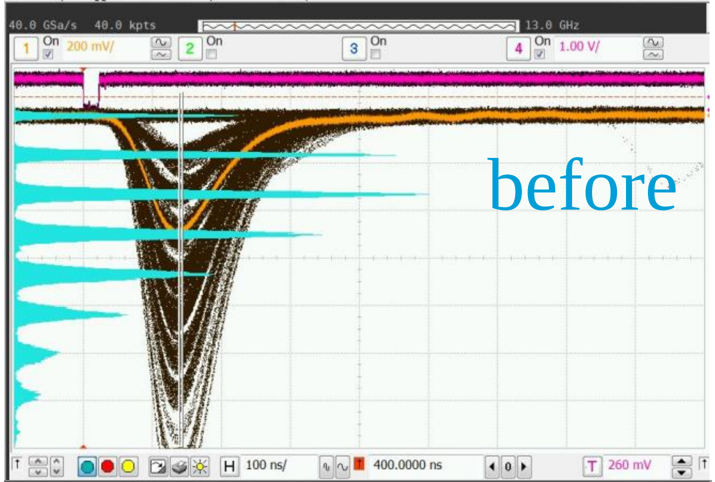


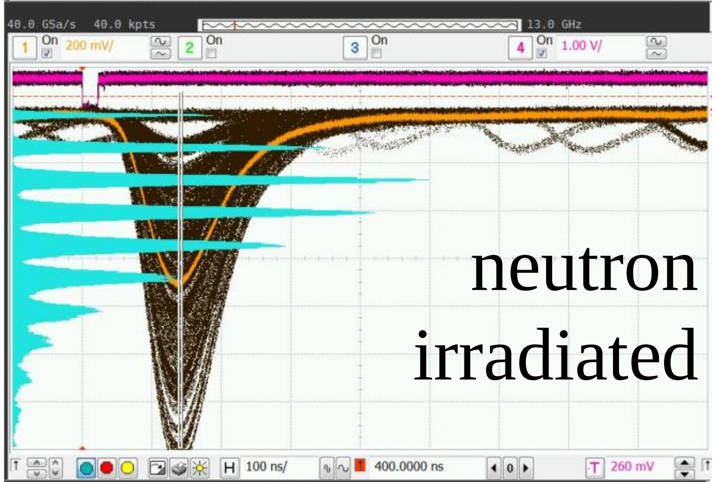
dark current ↓ , restore PNR

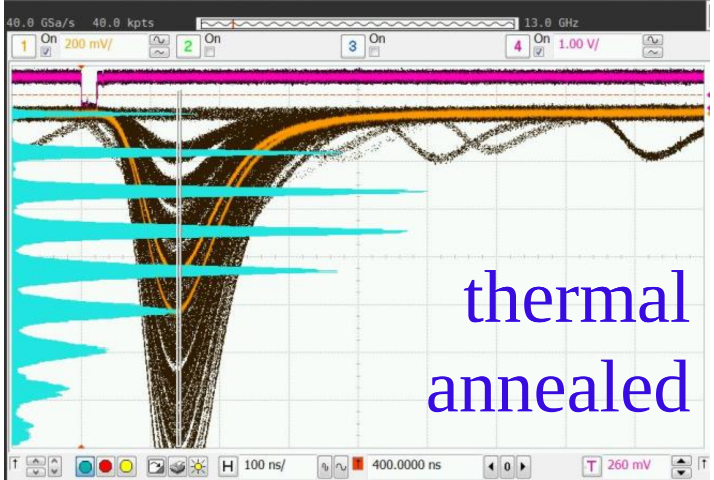
no significant change in PDE (on this batch)

reverse I-V
~84°K temperature









no significant change in PDE (on this batch)

room temperature IV

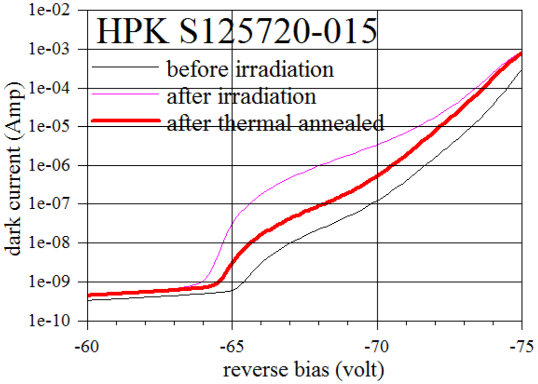
photoelectron spectrum

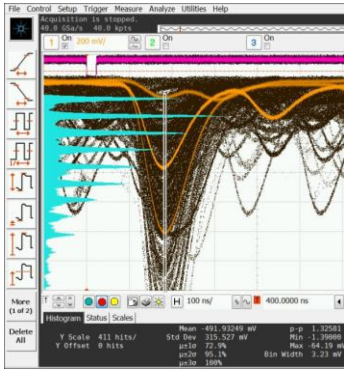
before irradiation

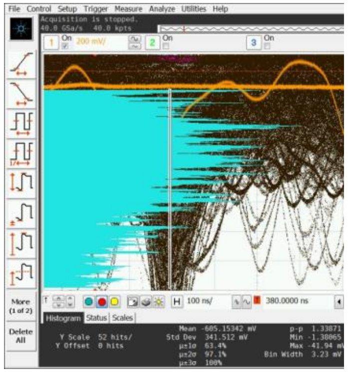
after irradiation

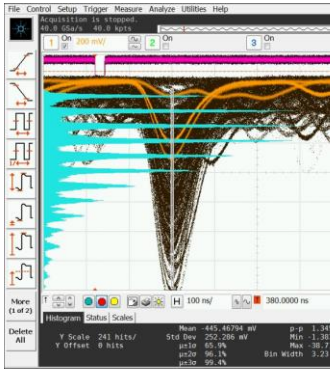
after thermal annealed

(a)

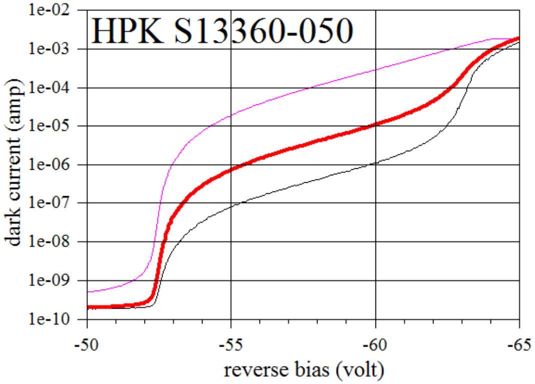


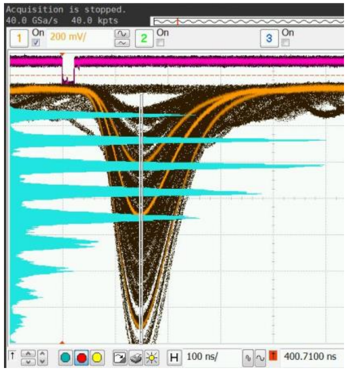


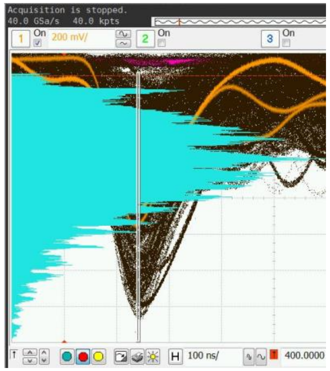


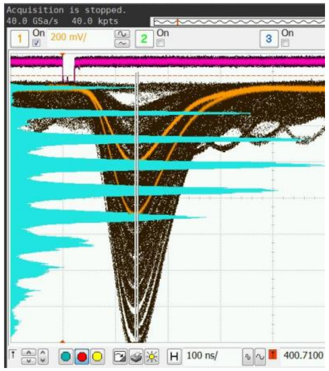


(b)

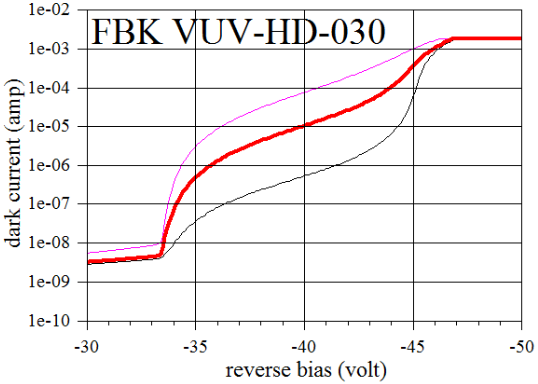


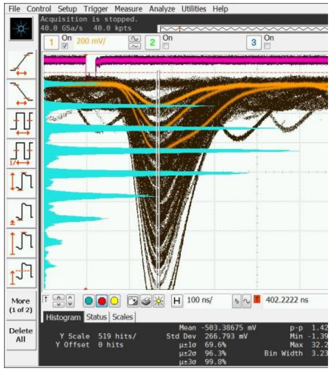


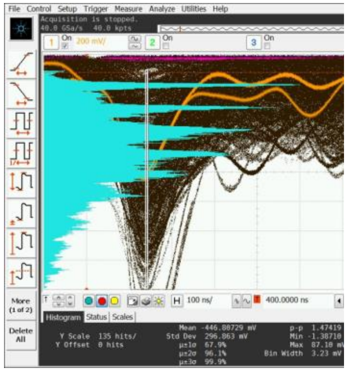


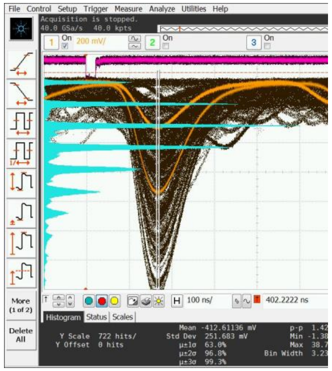


(c)

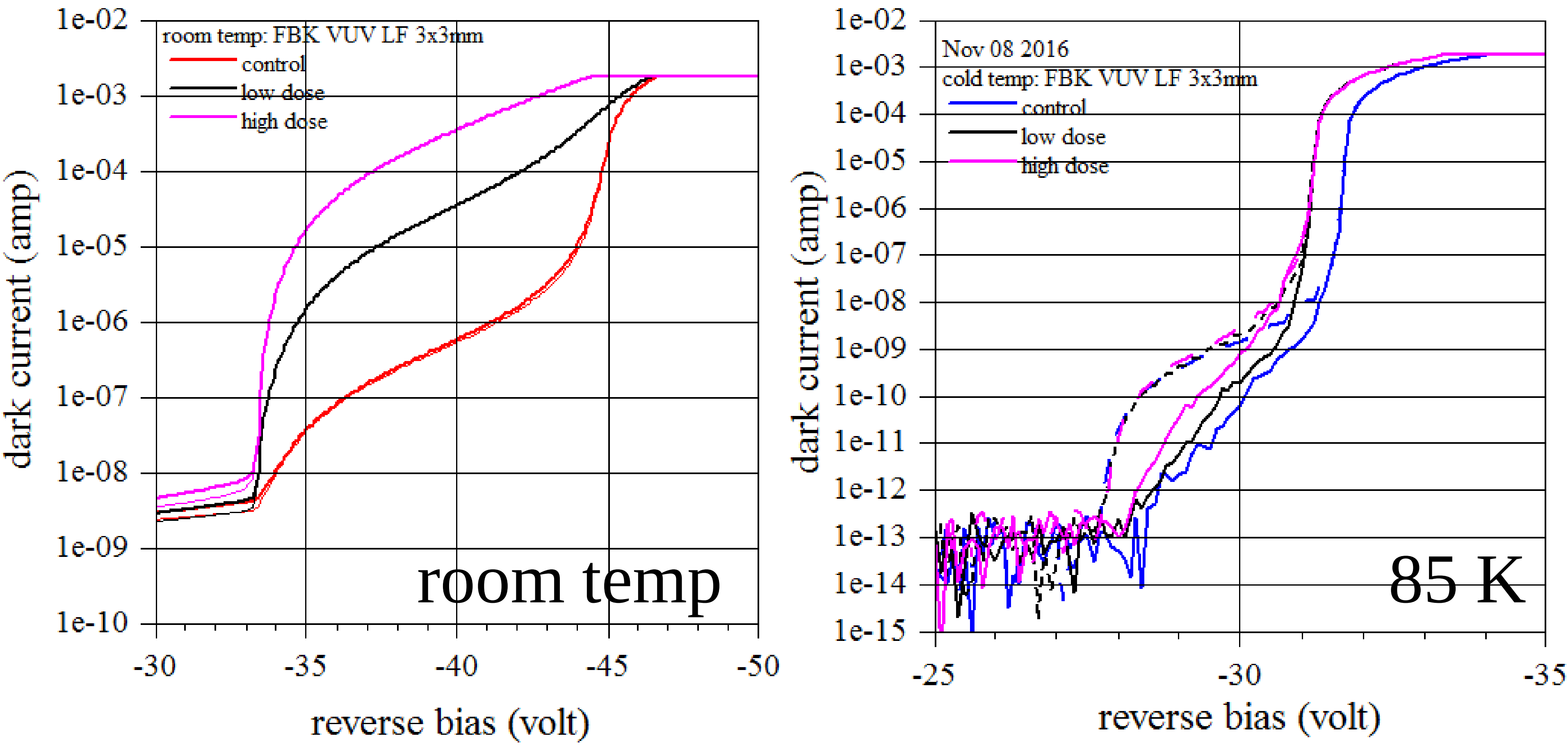








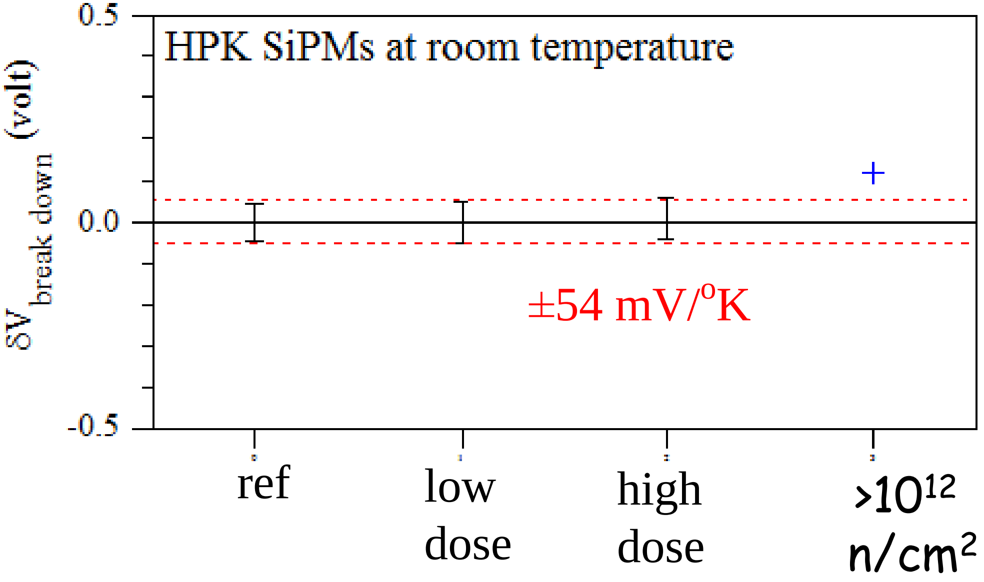
FBK VUV-HD LF 3x3 mm^2



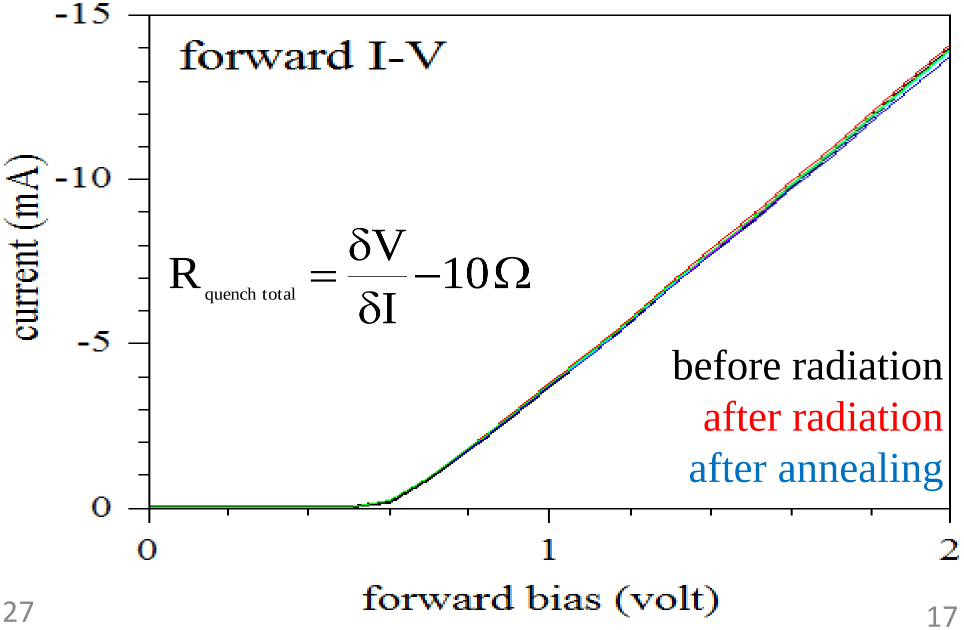
No change in breakdown voltage

$V_{\text{break-down}}$ & R_{quench}

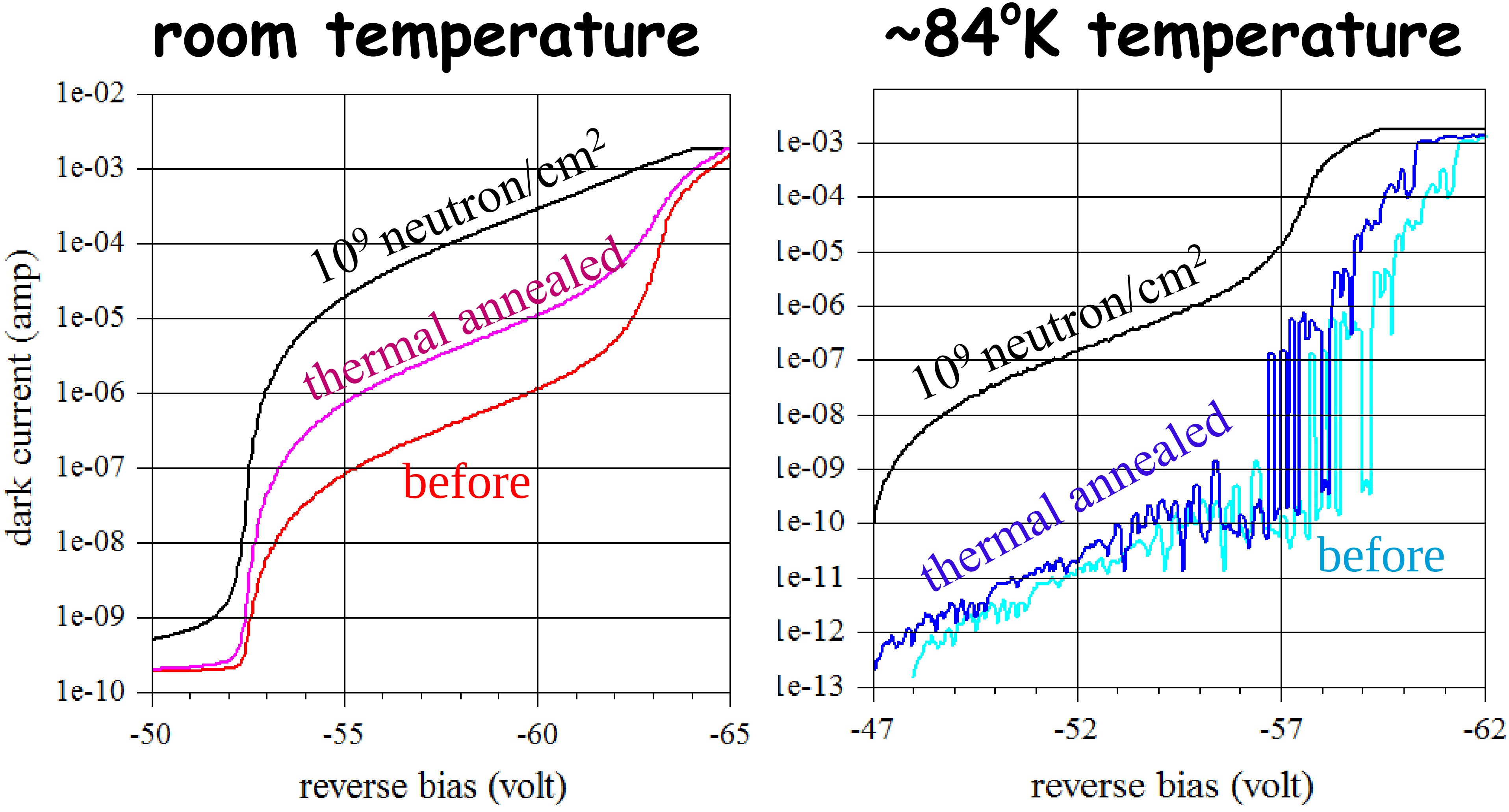
No significant change in $V_{\text{breakdown}}$ until ~10^{12} n/cm^2



No significant change in quench resistance



Summary: reverse I-V



PNR recovered after annealing

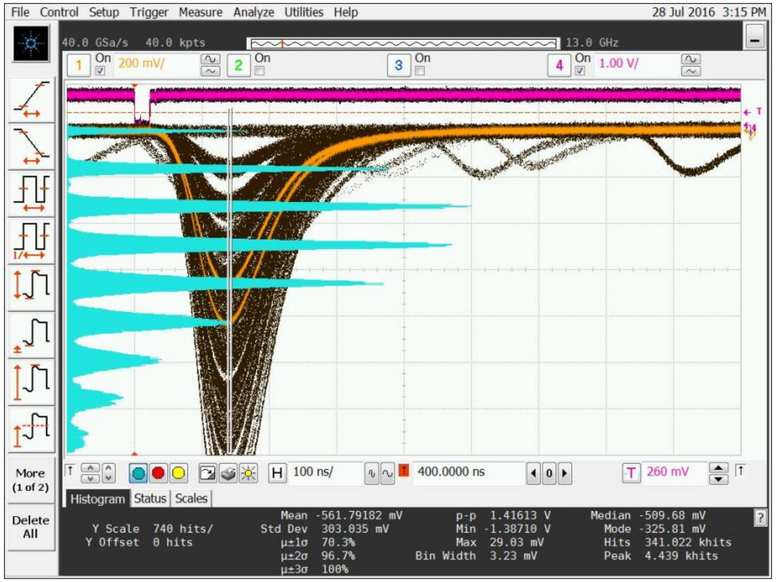
SiPM performs better in cold !

Temp. dependence: PNR capability

after neutron irradiation & thermal annealing
sample #441

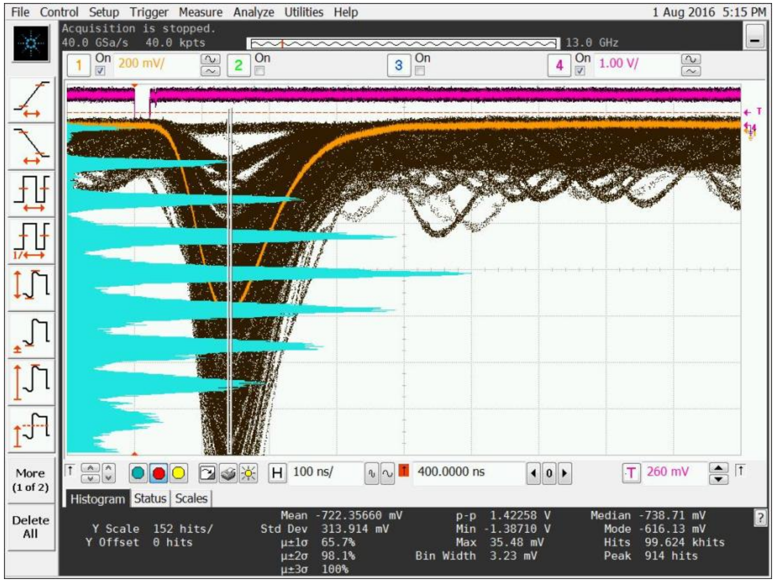
Dose: 10^9 n/cm^2

85K



```
                          Mean -561.79182 mV        p-p  1.41613 V      Median -509.68 mV
  Y Scale  740 hits/   Std Dev  303.035 mV          Min -1.38710 V        Mode -325.81 mV
 Y Offset  0 hits        μ±1σ  70.3%                Max  29.03 mV         Hits  341.022 khits
                         μ±2σ  96.7%          Bin Width  3.23 mV          Peak  4.439 khits
                         μ±3σ  100%
```

300K



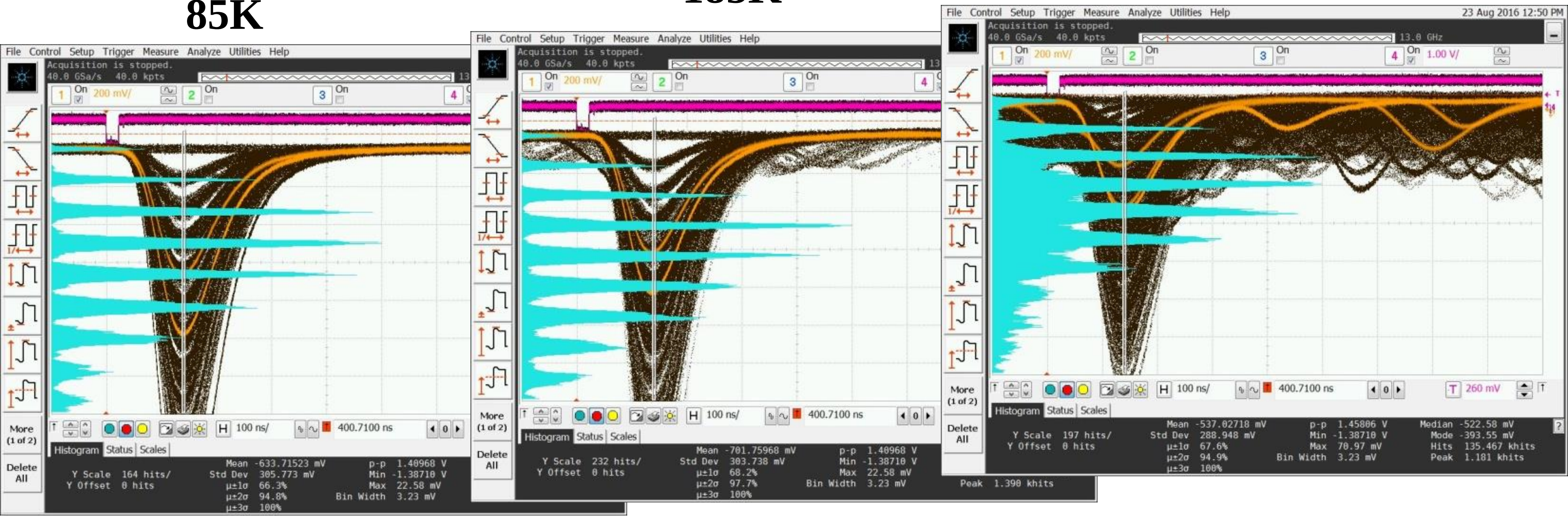
```
                          Mean -722.35660 mV        p-p  1.42258 V      Median -738.71 mV
  Y Scale  152 hits/   Std Dev  313.914 mV          Min -1.38710 V        Mode -616.13 mV
 Y Offset  0 hits        μ±1σ  65.7%                Max  35.48 mV         Hits  99.624 khits
                         μ±2σ  98.1%          Bin Width  3.23 mV          Peak  914 hits
                         μ±3σ  100%
```

Good photoelectron spectrum can be recovered at room temperature

Temp. dependence: PNR capability

after neutron irradiation & thermal annealing
sample #442

Dose: 10^{10} n/cm^2



85K

```
Acquisition is stopped.
40.0 GSa/s   40.0 kpts

                        Mean -633.71523 mV          p-p  1.40968 V
 Y Scale  164 hits/  Std Dev  305.773 mV           Min -1.38710 V
 Y Offset 0 hits        μ±1σ  66.3%                Max  22.58 mV
                        μ±2σ  94.8%          Bin Width  3.23 mV
                        μ±3σ  100%
```

185K

```
Acquisition is stopped.
40.0 GSa/s   40.0 kpts

                        Mean -701.75968 mV          p-p  1.40968 V
 Y Scale  232 hits/  Std Dev  303.738 mV           Min -1.38710 V
 Y Offset 0 hits        μ±1σ  68.2%                Max  22.58 mV
                        μ±2σ  97.7%          Bin Width  3.23 mV      Peak  1.390 khits
                        μ±3σ  100%
```

270K

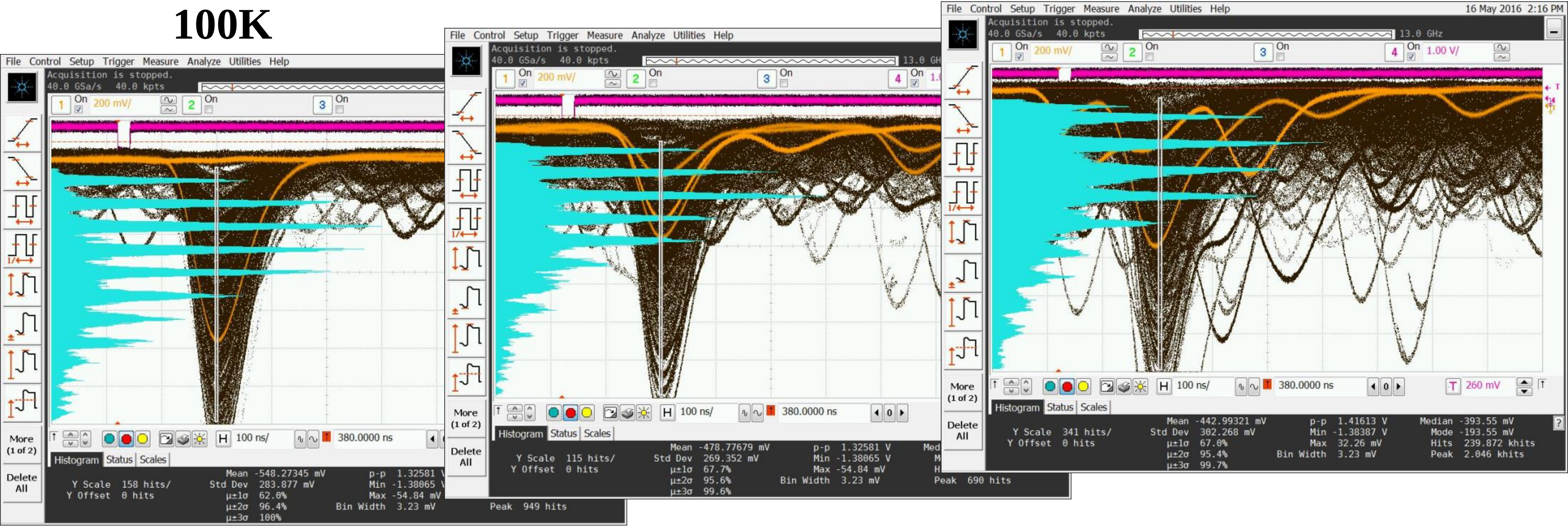
```
Acquisition is stopped.
40.0 GSa/s   40.0 kpts

                        Mean -537.02718 mV          p-p  1.45806 V     Median -522.58 mV
 Y Scale  197 hits/  Std Dev  288.948 mV           Min -1.38710 V       Mode -393.55 mV
 Y Offset 0 hits        μ±1σ  67.6%                Max  70.97 mV        Hits  135.467 khits
                        μ±2σ  94.9%          Bin Width  3.23 mV         Peak  1.181 khits
                        μ±3σ  100%
```

Good photoelectron spectrum can be recovered with moderate cooling !

Temp. dependence: PNR capability

after neutron irradiation & thermal annealing
sample #9

Dose: 10^{12} n/cm^2



100K

120K

220K

-53°C

100K:

```
Acquisition is stopped.
40.0 GSa/s   40.0 kpts
1 On 200 mV/    2 On    3 On
H 100 ns/    380.0000 ns

                  Mean -548.27345 mV        p-p  1.32581
 Y Scale  158 hits/   Std Dev  283.877 mV   Min -1.38065
Y Offset  0 hits       μ±1σ  62.0%          Max -54.84 mV
                       μ±2σ  96.4%    Bin Width  3.23 mV        Peak  949 hits
                       μ±3σ  100%
```

120K:

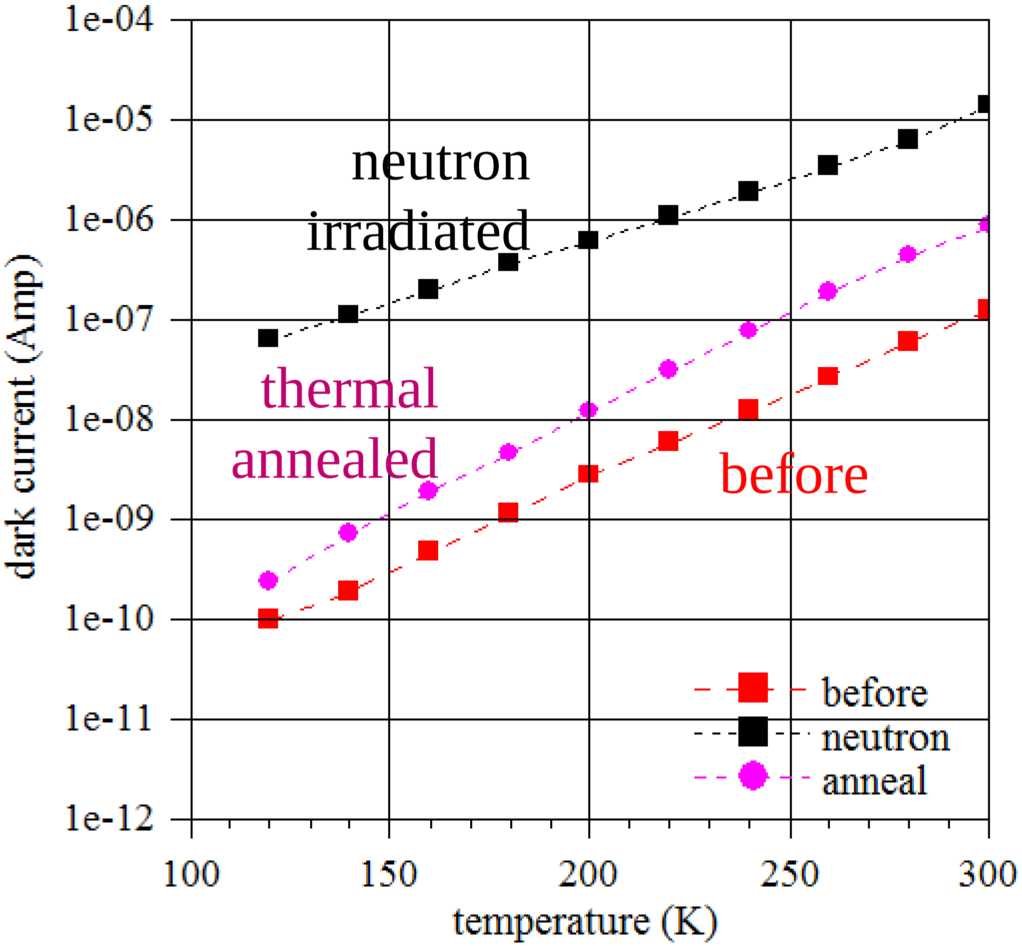
```
Acquisition is stopped.
40.0 GSa/s   40.0 kpts                    13.0 GH
1 On 200 mV/    2 On    3 On    4 On
H 100 ns/    380.0000 ns    0

                  Mean -478.77679 mV        p-p  1.32581 V
 Y Scale  115 hits/   Std Dev  269.352 mV   Min -1.38065 V
Y Offset  0 hits       μ±1σ  67.7%          Max -54.84 mV
                       μ±2σ  95.6%    Bin Width  3.23 mV        Peak  690 hits
                       μ±3σ  99.6%
```

220K:

```
Acquisition is stopped.
40.0 GSa/s   40.0 kpts                    13.0 GHz
1 On 200 mV/    2 On    3 On    4 On 1.00 V/
H 100 ns/    380.0000 ns    0    T 260 mV

                  Mean -442.99321 mV        p-p  1.41613 V     Median -393.55 mV
 Y Scale  341 hits/   Std Dev  302.268 mV   Min -1.38387 V       Mode -193.55 mV
Y Offset  0 hits       μ±1σ  67.0%          Max  32.26 mV        Hits  239.872 khits
                       μ±2σ  95.4%    Bin Width  3.23 mV         Peak  2.046 khits
                       μ±3σ  99.7%
```

Good photoelectron spectrum can be recovered with deep cooling !

Temperature dep. of dark current



At a fixed OV:

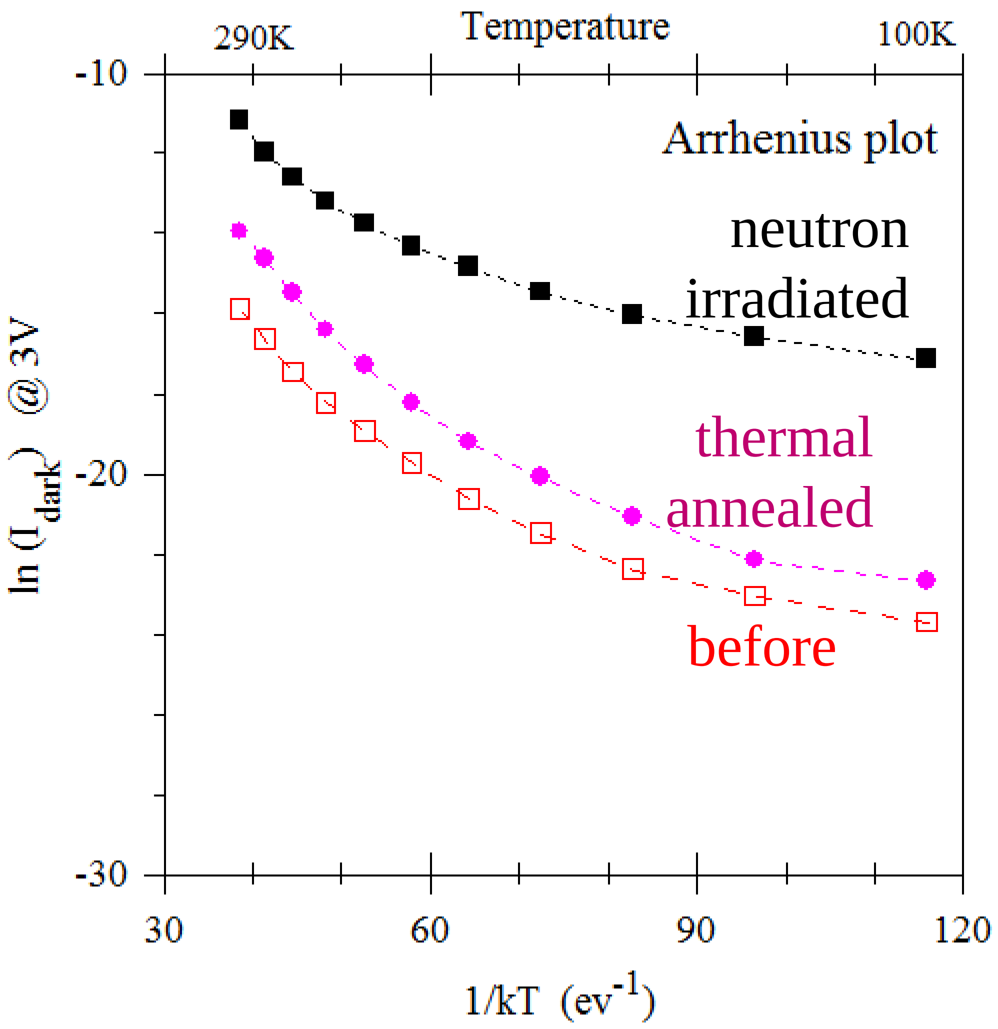
$$I_{dark} = c + a \times e^{-bT}$$

	a	**b**
before	7.5e-13	**0.041**
neutron	1.8e-9	**0.029**
anneal	1.15e-12	**0.045**

- I_{dark} (before) drops 1-decade/80°K
- I_{dark} (neutron) drops 1-decade/57°K

I_{dark} (neutron) has a fundamentally different activation energy

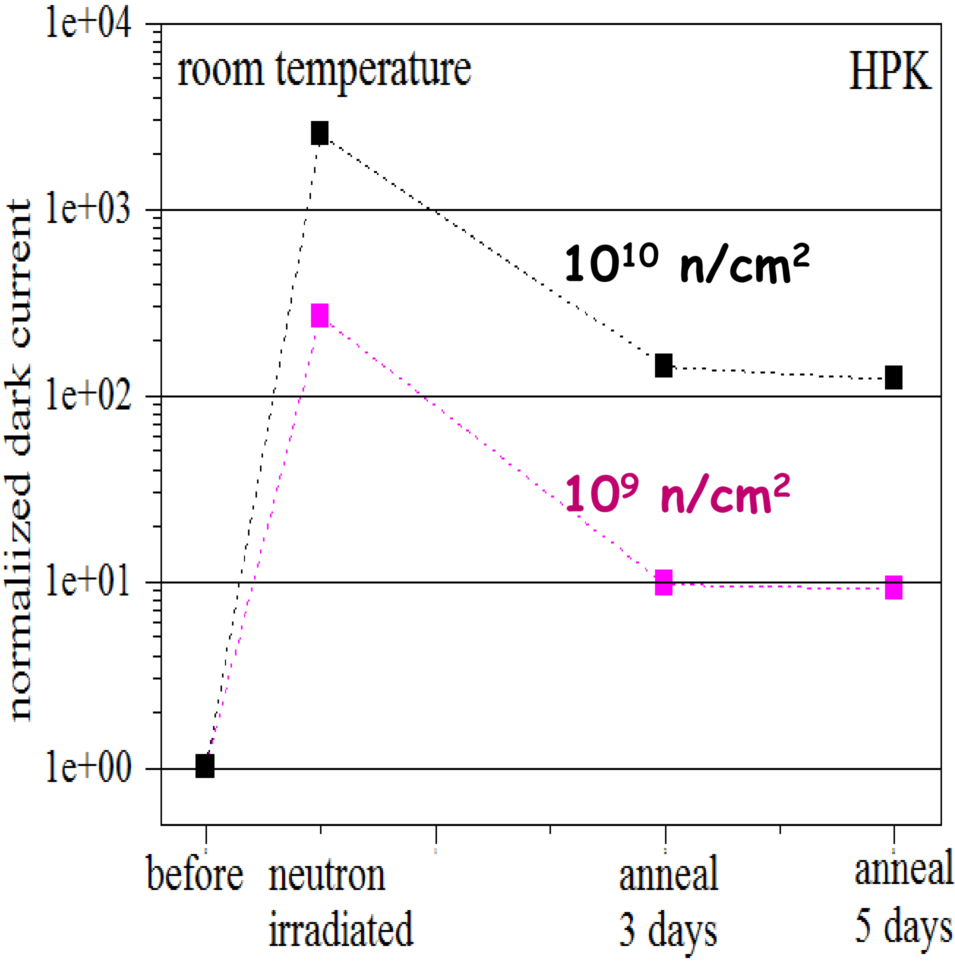
Temperature dep. of dark current - Arrhenius plot



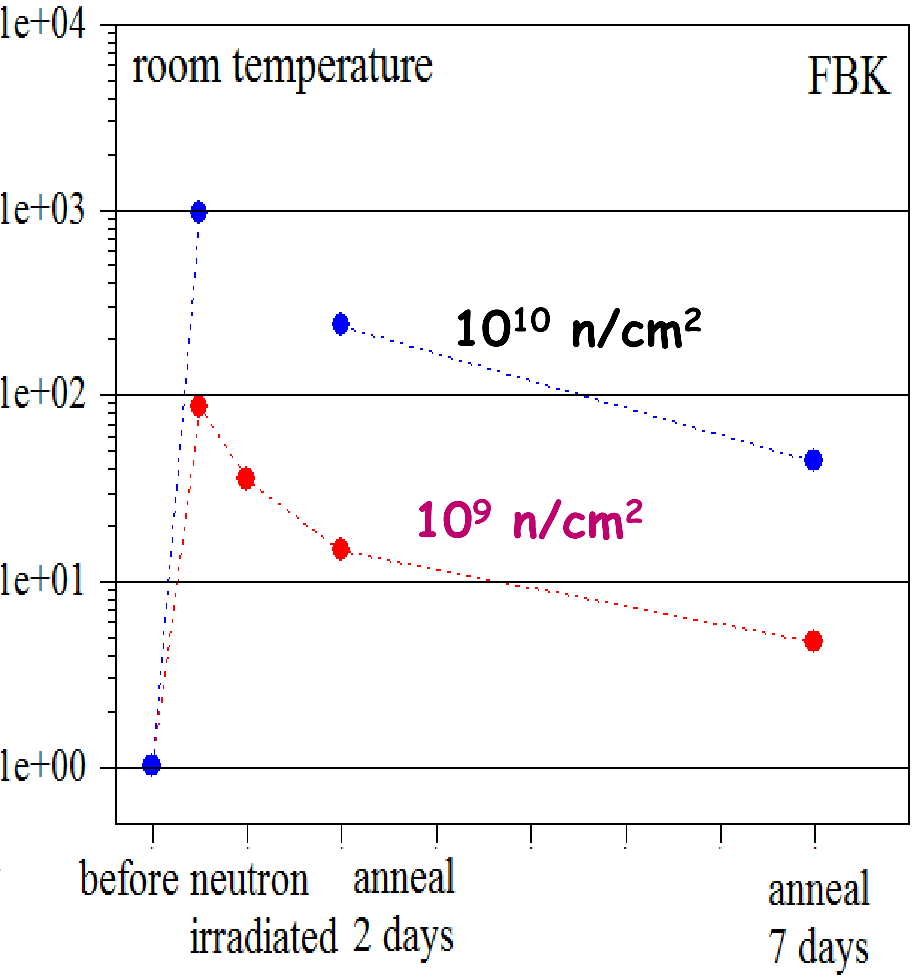
I_{dark} (neutron) has a fundamentally different activation energy

Qualitative: annealing time

HPK, 250°C, +8 mA



FBK, 230°C, +10 mA



thermal annealing takes time

(unable to fully recover the I_{dark} yet)

Neutron irradiation in LN_2 - unbias

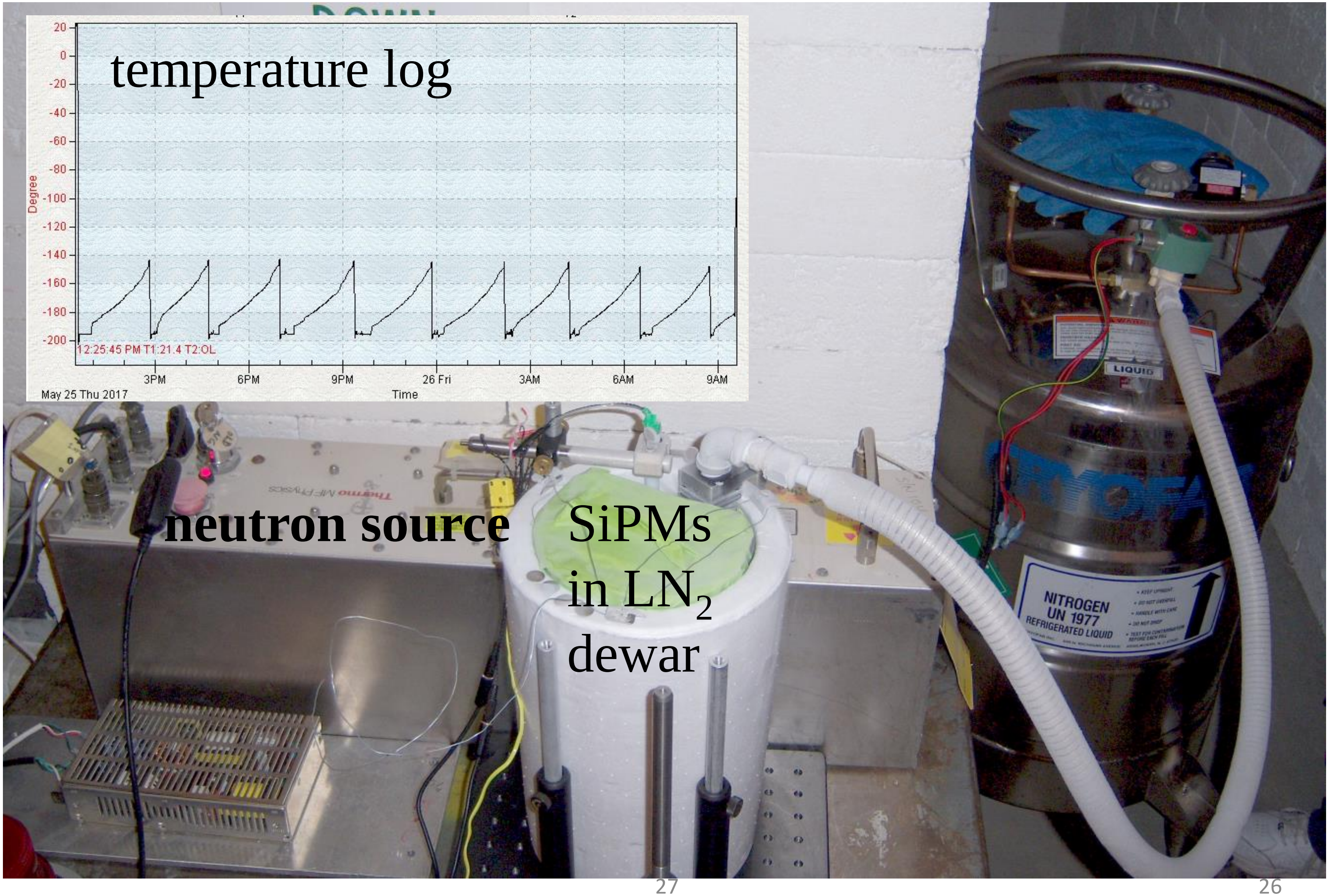
BNL14 MeV neutron source
(flux 10^5 neutrons/cm^2/sec)

HPK S13360-3050XPE

s/n	V_{op}	I_d (μA)	Ionization Radiation	
62432	55.64	0.15	7.2×10^9 n/cm^2	room
62433	55.60	0.151	7.2×10^9 n/cm^2	room
62434	55.48	0.148	3.8×10^9 n/cm^2	LN2
62435	55.49	0.14	3.8×10^9 n/cm^2	LN2
62448	55.37	0.157	3.8×10^9 n/cm^2	room
62449	55.37	0.138	control	

high dose 7.2×10^9 n/cm^2	**low dose 3.8×10^9 n/cm^2**
62432 room	**62434 LN2**
62433 room	**62435 LN2**
	62448 room

SiPMs irradiated in LN_2



temperature log

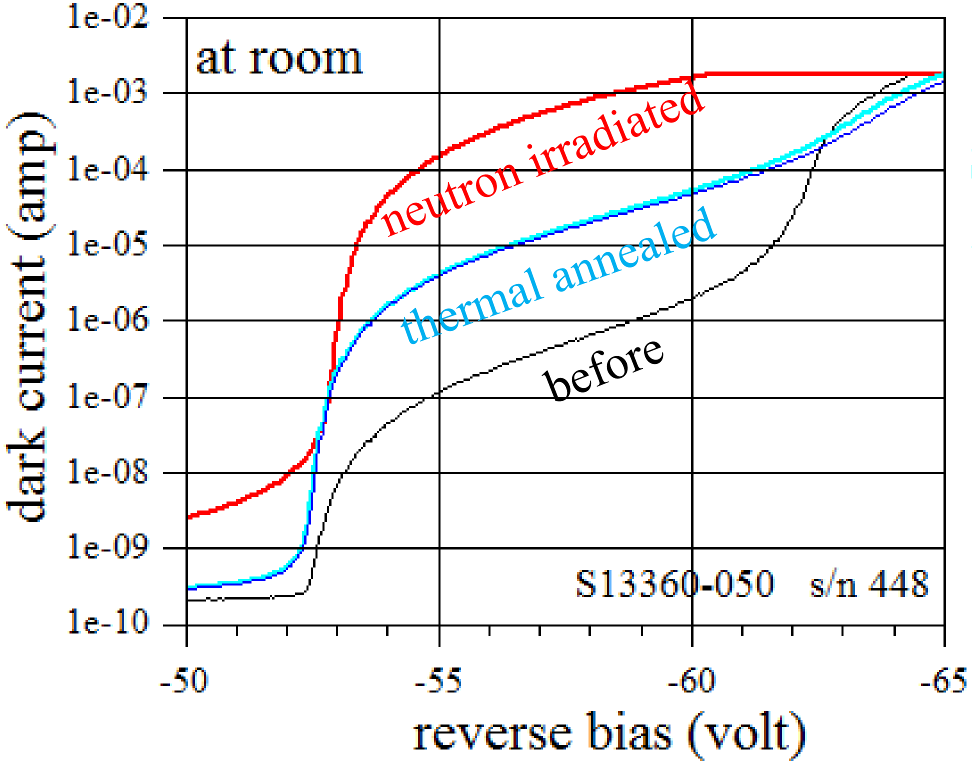
neutron source

SiPMs in LN_2 dewar

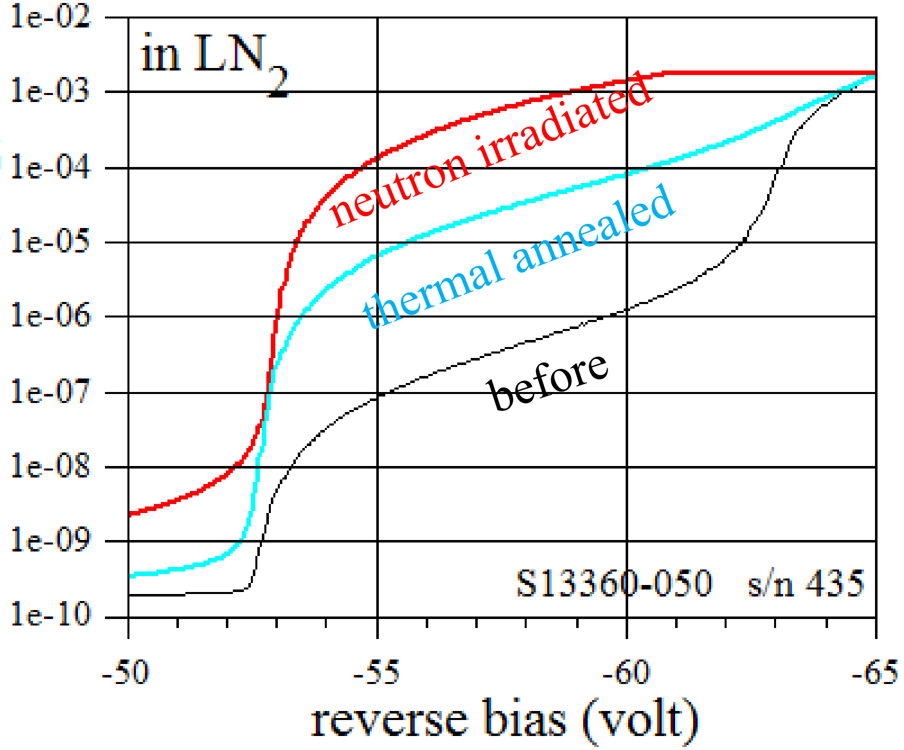
I-V before & after neutron irradiation & thermal annealing

3.8×10^9 n/cm^2

room



LN_2



no radiation hardening
when SiPMs are operated in cryogenic

Conclusions

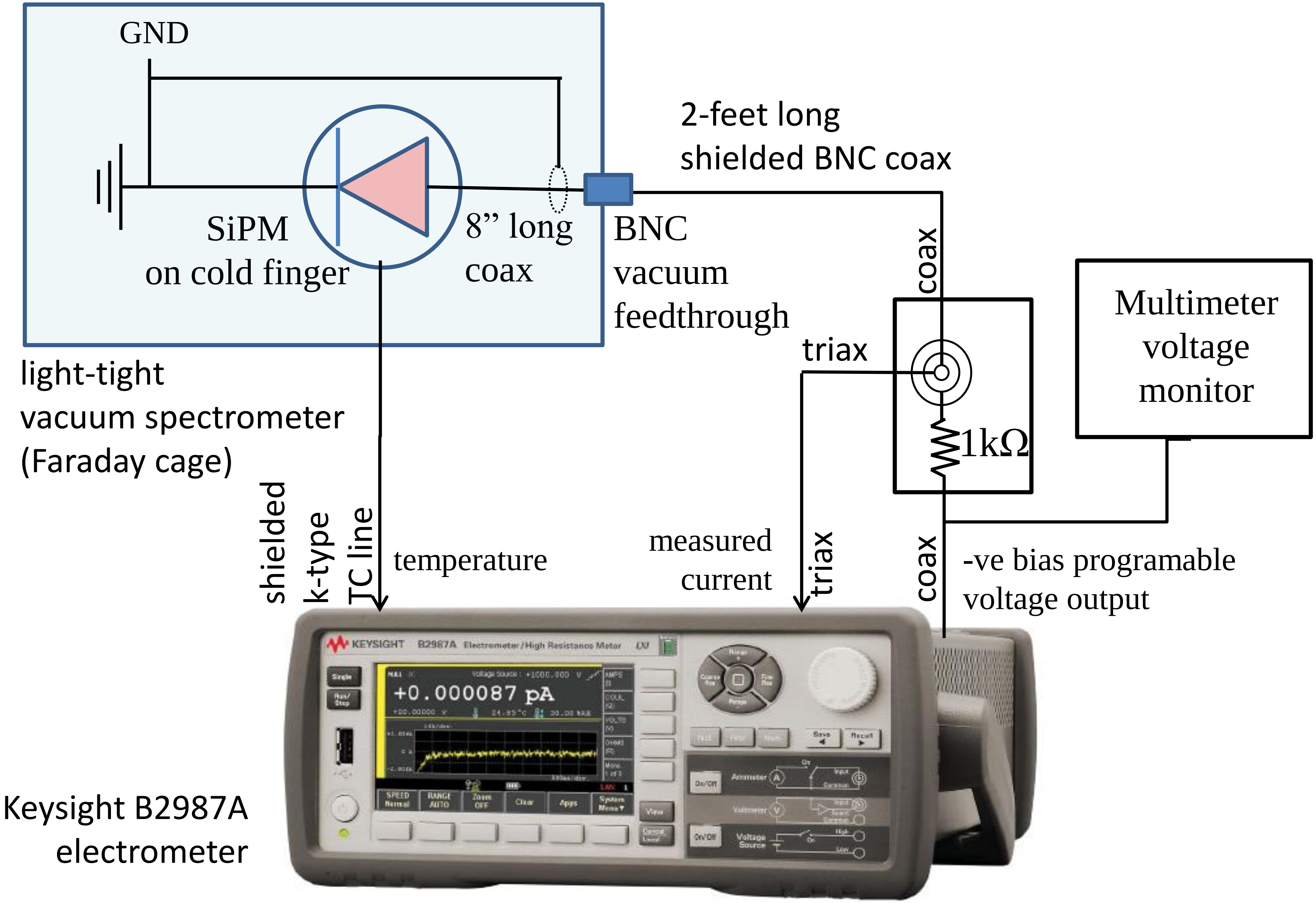
Hamamatsu: S12572 & S13660 & FBK, others?

1. At room temp. dark current increased by orders of magnitude with poor/no PNR.
2. In cold: dark current lowered. PNR power recovered.
3. Thermal annealing lower the dark current, restore the PNR capability for low dose SiPMs, but require moderate to deep cooling for higher dose SiPMs
4. Effectiveness of thermal annealing with forward bias is remarkable
5. Temperature dependence of I_{dark} (neutron) is fundamentally different than I_{dark} (intrinsic).
6. No difference if SiPMs are radiated at room or LN_2 temp.- no radiation hardening in cold.

Supplementary:

Measurement techniques

IV measurement setup



GND

SiPM
on cold finger

8” long
coax

BNC
vacuum
feedthrough

2-feet long
shielded BNC coax

light-tight
vacuum spectrometer
(Faraday cage)

coax

triax

1kΩ

Multimeter
voltage
monitor

shielded
k-type
TC line

temperature

measured
current

triax

coax

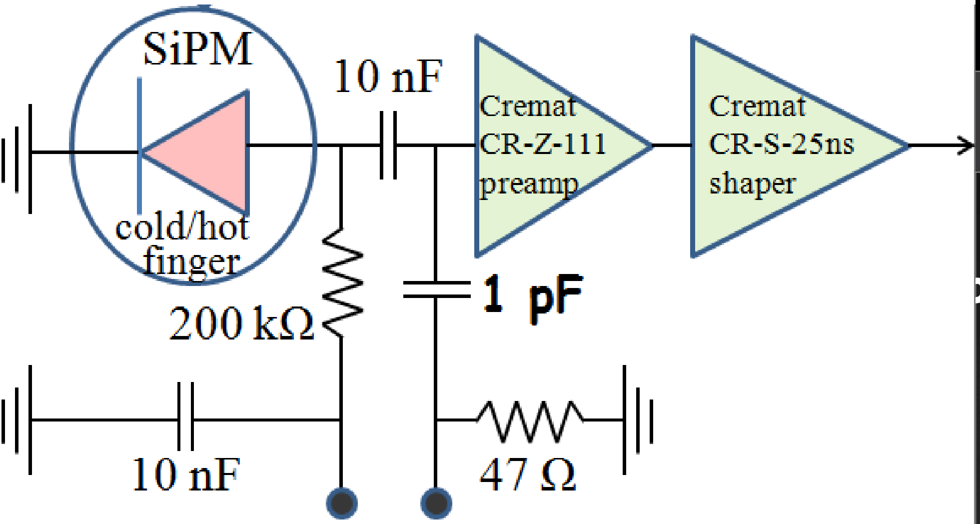
-ve bias programable
voltage output

Keysight B2987A
electrometer

Technique: charge gain calibration

Inject known charge to calibrate preamp

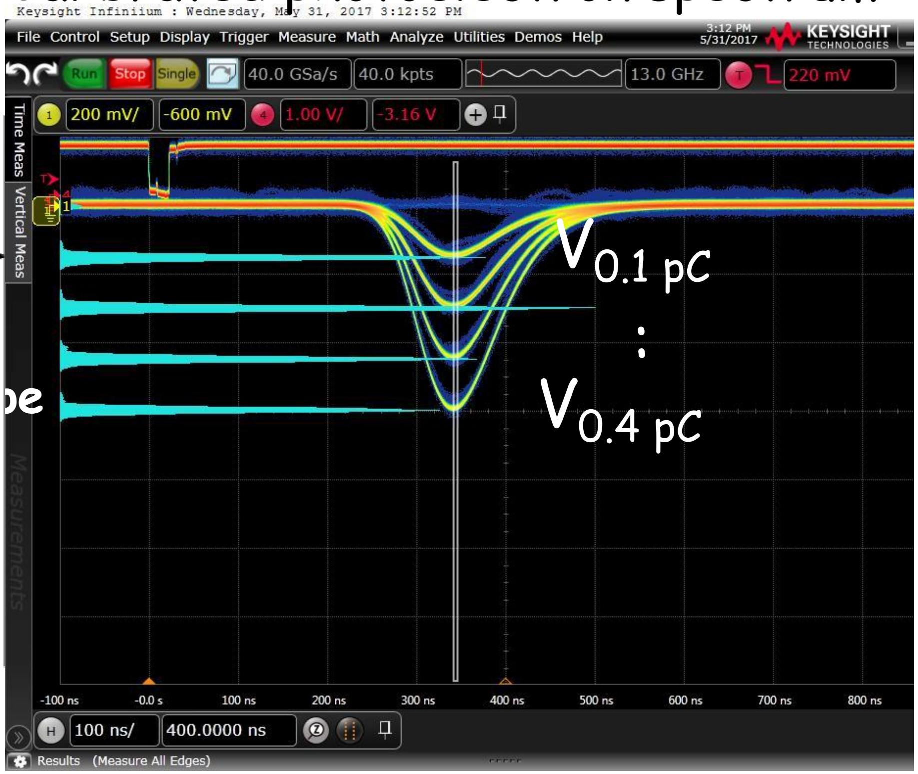
(with SiPM attached to preamp & biased)



bias

charge calibration
0.1 to 0.4 volt injection

Calibrated photoelectron spectrum

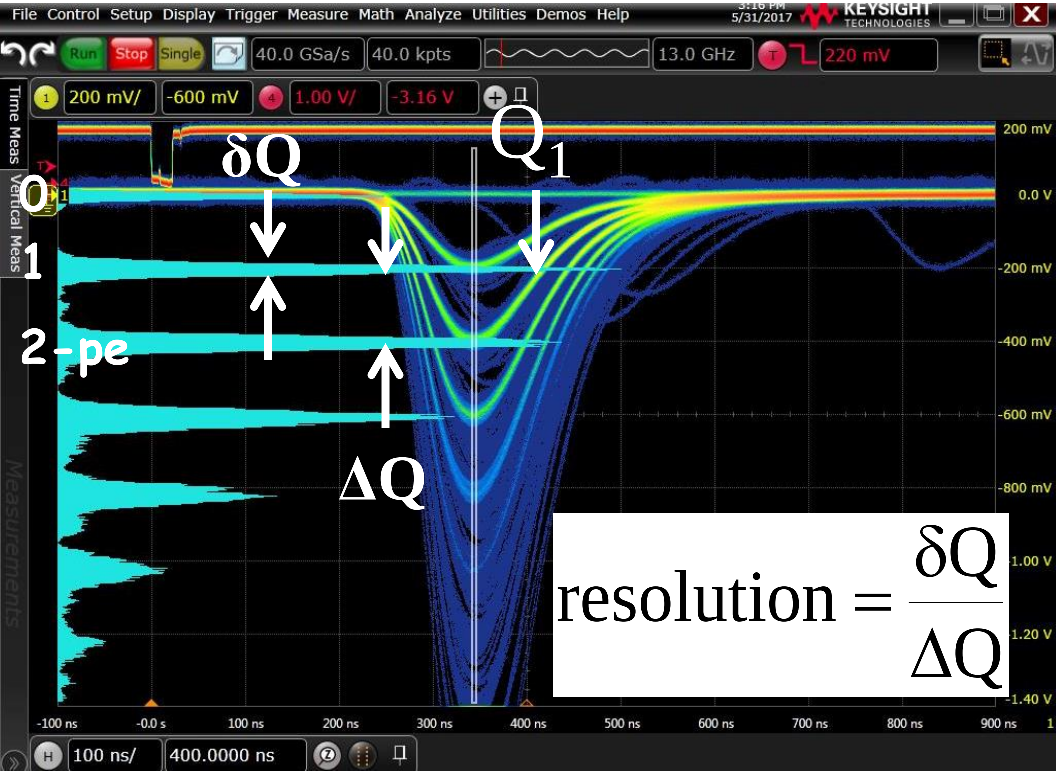


signal amplitude voltage V = photoelectron charge Q

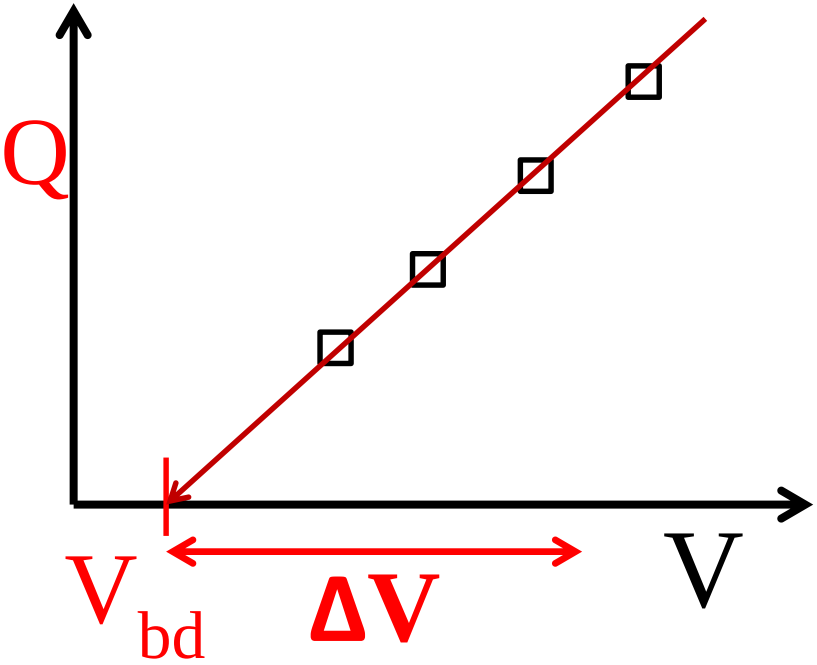
Technique: charge gain measurements

single-photoelectron spectrum

$$\text{gain} = \frac{Q}{N_{cell}\, e} = \frac{C_{junction}}{N_{cell}\, e}(V - V_{bd})$$



$$\text{resolution} = \frac{\delta Q}{\Delta Q}$$



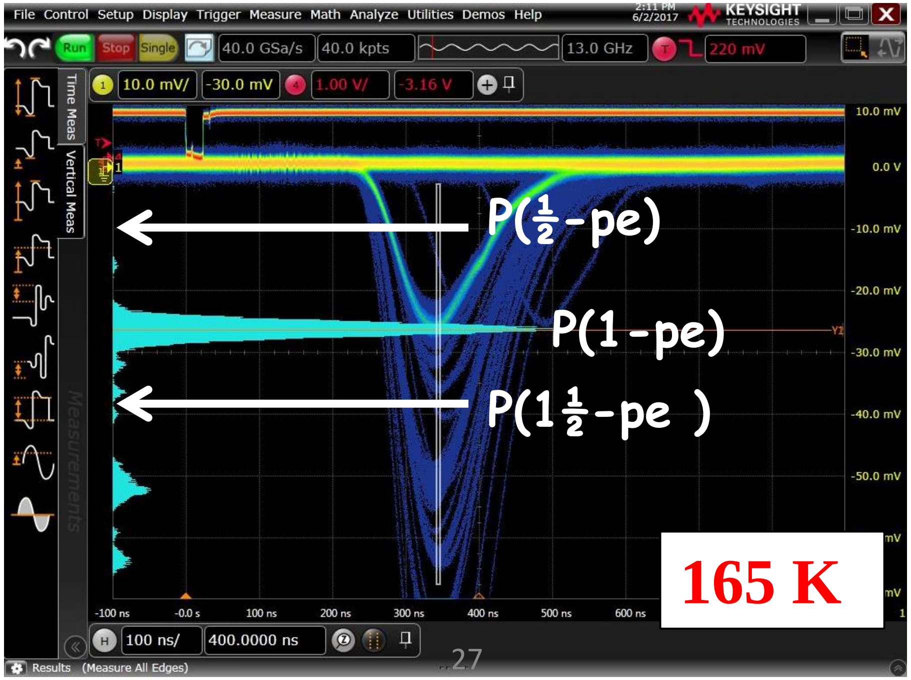
- Gain measured from well resolved photoelectron peaks
- Breakdown voltage linearly extrapolated

$$\boxed{\textbf{Gain, } C_{junction}\textbf{, } V_{break\ down}}$$

Technique: time-correlated crosstalk

Attenuate to « 1-photon/pulse
Determine 1-pe signal level
Measure count rate at ½-pe & 1½-pe levels (20 ns gate)

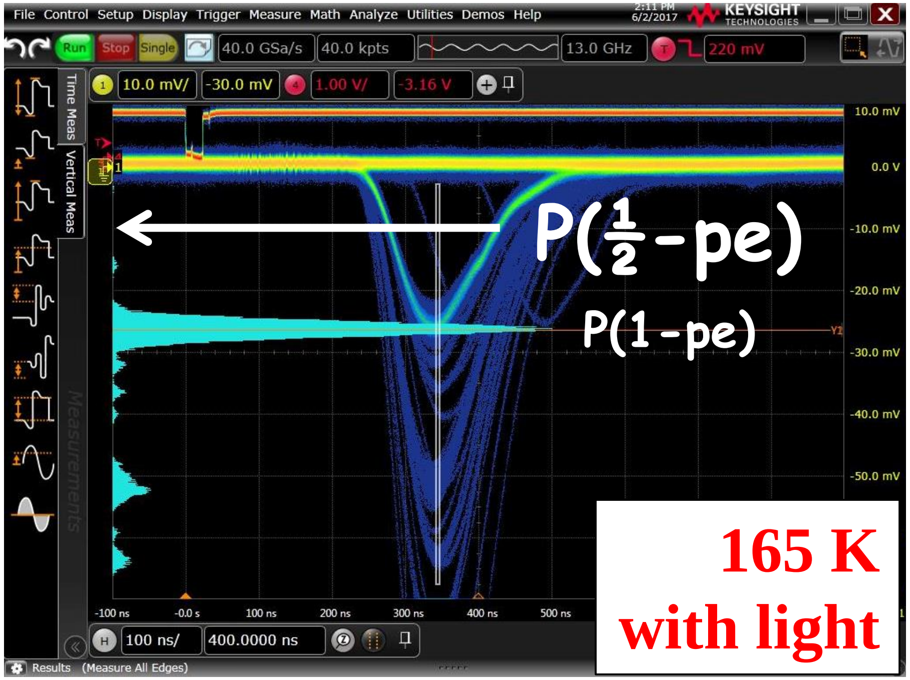
$$\text{crosstalk} = \frac{\text{count rate } {}^{3}\!/_{2}\text{-pe}}{\text{count rate } {}^{1}\!/_{2}\text{-pe}}$$



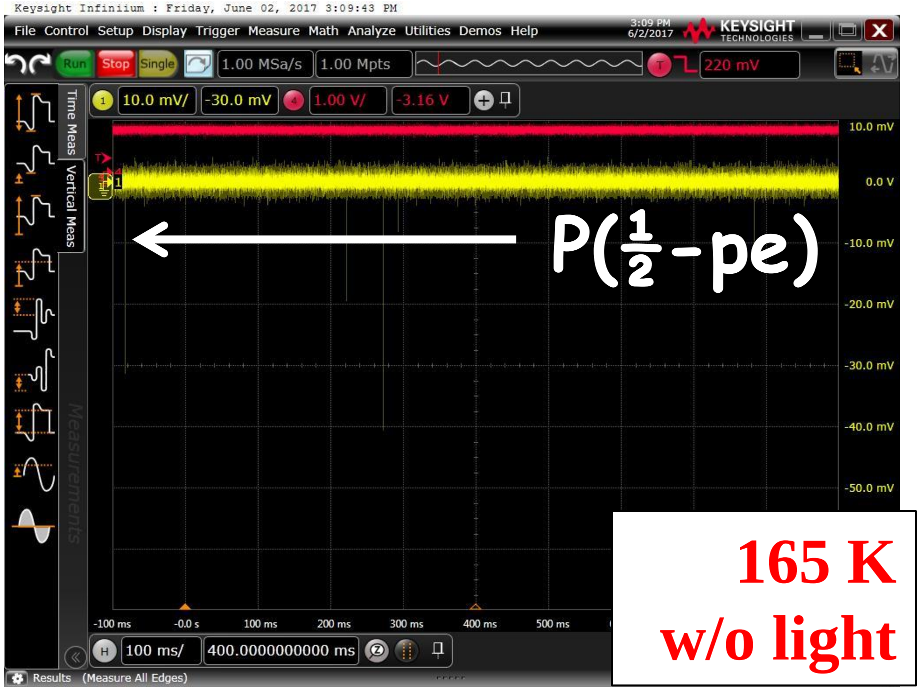
Technique: Dark Count Rate (DCR)

Attenuate to « 1-photon/pulse
Determine 1-pe signal level at every OV

DCR = count rate at ½-pe level (but in DARK)



165 K
with light



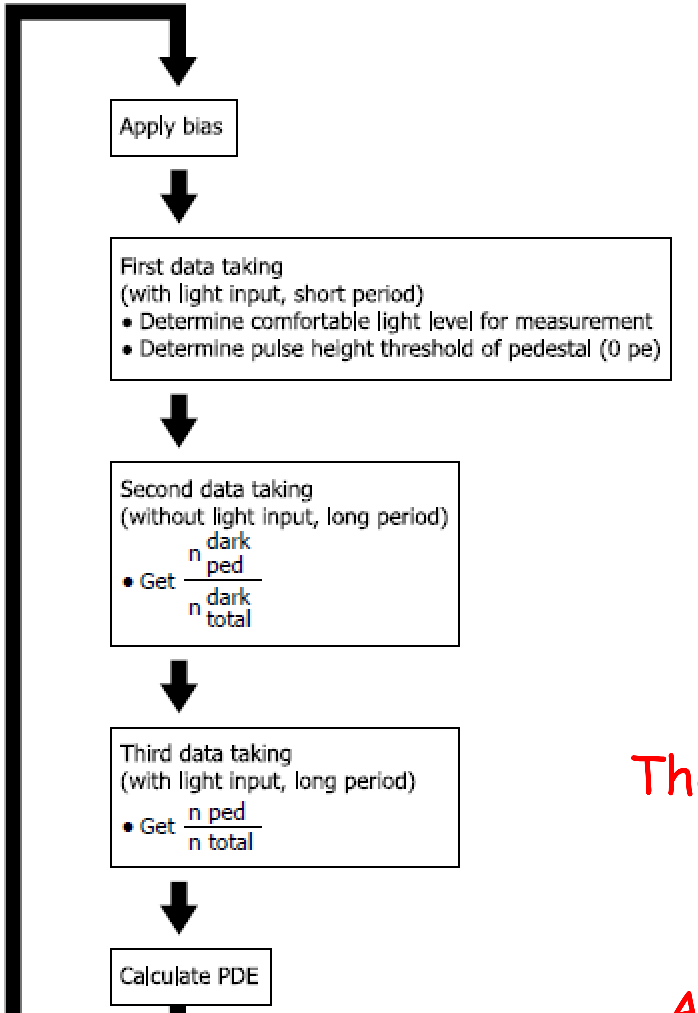
165 K
w/o light

PDE Exclusion of correlated noise (OCT & AP), measure charge pulse

PDE measurement flow chart

$$PDE = \frac{\#\,pe}{\#\,h\nu} = QE(\lambda) \times F_{geo.} \times \varepsilon_{e-p}(\lambda, \Delta V)$$

Poisson Dist: $P_{n,ph}(x,\kappa) = \frac{\kappa^n e^{-\kappa}}{n!}$


Apply bias

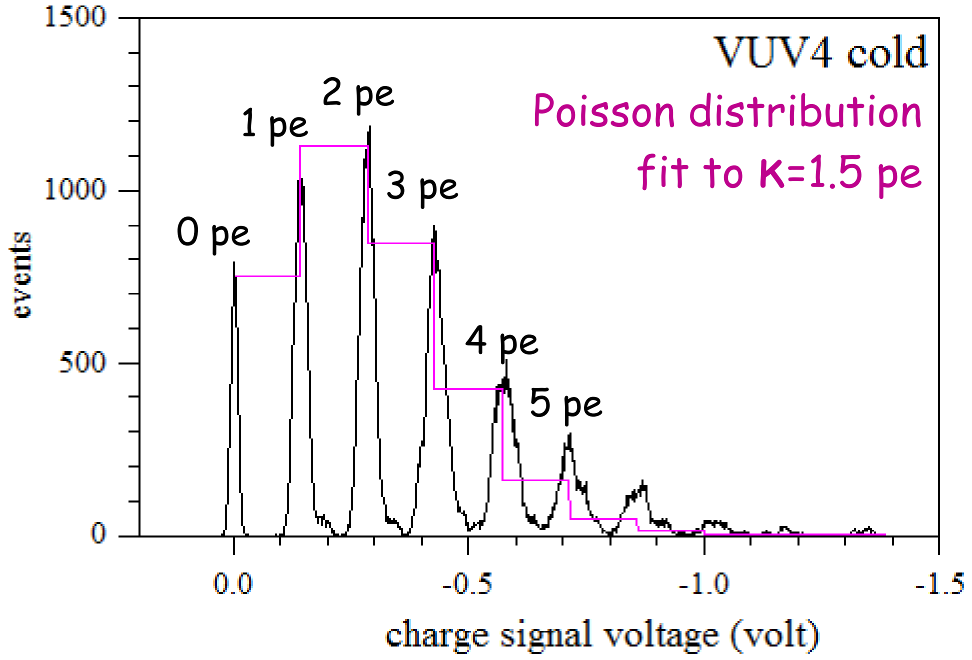
First data taking
(with light input, short period)
- Determine comfortable light level for measurement
- Determine pulse height threshold of pedestal (0 pe)

Second data taking
(without light input, long period)
- Get $\frac{n^{dark}_{ped}}{n^{dark}_{total}}$

Third data taking
(with light input, long period)
- Get $\frac{n\ ped}{n\ total}$

Calculate PDE

HPK Tech. note



The Poisson distribution is a good estimate on the average # of pe

Alternative: $$n_{pe} = -\ln\left(\frac{N_{ped}}{N_{total}}\right) + \ln\left(\frac{N^{dark}_{ped}}{N^{dark}_{total}}\right)$$