Update from the UCSC/SLAC ESTB T-506 Irradiation Study

FCAL Collaboration Meeting
CERN
March 6-7, 2017

Bruce Schumm
UC Santa Cruz Institute for Particle Physics

T-506 Motivation

BeamCal maximum dose ~100 MRad/yr

A number of ongoing studies with novel sensors: GaAs, Sapphire, SiC

➔ Are these radiation tolerant?

➔ Might mainstream Si diode sensors in fact be adequate, even given its propensity to develop significant leakage currents?

Si Detector Nomenclature:

- **"N" ("P") for n(p)-bulk**
- **"F" ("C") for Float-Zone (Czochralski) fabrication**

Radiation Damage in Electromagnetic Showers

Folk wisdom: Radiation damage proportional to non-ionizing component of energy loss in material ("NIEL" model)

BeamCal sensors will be embedded in tungsten radiator

Energy loss dominated by electromagnetic component but non-ionizing contribution may be dominated by hadronic processes

Hadronic Processes in EM Showers

There seem to be three main processes for generating hadrons in EM showers (all induced by **photons**):

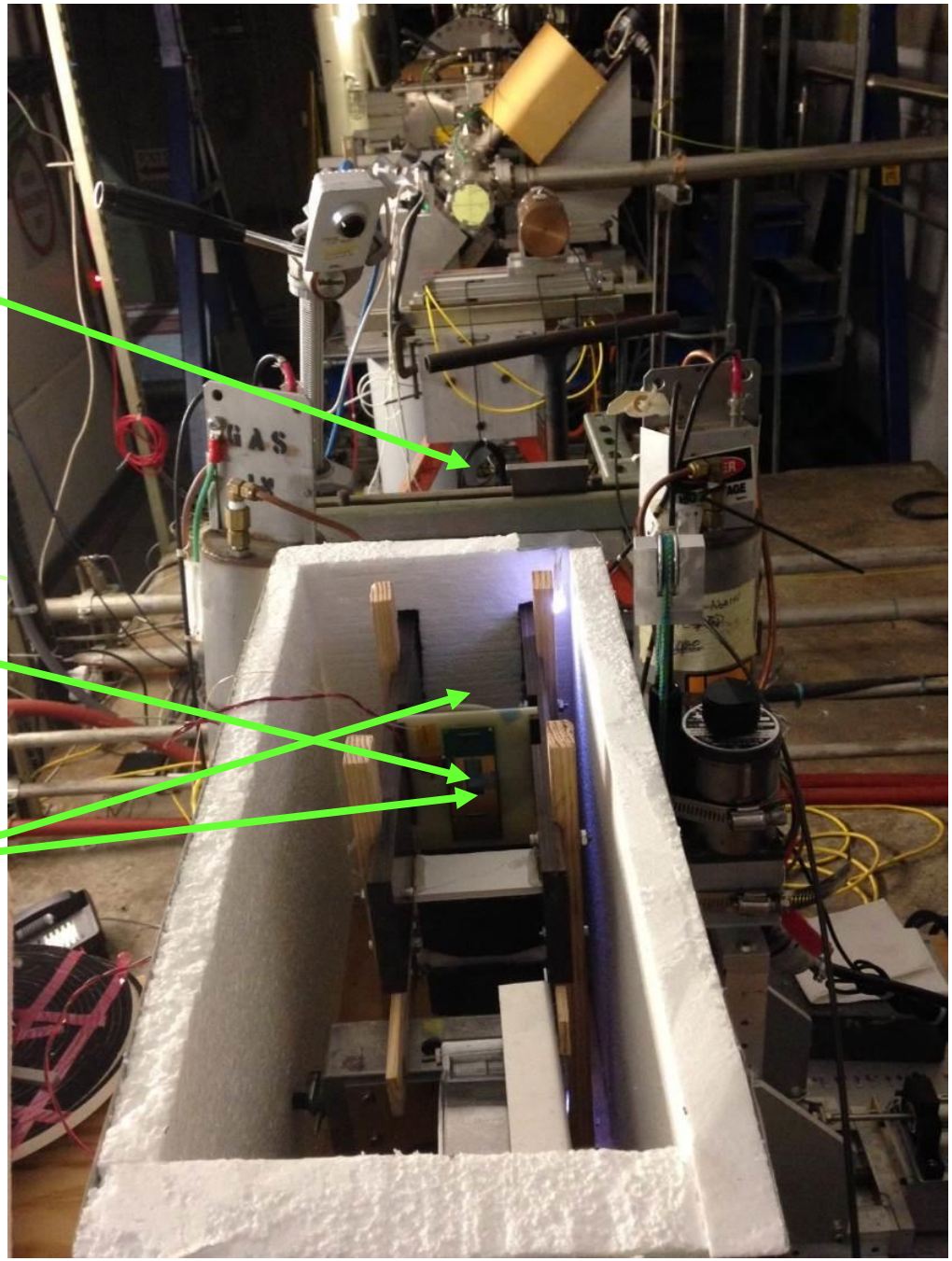
- Nuclear ("giant dipole") resonances
  Resonance at 10-20 MeV (~$E_{critical}$)
- Photoproduction
  Threshold seems to be about 200 MeV
- Nuclear Compton scattering
  Threshold at about 10 MeV; Δ resonance at 340 MeV

➔ These are largely isotropic; must have most of hadronic component develop near sample

2 X_0 pre-radiator; introduces a little divergence in shower

Sensor sample

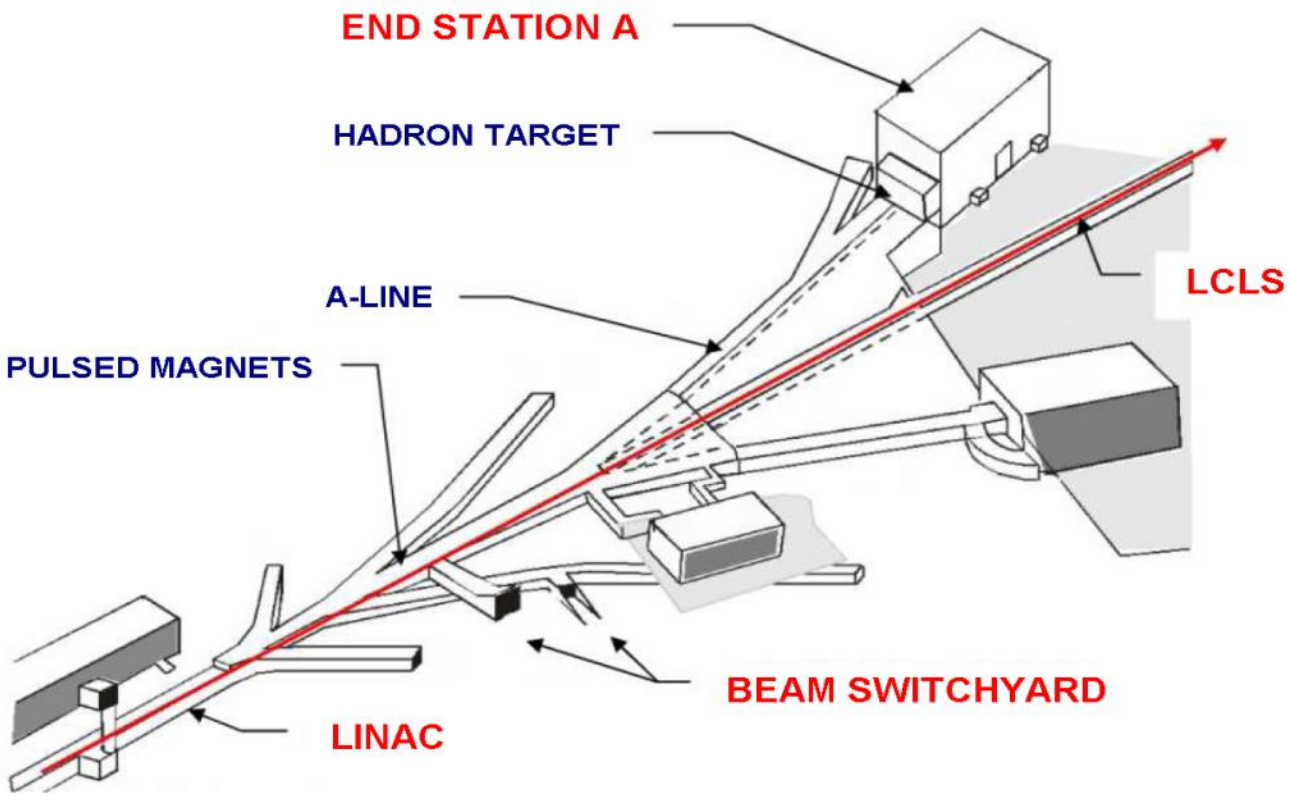
Not shown: 4 X_0 “post radiator” and 8 X_0 “backstop”



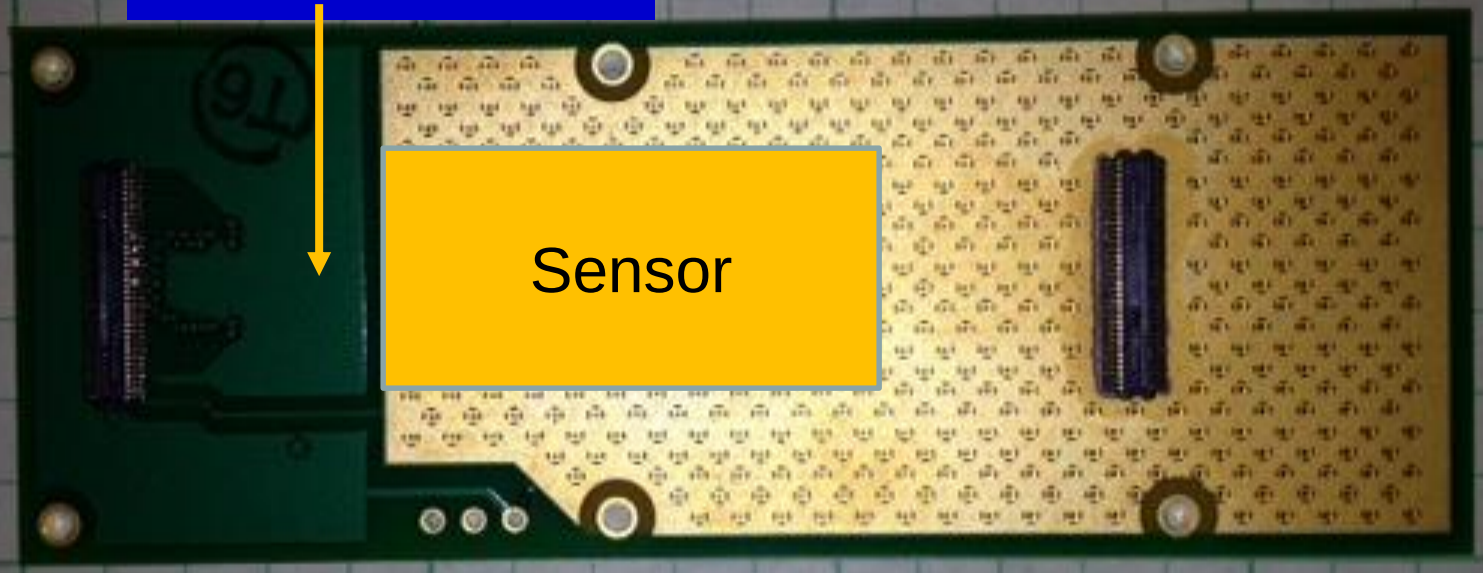
Irradiating the Sensors

LCLS and ESA

Use pulsed magnets in the beam switchyard to send beam in ESA.



Daughter Board Assembly



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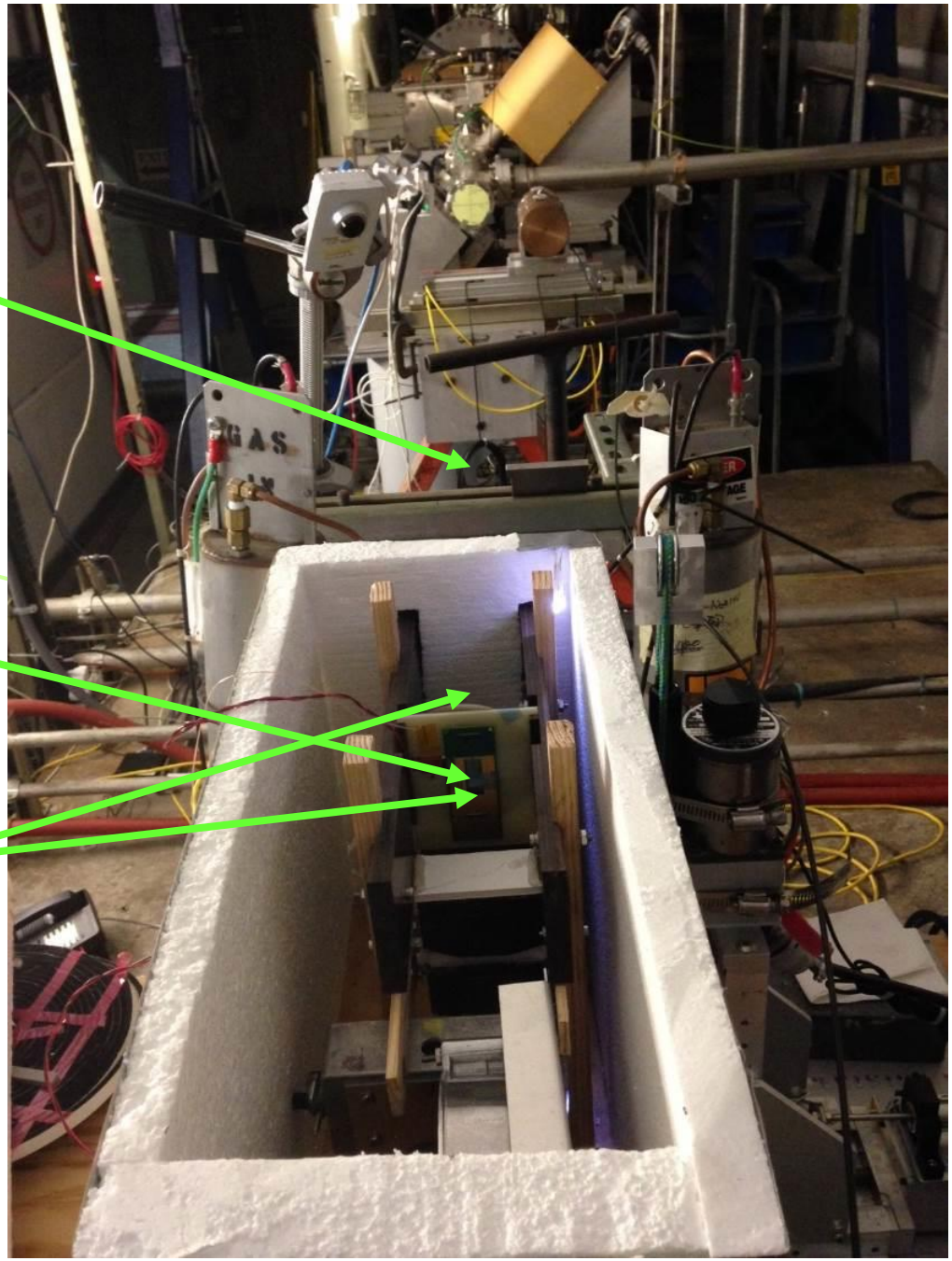


Summary of High-Dose Expsures

2015, 2016 offered high-rate exposures: 10 24hr days of ~20 Mrad/hr

Beam Energy (GeV)	2014-15 Shower Conversion Factor α	Dose per nC Delivered Charge (krad)
3	4.6	0.73
5	10.0	1.60
7	15.5	2.48
9	21.1	3.38
11	26.7	4.27
13	31.8	5.09
15	37.7	6.03
17	43.0	6.88

Sensor Type	Notable Exposures (Mrad)
GaAs	**20, 100**
SiC	**80**
Sapphire	**300**
Si PF	**270, 570**
Si NF	**300**
Si PC	**600**
Si NC	**290**
LumiCal Si Diode	**300**

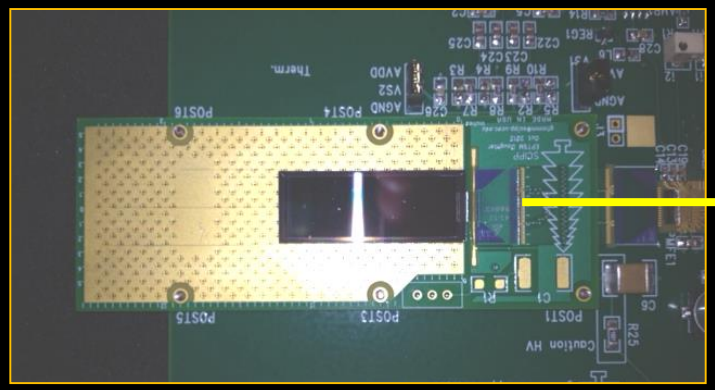
Operated at 12-15 GeV at close to 1 nA

Red → results available; others underway or await evaluation

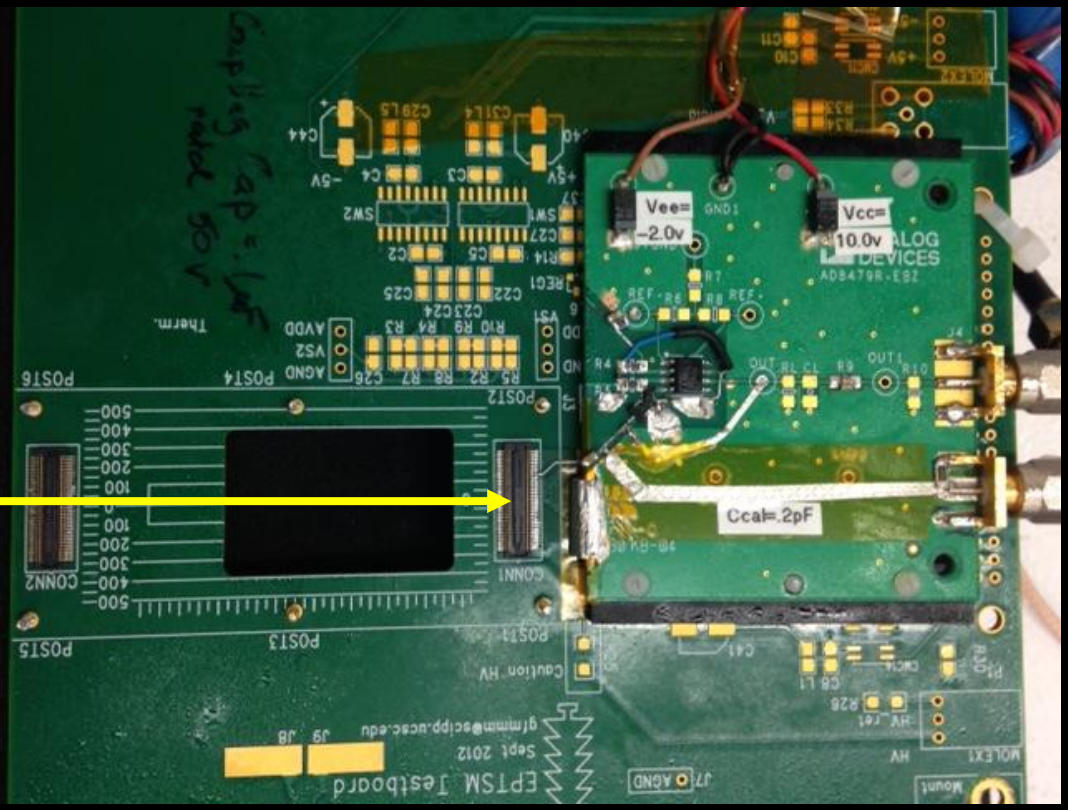
Assessing the Radiation Damage

Charge Collection Measurement

For pad sensors use single-channel readout

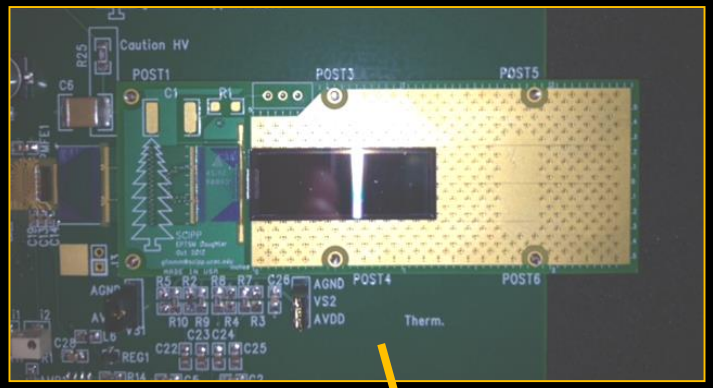


Daughter-board

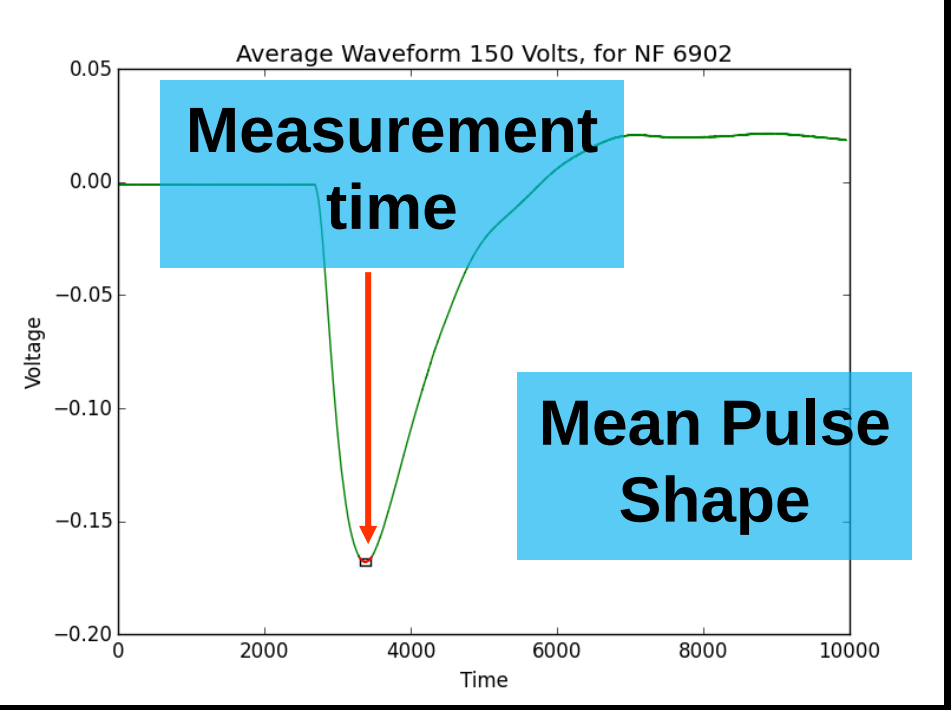


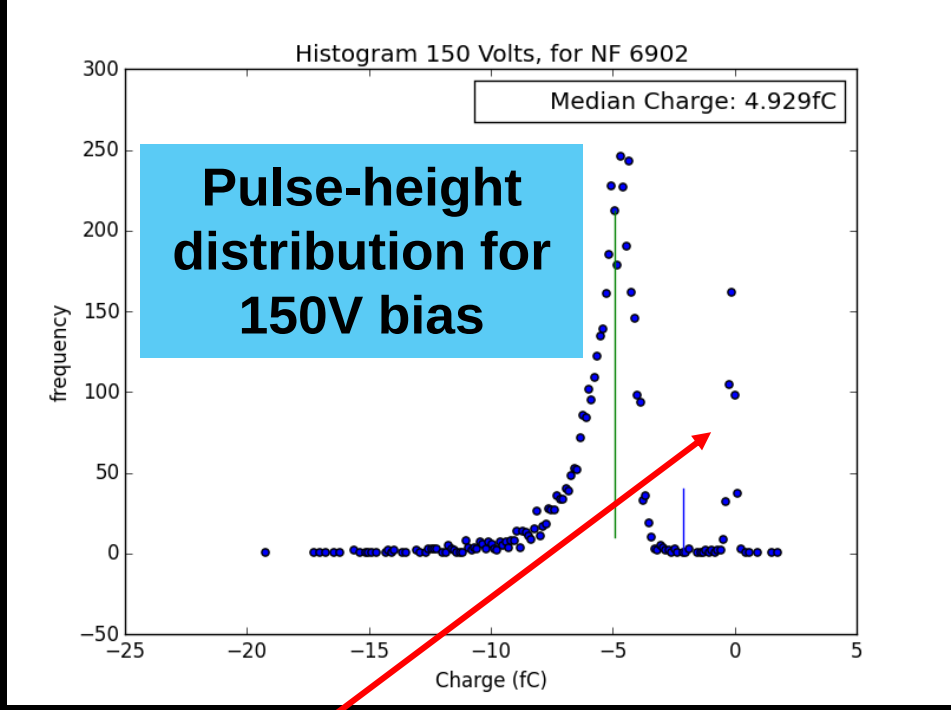
Low-noise amplifier circuit (~300 electrons)

Charge Collection Apparatus



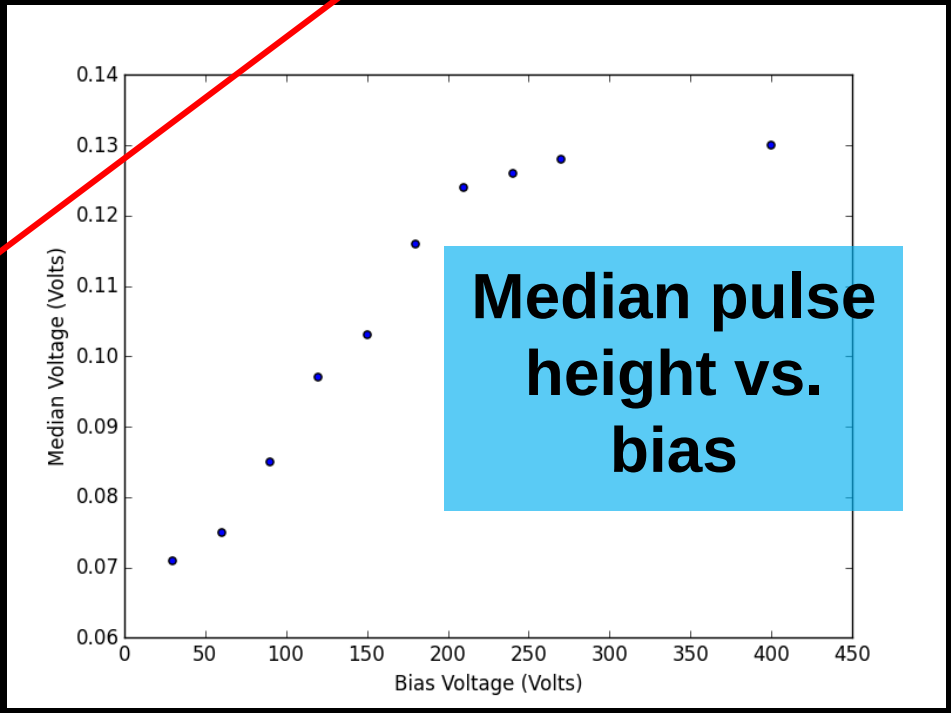
- Readout: 300 ns





Single-channel readout example for, e.g., N-type float-zone sensor

Readout noise: ~300 electrons (plus system noise we are still addressing)

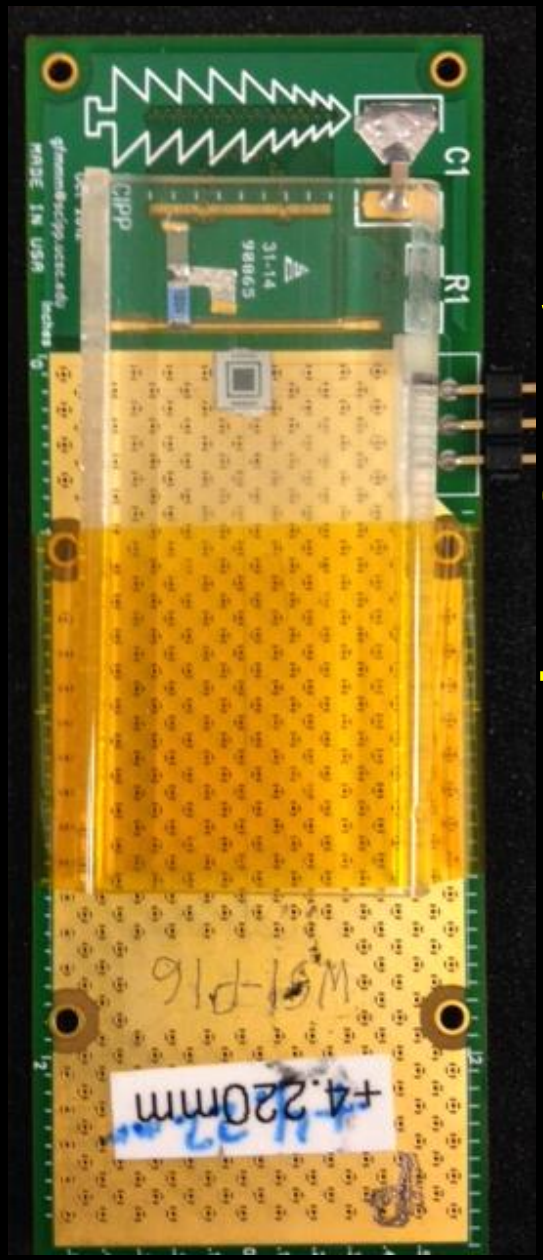


Results

Si Diode Results

- P-Type Float Zone (PF) to 270 and 570 Mrad
- N-Type Float Zone (NF) to 300 Mrad
- LumiCal Sensor Fragment

PF Si Diode
Area 0.025 cm^2



SI DIODE SENSORS

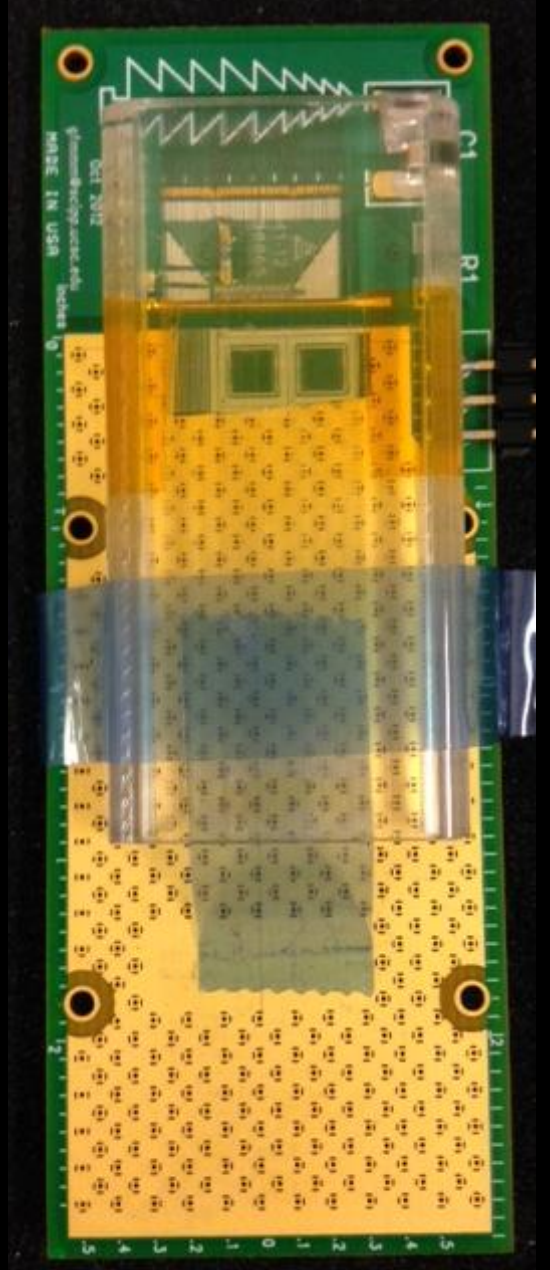
Sensors produced by the Micron Corporation

Thickness:

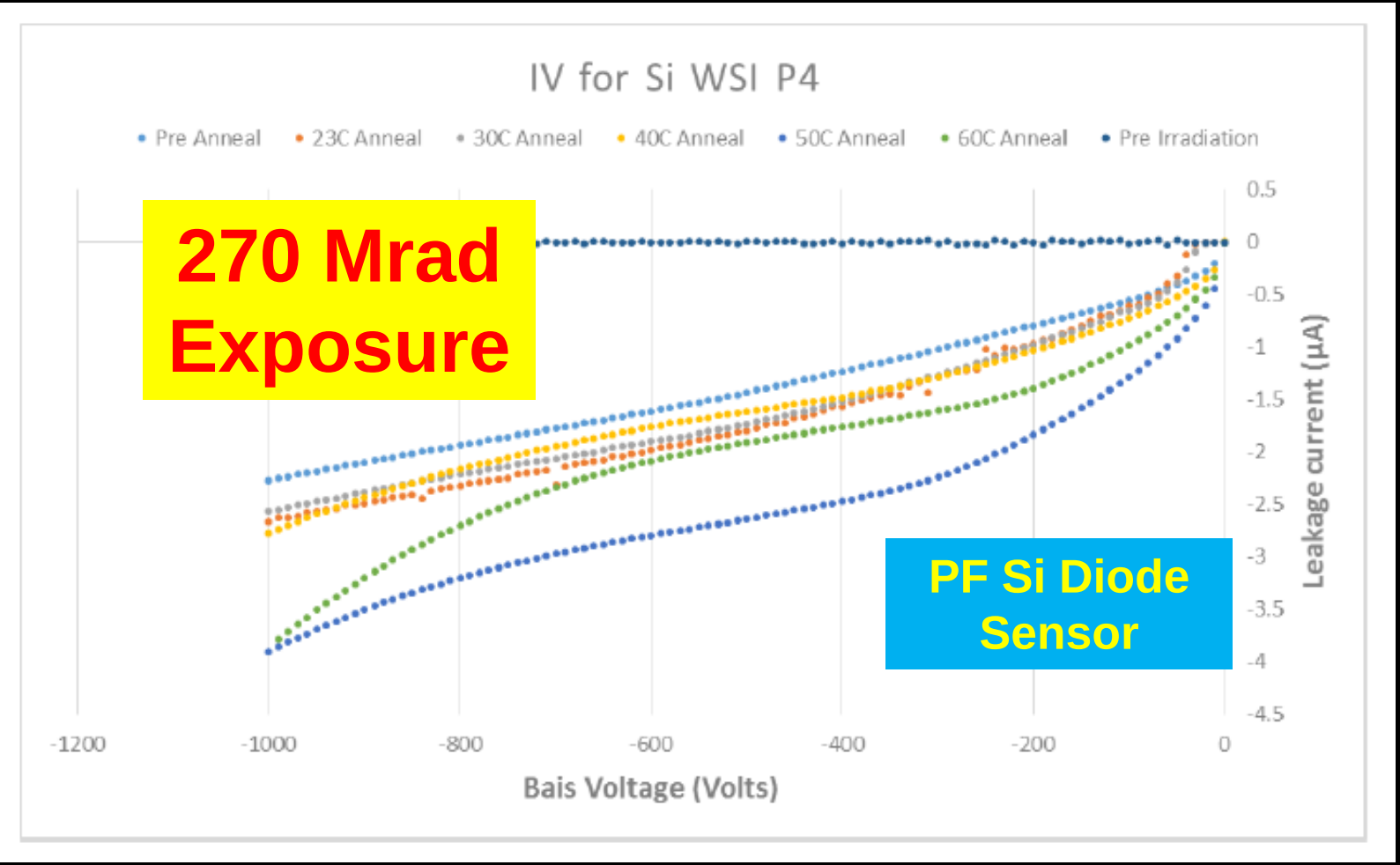
PF: ~300 μm

NF: ~400 μm

NF Si Diode
Area 0.09 cm^2

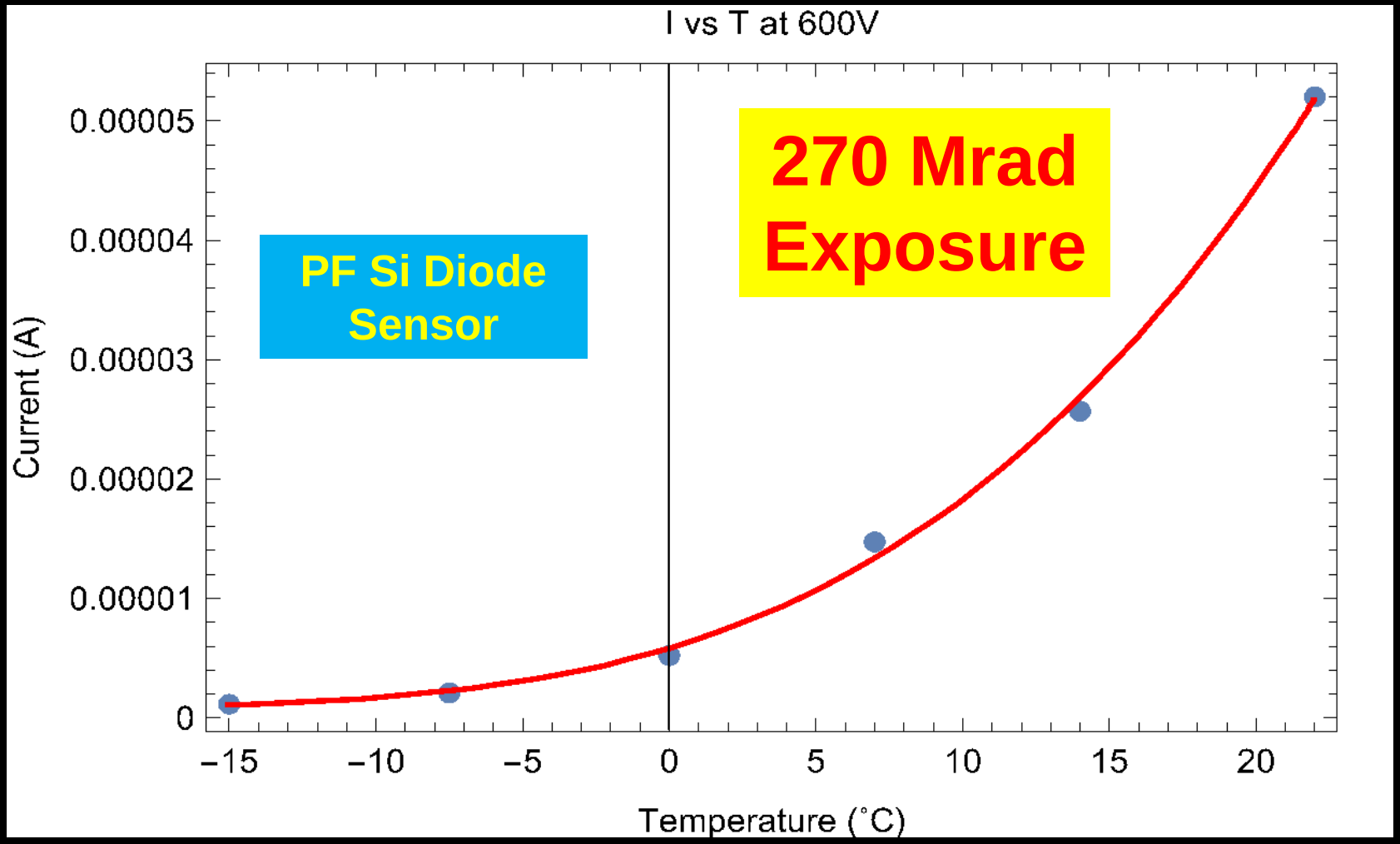


PF I-V after 270 Mrad Exposure (-10 C)



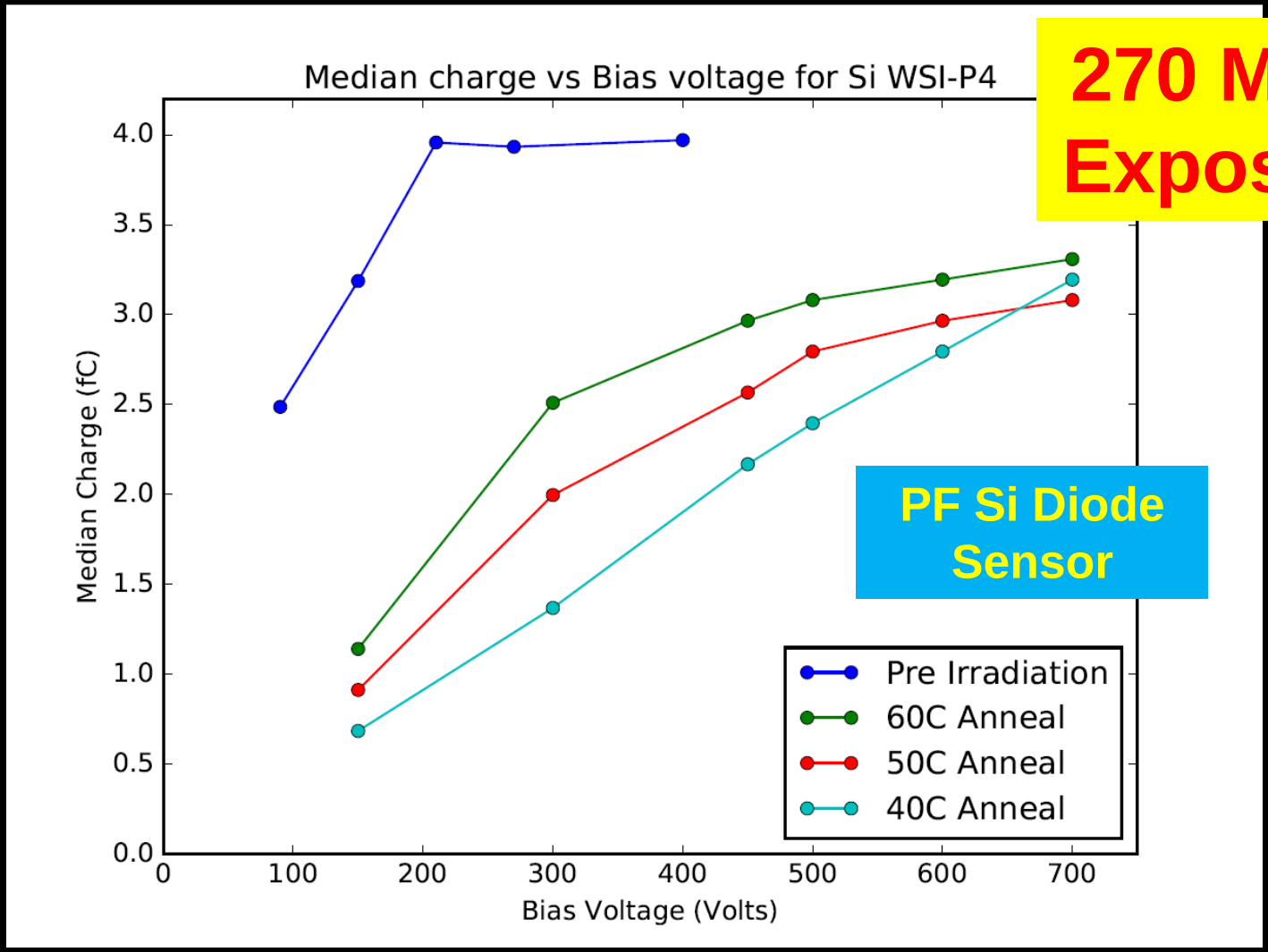
- At 600 V, about 80 µA (0.05 W) per cm^2 (sensor area ~ 0.025 cm^2)
- Not much improvement with annealing

PF I vs. Temperature; 270 Mrad



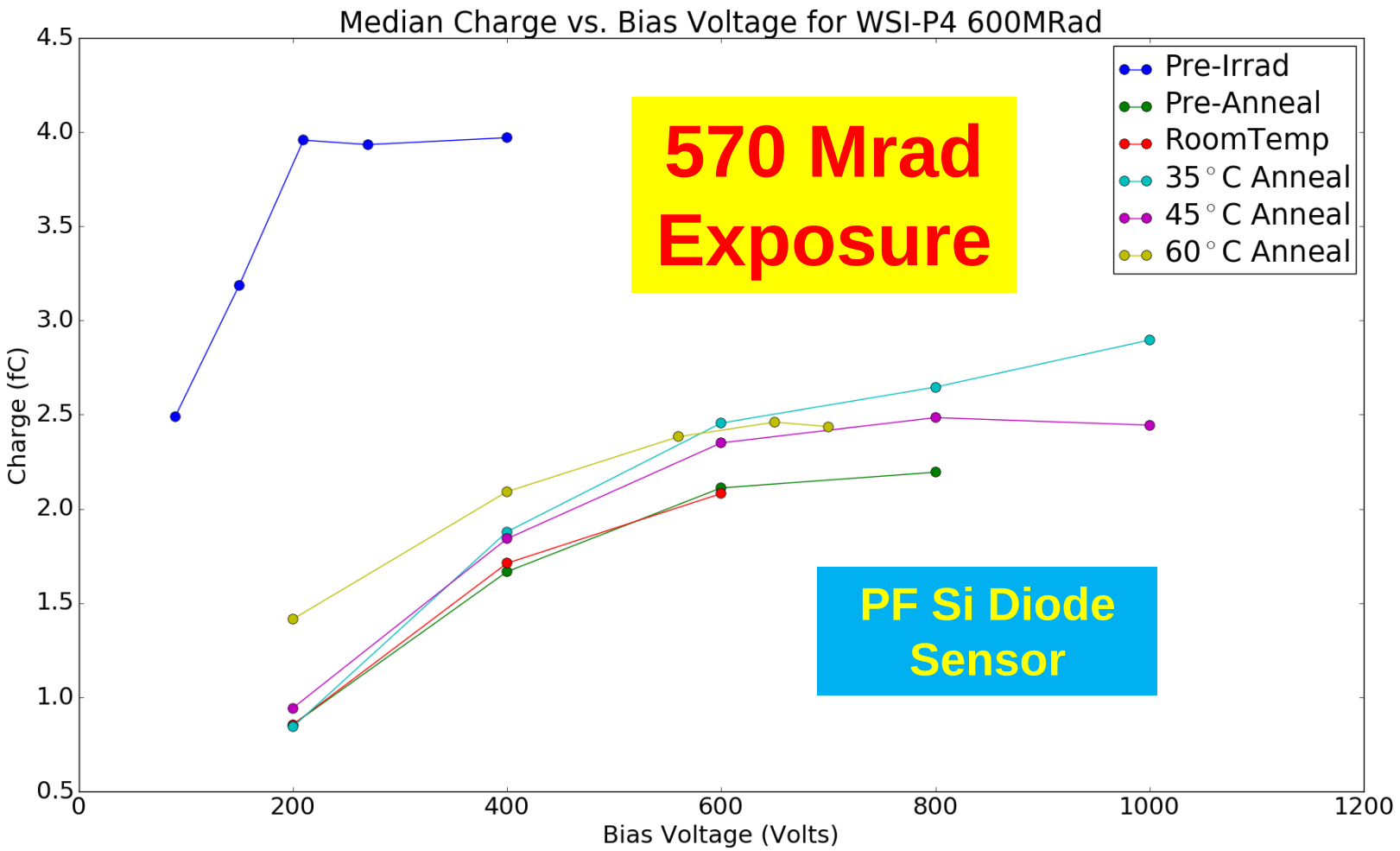
Current doubling for every 7ºC expected for Si Diode

PF Charge Collection after 270 Mrad



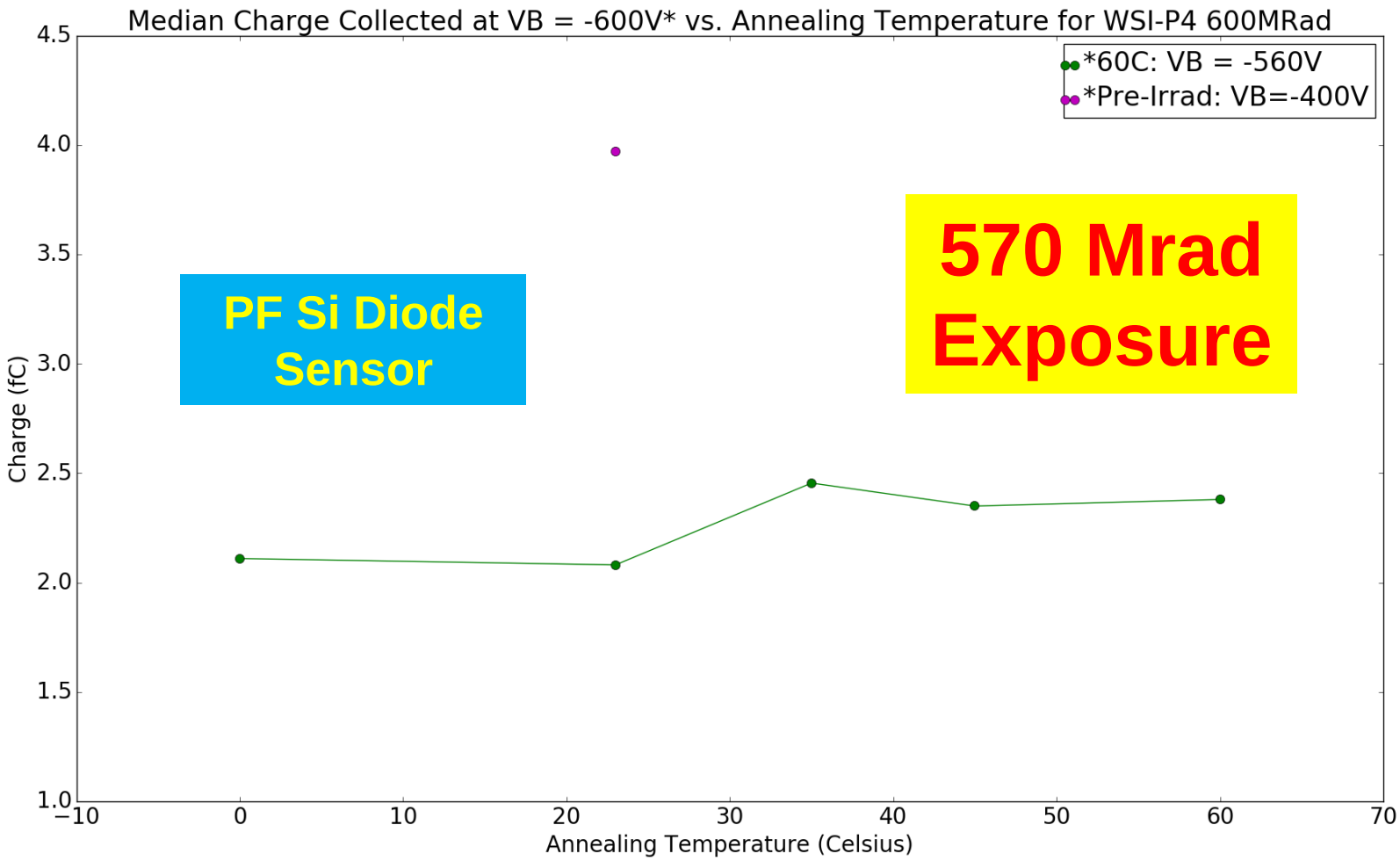
@600 V, ~20% charge collection loss (60C annealing)

PF Charge Collection for 570 Mrad



Currents roughly x2 that for 270 Mrad

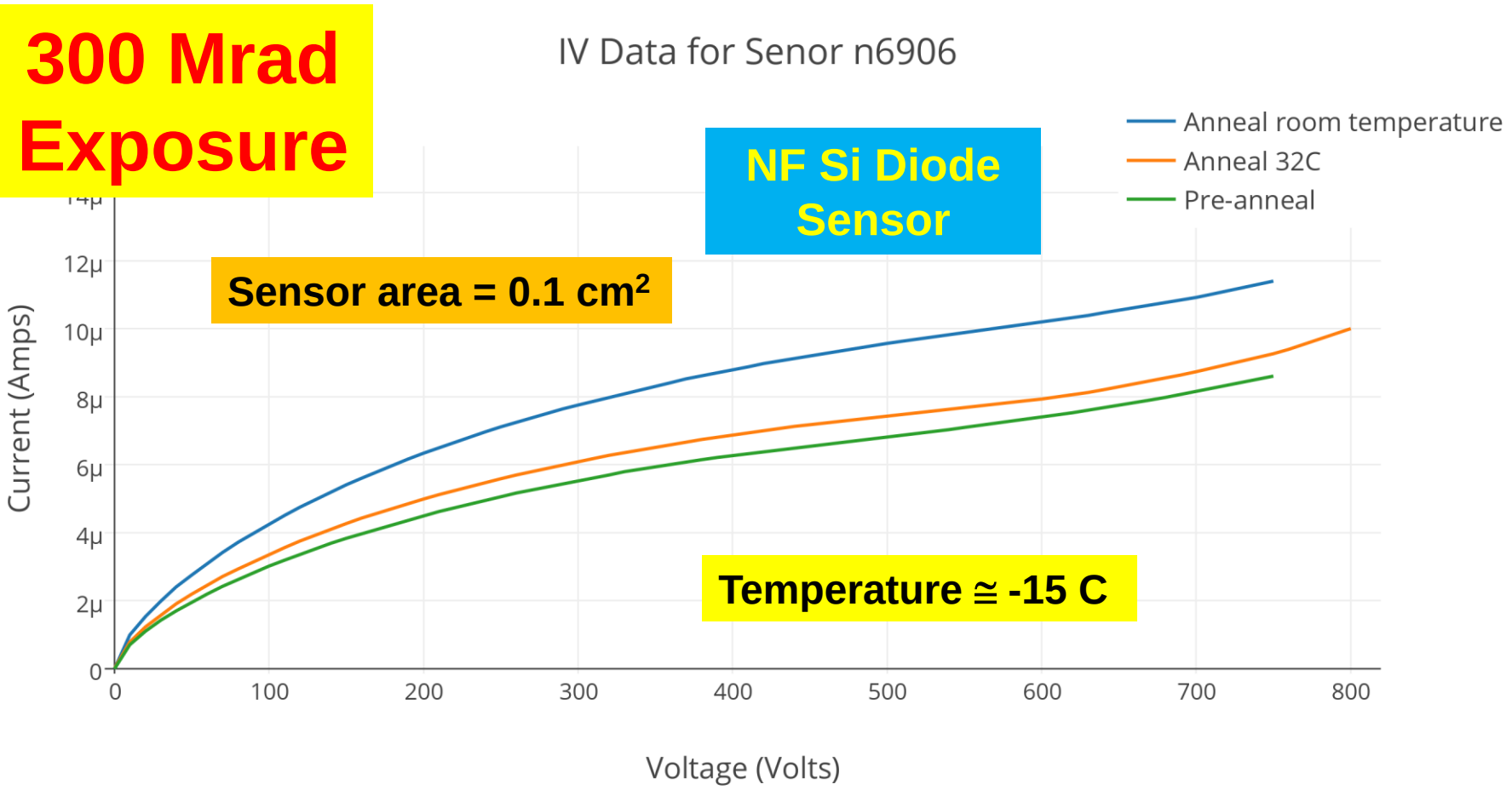
PF Charge Collection for 570 Mrad



At 600V bias, charge collection still greater than 50% after nearly 600 Mrad

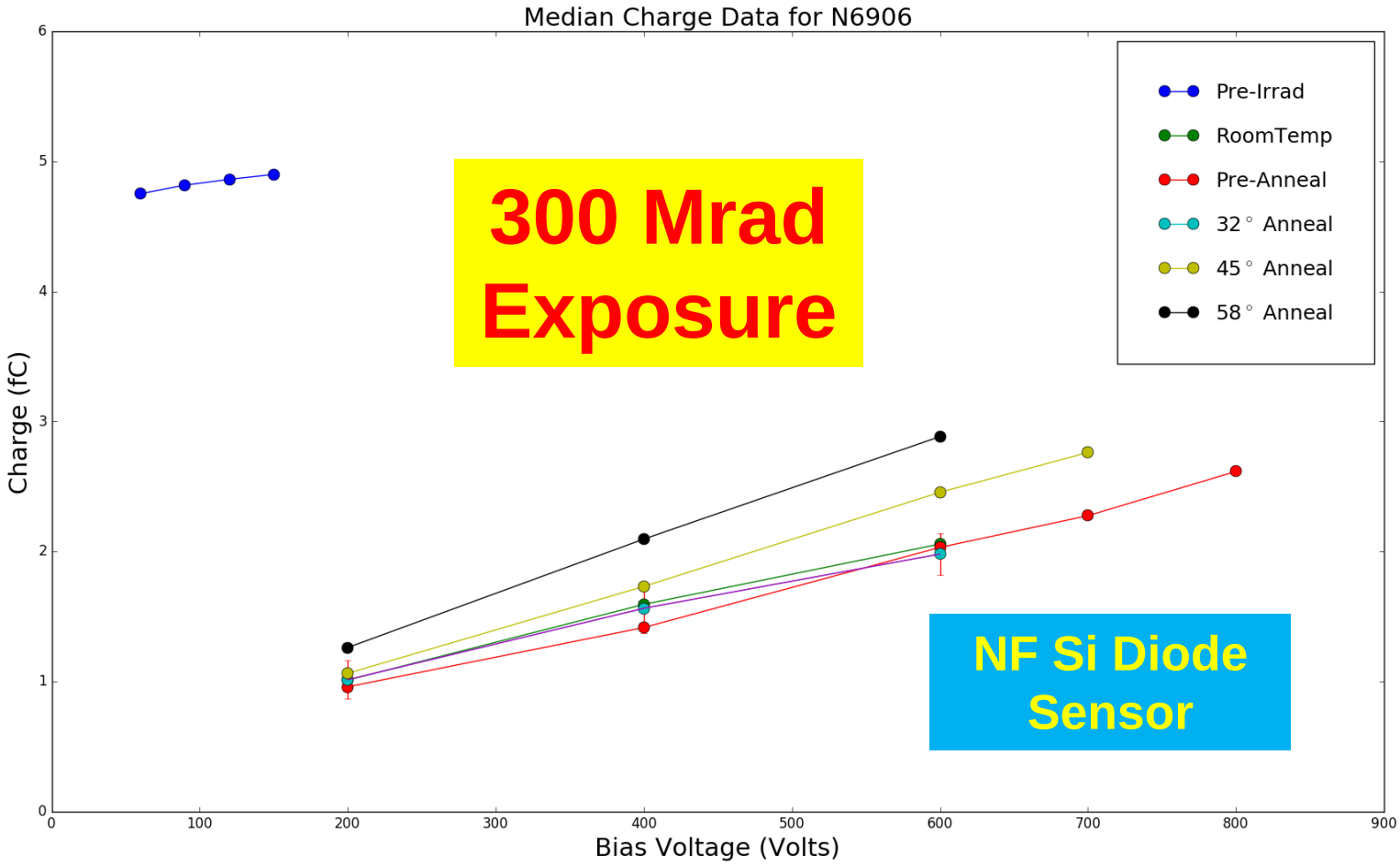
NF Leakage Current after 300 Mrad

300 Mrad Exposure



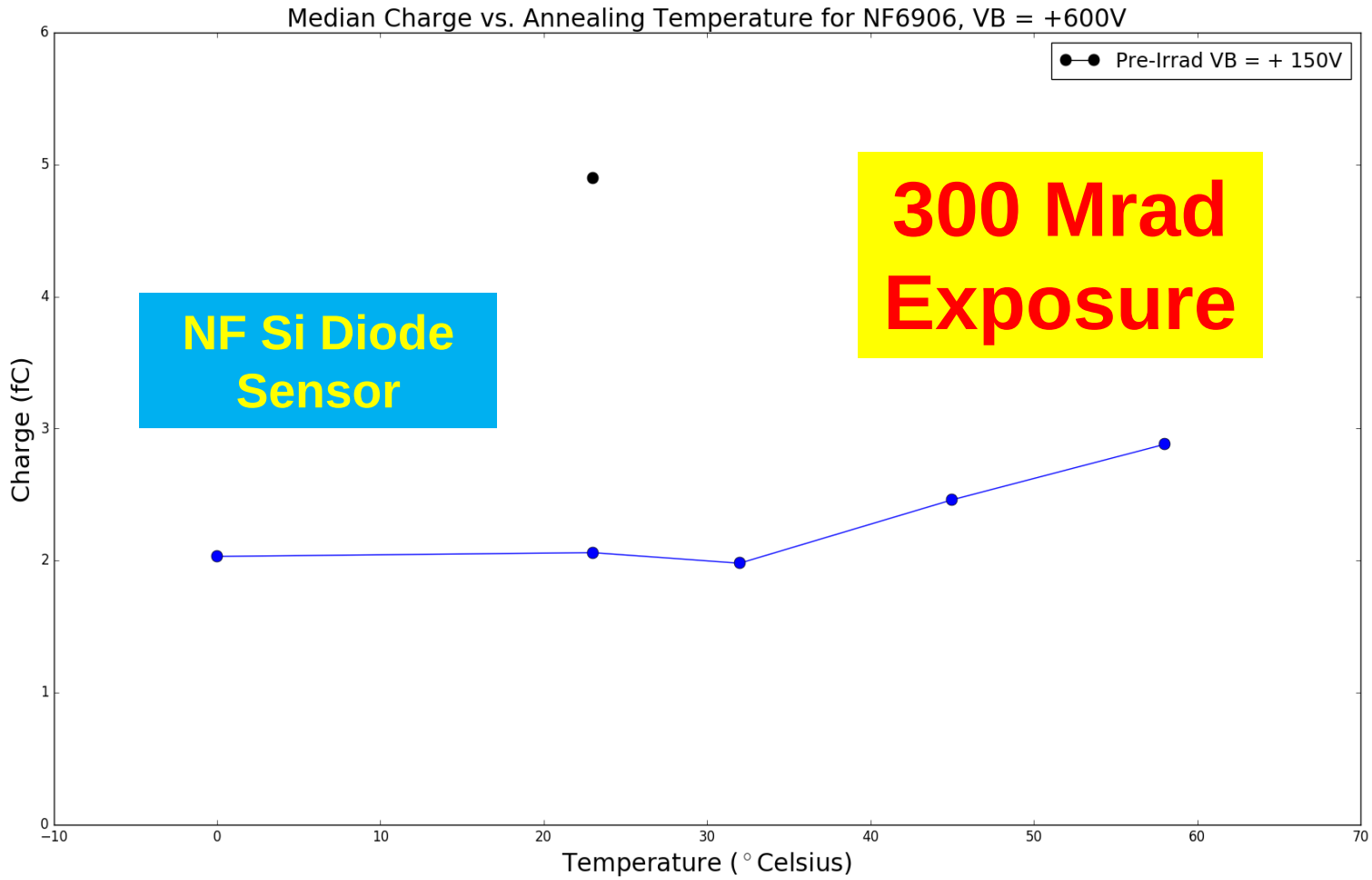
After normalizing for sensor area, results are similar to those for the PF sensor.

NF Charge Collection after 300 Mrad



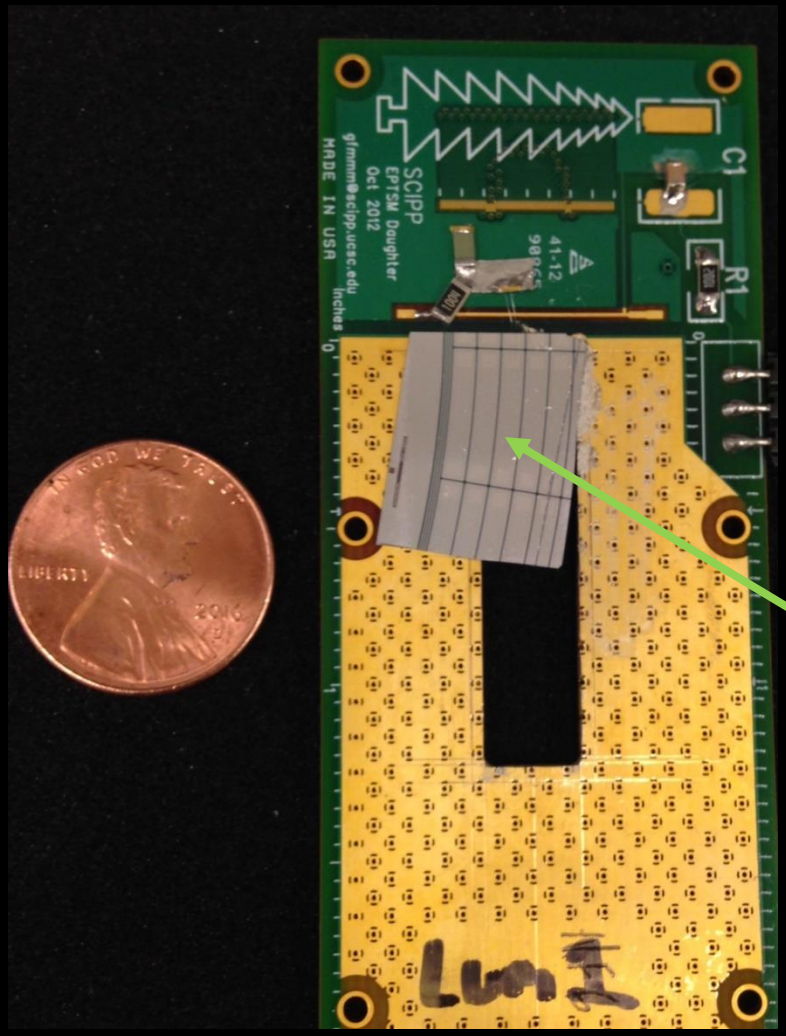
@600 V, ~40% charge collection loss (58C annealing)

NF Charge Collection after 300 Mrad



At 600V bias, (annealed) charge collection well above 50% after 300 Mrad exposure

LumiCal Sensor (N-Type)

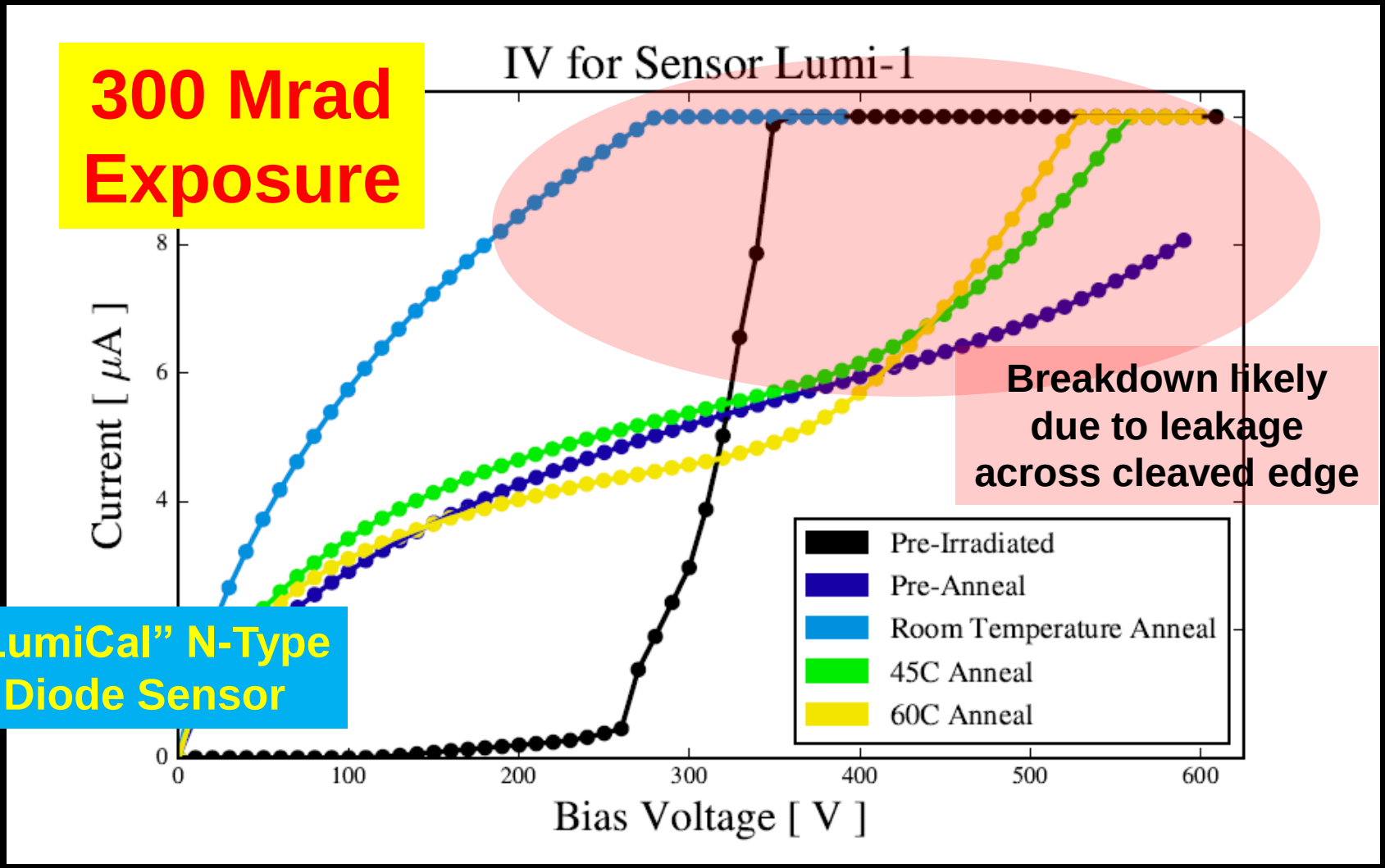


Fragment cleaved from broken sensor provided by Tel Aviv

After treatment (heat, UV light) were able to bias center strip to ~150V

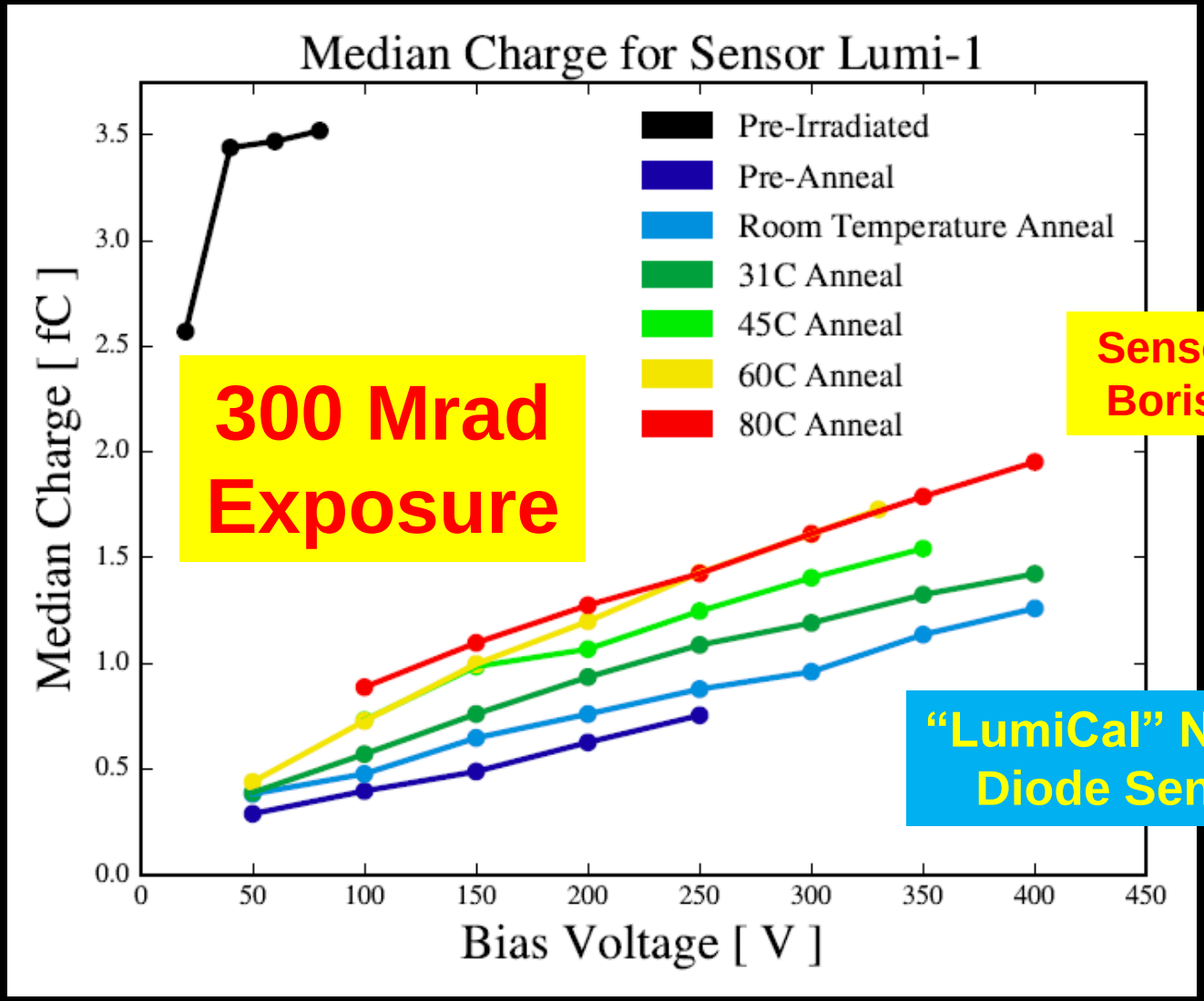
After 300 Mrad irradiation, could bias to > 300 V

N-Type LumiCal Prototype Fragment



Typical (~20 μA/cm^2) post-irradiation currents

N-Type LumiCal Prototype Fragment

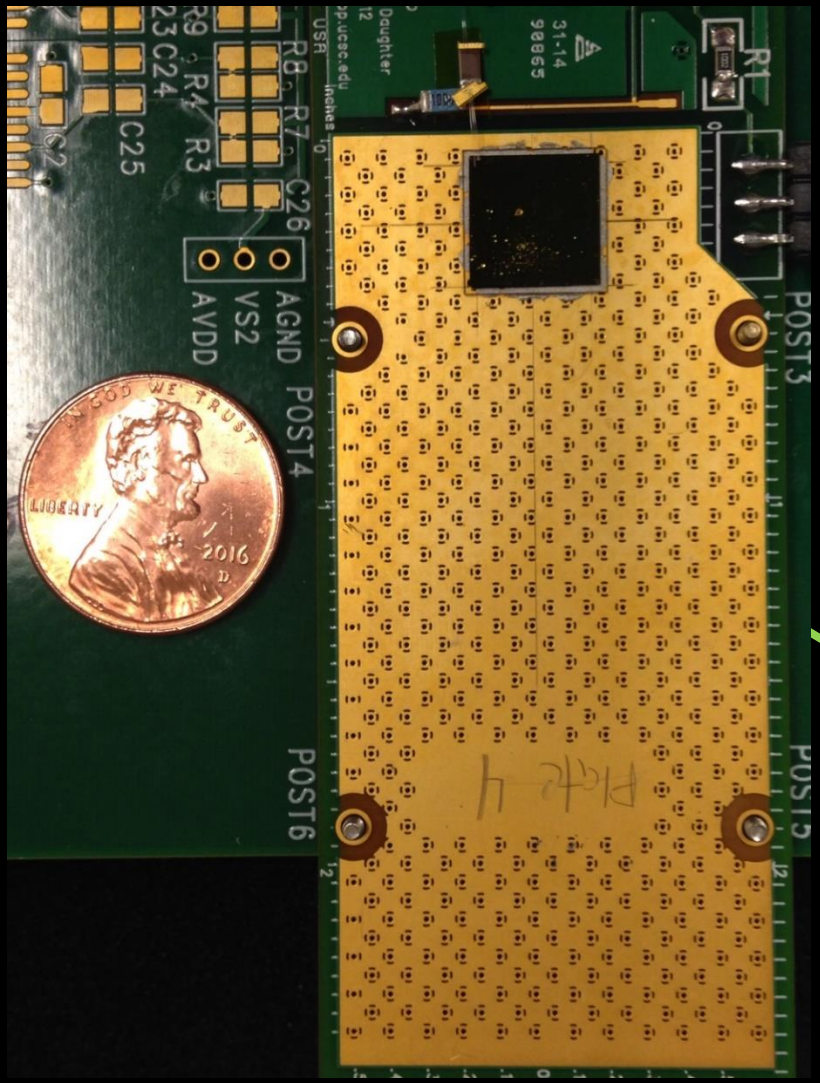


After annealing, charge collection at 600V likely well above 50% after 300 Mrad exposure

Bulk (non-Diode) Sensor Results

- Industrial Sapphire
- Gallium Arsenide
- Silicon Carbide

Industrial Sapphire



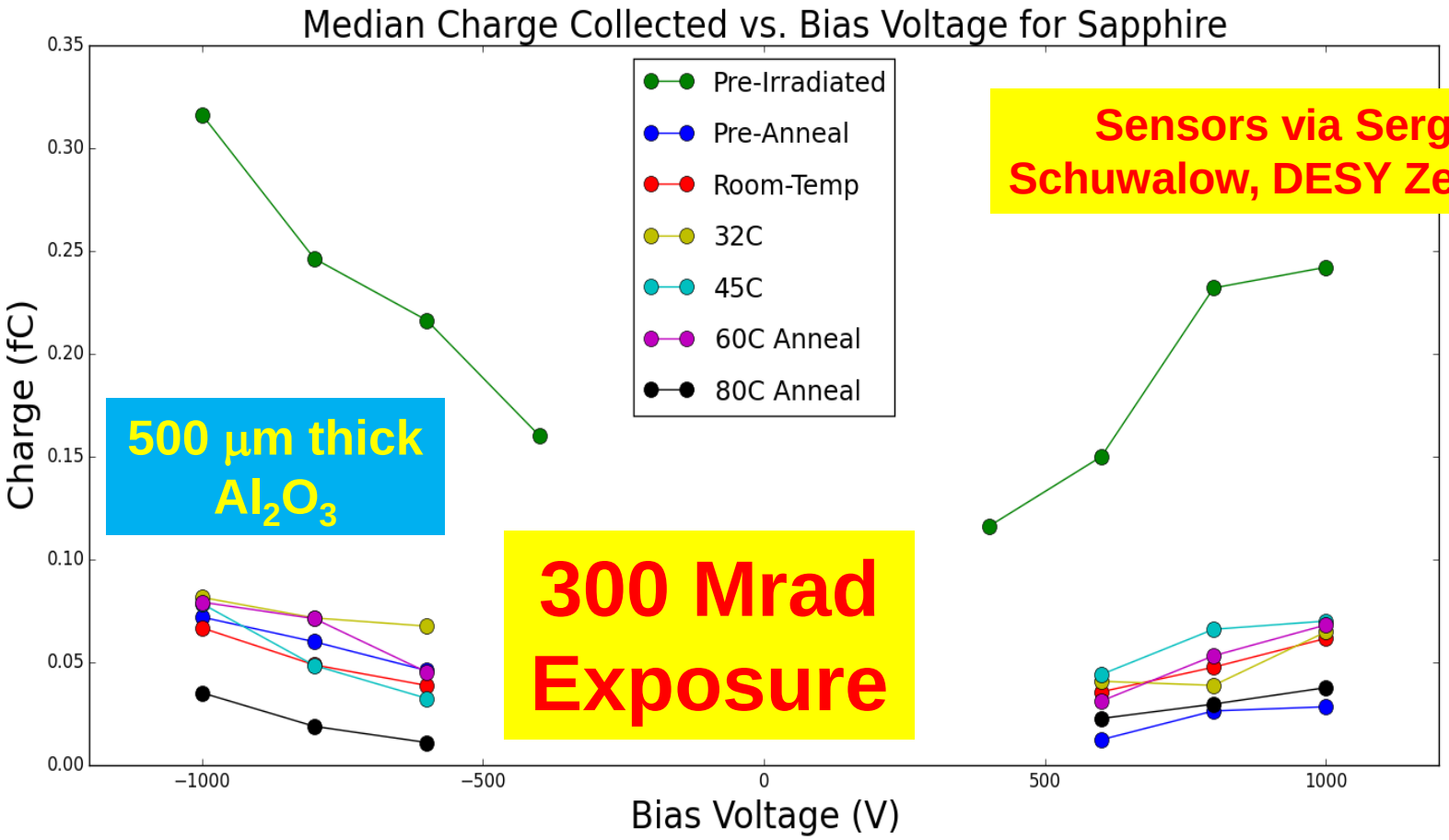
Sensor provided by Sergej Schuwalow

Fabricated by Crystal GmbH, Berlin

Layered Al-Pt-Au contact structure

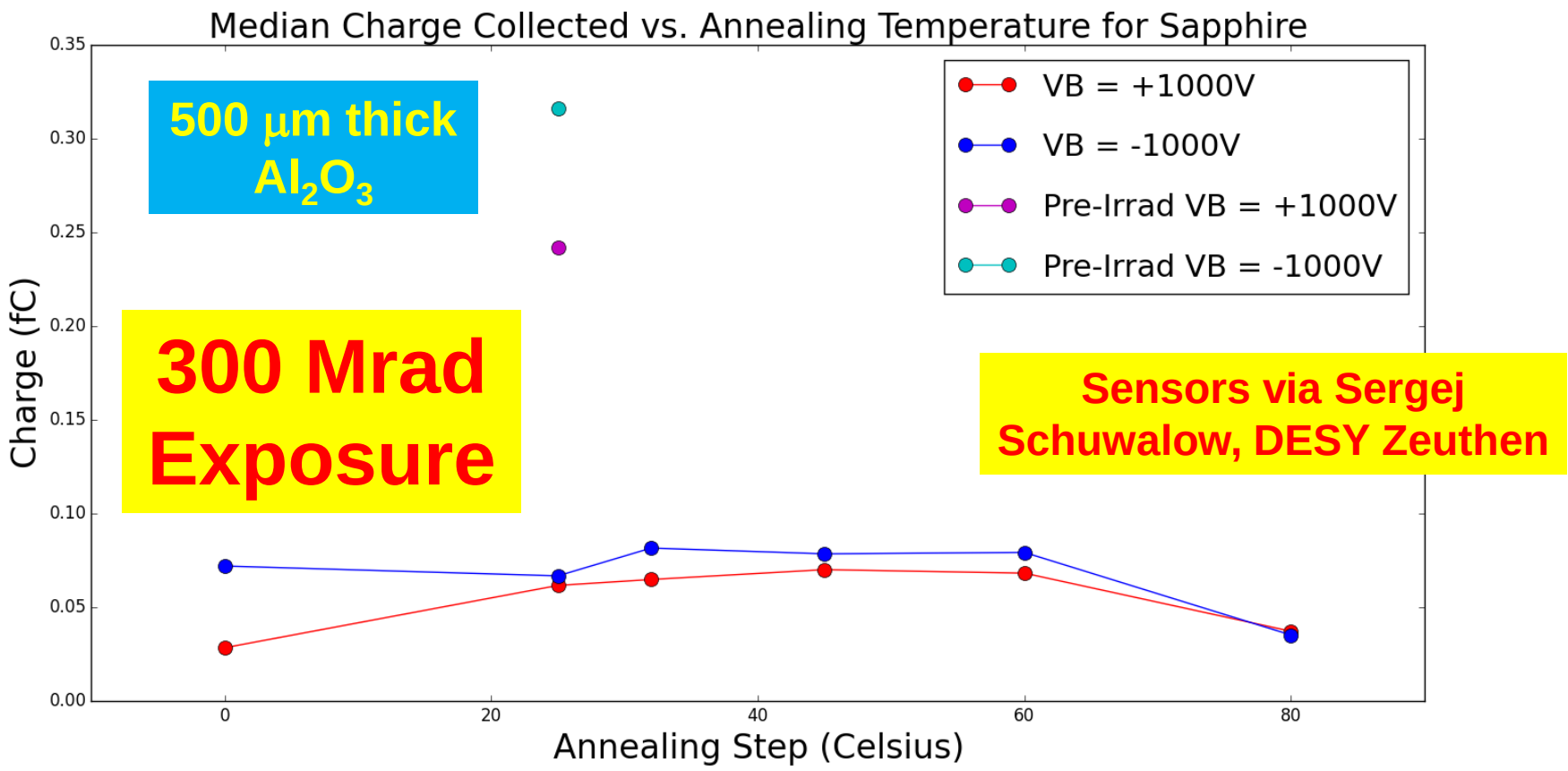
Current low (< 10 nA) after irradiation

Sapphire Charge Collection for 300 Mrad



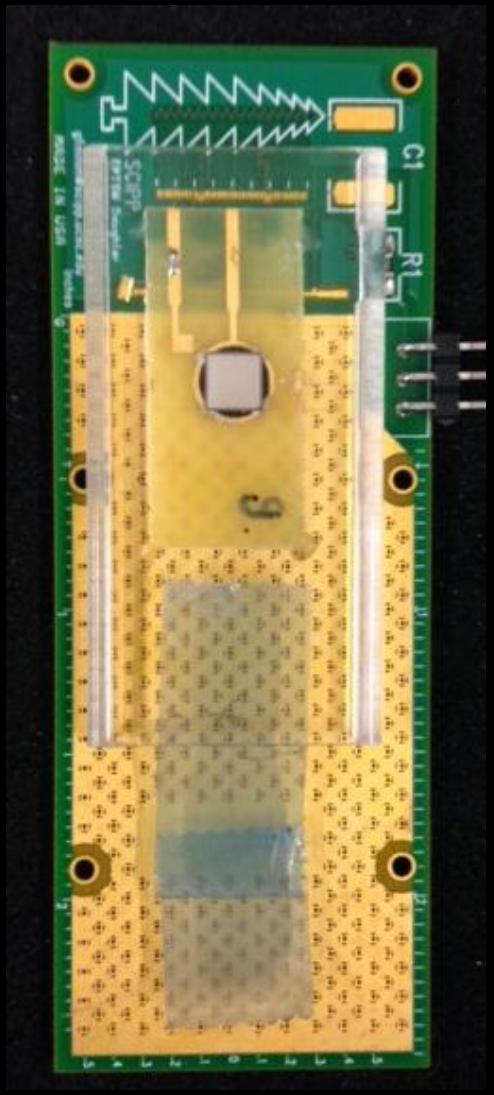
Low pre-irradiation charge-collection and significant charge loss after irradiation

Industrial Sapphire High-Bias Annealing Trends (300 Mrad)



Annealing does not seem to significantly restore charge collection

Gallium Arsenide

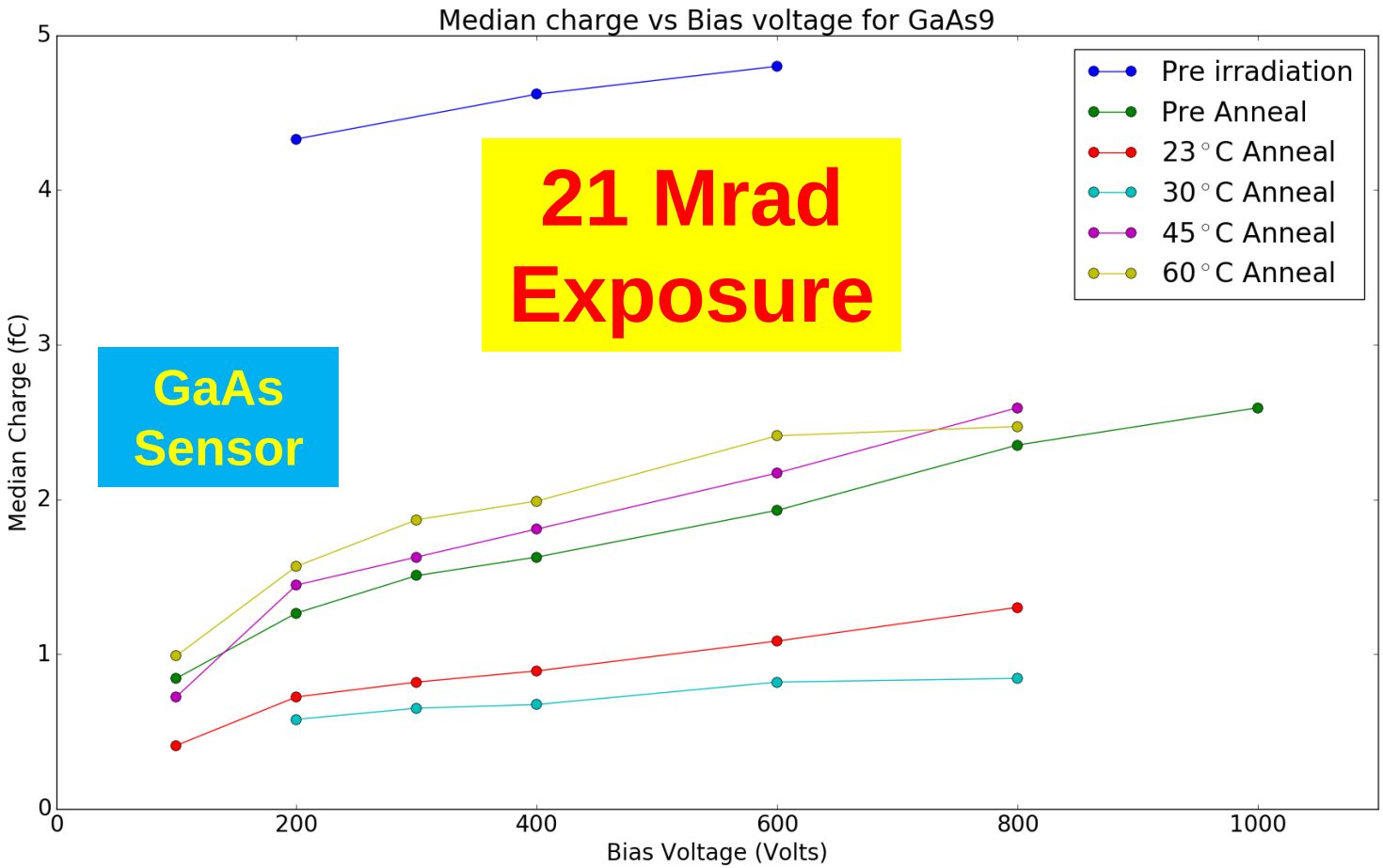


Sensor provided by Georgy Shelkov, JINR

Sn-doped Liquid-Encapsulated Czochralski fabrication

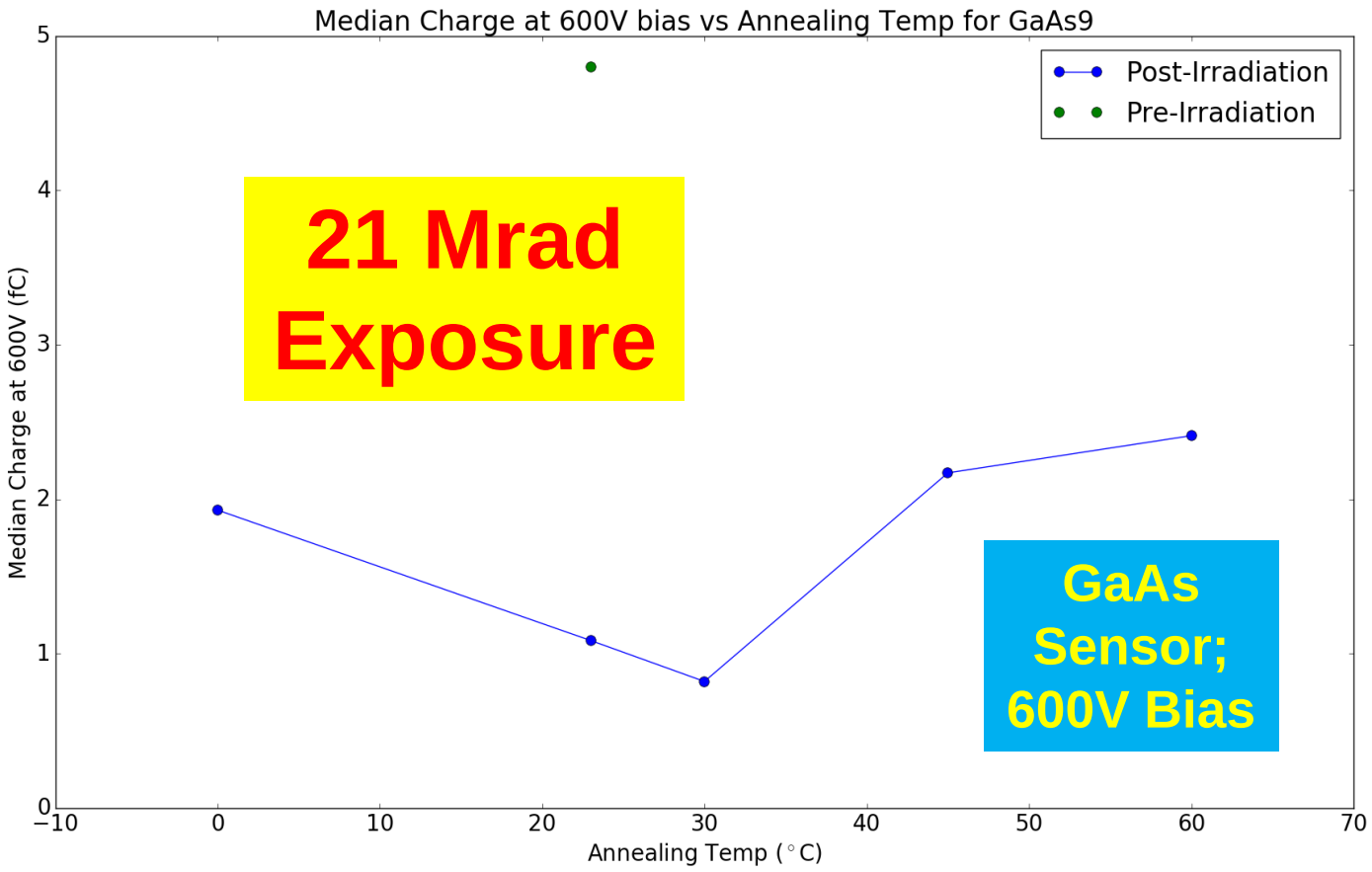
300 μm thick

GaAs Charge Collection for 21 Mrad



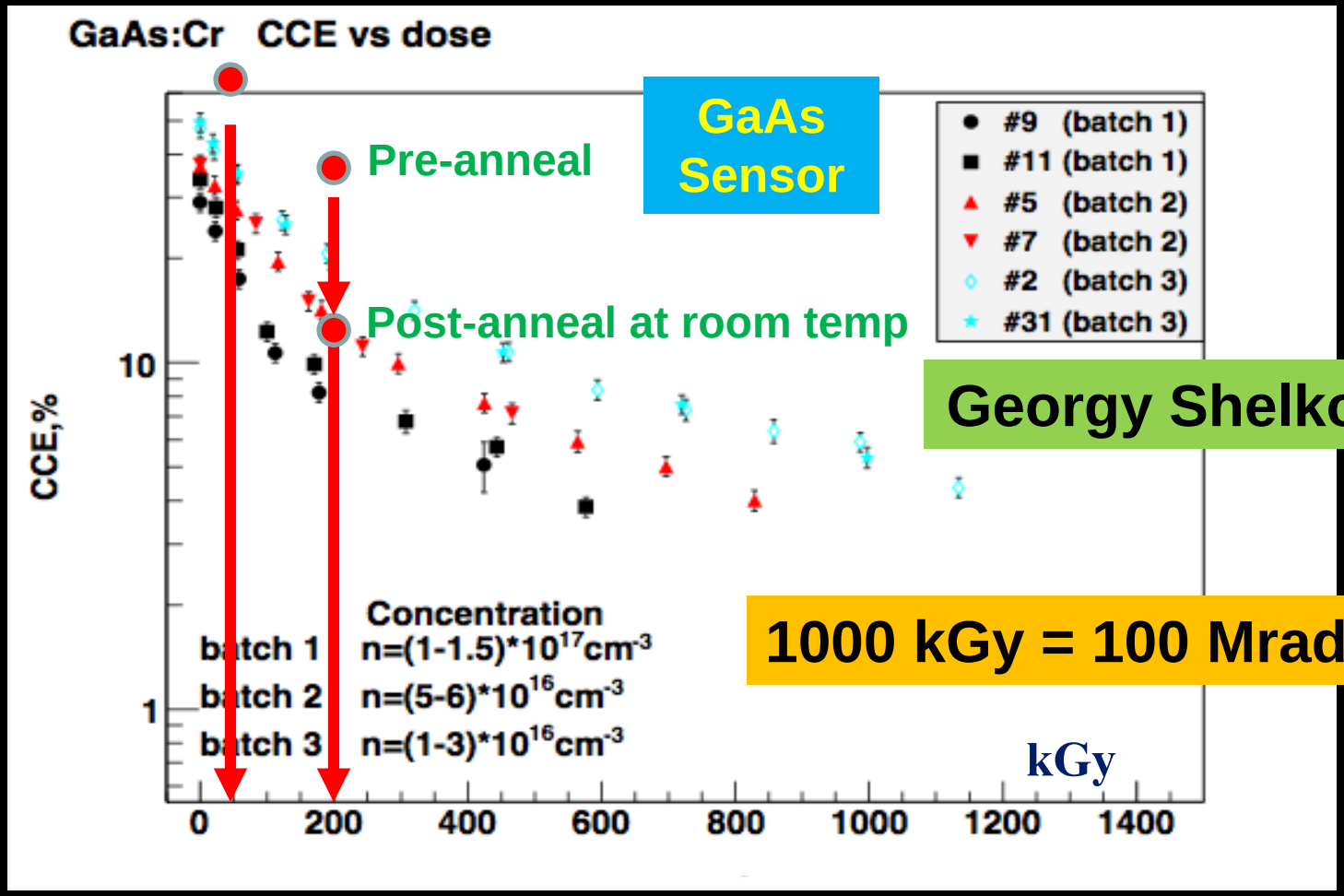
Significant charge collection loss

GaAs Charge Collection for 21 Mrad



Some recovery with annealing, but significant charge collection loss even at 20 Mrad

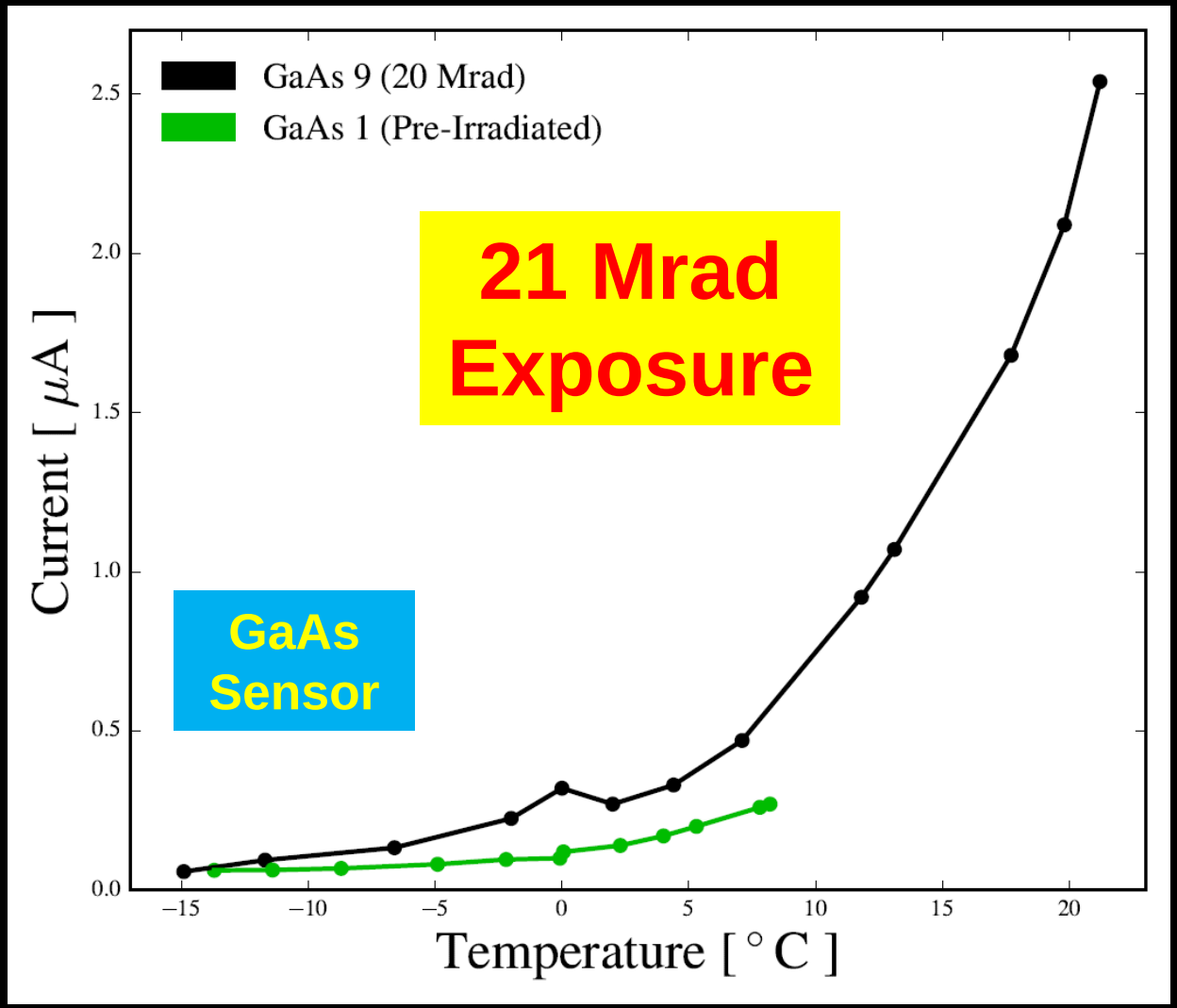
Compare to Direct Electron Radiation Results (no EM Shower)



Georgy Shelkov, JINR

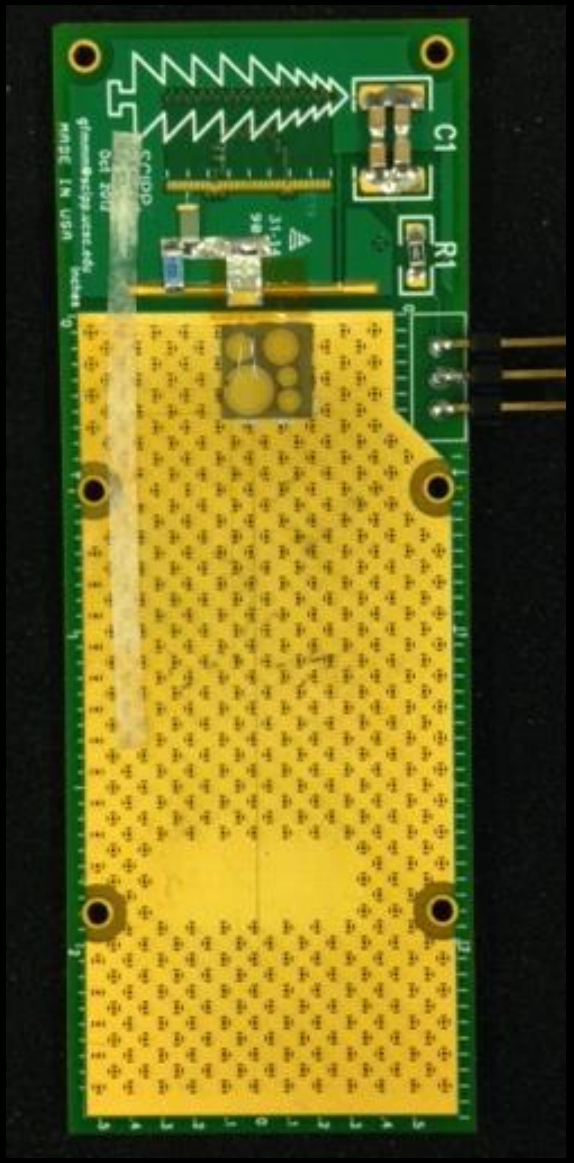
1000 kGy = 100 Mrad

GaAs Pre- and Post-Irradiation Current Draw



For V_B = 600 V; post-irradiation after 75°C anneal

Silicon Carbide

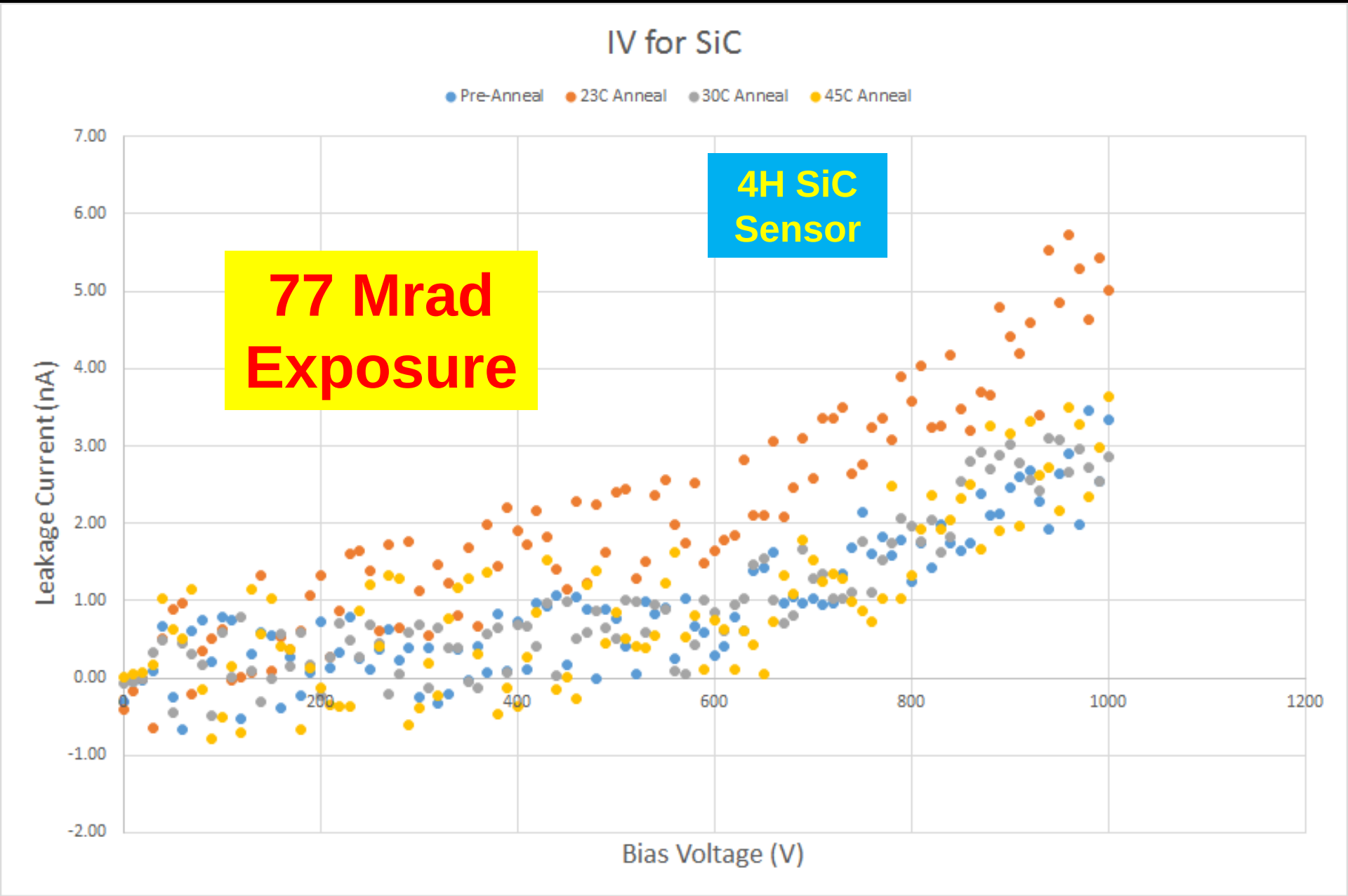


Sensor provided by Bohumir Zatko, Bratislava

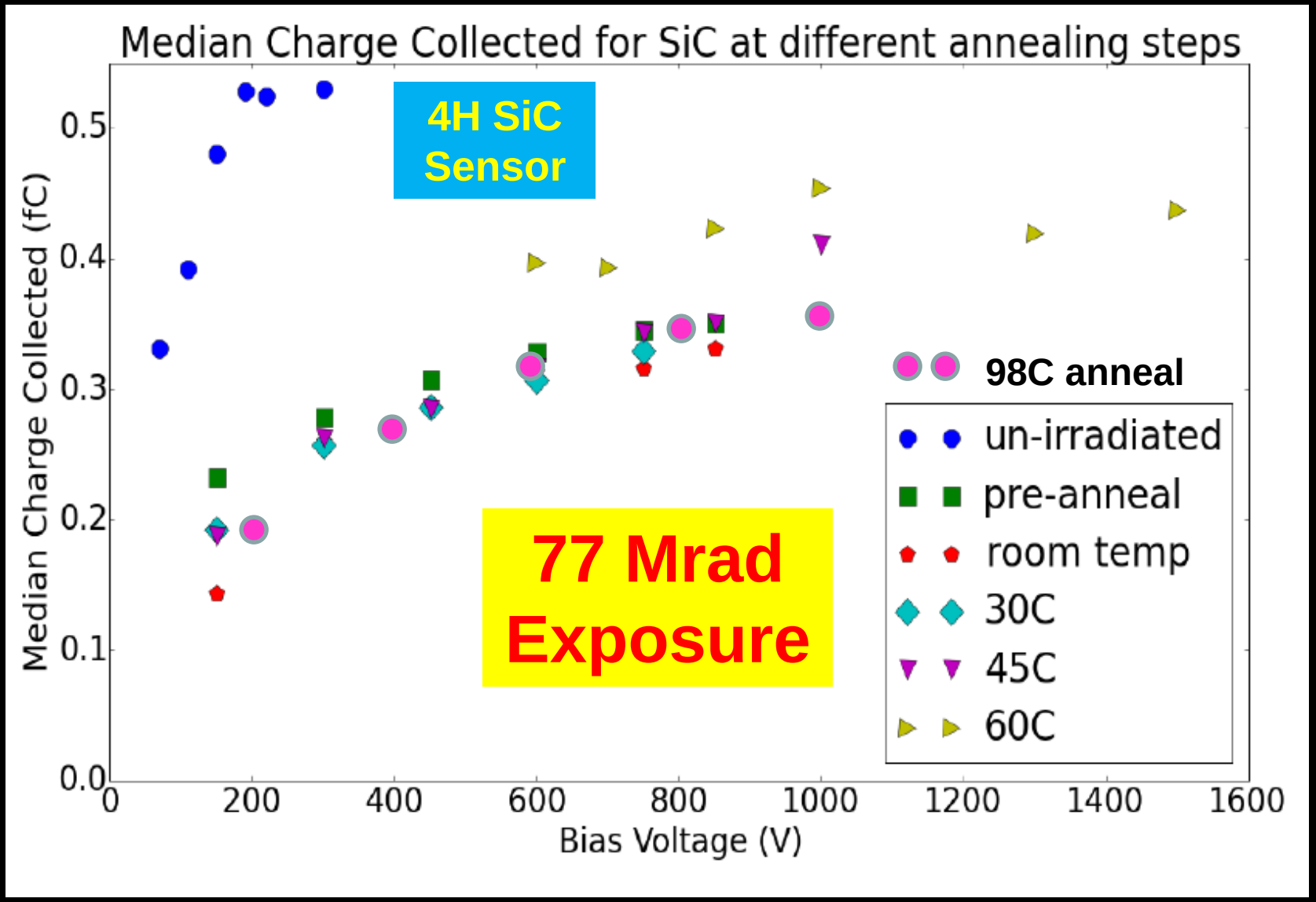
Schottky-barrier contacts mounted on 4H-SiC structure

Epitaxial (active) layer thickness 70 μm

SiC Dark Current for 77 Mrad

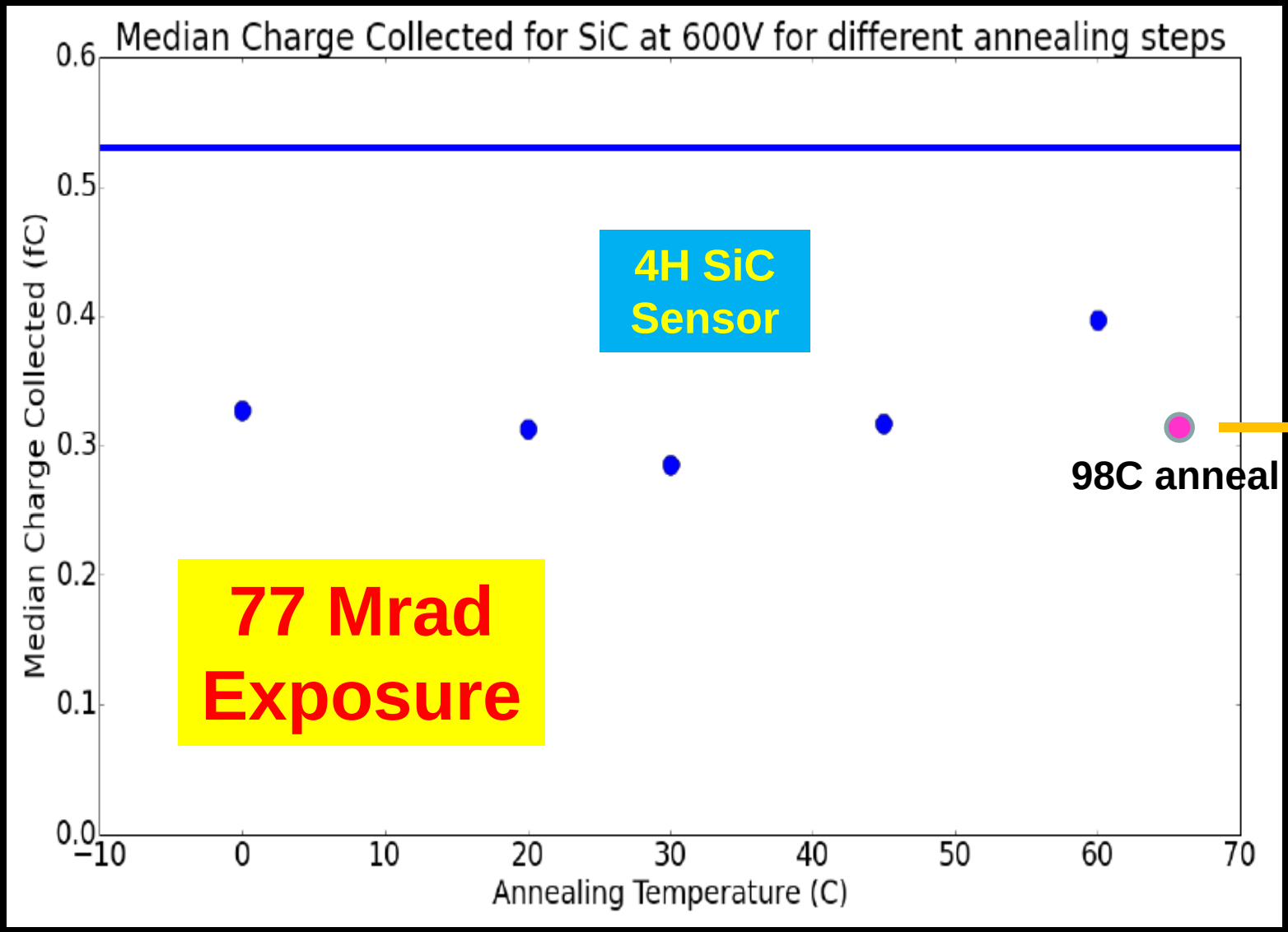


SiC Charge Collection for 77 Mrad



Charge collection mostly above 50%

SiC Charge Collection for 77 Mrad



For 600V bias

Summary and Outlook

- All Si diode sensors maintain good (>50%) charge collection for 300 Mrad doses; P-bulk sensor charge collection may be less affected.
- For all prototypes, Si diode leakage currents after 300 Mrad in range of 10's of $\mu A/cm^2$, with typical factor-of-2 per 7°C increase.
- All bulk sensors (GaAs, SiC, Sapphire) show significant charge loss for Mrad doses; SiC perhaps most robust.
- SiC, Sapphire leakage currents small, but GaAs shows significant temperature-dependent currents that increase even for 20 Mrad dose.

BackUp…

Summer 2013: Initial Si Doses

"P" = p-type **"N" = n-type**
"F" = float zone **"C" = Czochralski**

Sensor	V_{FD}	Irradiation Temp. (C)	Beam Energy (GeV)	Delivered Charge (μC)	Dose (MRad)
PF05	190	0	5.88	2.00	5.13
PF14	190	0	3.48	16.4	19.7
PC10	660	0	5.88	1.99	5.12
PC08	700	0	(5.88, 4.11, 4.18)	(3.82,3.33,3.29)	20.3
NF01	90	0	4.18	2.30	3.68
NF02	90	0	4.02	12.6	19.0
NF07	100	5	8.20	23.6	91.4
NC01	220	0	5.88	2.00	5.13
NC10	220	0	3.48	15.1	18.0
NC03	220	5	4.01	59.9	90.2
NC02	220	5*	(10.60,8.20)	(32.3,13.8)	220

T-506 Idea

Embed sample sensors in tungsten:

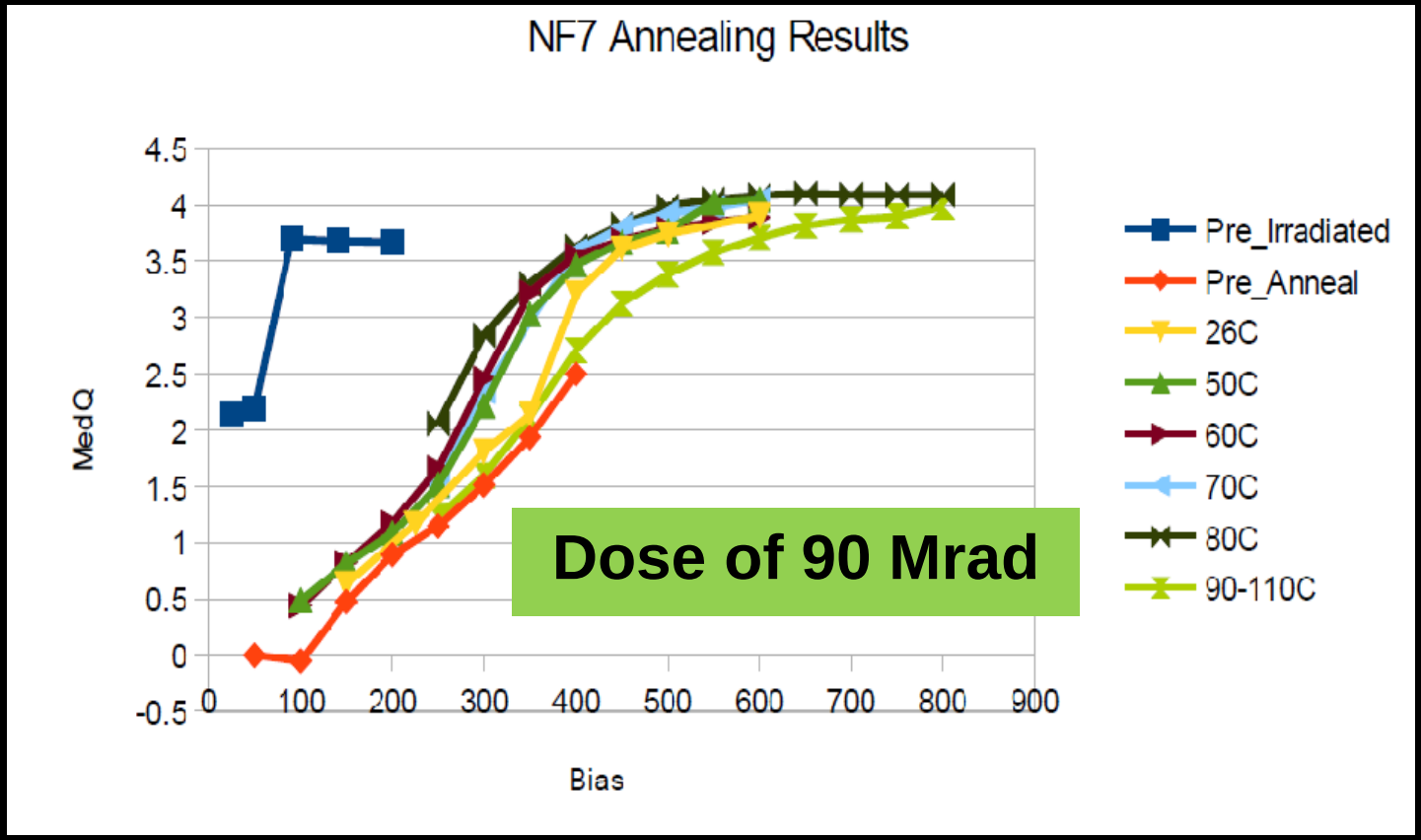
"Pre-radiator" (followed by ~50 cm air gap) spreads shower a bit before photonic component is generated

"Post-radiator" brings shower to maximum just before sensor

"Backstop" absorbs remaining power immediately downstream of sensor

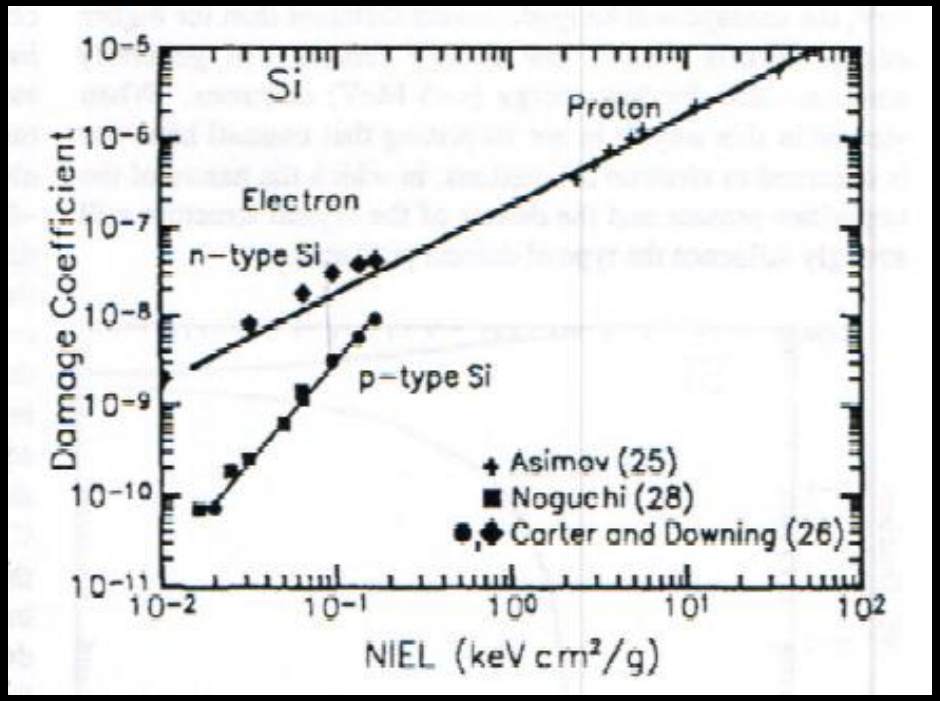
➔ Realistic EM and hadronic doses in sensor, calibrated to EM dose

Results: NF Sensor to 90 Mrad, Plus Annealing Study



Limited beneficial annealing to 90°C (reverse annealing above 100°C?)

Departure from NIEL (non-ionizing energy-loss) scaling observed for electron irradiation



NIEL	e⁻ Energy
2×10^{-2}	0.5 MeV
5×10^{-2}	2 MeV
1×10^{-1}	10 MeV
2×10^{-1}	200 MeV

G.P. Summers et al., IEEE Trans Nucl Sci **40**, 1372 (1993)

Also: for ~50 MRad illumination of 900 MeV electrons, little loss of charge collection seen for wide variety of sensors [S. Dittongo et al., NIM A 530, 110 (2004)]

But what about the hadronic component of EM shower?