

^{60}Co γ Irradiation of a CMS CROC v2 to 1.6 Grad



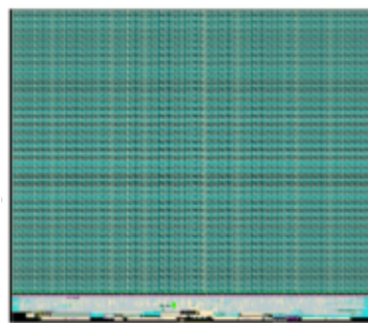
VERTEX 2025
Knoxville, TN
August 25-29, 2025

Steve Wagner (University of Colorado, Boulder)
For the CMS Tracker Project

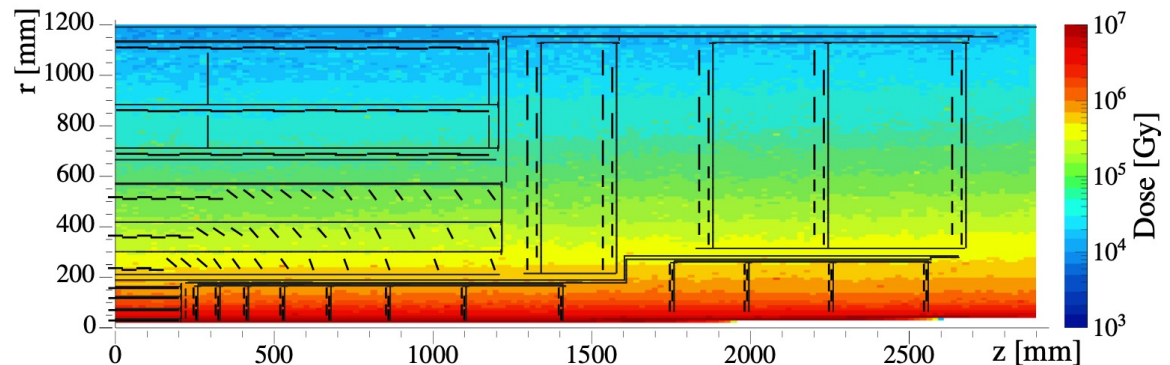
RD53 Read-Out-Chips for the HL-LHC

RD53 was a CERN collaboration of ATLAS & CMS chip designers to produce a common architecture for the pixel read-out-chips (ROCs) for the HL-LHC experiments

RD53A was a common prototype with 3 different analog front-ends. ATLAS & CMS each chose different FE's, and details such as buffering and size differ, but the final ROCs (CROC for CMS & ITkPix for ATLAS, v1 for pre-production RD53B & v2 for production RD53C architectures) share many common features and structures (such as ring oscillator banks, which measured radiation-induced changes).



RD53C-CMS (CROCv2)



The CROC (v1 or v2) has 432 x 336 pixels of 50 x 50 μm^2 area

RD53 electronics also share common design requirements, such as **a minimum threshold of 1000 e⁻, a minimum threshold dispersion of <100 e⁻, a noise of <150 e⁻ (with sensor), and a radiation tolerance of 1 Grad over 10 years at -15° C** (the dark red area in the Dose map from the CMS HL-LHC Tracker TDR is 10⁷ Gy = 1 Grad)

Why γ (and Not Just x-ray) Irradiations?

Used to be the industry/military (ISO) standard for radiation damage

Can possibly reveal damage not accessible to lower-energy (~ 10 keV) x-rays (materials, etc)

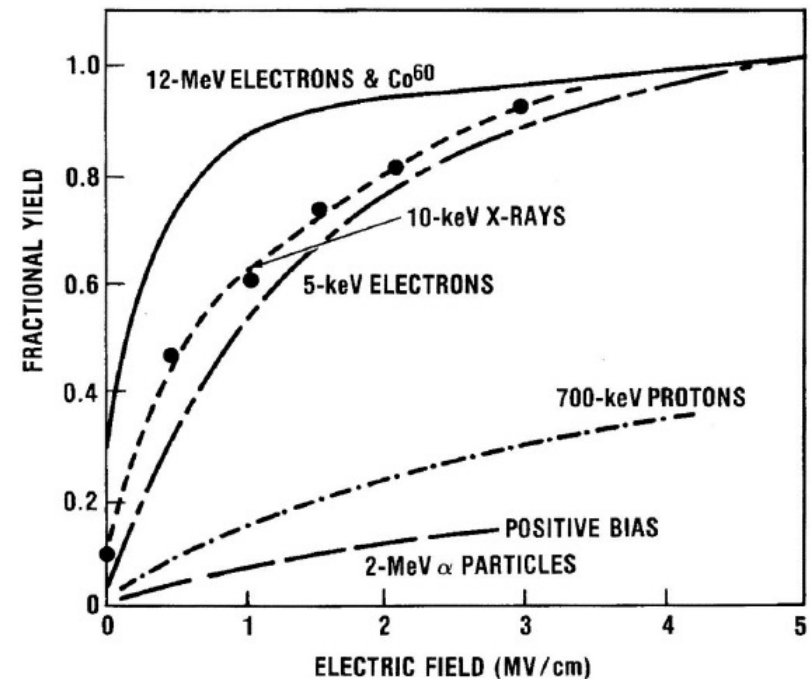
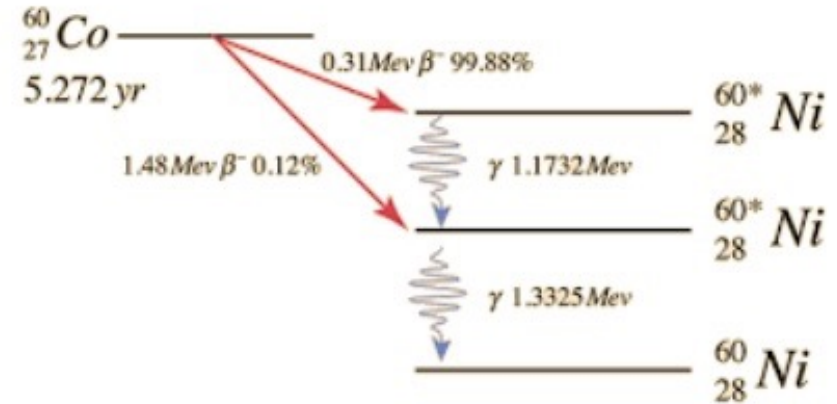
Fairly uniform irradiation – no “beam spot”

We have some experience doing this at the “Gamma Irradiation Facility” (GIF) at Sandia National Lab – from testing 65 nm transistor test structures for RD53

Drawbacks:

Harsh environment to work in

GIF is in very high-security part of a weapons lab. We are always escorted. Cannot access experiment on nights and weekends, or control or even view status remotely. Everything must be “ballistic” then



History of Sandia ^{60}Co γ Irradiations

We performed 3 ^{60}Co irradiations in 2023-24 – to 100 Mrad, ~300 Mrad, and 1600 Mrad – with cold (-20 C), powered and read-out CROCs

Unique cooling system (LN₂ boil-off keeps CROCs bone-dry as long as flow & positive pressure are maintained) & radiation source (^{60}Co ~1 MeV γ s) make this an interesting cross-check of x-rays CROC irradiations.

The first 2 irradiations were on CROC v1s (pre-production CROCs) which were not parylene coated. This irradiation was on a parylene-coated (at Oak Ridge NL) CROCv2 in much hotter array (not available for the first 2 irradiations)

For the 100 Mrad & ~300 Mrad irradiations, we saw lots of strange wire bond damage which seemed to occur *after* the irradiation was over. Presumably when CROCs were removed from clean N₂ gas environment and irradiation products on card interacted with moisture in air and etched away wire bonds (see Alan Honma talk, 14 Oct 2015, UK Wire Bonders Forum)

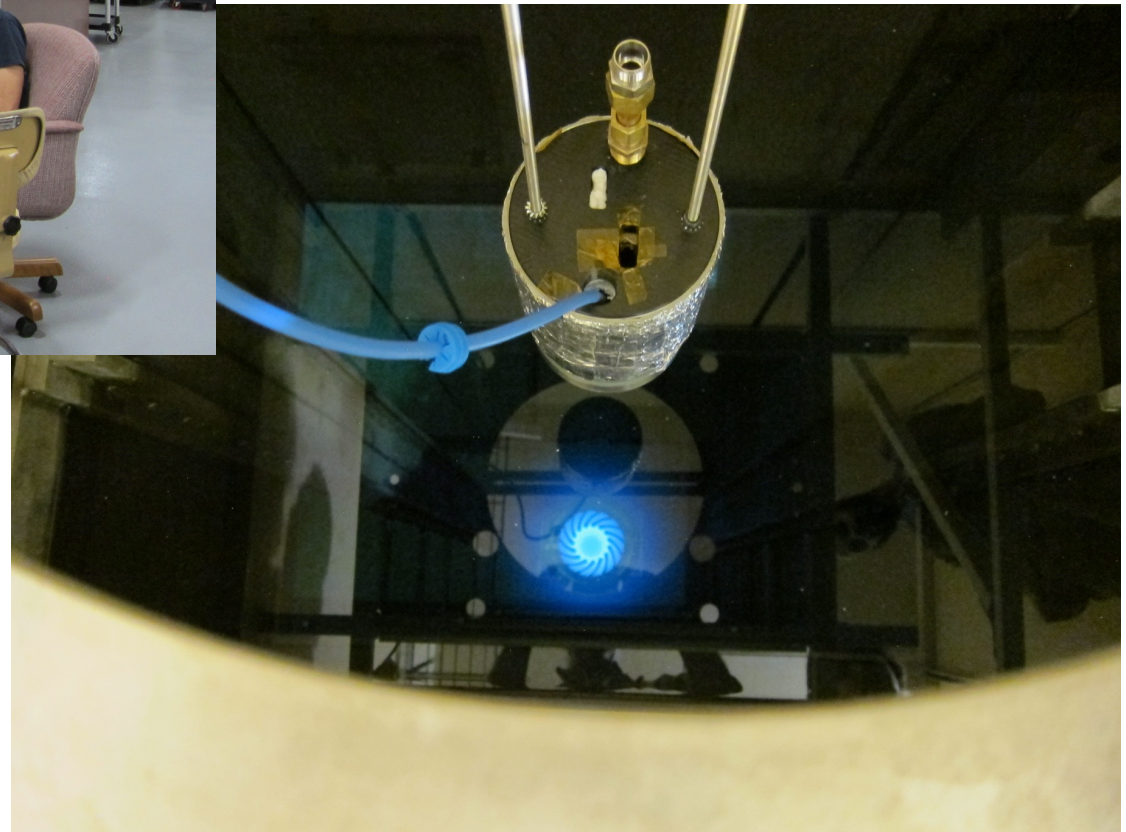
The CROCv2 was exposed to 1.8 Grad of γ 's, and was functional and tunable before a catastrophic collapse of LN₂ cooling system ended the irradiation at 1.6 Grad (ice blockage in LN₂ transfer lines outside cell). All wire bonds look fine after irradiation & two months later. Now big fan of parylene coating

The Set-up

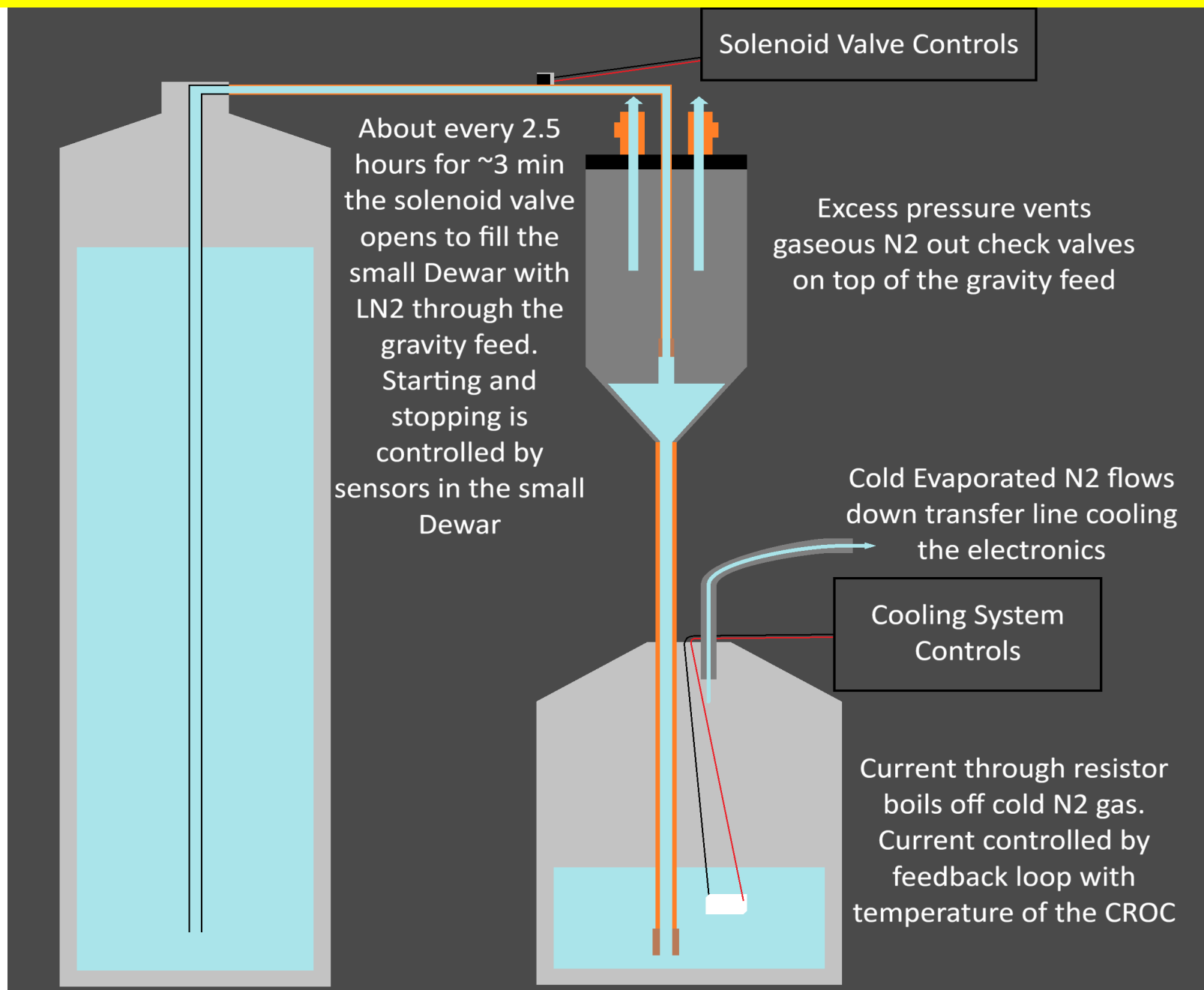


Zachary Franklin & Jessie Harris with our cooling system & FC7-based read-out, outside cell #1 at the GIF

CROC Thermos, without the CROC & cooling line but with the ion chamber to measure dose rate as soon as we exit cell #1 & the ^{60}Co shutter array moves up from bottom of pool to surround thermos



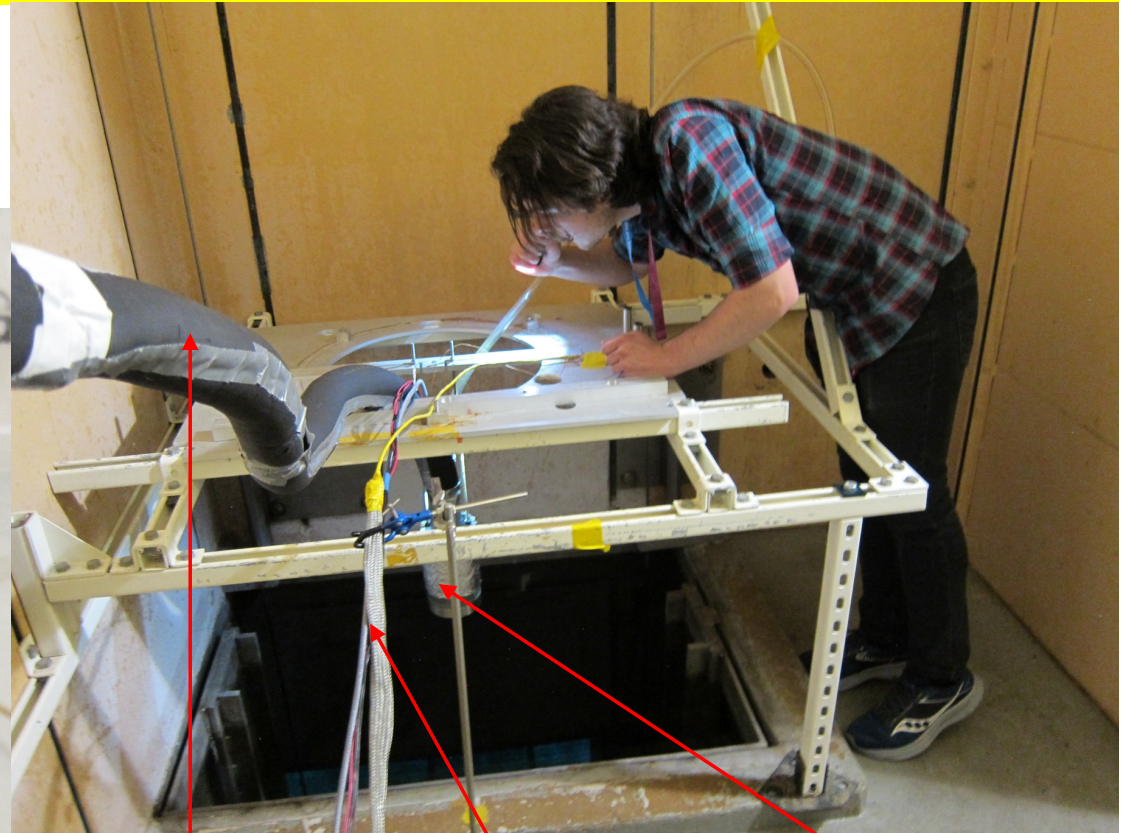
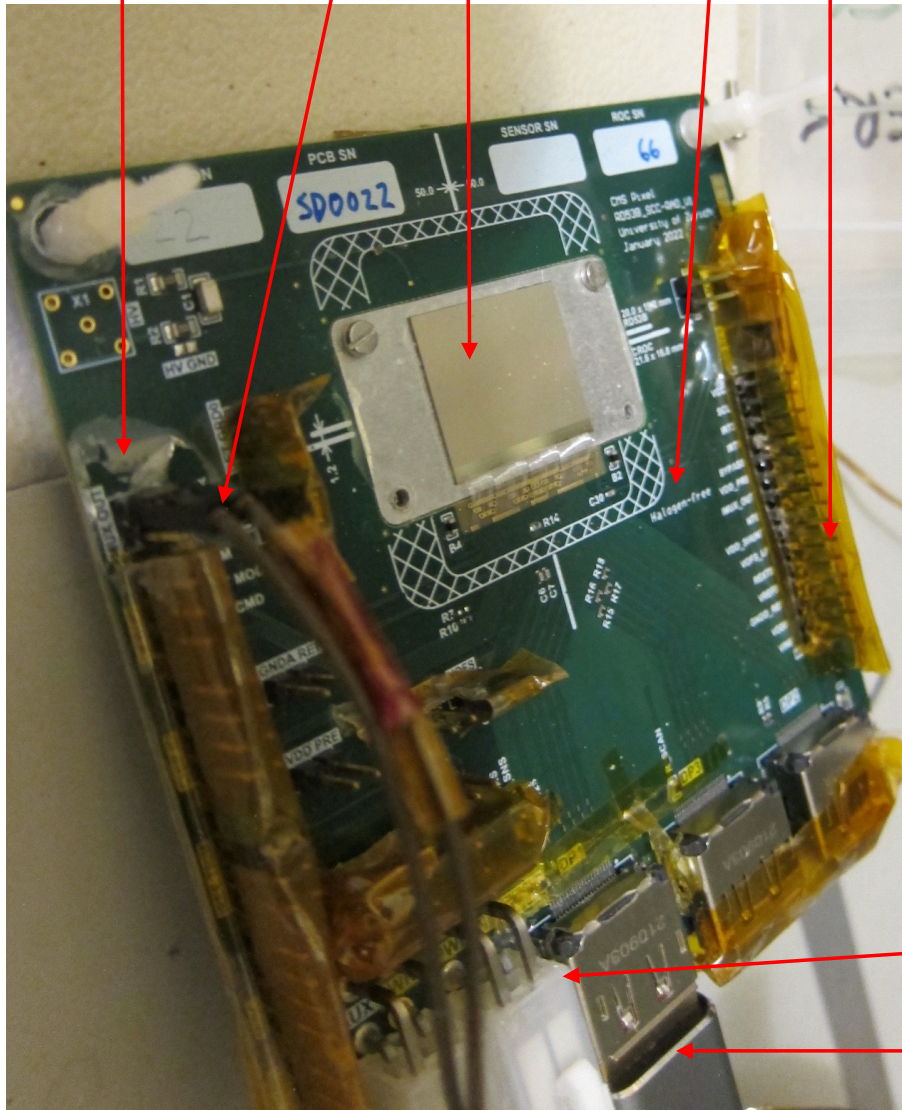
LN2 Refill System with Gravity Feed



Undressed CROC and Transfer Line

CROC with wire bonds
Mux (V & I) data
Torn parylene

Unused pin block
V read-out
Halogen-free



Heavily insulated cold
N₂ gas transfer line

Thermos

Shielded thermocouple
cables and other cables

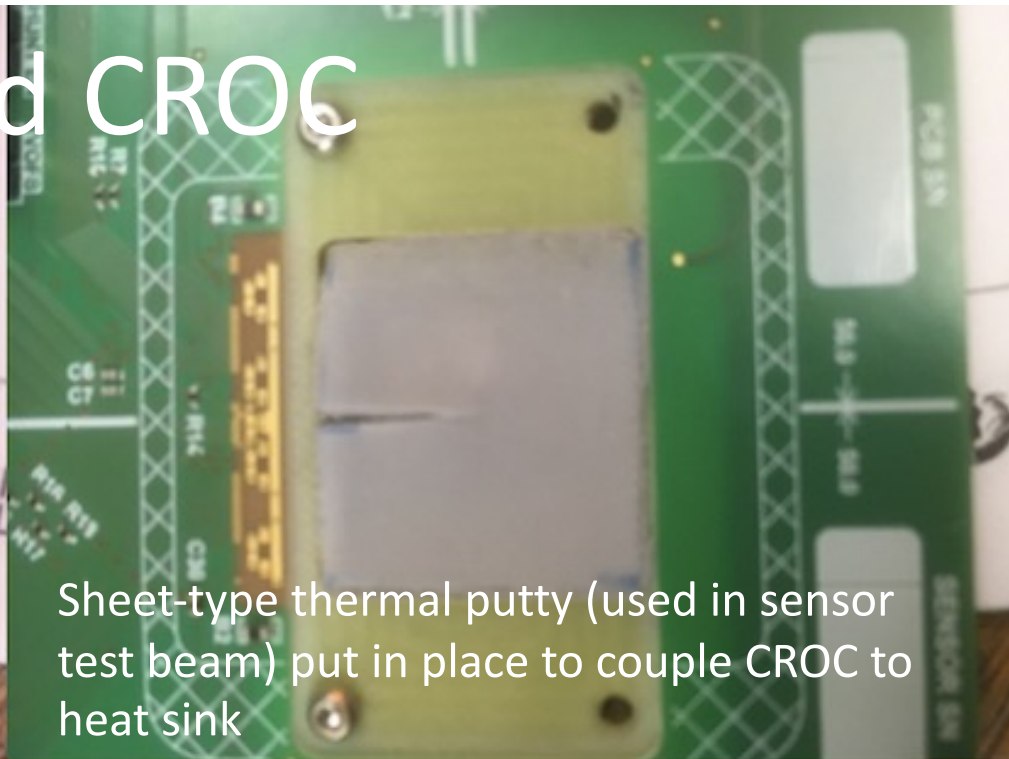
Analog and Digital Low Voltages

Display port cable carrying command and configure
data in, pixel & ring oscillator data out to FC7 DAQ

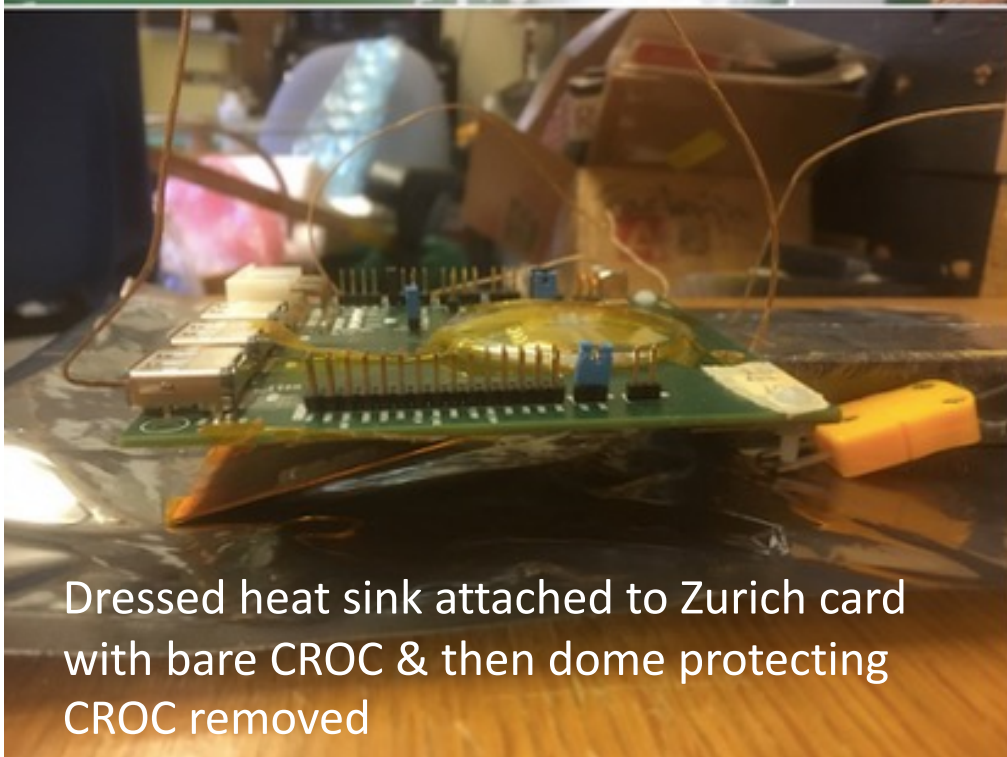
Dressed CROC



Kapton-covered K-type TC placed behind where CROC would be on heat sink



Sheet-type thermal putty (used in sensor test beam) put in place to couple CROC to heat sink

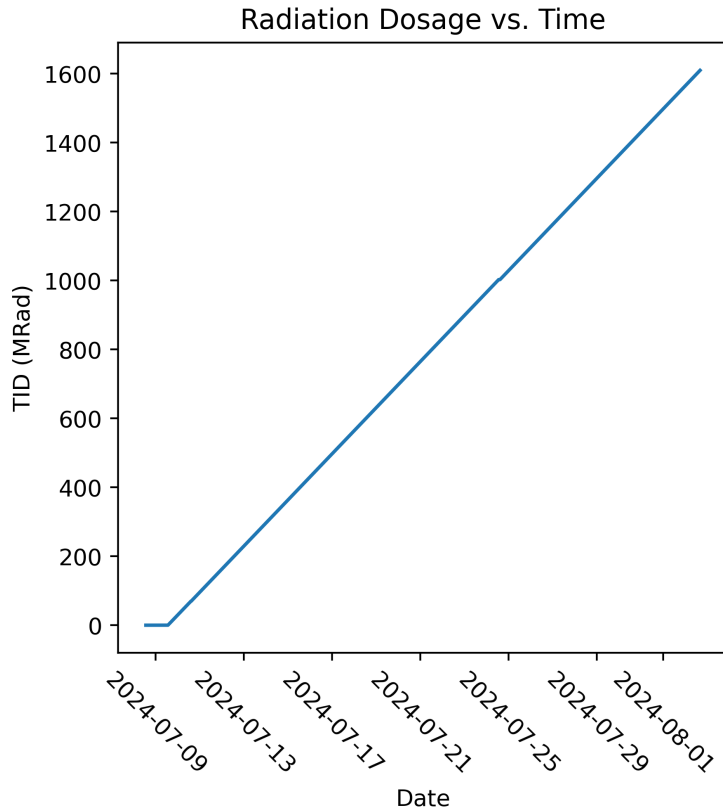


Dressed heat sink attached to Zurich card with bare CROC & then dome protecting CROC removed



Thick Kapton sheet placed over Zurich card to protect wire bonds but allow free flow of N₂ gas over CROC & wire bonds

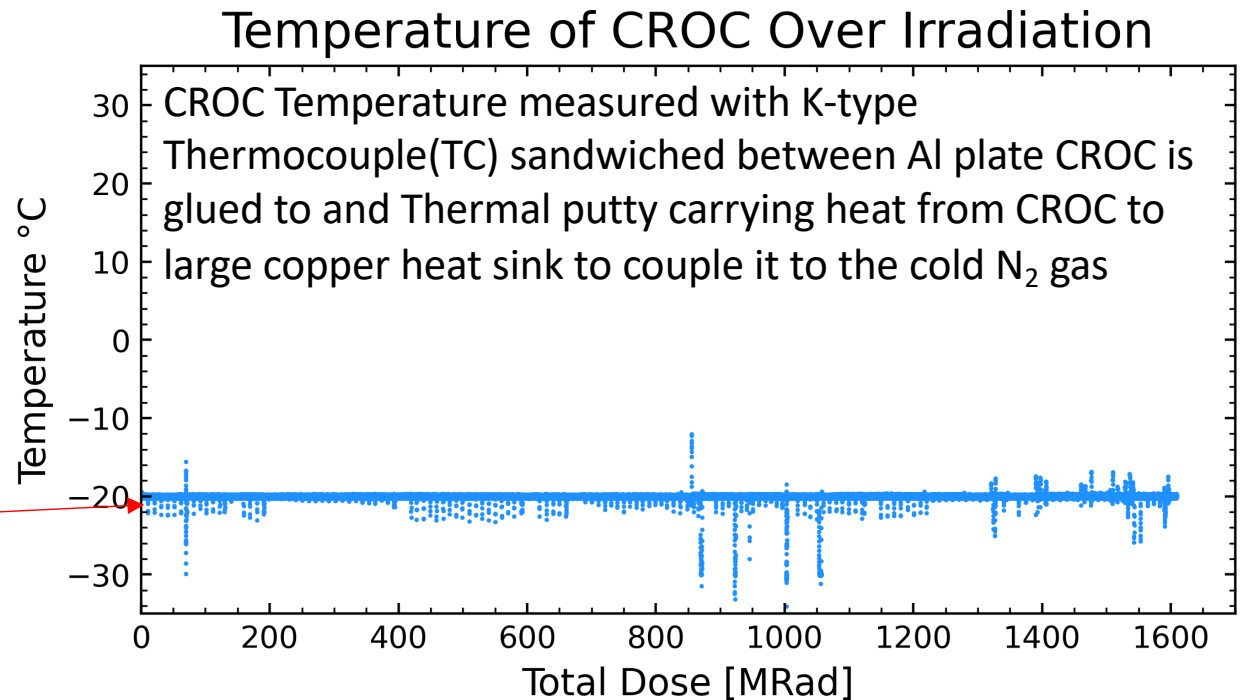
CROC Dose & Temperature for Irradiation



Dose rate measured to be 775 rad/sec = 2.79 Mrad/hour (~ 100 Mrad/36 hours) at center of CROC using a well-calibrated ion chamber before the irradiation. This rate was reconfirmed after irradiation

Dose is expected to be very uniform across CROC. Measurement 1.88 cm above centerline is 764 rad/sec, or 1.4% lower. A Sandia model predicts rate difference of ~0.4% 1 cm higher than CL

Regular small downward fluctuations are due to autofills of small dewar where cold N₂ gas is generated



Particulars of Current Irradiation

Started the irradiation at about 1:15 PM Tuesday July 9, 2024. We normally ran **auto-scans every 15 minutes – AnalogScan, MuxScan, and ShortRingOsc – even thru the night**, tho we suspended them when we were Threshold tuning (generally once in the morning & once in the afternoon) or any special testing

We also **recorded Power supplies (PS) Voltages and Currents every 10 minutes** (analog and digital each had their own supply)

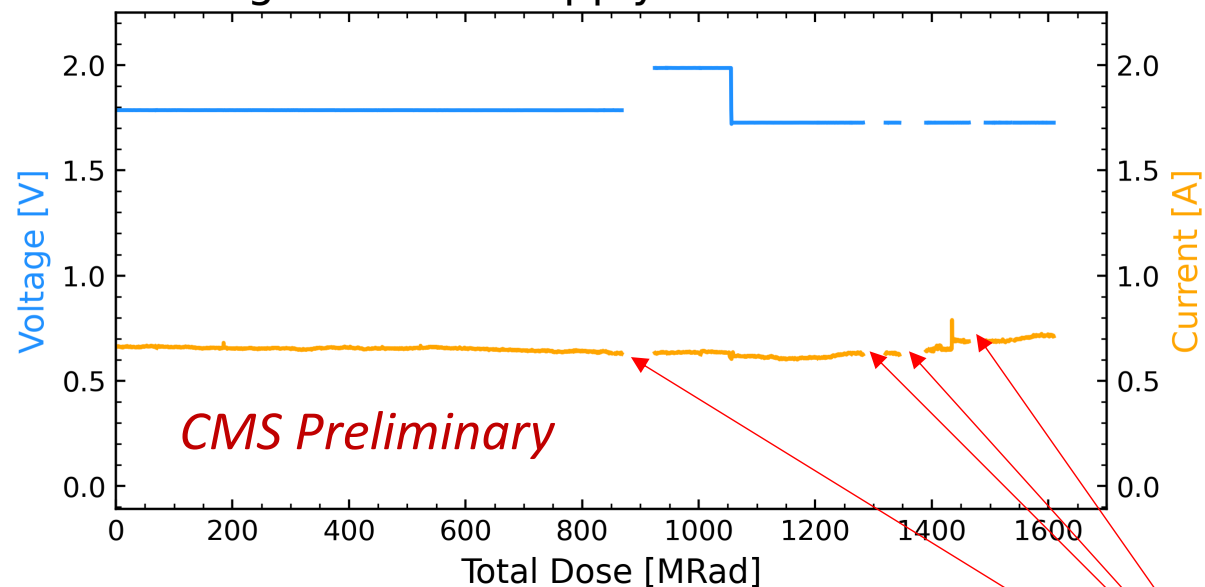
Accessed the thermos once on Wed July 10 for ½ hour. Wanted to keep ice from building up on lid but found more water than ice. Positive pressure keeps water from finding its way thru cracks into thermos, but completely RTV-ed the hole cables (DP, LV, MuxScan, TC) passed thru & put tube on cold gas exhaust to move away from lid

The irradiation can be broken into two parts. The first part – up to ~730 Mrad, almost ½ the data - went extremely well (few problems & none serious). Some data (the Mux data) had problems during the second half of the irradiation, but all the other data (scans) remain reliable

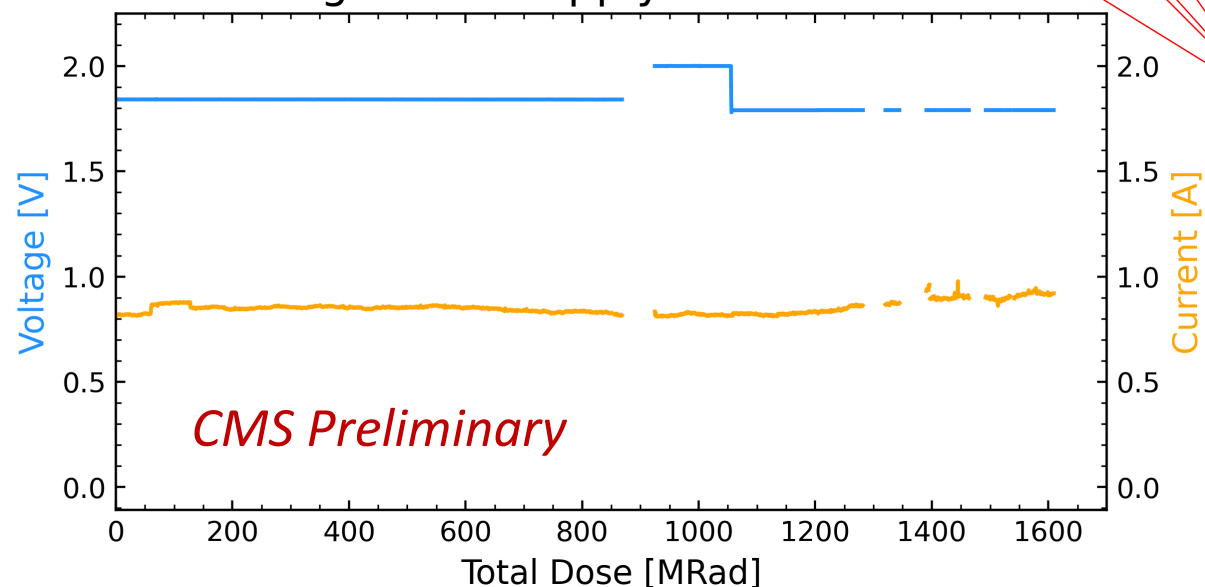
We'll show the good data from the entire irradiation first, and then focus on problem with the Mux data in the second half.

Supply Voltages and Currents

Digital Power Supply Over Irradiation



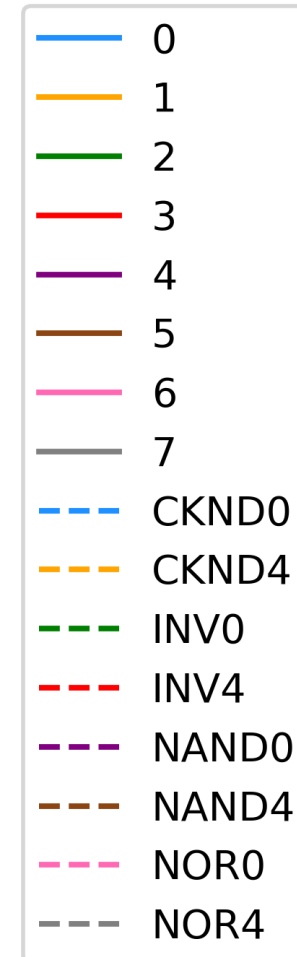
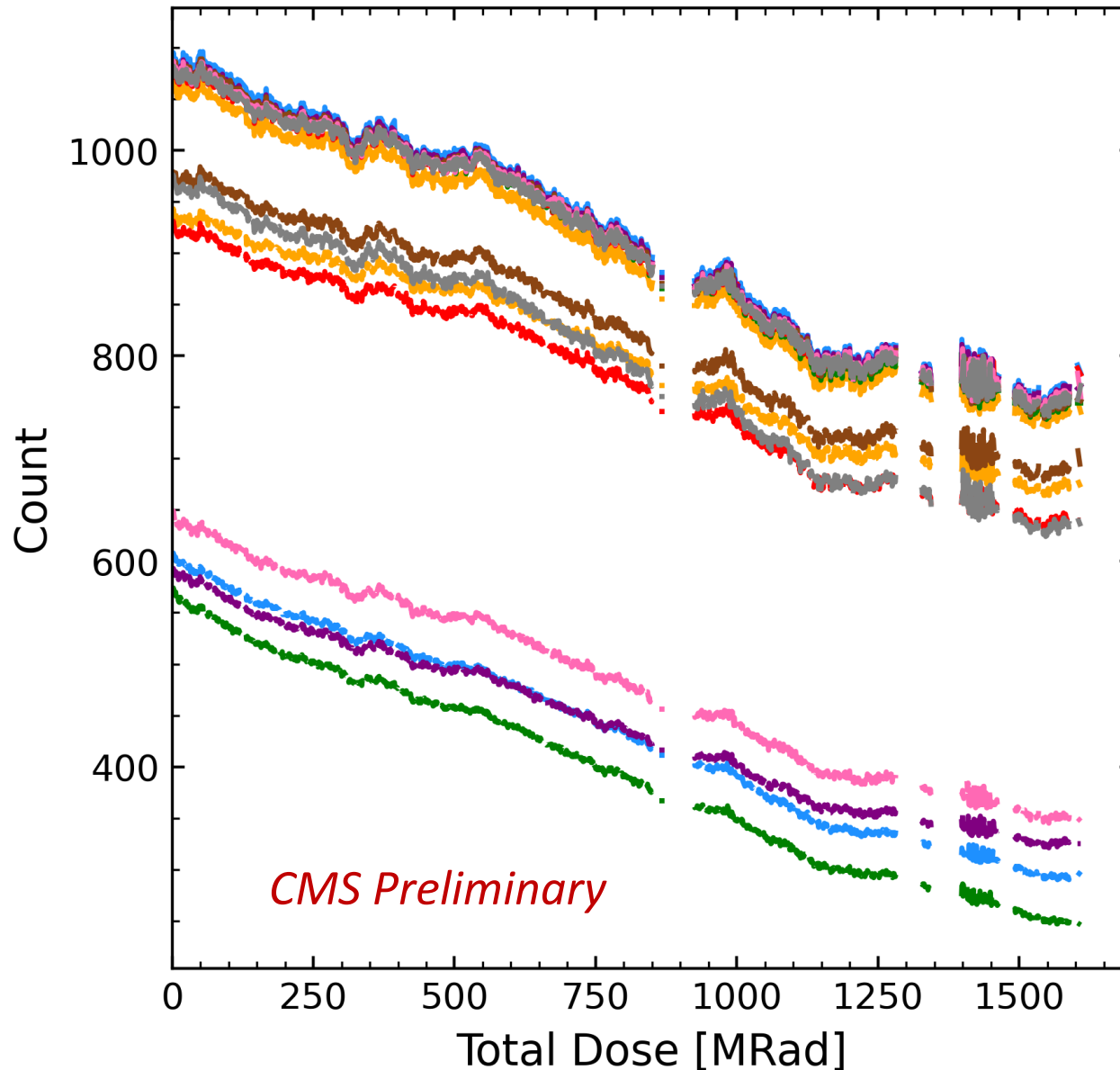
Analog Power Supply Over Irradiation



We're looking for long-term trends in current usage, so we remove times when the CROC is "misconfigured" and the current usage is different than normal. At these times, the voltage is usually on and normal

Ring Oscillators for Entire Irradiation

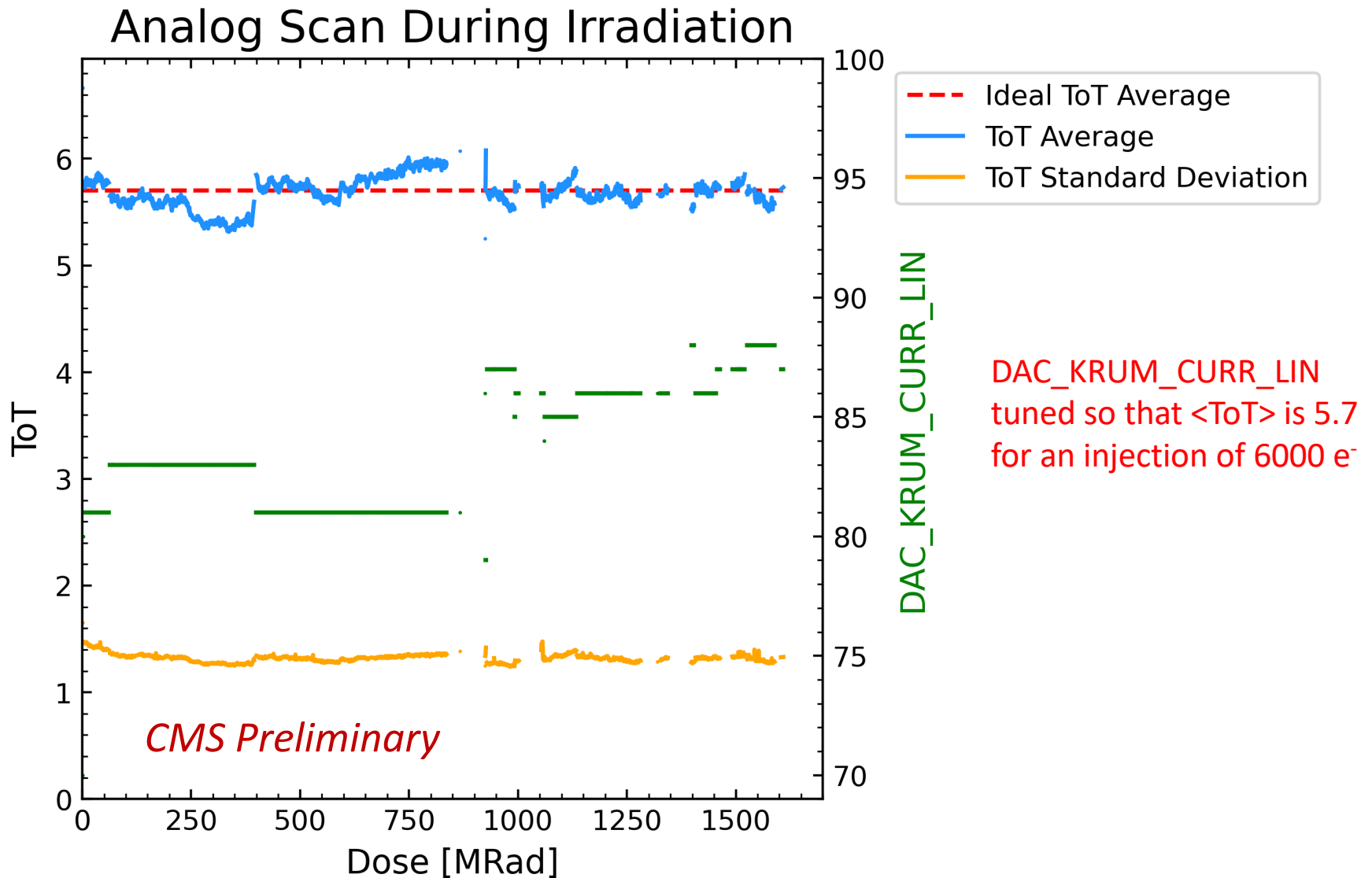
Ring Oscillators Over Irradiation



A version of this plot shown in early Fall 2024 had some of the Bank B Ring Oscillators (here labeled 0-7) mislabeled (parsing error). The Bank A ROs shown here are & were correct. All corrected in this plot

Our Ring Oscillators were not calibrated for changes in VDDD, but our values of VDDD were fairly stable, (as was our Temperature)

Analog Scans for Entire Irradiation



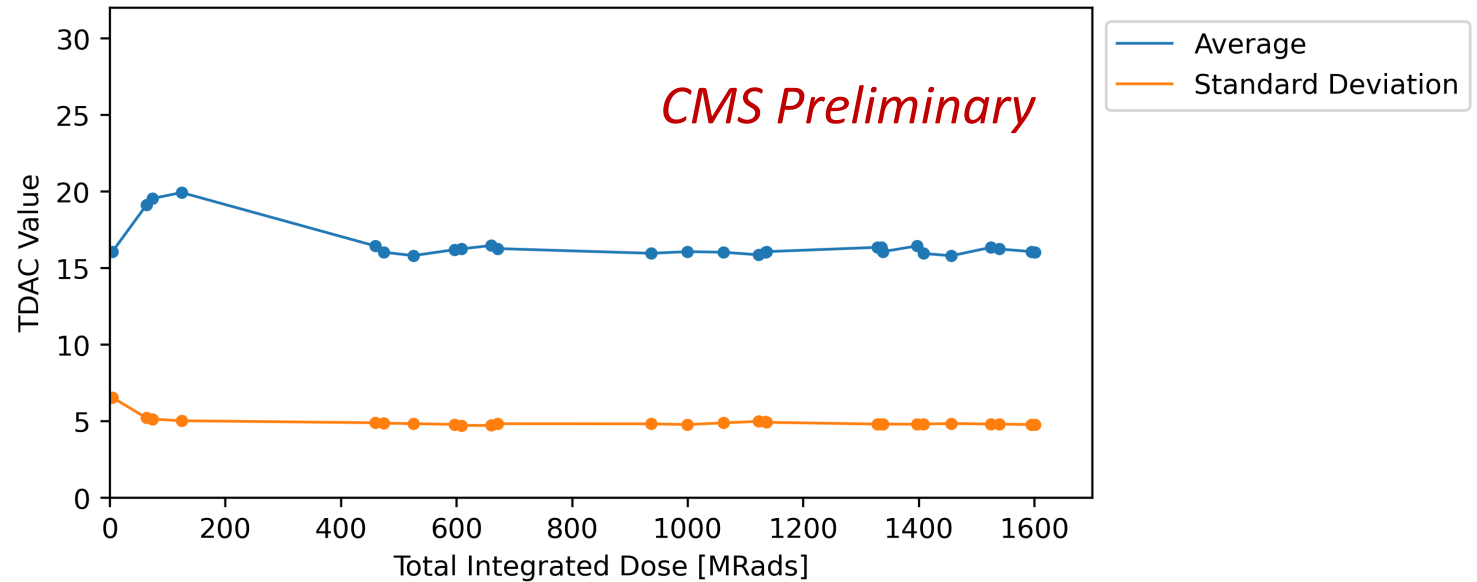
Threshold Tuning for Entire Irradiation

KRUM_CURR_LIN & ThresholdEqualization scan talk to each other a little, so AS & TE usually iterated to get desired $\langle \text{ToT} \rangle$ and $\langle \text{TDAC} \rangle$

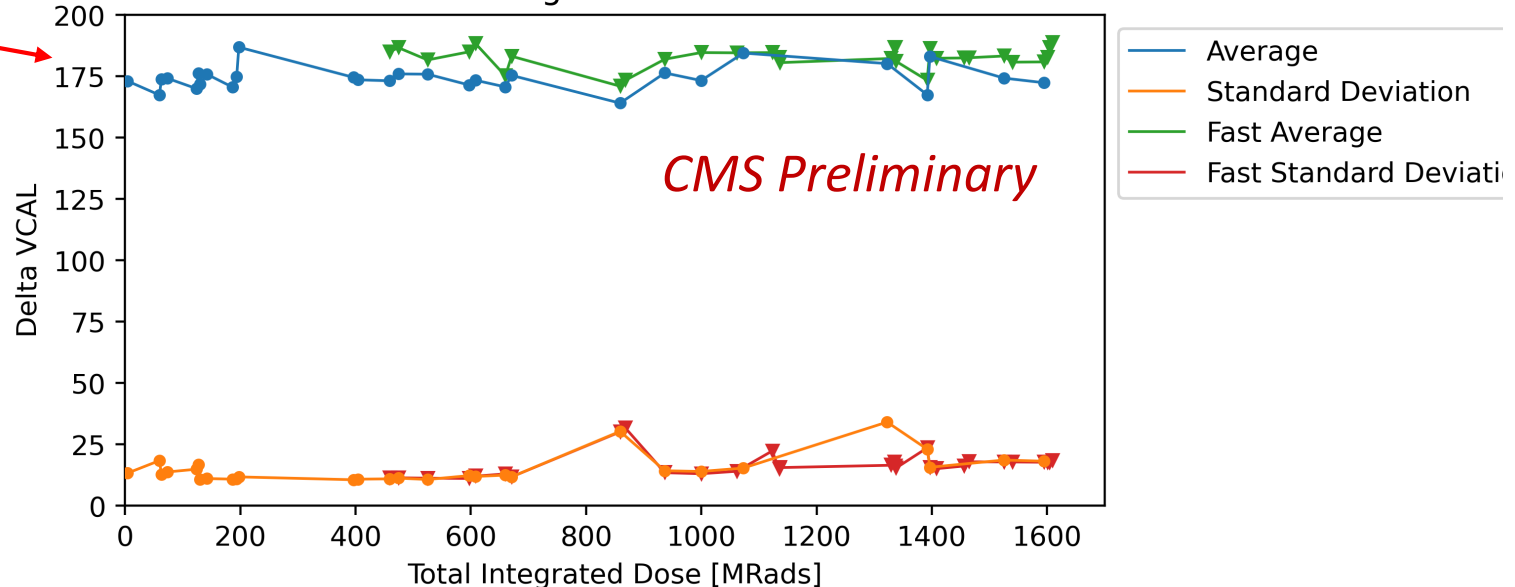
Target threshold of 1000 e- has a ΔVCAL of ~ 182.5

3 pixels masked out entire irradiation, $\sim 0-5$ stuck pixels every TE scan, $O(10)$ probit fits fail every TS

Threshold Tuning: TDAC Distribution

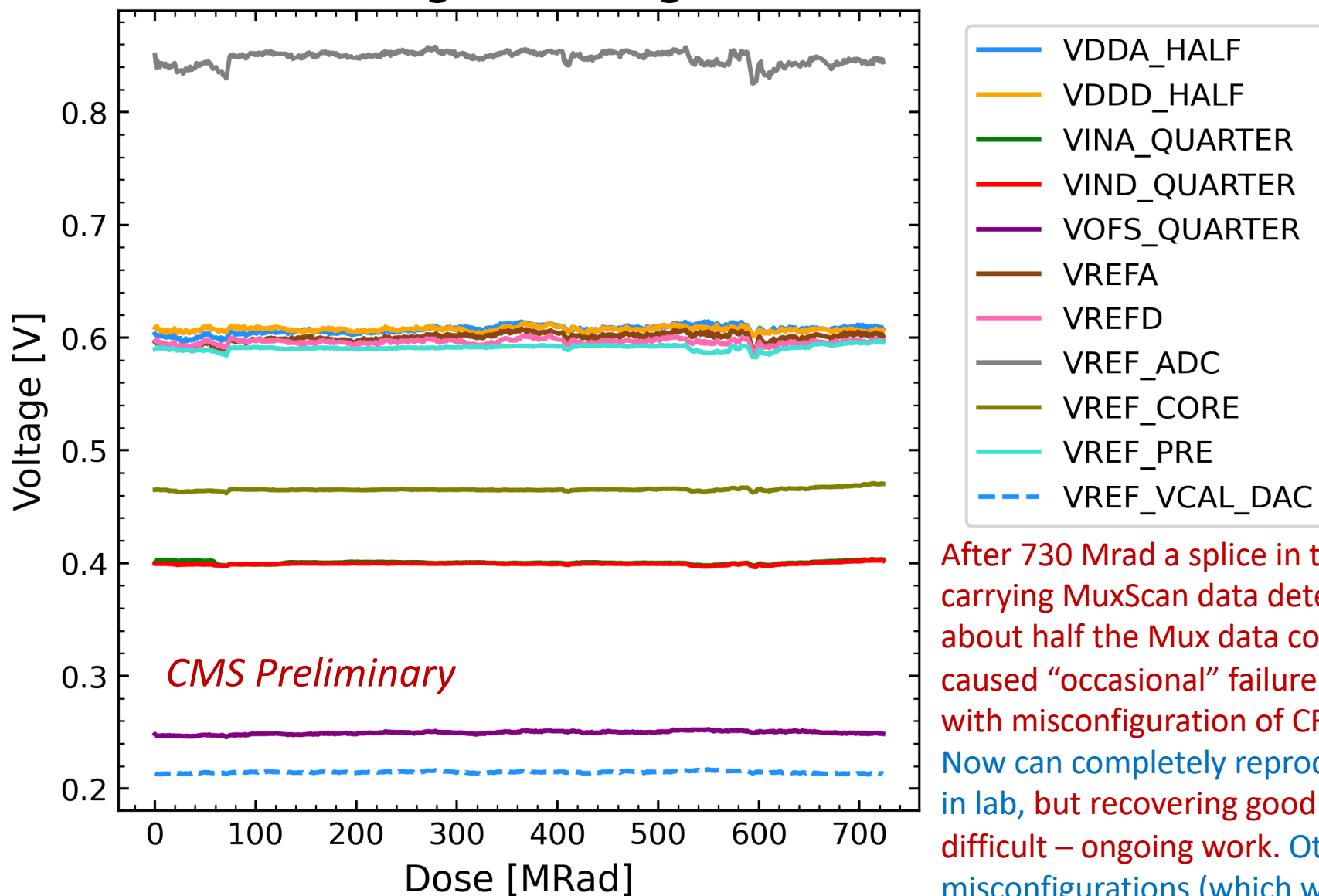


Threshold Tuning: Threshold Distribution



Important Voltages to 730 Mrad

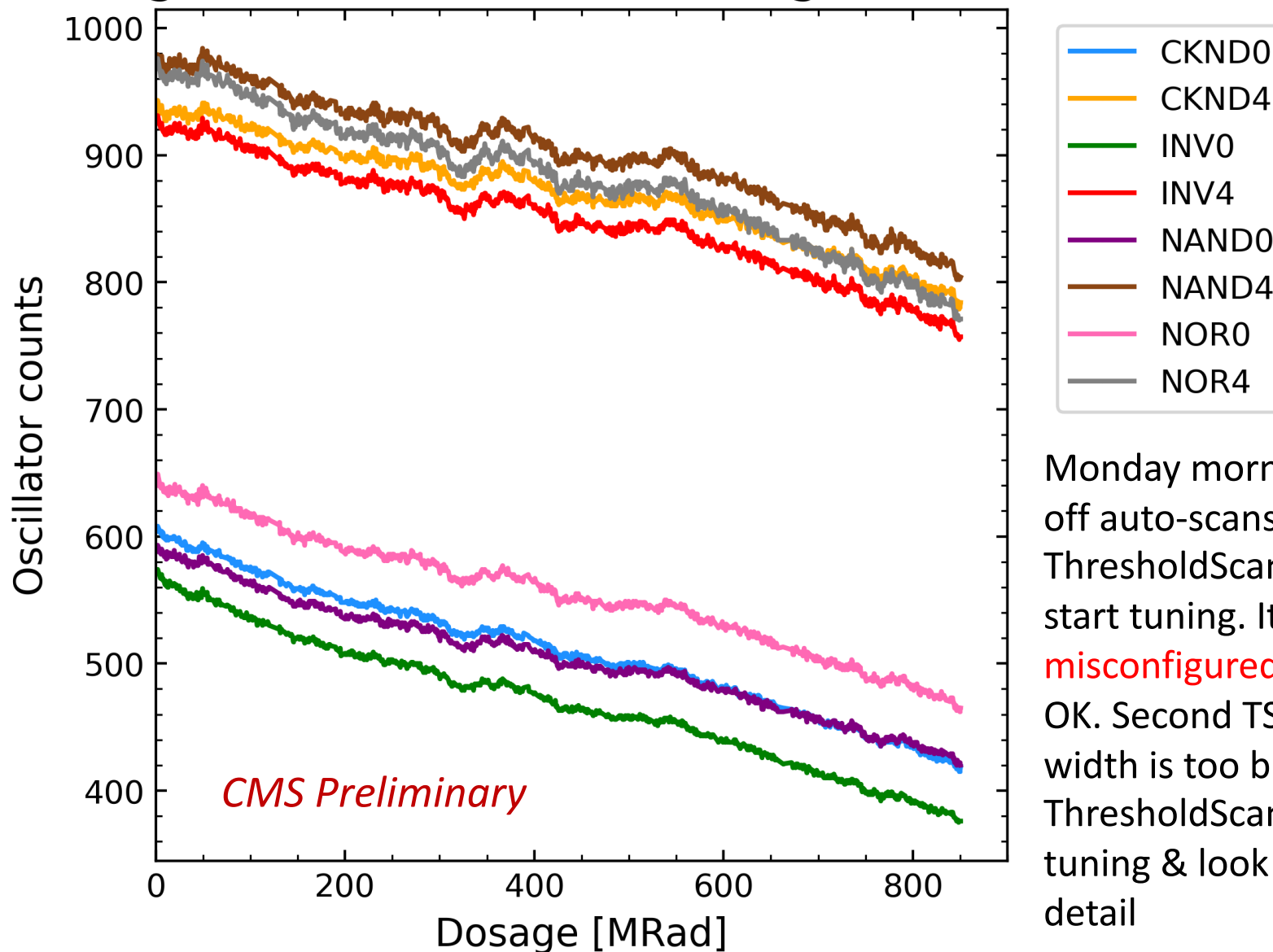
External Voltages During Irradiation



After 730 Mrad a splice in the cable carrying MuxScan data deteriorated, & about half the Mux data corrupt. Also caused "occasional" failure of MuxScan with misconfiguration of CROC voltages. Now can completely reproduce problems in lab, but recovering good data is difficult – ongoing work. Other than misconfigurations (which were reset) did not affect operation of CROC

Ring Oscillators to 850 Mrad

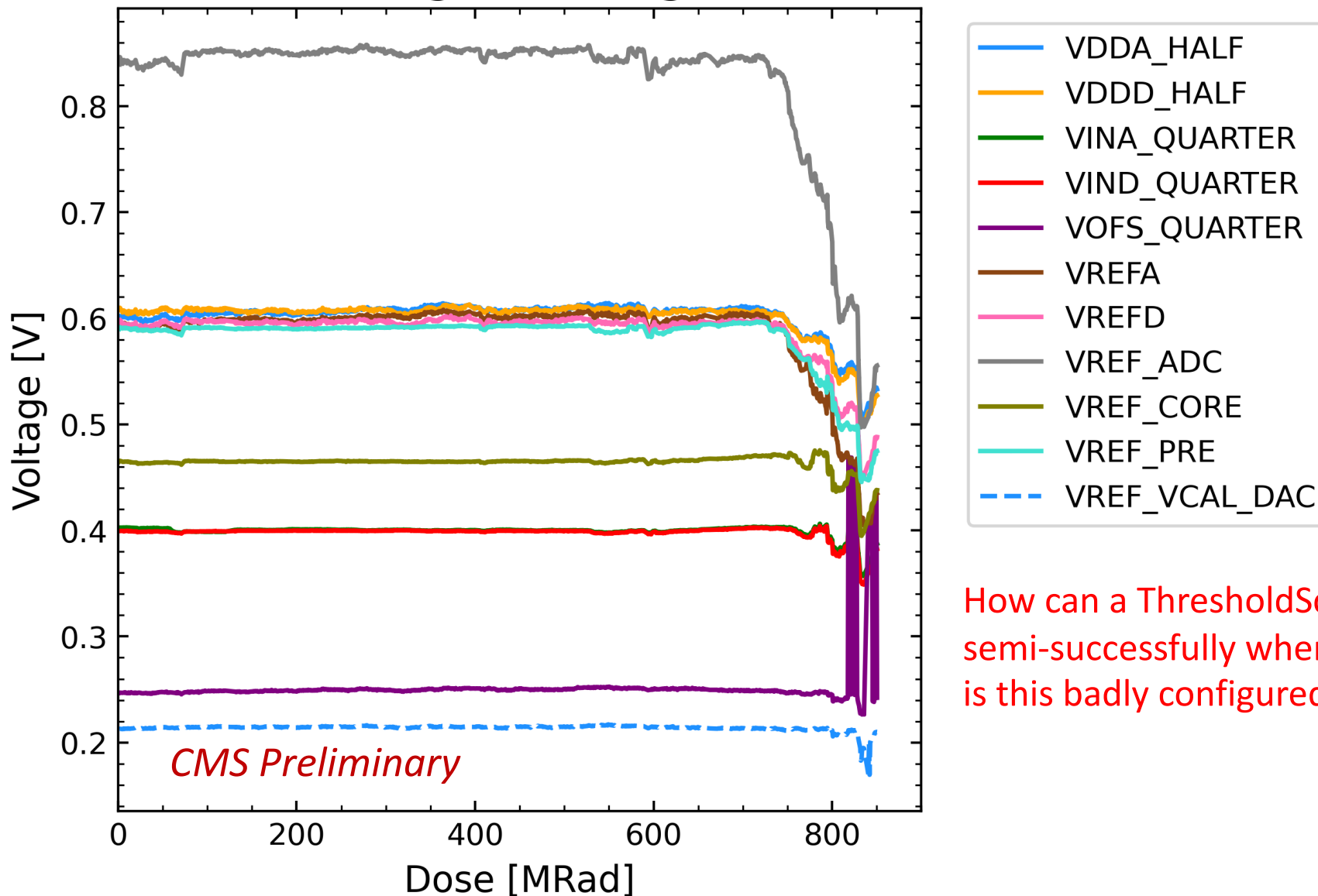
Ring Oscillator Bank A During Irradiation



Monday morning looks fine – turn off auto-scans & run a ThresholdScanFast before we start tuning. It fails – **PS are misconfigured** – cycle & they're OK. Second TSF runs fine, but width is too broad. Run ThresholdScan before starting tuning & look around in more detail

Important Voltages to 850 Mrad

External Voltages During Irradiation



Fixing the Wrong Problem

At this point 2 scenarios presented themselves: *either the CROC was badly configured, or the MuxScans were lying*

Since the ThresholdScans were running (just not well tuned), and VINA & VIND no longer tracked with the supply readings, we tended to favor the "lying MuxScans." But needed to retrieve the second shifter from the Sandia badging office, where they had spent the morning, & when we got back, we had decided to attack the "misconfigured CROC" first

To raise the Vs, we had 2 levers. One was the PS Vs, and the other the software trims on VREFA and VREFD. We changed the PS Vs first (easiest) – moving them up to ~2.0 V seemed to move VINA & VIND back to 1.6 V, where they should be.

VREFA, VREFD, and VREF_PRE were still not back where they needed to be, and we needed to move VREFA_TRIM & VREFD_TRIM to 15 to get them close (they had been at 7 & 10 for the entire irradiation up to that point). The CROC would not function with these, so they were backed down to 11 & 14. The auto-scans had been long suspended at this point, & we went back to Threshold tuning

The TDAC distributions now looked horrible, and the number of stuck pixels had soared (from a typical 0-5 to tens of thousands, but the scans still "worked." At this point we needed to be escorted out of the GIF, so we restarted the auto-scans (but with MuxScan removed)

Flying Blind

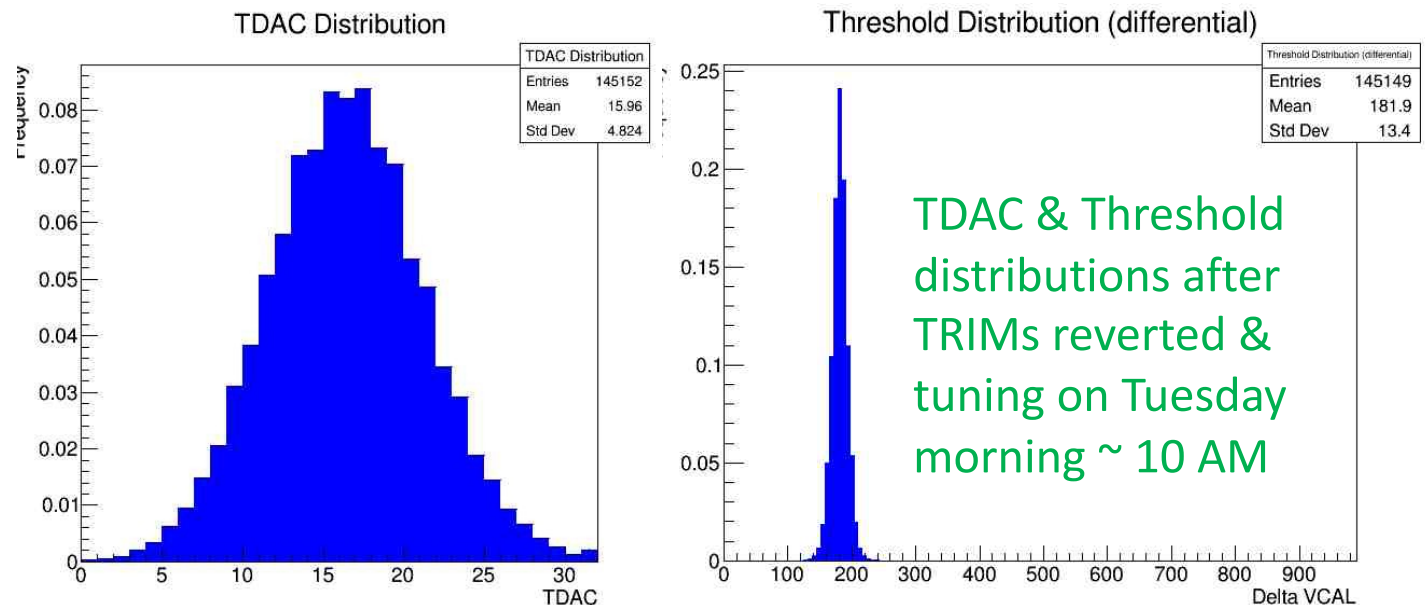
Discussions with Flavio Loddo very early in the morning (our time) Tuesday brought us back to the idea that it was the MuxScan that was lying to us

“Nothing should be working if VREF_PRE is less than 0.5 V.”

Came into GIF to find RingOscillators and AnalogScans all over the place, PS currents oscillating. Reverted VREFA_TRIM=7 & VREFD_TRIM=10 & reset, and everything went back to normal (except MuxScan still failing frequently). Were able to tune Thresholds (after one mis-step that was obvious & quickly backed out)

Were able to run like this all day & overnight, but had no idea what Vs on the CROC were (call this “flying blind”)

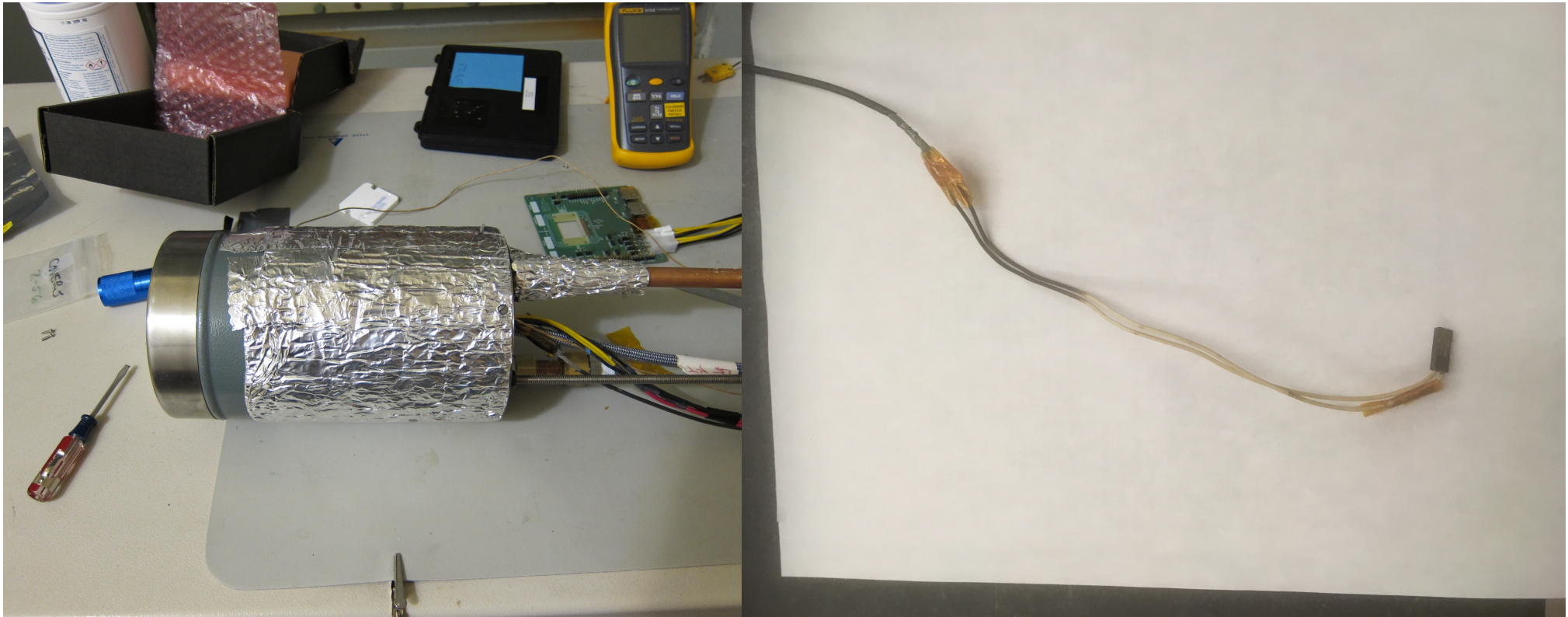
Pretty much “flew blind” until we passed 1 Grad (next day) and could drop the cell & access the thermos (tho kept up Threshold tuning as our “quality check”)



Try to Fix the MuxScan Cable Splice

On the drive to Sandia on Wednesday morning, we agreed that any problem with the MuxScan cable would almost certainly be where 2 cables were spliced together right outside the thermos. We did not want to open the thermos & replace the cable because SCC (& everything) becomes brittle with irradiation. So we decided to try to fix the splice first. **First MuxScan ran fine** but **next 4 had problems. Decided to close up & run overnight again without MuxScan**

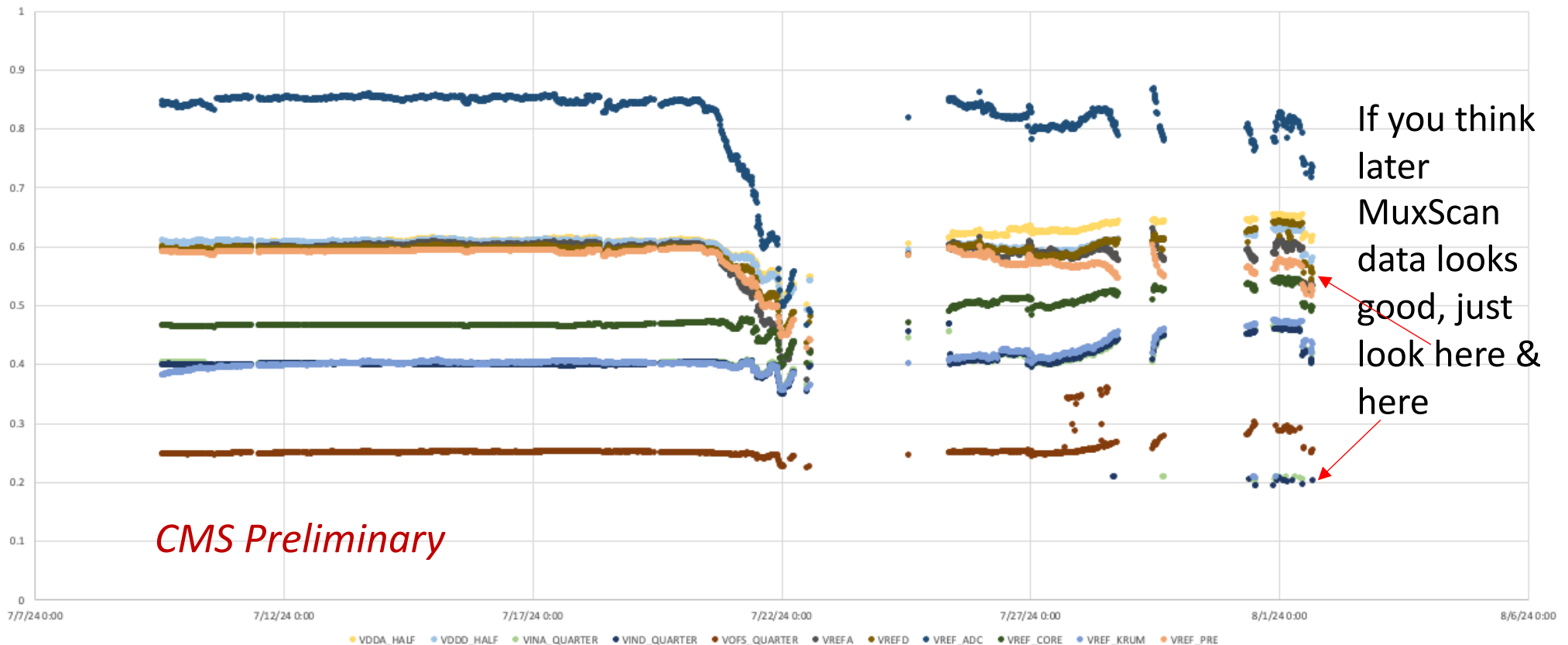
We came in the Thurs morning deciding if we should drop the cell & open the thermos. We ran MuxScan and it worked fine several time – added back to auto-scans, even overnight.



Thru the Last Week of Irradiation

New shifters came in on Monday morning to find auto-scans dead & CROC misconfigured by failing MuxScans (just like week before). This happened a few more nights (+ one night spent running ThresholdScanFast in place of MuxScan). But threshold tuning fine until 4:15 PM Friday

Also had problems getting LN2 from the big dewar into the small dewar (presaging the ice blockage on Friday night that ended the irradiation & fried the CROC). But there's always enough LN2 in the small dewar to keep the T control working fine (until Friday night)

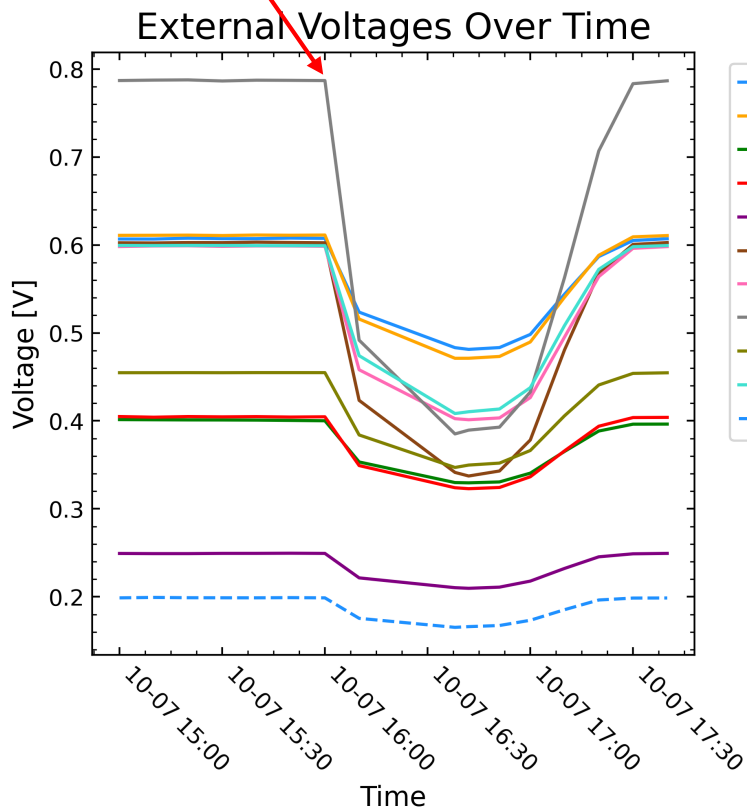


Bench Tests Later on Un-irradiated CROC

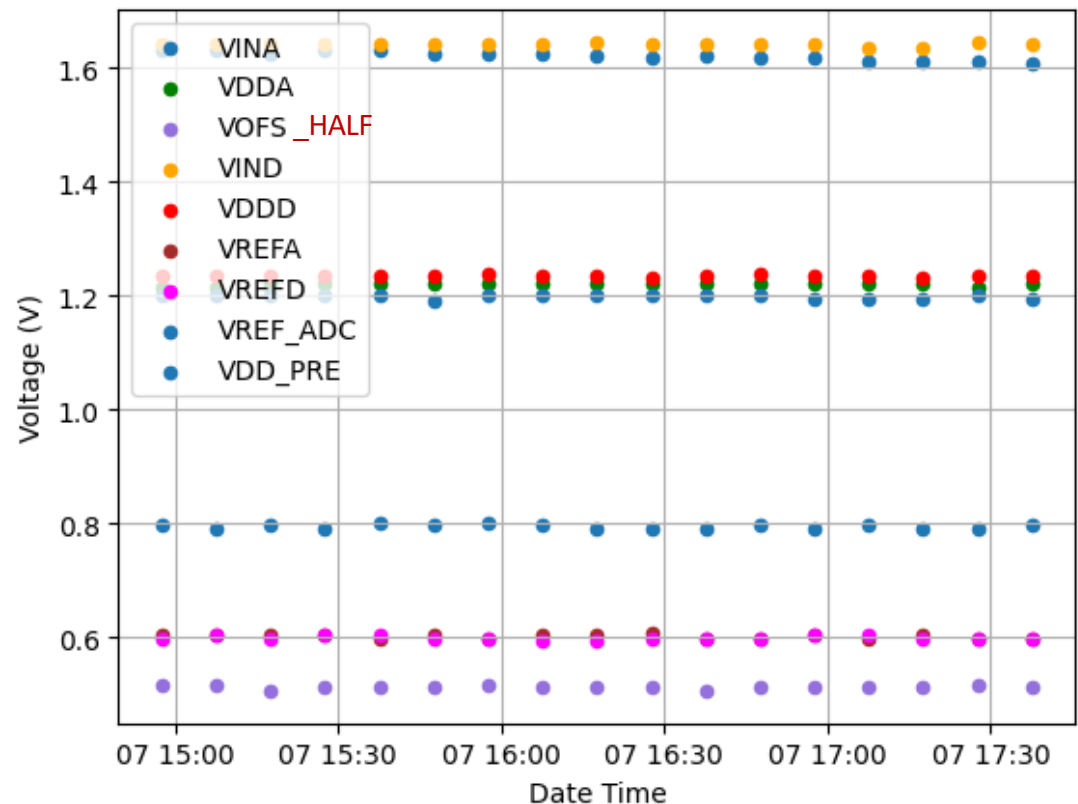
Use MuxScan cable that (we believed) caused problems with a fully-functional CROCV2

Mist water onto splice (high tech) – read Voltages thru MuxScan, reconfigure (only if necessary) & read Voltages from Pin Block

Voltages from MuxScan do not represent (or affect) Voltages on CROC when splice wet



Voltages read off pin block at the same time

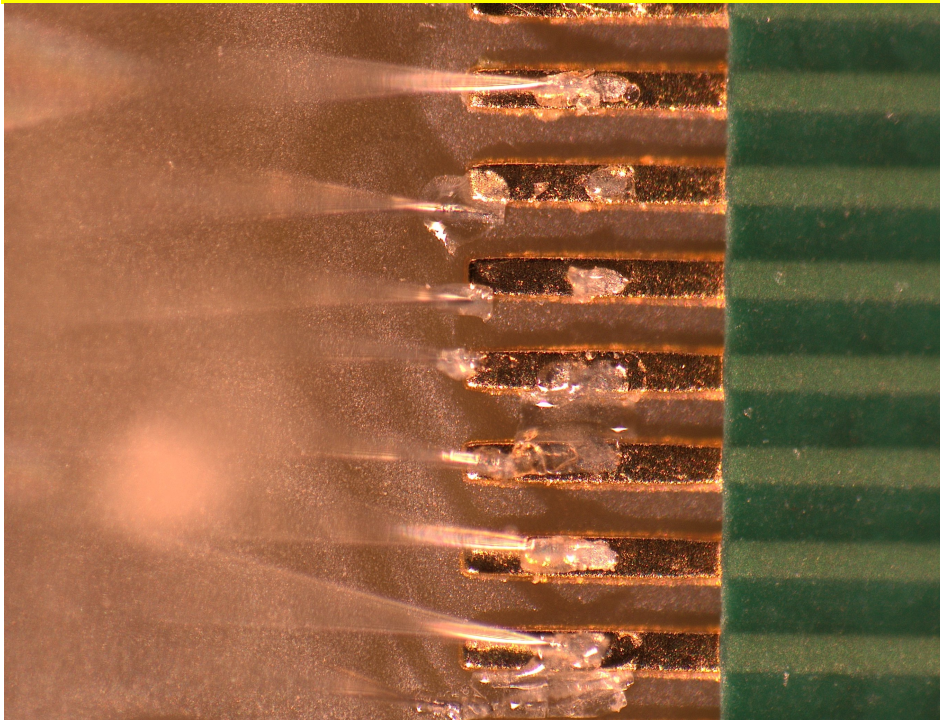


Problems Solved over Multiple Irradiations

LN2 cooling system:

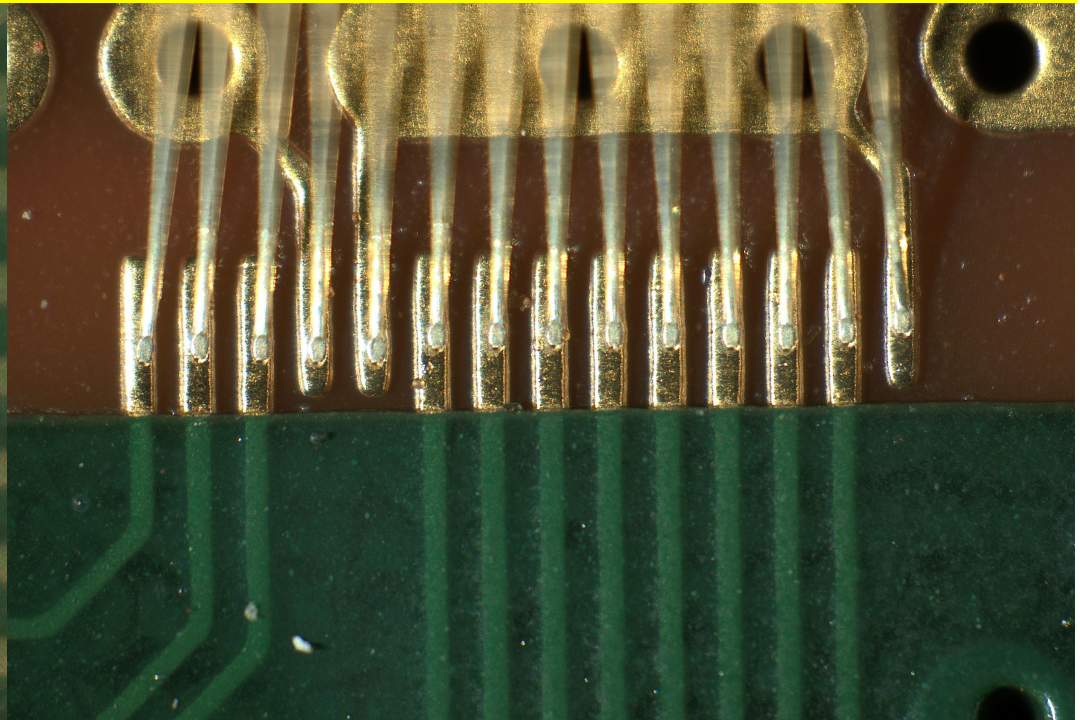
- Condensation and frost forming on the electronics
 - Fixed by switching to a dry LN boil off system
- Using too much LN2 to cool the electronics (Dewar empties before a night or weekend passes)
 - Fixed with high quality vacuum-lined LN2 transfer line
 - And with the addition of thermal putty conducting heat to a large heat sink
- Noise on the > 20 ft thermocouple line sometimes made control system unable to correctly maintain the temperature of the CROC
 - Fixed by adding a braided cable sleeve to shield the thermocouple line and proper grounding of the system
- Cooling system constantly over-corrects the temperature
 - Using linear extrapolation to have the feedback loop base its adjustments on where it will be, and precooling the transfer line before the temperature passes the set temp. Takes longer to reach set T but doesn't overshoot.
- Ice blockages forming from outside air finding its way into the gravity feed
 - Fixed over short-term using check valves to keep air out of system. However, never tested beyond two weeks. A redundant small dewar would have allowed us to de-ice the primary one while continuing irradiation.

Wire Bonds after > 1.6 Grad



SD5 wire bonds looked “OK” after 300 Mrad irradiation in Jan 2024 but began deteriorating quickly, so the CROC stopped working ~ 1 month after irradiation ended

Saw same thing after pause in Jan 2023 irradiation (at 100 Mrad) – actually kept us from restarting that irradiation



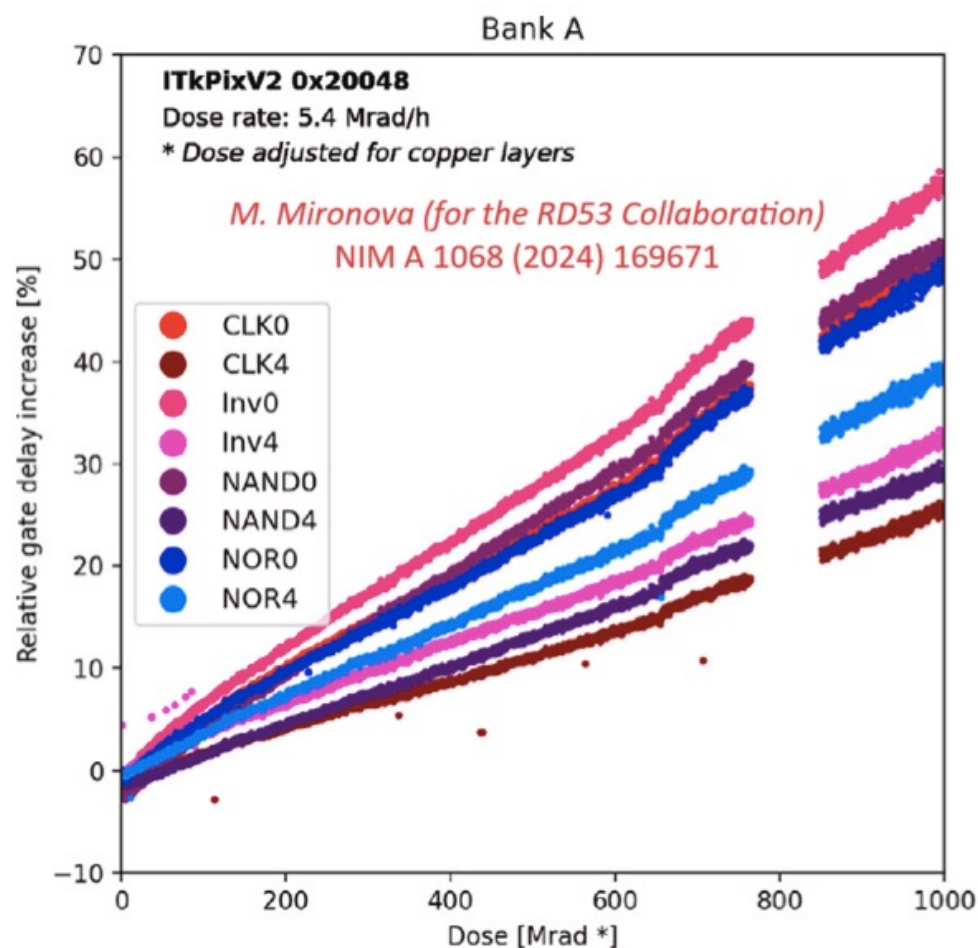
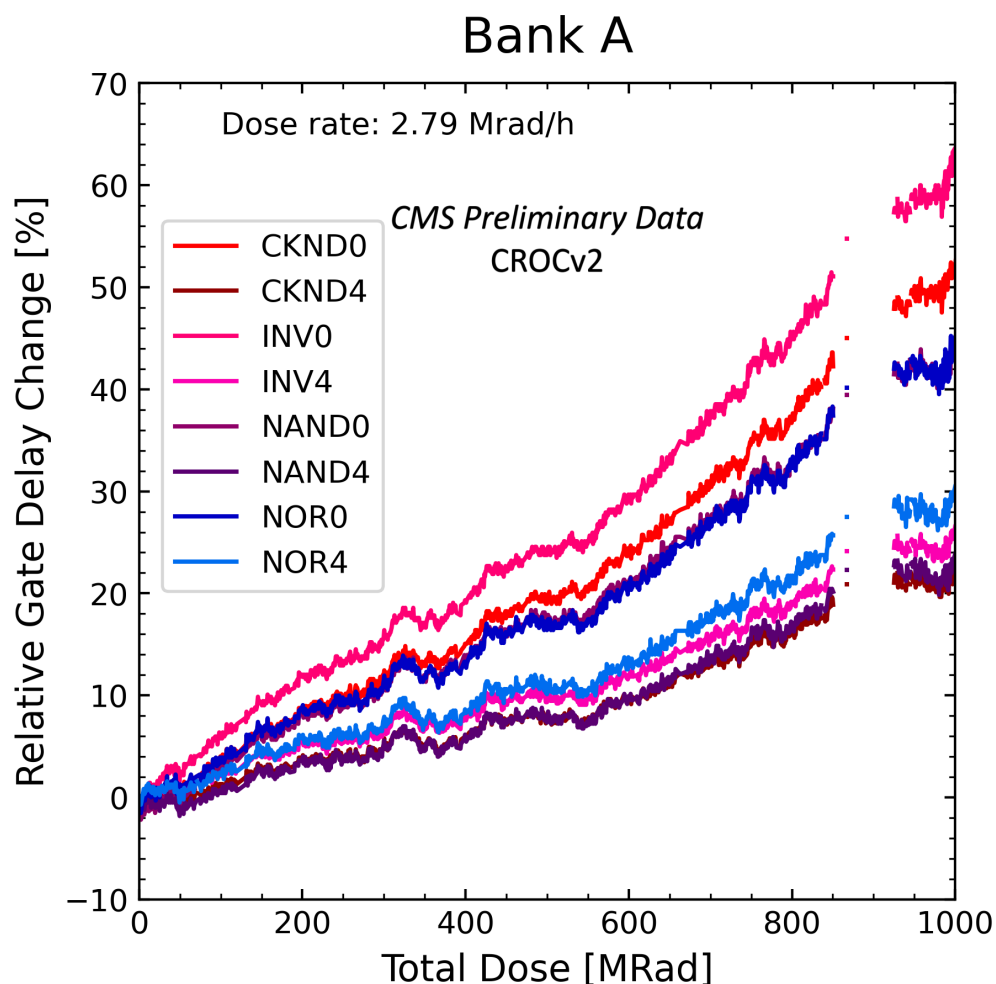
SD22 wire bonds look as good as they did before the irradiation – examined all ~200 & not one that looks problematic (photo 2 months after irradiation but still good ~ a year later)

And they were probably exposed to as much hazard after 1600 Mrad irradiation ended (heat & loss of positive pressure for ~60 hours) as they were during the irradiation – give credit to₂₄ parylene coating

How Does Our Data Compare to x-ray Irradiations?

Show Ring Oscillator Data Plotted as Dose vs increase in Gate Delay – this is the real effect that will limit the usefulness of the ROCs

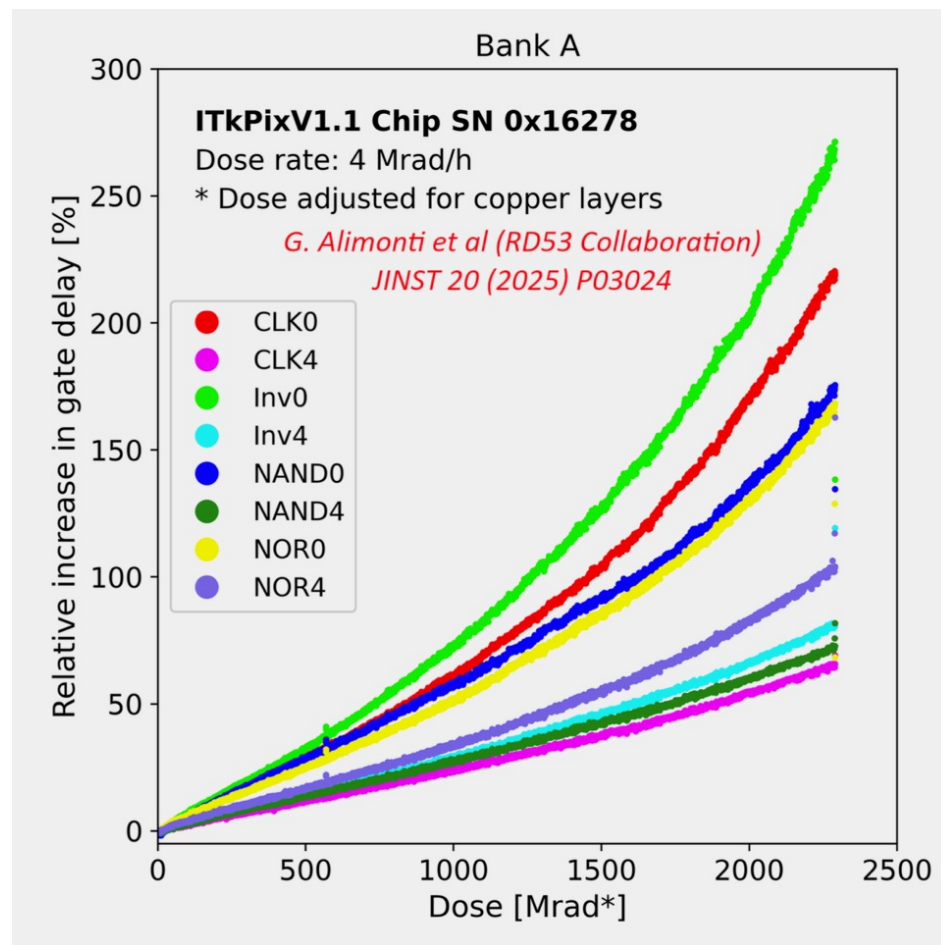
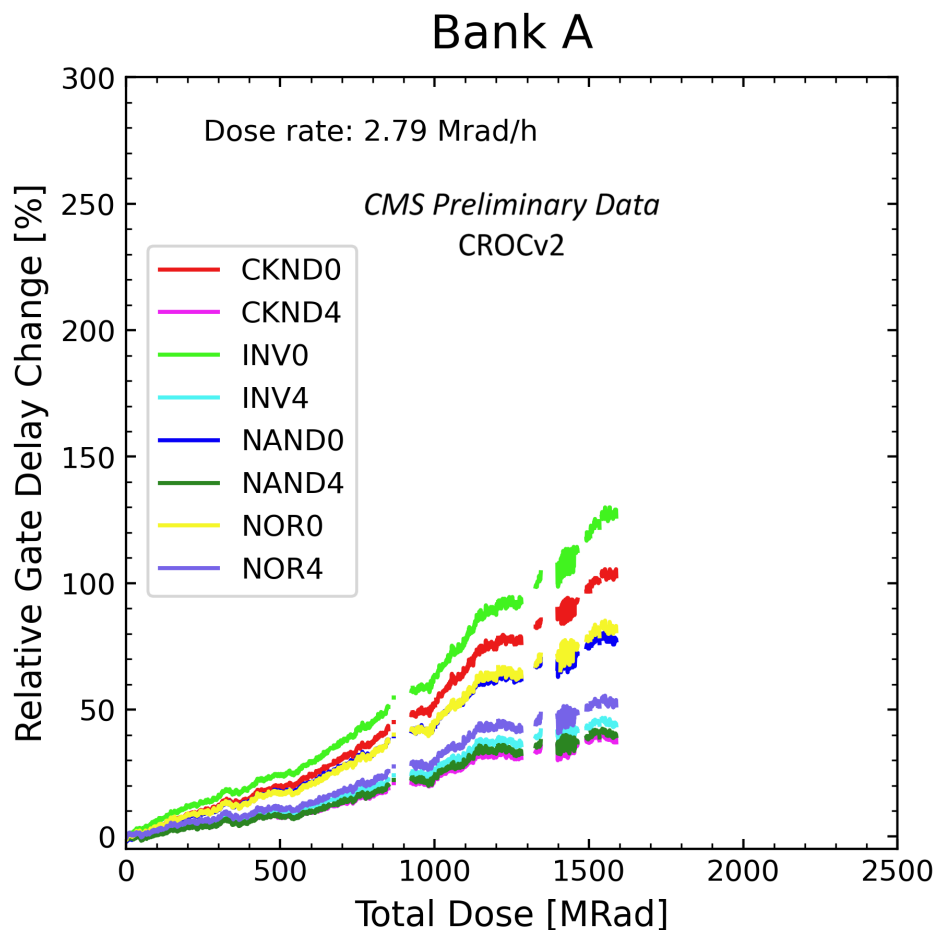
RD53 has published results for x-ray irradiations to 1 Grad (ITkPixV2) and 2.2 Grad (ITkPixV1)



How Does Our Data Compare to x-ray Irradiations?

A maximum Gate Delay increase of 200% is often taken as the tolerable limit. However, the results below need to be corrected for the observed increase at lower dose rates (which will be present at the HL-LHC).

See D. Bortoletto et. al., arXiv:2404.10963v1 [physics.ins-det] for more discussion



Conclusions

The CROCv2 in this irradiation worked very well for 1.6 Grad of dose. It was very (eerily) stable, which may have had something to do with its being parylene coated (& certainly had something to do with its careful design & testing)

Even the cooling system & the readback of the CROC voltage read-back worked very well, **until they didn't (for trivial, even foreseeable reasons)**. An irradiation like this is so harsh it will always find the weakest link

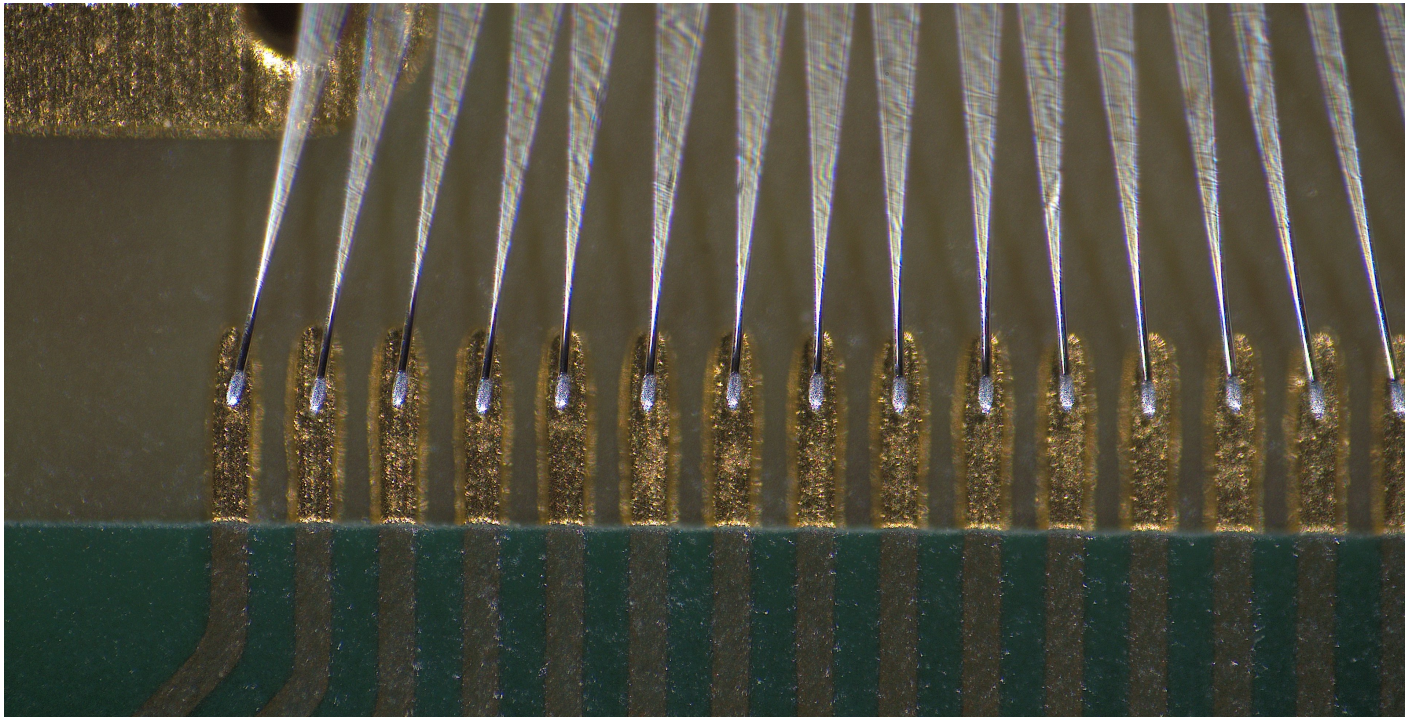
At ~730 Mrad the MuxScan readback started failing. Do not believe this was a failure of the CROC or the MuxScan code, but a failure of a splice in the ~20 foot 2-pin to lemo cable that was poorly insulated and occurred just outside the thermos, where the cell air, heated by the array, meets the outside of the cold thermos. At times water tends to accumulate here, just where the splice was.

Can now reproduce the splice/water problem in the lab, and show it does not affect internal voltages on CROC (if CROC not mis-configured) thru reading out internal V's by a pin-block. Also can explain another (smaller) problem with IMUX readout at beginning of irradiation that self-corrected at ~1.1Grad as parylene contamination (& later burn-thru) of IMUX jumper

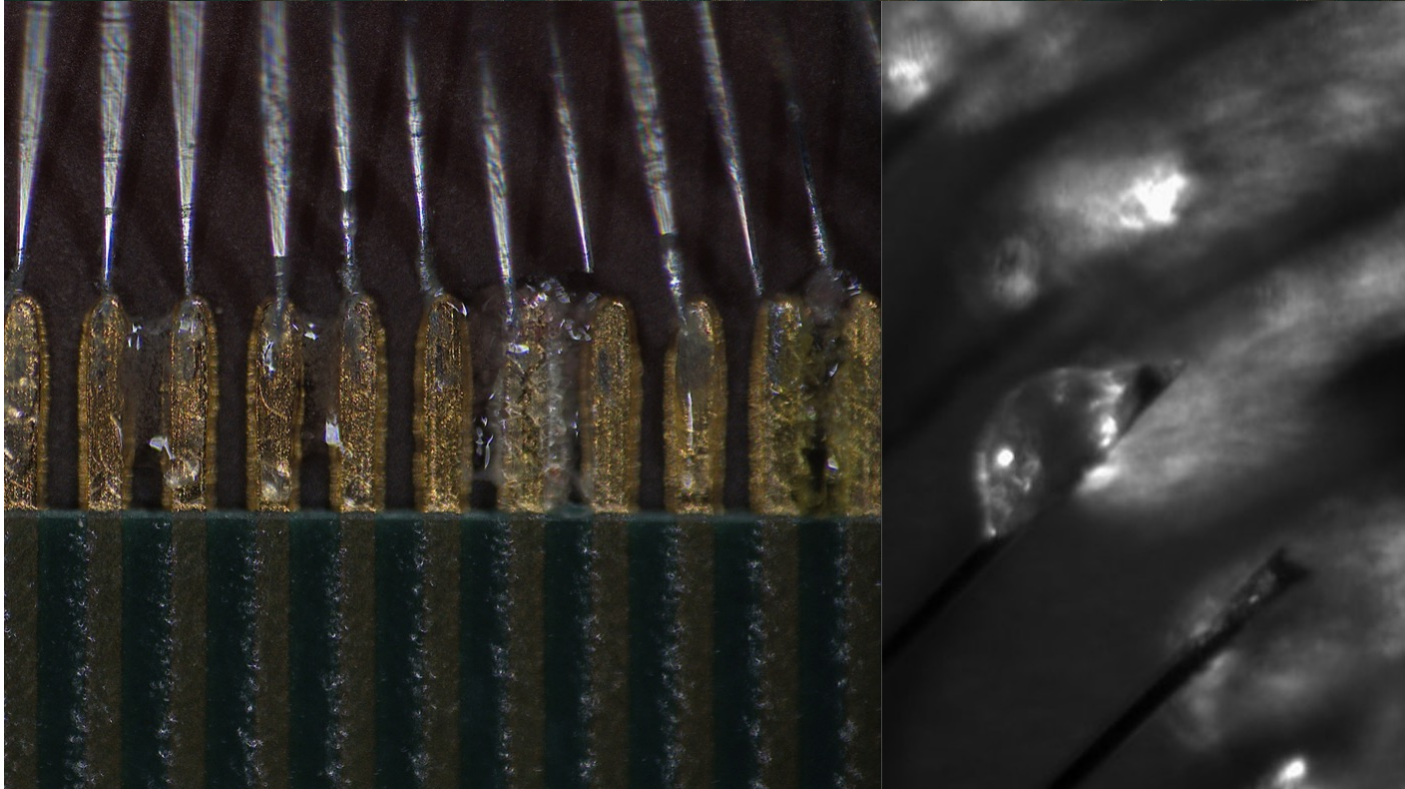
Many thanks to Don Hanson, Audrey Rotert, & Kevin McRunnels at the Sandia GIF for support & LN2, and to Mathieu Benoit at ORNL for parylene coating the final CROC

Back-up Slides





Microscope picture of unirradiated wire bonds on card (top)

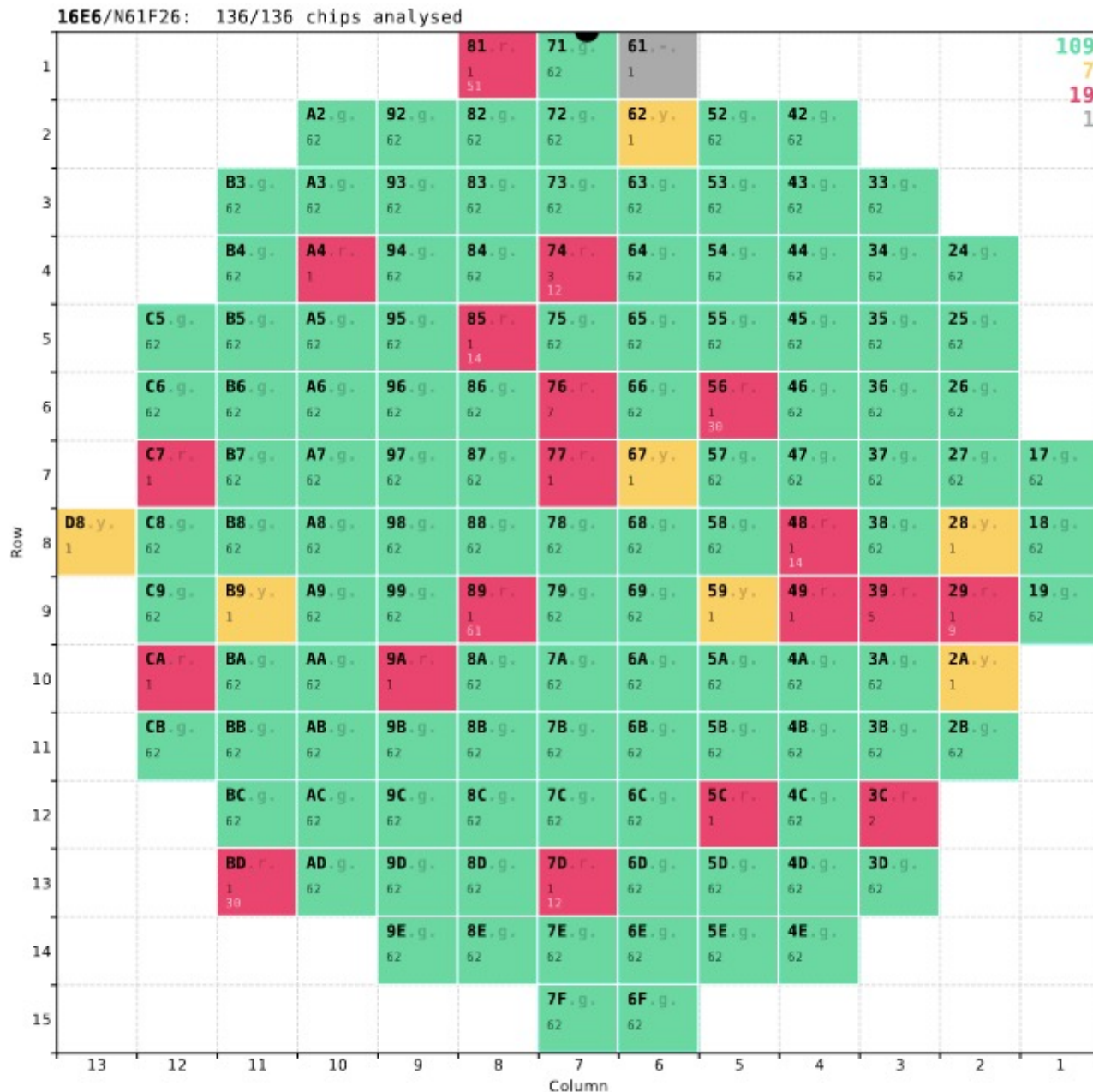


Broken wire bonds & crazed "dielectric(?)" on Jan 23 irradiated CROC at lower left

Foot lifts (one carrying "dielectric(?)" shard) 100s of um away from bond pads on irradiated CROC

Wire bonds on CROC look great both before & after irradiation

History of Irradiated CROC



First wafer from TSMC CROCv2 production (Engineering Run) probed at Torino – then diced for tests – no bumps, no flip-chip

CROC 66 tested “green” & was in a batch sent to Purdue & glued to an irradiation card (SD22)

Wire-bonded at Catholic University of America

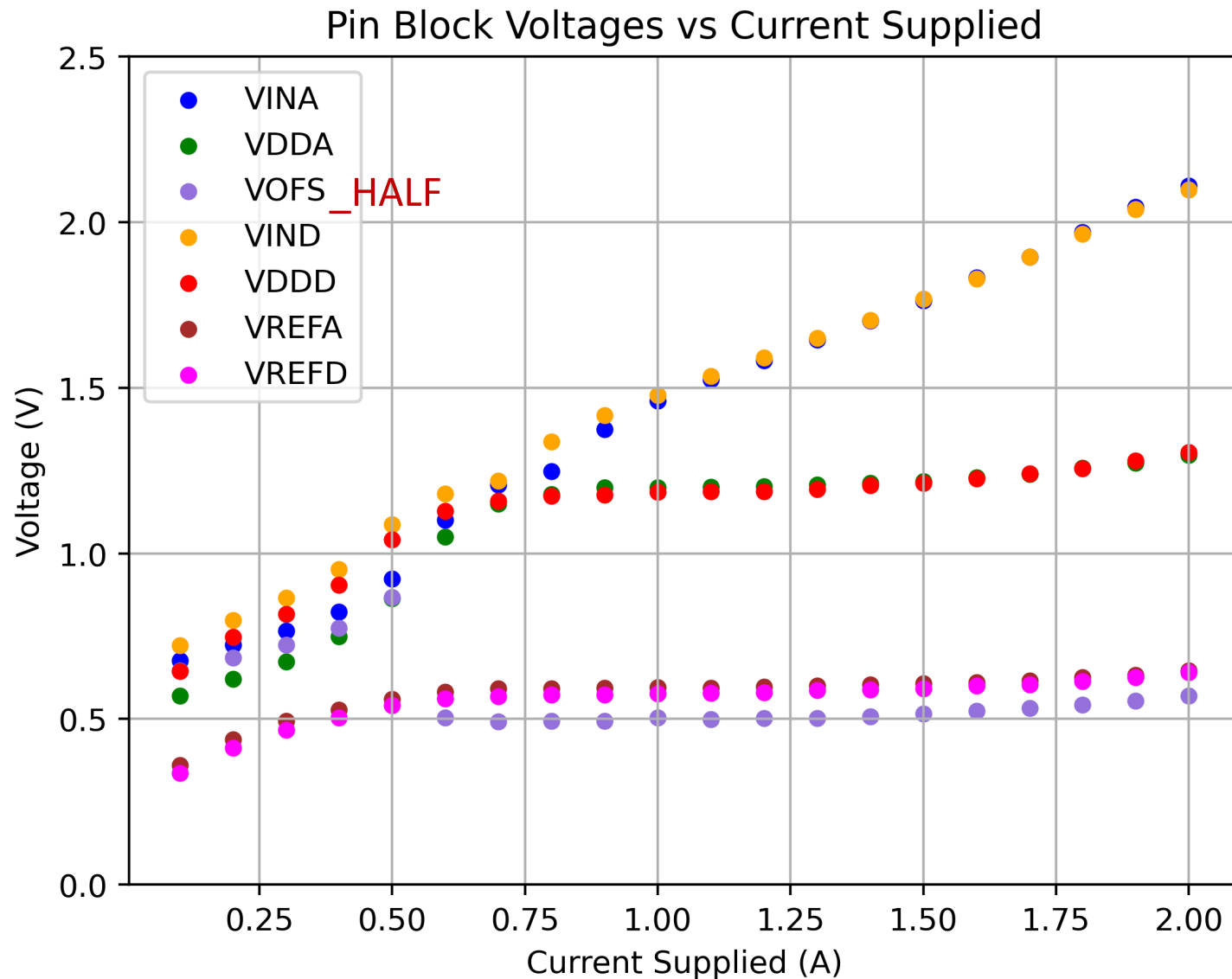
Sent to CU for testing – qualified for irradiation

Masked at CU & UTK. Parylene coated at ORNL

Unmasked & retested at CU

Irradiated at Sandia GIF July 2024

Un-Irradiated CROC Characterized in SLDO Mode



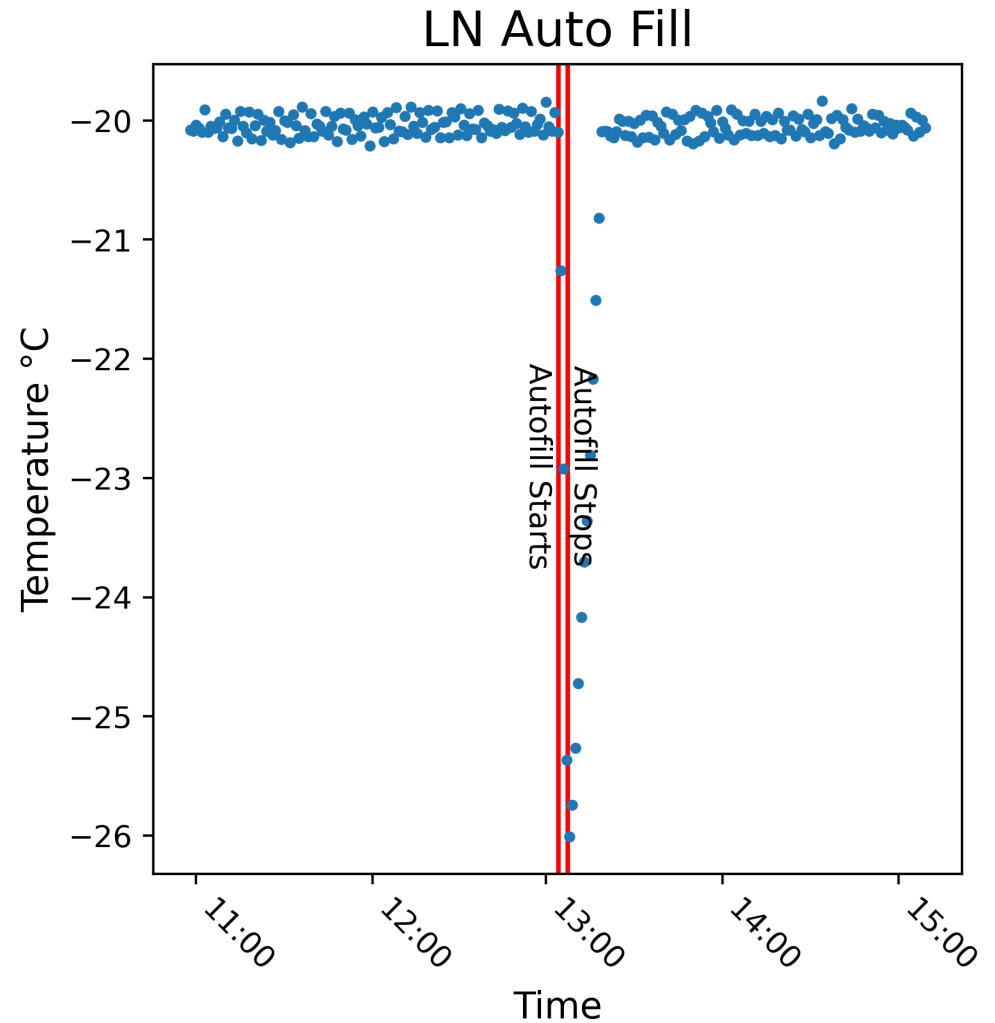
Looks fine – like all the other “green” CROCs before irradiation – but we always irradiated CROCs (x-ray or γ -ray) in LDO mode

Use LN₂ Cooling for CROC

Always had problems with water in thermos (to keep electronics cold) at Sandia when we used air-based cooling to -20 C

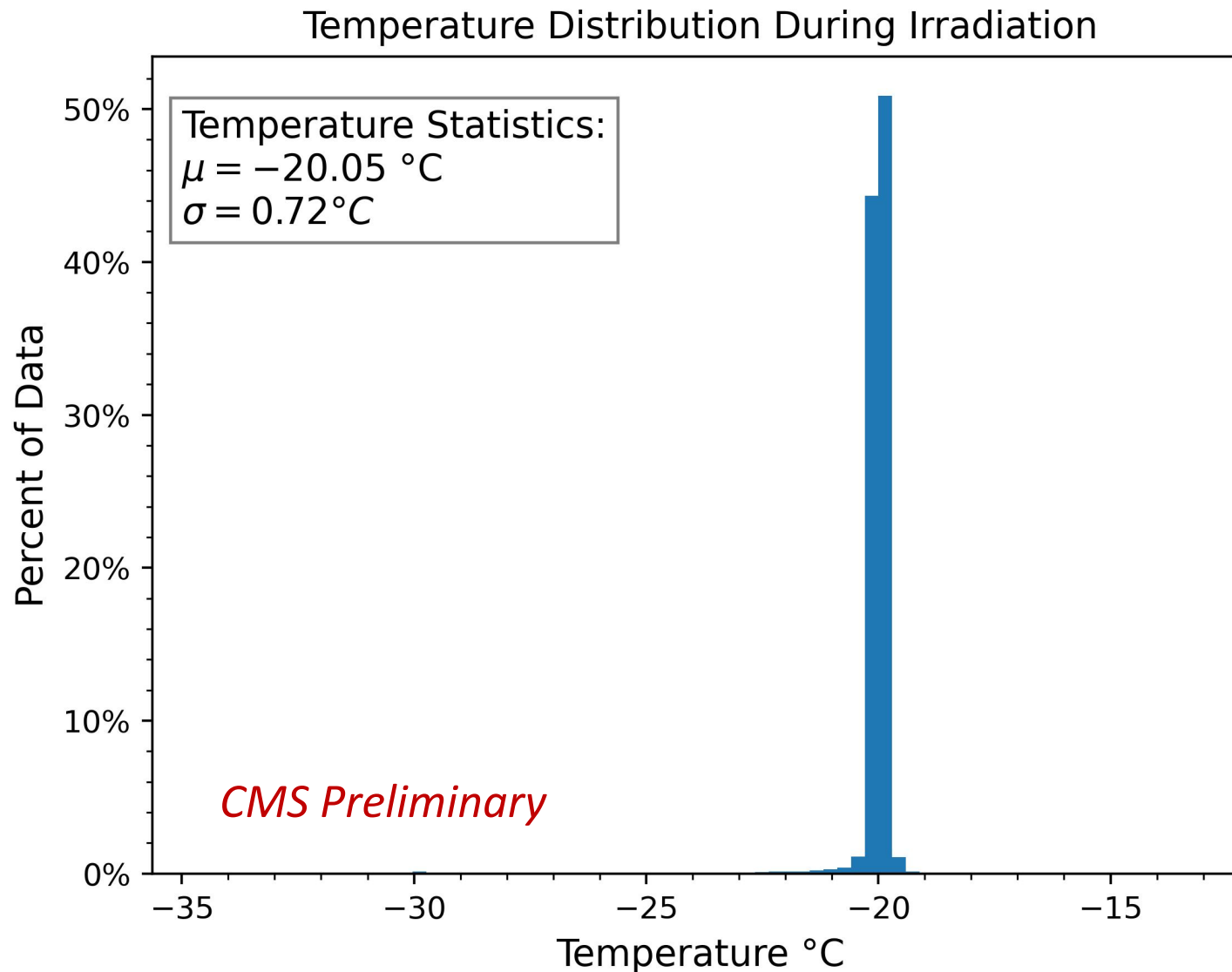
Current LN₂ based cooling leaves inside of thermos bone-dry (tho have to make sure any ice that builds up outside doesn't sneak in when positive pressure of LN₂ is removed)

N₂ gas is produced by “boiling” LN₂ in small dewar (with resistors) when TC on CROC says temperature too high. Take LN₂ automatically from large dewar (when needed) but have to buffer pressure of LN₂ from transfer (with gravity feed)



Take N₂ gas to CROC with 20 ft vacuum transfer line. Managed in 2023 to beat down noise on 20 ft TC cables & other problems (T overshoot on deep autofills, ...)

Distribution of Temp during Irradiation



Roughly 97% of the data points are within 0.5°C of -20°C

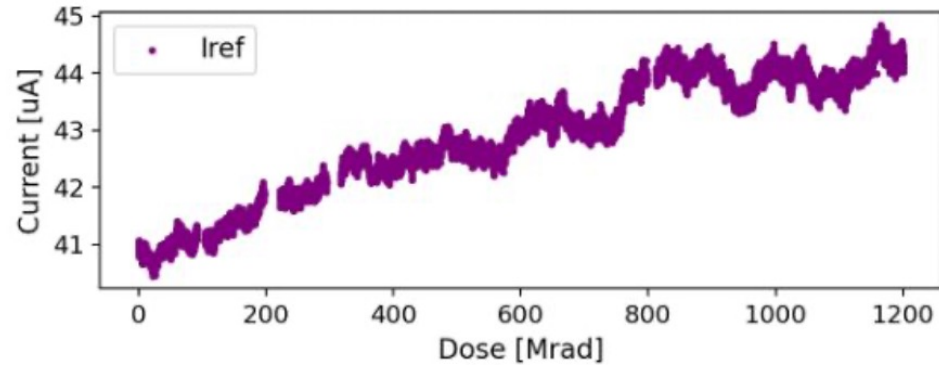
Types of Misconfiguration (Removed)

- 1a) **Purposeful moves by the experimenters** (drop the PS Vs to work safely on thermos, for example). Long enough to show up on PS plots. **Only 2 of these during irradiation** (1st and 3rd Wednesday, after ~66 Mrad and after 1 Grad)
- 1b) Quickly **drop and raise voltages to reset CROC**. Mostly too fast to be picked up by every 10-minute recording of PS V & I, but if you do it a lot, they will be
- 2a) Failure of a scan leaves the CROC in a poorly configured state. **Certain MuxScan failures left the CROC poorly configured**, but others did not. We couldn't figure out the difference from looking at the MuxScan output, & any additional information that might help is probably lost. ThresholdScanFast failures seem to do this also, again *sometimes* but not always, and not as bad as MuxScans seemed to (& they were only in auto-scans in place of the MuxScan 2 nights)
- 2b) **Experimenters**, trying under pressure to debug & fix problems, **could sometimes leave the CROC in a badly configured state**. To our knowledge this **happened only once** - new VREFA & VREFD SW trims induced instability in PS currents & even the ROs from 7/22/24 ~13:00 to 7/23/24 ~09:00 (when we reverted to the old trims & the instability went away). The data in this state is unusable & is cut away, but the VINs were OK, and the CROC did not seem to be damaged by this misconfiguration (RO, analog & threshold scans reverted to normal)

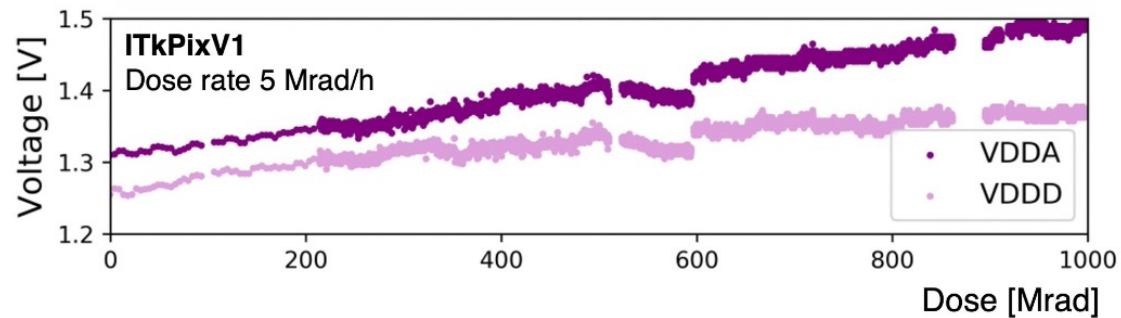
RD53 ITkPix x-ray Irradiations

Maria Mironova, "Lessons Learned from TID Irradiations," Final RD53 Meeting

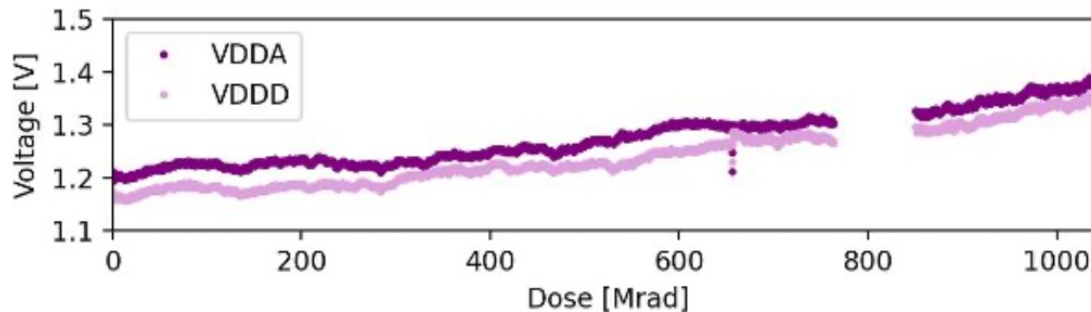
Iref



VDDA/D in ITkPixV1



VDDA/D in ITkPixV2

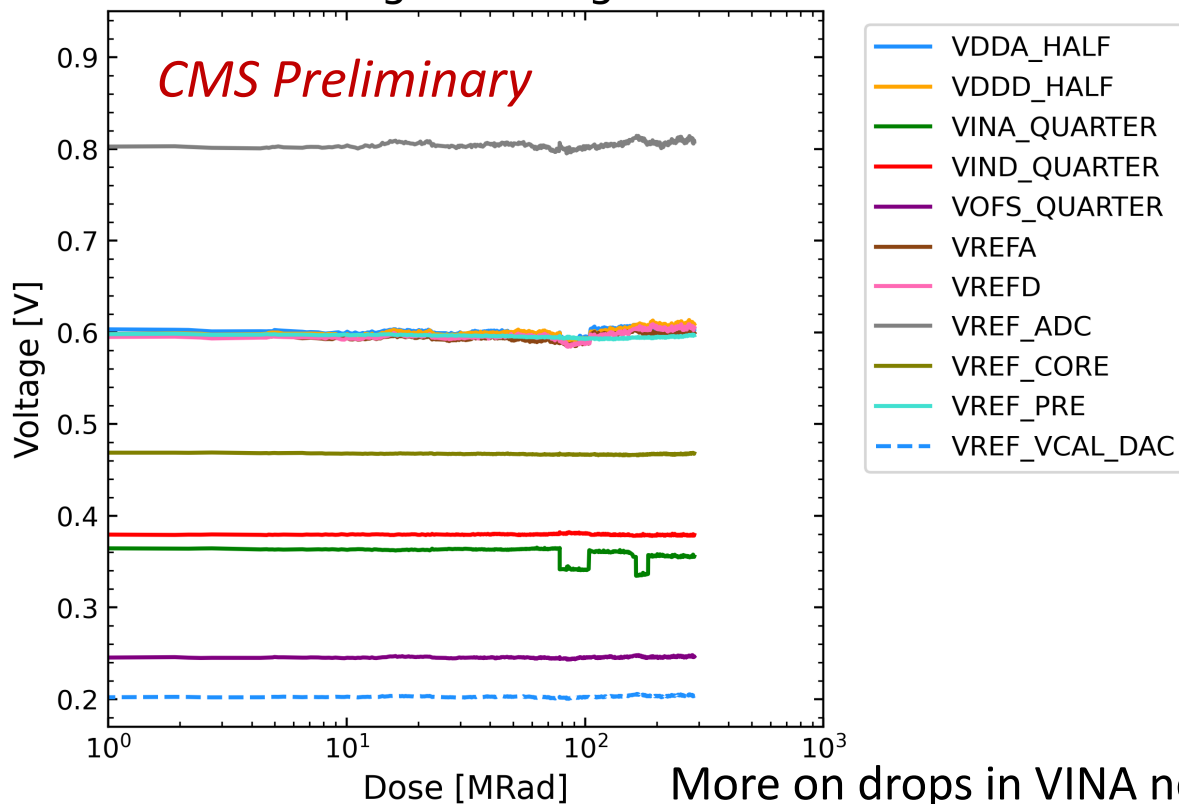


External Voltages – from MuxScan

From our Jan 24 300 Mrad irradi & 1 Grad x-ray irradi (both CROCv1)

VINA & VIND not set as precisely as they should have been, but other than VINA drops, does not seem to have affected performance

External Voltages During Irradiation

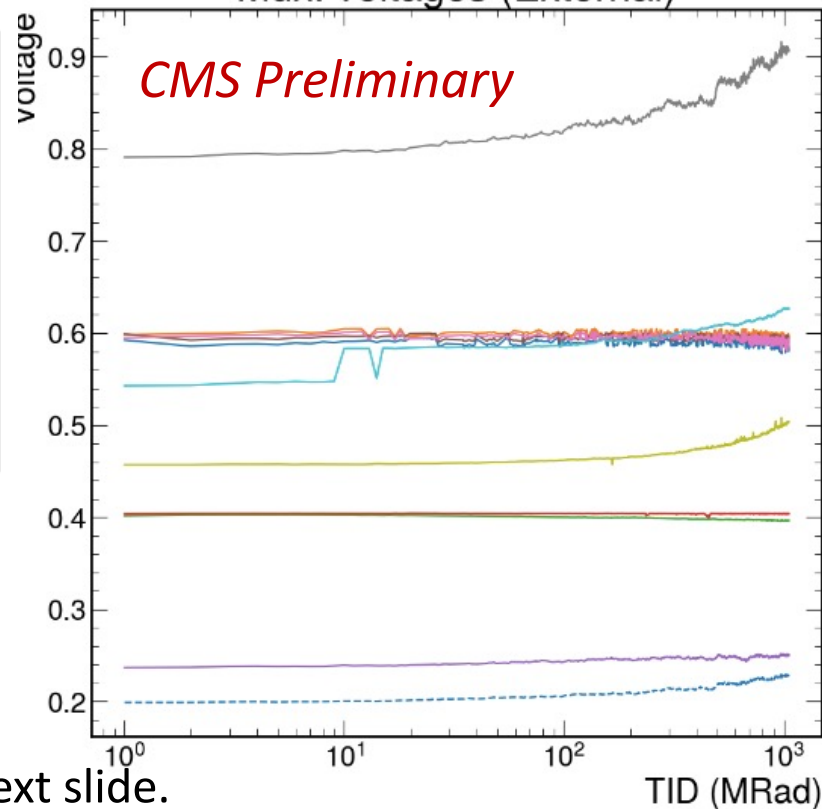


γ-ray irradiation

More on drops in VINA next slide.

Some voltages (like VREF_ADC) changed significantly by ~300 Mrad & we should have seen this.

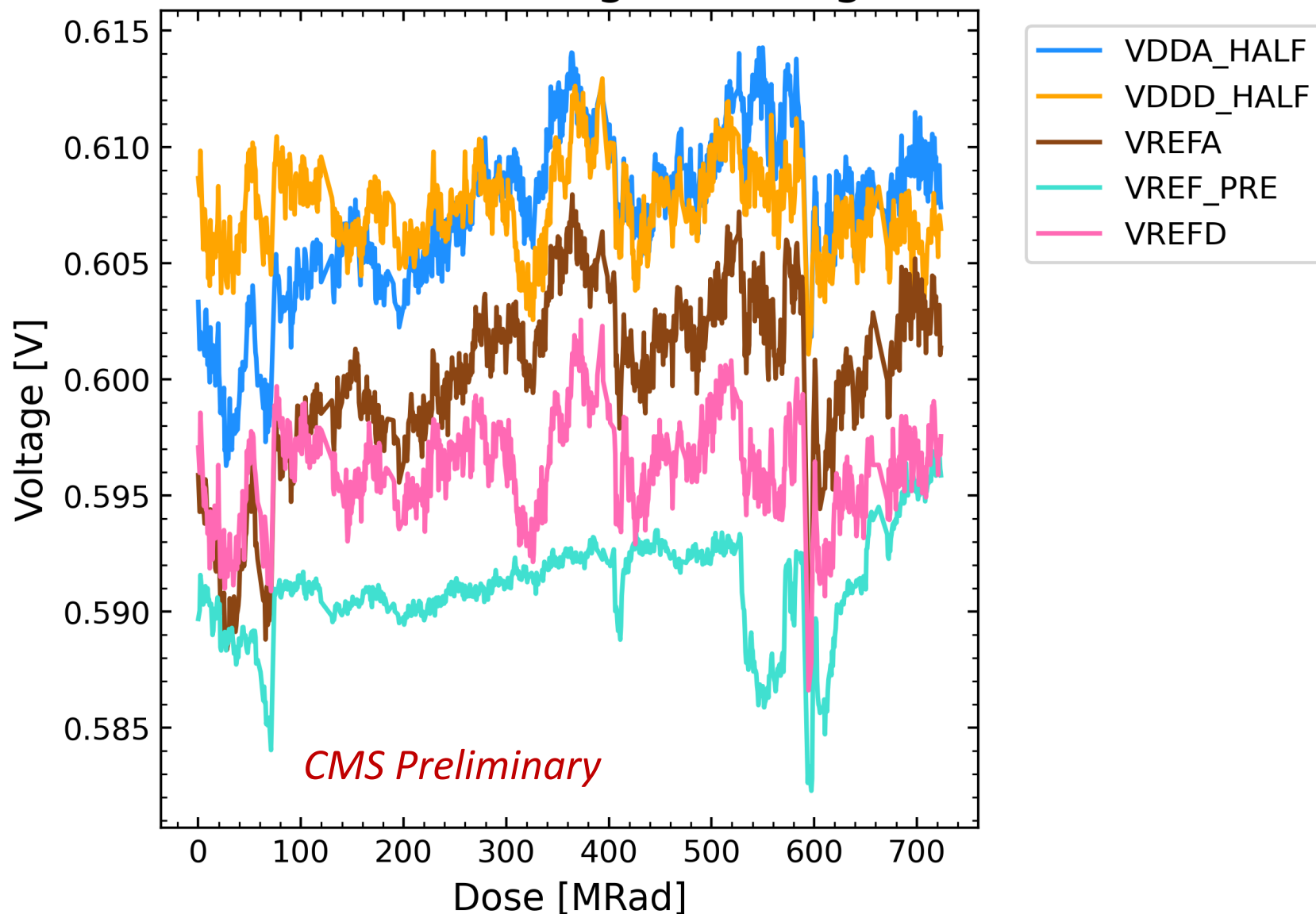
Mux: voltages (External)



x-ray irradiation

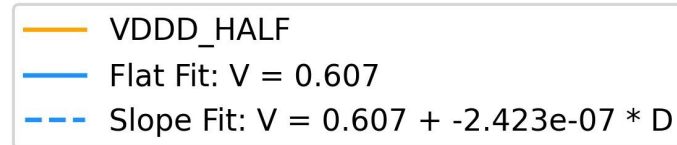
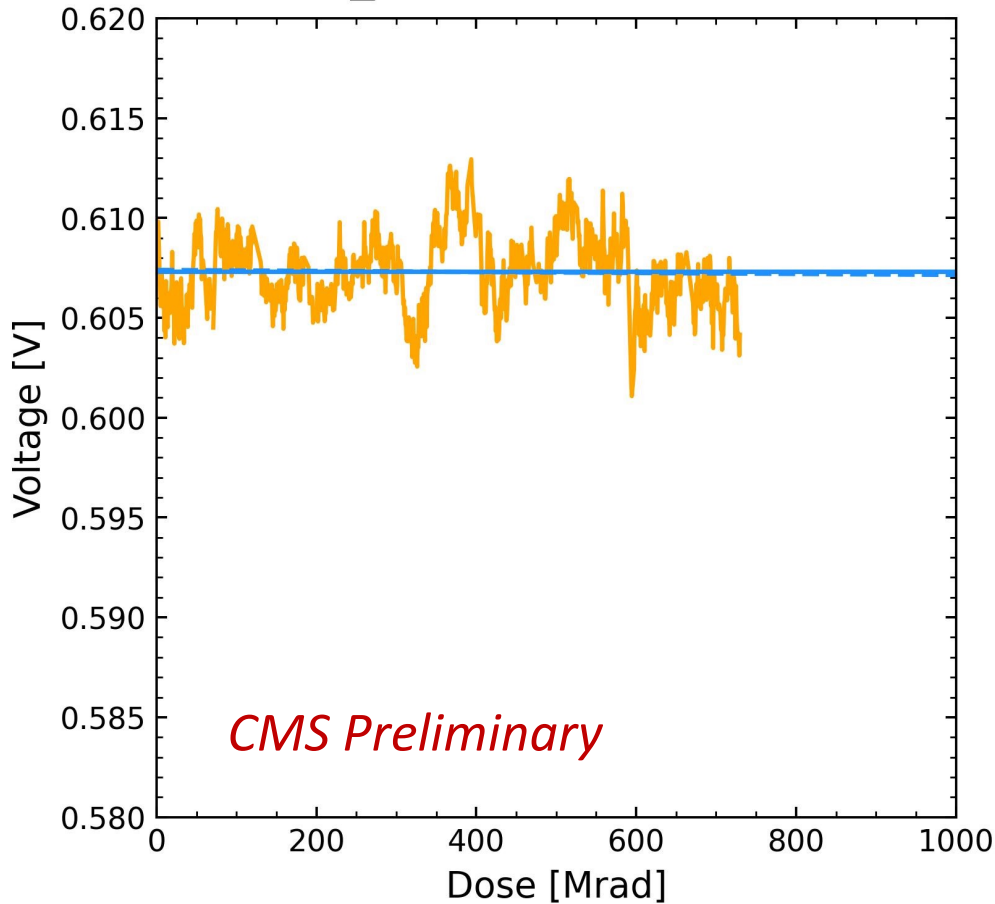
Blow-up of 0.6 V Region to 730 Mrad

Subset of External Voltages During Irradiation

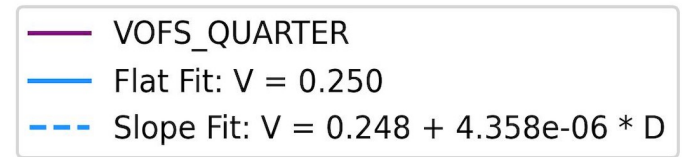
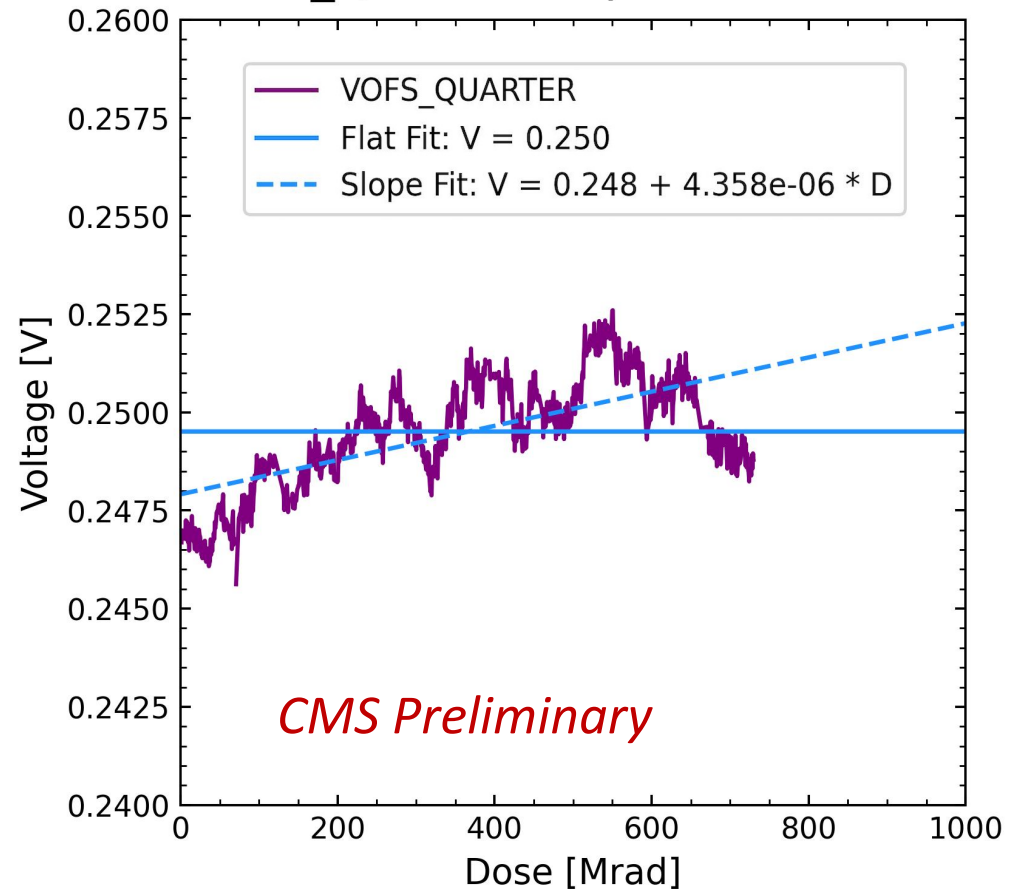


VDDD and VOFS to 730 Mrad

VDDD_HALF up to 730 Mrads



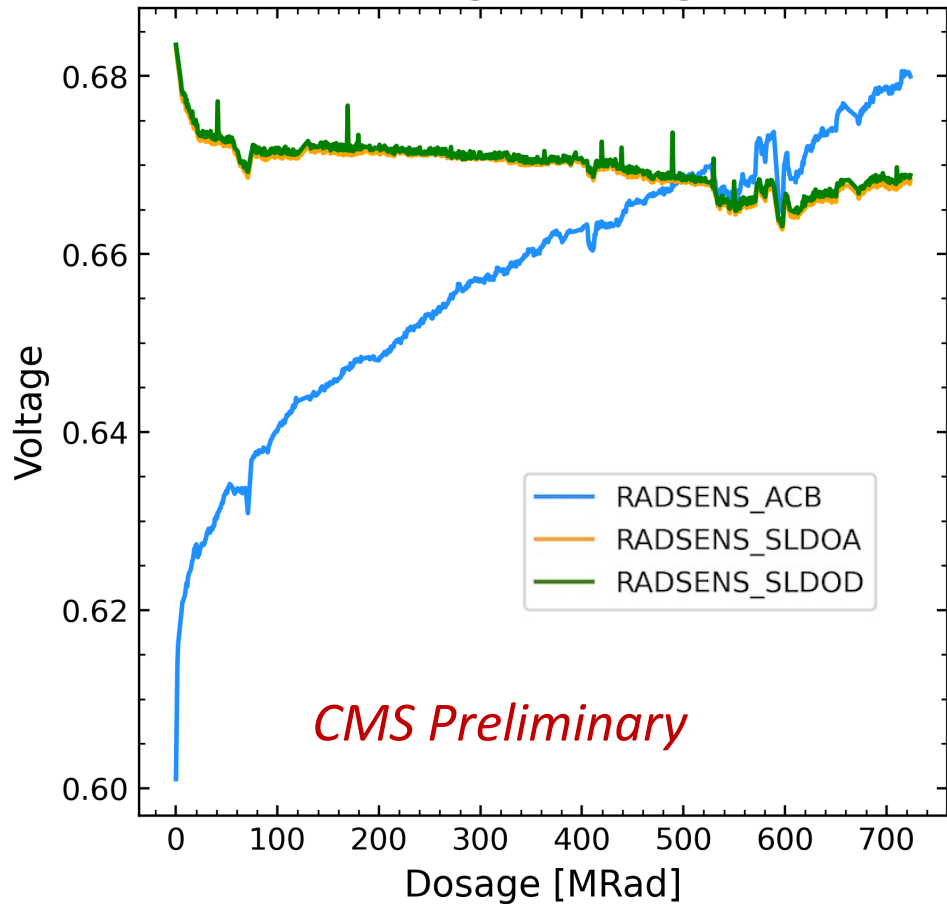
VOFS_QUARTER up to 730 Mrads



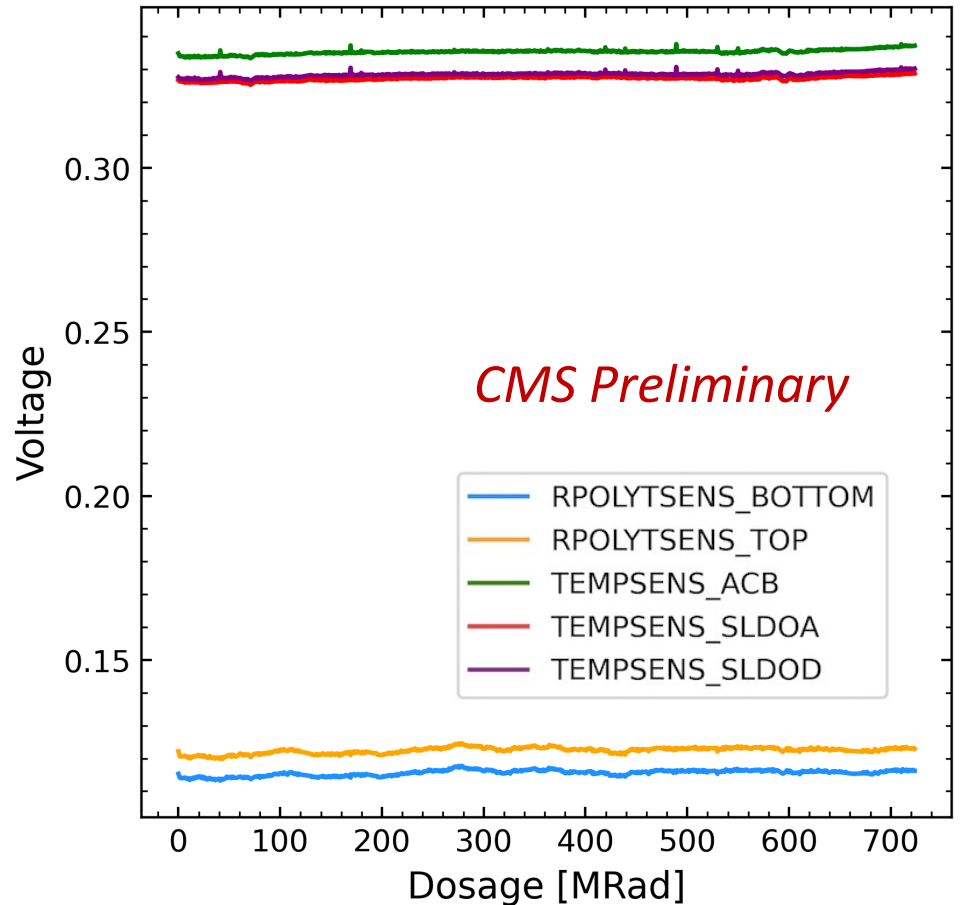
VOFS is the CROC proxy for Iref. Set jumpers on irradiation card so VOFS_HALF (measured on PIN block) reads 0.5 V. MuxScan reports VOFS_QUARTER

Other Voltages to 730 Mrad

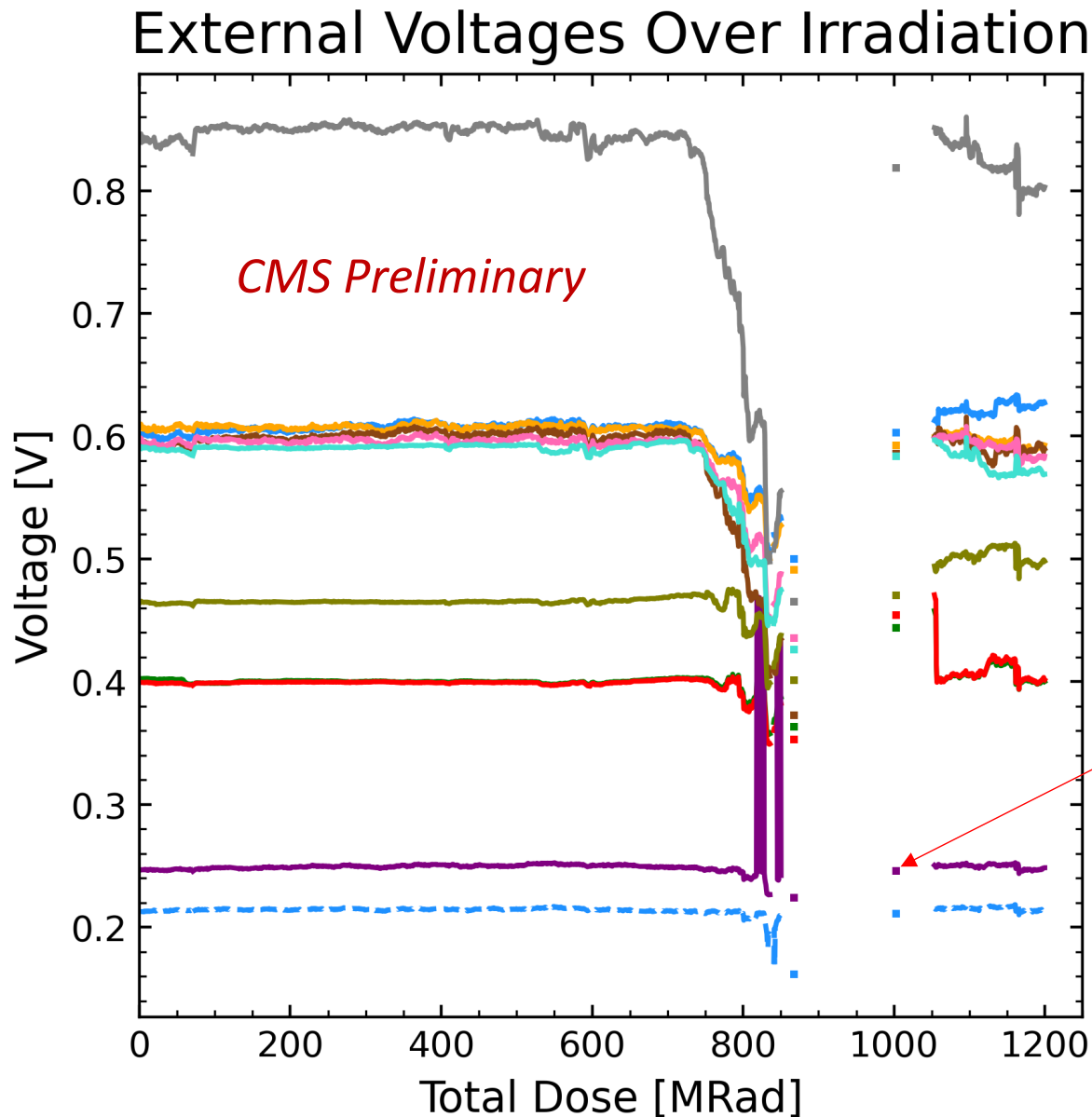
Radsens Voltage During Irradiation



Tempsens (External) During Irradiation



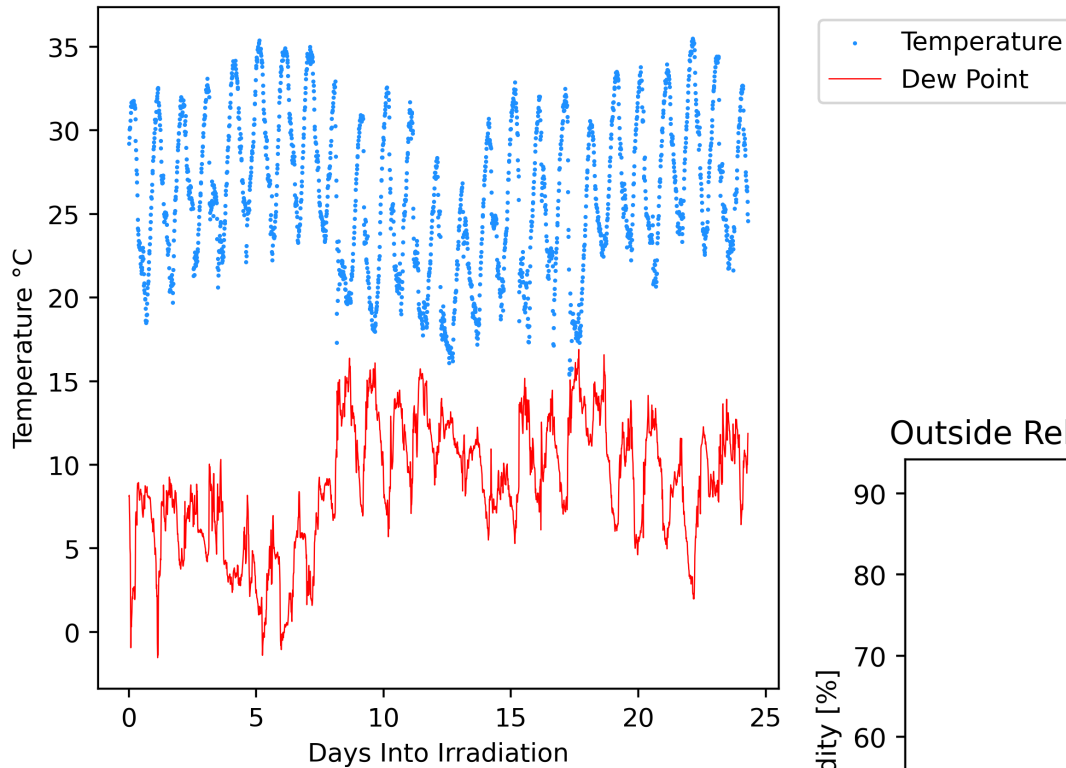
Irradiation to 1.2 Grad



Data from the 1 successful (manual) MuxScan taken while array was down & we were trying to fix the MuxScan cable splice (at ~ 1 Grad)

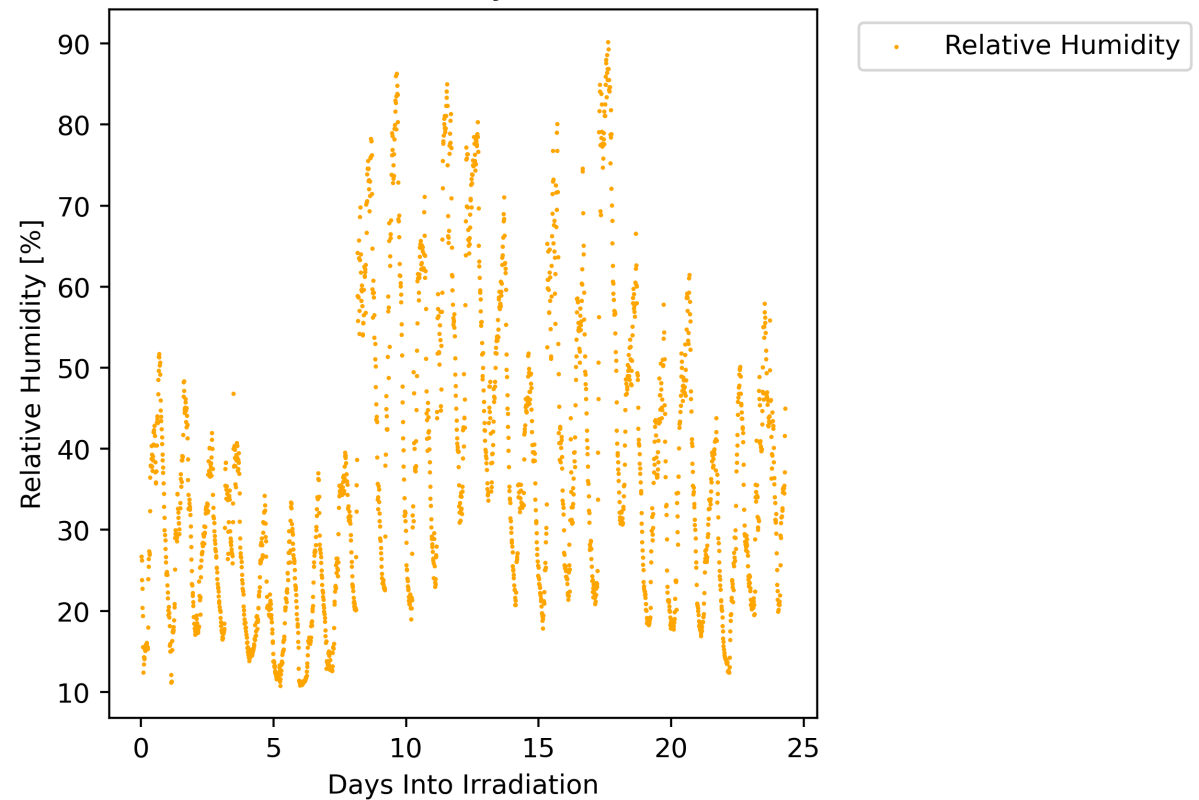
Weather in Albuquerque during Irrad.

Outside Temperature Over the Irradiation



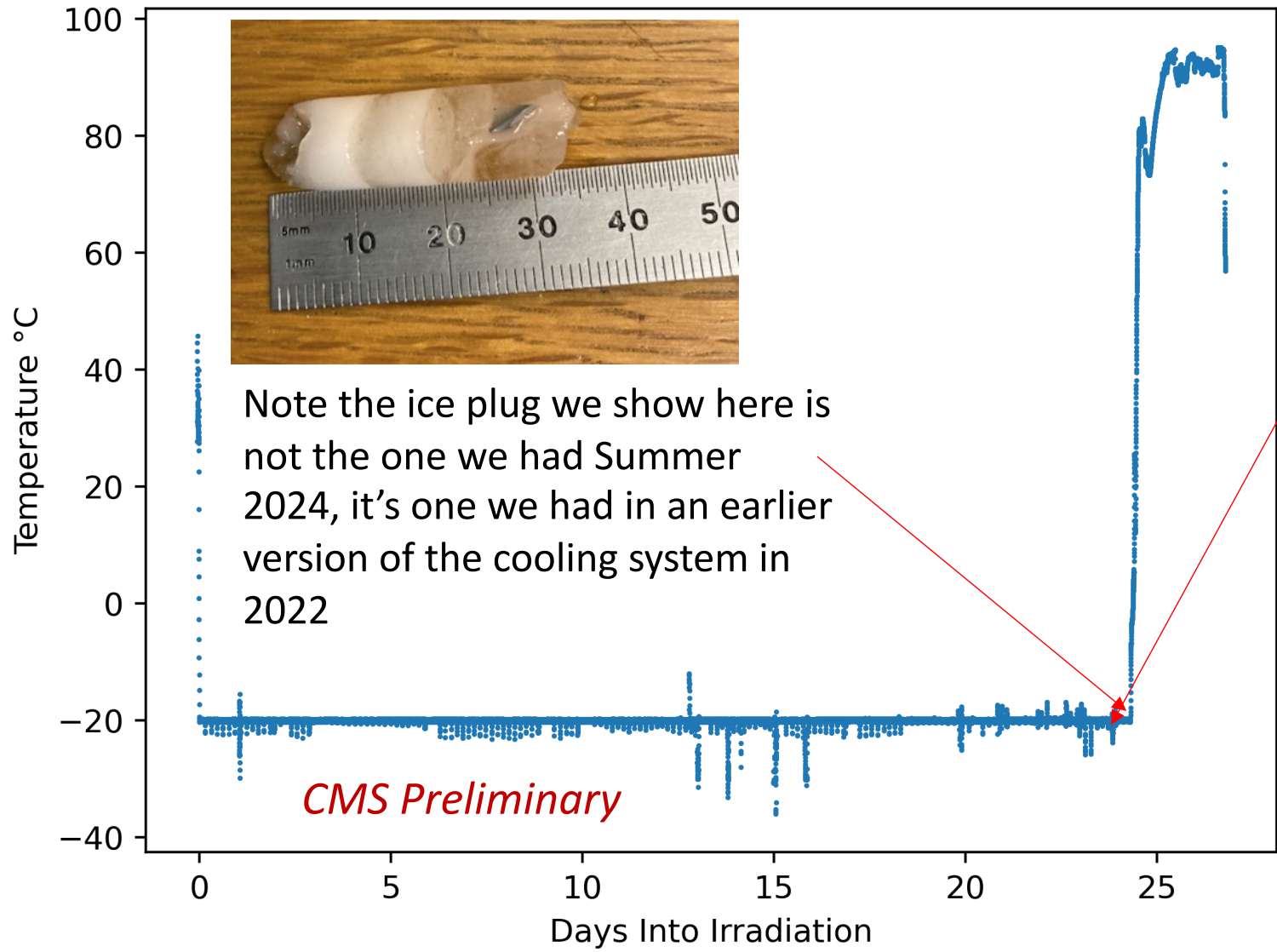
Measured in tower 10 m above
Sandia site, not in irradiation cell

Outside Relative Humidity Over the Irradiation



Ice Blockage Causes End Of Irradiation

Temperature Over the Irradiation



Note the ice plug we show here is not the one we had Summer 2024, it's one we had in an earlier version of the cooling system in 2022

CMS Preliminary

Official irradiation ends a few hours earlier with last good TSF scan