Silicon Detector Challenges

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For the Nab Detector Review

October 26, 2023

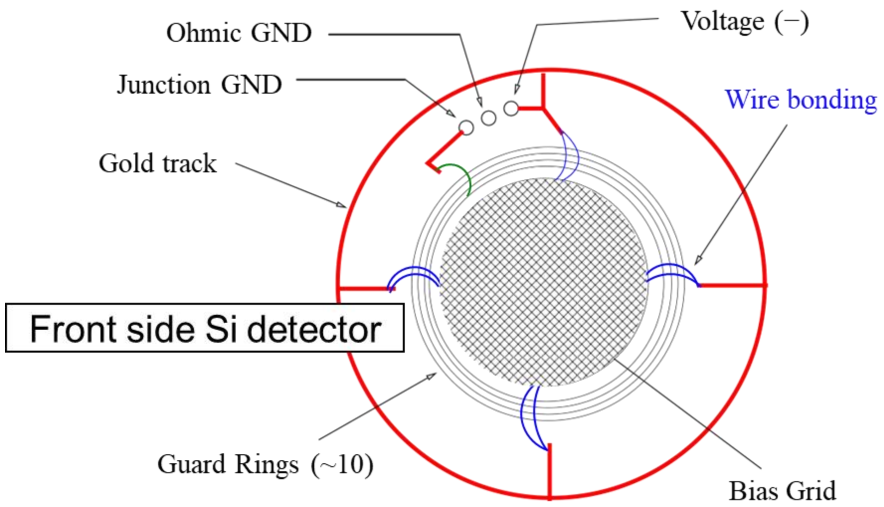
Summary: Issues to be Discussed

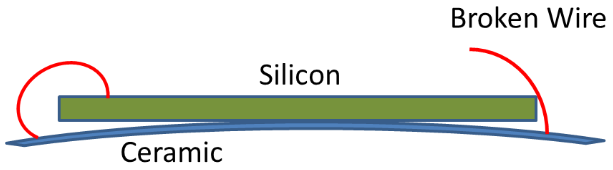
1. Wire Bond Breakages
   - Should we preemptively replace wirebonds?
2. High Leakage Current on Lower Detector
   - How can we diagnose and remedy these issues?
3. Proton Peak Lower than Expected
   - How can we determine the cause?
4. Installation
   - Can we improve our procedures?

Issue 1: Wire Bond Breakages

Wire Bond Breakages

- Thermal cycles break the wirebonds
- Possible causes:
  - Uneven stress on detector ceramic causing flexing?
  - Wirebonds too tight?
- Assessment from T. McKnight (ORNL):
  - "There is insufficient LOOP of the wire from the bonding pad on the wafer to the exterior wirebonding posts"

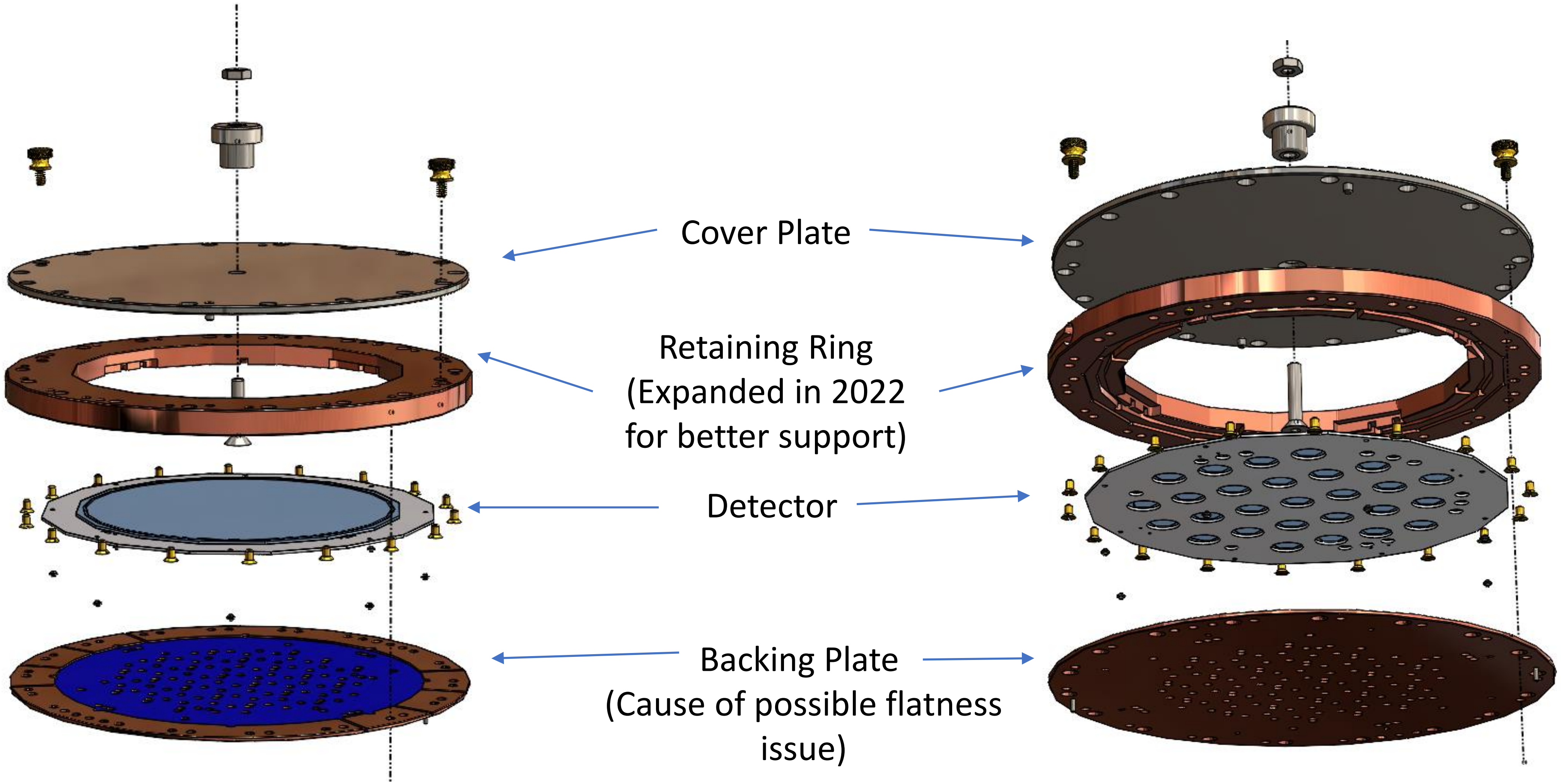




Intact Wirebond

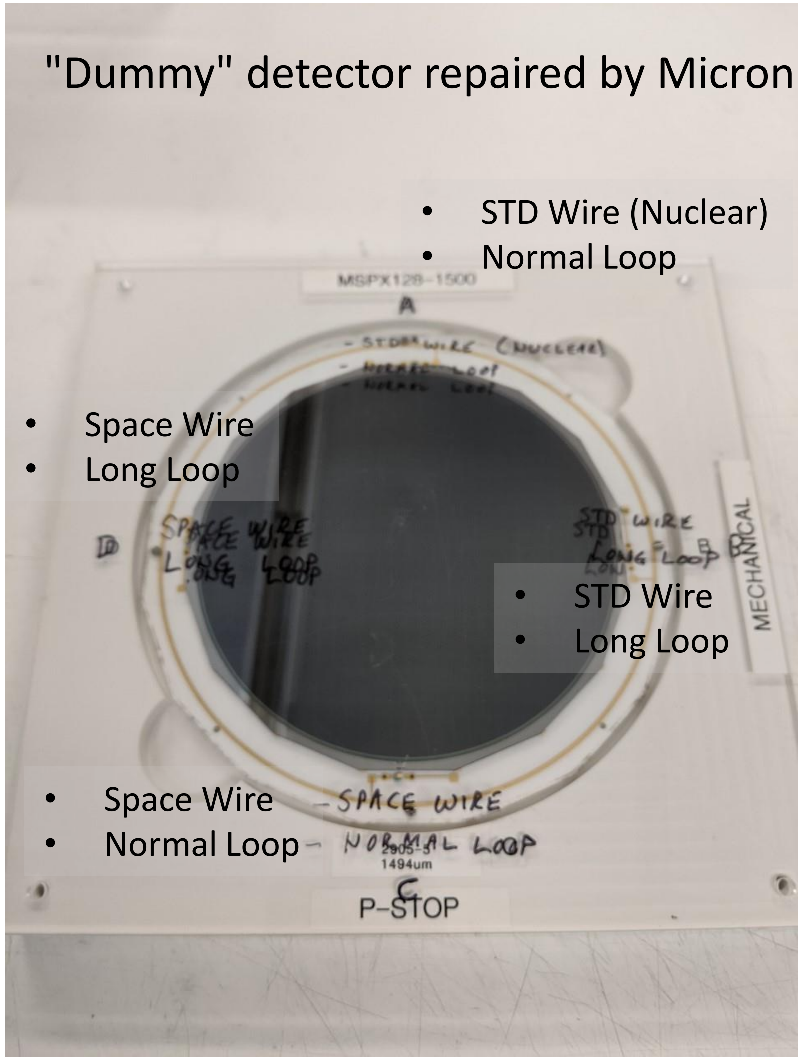
Broken Wirebond

Re-machined Detector Armor



Re-done Wirebonds

- Repaired wirebonds with more slack
- Repairs done at both Micron and ORNL (Tim McKnight)
  - Micron repairs slow (~2 years, but during COVID-19)
  - Tim has retired
- Combination of repaired wirebonds and new armor has survived many thermal cycles
  - Only have 1 “good” detector with wirebond modification



Should we pre-emptively modify the wirebonds? How?

Major Issue 2: High leakage current on lower detector

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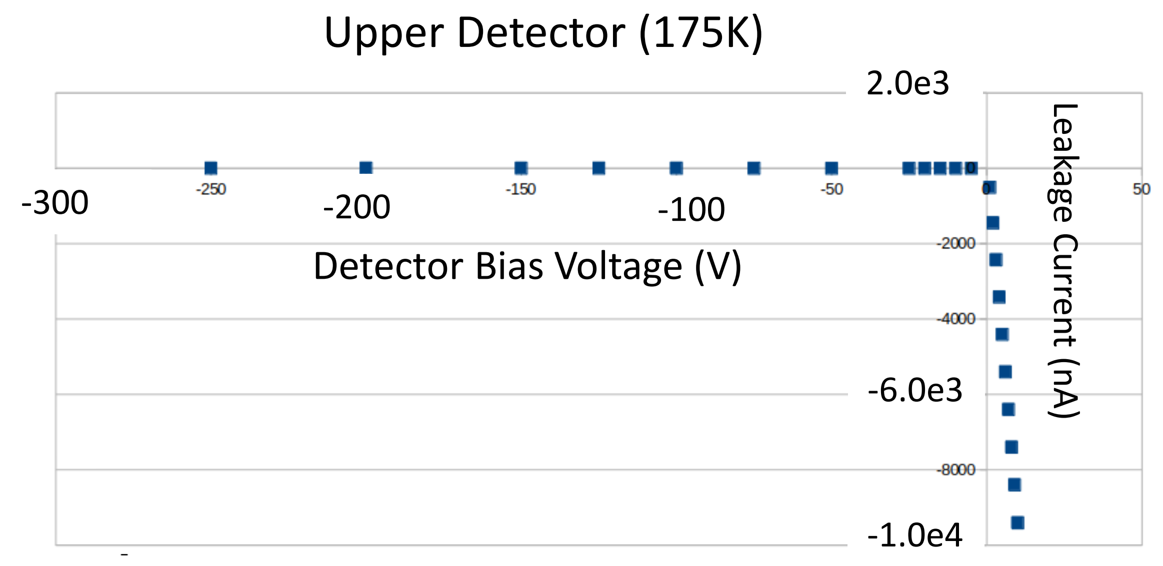
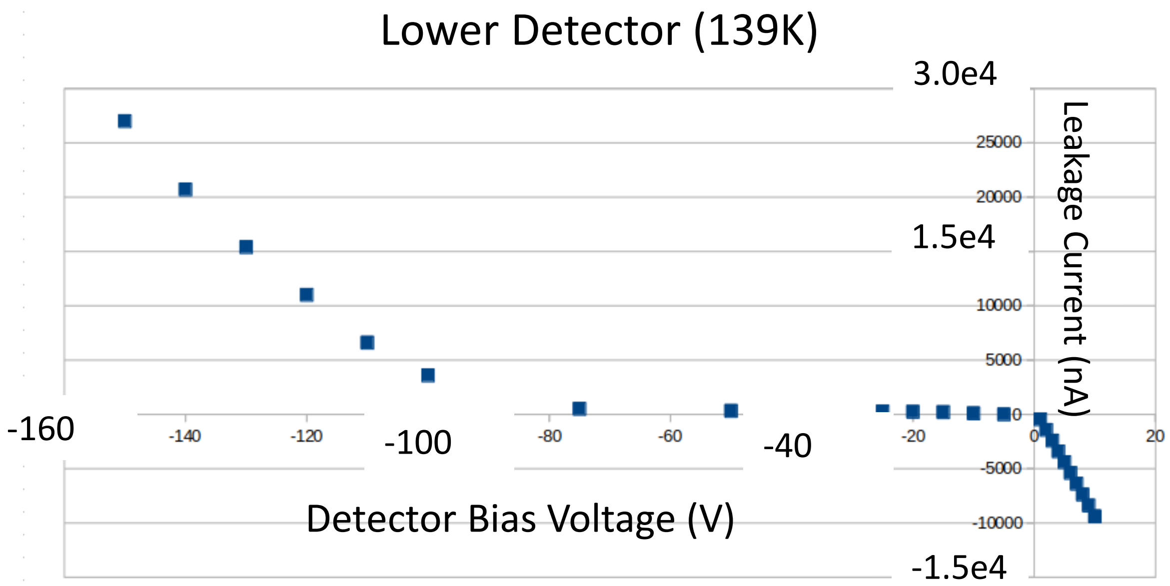
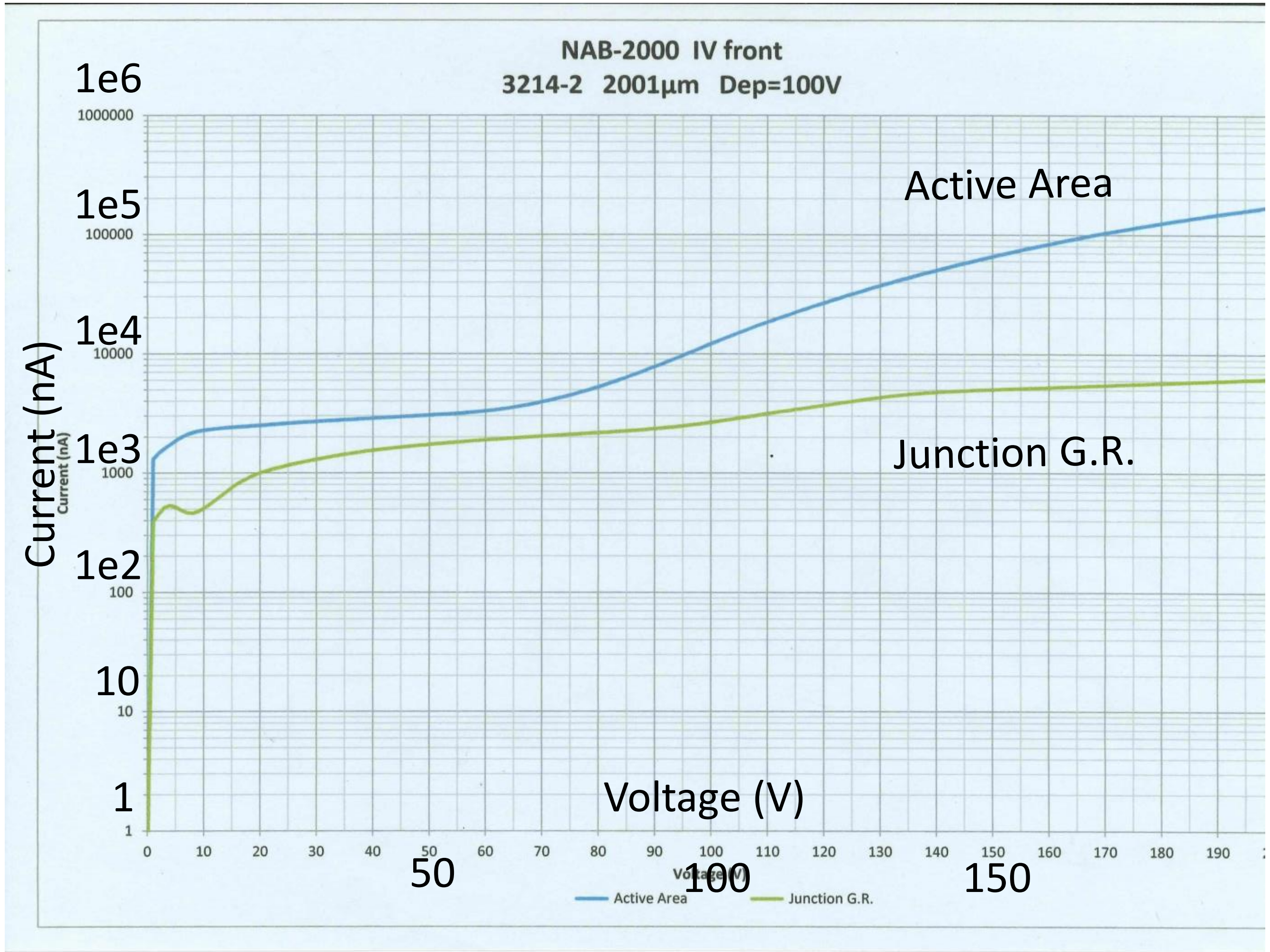
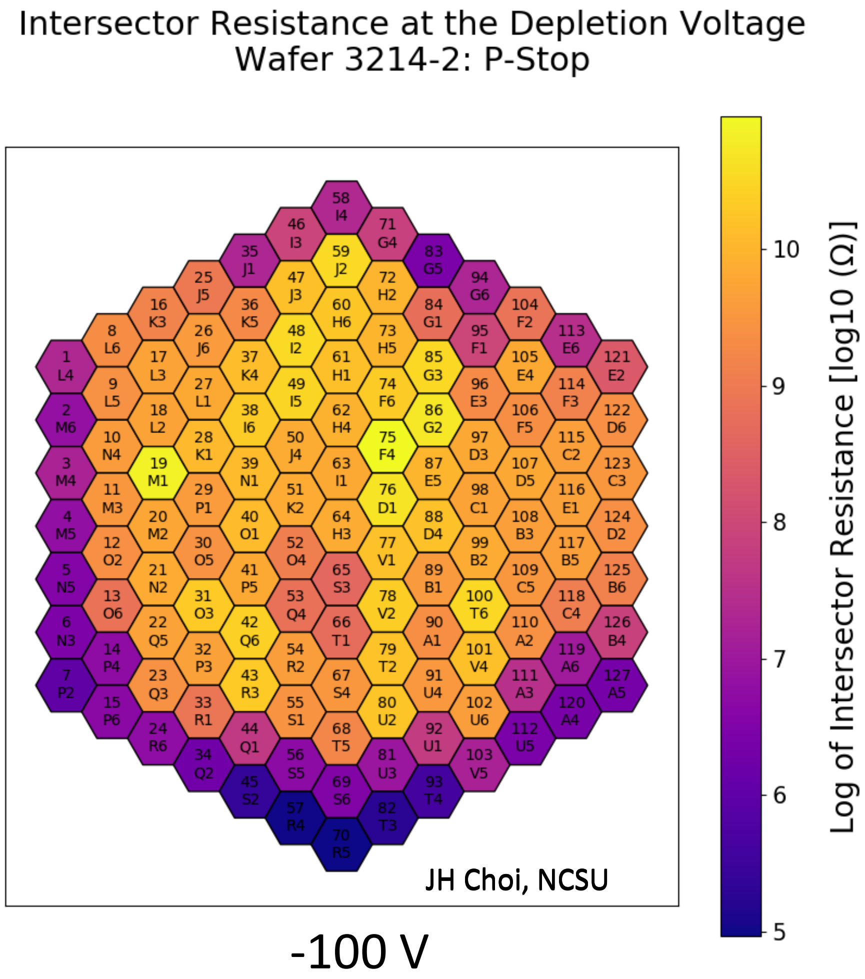
- Two detectors installed into spectrometer
  - Upper detector underwent extensive testing at Manitoba
  - Lower detector installed with wirebonds recently repaired by Micron
  - No low temperature or source tests on lower detector due to long turnaround
- After installation of lower detector:
  - Anomalously high leakage current
  - Negative pulses (assume from detector breakdowns – surface contamination?)
  - Prevents operation above –50V bias





Data from Micron (at room temperature)

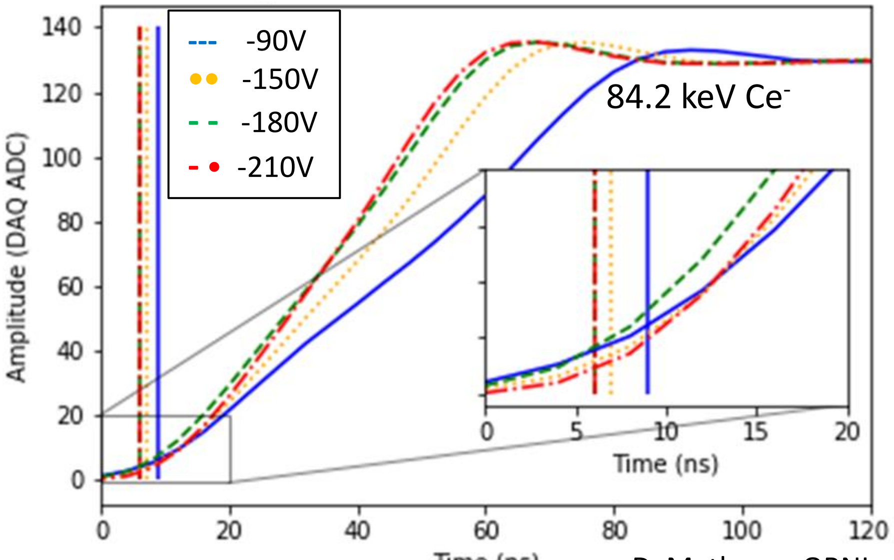




Consequences of Underdepleted detector

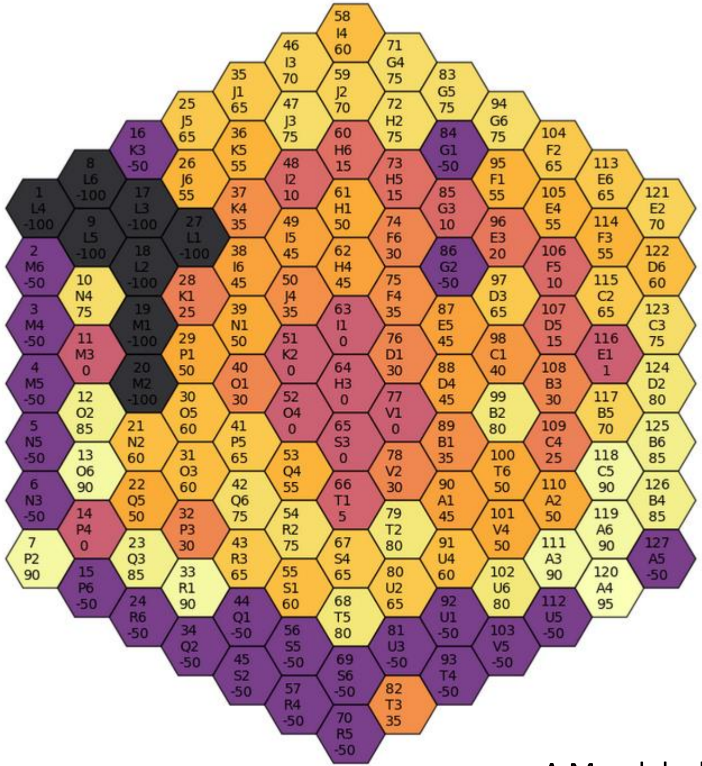
- Unable to fully bias detector before overwhelmed by noise
  - Ran at -50V for most data-taking
  - Distortion in waveform shapes
  - Not all pixels active!

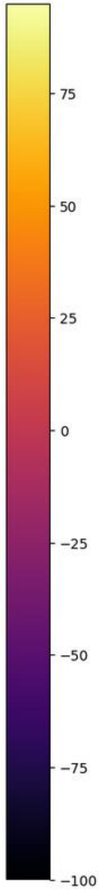
Average Waveforms from Manitoba Cd109 Run



D. Mathews, ORNL

Lower Detector Pixel Turn-on Bias Voltage





A Mendelsohn,
U. Manitoba

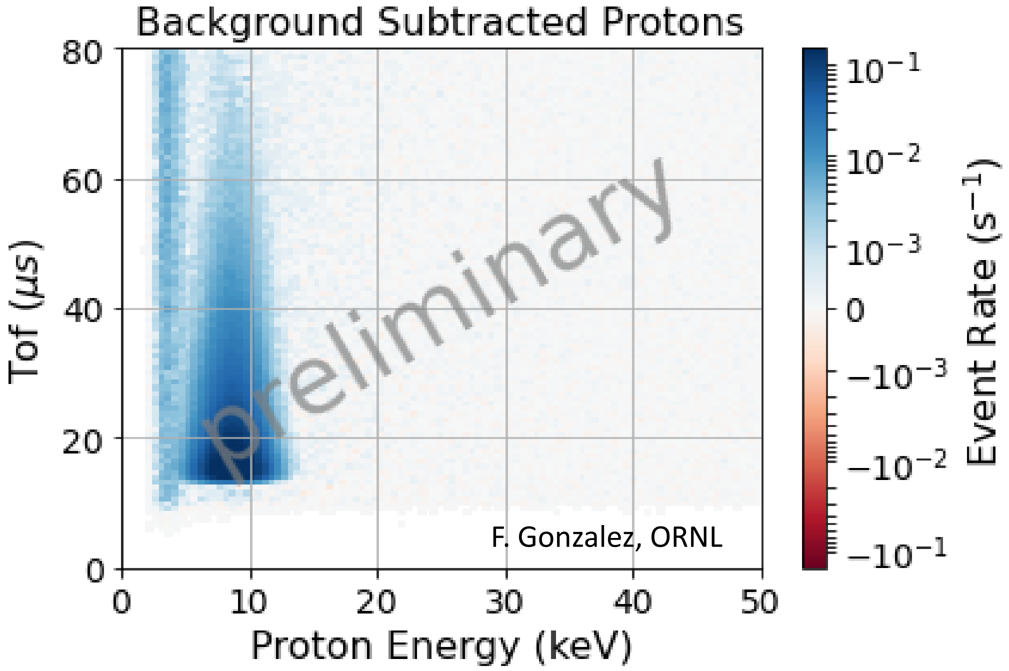
How can we diagnose which of our detectors are "good"?

Issue 3: Proton Peak Lower Than Expected

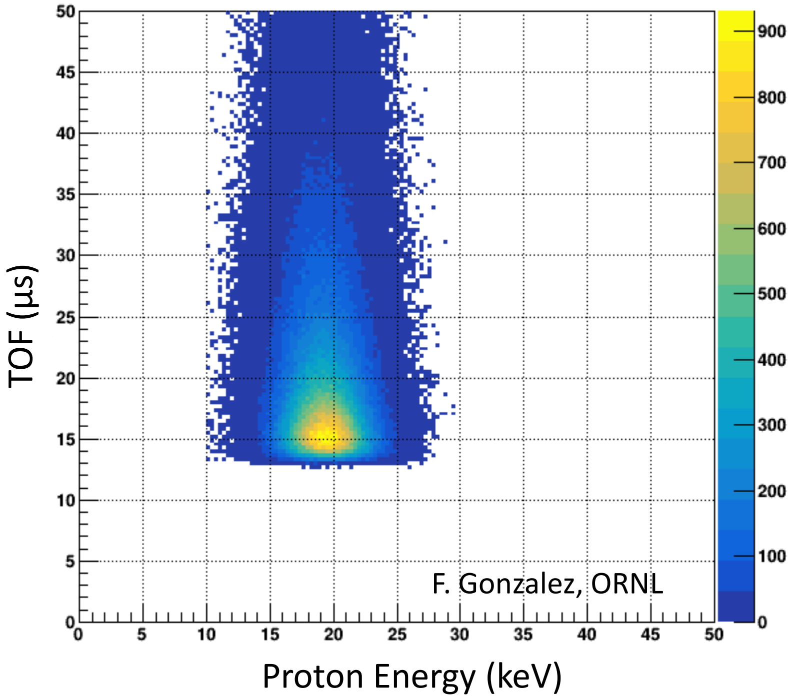
Proton Peak Lower than Expected

- Recall: Protons accelerated to detector by 30 kV accelerating potential
  - Expect to see proton peak from 30 keV protons at ~19 keV given 100 nm Si deadlayer (ideal case)
  - See peak ~2x lower than expected (but still working on low energy calibration)

Summer Data



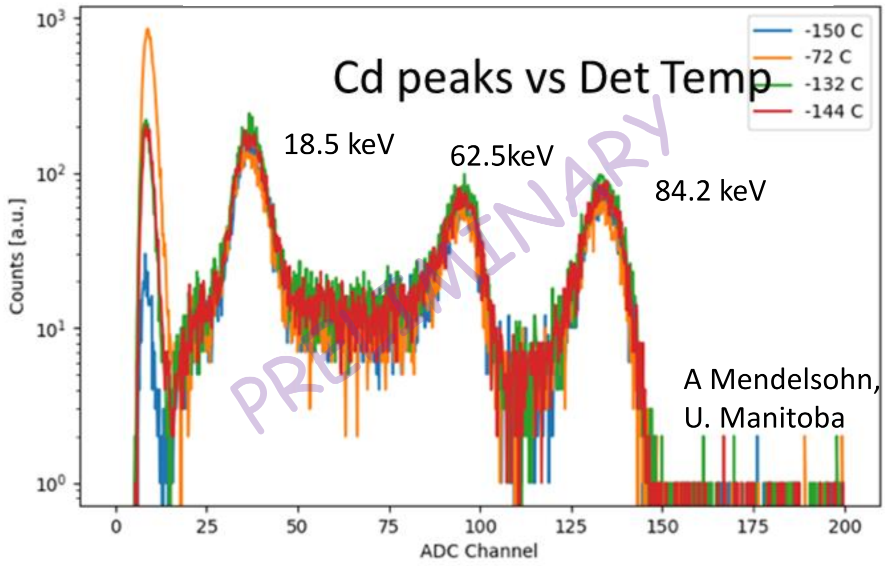
GEANT4 Simulation



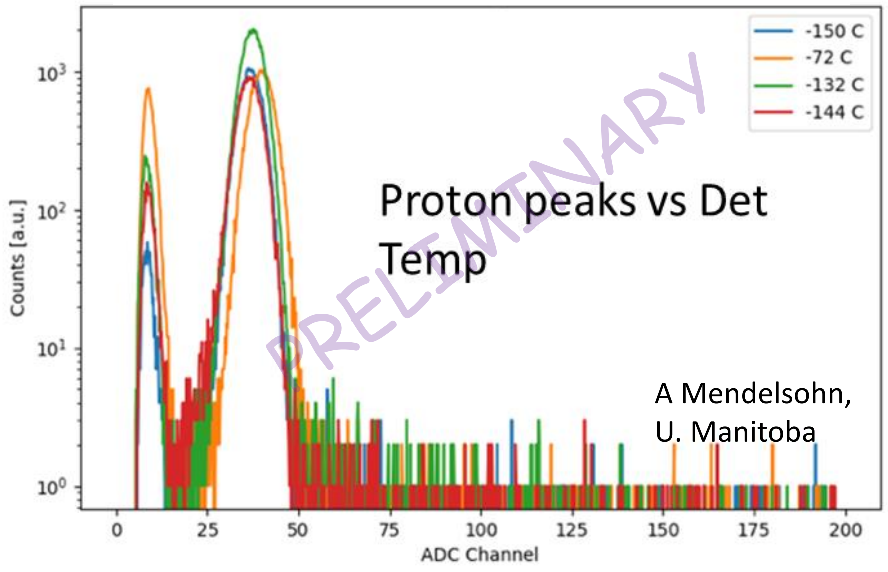
History of this Detector

- Characterized at LANL – wire bonds damaged (2018 – 2020)
- Wire bonds repaired at ORNL (June 2020)
- Characterized at Manitoba (2021-2022)
    - Proton peak at expected location
    - Used a beam of 30 keV protons
    - Different set of electronics
- Shipped from Manitoba to ORNL (May 2022)
- Installed in spectrometer May 2022
    - No data due to magnet failure
- Installed in test stand, calibrated with sources (April 2023)
- Installed in spectrometer, proton peak appeared much lower (May 2023 – now)
    - Calibration currently underway, investigating low energy

Source data at Manitoba



Proton data at Manitoba



Potential causes of low proton energy

1. *Low energy calibration?*
2. *Ice buildup due to imperfect vacuum conditions (seen at LANL during Nab prototyping)?*
3. *Non-volatile contamination (not seen before in Nab, but other experiments have seen this as consequence of HV discharges)?*

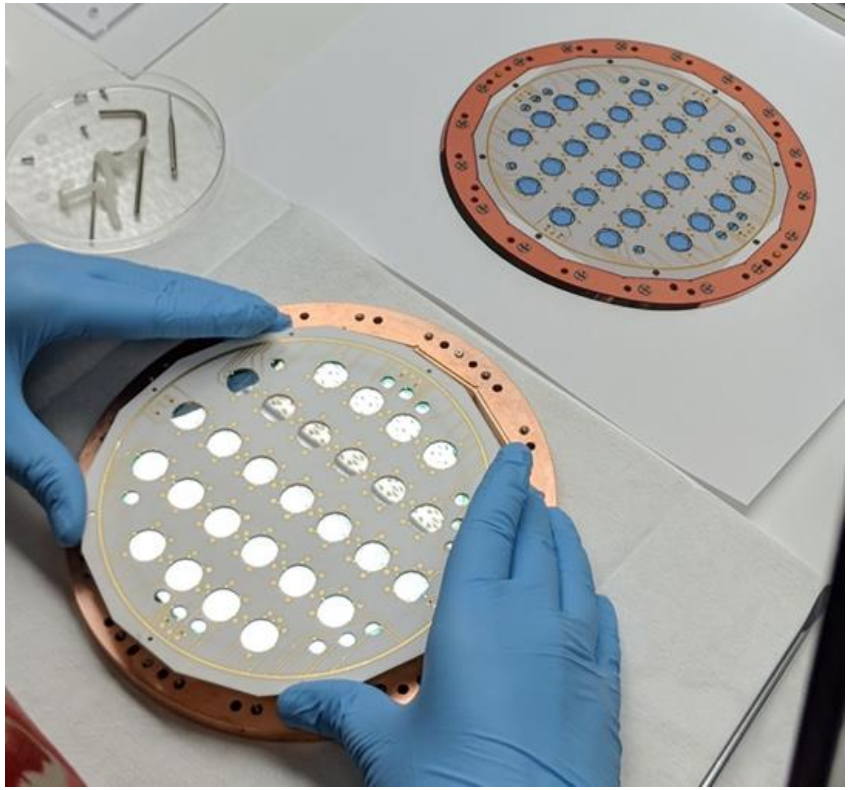
- Low energy calibration studies underway
- We have attempted warming up detector to test for ice, but inconclusive.
- Attempts to assess deadlayer with alpha source ongoing, careful test stand measurements may be necessary

Are there other potential causes? How would we diagnose and fix these?

Issue 4: Installation

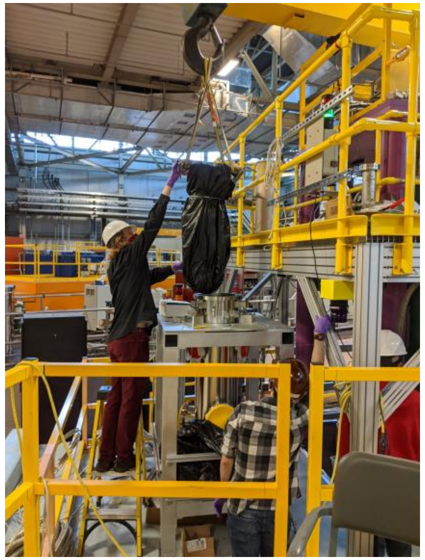
Installation into the Armor

- Done in laminar flow hood but not clean room
  - Use gloves, face masks during install



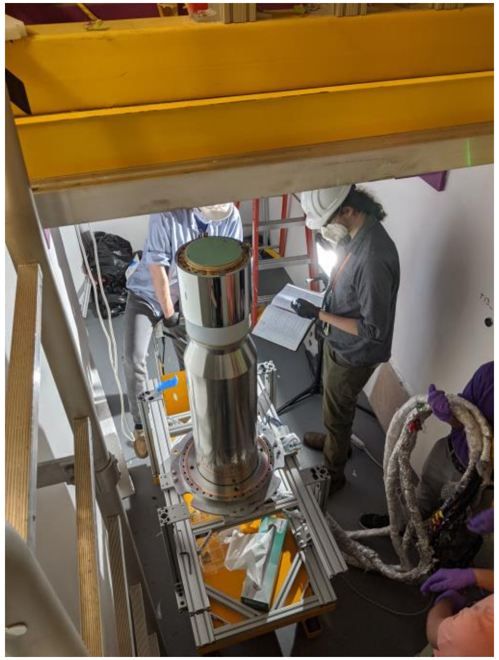
Installation into the Test Stand/Upper Spectrometer

- Requires use of two different cranes
  - Detector covered by lid during lift
  - Temporary storage in test stand vacuum chamber
  - Detector uncovered and electrode cap installed prior to insertion into spectrometer
- After detector install, install cablings and HV



Installation into Lower Spectrometer

- Crane detector mount into cave pit
  - Cables already attached to detector electronics
  - Once in pit, install detector and electrode cap
- Lift detector mount into spectrometer on scissor lift
  - Build temporary frame in-situ due to space constraints and short range of lift



Summary and Discussion Points

- Wire Bonds:
  - Should we pre-emptively modify the wirebonds? How?
- Detector diagnoses and leakage current:
  - How to systematically tell if detectors won't cause issues?
  - Is there a way to clean possible surface contamination causing breakdowns?
- Lower Proton Peak:
  - We are still assessing our low energy response and calibration and are attempting to assess the deadlayer with alphas
  - Is this ice/other contamination on the detector? Electronics issues? How can we tell?
  - Assuming this is our issue, is there a way to clean possible surface contamination? Micron suggests IPA vapors; any other ideas that will preserve adhesion to ceramic and wirebonds?
- Installation:
  - Installation is in an inherently dusty environment (the SNS), can we improve this? Major improvements would benefit the input of a professional designer.
  - Should we clean detectors?

Extra Slides:

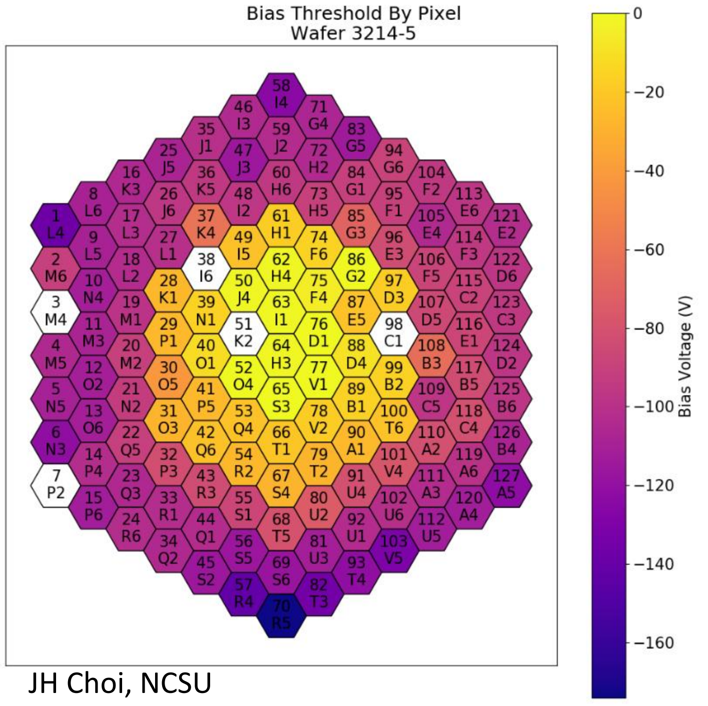
Charge Questions Addressed in this Talk

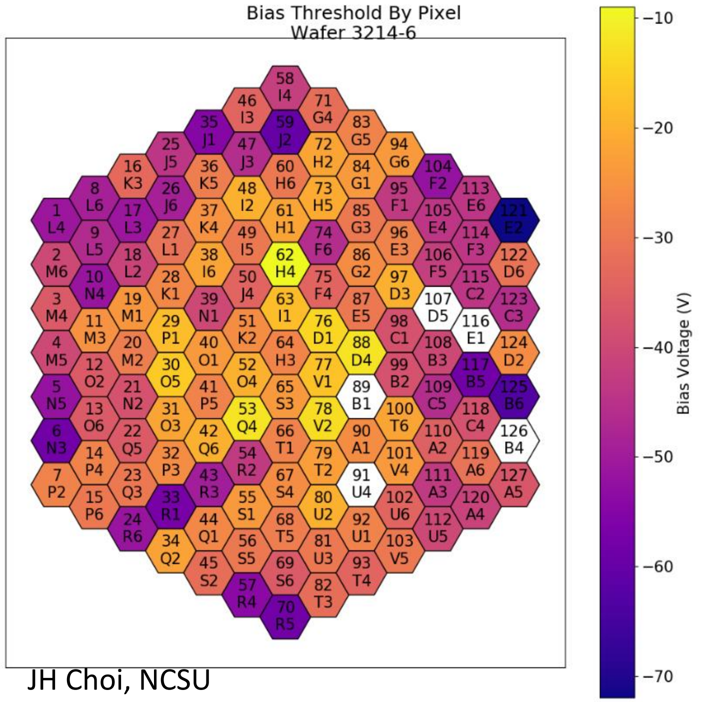
1. **Weaknesses of the current detection system**: Identify the primary weaknesses of the system, with particular emphasis on:
   a. Failure of the detector and electronics readout chain to report signals from individual pixels and recommend prevention, mitigation, and hardening strategies;
   b. Detection system stability and resilience to oscillations: investigate at least grounding and noise as contributing factors. Recommend mitigating actions.
   c. Investigation of the hypothesis of ice formation on the detector versus contamination and recommendation of a remediation strategy as is feasible at the time of the review.
2. **HV discharges**: Evaluate to the best extent possible the HV configuration to identify the origin of the discharges and strategies to protect the electronics.
3. **DAQ system**: Evaluate the full data acquisition system to ensure its robustness.
4. **Silicon detectors:**
   a. Evaluate the mechanical robustness of the silicon detectors;
   b. Evaluate calibration of electron energy and proton time-of-flight response.
   c. Detector bias issues, depletion depth and charge collection across the detector: Propose a diagnostics and remediation measures.
5. **Risks**: Summarize the risks identified in achieving the physics goals.

Communication from Tim McKnight

- Assessment of problem (Feb 2020):
  - There is insufficient LOOP of the wire from the bonding pad on the wafer to the exterior wirebonding posts. The wire therefore is tensioned across the edge of the wafer and this is imparting stress to the wire (particularly if there is any differential thermal expansion after the bond is made) and pulling the wire off typically at the pad on the wafer, but also sometimes on the exterior post. The bend in the wire caused by this can be seen at 3 of the 4 quadrants.
  - Solution is the provide more loop to the wire such that it does not interact with the edge of the wafer. If the wirebonder LOOP settings do not provide sufficient loop, then a manual process can be used whereby you drag the bonder beyond the target pad and then move back to the target pad prior to making the second bond. This will feed additional wire to provide sufficient loop
  - Another issue I see is that there is some material on one of the four quadrant bonding pads. This appears to be a glue or adhesive (epoxy) perhaps used to help secure the bond. This will need to be removed from the pad prior to attempting to repair this bond. Any info on what this material is would be beneficial to aid in decisions regarding its removal.
- Repair (June 2020):
  - I have been able to successfully repair I believe all 4 quadrant connections on your detector, in addition to the 'grounding' ring at the periphery. 3 of the 4 quadrants and the ground ring have two bonds for a bit of redundancy, but the remaining quadrant has only 1. This latter was the one covered in 'goop'. Upon trying to make a bond, the goop appeared to be still liquid and I believe the Wedge bonder pressed through it to make the connection. This connection may be more resistive than others if there is an interfacial layer of goop. I tried to make two bonds on this electrode, but subsequent bonds were unsuccessful. All bonds have sufficient loop so as to not be in contact with the edge of the detector. Hopefully this will resolve any thermal/mechanical problems associated with the wire being stressed over the edge as the previous bonds were.
  - Note, the bonds were made after transferring the wedge bonder to the clean room. I performed the bonding wearing cleanroom garb, including facemask. I emphasize this because while making the bonds I noted that the detector surface was actually quite dirty. There are particulates on it, as well as what looks like residual spots from liquids. In addition, there are particulates in the periphery on the plastic carrier. I attempted to blow off some of these with clean dry air… but a solvent cleaning process would probably be more successful.
  - The device is ready to test as is. However, I believe I can probably remake these bonds several times so inquiring whether you wish to see if the device is operational or perhaps we revisit a cleaning process whereby we spin the wafer is cleaning solvent and remake these bonds after the cleaning process. If the latter, requesting info on how best to do this. I can probably spray isopropanol and blow with clean dry air, but seeking your assurance regarding material compatibility etc.

"Turn On" Voltage Studies



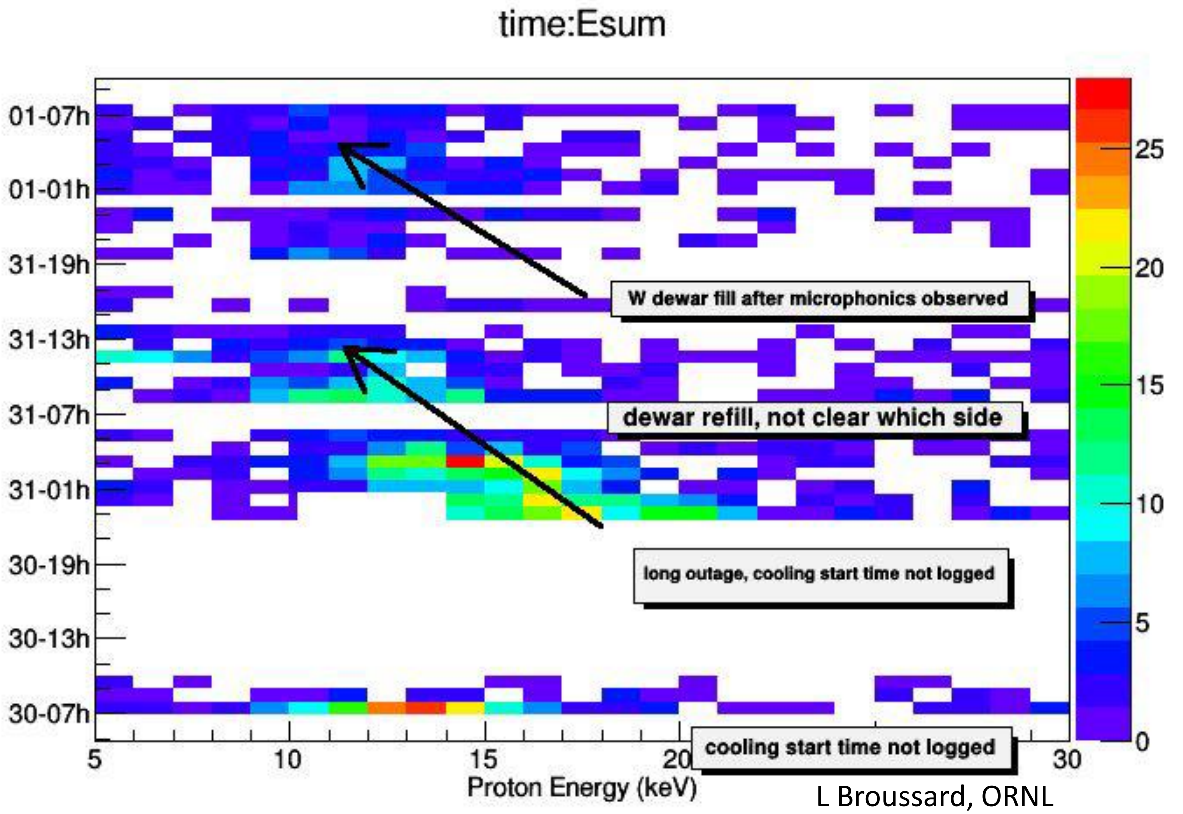


- "Turn on" is point when the pixel starts to produce realistic pulses on the scope.
- The maximum voltage is comparable to the stated depletion voltage measure by Micron.
- Initial discussion with Micron about the patterns was not very enlightening, but as we test more detectors we hope to identify the source of the variation. These two detectors did have slightly different processing.
- White pixels indicate no data – usually due to connectors or damaged FET channel

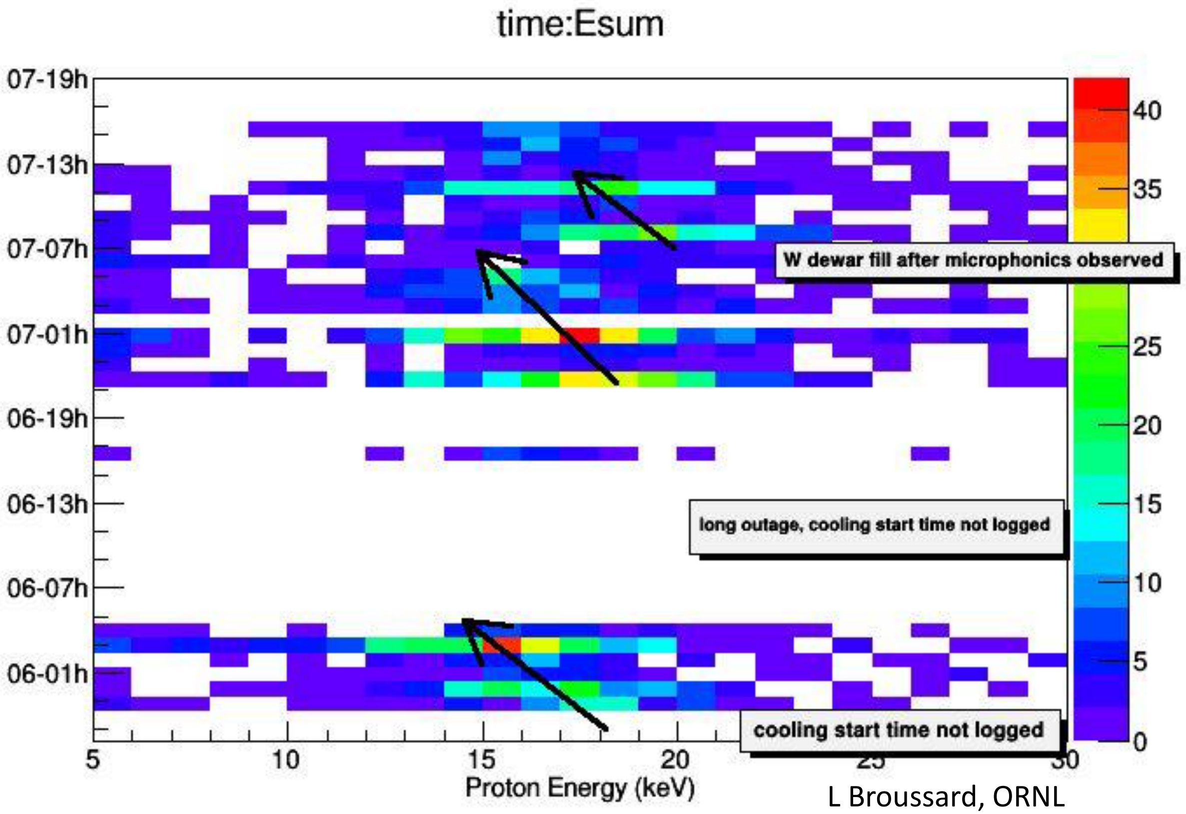
Ice formation previously observed

Observations from LANL prototype

- Expected proton energy w/ 100 nm Si = ~19 keV
- Expected proton energy w/ 100 nm Si + 70 nm ice = ~14 keV
- LANL pressure = 5e-7 mbar. Protons lose ~5 keV per ~12 hours



L Broussard, ORNL

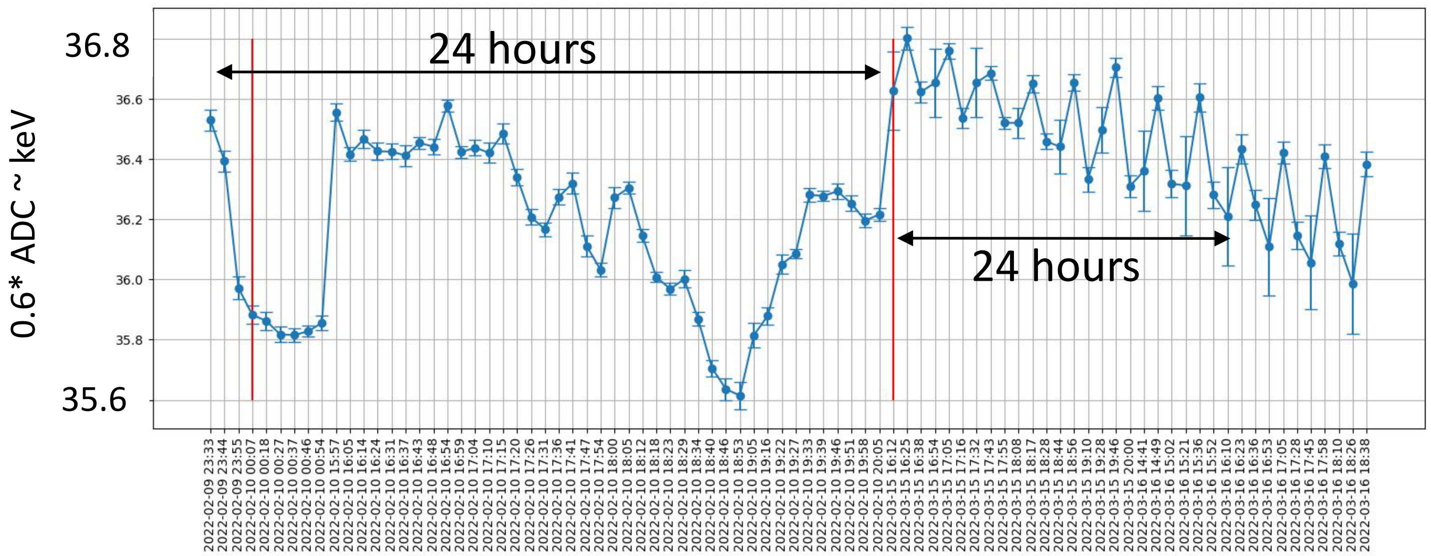


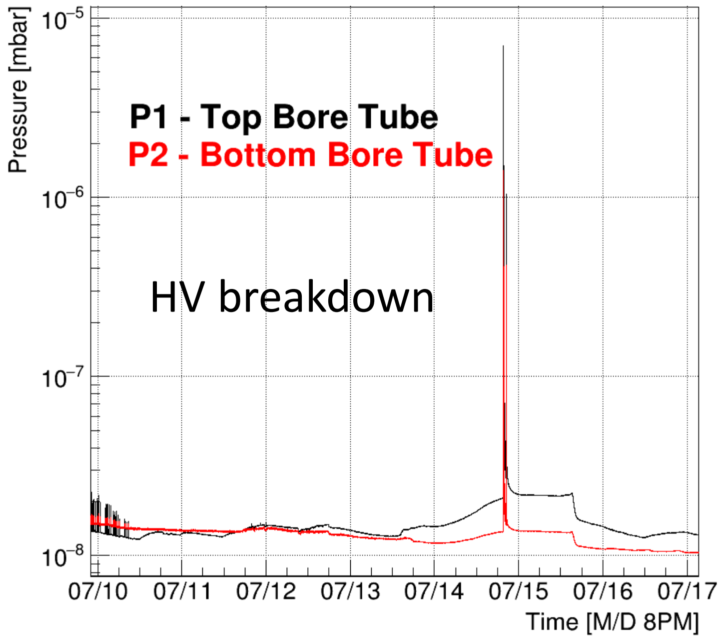
L Broussard, ORNL

Could ice buildup be suspect in Nab

- Pressure at Manitoba 5e-9 – 1e-8 mbar. Warm system.
- Nab spectrometer: 1e-8 mbar (top) and 1e-9 mbar (bottom); cold bore
- HV and SRSIS have caused pressure spikes

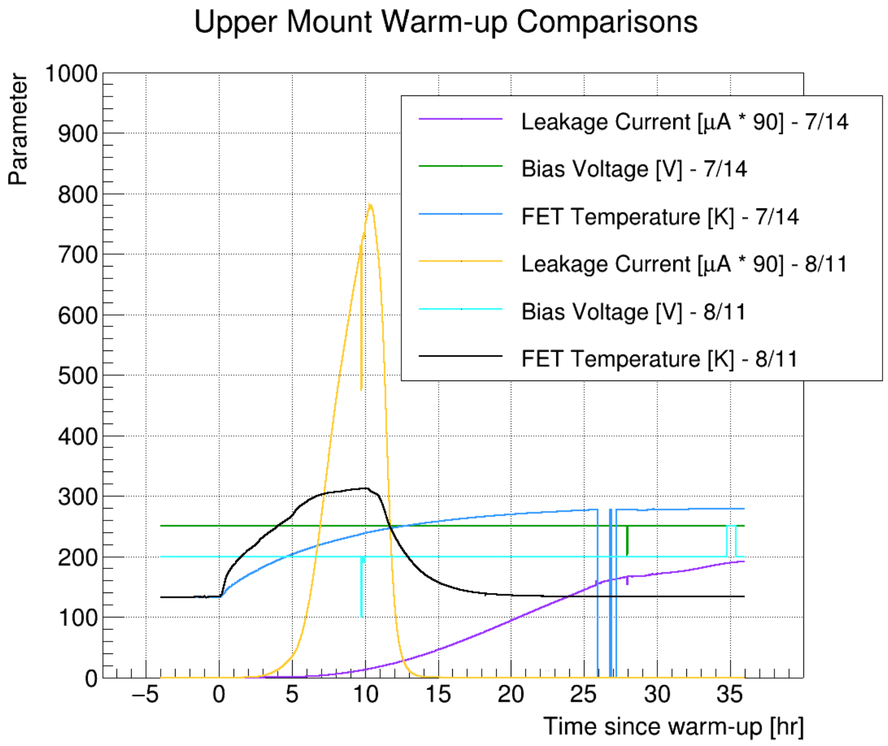
Proton Peak Mean vs Time at Manitoba





Fast Detector Warmup at ORNL

- Before summer data-taking, at FET temp 288K and –200V, I_L = 3.3 uA
- After too-low proton energy observed, attempted warmup of detector to remove ice
  - Note: no working detector temperature sensor, FETs previously within 10K of detector, but detector has much slower time constant (several hours slower to stabilize)
  - Used detector leakage current. Warmed up to I_L = 8.6 uA (at 200V).
  - Aborted warmup due to concerns about magnet temperature (quench risk)
- No change in detected proton energy after warmup



How reliable / repeatable is leakage current as proxy for detector temperature?

Hypothesis: contamination on detector

- Tim McKnight's observations pre-Manitoba:

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  - No cleaning attempted. Protons detected at expected energy.
- Why is situation worse at ORNL?
  - Cleanliness in operations not obviously worse at ORNL
  - Average humidity somewhat higher at ORNL vs Winnipeg/Los Alamos
  - Exposure to unclean environment in test stand? Oil in foreline?

Leakage current vs temp

- Detector temp offset from FET temp
- Should be able to look at older data to compare detector temp time constant vs FET – Nick?