Nab experiment requirements and electronics challenges

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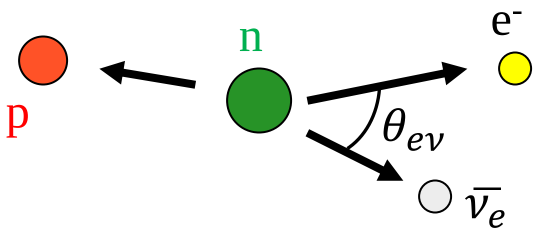
Nab Detector Electronics Review Schedule

*ET	Event
9:00 am	Nab experiment requirements and electronics challenges (15+15) Speaker: Stefan Baessler
9:30 am	Electronics bench testing and outcomes (15+15) Speaker: Chuck Britton
10:00 am	Electronics circuit design improvements (5+25) Speakers: Chuck Britton
10:30 am	Break
10:45 am	Connector improvements (5+10) Speaker: Chuck Britton
11:00 am	Pixel map requirements (5+5) Speaker: Leah Broussard
11:10 am	Transition board redesign (15+15) Speaker: Kyle Reed
11:40 am	Schedule and closeout discussion (5+15) Speaker: Leah Broussard

Idea of Nab experiment



$$d\Gamma \propto \varrho(E_e)\left(1 + a\frac{p_e}{E_e}\cos\theta_{e\nu} + b\frac{m_e}{E_e}\right)$$

$a = a(\lambda)$
(Test of Quark Mixing)

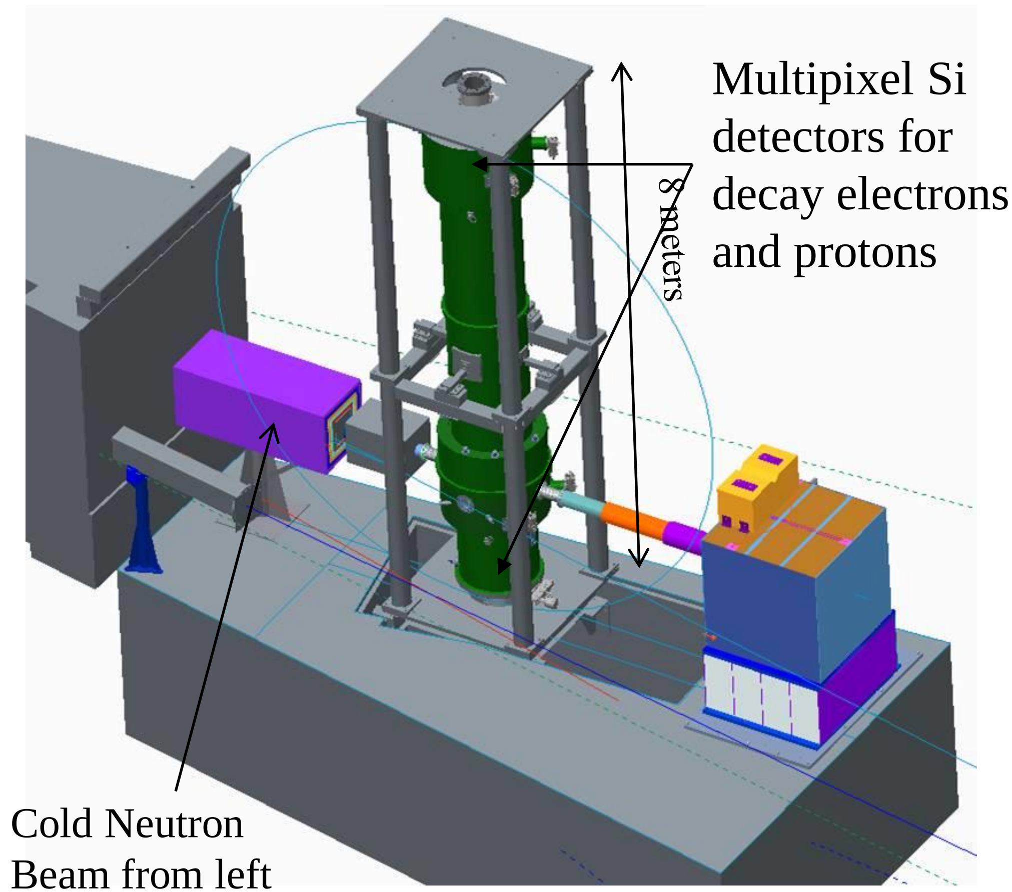
$b \neq 0$ indicates S,T interactions

Measurement of electron energy spectrum gives the Fierz term b.

Measurement of a from measurement of proton and electron energy:

Consequence: Multipixel Si detector must detect electrons (energy deposit 50 keV to 1000 keV), protons (energy deposit 10 keV to 25 keV), and (very precisely) their arrival time difference (typ. 20 μs), as this is our only handle on proton energy.

Nab @ Fundamental Neutron Physics Beamline (FNPB) @ Spallation Neutron Source (SNS)

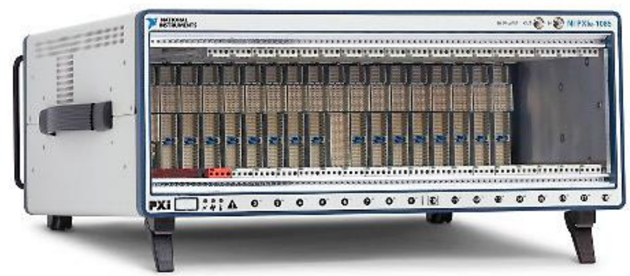


General Idea: J.D. Bowman, Journ. Res. NIST 110, 40 (2005)
Original configuration: D. Počanić et al., NIM A 611, 211 (2009)
Asymmetric configuration: S. Baeßler et al., J. Phys. G 41, 114003 (2014)

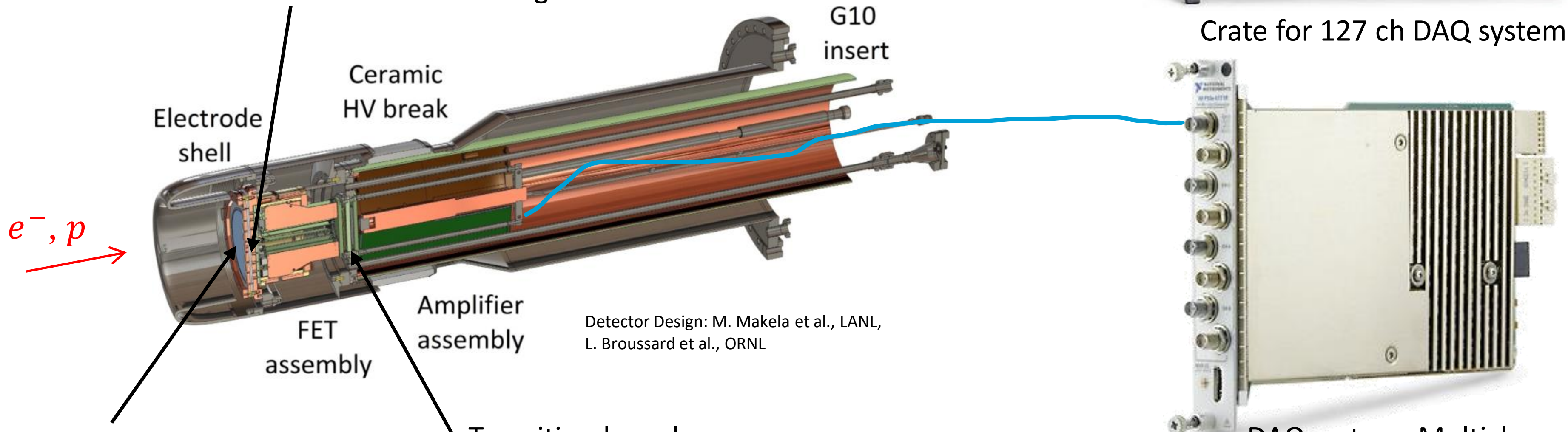
Nab detector system and DAQ system

- 127 pixel Si detector, 2 mm thick
- Each Si pixel connected to preamp channel and DAQ system channel

Data transfer to host PC

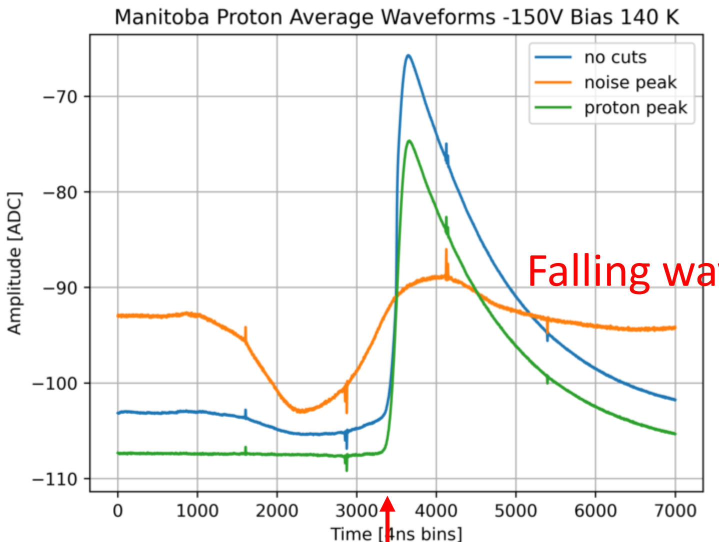


Crate for 127 ch DAQ system



DAQ system: Multichannel oscilloscope

Nab detector: Current output waveforms

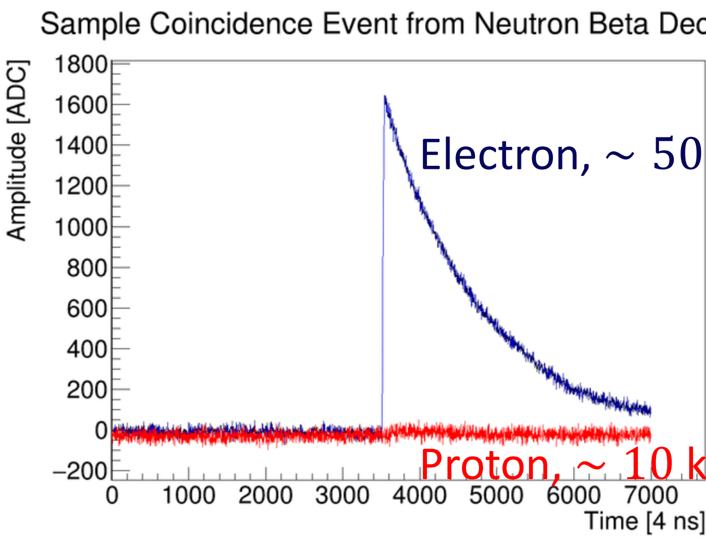


Average waveform (spikes are small DAQ artifacts, now gone)

Falling waveform $V \propto e^{-t/t_F}$ with $t_F \sim 5\ \mu s$

Risetime typically 50 ns, partly due to electronics.

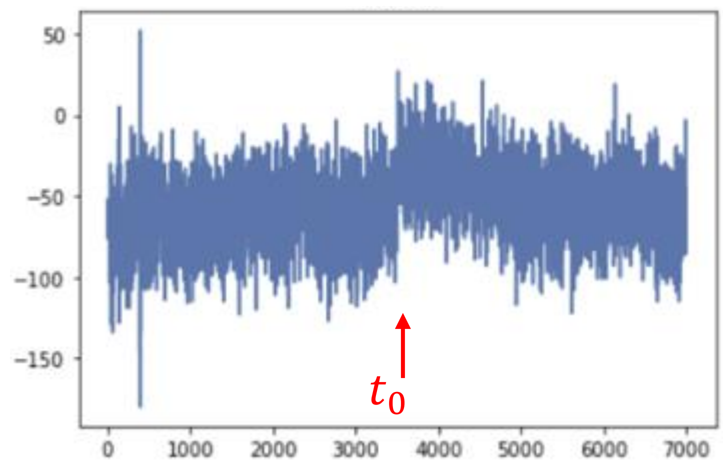
Start of pulse t_0 is a physics observable



Electron, $\sim$ 500 keV

Proton, $\sim$ 10 keV

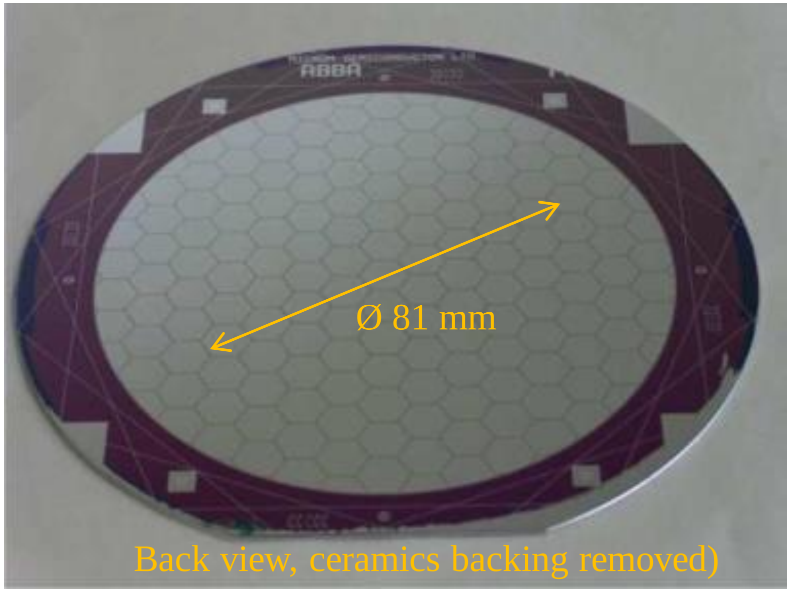
Single proton waveform, no averaging



t_0

Time / 4 ns

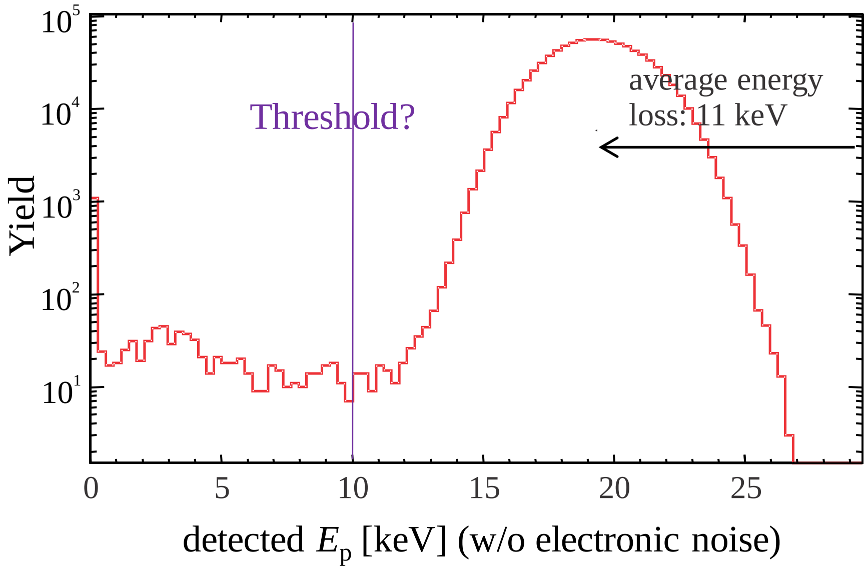
Nab detector requirements: proton detection



Nab detector: Multipixel silicon detector (127 hexagonal pixels with $A \sim 1\ cm^2$)

The proton detection threshold must be below the mean proton peak; in simulations a threshold of 10 keV is just sufficient to avoid a substantial systematic uncertainty due to the proton energy dependence of the proton detection efficiency.

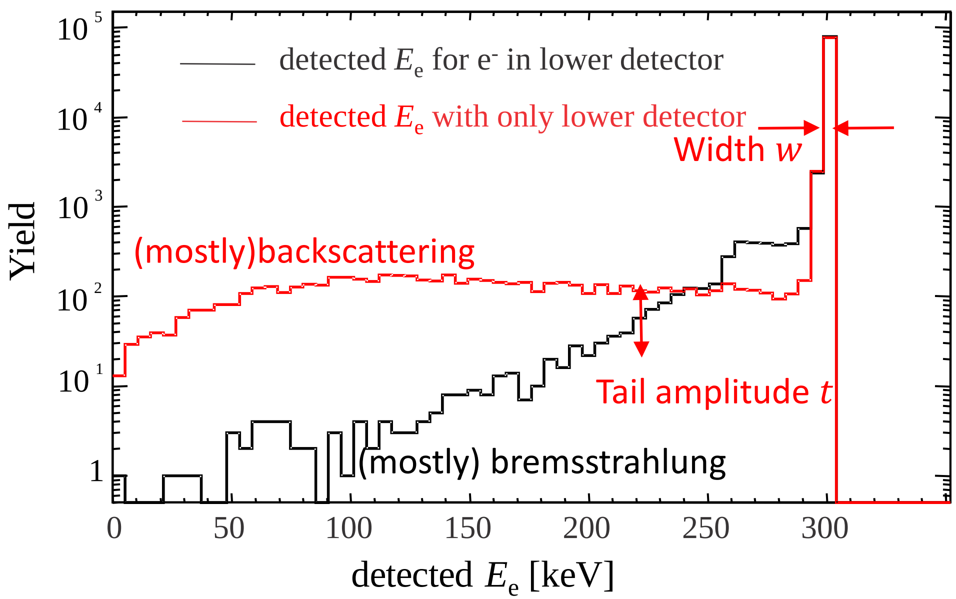
Nab detector must detect protons and electrons. Typical 30 keV protons make a small energy deposit (in average 18 keV), so we need small pixels and a very low noise readout electronics. They also need to detect up to 780 keV electrons, which requires them to be thick (1.5 to 2 mm).



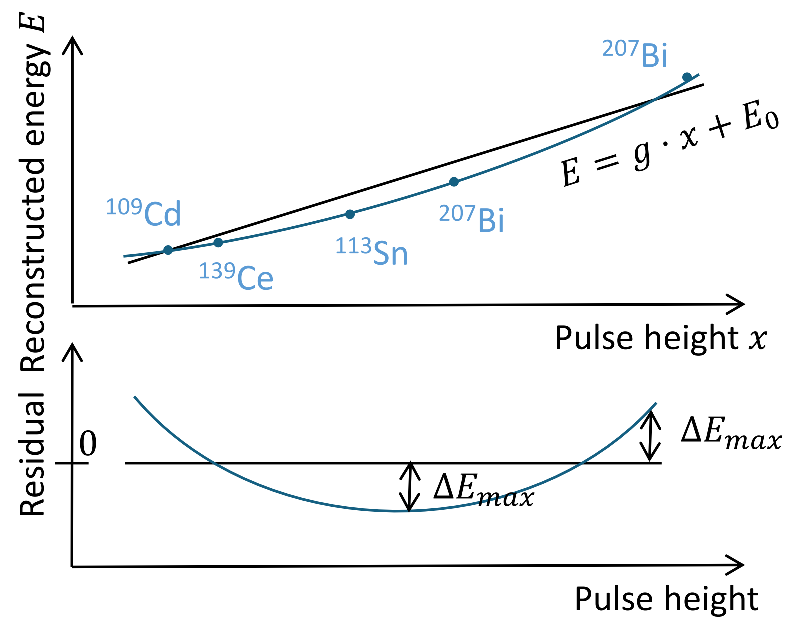
In last beam cycle energy deposit of protons was likely only 10 keV, and the threshold was somewhat lower (not exactly determined).

Nab detector requirements: electron detection

Detector response in Si detector for incoming E_e = 300 keV, (Maximum impact angle of electrons is 12°, due to filter)



Electron energy calibration:



Requirements on electron detection: The gain factor g will be a fit parameter, but nonlinearities have to be understood: Offset error $\Delta E_0 < 200$ eV, non-linearity $\Delta E_{max} <$ 1500 eV within a dynamic range of 50 keV-1000 keV. For the Fierz term, limits are 80 eV. The peak width of the electron energy response function has to be known to $\Delta w < 1$ keV, and the amplitude of the tail $t = 2.1\%$ has to be known to $\Delta t/t < 1\%$.

There is no particular requirement on the amplifier gain other than Si detector, amplifier, and DAQ system together need to fulfill the characteristics above.
We have shown linearity to better than 10^{-3} with a precision pulser and our current electronics, although the input waveform is not the same as for true signals.

Nab detector requirements: timing

The electronics has to be fast enough ($< 20\ ns$ on event by event basis) to allow us to reconstruct the hit history for electrons, and allow a determination of the flight time difference between proton and electron with a systematic bias of less than 300 ps.

There is no particular requirement on the risetime other than it must allow to determine the onset, e.g. by fitting a template, to the requirements given above. As longer the risetime is, as harder it is to achieve the specification (which means, as more demanding it is to have a good model).

Falltime cannot be more than $t_F \sim 5\ \mu s$, otherwise we cannot distinguish electrons and subsequent protons.

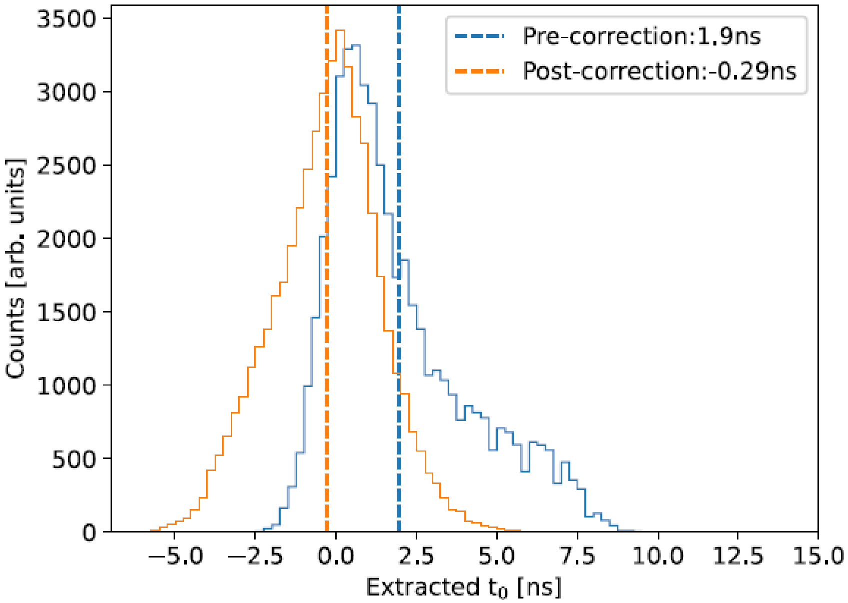


FIG. 33. Cumulative histogram of extracted t_0 bias on an individual waveform before and after corrections from pulse shape discrimination. Similarly to Fig. 32, the hit positions were weighted geometrically. At a signal to noise ratio of 100:1 (where SNR is taken as the square of the ratio of signal and noise amplitudes, respectively) a reduction in the mean bias from 1.9 to −0.3 ns was achieved.

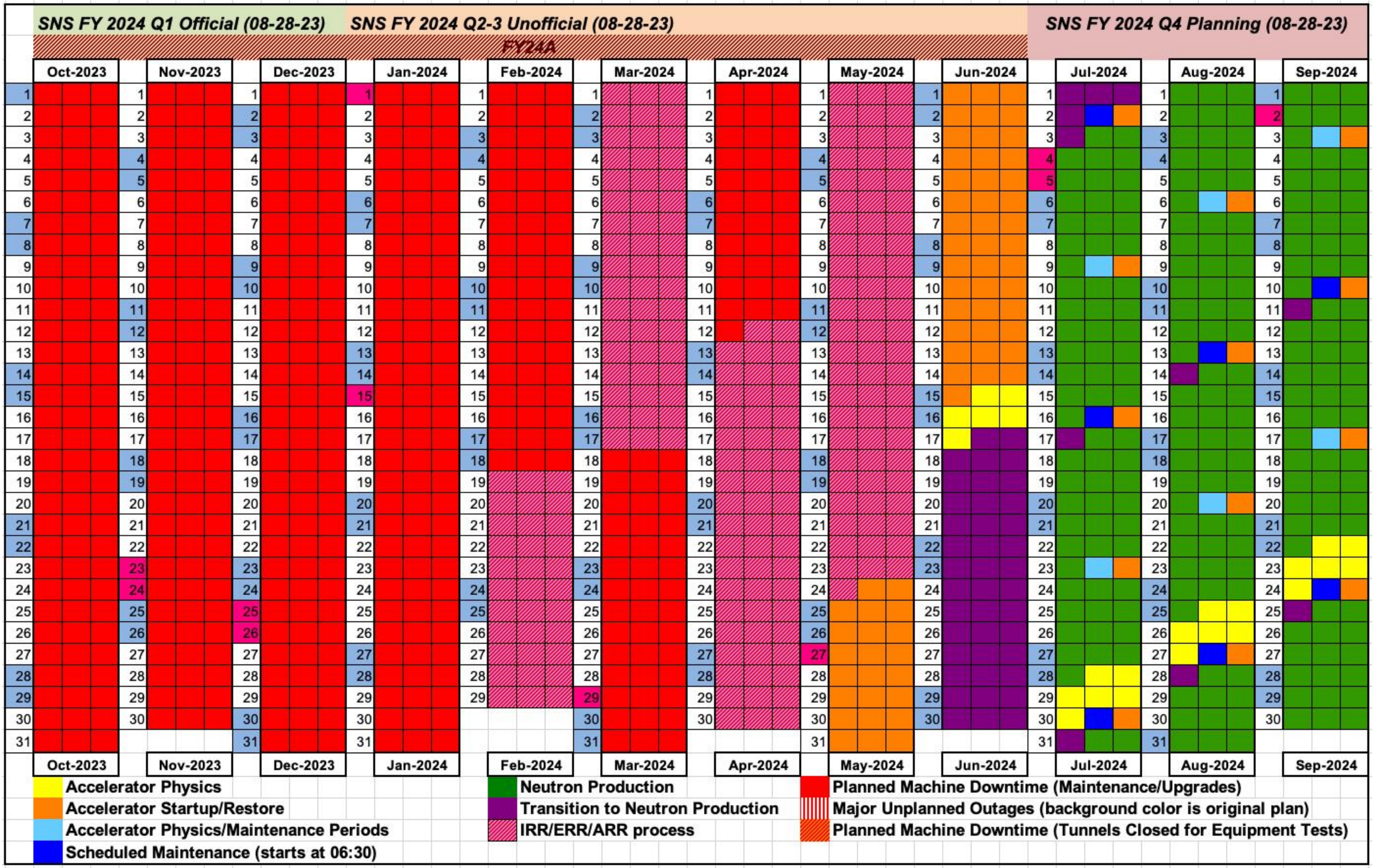
From L. Hayen, PRC 107, 065503 (2023)

Timing reconstruction works well in NCSU detector model for events with SNR 100:1, which was the expected SNR for protons, but our SNR was 9:1, and the model needs more detector characterization to verify whether it matches reality.

Summary of requirements on detector system

Property	Specification
Electron detection	Understand energy calibration from 50 keV to 1 MeV with a precision of 200 eV (for a coefficient) and 80 eV (for b coefficient). Best to have linearity at that level.
	No specific requirement on gain factor
Proton detection	Low threshold (< 10 keV), to be below main proton energy deposition peak with a HV of $30\ keV$ on the upper detector
	No specific requirement on noise other than it must allow to set threshold with no more than about 10 s^{-1} of events above threshold per pixel.
Timing requirement	Fast readout electronic that allows to determine start of waveform to 20 ns (event by event), and avoids bias between electron and proton to 300 ps.
	Falltime must be not more than $5\ \mu s$.

SNS schedule until next summer



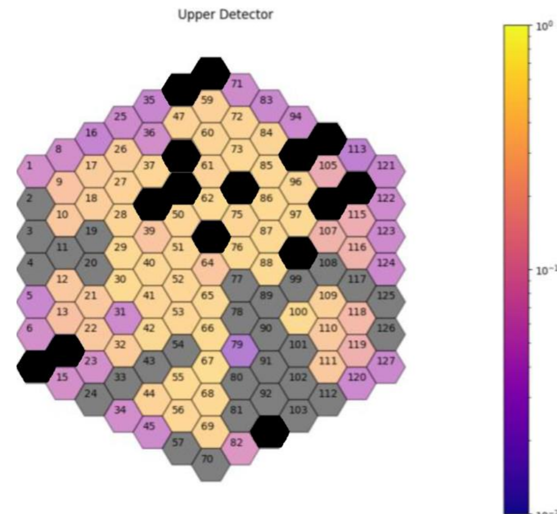
Current outage extends until end of June 2024. Need working system at that time.

ORNL Internal Review of Nab Detector System

We presented 2 issues as our highest-priority:

1. **Detector electronics are marginally stable:** We cannot power all electronics channels at once, as the electronics boards undergo rail-to-rail oscillations. Oscillations are also triggered by system disturbances such as HV sparks. The history and conditions impacting system stability was discussed.
    - Main topic for this review, see Chuck Britton's talks

2. **Missing pixels:** After demonstrating 100% operation on the test bench, due to damage to connectors, pogo-pins, and components during installation, fewer pixels than expected are working in the magnet. System stability also worsens with damage. We discussed our observations and installation constraints.
    - Another topic for this review, see Kyle Reed's talk.



Black: Missing, Gray: Unplugged

Other issues, probably not for today:

3. **Proton energy too low**
4. **Wirebonds integrity on Si detector**
5. **Si detector qualification for use**
6. **Detector cleanliness**

Recommendations from Review in October 2023

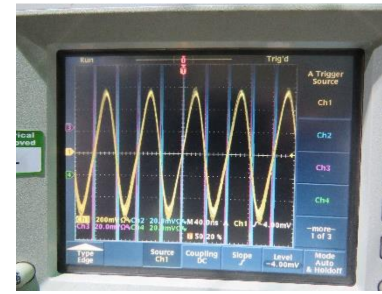
1. **Investigation and Optimization of System Ground, Power, and Signal Connectivity**
   See Chuck's talk
2. **System Specifications Refinement**
   Translation from physics requirements into electronics requirements requires a sufficiently precise model for the electronics. We don't think we have that yet. Albert Young has presented current state in October review. We are missing detector characterization measurements.
3. **Bench Testing of Hardware**
   See Chuck's talk
4. **Spare Micron Detector Array Evaluation**
   Was said to be low priority, nothing to report
5. **Detector Cleaning, Packaging, Handling, and Storage Procedure Development**
   Nothing to report yet, plan to assess in test stand effectiveness
6. **Grounding/Disabling of Unused Detector Channels**
   Plan is to improve reliably of assembly so that unused channels are used in advance.
7. **Reduced Pixel Simulations & Transition PCB Redesign**
   See Kyle's talk for plan to remap pixels and reduce their number. Study had been done previously that the proposed change does not hurt signal count rate in experiment, but it doesn't allow to use uninstrumented pixels for background studies.

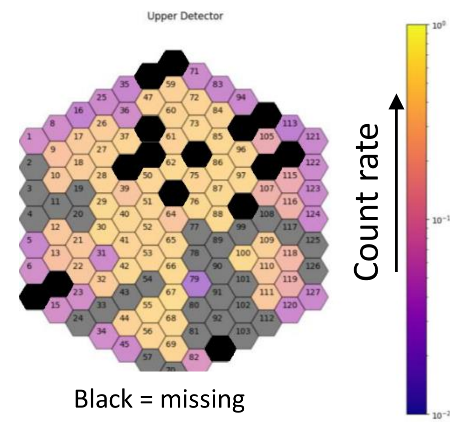
Recommendations from Review in October 2023, cont.

8. **HV System Optimization and Corona Suppression**
   Not discussed today
9. **Wire Bonding Optimization**
   Wire bonder not currently operational. One Postdoc will learn.
10. **Power Supply Stability Testing**
    See Chuck's talk for power distribution box
11. **System Assembly and Disassembly Optimization**
    See Chuck's talk for connector issues. Cleanliness of detector handling addressed in item 5.
12. **Project Management**
    Leah is leading detector team.

Detector electronics improvements

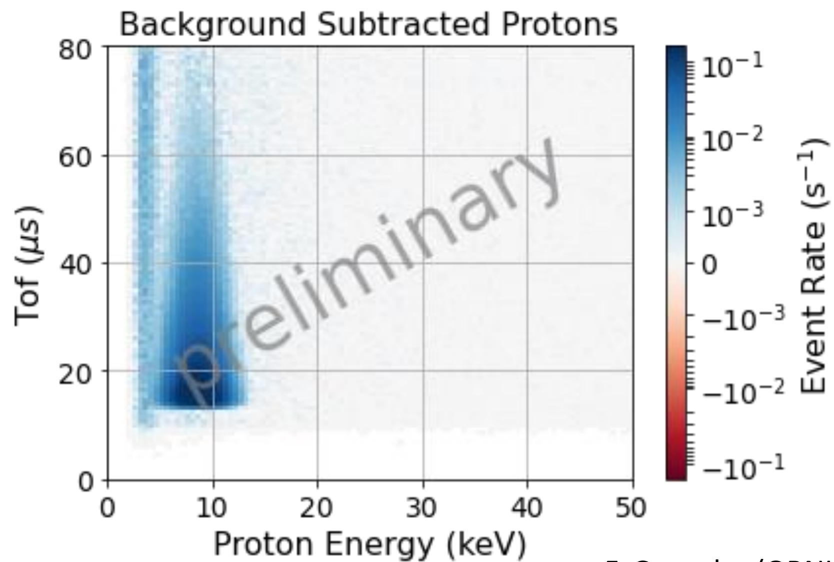
- We have developed a plan to improve electronics and have made significant progress
  - 3-stages of bench testing with ORNL electrical engineer team support: (1) single board, (2) full assembly, (3) full assembly + cold detector. You will hear about (1) and (2)
- **<u>Plan A</u>**: identify source of oscillations in bench testing, design correction, prototype, test, and install
- **<u>Plan B</u>**: redesign transition boards so that only the outer ring of pixels is disconnected
- Plan A will not be ready for beamtime. We therefore proceed with Plan B, and continue Plan A in parallel.
- Other improvements including robust connectors will also be implemented.





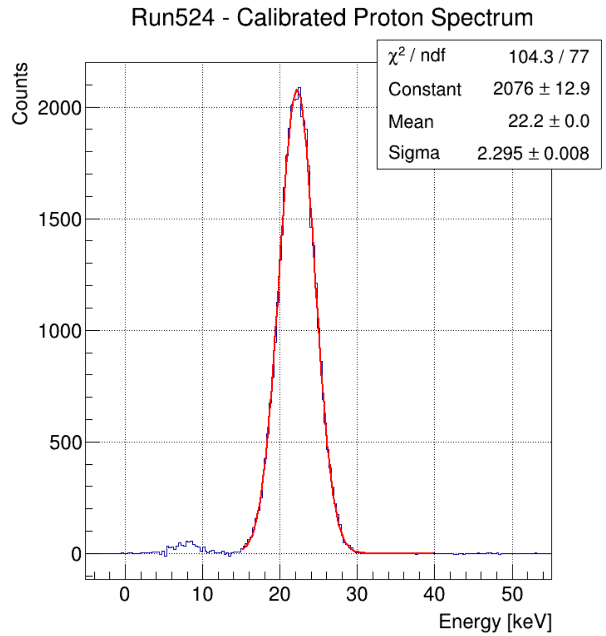
Black = missing
Gray = unplugged

Potential deadlayer on upper detector



F. Gonzalez (ORNL)

Coincident proton energy spectrum from 2023 SNS Beam cycle



J. H. Choi (NCSU)

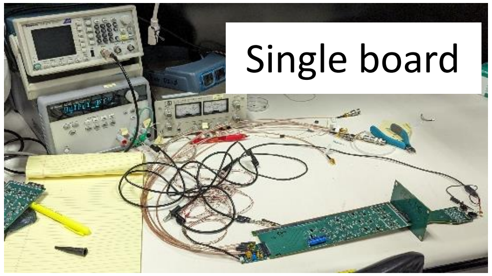
30 keV proton energy spectrum from University of Manitoba proton accelerator, spectrum matches GEANT4 simulation, which matches SRIM simulation.

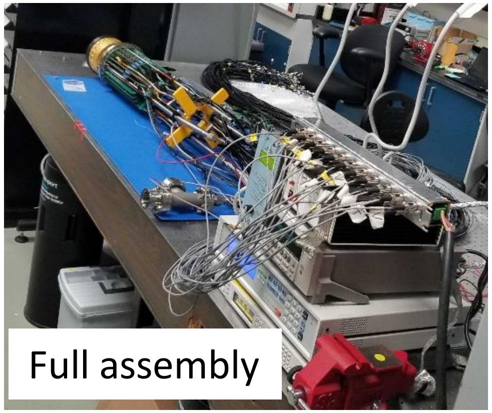
Energy of the protons being detected from the SNS running is lower by at least 10 keV. Possible causes: unwanted crud/ice layer on detector (have only tested one), incorrect low energy calibration.

Consequence: We are running with a threshold of approximately 5 keV (if calibration is linear). Not a requirement for future, we need to solve crud layer issue.

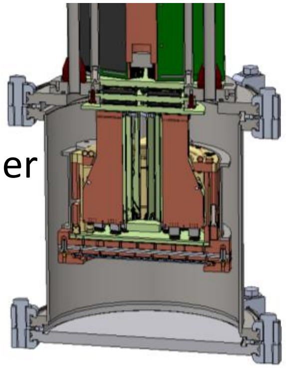
Detector electronics improvements: Plan A

- **Plan A**: identify source of oscillations in bench testing, design correction, prototype, test, and install
- Battery of tests performed under direction of ORNL EE team; informed by SPICE simulation
  - Two stations: (1) single board and (2) full assembly. Isolated ground optical table = master ground
  - Comparisons of waveform shape response and stability from SPICE vs measurement at several points
  - Minor circuit modifications: added op-amp isolation filters, changed op-amps
  - Studied impact of: output termination, which channels are powered, power supply and distribution, connector damage, ground isolation of bias-pulser input / preamp / feedthrough / FET, FET input connection
  - Next: replace power cables, investigate power distribution design
- (3) Mini-chamber for cold detector tests is out for quotes / some parts being fabricated
- Preliminary Conclusion: Circuit is stable, but system oscillates. Identified several improvements needed, but no clear source of oscillation identified or clear path forward. ORNL EE is developing revised layout and simulating with SPICE and testing.





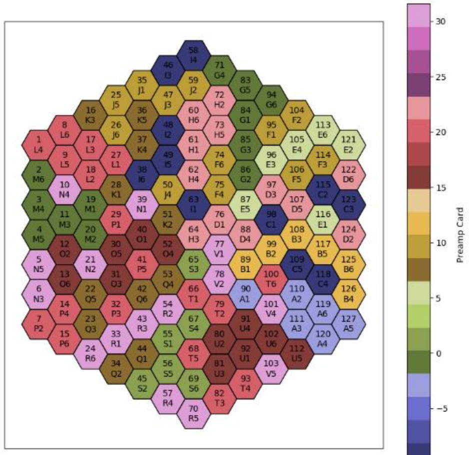
Mini-chamber



Detector electronics improvements: Plan B

- System can be operated stably with 2-3 cards disconnected. Disconnecting any card results in large “hole” in detector.
- **Plan B**: redesign transition boards so that only the outer ring of pixels is disconnected
  - Black hexagon = most critical for beta-decay data-taking
  - Outer pixels = useful for backgrounds / understanding edges
- New transition boards will be tested and installed before beamtime
  - Status: mechanical corrections implemented, layout design in progress.
  - Anticipated to minimize impact of missing pixels
- Improved connector/cabling assembly to be prototyped and installed before beamtime
- Prototyping of FET/Preamp boards continues in parallel.
  - Upon success, electronics assembly package in magnet can be swapped with 1 week downtime
  - We are evaluating costs of full prototyping program

Current map



Proposed map