JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

The Visibility of Error Bursts in Superconducting Qubits from Electron Impacts

We coupled an electron linac with a dilution refrigerator: The CLIQUE Facility

Alan W. Hunt, T. McJunkin, Y. S. Jones-Alberty, T. M Haard, M. K Spear and K. M Schultz

Alan.Hunt@jhuapl.edu
(240) 228-3169

What is the Probability a MIP Causes an Error Burst?

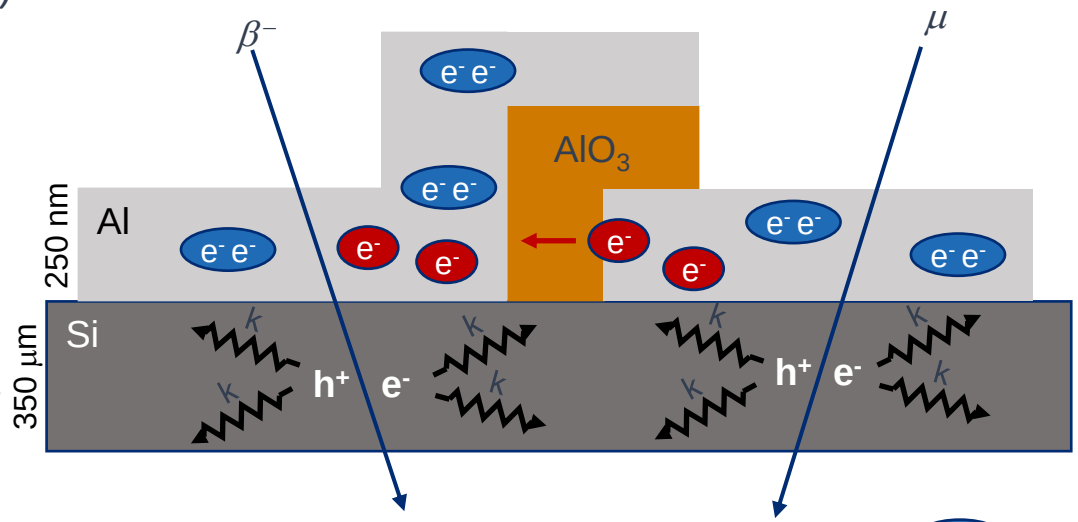
- Ionizing radiation interactions with qubits
  - Deposits energy: ~100 keV ends up as phonons (10^9 more than ΔE_{01})
    - $\Delta E_{01} \approx 20$ μeV (i.e. 5 GHz microwave photon)
  - Si Phonons → Al Phonons → Break Cooper Pairs → Quasiparticles
  - Quasiparticles "spoil" the qubit state
  - Generate error bursts (phonons propagate everywhere)

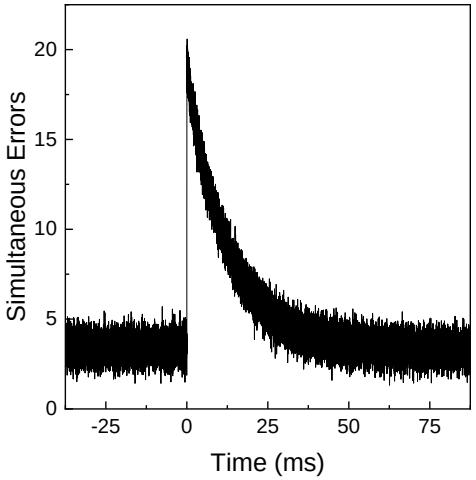
- Studied using background radiation and radioactive sources
  - Difficult to get temporal data (i.e. when radiation hit qubit)
  - Incident flux is largely unknown
  - Contradictory coincident detection experiments
    - P. M. Harrinton et. al 2024 – "…likely all cosmic-ray impacts…"
    - X. Li et. al 2025 – All muons do not cause multi-qubit bit flip errors
      - All muons cause multi-qubit charge parity jumps

- **Goal measure error burst cross section (or probability)**
  - **Error burst cross section:** $\sigma_{eb} = {}^{N_{eb}}/_{\Phi_{mip}}$
  - **Error burst probability:** $\varepsilon_{eb} = {}^{N_{eb}}/_{N_{mip}}$
  - Often how radiation error sensitivity reported for semiconductor devices

Josephson Junction

(critical component of a superconducting qubit)

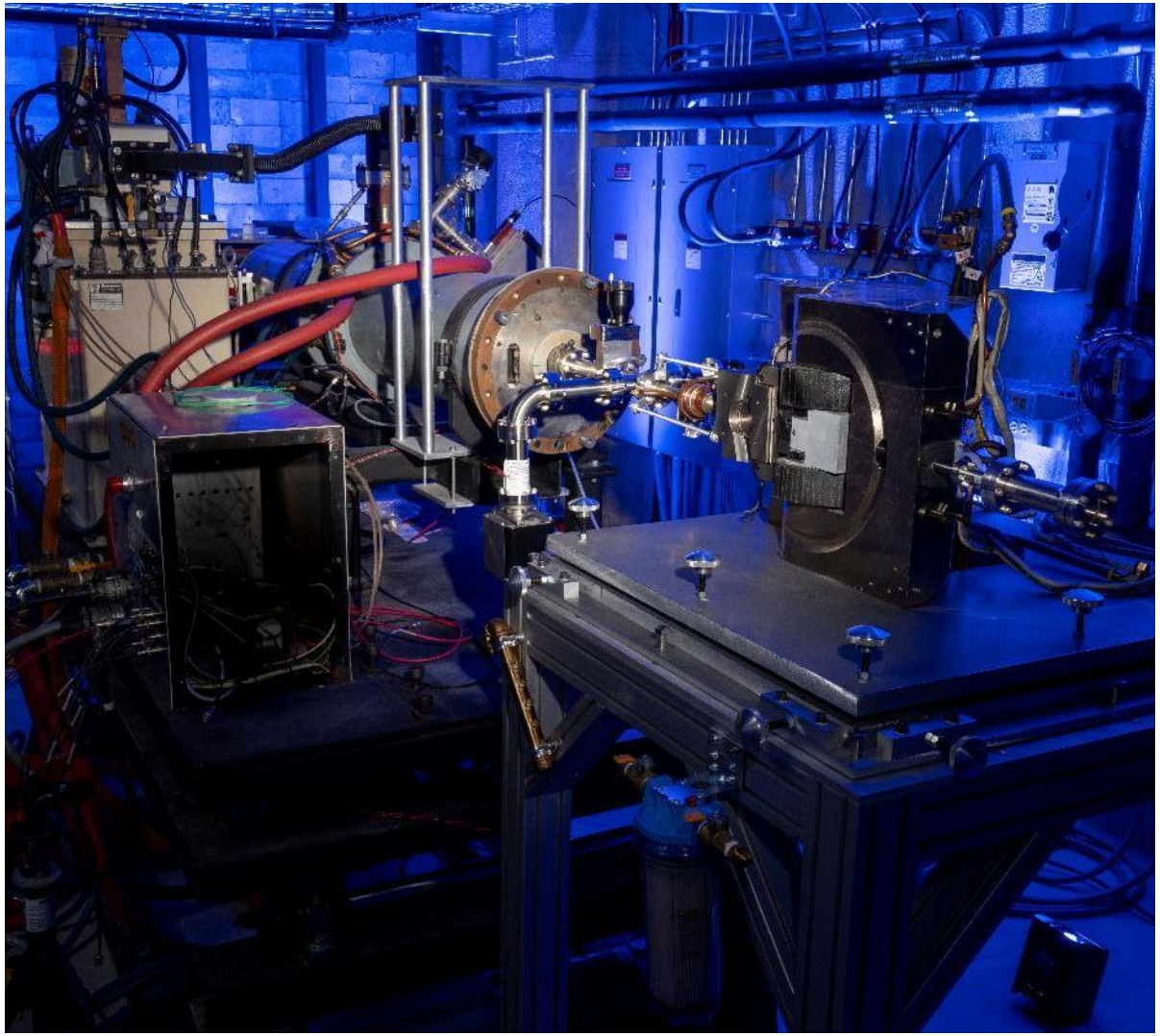




High-Energy Electron Accelerator for Qubit Irradiation

- Accelerator Parameters

Accelerator Waveguide Model	Varian 2500
Fundamental RF Frequency	~2.856 GHz
Electron Energy	5 to 25 MeV
Pulse Width	200 ns to 4 μs
Repetition Rate	0 to 100 Hz
Maximum Charge per Pulse	360 nC
Maximum Time Averaged Current	36 μA
Maximum Time Averaged Power	750 W

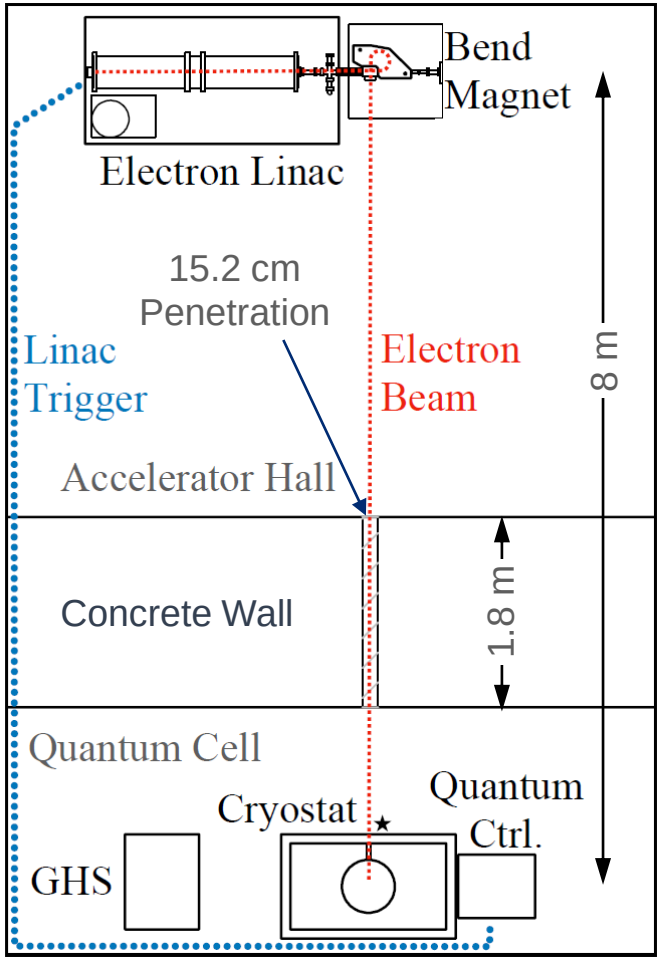


- Advantages of accelerator driven qubit irradiation
  - **Intrinsic temporal data (i.e. accelerator trigger)**
  - Quickly induce upsets

- Challenge: Requires very low currents
  - Accelerator designed to maximize dose (medical/industrial)
    - Charge per pulse 360 nC
  - For qubits operate at 22 fC per accelerator pulse
    - Current stability is not the best

Electron Transport to the Qubits

- Accelerator transport
  - Inject 18 keV electrons into accelerating structure
  - Accelerate to 18.5 MeV through 36 cavities over ~1.9 m
  - 270º bending magnet redirects electrons towards refrigerator
  - Electrons exit through 250 μm Be window into atmosphere
    - Beam diameter ~3 mm
- Beam expands during transport through atmosphere
  - 40 cm diameter at penetration in concrete wall
    - Beneficial: Decreases electron flux
  - Penetration spatially collimates beam to 15.2 cm
  - **Final 3 cm aluminum collimator before refrigerator**
  - Electron lose ~1.6 MeV over ~7.6 m
- Modified Bluefors LD400 to facilitate electron penetration
  - Outer vacuum chamber with 25 μm Ti window, 3.8 cm diameter
  - Four thermal shields with 25 μm Al window, 3 cm diameter
  - Magnetic shield 1 mm mumetal (electrons lose ~1.7 MeV)
  - **Electron energy at qubit ~14.5 MeV**

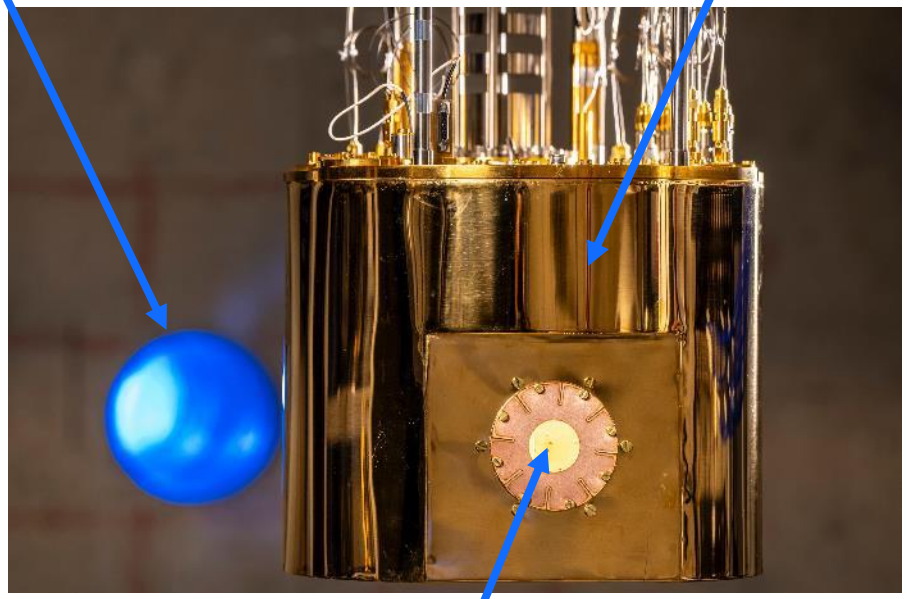


First and only facility to couple accelerator and qubits?

Dilution Refrigerator in Pictures

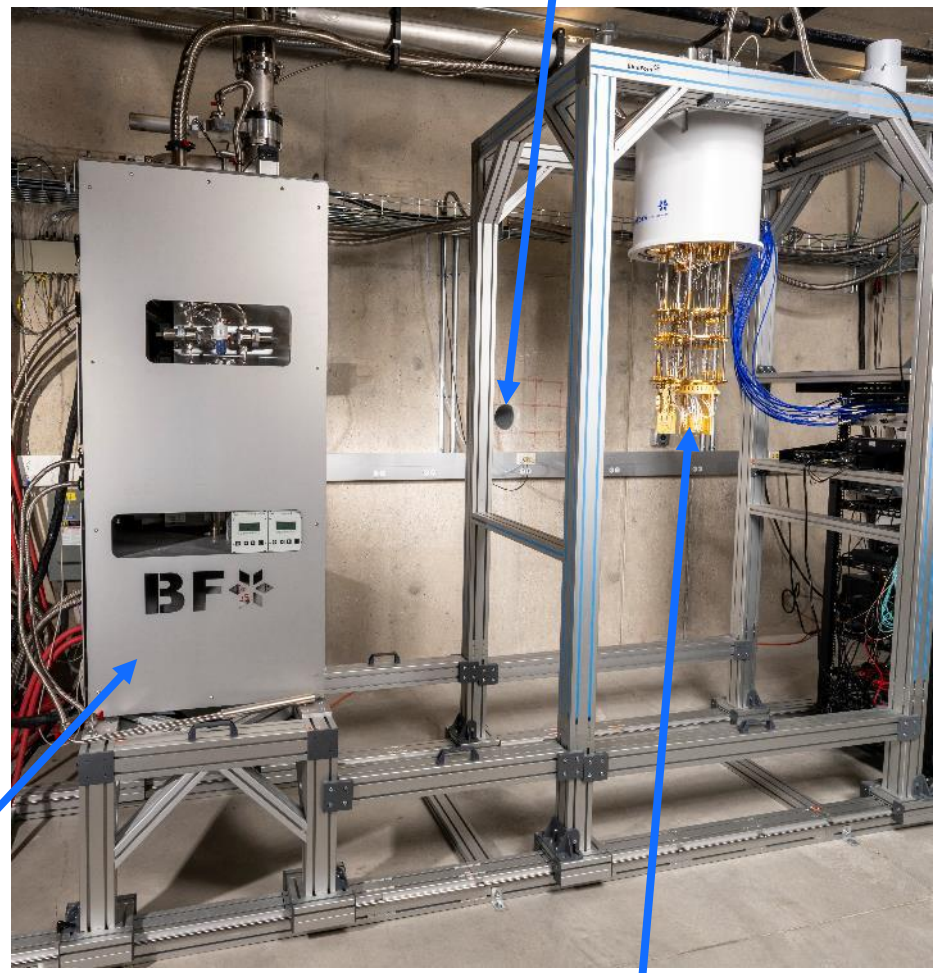
6” OD penetration to Accelerator Hall

Inner thermal shield ~1 mm Cu



Window ~25 μm Al (removed)

6” OD penetration to Accelerator Hall

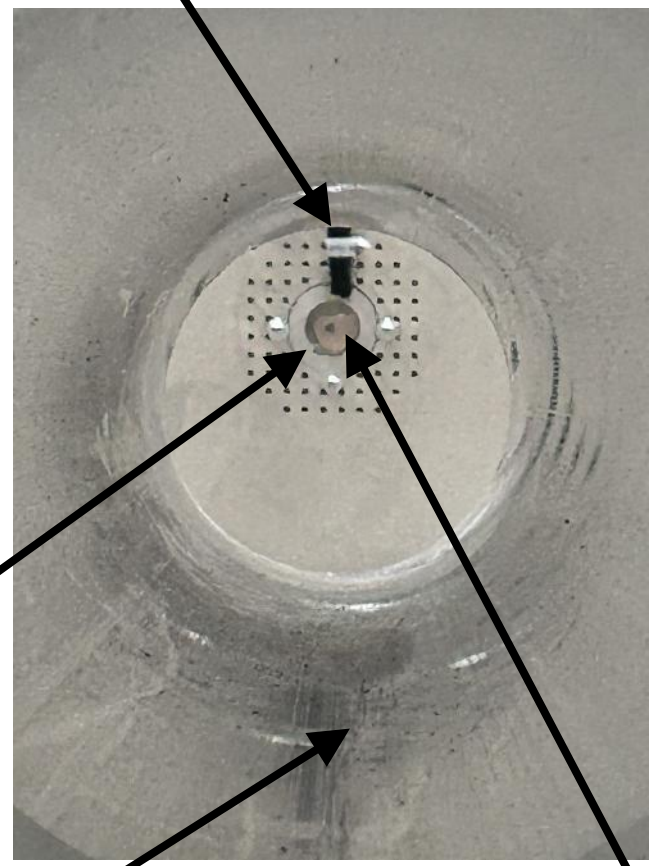


Gas handling system Circulates ^{3}He/^{4}He

Qubits

Electron Flux Monitored with Plastic Scintillators

- Electron detector
  - 1 cm^2, 4 mm thick plastic scintillator on PMT
  - Energy deposition through 4 mm scintillator
    - 634 keV × number of electrons in pulse
  - Detector #1: outside fridge, always present as flux monitor
  - Detector #2: inside warm fridge, measure flux at qubit
  - **Inside/outside detectors linearly correlated**
- Data acquisition
  - Standard pulse height analysis
  - Accelerator trigger injected into data stream
- Energy calibration
  - Originally used Compton edges
  - Currently use electrons
- Currently switching to Si PIN diodes
  - Easier to measure larger or smaller fluxes



Increase Electron Fluence by Increasing Grid Pulse

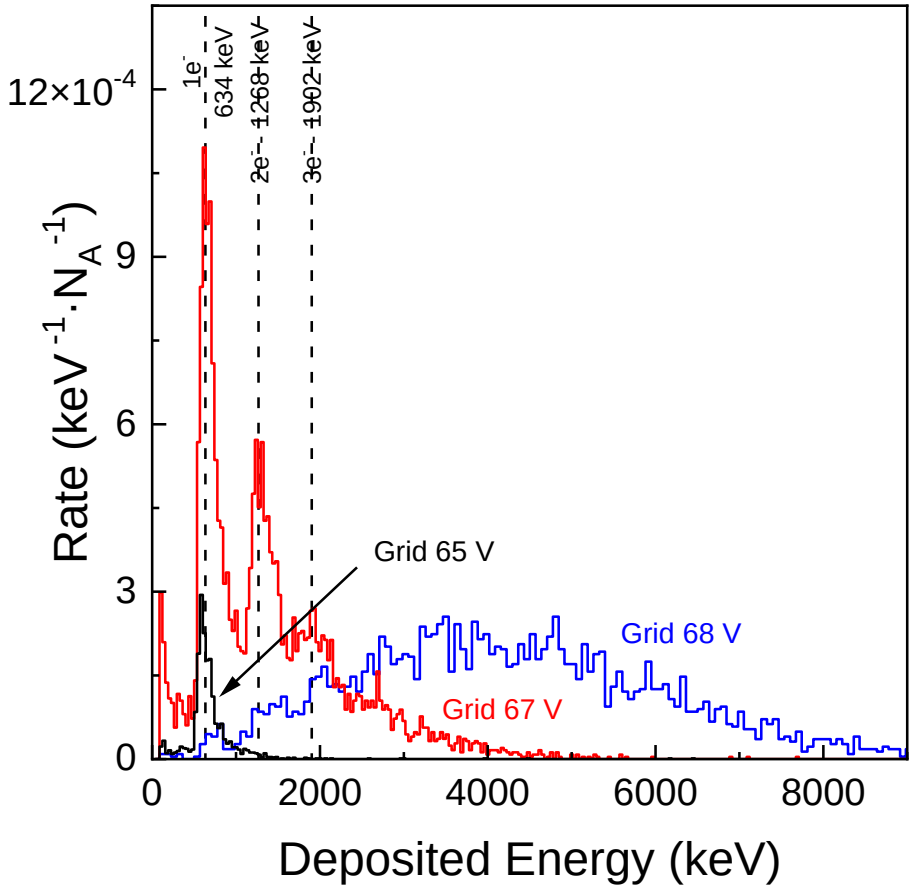
- Electron gun grid bias
  - Grid prevents electron injection into accelerator
  - Increased grid pulse → more electron injection

- Increase grid pulse
  - Observe 1, 2, 3… electron peaks
  - Spectrum gets more complicated
    - More combination of different event types
    - Detector response function
  - **Number of e^- in any given pulse follows Poisson distribution**

$$P(n;\lambda_T) = \frac{{\lambda_T}^n e^{-\lambda_T}}{n!}$$

    - True number of electrons: $\lambda_T = -\ln(1 - P_M)$
    - P_M probability to detect 1 or more electrons (easily measurable)

- Increase grid pulse even more → even more electrons
  - Average energy deposition increases drastically
  - Cannot identify individual peaks
  - Grid bias only changes by a few volts
  - Deposited energy proportional to number of electrons



Correlate Electron Fluence Inside to Outside

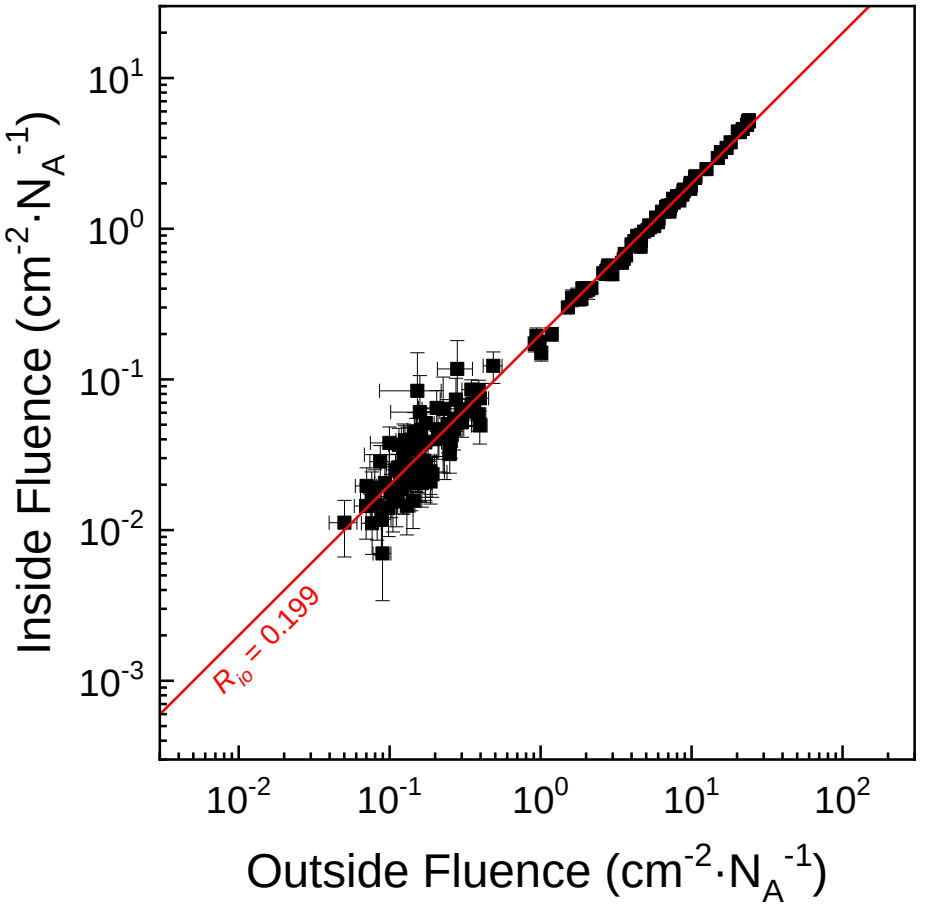
- Install electron detector #2 inside refrigerator
  - Identical detector as #1
  - Calibration technique is the same
  - Add material in front of detector to mimic device package
  - Fridge is at room temperature

- Linear correlation between inside and outside fluences
  - Cannot be anything else
  - Simple equation for inside electron fluence

$$\langle \Phi_{in} \rangle = \frac{d\Phi_{in}}{dE_{out}} \langle E_{out} \rangle; \qquad \frac{d\Phi_{in}}{dE_{out}} = 0.31 \frac{1}{\mathrm{MeV} \cdot \mathrm{cm}^{-2}}$$

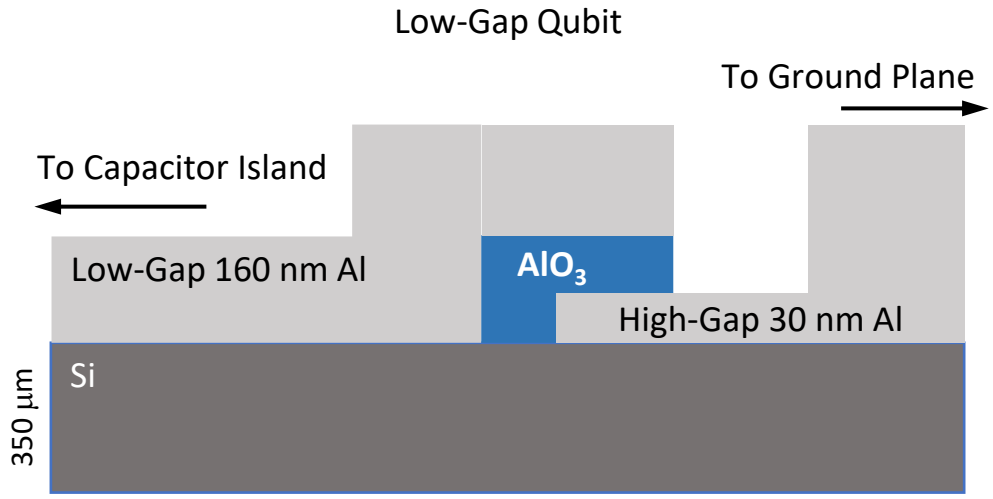
  - Constant depends on setup (e.g. mumetal vs. no mumetal)

- **Qubit fluence ranges that can be monitored**
  - **Low: ~3×10^{-2} cm^{-2}**
  - **High: ~300 cm^{-2}**
  - **Energy deposition ~100 keV to 10 MeV (25 mm^2; 350 μm thick Si)**

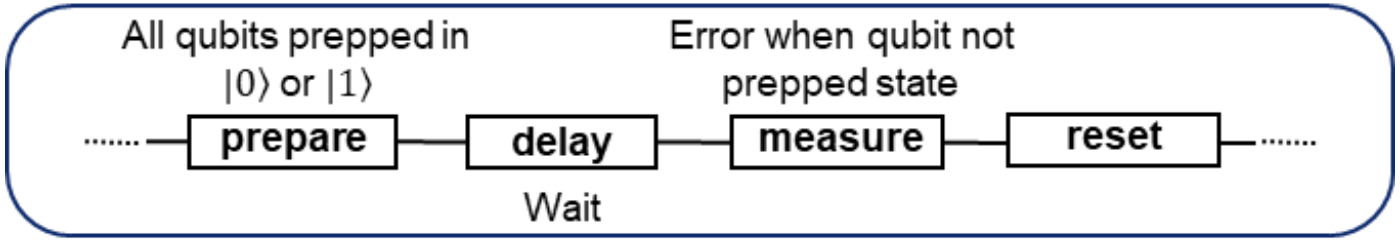


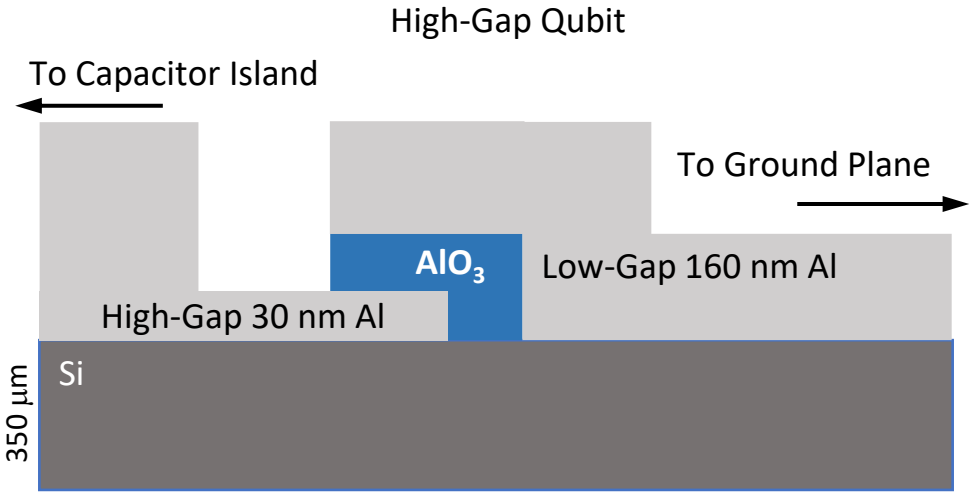
Multi-Qubit Device Has Incidental Gap Engineering

- Quantum device
  - 8 fixed-frequency uncoupled transmon qubits
  - SQUILL fabricated, Al on a 25 mm^2 Si
  - T1 across chip is ~30 - 90 μs
  - Incidental gap engineering
    - 4 Low-Gap → Slower recovery
    - 4 High-Gap → Faster recovery



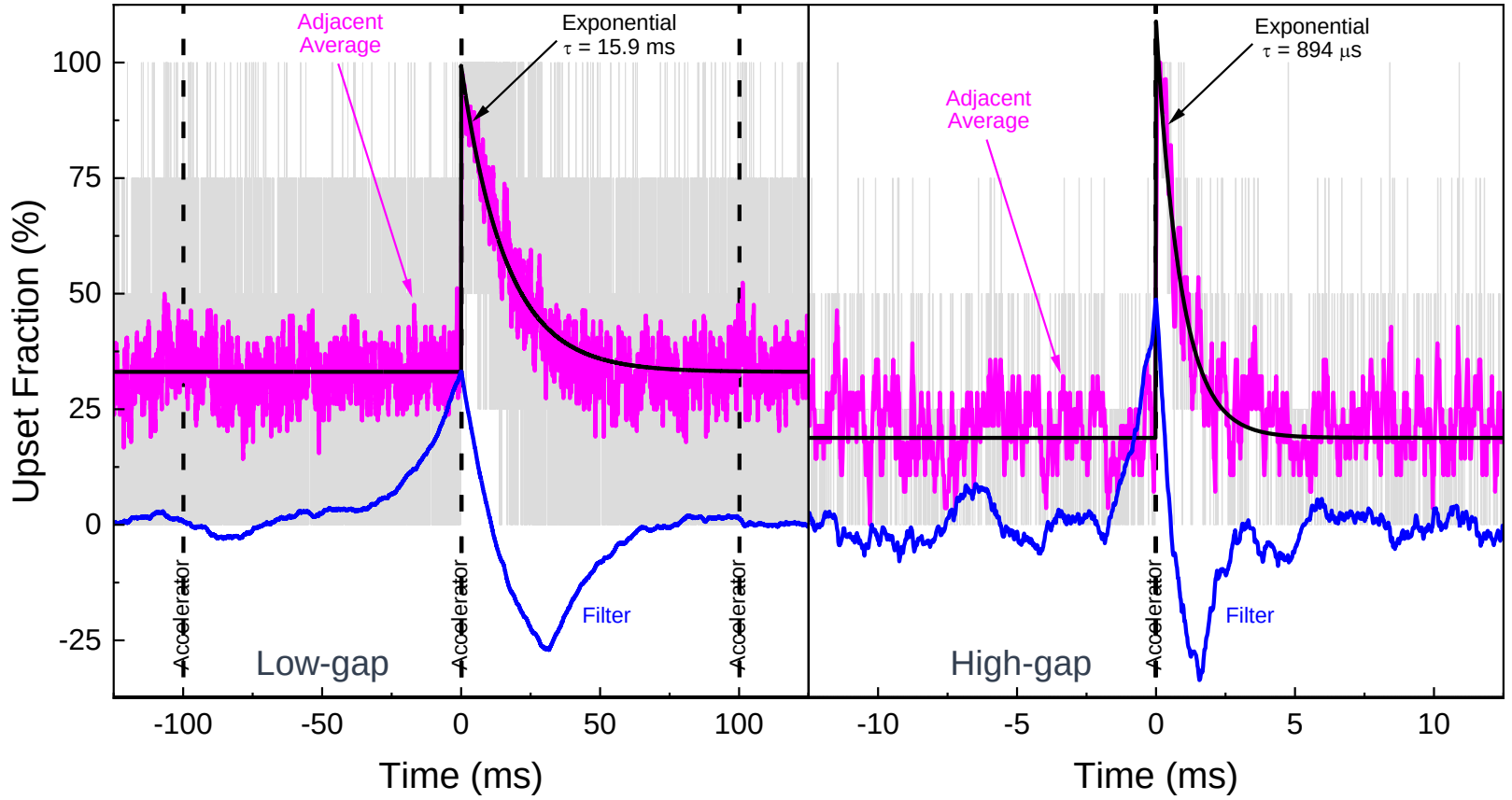
- Quantum control
  - Fast active readout for few-μs shot time
  - **Linac trigger integrated into data stream**
  - Qubit measurement scheme





  - Detection delay varied between 200 ns to 12 μs
  - Sequence time range between 4.96 to 16.76 μs

Linac Based Qubit Error Burst Experiment



Detection delay: 12 μs

- Linac experimental protocol
  - ~18.5 MeV, 10 Hz repetition rate
  - Electron flux at qubit: ~0.8 cm^{-2} per accelerator trigger
    - ~0.2 e^- strikes qubit silicon per pulse
  - Keeping electron flux steady was challenging
- Low-gap qubits recover more slowly
  - Error bursts appear exponential
  - Only ~18% of accelerator pulses contained 1 or more e^-
  - Low-gap recovery time 15.9 ms
  - High-gap recovery time 894 μs

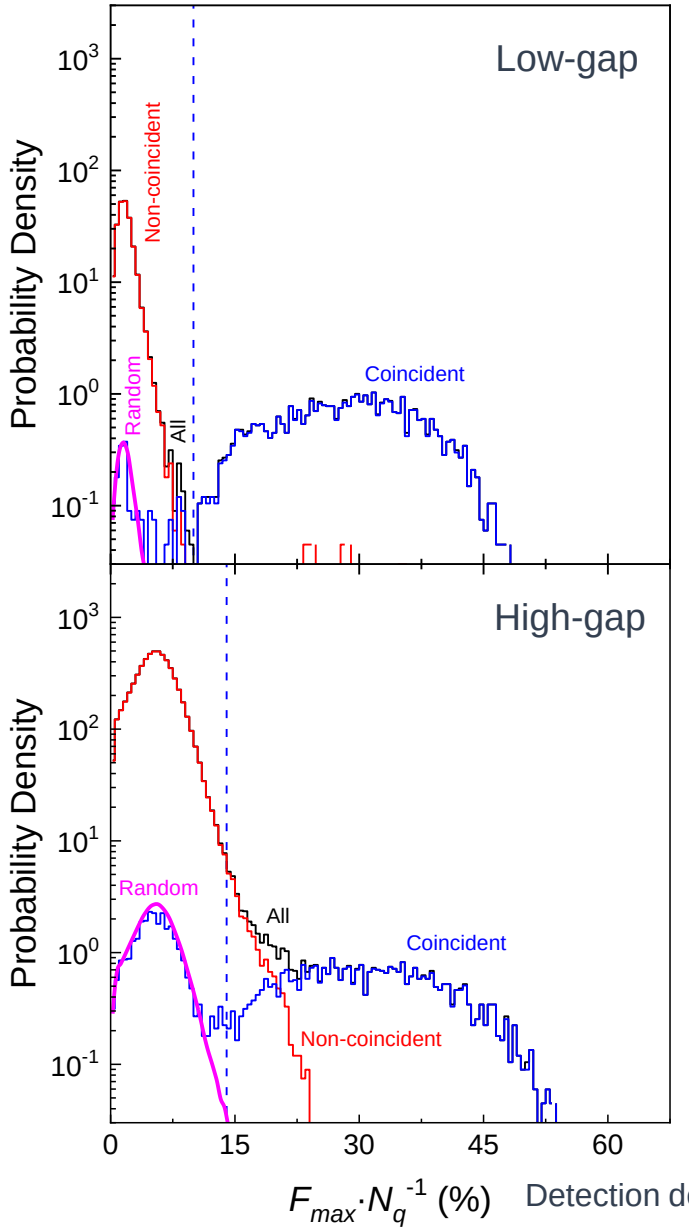
Peak Height Spectra Identifies Error Bursts

- Histogram F_{max} for coincident and non-coincident events

- Non-coincident events
  - Large peak at small F_{max}
  - Quiescent qubit errors and filter constant → peak position and width
  - Few events with large F_{max}

- Coincident events
  - Smaller peak at small F_{max} from random coincidences with the noise
    - Easy to estimate from non-coincident spectrum
  - Broad “peak” at large F_{max} from radiation induced error bursts
  - Good separation between error bursts and background
    - For low-gap qubits do not need coincidences to separate
    - Separation is better for larger detection delays

- Can measure number of error bursts
  - Define F_{max} threshold
  - Count number of bursts above threshold



Detection delay: 12 μs

Every Electron Impact → Qubit Relaxation Error

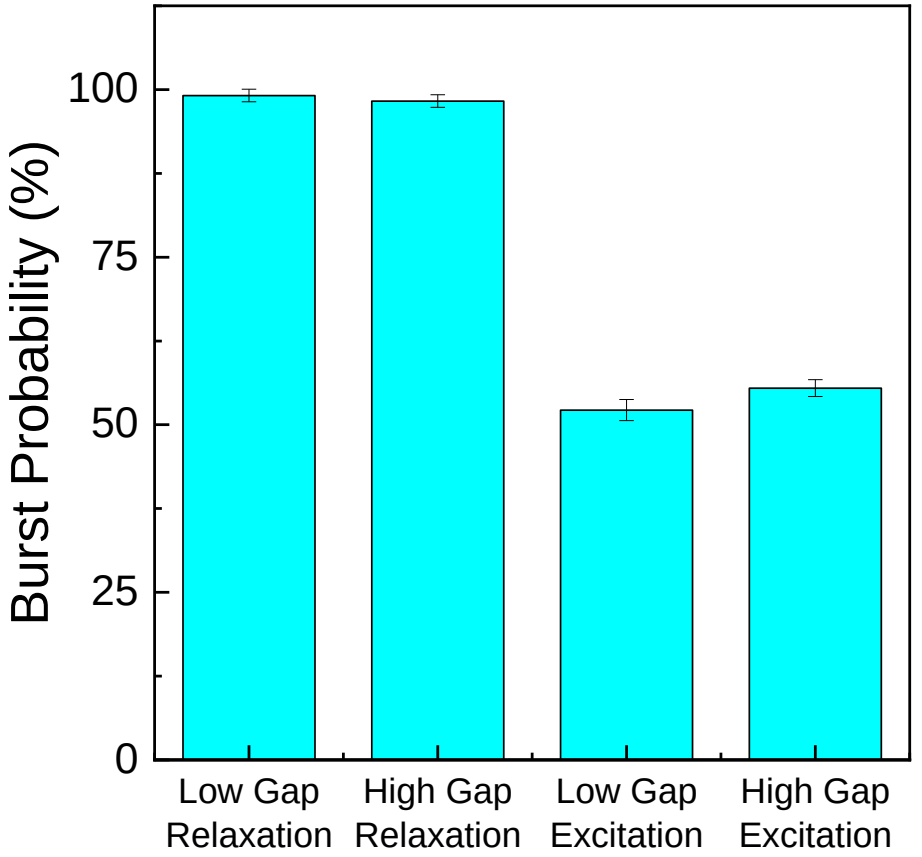
- Error burst detection probability
  - Combine qubit and electron data

$$\varepsilon_{eb} = \frac{N_{eb}}{N_{e^-}}$$

  - Probability to detect an error burst per electron strike

- Relaxation errors ~99% (4 qubits)
  - Independent of detection delays studied
  - Same probability for low and high-gap qubits
  - Suggests $\sigma_{eb} > 25$ mm^2
  - Still need to explore how this changes with number of qubits

- Excitation errors ~52% (4 qubits)
  - Analysis is still ongoing
  - Smaller error response → harder to detect
  - Did not discuss in this presentation.



Conclusions

- Coupled a high-energy electron linac with dilution refrigerator
  - Standard pulsed S-band electron linac
  - Dilution refrigerator modified with thin windows on vacuum can and thermal shields to facilitate electron penetration

- Developed “single” electron operation technique
  - Low currents achieved by decreasing electron gun grid pulse
  - **Electron fluence from 0.03 to 300 cm^{-2} per accelerator pulse at qubit**
  - Accelerator can go higher but need to change electron detector, also will start to heat up the dilution refrigerator
  - Electron fluence at qubit monitored by plastic scintillator outside dilution refrigerator
    - Linear relationship with electron fluence inside dilution refrigerator

- Time resolution: A couple of qubit measurement sequences
  - Enables investigation of many qubit/radiation phenomenon

- Measured probability to detect error burst per electron impact
  - Relaxation errors: ~99%
  - Excitation errors: ~52%

The CLIQUE Facility supports external research.

- We invite the quantum x radiation community to leverage the experimental advantages of this facility for their research.
- We can support a wide range of quantum devices, measurement schemes, and collaboration styles.
- We have already hosted a gap-engineering study with MIT, quantum dot measurements with Wisconsin, and an MKID study with LLNL.
- Reach out to **CLIQUE.Facility@jhuapl.edu** to learn more!

CLIQUE
Controlled Linac Irradiation of Quantum Experiments

CLIQUE.Facility@jhuapl.edu



JOHNS HOPKINS APPLIED PHYSICS LABORATORY

CLIQUE User Project Application

The Controlled Linac Irradiation of Quantum Experiments (CLIQUE) facility at the Johns Hopkins University Applied Physics Laboratory (JHU/APL) is a community resource for studying ionizing radiation effects in quantum systems. The main facility components include a pulsed electron linear accelerator (linac) and a modified dilution refrigerator equipped with standard RF quantum control hardware.

The linac is capable of delivering ~microsecond pulses of ~20 MeV electrons toward the refrigerator, which is housed in an adjoining room to minimize RF and ionizing radiation spillage. The fridge shielding layers have been thinned at 3 cm diameter ports below the mixing chamber to minimize energy loss of the incident electrons. The fridge can optionally be removed from the beamline for room-temperature experiments.

The electron flux at the refrigerator is tunable, allowing from fewer than one to many electrons per square centimeter per pulse. The linac can optionally be ran as a Bremsstrahlung radiator, sending a shower of X-rays and electrons toward the fridge. The pulse frequency is adjustable, ranging from a single on-demand pulse up to 100 Hz. The linac pulse trigger is routed to the quantum control and measurement system (Quantum Machines), providing timing precision better than 10 microseconds.

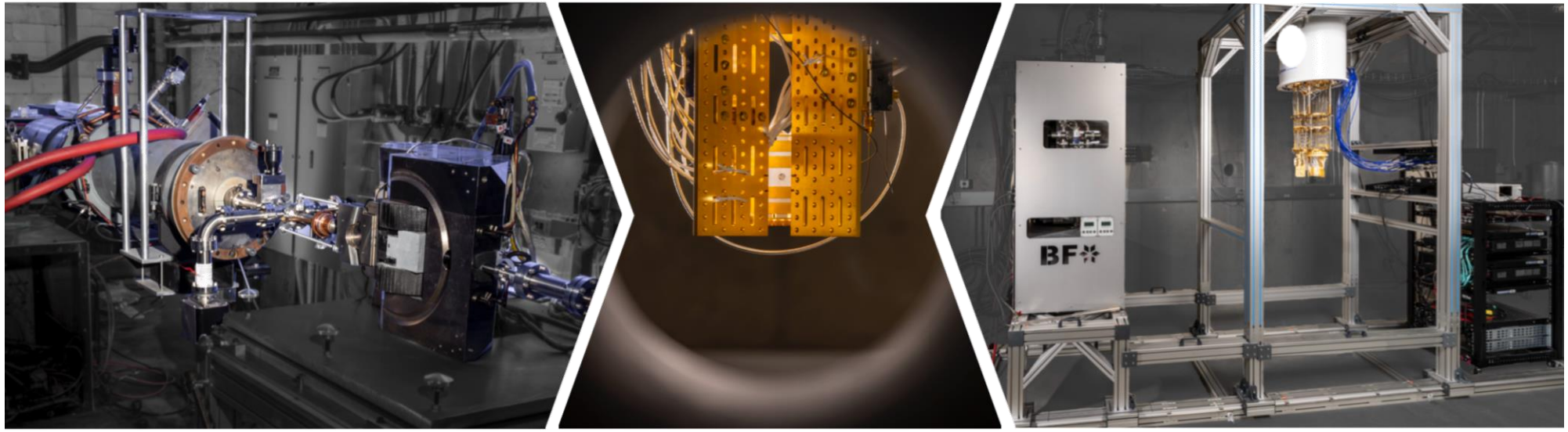
The system currently supports simultaneous independent control of approximately 10 superconducting qubits or a multi-dot semiconductor spin qubit system.

To share these capabilities with the broader quantum community, the CLIQUE facility is open to collaboration with external researchers. Potential device platforms include, but are not limited to, quantum computing systems, particle detectors, and cryogenic computing systems. Collaborators may choose to send devices and any additional test equipment to JHU/APL for our researchers to test, or may also visit the lab to aid or lead experiments themselves. Any visitors to JHU/APL must be US citizens, though research teams may include non-citizens.

If you are interested in leveraging these capabilities for your research, please complete this form to join the JHU/APL CLIQUE.

Review: The CLIQUE Facility is a powerful tool to study the effects of ionizing radiation on quantum systems.

- The electron linear accelerator provides a on-demand irradiation similar to muons.
- Thousands of events with high timing precision and known energy can be collected in minutes.
- Subtle error mechanisms like excitation and detuning are easily extracted.
- The CLIQUE facility is open to external collaborations.
- Future directions include TLS studies, parity switching, mitigation techniques, other quantum systems.



arXiv:2603.13124

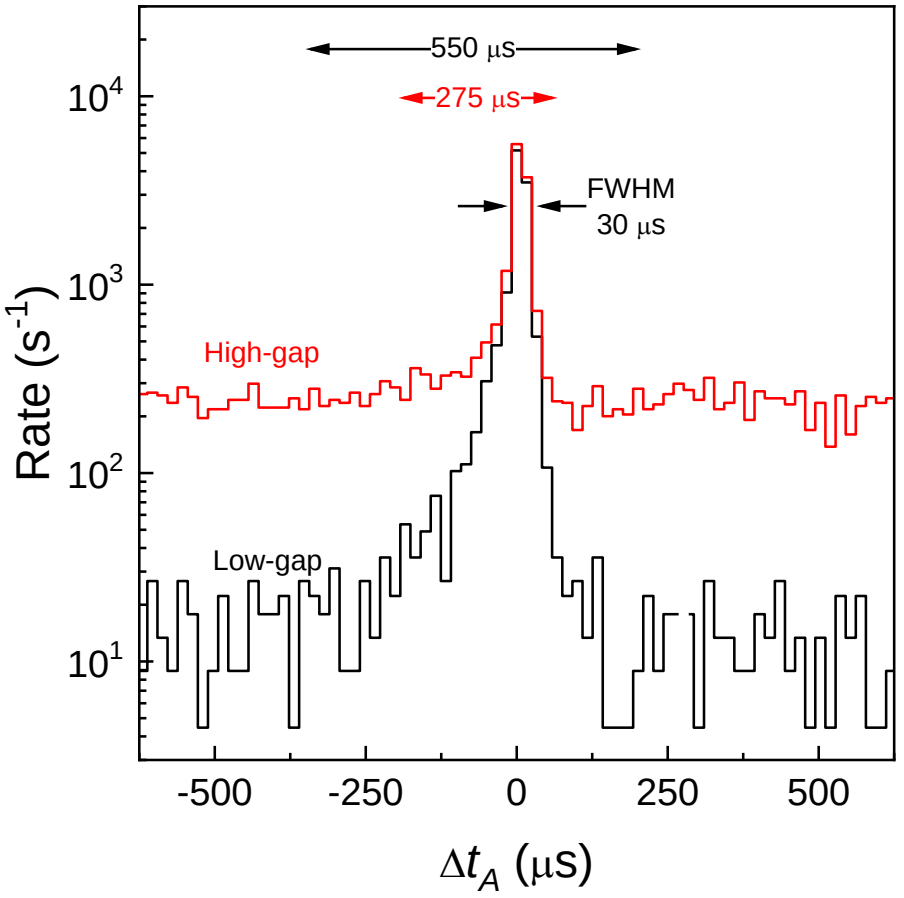

APL

Time Resolution: Few Qubit Measurement Rounds

- Apply filter to raw data
  - Initially do not consider accelerator triggers
  - Initially do not use a threshold on F_{max}
  - Find coincident and non-coincident events

- Coincidence timing upsets with accelerator trigger
  - $\Delta t = t_A - t_Q$: accelerator trigger – filtered upset peak
  - FWHM ~30 μs (~1.8 qubit measurement sequences)
  - Tail in $-\Delta t$ from fluctuations on slower rising edge
  - Can we do better with traditional radiation detection filters?

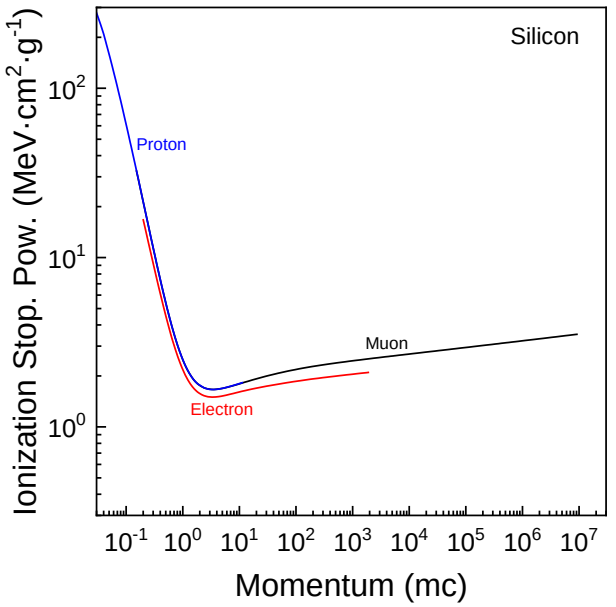
- Can measure number of coincident error bursts
  - Utilize sideband subtraction techniques
    - Integrate under peaks
    - Use flat backgrounds to subtract background
  - Define coincidence windows around peaks



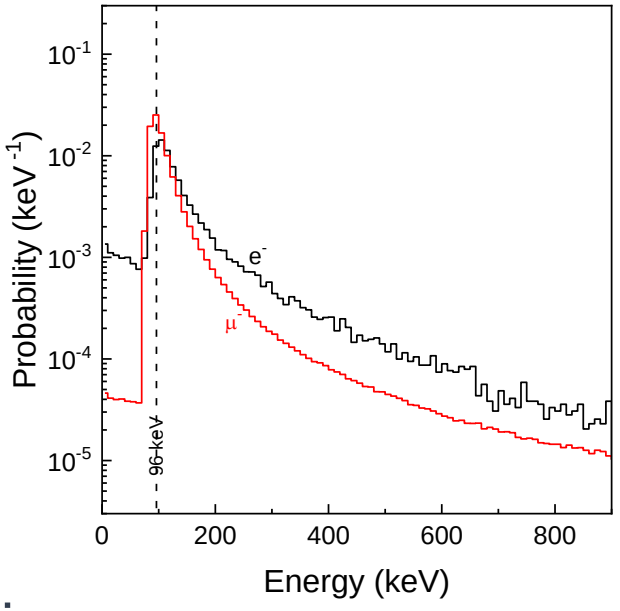
Detection delay: 12 μs

High-Energy Electrons are Minimum Ionizing Particles

- Charged particles at minimum energy deposition
  - Proton 2.5 GeV
  - Muon 270 MeV
  - Electron 1.2 MeV
  - Minimum Ionizing Particles (MIPs)
- Energy deposition increases slowly after minimum
  - Increase energy by 1,000 → 55% increase in energy deposition



- What is a typical cosmogenic muon
  - Average energy: ~4.5 GeV
  - Most probable energy: ~350 MeV



- Average energy deposition in 350 μm of Si
  - Average muon: 168 keV
  - Most probable muon: 136 keV
  - 14.5 MeV electron: 141 keV
  - **Electron energy deposition within 20% of a muon**
- Much more to the radiation environment: γ-rays, neutrons, alphas, protons etc…

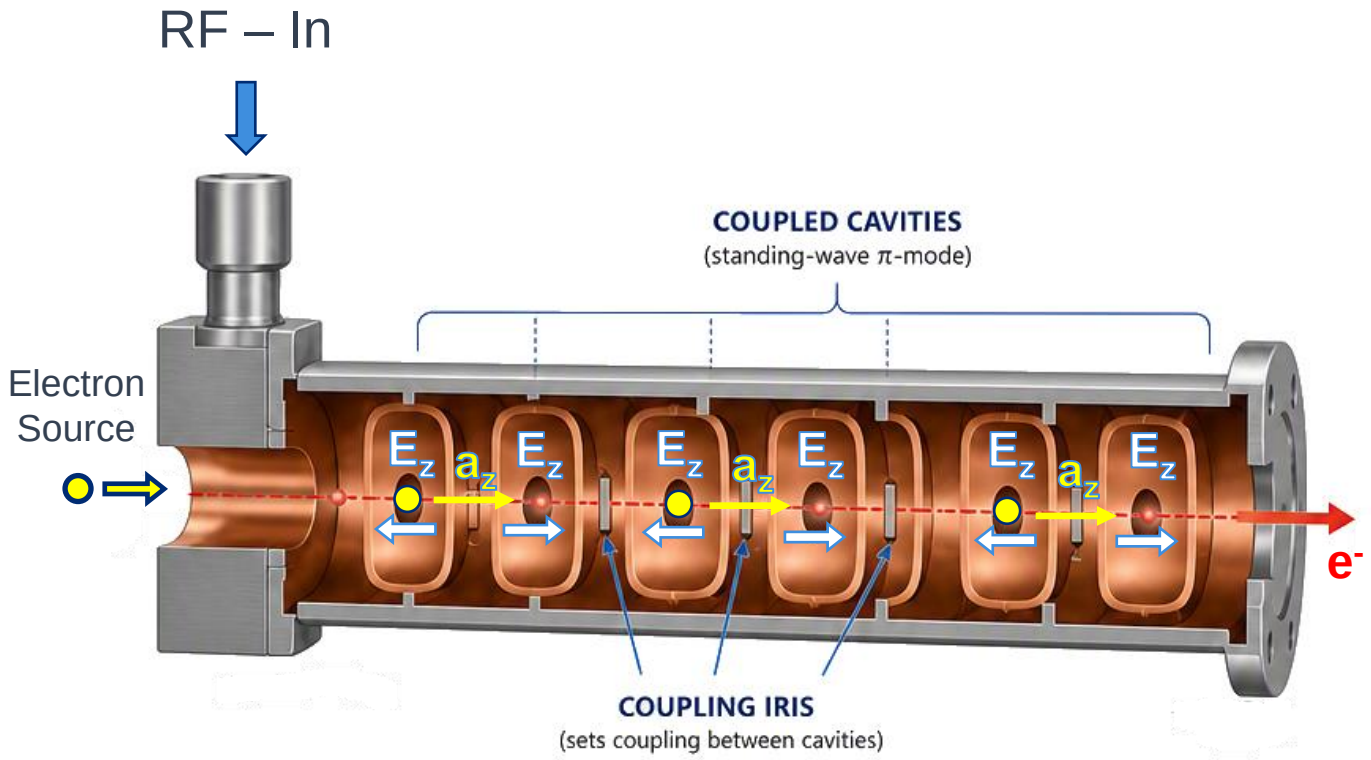
Pulsed Radiofrequency Electron Linac – Primer

- Resonant cavities
  - Metallic structure supports accelerating electric fields
  - Normal metal or superconducting
  - Standing or traveling wave
  - Resonant frequency for S-band 2.856 GHz

- RF Power
  - Pulsed klystron amplifies input RF power by ~10^6
  - Typical output power ~5 MW over 10 μs
  - Frequency matches resonant cavities e.g. 2.856 GHz
    - Potential interference with qubits?

- Electron source
  - Thermionic triode source – hot filament with control grid
  - Photosource – photocathode with laser/diode

- Many supporting systems
  - Beam optics, pulsed power, cooling etc…



Drawing mostly AI generated

Anatomy of Electron Detector Spectrum

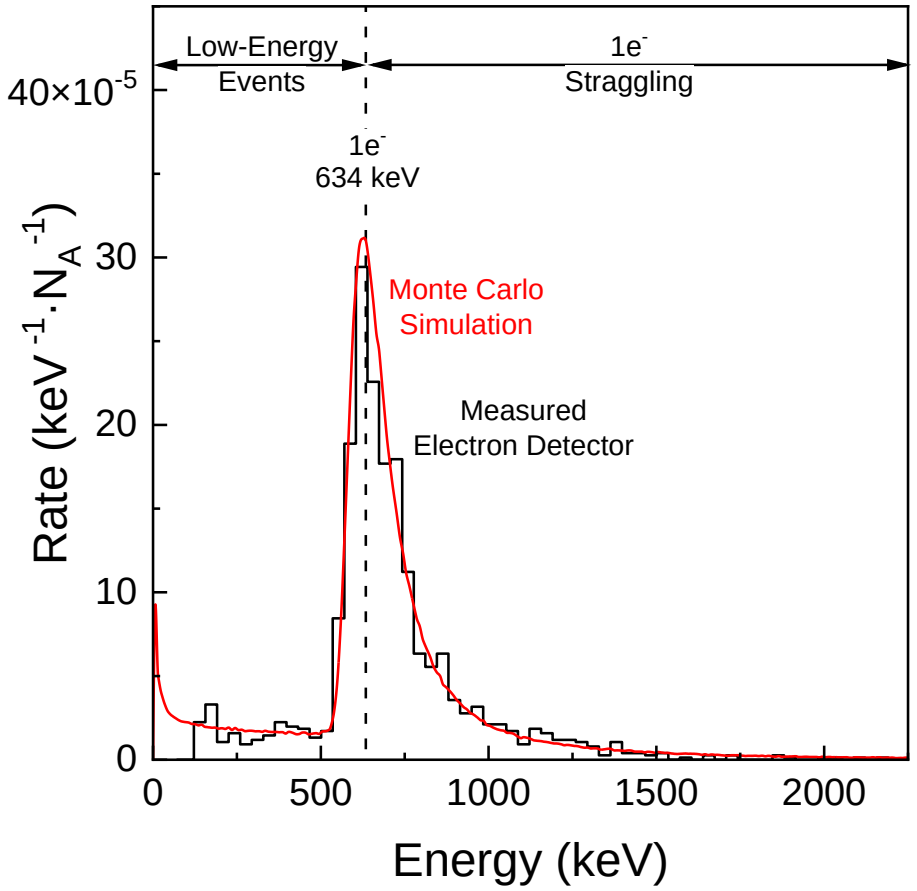
- Low-energy events
  - Photon interactions
    - Generation: exit window, atmosphere, scrapping in magnet…
  - Low-energy secondary electrons
    - Generation: exit window, atmosphere…
  - Less than full traversal (e^- scatters out)

- One electron – full traversal
  - Electron traverses full detector thickness (i.e. 4 mm here)
  - Energy deposition follow Landau distribution

$$E_{mp} = \xi_{bet}\left[ln\left(\frac{2mc^2\beta^2\gamma^2 \cdot \xi_{bet}}{I^2}\right) + 0.2 - \beta^2 - \delta\right]$$

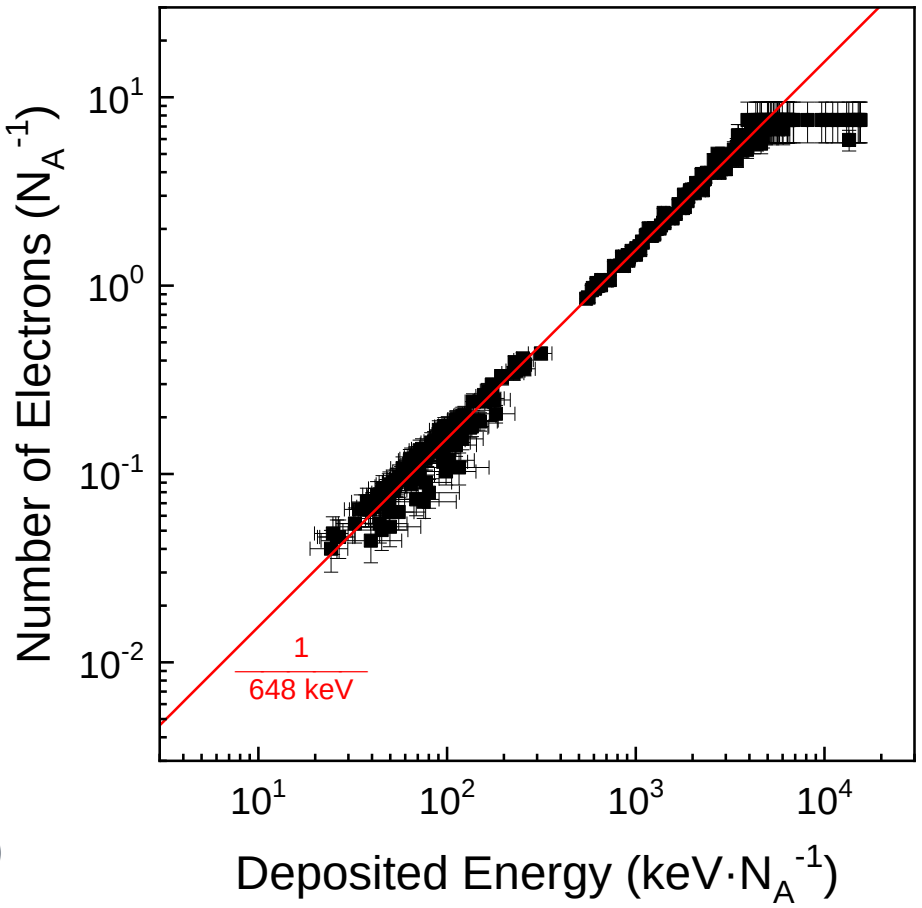
  - High-energy tail from straggling: large energy transfer
  - $E_{mp} = 634$ keV for 4 mm plastic at 14.5 MeV

- Two, three, four or more electron – full traversal
  - Increase electron gun grid bias → more electrons per accelerator pulse



Higher Electron Fluences Use Energy Deposition

- Low fluences
  - Electron rate linear related to energy deposition
  - Measure electron rate using Poisson method
  - Energy deposition is mean energy over multiple pulses
  - Calibration: ~648 keV per electron
- High fluences
  - Simple counting fails at $\lambda_T \approx 3.5$
  - Detect on every pulse → limited information
  - Assume low fluence linearity holds at higher fluence
  - Assumes energy calibration is good at higher energies
- Calibration is stable
  - Calibration constant same since June 2024 (multiple PMT gain changes)
  - Cross calibrated with “shielded” detector
    - Calibration good to ~70 MeV



Identify Error Bursts with Matched Filter

- Notional qubit response
  - $\mathrm{U}(t) = U_o e^{-\lambda_U (t-t_o)}\,\Theta(t-t_o) + U_{bkg}$

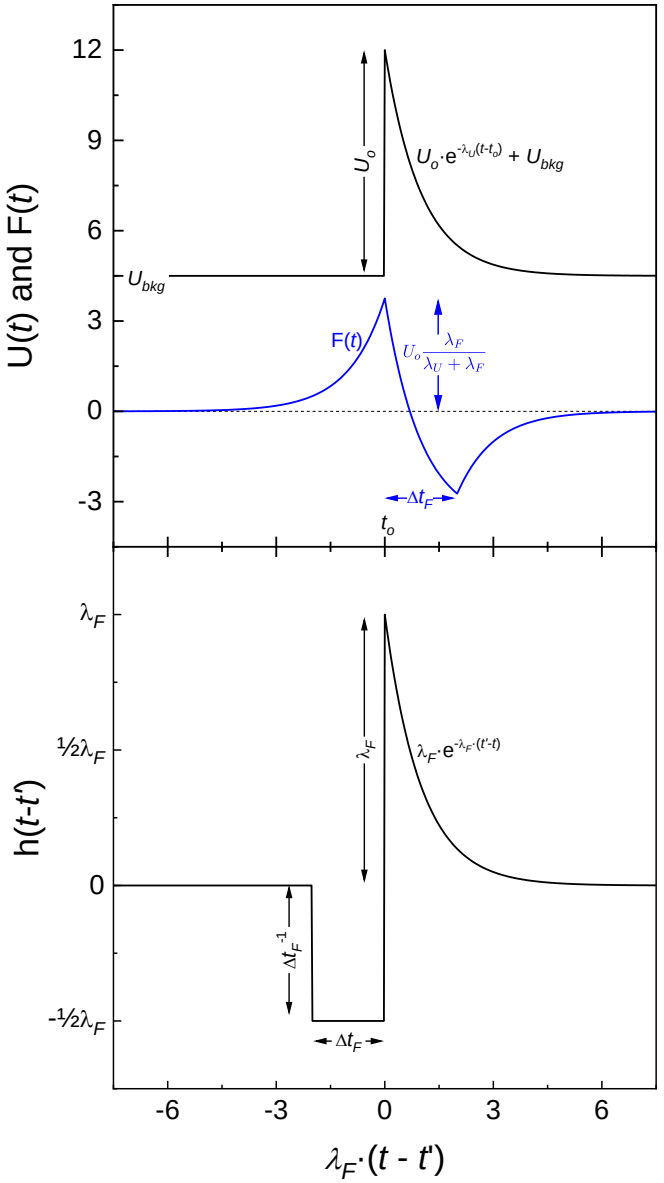
- Matched filter
  - Forward exponentially weighted moving average
  - Subtract the trailing mean removes local quiescent qubit errors
  - Filter output is bipolar response with a maximum at $t = t_o$

$$F_{max} = U_o \frac{\lambda_F}{\lambda_U + \lambda_F},$$

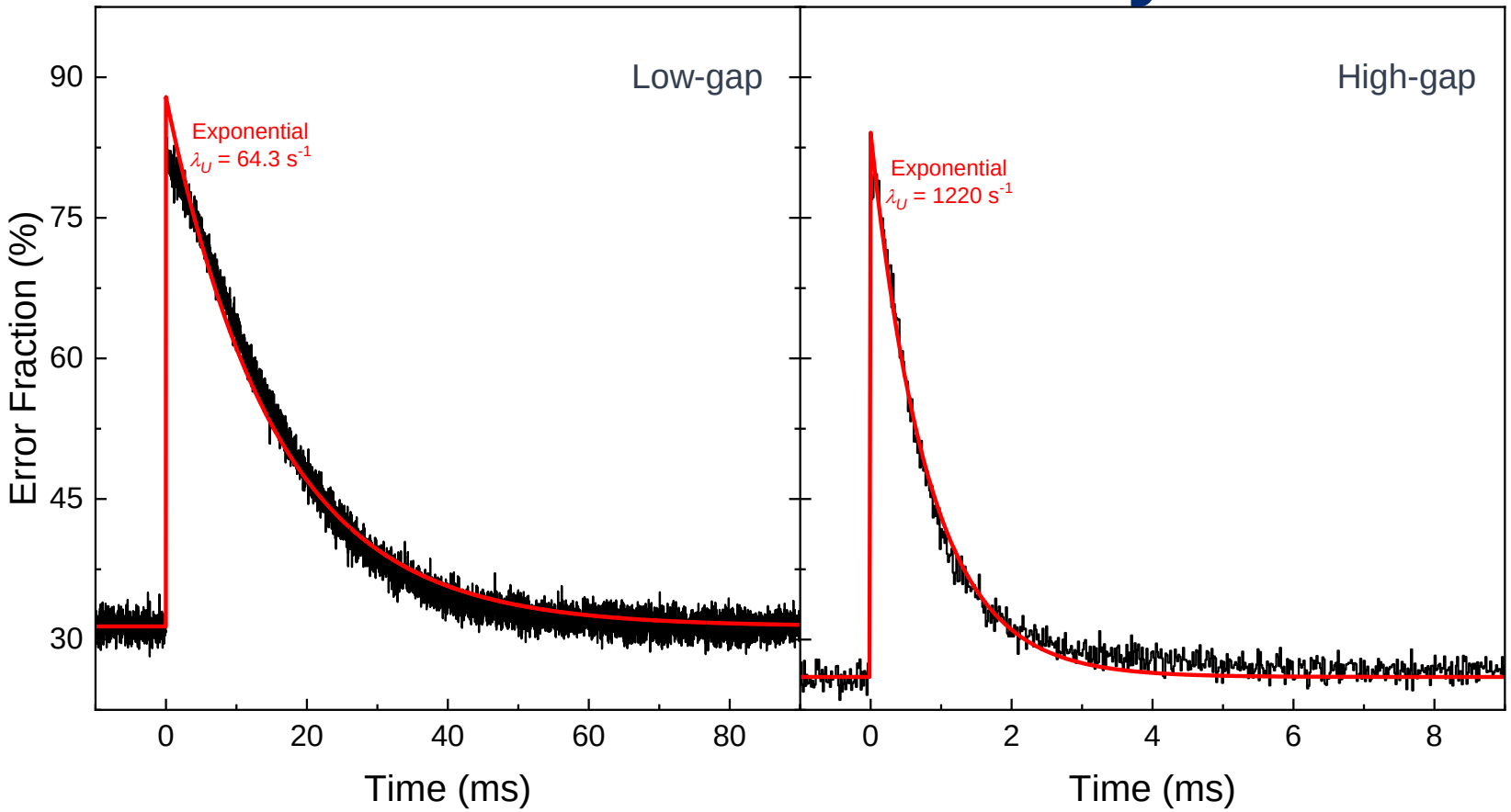
  - F_{max} provides an event–by–event measure of error burst size
  - Signal to noise ratio for binomial distributed quiescent errors

$$\frac{F_{max}}{\sigma_F} = u_o \frac{\lambda_F^{\frac{1}{2}}}{\lambda_U + \lambda_F} \left(\frac{N_q\,(1-p_{bkg})}{p_{bkg}\left(\frac{1}{2} + \frac{1}{\alpha_F}\right)\Delta t_{qs}} \right)^{\frac{1}{2}}.$$

  - SNR maximized when $\lambda_F = \lambda_U$
    - Expected for matched filter



Easy to Measure Effective Recovery Constant



Detection delay: 12 μs

- Average responses to measure recovery
  - Easy with time tagged radiation source
  - Non-exponential behavior observable
  - Shorter detection delays appear exponential
  - Average recovery constants: 64.3 and 1220 s^{-1}
- Normalized to per pulse with an electron
  - Represents the average response to a MIP
  - Quiescent errors ~30%
  - Particle impact error fraction jumps to 80%
  - Recovery