

7th INTERNATIONAL CONFERENCE ON PUBLIC KEY INFRASTRUCTURE AND ITS APPLICATIONS (PKIA 2026) SEPTEMBER 10-11th, 2026

**Q-FRAP: Quantum-Fidelity Residual Anomaly Prediction
for Healthy-Only Thermal Fault Detection in Lithium-Ion Battery Packs**

Sakthi Prabhu Gunasekar | Prasanna Kumar Rangarajan

Department of Computer Science and Engineering, Amrita School of Computing, Amrita Vishwa Vidyapeetham, Chennai, India

MOTIVATION: WHY EARLY THERMAL-FAULT DETECTION IS HARD

SAFETY-CRITICAL

1

EV packs must catch cooling, airflow, and sensor faults **BEFORE** protection thresholds trip.

EARLY DETECTION = MORE TIME TO ACT

Thermal runaway can propagate in minutes. Every minute of early warning gives the BMS more time to derate, isolate a module, or alert the driver — turning a potential fire into a repair-shop visit.

THRESHOLDS REACT LATE

2

A developing fault can stay below the hard temperature limit while thermal behaviour is already abnormal.

PHYSICS RESIDUALS = EARLIER SIGNAL

Absolute-temperature rules trigger only after damage is likely already done. Residuals between measured and physics-model temperatures reveal the same fault long before hard limits are crossed.

LOW FALSE ALARMS MATTER

3

A detector that cries wolf gets ignored — sensitivity must come with a very low false-alarm rate.

ZERO FA IN VALIDATION = OPERATOR TRUST

Every false alarm erodes operator trust and can trigger costly interventions. Q-FRAP is calibrated purely on healthy validation and reports 0/30 false alarms at its operating point.

CORE IDEA: THE SIGNAL IS THE RESIDUAL, NOT THE TEMPERATURE

RESIDUAL

$$r(t) = T \text{ measured}(t) - T \text{ model-estimated}(t)$$

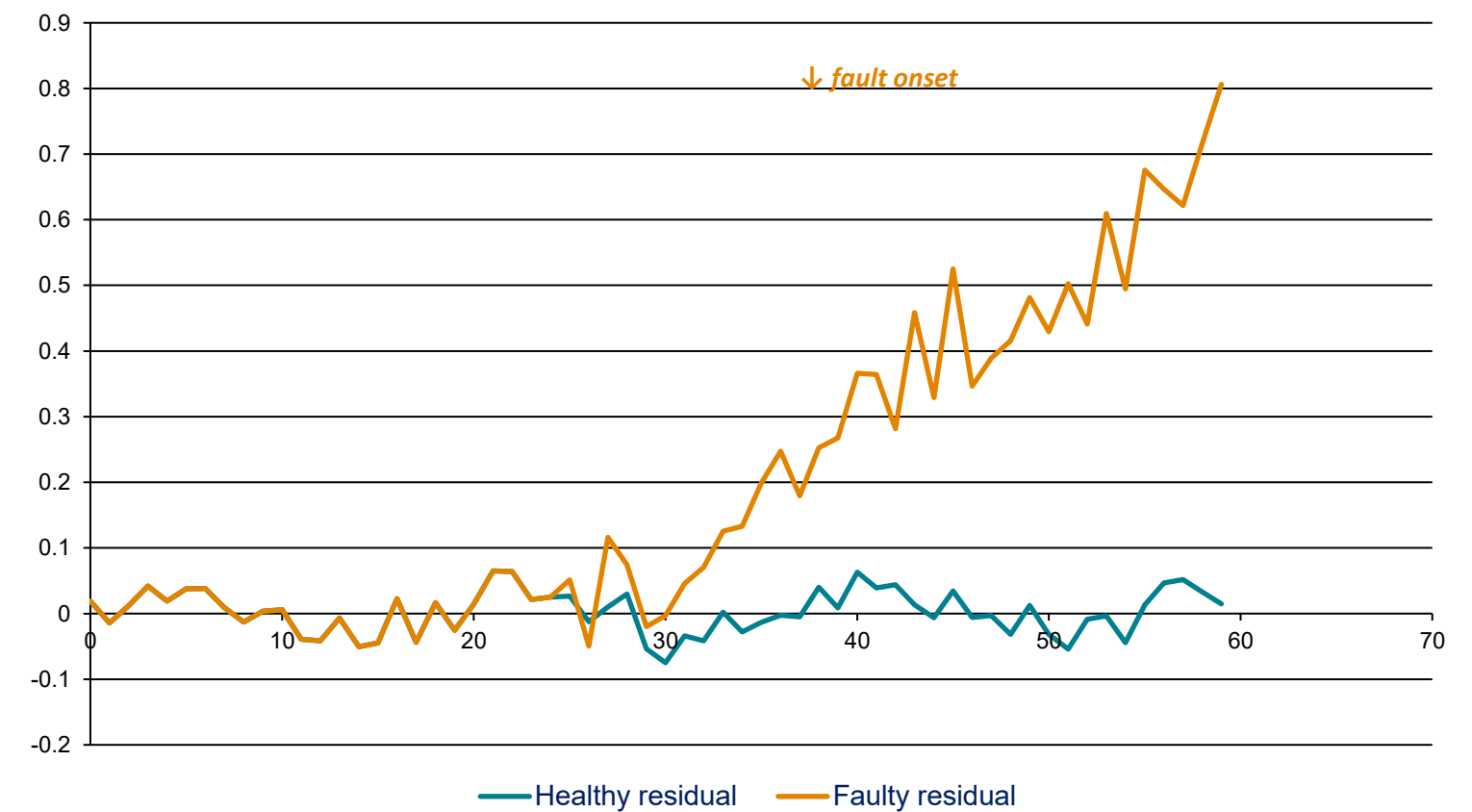
A physics/thermal model predicts each cell's expected temperature. Subtracting it from the actual measurement gives the residual for that cell.

- **Healthy operation** → residuals stay small and well-behaved.
- **Fault onset** → residuals grow, drift, or spread — often long before absolute temperature would ever alarm.

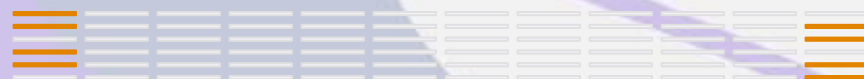
8 monitored cells: {1, 13, 24, 36, 37, 49, 60, 72} — spatial coverage across the pack.

Everything Q-FRAP does from here on operates on RESIDUALS, not raw temperatures.

Residual over time — illustrative



8 monitored cells across the 72-cell pack:



monitored (8 cells) — cells {1, 13, 24, 36, 37, 49, 60, 72}

WHERE Q-FRAP SITS AMONG RELATED WORK

Method	Quantum	Healthy-only	Residual / physics-structured	Multi-channel fidelity
One-Class SVM [6]	X	✓	X	X
Isolation Forest [7]	X	✓	X	X
LP+FNN residual detector [4]	X	✓	✓	X
QLSTM [2]	✓	X	X	X
Quantum autoencoder [3]	✓	✓	X	X
Q-FRAP (ours)	✓	✓	✓	✓

✓ / X indicate which mechanism each approach uses — not a quality score.

Q-FRAP is the only approach combining all four.

DATASET: PUBLIC 72-CELL AIR-COOLED BATTERY PACK

WHAT IT IS

- Public benchmark from Naguib et al. (2025), Borealis Dataverse — same group that built the LP+FNN detector we compare against.
- Real 72-cell air-cooled Li-ion pack on automotive drive cycles, healthy and with faults deliberately introduced.
- Per step: measured & model-estimated temperatures, current, voltage, SOC.
- 8 monitored cells (1, 13, 24, 36, 37, 49, 60, 72) — spatial coverage, lightweight.
- Healthy → training & thresholds; faults → test only. No fault labels in training.

Physical fault	Drive cycle	Signature
Fanoffon (long)	fan off → on	cooling loss + recovery
HWFET blocked	highway	module blockage
LA92 high-fan	aggressive urban	over-cooling
UDDS blocked	city stop-go	blocked airflow

Two axes: too little cooling (fan-off, blockage) vs too much (high-fan), across city vs highway dynamics.

SYNTHETIC SENSOR FAULTS (SCORED SEPARATELY)

freeze • +2°C offset • −5% scale
a corrupted sensor differs from a real thermal fault.

Q-FRAP: THREE PHYSICALLY-MOTIVATED FIDELITY CHANNELS

Q-FRAP IN ONE LINE

Residual features

Quantum state

Fidelity gap from healthy

Alarm (OR of 3)

PREDICTIVE

WATCHES FOR

Unexpected future residual evolution

TARGETS

Dynamic / fan-off faults

$$F(pred) = 1 - |\langle \psi_{healthy(pred)} | \psi_{obs(pred)} \rangle|^2$$

COLD-TRANSITION

WATCHES FOR

Over-cooling, negative residual drift

TARGETS

High-fan faults

$$F(cold) = 1 - |\langle \psi_{healthy(cold)} | \psi_{obs(cold)} \rangle|^2$$

TOPOLOGY-AWARE

WATCHES FOR

Spatial imbalance across the pack

TARGETS

Blockage faults

$$F(topo) = 1 - |\langle \psi_{healthy(topo)} | \psi_{obs(topo)} \rangle|^2$$

WHAT “QUANTUM FIDELITY” MEANS HERE

FIDELITY-GAP SCORE

$$a(t) = 1 - |\langle \psi_{\text{ref}} | \psi_{\text{obs}} \rangle|^2$$

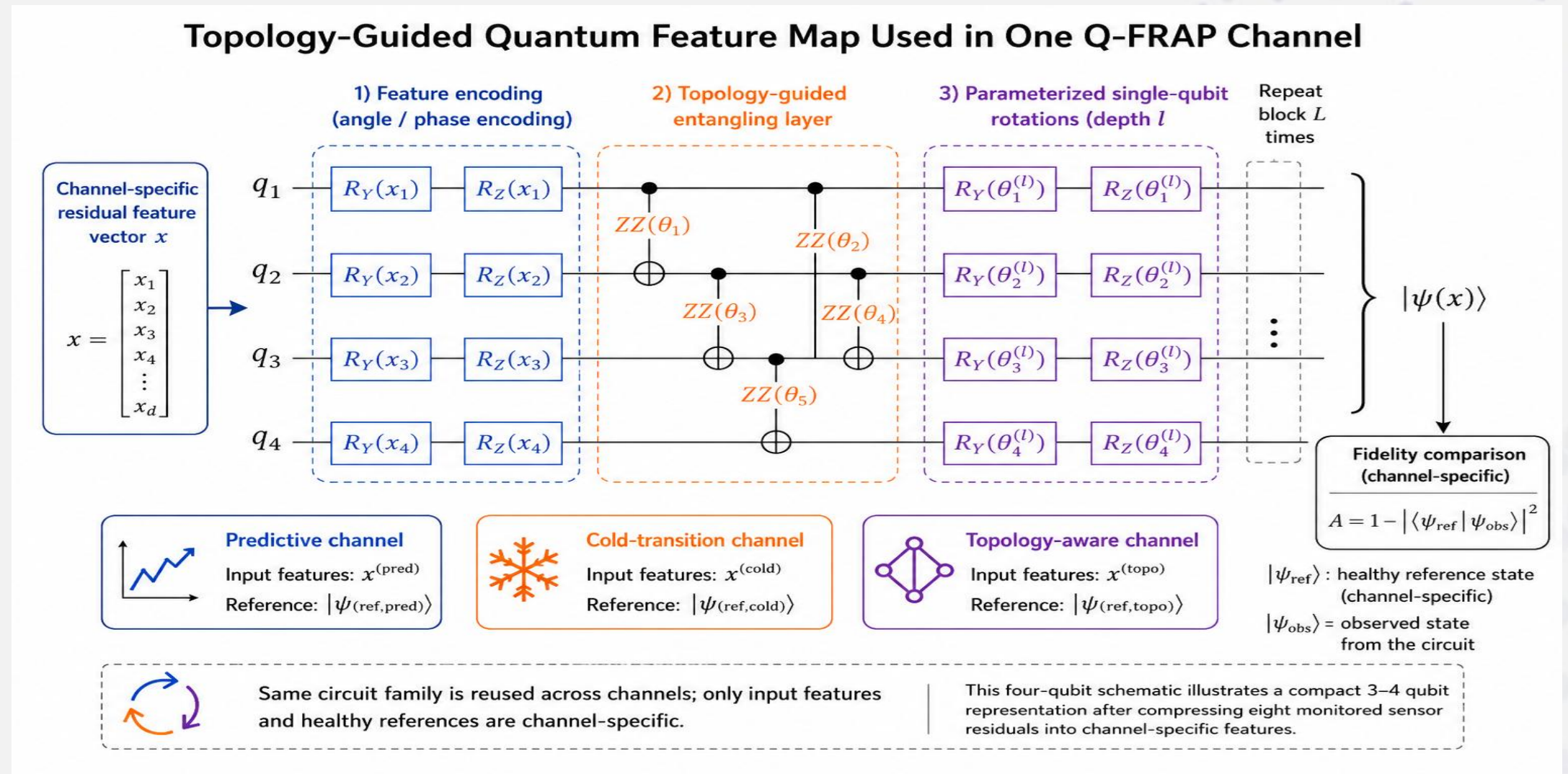
INTERPRETATION

- Identical states $\rightarrow$ overlap 1 $\rightarrow$ gap 0 (healthy).
- States pulled apart $\rightarrow$ overlap drops $\rightarrow$ gap grows (fault).
- Reference ρ^h is the density operator averaged over healthy training states — not a single one.

PRACTICAL POINTS

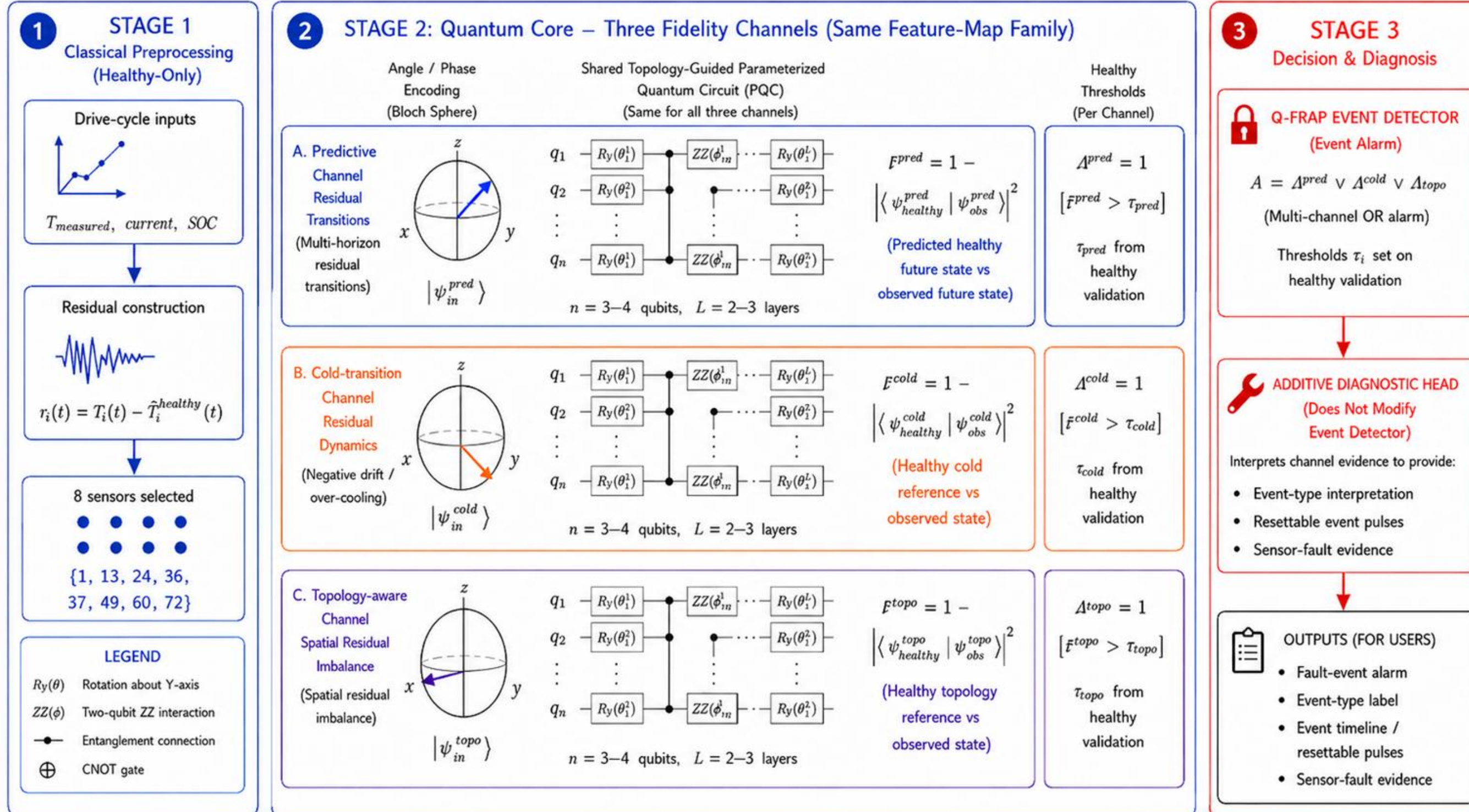
- Feature map is FIXED — no trained weights, score is deterministic in simulation.
- 3–4 qubits per channel; angle/phase encoding; topology-guided ZZ(θ); 2–3 layers.
- Exact statevector in simulation; finite shots only on the IBM hardware spot-check.

Large fidelity gap = “this no longer looks healthy.”



THE FULL Q-FRAP PIPELINE

Q-FRAP (Quantum-Fidelity Residual Anomaly Predictor) Pipeline



Q-FRAP ARCHITECTURE IN DETAIL

A. CHANNEL FEATURE CONSTRUCTION

- x^{pred} — multi-horizon future residual predictions at $h = 10, 30, 60, 120$ s.
- x^{cold} — negative-direction / cold-transition residual changes (over-cooling).
- x^{topo} — topology-aware spatial spread across the 8 monitored sensors.
- Auxiliary context (current, mean voltage, mean SOC) used ONLY for residual interpretation — never as fault labels.

B. FEATURE MAP + COMPRESSION

- 8 sensor residuals $\rightarrow q = 3-4$ qubits per channel via spatial-group averaging.
- Encoding: R_y and R_z angle + phase rotations at each qubit, per feature.
- Entangling: topology-guided $ZZ(\theta)$ between sensor-group qubits; $L = 2-3$ layers.
- Feature map is FIXED — no trained variational parameters, deterministic in simulation.

C. HEALTHY REFERENCE STATE ρ^h

- $\rho^h_c = (1 / N^h) \sum_k |\psi^h_{c,k}\rangle\langle\psi^h_{c,k}|$ — density operator averaged over N^h healthy training states.
- Robust to normal operational variability — NOT a single canonical healthy state.
- Cold-transition and topology channels use this mixed-state reference for fidelity comparison.
- Predictive channel: reference is the per-step predicted healthy future state.

D. DIAGNOSTIC HEAD & EVENT-PULSE

- Dominant channel near the first alarm $\rightarrow$ event type (dynamic / over-cooling / blockage).
- Additive — the diagnostic head does NOT modify the event alarm itself.
- Event-pulse view: resettable pulses distinguish new events from recovery-interval latching.
- Sensor-fault evidence is tracked separately from physical thermal-fault evidence.

Everything above is fixed at design time — no fault labels used anywhere in Q-FRAP.

MAIN RESULTS ON SHARED EVALUATION WINDOWS

0.924

AUC

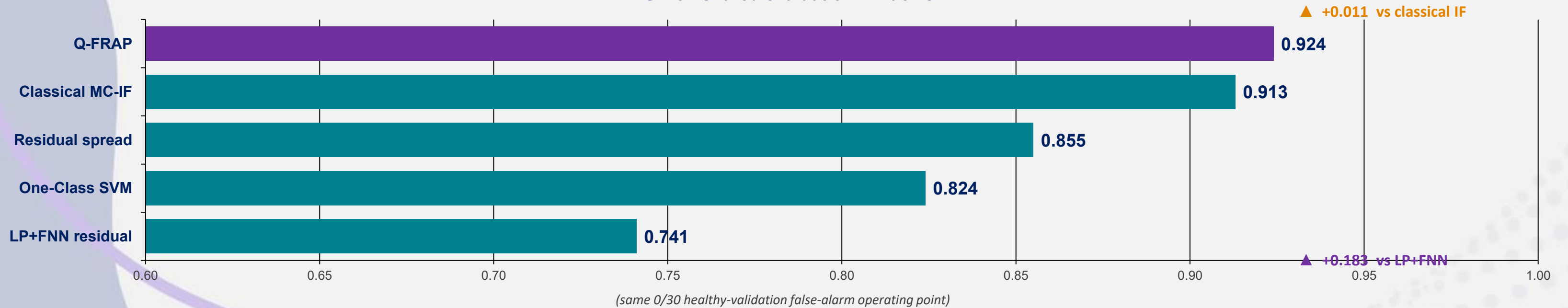
84.73%

FAULT DETECTION

0 / 30

HEALTHY FALSE ALARMS

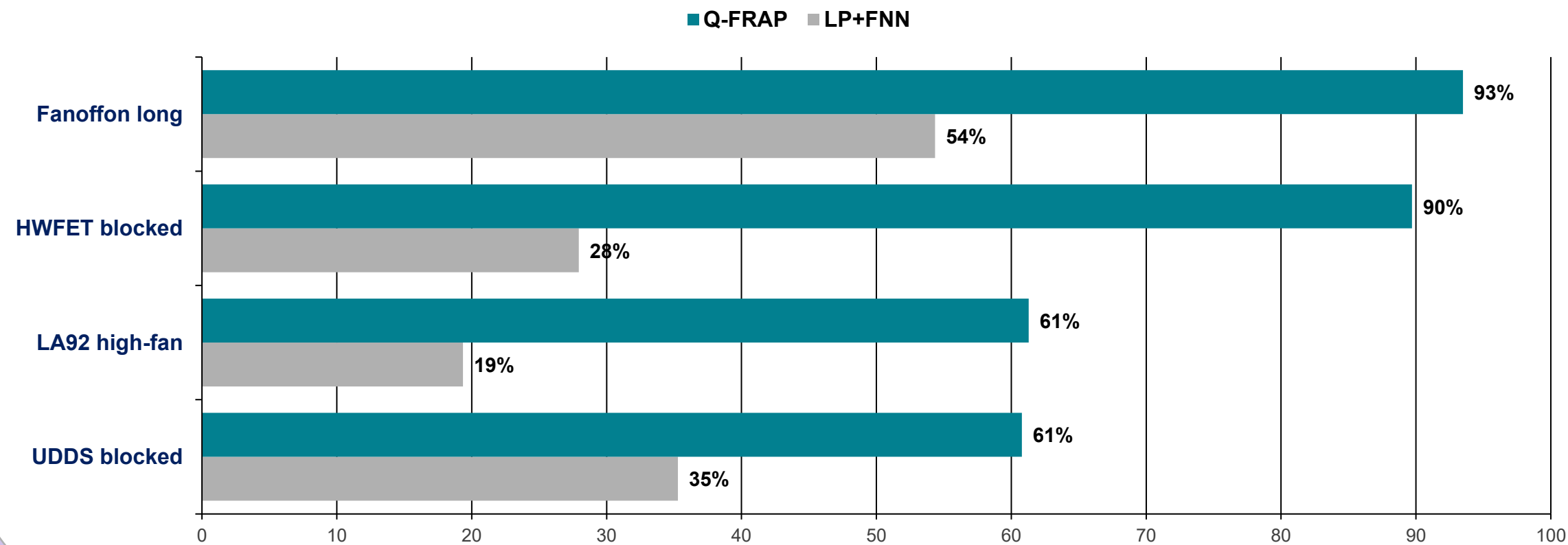
AUC on shared evaluation windows



PER-FAULT DETECTION AND EVENT TYPING

Fault-window detection rate (%)

Q-FRAP improves detection on EVERY physical fault vs the LP+FNN baseline.



DIAGNOSTIC EVENT TYPING

The channel that dominates near the first alarm labels the fault type — correct on all 5 physical events:

Fan-off	→ Dynamic / fan-off
High-fan	→ Over-cooling
HWFET blocked	→ Blockage / spatial
LA92 high-fan	→ Over-cooling
UDDS blocked	→ Blockage / spatial

Interpretable evidence — not a full diagnosis system (only 5 physical events available).

FEASIBILITY: TOPOLOGY-CHANNEL ON REAL IBM HARDWARE

THE EXPERIMENT

- IBM ibm_marrakesh QPU spot-check via the Qiskit Runtime Sampler primitive.
- 19 selected healthy-fault window pairs (10 healthy control, 9 fault).
- Direct 8-qubit topology encoding — one qubit per monitored sensor.
- 1024 shots per circuit; transpiled depth 69–96.
- Isolates the topology-channel fidelity primitive on real hardware — not the full multi-channel detector.

0.911

IDEAL CIRCUIT — AUC

$\Delta = -0.033$ (ordering kept)

0.878

IBM QPU — AUC

Ordering survives real noise — fault gaps stay above healthy gaps.

CONTRIBUTION

A reproducible, healthy-only, multi-channel quantum-fidelity architecture for battery-pack thermal fault-event detection.

THANK YOU



Dataset

QUESTIONS • CONTACT

Sakthi Prabhu Gunasekar
sakthiprabhu.g@gmail.com

Prasanna Kumar Rangarajan
r_prasannakumar@ch.amrita.edu

Amrita School of Computing, Amrita Vishwa Vidyapeetham, Chennai, India • Paper: IEEE PKIA 2026 Proceedings