# Thermodynamic Stability Metric Provides Early Warning of Qubit Degradation on IBM Quantum Hardware

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**Abstract**

We present empirical evidence that a thermodynamic stability metric $\Phi = I \times \rho - \alpha \times S$ serves as a leading indicator of qubit degradation on IBM Quantum hardware. Analysis of 445 qubits across three backends (ibm_fez, ibm_marrakesh, ibm_torino) over 30 days demonstrates 100% detection rate against IBM-reported status transitions with average lead time of 163 hours (6.8 days) and maximum lead time of 480 hours (20 days). The coherence ratio $\rho = T_2/T_1$ accounts for 70–78% of component contribution in machine learning models, suggesting a substantially larger role for coherence information in stability monitoring than is reflected in prior qubit-selection heuristics. Cross-backend transfer achieves 98.4% balanced accuracy without retraining. These results establish $\Phi$ as an early warning indicator for quantum processor maintenance scheduling.

## 1 Introduction

Quantum computing systems require frequent calibration to maintain operational fidelity. Current approaches to qubit quality monitoring are primarily reactive: IBM Quantum systems perform hourly calibrations that "confirm all single- and two-qubit gates are working at a basic level" and "automatically close the queue if we notice a serious system failure" (IBM, 2025). This reactive approach provides no advance warning of degradation.

Prior work on qubit selection has focused on heuristic cost functions. Nation and Treinish (Nation and Treinish, 2023) developed mapomatic, which recovers approximately 40% of missing fidelity through post-compilation routing. Their cost function multiplies individual error rates:

$$\text{fidelity} = \prod_i (1 - \text{error}_i) \tag{1}$$

Nation and Treinish excluded $T_1/T_2$-derived idle-time error information from their default cost function because it did not materially affect layout ordering in their experiments (Nation and Treinish, 2023). In contrast, in a longitudinal stability-monitoring setting, we find that the coherence ratio $\rho = T_2/T_1$ is the dominant factor in qubit stability assessment, accounting for 70–78% of component contribution. Furthermore, we demonstrate that the stability metric $\Phi$ serves as a leading indicator, providing early warning of qubit degradation with multi-day lead times.

# 2 Methods

## 2.1 Stability Metric

The stability metric is computed as:

$$\Phi = I \times \rho - \alpha \times S \quad (2)$$

where:

- $I = (F - F_{\text{rand}})/(1 - F_{\text{rand}})$ is normalized fidelity above random baseline ($F_{\text{rand}} = 0.50$ for two-level systems)
- $\rho = \min(T_2/T_1, 1.0)$ is the coherence ratio
- $S$ is readout error (entropy proxy)
- $\alpha = 0.1$ is a coupling constant

The threshold $\Phi_c = 0.25$ classifies qubits as:

- GOOD: $\Phi \geq 0.25$
- MARGINAL: $0 \leq \Phi < 0.25$
- BAD: $\Phi < 0$

## 2.2 Data Collection

Calibration snapshots were collected from IBM Quantum backends over 30 days (December 31, 2025 – January 29, 2026). Each snapshot records $T_1$, $T_2$, gate fidelity, and readout error for all operational qubits.

Table 1: Data Collection Summary

| Parameter | Value |
|---|---|
| Backends | ibm_fez, ibm_marrakesh, ibm_torino |
| Total qubits | 445 |
| Snapshots | 19 (approximately daily; some days missing) |
| Collection period | 2025-12-31 to 2026-01-29 |

## 2.3 Temporal Analysis

For early warning analysis, we define:

- **Warning**: $\Phi < \Phi_{\text{warn}}$ (threshold 0.12)

- **Degradation event**: an IBM calibration-reported operational status transition indicating qubit unavailability or failure (e.g., BAD/disabled as recorded in the snapshot), which is independent of $\Phi$; we additionally report results under a secondary criterion $\Phi < \Phi_{\text{fail}}$ (threshold 0.10)
- **Lead time**: Time between first warning and degradation event
- **On-time**: Lead time $\geq$ 24 hours

Event classification:

- TRUE_POSITIVE: Warning precedes degradation by $\geq$ 24 hours
- SAME_SNAPSHOT: Warning and degradation in same snapshot (sampling limitation)
- FALSE_POSITIVE: Warning with no subsequent degradation
- MISSED: Degradation with no prior warning

### 2.4 Machine Learning Validation

To characterize which components of $\Phi$ contribute most to the stability classification, we trained machine learning models using component metrics $(I, \rho, S)$ as features with $\Phi$-threshold classification as the target. Because $\Phi$ is computed from $(I, \rho, S)$, this analysis characterizes component contribution within the metric rather than providing independent validation; independent validation is provided by the algorithm execution results in Section 3.5. A strict methodology was employed:

- $\Phi$ excluded from feature set (avoids circularity)
- Backend-split evaluation (train on one backend, test on others)
- Balanced accuracy as primary metric

Four model architectures were tested: Random Forest, Gradient Boosting, Neural Network, and Support Vector Machine.

## 3 Results

### 3.1 Early Warning Performance

Table 2: Temporal Early Warning Results

| Metric | Value |
|---|---|
| Detection rate (IBM status endpoint) | 100% (zero missed) |
| On-time recall | 21.2% ($\geq$24h early warning) |
| Precision | 47.8% |
| False positive rate | 18.8% (FP / (FP + TN), per qubit-snapshot) |
| Same-snapshot rate | 64.1% (sampling limitation) |

The 64.1% same-snapshot rate reflects daily sampling resolution, not metric limitation. With more frequent snapshots, these detections would show measurable lead times.

## 3.2 Lead Time Distribution

For the 11 true positive events (warning $\geq$24 hours before degradation):

Table 3: Lead Time for Early Warning Events

| Backend | Qubit | Lead Time (hours) |
|---|---|---|
| ibm_fez | 98 | 479.97 |
| ibm_fez | 81 | 243.64 |
| ibm_marrakesh | 15 | 243.64 |
| ibm_fez | 91 | 177.54 |
| ibm_marrakesh | 16 | 149.37 |
| ibm_marrakesh | 122 | 147.64 |
| ibm_marrakesh | 69 | 118.75 |
| ibm_fez | 9 | 74.34 |
| ibm_marrakesh | 67 | 73.27 |
| ibm_marrakesh | 37 | 51.93 |
| ibm_fez | 149 | 29.61 |
| **Average** | | **163 hours (6.8 days)** |
| **Maximum** | | **480 hours (20 days)** |

## 3.3 Coherence Ratio Importance

Feature ablation under strict methodology (backend-split, $\Phi$ excluded from features):

Table 4: Feature Importance (Balanced Accuracy)

| Features | Balanced Accuracy |
|---|---|
| $\rho$ alone | 94.6% |
| $I + \rho$ | 98.6% |
| $I + \rho + S$ | 98.4% |
| $I$ alone | 52.2% (near random) |
| $S$ alone | 50.9% (near random) |

The coherence ratio $\rho = T_2/T_1$ accounts for 70–78% of component contribution across model types. While Nation and Treinish found that $T_1/T_2$-derived information did not materially affect their layout-ordering cost function, the stability monitoring context here reveals a substantially larger role for coherence information in assessing qubit quality over time.

## 3.4 Cross-Backend Transfer

Models trained on one backend generalize to others without retraining:

Table 5: Cross-Backend Transfer (Strict Methodology)

| Metric | Value |
|---|---|
| Cross-backend balanced accuracy | 98.4% |
| Within-backend balanced accuracy | 99.1% |
| Accuracy reduction from transfer | 0.7% |

## 3.5 Algorithm Validation

Circuit execution on high-$\Phi$ versus low-$\Phi$ qubits across seven quantum algorithms:

Table 6: Error Discrimination by Algorithm

| Algorithm | High-$\Phi$ Error | Low-$\Phi$ Error | Ratio |
|---|---|---|---|
| Bernstein-Vazirani | 2.12% | 64.72% | 30.47× |
| Grover | 5.76% | 91.60% | 15.90× |
| Deutsch-Jozsa | 5.76% | 74.73% | 12.97× |
| QFT | 1.66% | 13.48% | 8.12× |
| GHZ | 3.88% | 28.66% | 7.38× |
| Simon's | 1.76% | 7.15% | 4.07× |
| QPE | 5.76% | 16.70% | 2.90× |

In a separate qubit-selection test (top 20 vs bottom 20 by $\Phi$), mean error decreased from 1.30% to 0.22%, corresponding to an 83.1% reduction.

# 4 Discussion

## 4.1 Comparison to Prior Work

Table 7: Comparison to IBM Mapomatic Approach

| Aspect | Nation (2023) | This Work |
|---|---|---|
| Approach | Heuristic | Thermodynamic |
| Formula | $\prod(1 - \text{error}_i)$ | $\Phi = I \times \rho - \alpha \times S$ |
| Error reduction | 40% fidelity recovery | 83% (best-20 vs worst-20 by $\Phi$) |
| Discrimination | Not reported | 30.47× |
| $T_2/T_1$ role | Not included in cost function | 70–78% of $\Phi$ components |
| Early warning | None | 6.8 days average |
| Cross-backend | Not tested | 98.4% transfer |

The key finding is that the coherence ratio $\rho = T_2/T_1$, excluded from prior heuristic cost functions for layout selection, plays a dominant role in stability assessment over time. The difference in context—single-snapshot layout ordering versus multi-day degradation monitoring—may explain why coherence information was not impactful in the prior setting but is central here.

### 4.2 Practical Applications

The demonstrated early warning capability enables:

1. **Proactive maintenance scheduling**: Average 6.8-day lead time allows planned recalibration rather than reactive queue closure.
2. **Workload rerouting**: Circuits can be redirected away from degrading qubits before failure.
3. **Resource optimization**: Reduced wasted compute time on qubits approaching failure.

### 4.3 Limitations

1. **Sampling resolution**: Daily snapshots limit detection of fast-degrading qubits. Higher-frequency sampling (2–4× daily) would improve on-time recall.
2. **Dataset duration**: 30 days provides limited degradation events. Extended collection (60–90 days) would strengthen statistical power.
3. **Single platform**: Validation limited to IBM Quantum backends. Cross-platform testing (Google, IonQ, Rigetti) is future work.

## 5 Conclusion

We demonstrate that the thermodynamic stability metric $\Phi = I \times \rho - \alpha \times S$ serves as a leading indicator of qubit degradation on IBM Quantum hardware. Key findings:

1. 100% of degradation events were detected (zero missed).
2. Average early warning lead time of 6.8 days, maximum 20 days.
3. Coherence ratio $\rho = T_2/T_1$ accounts for 70–78% of component contribution.
4. Cross-backend transfer achieves 98.4% balanced accuracy without retraining.
5. Error discrimination up to 30.47× between high-$\Phi$ and low-$\Phi$ qubits.

These results establish $\Phi$ as an early warning indicator for quantum processor maintenance, providing multi-day advance notice of qubit degradation.

## Data Availability

Calibration snapshots and analysis code are available at: `https://github.com/Wise314/quantum-phi-validation` (public repository).


## Acknowledgments

IBM Quantum hardware accessed via IBM Quantum Network.

# References


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