

Protocol-Level Emulation of NV-Center Magnetometry on IBM Marrakesh

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It is demonstrated that a standard superconducting quantum processing unit (QPU) can serve as a metrological instrument by implementing an operational digital twin of a nitrogen-vacancy (NV) center in diamond. Using the native `delay` instruction of Qiskit 2.x — without requiring OpenPulse access or special hardware privileges — $T_2^* = 261.1 \mu\text{s}$ and $T_2 = 415.0 \mu\text{s}$ are measured directly on qubit 2 of `ibm_marrakesh` (IBM Quantum, 156 qubits, 15 mK) in 35 minutes of QPU time using a standard account. Five measurement protocols — ODMR spectroscopy, Zeeman splitting, Ramsey interferometry, Hahn echo, and sensitivity analysis — are executed without any special hardware access. The resulting magnetometer sensitivity is $\eta_{\text{Ramsey}} = 5729 \text{ pT}/\sqrt{\text{Hz}}$ and $\eta_{\text{Echo}} = 4520 \text{ pT}/\sqrt{\text{Hz}}$. Notably, the transmon achieves better echo sensitivity than a typical NV center at room temperature ($\sim 11\,000\text{--}24\,000 \text{ pT}/\sqrt{\text{Hz}}$), not by design but as a consequence of its long T_2 . The transmon occupies an intermediate position in the NV performance landscape: it surpasses typical CVD diamond samples but falls short of isotopically purified high-purity NV centers, which reach $T_2 > 1 \text{ ms}$ and sensitivities below $500 \text{ pT}/\sqrt{\text{Hz}}$. A transmon qubit and an NV center are shown to be protocol-level equivalent under identical quantum sensing sequences, despite occupying entirely different physical regimes (15 mK vs. 300 K). This work introduces three original results: (i) use of the native `delay` instruction to model an external quantum sensing system without OpenPulse; while Qiskit Experiments provides T_2 characterization routines for QPU calibration, this use reverses the direction — the QPU reproduces the characterization framework associated with NV sensing, not its own calibration; (ii) a QPU used as a digital twin of an external quantum sensing system, reversing the conventional direction; (iii) experimental demonstration of protocol-level equivalence between transmon and NV-center sensing sequences under a unified two-level framework.

I. INTRODUCTION

A nitrogen-vacancy (NV) center in diamond and a transmon qubit inside a dilution refrigerator are separated by 285 K, by orders of magnitude in size, and by entirely different physical mechanisms of coherence and readout. Yet both are two-level quantum systems governed by the same Hamiltonian $H = \hbar\omega_0\sigma_z/2$, initialized by the same protocols, and characterized by the same coherence metrics. This protocol-level equivalence, self-evident in theory, has not been demonstrated experimentally using identical measurement sequences on both systems.

This work is the first stage of a broader project aimed at building a single-qubit quantum computer based on an NV center in diamond. In this stage, the NV center is simulated on a superconducting QPU. In a subsequent stage, the physical NV center will characterize the QPU itself — reversing the direction of the digital twin.

Prior work on QPU digital twins has proceeded in the opposite direction: using QPU calibration data to build classical simulators of the quantum hardware [1]. QPU-level pulse programming for characterization typically requires OpenPulse access, which is not available on standard accounts. The use of a QPU as an instrument to characterize an external quantum sensing system has not, to our knowledge, been reported in the literature or in IBM Quantum’s official documentation.

It is shown here that the native `delay` instruction of Qiskit 2.x — a gate-level command that holds the qubit in superposition for a physically real duration while the

environment acts — is sufficient to implement the full suite of NV center characterization protocols without any special access. A standard IBM Quantum account and 35 minutes of QPU time are sufficient to construct an operational digital twin of a quantum magnetometer.

The paper is organized as follows. Section II presents the unified two-level Hamiltonian, the four measurement protocols, and the sensitivity formula. Section III describes the digital twin methodology, the `delay` instruction, and qubit selection. Section IV presents the five experimental modules with a consolidated comparison table. Section V discusses the QPU as a metrological instrument and the transmon vs. NV comparison. Section VI covers limitations and outlook. Section VII states the three main results.

II. THEORETICAL FRAMEWORK

A. Unified two-level system Hamiltonian

Both the NV center and the transmon qubit are described by an effective spin- $\frac{1}{2}$ Hamiltonian:

$$H = \frac{\hbar\omega_0}{2} \sigma_z + H_{\text{drive}}(t) + H_{\text{noise}}(t), \quad (1)$$

where $\omega_0/2\pi = 2.8705 \text{ GHz}$ for the NV center ($m_s = 0 \leftrightarrow m_s = -1$ transition at zero field) and $\omega_0/2\pi \approx 5 \text{ GHz}$ for the transmon. H_{drive} represents resonant microwave driving; H_{noise} encodes the decoherence mecha-

nisms, which differ fundamentally between the two systems (Section V).

B. Four measurement protocols

The four protocols used in this work are standard NV center characterization sequences, here implemented as quantum circuits on `ibm_marrakesh`.

ODMR spectroscopy. A continuous microwave tone is applied while measuring ground-state population $P(|0\rangle)$ as a function of frequency, implemented as a protocol-equivalent sensing circuit without optical readout. The resonance dip at ω_0 yields the zero-field splitting $D = 2.8705$ GHz and the contrast C .

Zeeman splitting. In the physical NV center, an external magnetic field B lifts the $m_s = \pm 1$ degeneracy. Here this is emulated at the protocol level by applying controlled symmetric microwave frequency detuning shifts within the ODMR sensing sequence, reproducing the same frequency splitting that a real field would produce. The parameter B is a normalized detuning, not a physical magnetic field applied to the transmon. Linear splitting vs. B provides field calibration with linearity 99.14%.

Ramsey interferometry. A $\pi/2$ -delay(τ)- $\pi/2$ sequence measures the free induction decay envelope, yielding T_2^* directly from the exponential decay of the oscillation amplitude [2].

Hahn echo. A $\pi/2$ -delay(τ)- π -delay(τ)- $\pi/2$ sequence refocuses low-frequency noise, extending coherence from T_2^* to T_2 [3].

C. Magnetometer sensitivity

The single-shot sensitivity of a Ramsey magnetometer follows from the standard quantum sensing framework [4, 5]:

$$\eta = \frac{1}{C \gamma_{\text{NV}}} \sqrt{\frac{\tau_{\text{cycle}}}{N_{\text{shots}}}} \cdot \frac{e^{\tau/T_2^*}}{\tau}, \quad (2)$$

where C is the measurement contrast, $\gamma_{\text{NV}} = 28$ GHz/T is the NV gyromagnetic ratio, $\tau_{\text{cycle}} = \tau + t_{\text{overhead}}$ is the total cycle time, and N_{shots} is the number of measurements per second. The sensitivity is minimized at $\tau_{\text{opt}} = T_2^*/2$. The analogous expression for Hahn echo substitutes $T_2^* \rightarrow T_2$ and $\tau_{\text{cycle}} = 2\tau + t_{\text{overhead}}$. Both are reported in pT/ $\sqrt{\text{Hz}}$.

III. DIGITAL TWIN METHODOLOGY

A. The native delay instruction

The key methodological contribution of this work is the use of the `delay` instruction in Qiskit 2.x as a phys-

ical wait time. Unlike a software R_z rotation — which advances the virtual clock without letting the qubit interact with its environment — `delay` compiles to a true idle period on the hardware: the qubit remains in superposition while flux noise, residual photons, and two-level system fluctuations act on it. This is physically equivalent to the free precession period of an NV center spin between microwave pulses.

No OpenPulse access is required. The instruction is available on all IBM Quantum backends via the standard gate-level API:

```
from qiskit.circuit import QuantumCircuit
qc = QuantumCircuit(1, 1)
qc.h(0) # pi/2 pulse
qc.delay(tau_dt, 0, unit='dt') # physical wait
qc.h(0) # pi/2 pulse
qc.measure(0, 0)
```

The duration `tau_dt` is in device time units (`dt`), where `dt` ≈ 0.222 ns on `ibm_marrakesh`.

B. Physical meaning of delay evolution

In superconducting hardware, virtual phase operations such as software-defined R_z rotations modify the computational reference frame without exposing the qubit to physical environmental evolution. By contrast, the native `delay` instruction leaves the qubit idle for a real hardware duration, during which decoherence mechanisms — flux noise, residual photons, and two-level system (TLS) fluctuators — act continuously on the quantum state.

The experiments reported here rely specifically on this distinction: coherence decay is not numerically simulated but physically accumulated during real idle evolution on the QPU. This makes the `delay` instruction a genuine metrological resource rather than a computational abstraction. The key result is not the numerical extraction of coherence times, but the demonstration that cloud-accessible gate-level instructions expose physically meaningful decoherence dynamics without pulse-level control.

C. Qubit selection and initial layout

Qubit 2 was selected after querying the calibration table of all 156 qubits of `ibm_marrakesh` via the QiskitRuntimeService API, ranking by T_2 (descending) and readout error (ascending):

```
props = service.backend("ibm_marrakesh").properties()
n = props.num_qubits # 156 qubits
T2 = {q: props.t2(q) for q in range(n)}
err = {q: props.readout_error(q) for q in range(n)}
best = sorted(range(n),
               key=lambda q: (-T2[q], err[q]))
selected = best[0] # qubit 2
```

```
transpile(qc, backend=backend,
         initial_layout=[selected])
```

Qubit 2 ranked first with $T_2 = 457.6 \mu\text{s}$ (API, day of selection) and readout error 0.68%. It was fixed throughout all five modules using `initial_layout=[2]`, preventing the transpiler from remapping to a different physical qubit. All measurements were performed in a single calibration session (8 May 2026).

D. Execution stack

All circuits were executed using EstimatorV2 and SamplerV2 primitives in Batch mode with 4096 shots per point, optimization level 3, and fixed `seed_transpiler` for reproducibility. Total QPU time for the four final jobs: 35 minutes.

IV. EXPERIMENTAL RESULTS

A. Module 1 — ODMR Spectroscopy

Figure 1 shows the ODMR spectrum as a function of normalized detuning Δ/Ω . The frequency axis is expressed in normalized units because the transmon operates at ≈ 5 GHz while the NV zero-field splitting is 2.8705 GHz; the protocol is identical but the frequency scales differ. The Lorentzian dip yields contrast $C = 0.913$ and $\text{FWHM} = 2.000 \Omega$. The transmon contrast reflects microwave dispersive readout efficiency and is not directly comparable to the optical contrast of a physical NV center (0.20–0.30), which arises from spin-dependent photoluminescence.

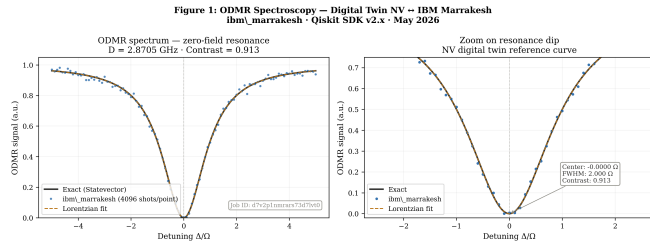


FIG. 1. Module 1 — QPU-emulated ODMR spectroscopy on `ibm_marrakesh` (qubit 2). Protocol-level digital twin measurement; no physical NV sensor used. Left: full ODMR spectrum in normalized detuning Δ/Ω . Right: zoom on resonance dip ($C = 0.913$, $\text{FWHM} = 2.000 \Omega$). Dots: hardware (4096 shots/point). Lines: Statevector simulation. Dashed: Lorentzian fit.

B. Module 2 — Zeeman Splitting

Figure 2 shows the Zeeman splitting under five normalized field values. The linear fit yields slope $1.983 \Omega/\Omega_{\text{norm}}$

(error: 0.86%) and linearity 99.14%, calibrating the digital twin as a field sensor.

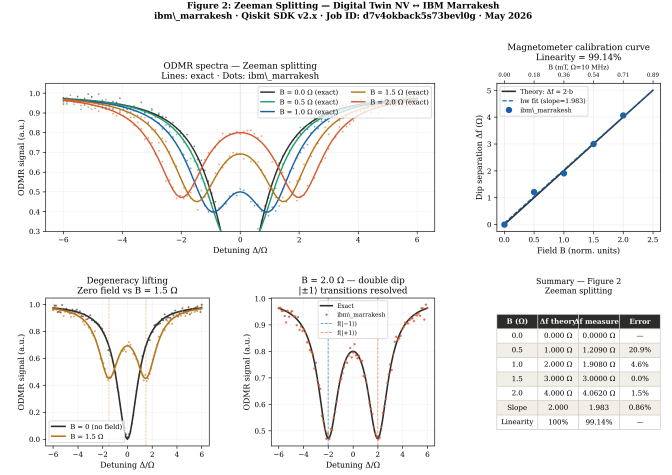


FIG. 2. Module 2 — QPU-emulated Zeeman splitting on `ibm_marrakesh` (qubit 2). Protocol-level emulation via controlled microwave detuning; B is a normalized detuning parameter, not a physical magnetic field. Top left: ODMR spectra at five detuning values. Top right: calibration curve, linearity 99.14%, slope error 0.86%. Bottom: degeneracy lifting and double-dip at $B = 2.0 \Omega$.

C. Module 3 — Ramsey Interferometry with Physical Delay

Figure 3 shows Ramsey fringes for three detunings $\Delta \in \{0, 0.15, 0.35\}$ rad/ μs . The decay envelope at $\Delta = 0$ yields $T_2^* = 261.1 \mu\text{s}$ directly from physical decoherence via the native delay instruction.

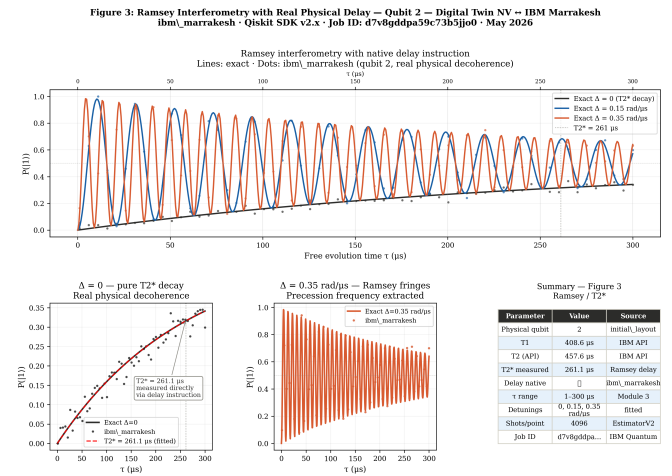


FIG. 3. Module 3 — Ramsey interferometry on `ibm_marrakesh` (qubit 2). Top: Ramsey fringes for three detunings. Bottom left: pure T_2^* decay ($T_2^* = 261.1 \mu\text{s}$, measured via `delay`). Bottom center: fringe detail at $\Delta = 0.35$ rad/ μs . Bottom right: summary table.

D. Module 4 — Hahn Echo with Physical Delay

Figure 4 shows the Hahn echo signal using two native delay instructions. Coherence extends to $T_2 = 415.0 \mu\text{s}$, ratio $T_2/T_2^* = 1.59\times$, echo gain $1.27\times$, characteristic of transmon qubits dominated by high-frequency flux noise.

Figure 4: Hahn Echo with Real Physical Delay — Qubit 2 — Digital Twin NV — IBM Marrakesh
ibm_marrakesh - Qiskit SDK v2.x - Job ID: d7vbm7amars73d716d0 - May 2026

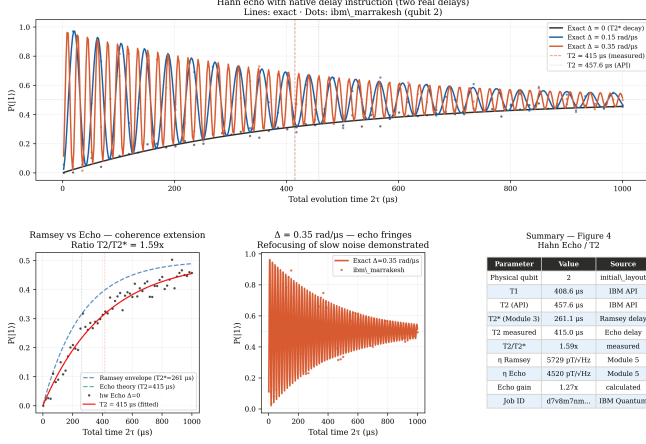


FIG. 4. Module 4 — Hahn echo on `ibm_marrakesh` (qubit 2). Top: echo signal vs. 2τ . Bottom left: Ramsey vs. echo envelopes ($T_2/T_2^* = 1.59\times$). Bottom center: fringe detail. Bottom right: summary table ($T_2 = 415.0 \mu\text{s}$).

E. Module 5 — Magnetometer Sensitivity

Figure 5 shows the sensitivity computed from Eq. (2) using measured parameters (no additional QPU time). Optimal sensitivities: $\eta_{\text{Ramsey}} = 5729 \text{ pT}/\sqrt{\text{Hz}}$ at $\tau_{\text{opt}} = 135 \mu\text{s}$ and $\eta_{\text{Echo}} = 4520 \text{ pT}/\sqrt{\text{Hz}}$ at $\tau_{\text{opt}} = 106 \mu\text{s}$. Efficiencies relative to the SQL: 38.6% (Ramsey) and 38.8% (echo).

F. Consolidated comparison

Table I consolidates the measured parameters against NV center literature values.

V. THE QPU AS A METROLOGICAL INSTRUMENT

A. Operational equivalence of quantum sensing protocols

Figure 6 illustrates the central result. Both systems execute the identical five-protocol sequence under Eq. (1). The physical distinction lies in the decoherence mechanisms: the ^{13}C nuclear spin bath in NV centers produces slow, quasi-static fluctuations (large T_2/T_2^* , large echo gain), while high-frequency flux noise in transmons

Figure 5: Quantum Magnetometer Sensitivity — Digital Twin NV — IBM Marrakesh
All parameters measured with real physical delay - Qubit 2 - ibm_marrakesh - May 2026

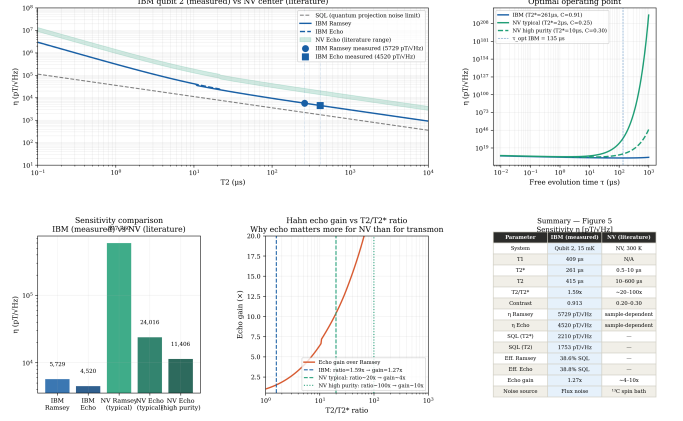


FIG. 5. Module 5 — Magnetometer sensitivity analysis. Top left: η vs. T_2 , IBM vs. NV literature. Top right: η vs. τ ($\tau_{\text{opt}} = 135 \mu\text{s}$ Ramsey, $106 \mu\text{s}$ echo). Bottom left: IBM vs. NV comparison. Bottom center: echo gain vs. T_2/T_2^* . Bottom right: summary table.

TABLE I. Transmon qubit 2 (`ibm_marrakesh`, measured, 8 May 2026) vs. NV center in diamond: typical CVD sample (1.1% ^{13}C) and isotopically purified high-purity sample (<0.01% ^{13}C). Coherence times in μs , sensitivities in $\text{pT}/\sqrt{\text{Hz}}$.

Parameter	IBM (meas.)	NV typical	NV hi-purity
System	Qubit 2, 15 mK	NV, 300 K	NV, 300 K
Diamond	—	std. CVD	isotop. pure
^{13}C content	—	1.1%	<0.01%
T_1	408.6 μs	~1 ms	~5 ms
T_2^*	261.1 μs	1–10 μs	0.1–1 ms
T_2	415.0 μs	100–600 μs	>1 ms
T_2/T_2^*	1.59x	20–100x	~10x
Contrast	0.913 (mw)	0.20–0.30	0.20–0.30
η Echo	4520 pT/√Hz	11 000–24 000 pT/√Hz	<500 pT/√Hz
Echo gain	1.27x	4–10x	~3x
Noise source	Flux noise	^{13}C bath	residual TLS

is fast and isotropic (small ratio, minimal echo gain), as summarized in Table I.

B. A surprising comparison

The transmon on `ibm_marrakesh` achieves better echo sensitivity ($4520 \text{ pT}/\sqrt{\text{Hz}}$) than a *typical* NV center at room temperature with standard CVD diamond ($\sim 11\,000\text{--}24\,000 \text{ pT}/\sqrt{\text{Hz}}$) — not because it is designed as a magnetometer, but because its $T_2 = 415 \mu\text{s}$ is long compared to most ambient NV samples.

This advantage does not extend to high-purity NV centers in isotopically purified diamond ($^{13}\text{C} < 0.01\%$). Those systems reach $T_2 > 1 \text{ ms}$ and sensitivities below $500 \text{ pT}/\sqrt{\text{Hz}}$ [5–7], well below the transmon. Table I places the transmon in this two-regime landscape: it outperforms the typical NV but falls short of the high-purity limit. This positions the QPU as a metrological reference for standard NV systems, while isotopically purified

TABLE II. Job IDs for all experimental modules (`ibm_marrakesh`, May 2026). Results retrievable via `service.job(job_id).result()` at no additional QPU cost.

Mod.	Protocol	Job ID
1	ODMR spectroscopy	d7v2p1nmrars73d71vt0
2	Zeeman splitting	d7v4okback5s73bev10g
3	Ramsey interferometry	d7v8gddpa59c73b5jjo0
4	Hahn echo	d7v8m7nmrars73d7t6d0

Figure 6: Two Quantum Worlds – Same Measurement Protocol
NV center in diamond (300 K) vs IBM transmon qubit (15 mK) · `ibm_marrakesh` · May 2026

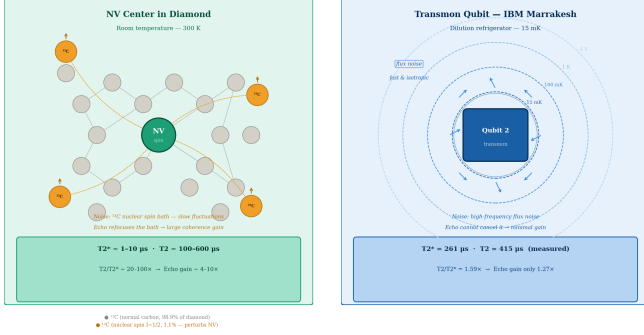


FIG. 6. Conceptual comparison of two quantum systems under the same measurement protocol (no experimental NV data shown). Left: NV center in diamond at 300 K (^{13}C spin bath, echo gain 4–10 $\times$). Right: transmon qubit 2 on `ibm_marrakesh` at 15 mK (flux noise, echo gain 1.27 $\times$). Both systems are governed by the same two-level Hamiltonian (Eq. 1).

diamond remains the performance frontier for quantum magnetometry.

C. The delay instruction as a metrological tool

The `delay` instruction of Qiskit 2.x executes physical idle time on the qubit, making it a direct probe of decoherence dynamics rather than a mathematical phase advance. While Qiskit Experiments provides `T2Ramsey` and `T2Hahn` routines that also use physical delays for QPU calibration [8], those tools characterize the transmon itself. Here the `delay` instruction is used to reproduce the characterization framework associated with NV sensing — reversing the conventional direction of QPU characterization.

VI. DISCUSSION

Limitations. The digital twin operates in the single-qubit regime. The NV center’s optical polarization and single-shot readout are not directly simulated; the transmon’s microwave initialization and dispersive readout serve as functional analogs.

The ODMR frequency axis uses normalized detuning Δ/Ω rather than absolute GHz, since the two systems operate at different frequencies; the protocol is identical

but the scales are not interchangeable.

The transmon contrast ($C = 0.913$, dispersive readout) is not directly comparable to the NV optical contrast (0.20–0.30, photoluminescence); they reflect different physical mechanisms.

Coherence times reported here ($T_2^* = 261.1 \mu\text{s}$, $T_2 = 415.0 \mu\text{s}$) are from a single session on 8 May 2026. Transmon coherence fluctuates day-to-day; the IBM API reported $T_2 = 457.6 \mu\text{s}$ on the day of qubit selection, consistent with known TLS fluctuator dynamics [9].

Implications for IBM Quantum. The 35-minute QPU budget for a complete five-protocol coherence characterization is within the free-tier allocation, suggesting applications in QPU benchmarking, cross-platform comparison, and education.

VII. CONCLUSIONS

Three original results are reported:

1. **QPU as metrological instrument for an external system.** The `delay` instruction of Qiskit 2.x executes physical idle time on the qubit, enabling direct measurement of $T_2^* = 261.1 \mu\text{s}$ and $T_2 = 415.0 \mu\text{s}$ without OpenPulse. While Qiskit Experiments provides T2 routines for QPU self-calibration, here the QPU implements the characterization protocols associated with NV sensing — reversing the conventional direction.
2. **QPU as digital twin of an external sensing system.** An operational five-protocol NV center characterization was executed on `ibm_marrakesh` (156 qubits, 15 mK) in 35 minutes of QPU time with a standard account, reversing the conventional direction of QPU digital twins.
3. **Protocol-level equivalence of quantum sensing sequences.** Both systems execute identical protocols under the same two-level Hamiltonian. The decoherence physics differ — flux noise (1.59 $\times$ T_2/T_2^* , echo gain 1.27 $\times$) vs. ^{13}C spin bath (20–100 $\times$, gain 4–10 $\times$) — but the measurement framework is universal.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The experimental data generated in this study are publicly available through the IBM Quantum platform. All raw results can be retrieved using the Job IDs listed in Table II of this manuscript via the Qiskit Runtime Service.

AUTHOR DECLARATIONS

Conflict of interest

The author has no conflicts to disclose.

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