Towards Reproducible Performance Across Neutral-Atom Quantum Processors

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Over the past years, neutral-atom quantum processors have emerged as a promising platform for scalable quantum computing. At PASQAL, we develop Quantum Processing Units (QPUs) that implement analog quantum computation based on Rydberg interactions, effectively realizing programmable Ising-type Hamiltonians through the control of key experimental parameters. Their operation relies on highly complex experimental systems, where tightly coupled optical, atomic, and electronic components must be precisely controlled. Hardware variability, environmental fluctuations, and calibration drifts make reproducible performance across QPUs a central challenge.

In this work, we present a comprehensive framework for monitoring, calibration, and benchmarking of QPUs, aimed at achieving consistent and reproducible performance. Our approach is based on a multi-layer characterization of the system.

First, at the hardware level, we monitor the stability of critical experimental systems — including lasers, vacuum, and magnetic field control — together with environmental conditions, ensuring stable operation and enabling diagnostic correlations with atomic behavior. Second, we calibrate and characterize atomic observables that define the operating condition of the system, including register preparation, state initialization and readout, and analog processing of key parameters such as the Rabi frequency and the detuning. This step enables the quantitative identification of dominant error sources and the extraction of parameters required to construct a consistent noise model. In practice, our calibration procedures achieve percent-level control of the Rabi frequency, detuning stability at the 50 kHz level, and sub-percent precise distance calibration for atomic arrays of up to 256 atoms with arbitrary geometry. Finally, we develop and validate comprehensive noise models based on experimental many-body results and benchmarking protocols. Once validated, these models establish a coherent framework for device-level validation and cross-QPU performance assessment.

By combining these layers, we establish a methodology for reproducible performance and standardized benchmarking of large-scale neutral-atom quantum processors while achieving high-fidelity and low-noise control.

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