Development of an open-source calibration framework for superconducting qubits

Master degree in Physics

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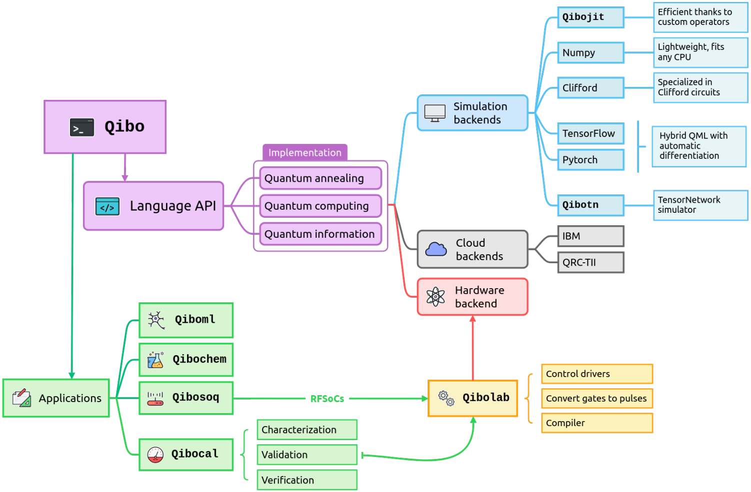
Qibo framework



Superconducting qubits

Artificial atoms

Qubit: two level system

Superconducting qubits: use Josephson Junctions to build anharmonic oscillators

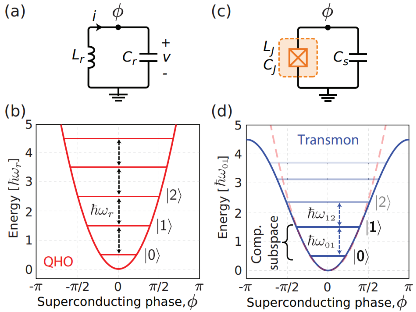


Figure 1: DOI: 10.1109/MAP.2022.3176593

State readout

Qubit - resonator hamiltonian:

$$\hat{H} = \hbar\omega_r \hat{a}\hat{a}^\dagger - \frac{\hbar\omega_{01}}{2}\hat{\sigma}_z + \hbar g(\hat{\sigma}^+\hat{a} + \hat{\sigma}^-\hat{a}^\dagger)$$

Dispersive regime ($g \ll \omega_q - \omega_r$):

$$\hat{H}_{disp} = \hbar(\omega_r - \chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} - \frac{\hbar}{2}(\omega_{01} + \chi)\hat{\sigma}_z$$

dispersive shift: $\chi = \frac{g^2}{\Delta}$,
$\Delta = \omega_q - \omega_r$

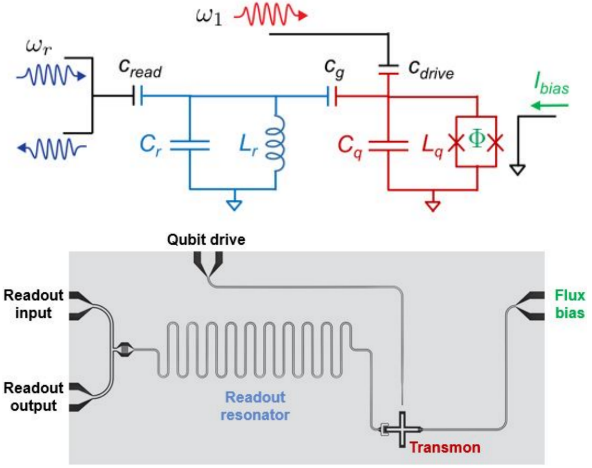
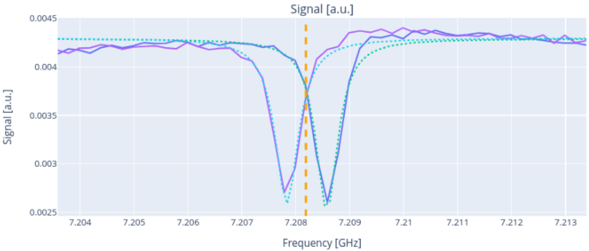
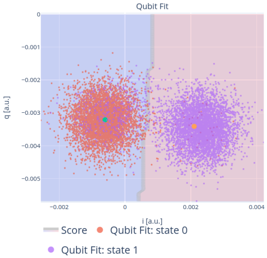


Figure 2: DOI: 10.1109/MAP.2022.3176593

Superconducting qubit calibration





Procedure:

1. Resonator characterization
2. Qubit characterization
3. Gate calibration
4. Gate set characterization

Metrics example:

- readout & assignment fidelity
- relaxation time T_1
- decoherence time $T_2 2$
- gate fidelity

Superconducting qubit calibration

Qubit	Readout Fidelity	Assignment Fidelity	T1 [μs]	T2 [μs]	Gate infidelity ($\cdot 10^{-3}$)
D1	0.876	0.938	26.4 ± 0.4	13.0 ± 2.0	27.0 ± 21.0
D2	0.945	0.973	14.9 ± 0.1	18.0 ± 10.0	20.5 ± 6.2
D3	0.905	0.952	23.6 ± 0.3	28.0 ± 12.0	7.0 ± 18
D4	0.929	0.964	20.6 ± 0.2	38.0 ± 5.2	4.4 ± 4.8
B2	0.902	0.951	17.5 ± 0.2	27.5 ± 5.2	18.0 ± 16

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Average Clifford gate fidelity optimization

Randomized Benchmarking

Randomized benchmarking estimates average gate fidelity by applying random sequences of Clifford gates followed by an inverting gate.

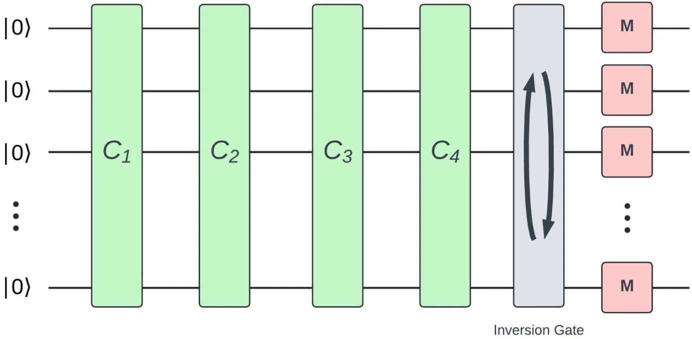
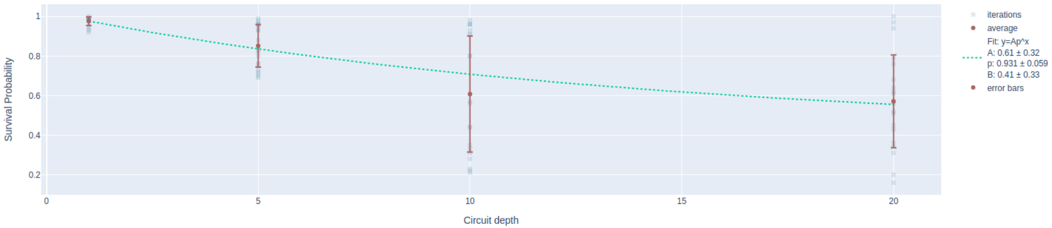


Figure 3: DOI: 10.1007/s10773-024-05811-8

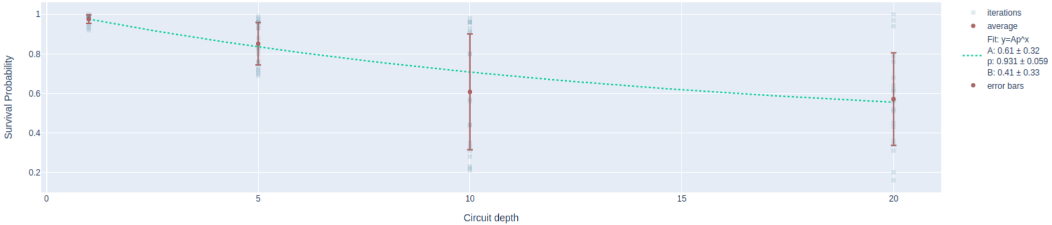
Randomized Benchmarking

Randomized benchmarking estimates average gate fidelity by applying random sequences of Clifford gates followed by an inverting gate.



Randomized Benchmarking

Randomized benchmarking estimates average gate fidelity by applying random sequences of Clifford gates followed by an inverting gate.



Can we optimize the average gate fidelity to automate *RX* gate reacalibration?

RB optimization [Kelly et al. 2014]

Library additions

Native RX90

`Qibolab` native gates: RX, MZ

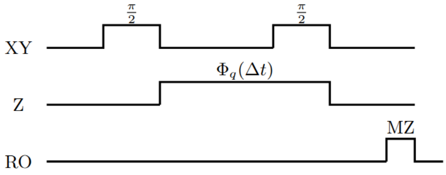
Flux pulse reconstruction [Rol et al. 2020]

Transmon flux dependence:

$$f_q(\Phi_q) \approx \left(\sqrt{8 E_J E_C \left| \cos\left(\pi \frac{\Phi_q}{\Phi_0} \right) \right|} \right)$$

Detuning as function of the flux pulse:

$$\Delta f_R = \frac{1}{\Delta\tau} \int_{\tau}^{\tau+\Delta\tau} \Delta f_Q(\Phi_{Q,\tau+\Delta\tau}(t))$$



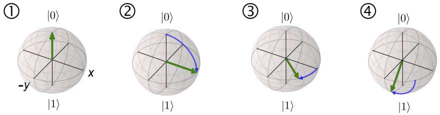
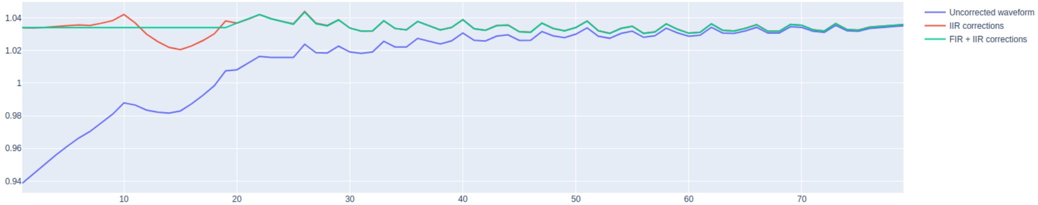


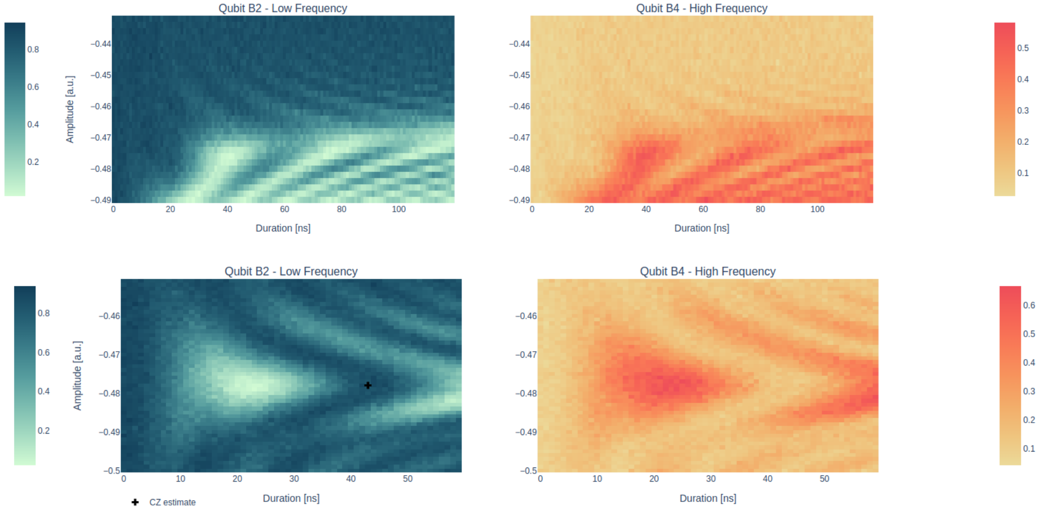
Figure 4: DOI: 10.1039/D2TC01258H

Filter determination



1. Determine exponential correction
2. Obtain IIR filters from exponential correction
3. Determine FIR
4. Apply pre-distortion

Impact on chevron plots



Conclusions & Outlooks

Questions?

References

Kelly, J. et al. (June 2014). **“Optimal Quantum Control Using Randomized Benchmarking”.** en. In: *Physical Review Letters* 112.24, p. 240504. ISSN: 0031-9007, 1079-7114. DOI: 10.1103/PhysRevLett.112.240504. URL: https://link.aps.org/doi/10.1103/PhysRevLett.112.240504 (visited on 02/24/2025).

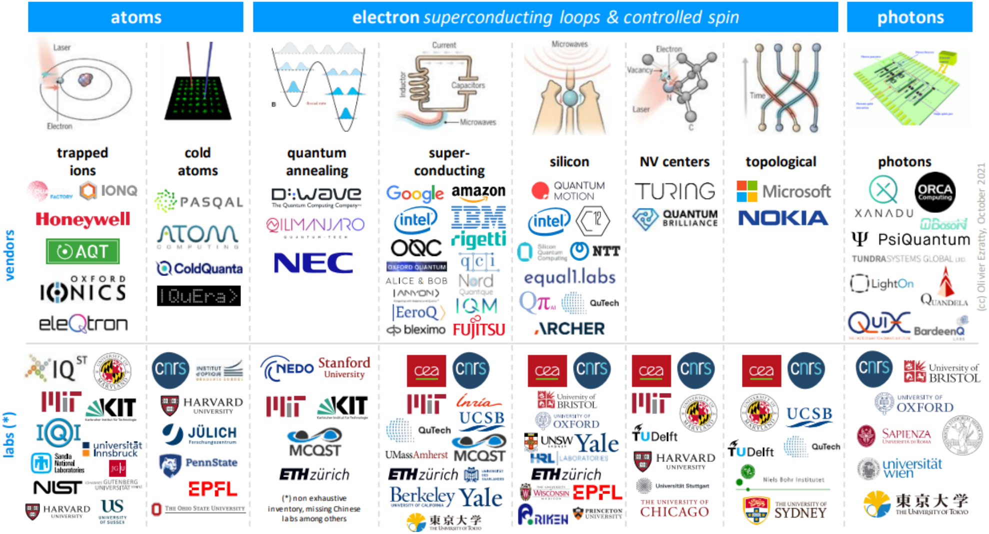
Rol, M. A. et al. (Feb. 2020). **“Time-domain characterization and correction of on-chip distortion of control pulses in a quantum processor”.** en. In: *Applied Physics Letters* 116.5. arXiv:1907.04818 [quant-ph], p. 054001. ISSN: 0003-6951, 1077-3118. DOI: 10.1063/1.5133894. URL: http://arxiv.org/abs/1907.04818 (visited on 02/24/2025).

Backup slides

What is for?

- **Simulation of quantum system:**
  "Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy"
- Optimization and modeling (chemistry, finance, traffic, weather...), eg. VQE, QAOA
- Quantum Algorithms
- Quantum Machine Learning

Qubit platforms



Standard Randomized Benchmarking protocol

RB protocol

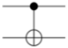
1. Initialize the system in the ground state
2. For each sequence length m draw a sequence of Clifford group elements
3. Calculate the inverse gate
4. Measure sequence and inverse gate
5. Repeat the process for multiple sequences of the same length while varying the length

RB features

- robust to SPAM errors
- faster than state tomography
- hardware-agnostic

Clifford gates

- Special subset of quantum gates that map Pauli operators to Pauli operators under conjugation
- Clifford gates group is generated by H, S, $CNOT$ gates
- Quantum circuits that consist of only Clifford gates can be efficiently simulated with a classical computer (Gottesman–Knill theorem)

Hadamard (H)		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
Controlled Not (CNOT, CX)		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$