Scalable Benchmarking Protocol for Mid-circuit Measurements

Jaewon Jung, Jinwoo Yu, Daniel Donghyon Ohm, Minwoo Kim, JM Lee, and Eunjong Kim*
Department of Physics and Astronomy, Seoul National University, Seoul 08858, Korea
*E-mail: eunjongkim@snu.ac.kr

KIAT Korea Institute for Advancement of Technology 한국산업기술진흥원

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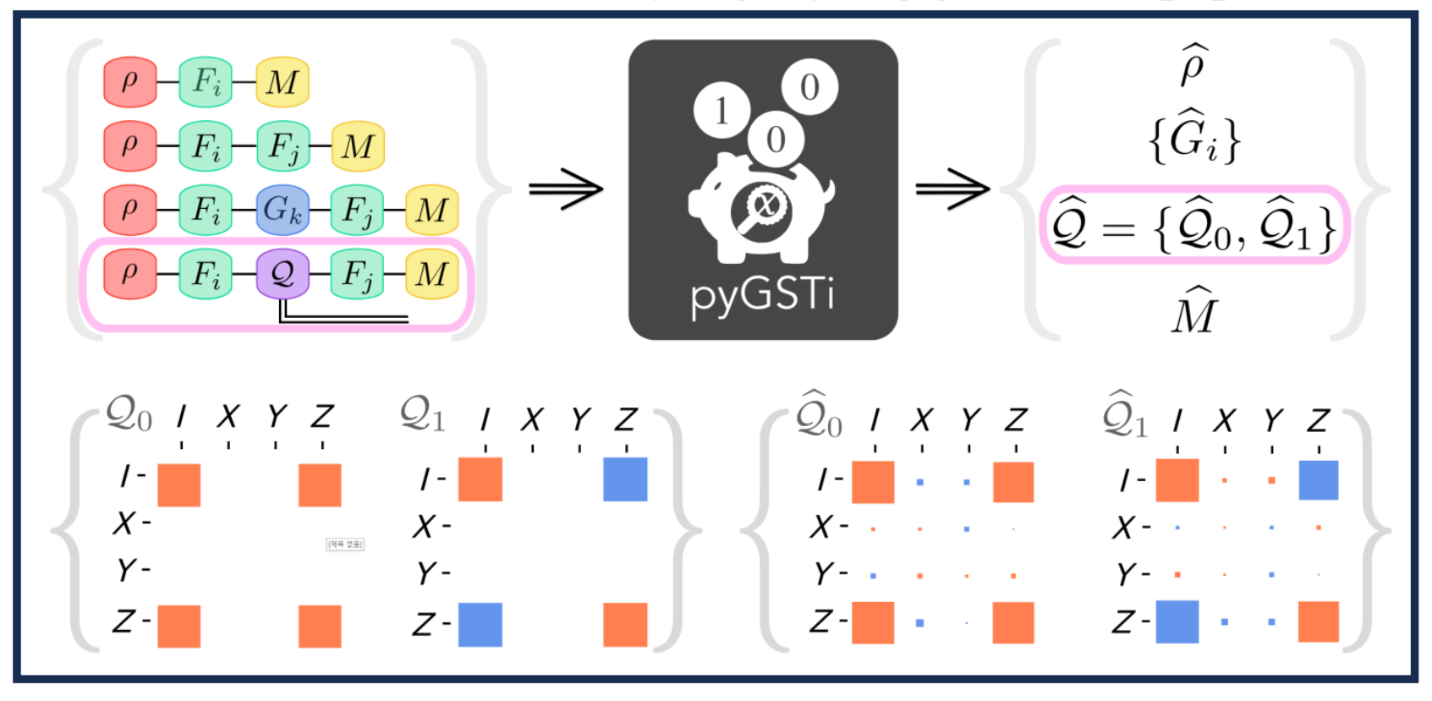
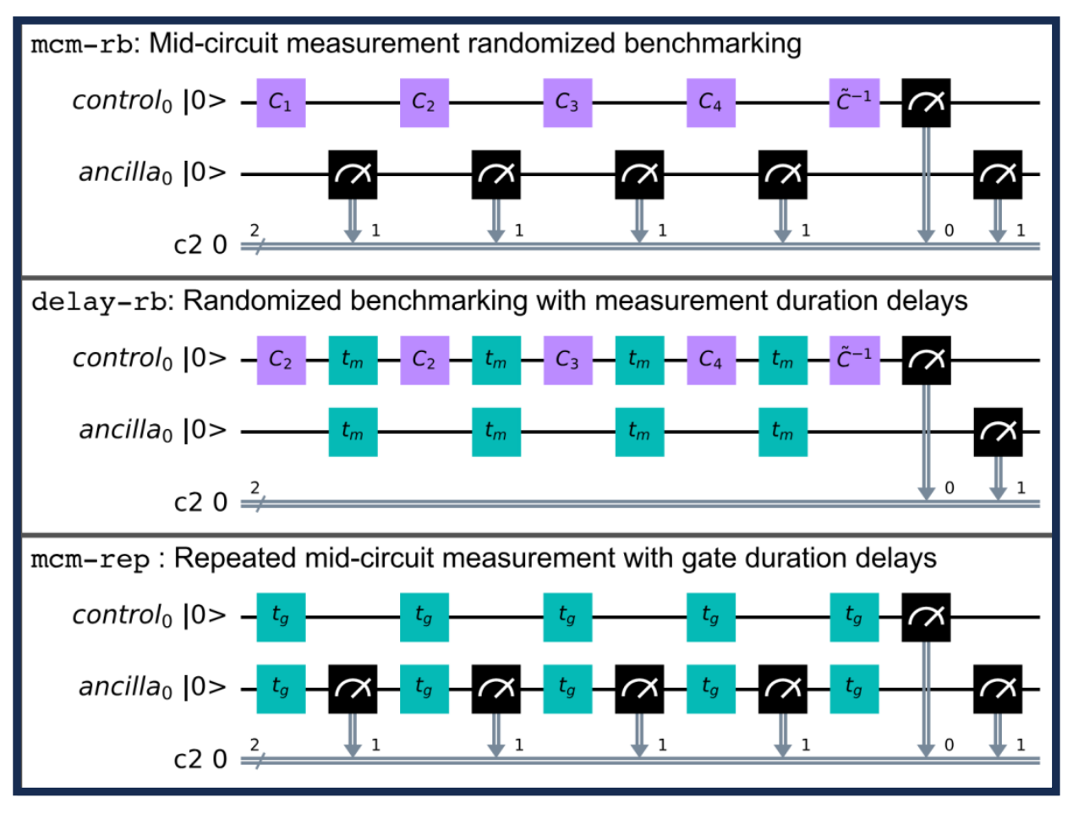
Motivation

- Mid-circuit measurements (MCMs) are core building blocks for fault-tolerant quantum computing.

Gate Set Tomography approach [1]



Randomized benchmarking approach [3]


`mcm-rb`: Mid-circuit measurement randomized benchmarking

`delay-rb`: Randomized benchmarking with measurement duration delays

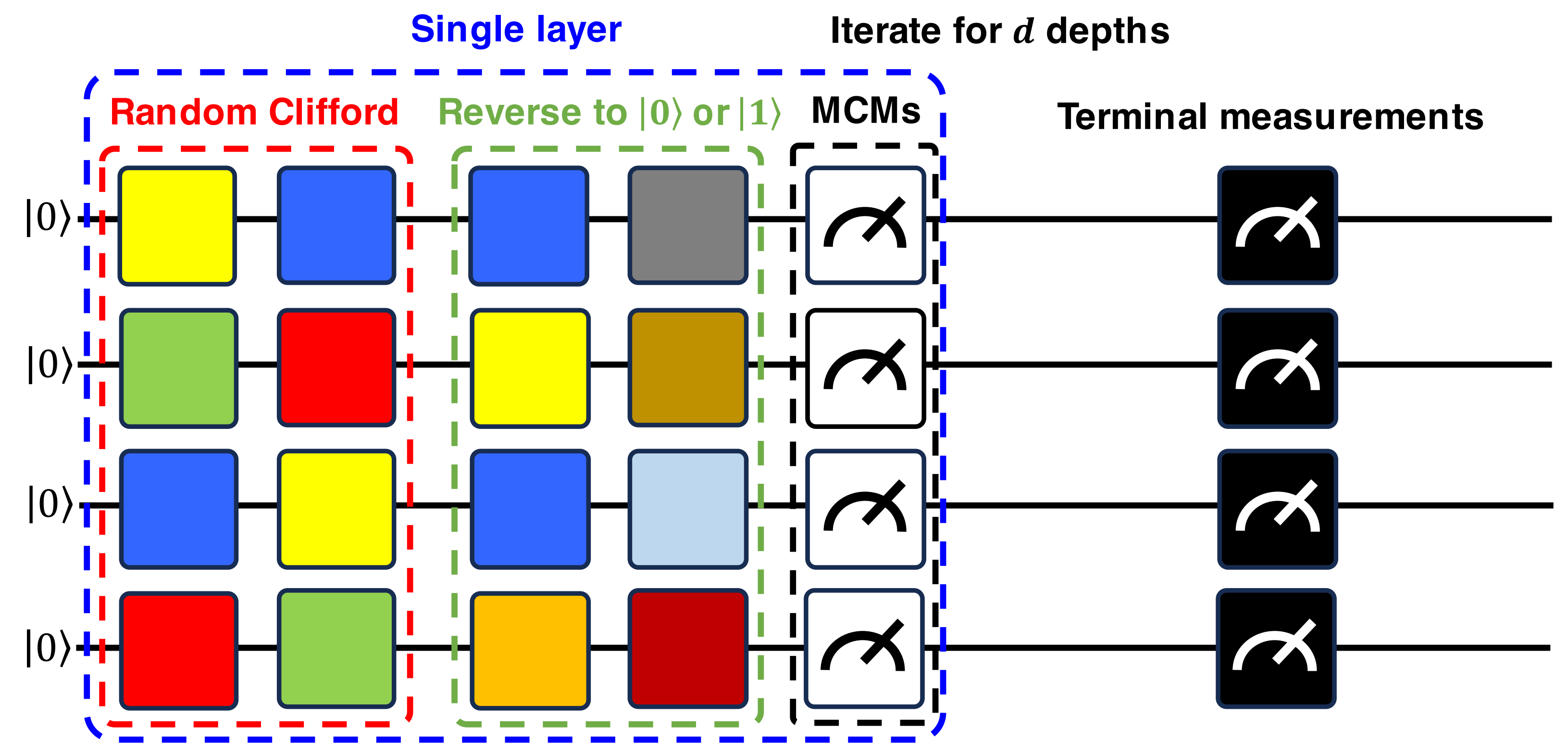
`mcm-rep` : Repeated mid-circuit measurement with gate duration delays

- Randomized benchmarking has the advantage of efficiency and scalable average fidelity measurements, in contrast to tomography based methods which provide detailed but non-scalable characterizations. [1-3].
- An efficient and scalable benchmarking protocol capable of characterizing and measuring the error rates of MCMs will serve as a good testbed for calibration and optimization of MCMs.

Randomized benchmarking with interleaved MCMs layers

Scheme 1

Effectively Measurement-induced control error free


Single layer

Iterate for d depths

Random Clifford

Reverse to $|0\rangle$ or $|1\rangle$

MCMs

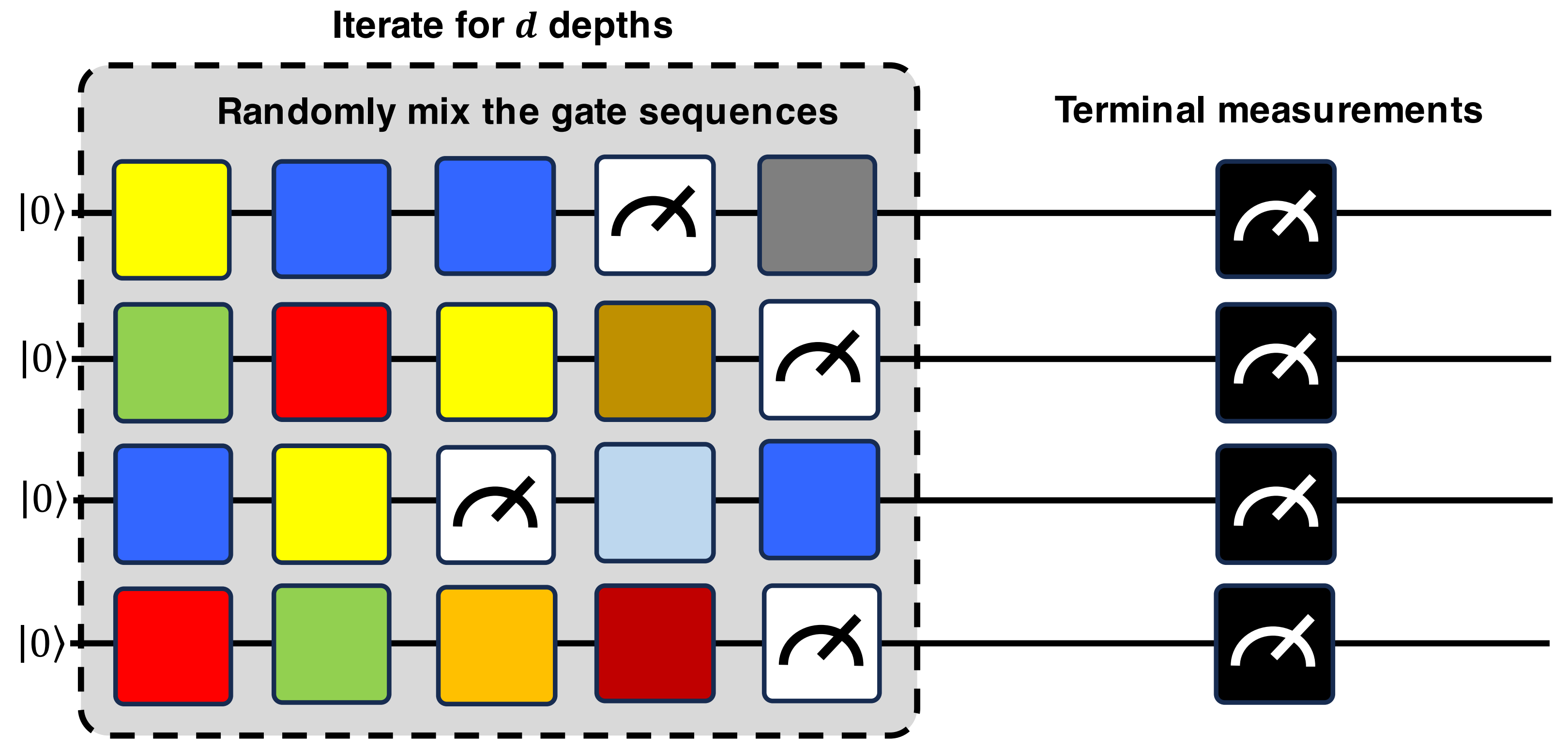
Terminal measurements

$|0\rangle$
$|0\rangle$
$|0\rangle$
$|0\rangle$

- MCMs and single qubit gates are not performed at the same time which effectively prevents measurement-induced control errors from qubits.

Scheme 2

Measurement-induced control error added


Iterate for d depths

Randomly mix the gate sequences

Terminal measurements

$|0\rangle$
$|0\rangle$
$|0\rangle$
$|0\rangle$

- Mixing the gate sequences enables single qubit gates and MCMs to be overlapped so that measurement-induced control errors can be added.
- By adjusting the rate of qubit reversal to 0 or 1, state-dependent errors such as the residual ZZ interaction can be tuned.
- MCM errors are extracted using interleaved randomized benchmarking.
- Controlling the overlap between MCMs and single qubit gates is crucial.

Error signatures of MCMs [3]

Measurement induced control error

Stark shift error

$$\widehat{U}_{\mathrm{Stark}} = e^{-i\phi\hat{\sigma}_z}$$

$$\phi = 2\chi\bar{n}T$$

χ: dispersive shift.
$\bar{n}$: mean photon number in readout resonator.
T: measurement duration.

Cross-measurement error

$$\widehat{K}_0 = \sqrt{p_{\mathrm{m}}}|0\rangle\langle 0|$$

$$\widehat{K}_1 = \sqrt{p_{\mathrm{m}}}|1\rangle\langle 1|$$

$$\widehat{K}_2 = \sqrt{1-p_{\mathrm{m}}}\hat{\mathrm{I}}$$

p_{m}: cross-measurement probability

Local measurement error

Non-QND error

$$\varepsilon_{\mathrm{dep}}(\rho) = (1-\eta)\rho + \eta\frac{\hat{\mathrm{I}}}{2}$$

η: depolarization probability

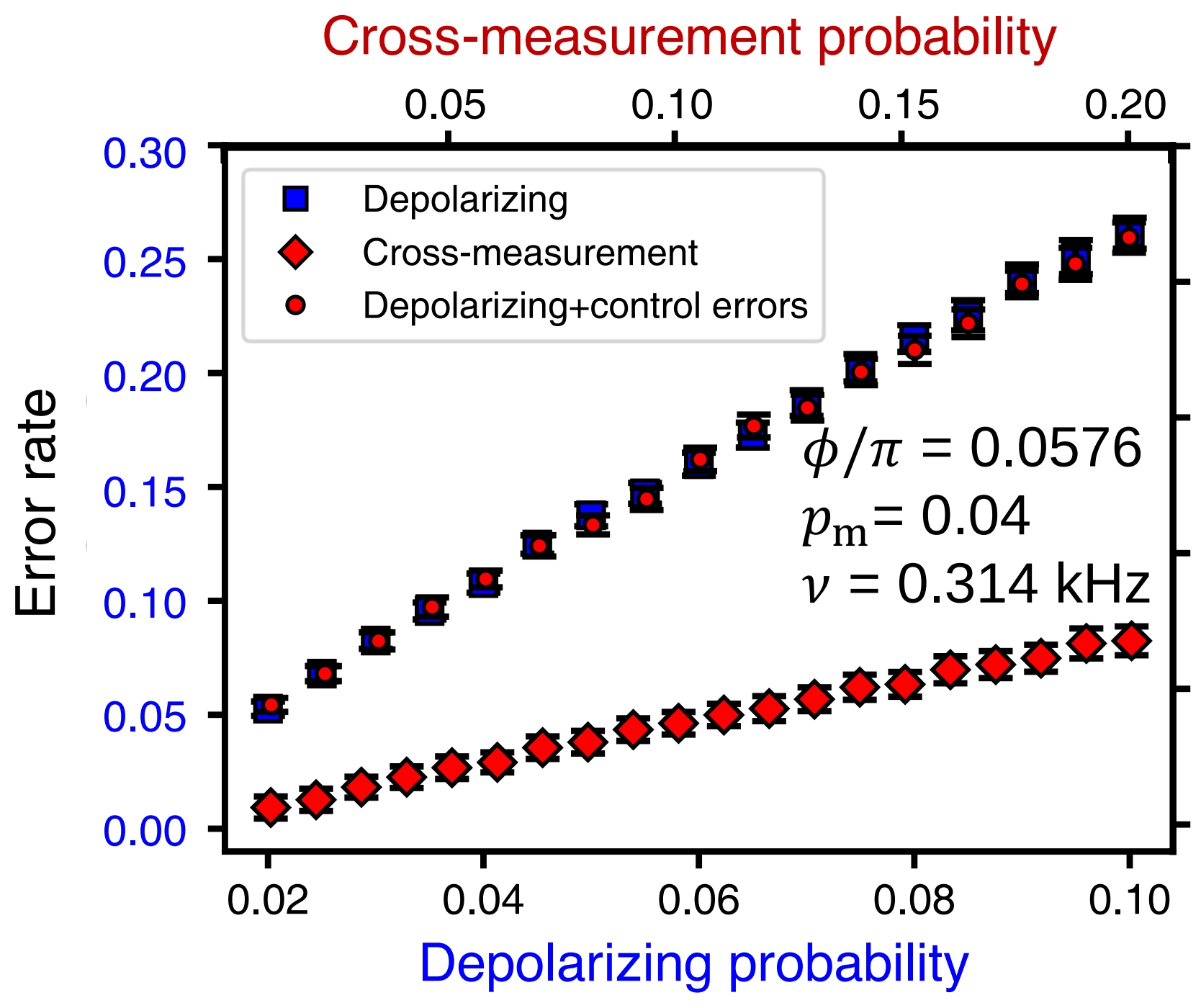
Residual ZZ interaction

$$\widehat{U}_{ZZ} = e^{-i\widehat{H}_{ZZ}T}$$

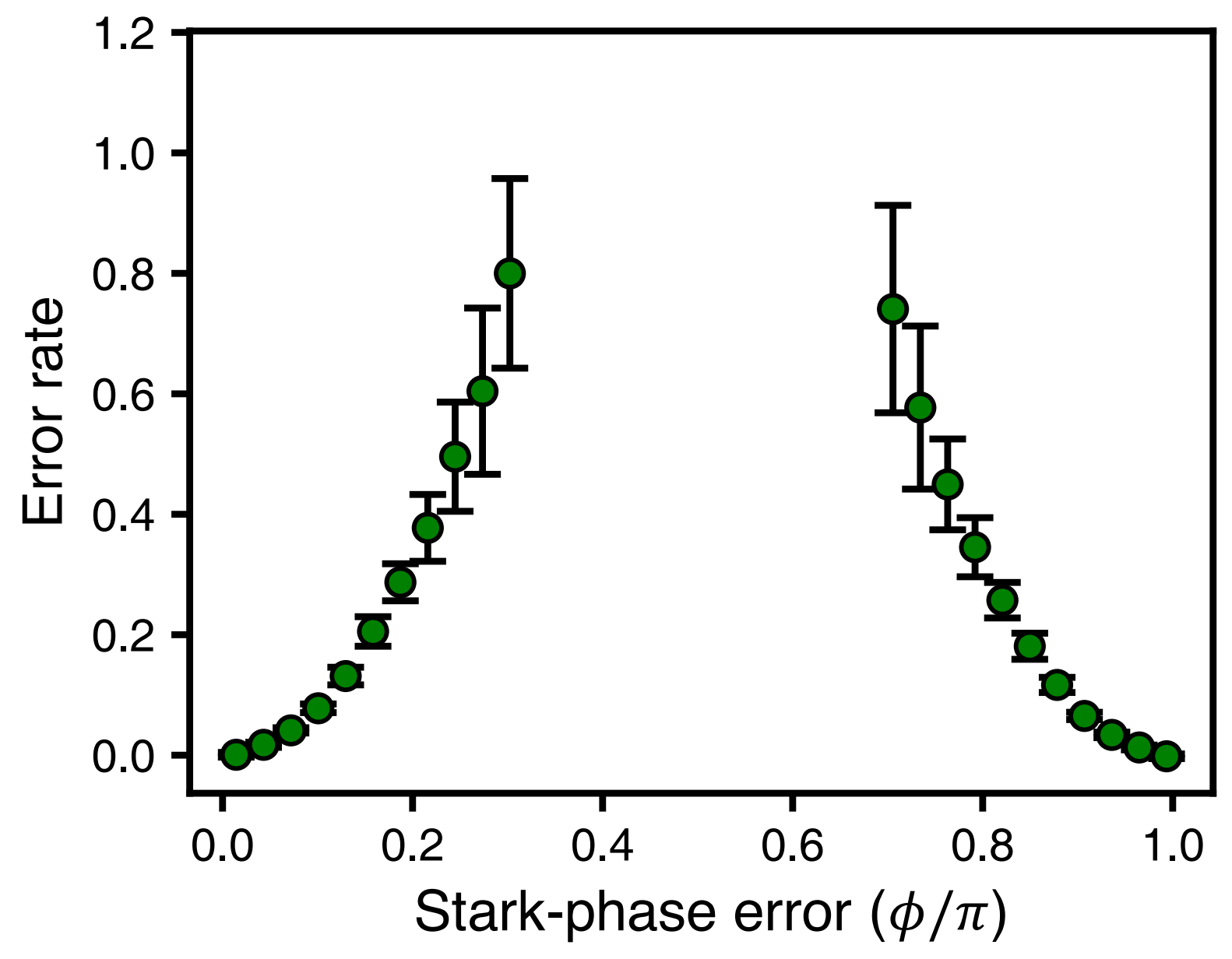
$$\widehat{H}_{ZZ} = \nu|e\rangle\langle e|_{\mathrm{measured}} \otimes \hat{\sigma}_z^{\mathrm{neighbor}}$$

ν: coupling rate

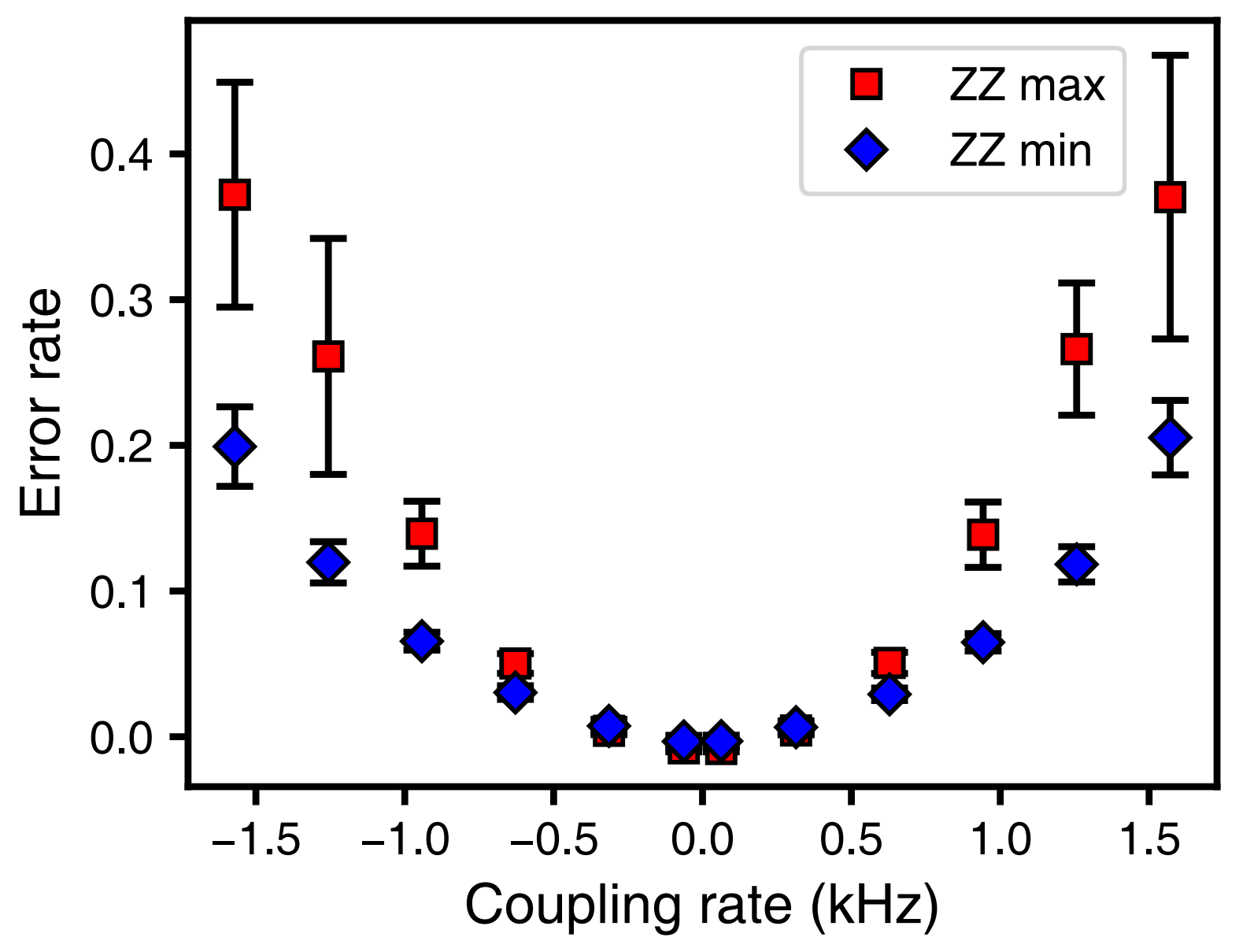
Noisy simulation results



Stark shift error



ZZ coupling error

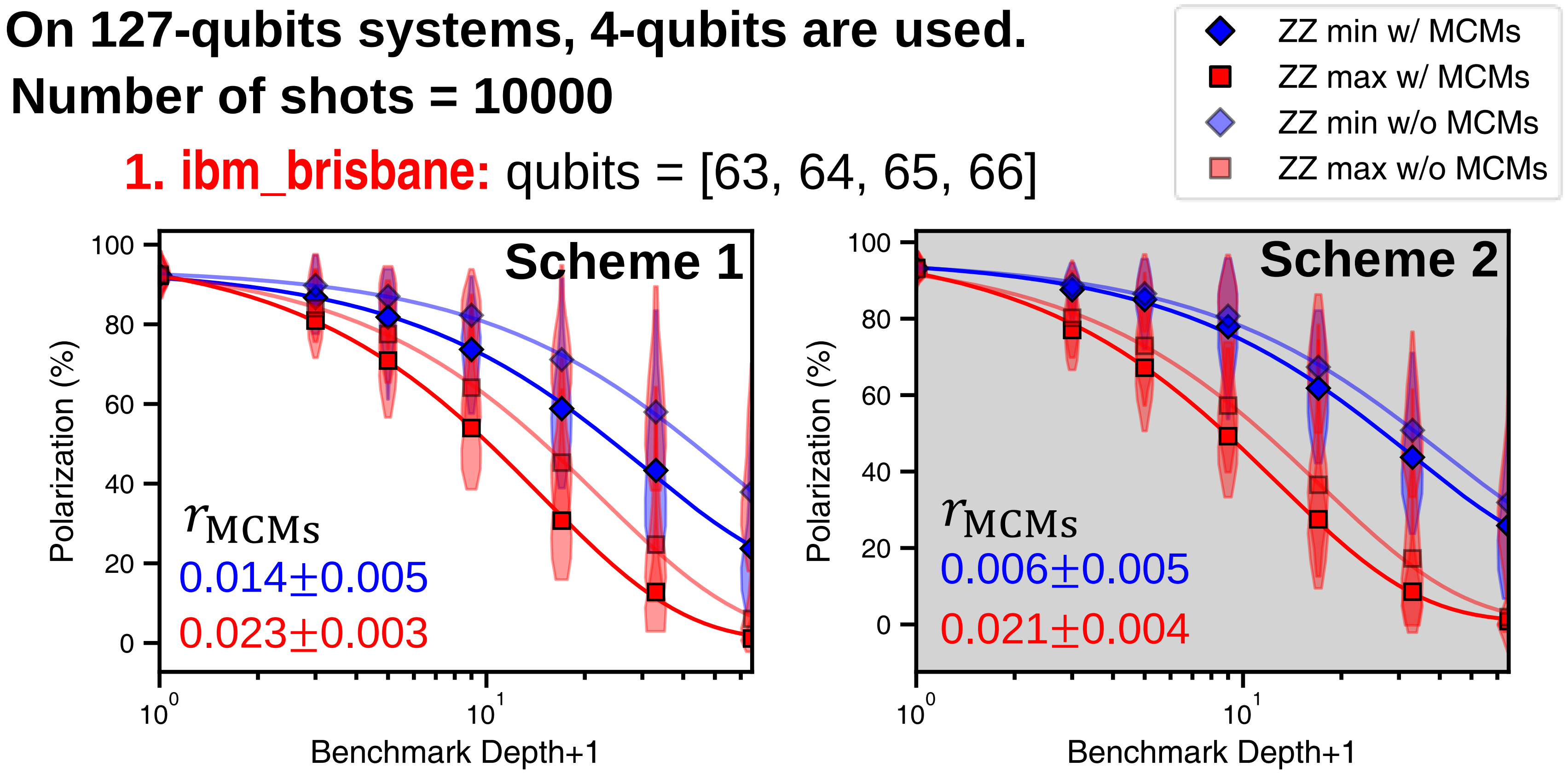


- Circuit generation was done using **pyGSTi** [4].
- Noisy simulations were done with **Qiskit** density matrix simulator with 4-qubits.
- 1q error: 0.1 %, $T_1(T_2)$: 345(280) μs
- MCM(1q gate) duration: 720(60) ns
- ZZ max(min) means reversing the layers converts a qubit into the $|1\rangle(|0\rangle)$ state.

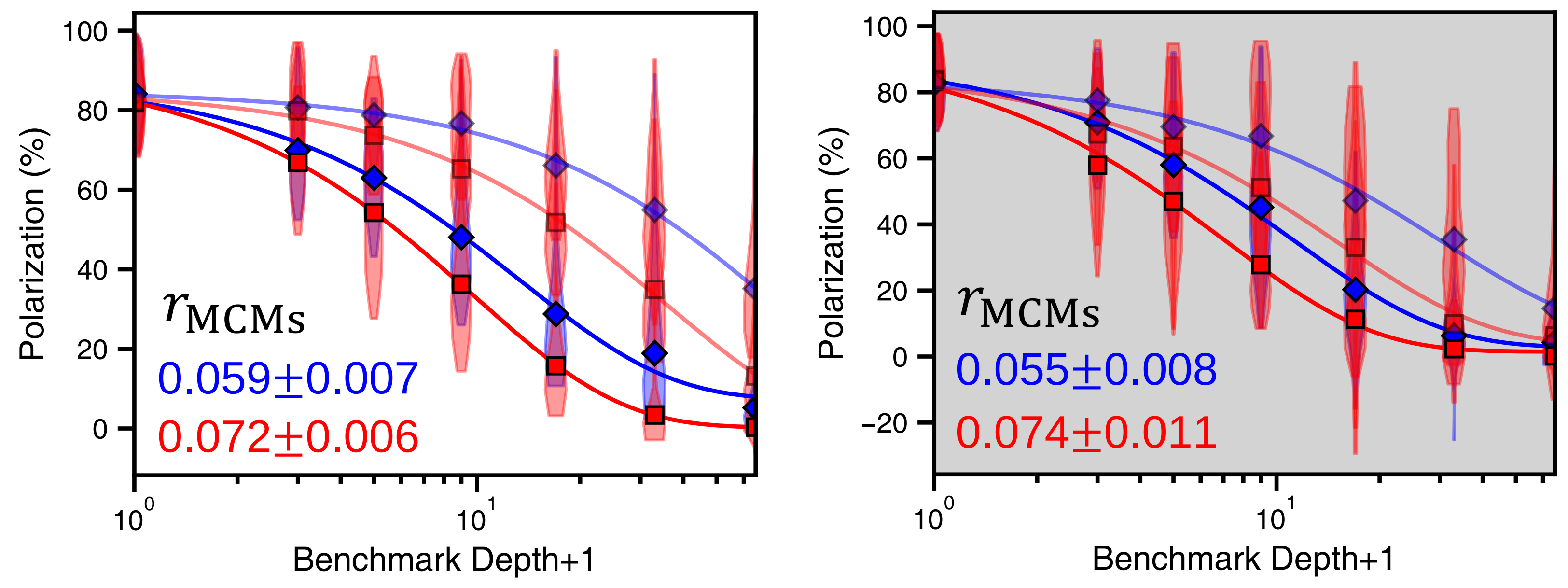
IBM backend results

On 127-qubits systems, 4-qubits are used.
Number of shots = 10000

1. ibm_brisbane: qubits = [63, 64, 65, 66]



2. ibm_osaka: qubits = [63, 64, 65, 66]



Calibration data

Brisbane (Osaka)	**Readout assignment error**	**Prob. meas0 prep1**
q[63]	0.0060 (0.0097)	0.0048 (0.0106)
q[64]	0.0063 (0.0086)	0.0080 (0.0102)
q[65]	0.0166 (0.0113)	0.0200 (0.0132)
q[66]	0.0698 (0.00863)	0.0494 (0.0084)

MCMs parameters

MCMs duration: 720 (720) ns
Depopulating time after MCMs: 1640 (340) ns

Conclusion

- Randomized benchmarking based schemes ensure scalability and efficient measurement of MCM errors.
- Adjusting the gate and MCM timing enables characterization of the error signatures of MCMs.
- Demonstration of benchmarking protocol both on a noise simulator and superconducting qubit systems-ibm_brisbane and ibm_osaka.

References

[1] K. Rudinger et al., Phys. Rev. Appl. **17**, 014014 (2022).
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[3] L. C. G. Govia et al., New Journal of Physics **25**, 123016 (2023).
[4] Nielsen, Erik, et al., Quantum science and Technology **5.4**, 044002 (2020).

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