2024/03/27 ムーンショット目標6公開シンポジウム2024
10:15~10:45
ベルサール秋葉原2F HALL A/B

「超伝導量子回路の集積化技術の開発」プロジェクト成果紹介

日本電気株式会社
セキュアシステムプラットフォーム研究所
山本剛

超伝導量子回路の集積化技術の開発 (ms-iscqc.jp)
https://ms-iscqc.jp/

© NEC Corporation 2024

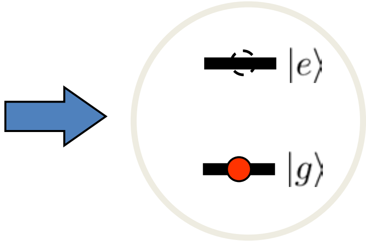
Outline

1. 一般向け
    - プロジェクト概要
    - 成果紹介（単一磁束量子回路）
2. 専門家向け
    - カーパラメトリック発振器における量子干渉の観測とゲート操作
    - システムレベルでの量子コンピュータアーキテクチャの探索
    - 量子ビット高強度読出しの解析のための効率的数値計算手法の開発

Superconducting qubit

- electric circuit made of superconductor and Josephson junctions
- nonlinear oscillator with ~5 GHz resonance frequency
- operated at ~10 mK using a dilution refrigerator
- lithographically fabricated (⇔ decoherence)
- design flexibility (⇔ non uniformity)

Y. Nakamura et al., Nature **398**, 786 (1999).



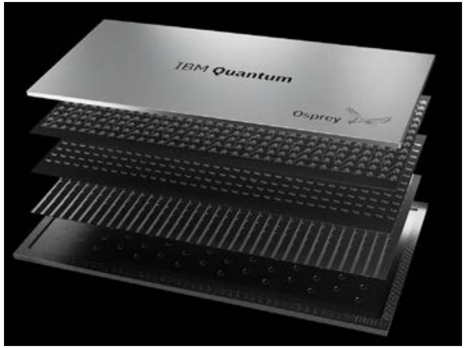
© NEC Corporation 2024

Superconducting NISQ processors

Google

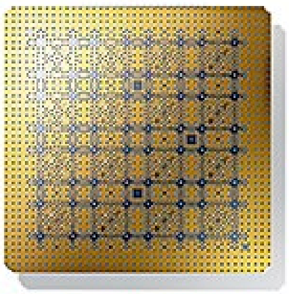
Arute *et al.*, Nature **574**, 505 (2019).

IBM, 433 qubits



IBM Unveils 433-Qubit Osprey Chip - IEEE Spectrum

RIKEN RQC, 64 qubits

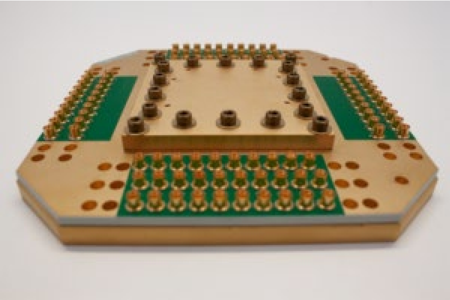


理化学研究所 量子コンピュータ研究センター センター長 中村泰信氏｜電子デバイス産業新聞（旧半導体産業新聞） (sangyo-times.jp)

USTC, 66 qubits

Zhu et al.,
Science Bulletin **67**, 240 (2022).

Rigetti, 80 qubits

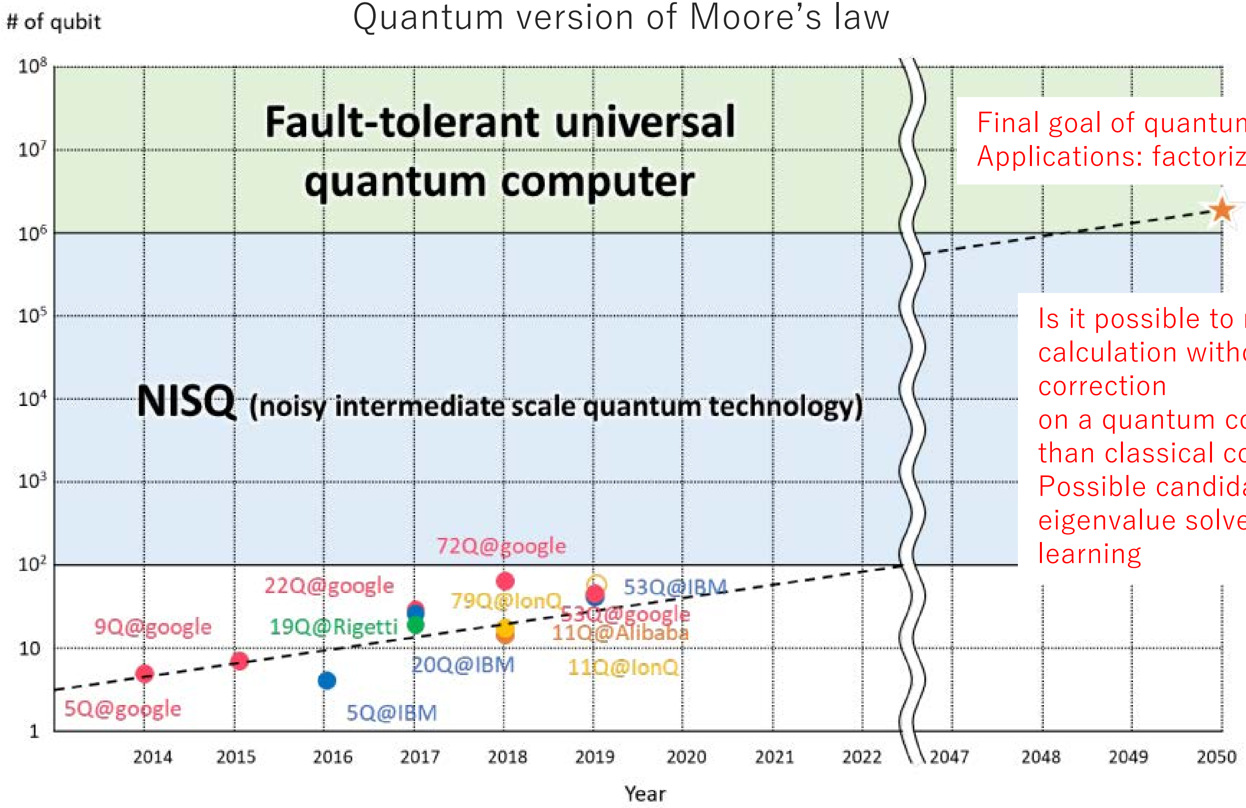


Rigetti Announces Commercial Availability of Aspen-M System and Results of CLOPS Speed Tests (hpcwire.com)

© NEC Corporation 2024
\Orchestrating a brighter world NEC

beyond NISQ

Quantum version of Moore's law



Final goal of quantum computer R&D.
Applications: factorization, simulation, etc

Is it possible to run some useful calculation without error correction on a quantum computer faster than classical computer?
Possible candidates: optimization, eigenvalue solver, machine learning

https://www8.cao.go.jp/cstp/english/moonshot/concept6_en.pdf

© NEC Corporation 2024
\Orchestrating a brighter world NEC

Toward realization of fault-tolerant QC

- Two main problems in hardware development:
  - required large number of physical qubits

Physical qubit error rate	10^{-3}	10^{-6}	10^{-9}
Physical qubits per logical qubit	15,313	1,103	313
Total physical qubits in processor	1.7×10^6	1.1×10^5	3.5×10^4
Number of T state factories	202	68	38
Number of physical qubits per factory	8.7×10^5	1.7×10^4	5.0×10^3
Total number of physical qubits including T state factories	1.8×10^8	1.3×10^6	2.3×10^5

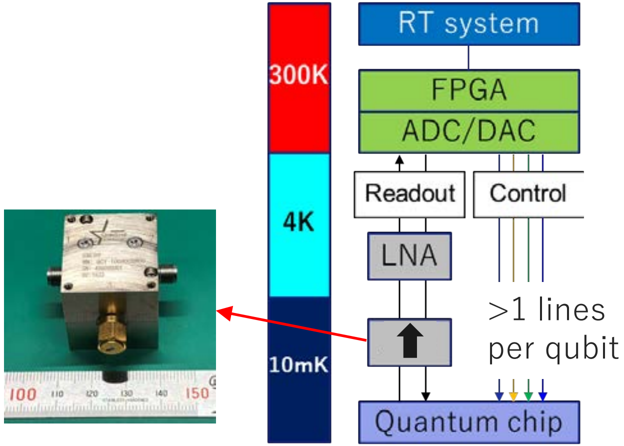
TABLE 3.1 Estimates of the Resource Requirements for Carrying Out Error-Corrected Simulations of a Chemical Structure (FeMoco in Nitrogenase) Using a Serial Algorithmic Approach for Hamiltonian Simulation and the Surface Code for Error Correction

Quantum Computing: Progress and Prospects (2019)

~10^8 qubits?

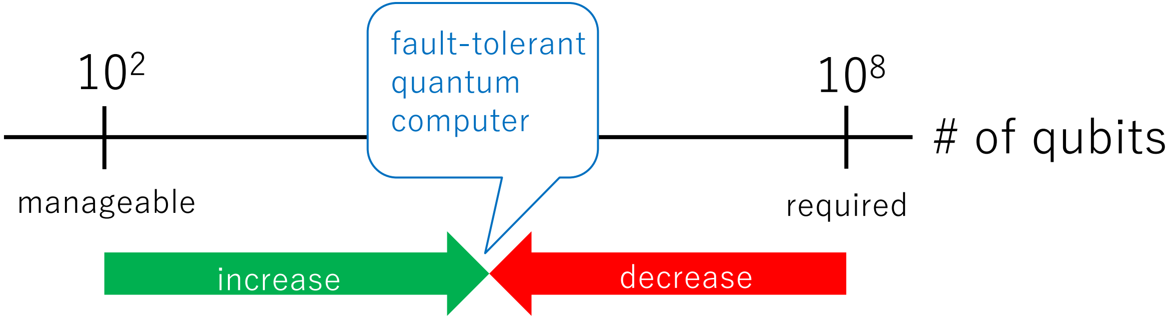
  - not scalable wiring & electronics
    - >1 coax line per qubit from RT to mK for control
    - bulky μ-wave components (amplifier, isolator) for readout

<~10^2 qubits?



© NEC Corporation 2024

Required technologies



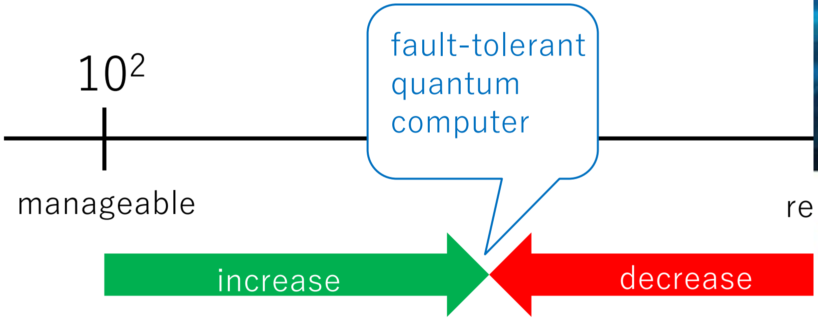
- cryo-electronics
- high-cooling-power refrigerator
- high-density wiring
- chip-to-chip interconnection
- …

- improved coherence
- gate optimization
- hardware-efficient QEC scheme
- …

System-level architecture optimization

© NEC Corporation 2024
\Orchestrating a brighter world NEC

Required technologies



- cryo-electronics
- high-cooling-power refrigerator
- high-density wiring
- chip-to-chip interconnection
- …

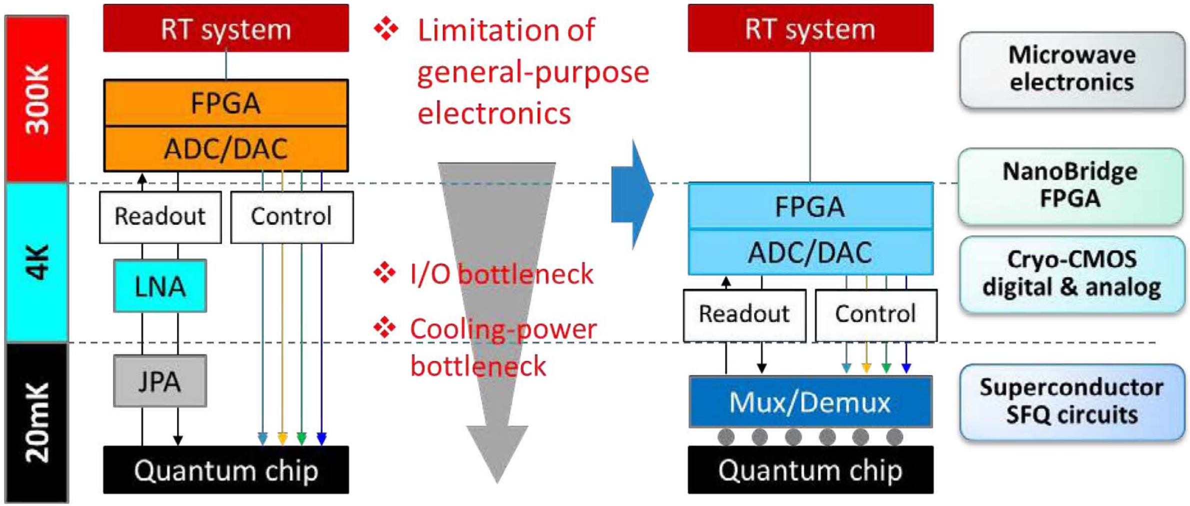
- improved coherence
- gate optimization
- hardware-efficient QEC scheme
- …

System-level architecture optimization

© NEC Corporation 2024

Cryo-electronics

- Cryo-CMOS, SFQ, AQFP etc.
- Potentially reduces the number of physical interconnects (coaxial lines) between the quantum–classical interface and room-temperature electronics



© NEC Corporation 2024

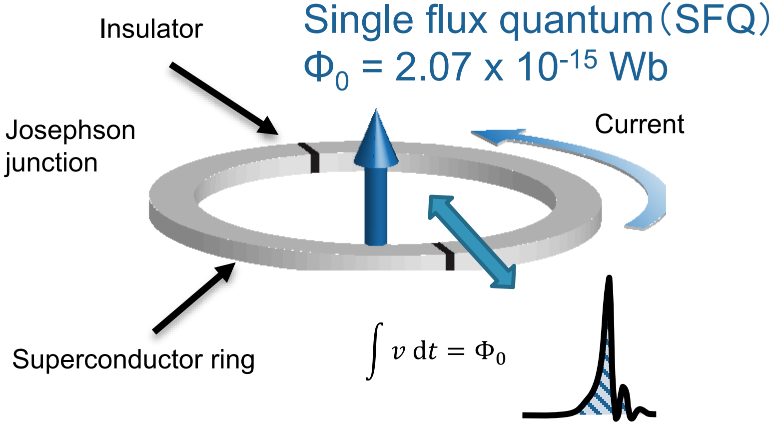
Single-Flux-Quantum Logic Circuits

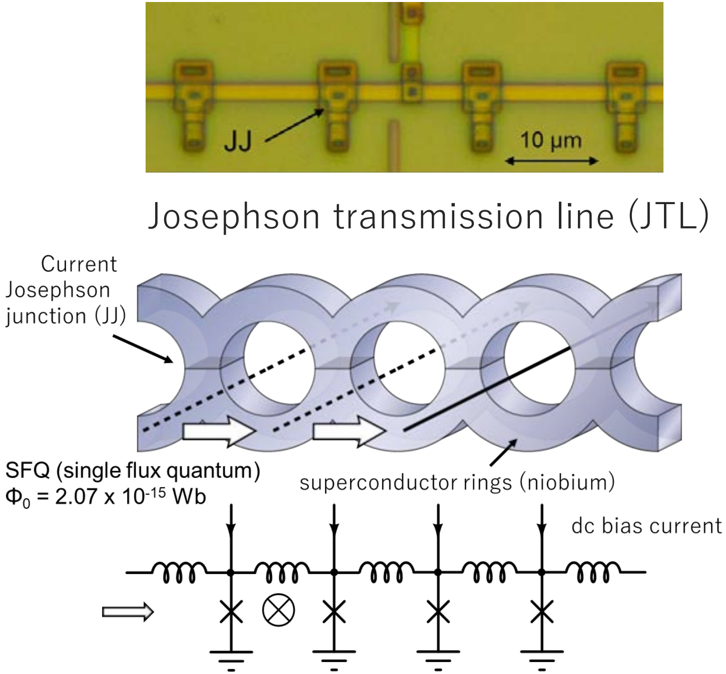
NAGOYA UNIVERSITY

NEC


M. Tanaka


T. Yamamoto





K. K. Likharev and V. K. Semenov, IEEE Trans. Appl. Supercond. **1** (1991).

High-speed digital LSIs using quantized magnetic flux

- Voltage pulse-driven logic
- 10+ GHz, low-power operation
- Transmission line interconnects

© NEC Corporation 2024

Large-Scale SFQ LSIs

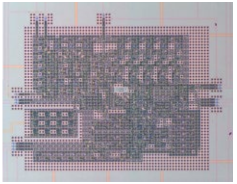
Nb 9-layer Device (AIST ADP2)

S. Nagasawa et al. *IEICE* **E97-C** (2014) 132.

CRAVITY Qufab

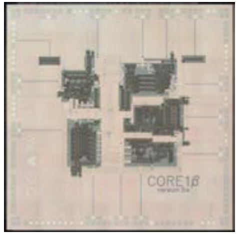
◆ Demonstration of SFQ processors

- Bit-serial processing: simple & efficient design
- Bit-parallel processing: high-throughput performance



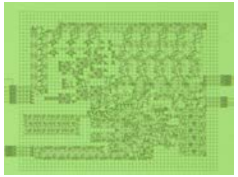
CORE1α (2003)
4999 JJs, 15 GHz
M. Tanaka,
ISSCC 2004

First demonstrated SFQ processor



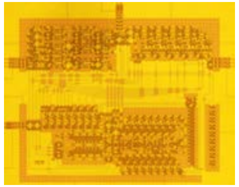
CORE1β (2006)
10955 JJs, 25 GHz
Y. Yamanashi,
IEEE TAS 2006

Pipeline processing



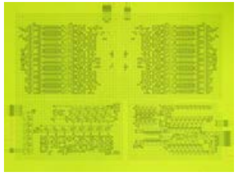
CORE1LV (2013)
3869 JJs, 35 GHz
M. Tanaka,
SSDM 2013

Low-voltage 0.2-mW operation



CORE100 (2014)
3073 JJs, 100 GHz
M. Tanaka,
ASC 2014

Ultra high clock frequency

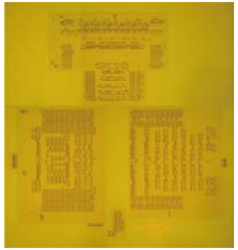


CORE e2 v5h (2016)
10603 JJs, 50 GHz
M. Tanaka,
APL 2023

Stored-program computing demo

GLP w20 (2019)
23713 JJs, 32 GHz
K. Ishida,
VLSI 2020

Implementation of Gate-level-pipeline



BLOSSOM1 (2022)
57200 MIPS,
I. Nagaoka,
A-SSCC 2022

Extremely high throughput

After M. Dorojevets et al., *IEEE Trans. Appl.* Supercond. **11** (2001) 326.

NAGOYA UNIVERSITY · YOKOHAMA National University · 京都大学 KYOTO UNIVERSITY · KYUSHU UNIVERSITY · AIST

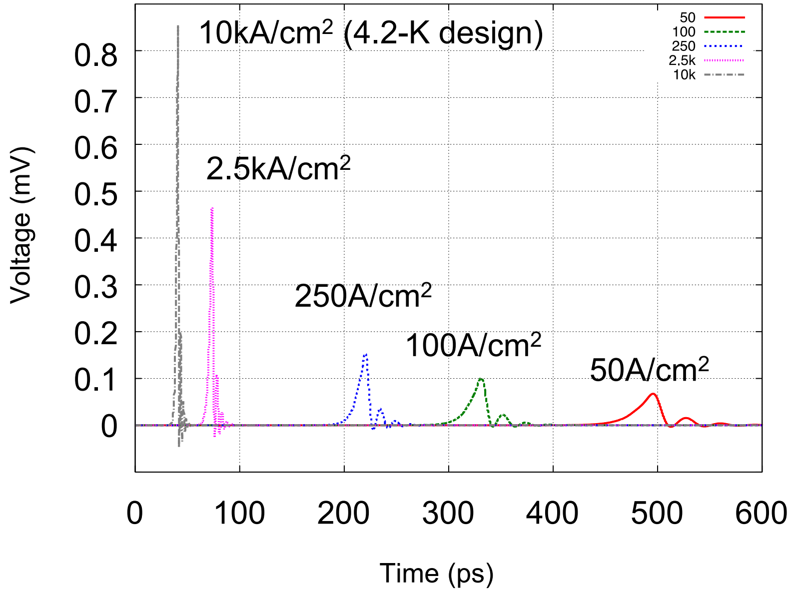
© NEC Corporation 2024
\Orchestrating a brighter world NEC

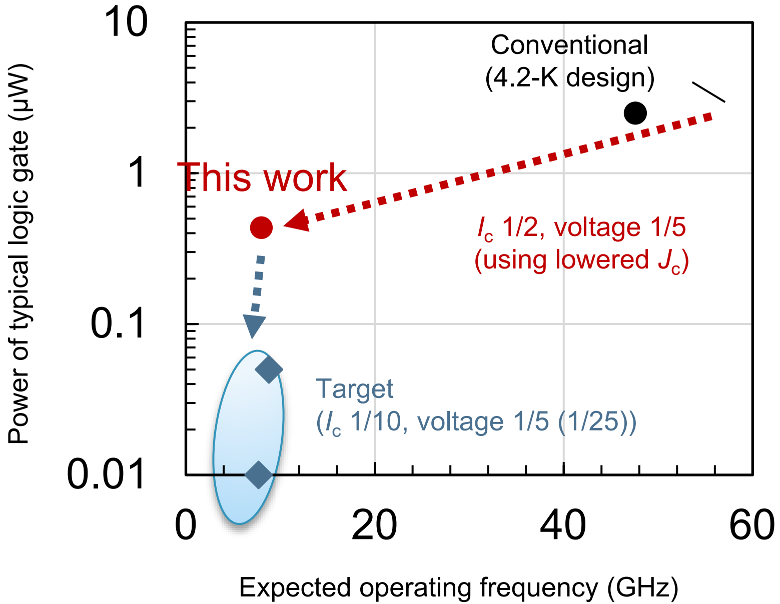
Selection of Critical Current Density (J_c)

M. Tanaka et al.,
IEEE Trans. Appl. Supercond. 33, 1700805 (2023).

- Easy to fabricated small I_c JJs (2–10 μA)
- Acceptable operating frequency (10GHz)

→ J_c = 250 A/cm²

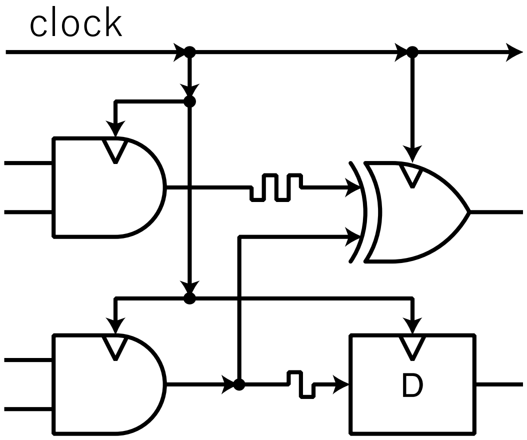


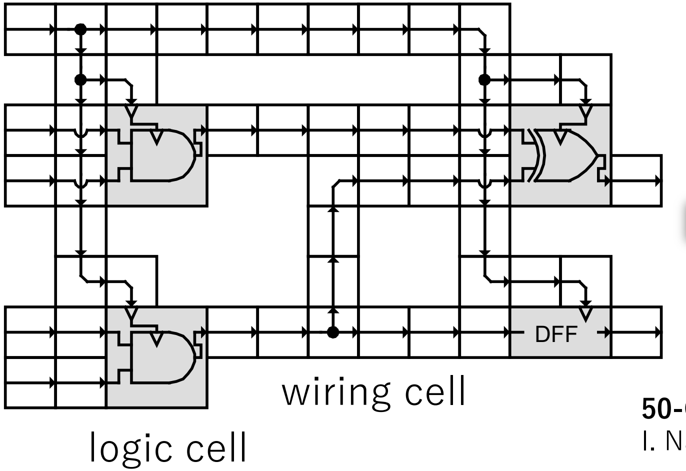


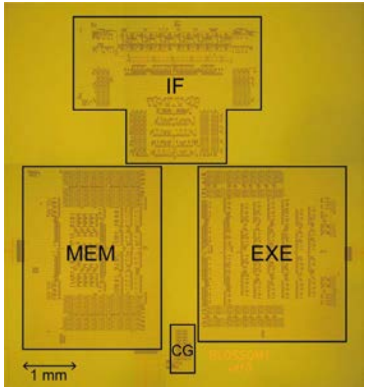
© NEC Corporation 2024
\Orchestrating a brighter world NEC

Standard-Cell-Based Design

- CONNECT: Standard cell library specialized for SFQ circuits
  - Clocked logic gates and special gates, such as non-destructive readout gate
  - Wiring element (pulse splitters, delay elements, passive transmission lines)







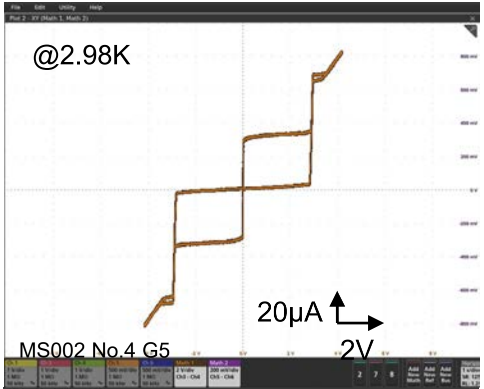
50-GHz 8-bit processor (33k JJs)
I. Nagaoka et al., ASSCC 2022.

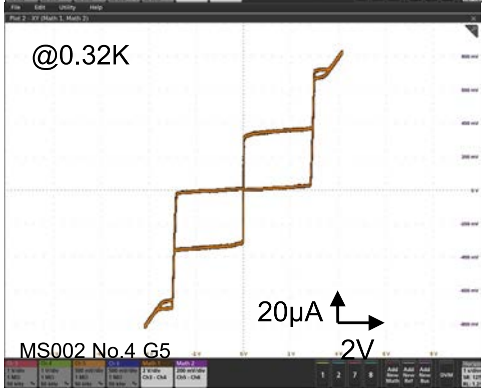
S. Yorozu et al., “A single flux quantum standard logic cell library” Physica C **378** (2002).

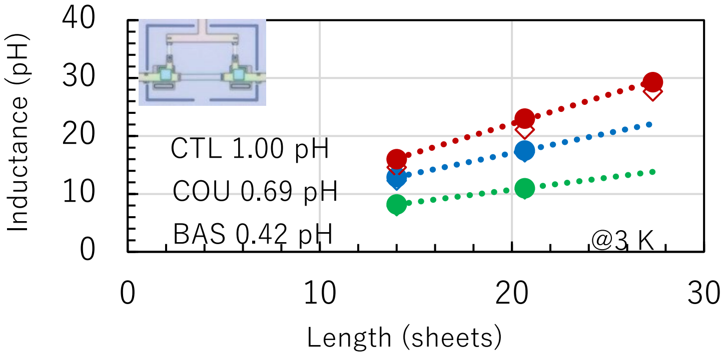
© NEC Corporation 2024
\Orchestrating a brighter world NEC

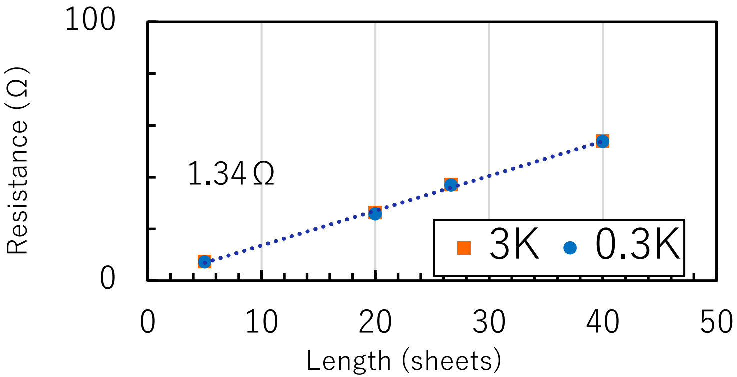
Parameter Extraction

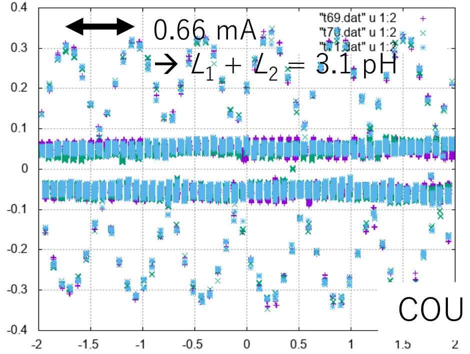
- ✓ JJ critical current: 7% increase when 3 → 0.3 K
- ✓ *L*, *R*, JJ capacitance: no temperature dependence

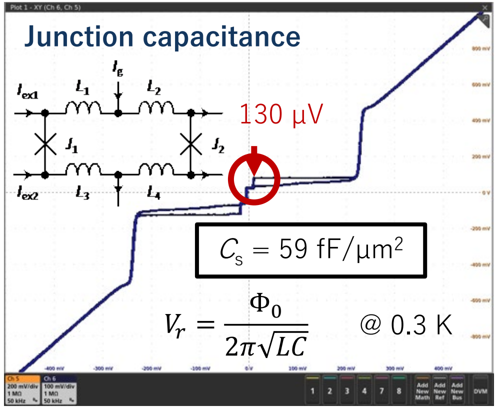






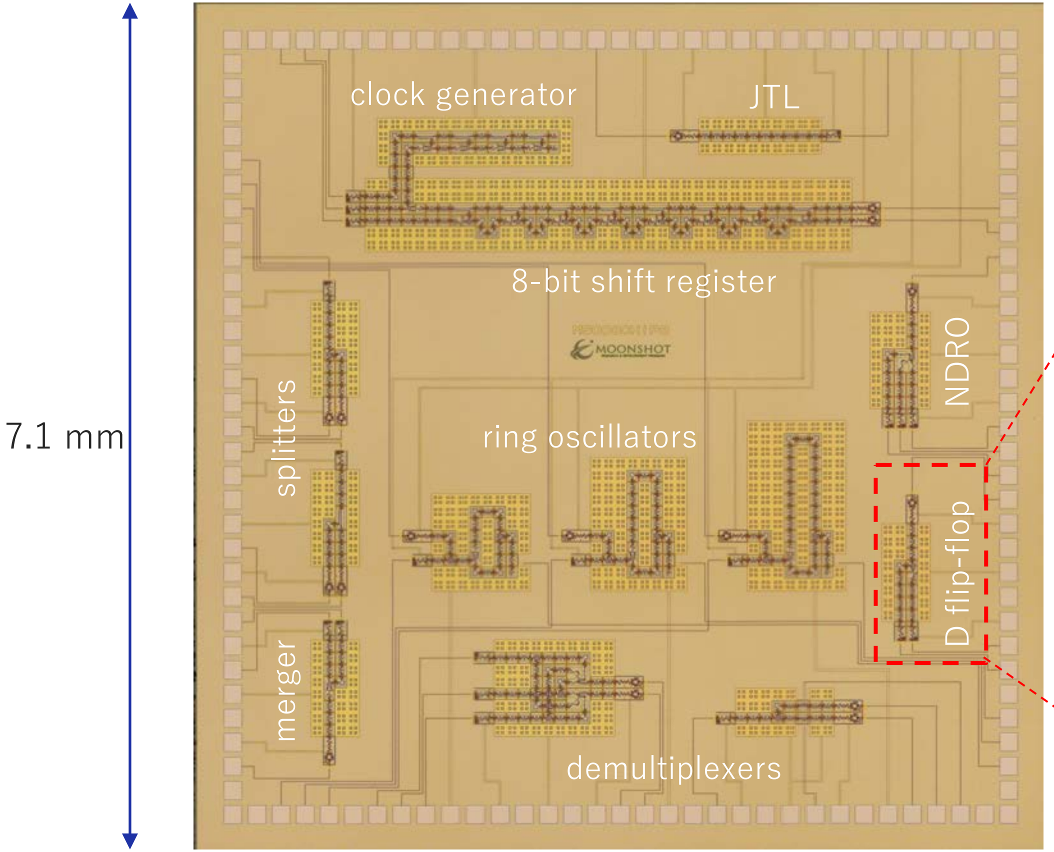


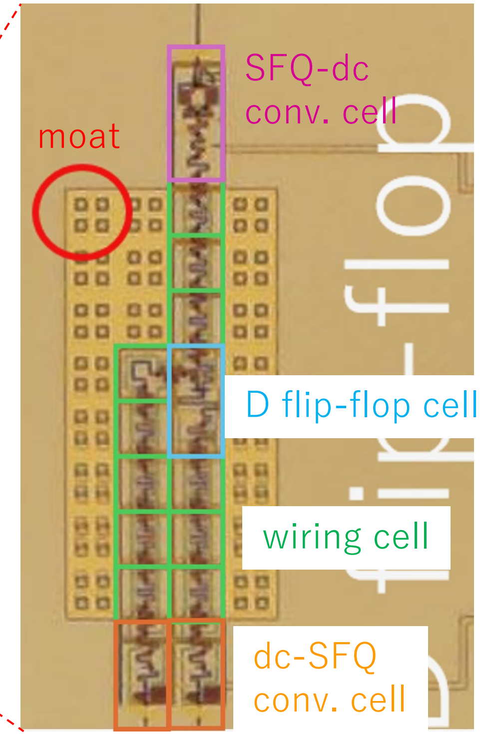




© NEC Corporation 2024

Test chip for low power cells

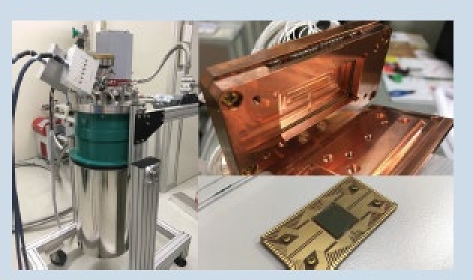


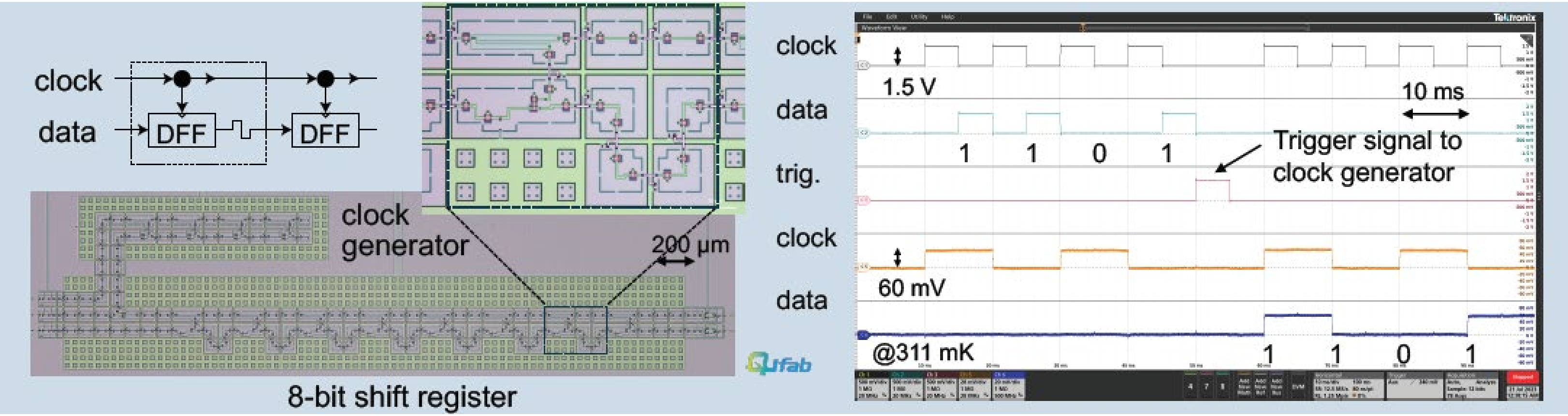


© NEC Corporation 2024
\Orchestrating a brighter world NEC

High-Speed On-chip Test of Shift Registers

- We tested the 8-bit SFQ shift registers using a ^{3}He cryocooler at 300 mK.
- We successfully obtained correct operation with high-frequency clock signals.



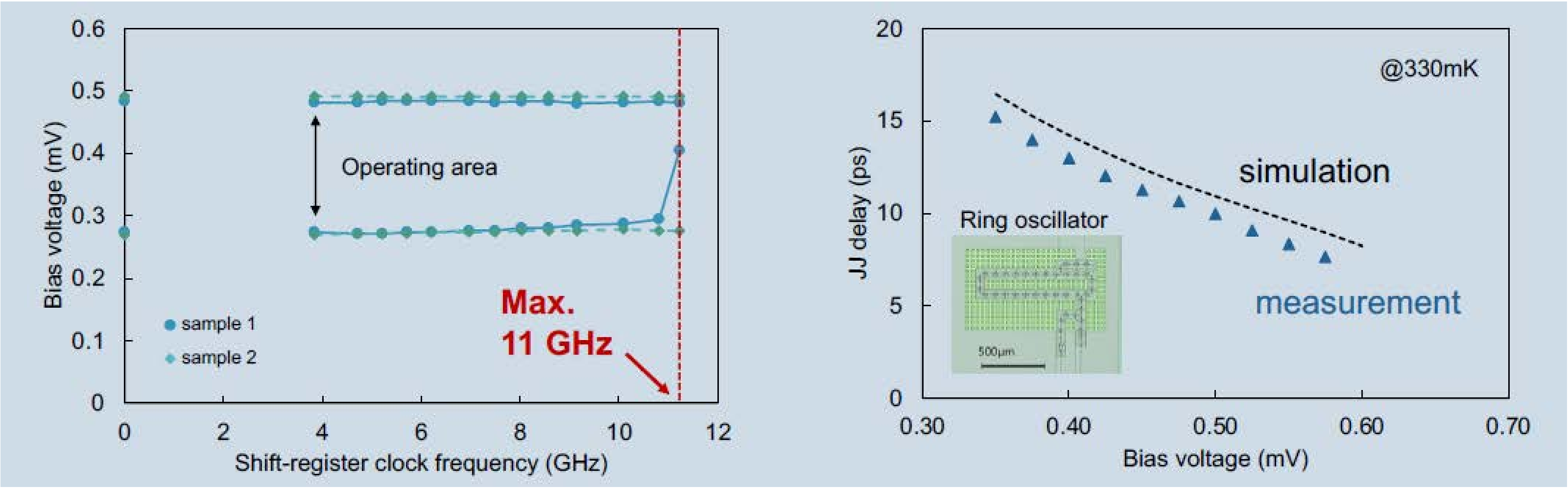


M. Tanaka et al., 2023 International Conference on IC Design and Technology, pp. 84-87 (2023).

© NEC Corporation 2024

Clock Frequency Measurement and Verification

- We calculated the frequencies using an analog circuit simulator with the bias currents and extracted parameters from the fabricated chip.
- We verified the clock frequency by ring oscillator measurements.

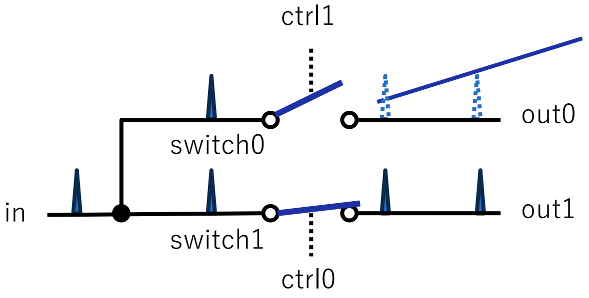


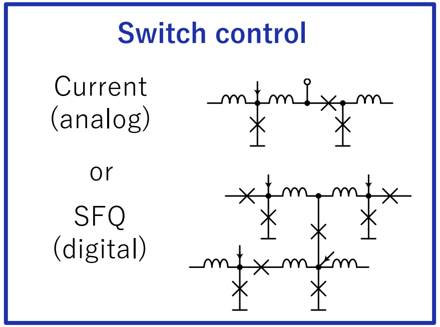
M. Tanaka et al., 2023 International Conference on IC Design and Technology, pp. 84-87 (2023).

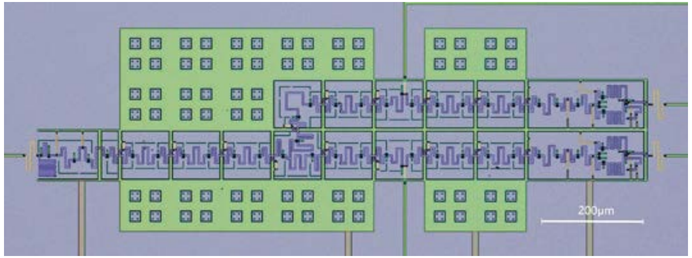
© NEC Corporation 2024
er world NEC

1:2 Demux (Demultiplexer) Demo

- Demux forwards the input signal (SFQ pulse trains) to one of the outputs based on the control signals.

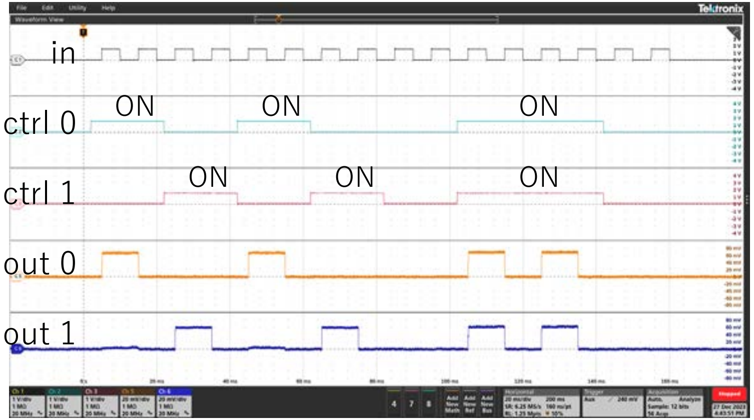






- JJ count: 29
- Bias current: 418 μA
- Area: 0.32 mm2
- Power: 41.8 nW
- Latency: 319.0 ps

Demonstration of current-controlled 1:2 demux



© NEC Corporation 2024
\Orchestrating a brighter world

テストベッド量子コンピュータの立ち上げ

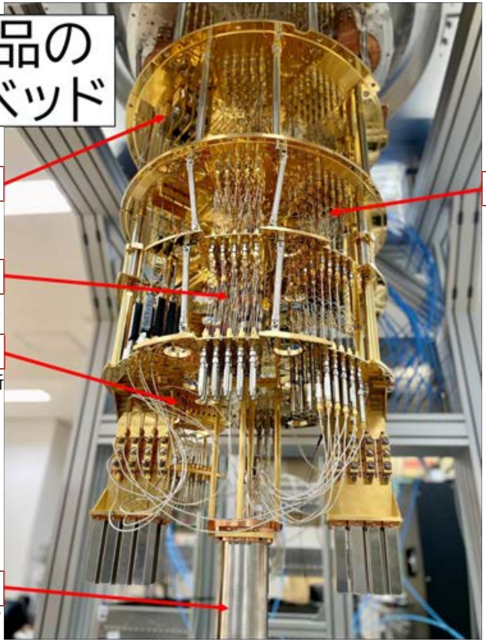
M. Negoro

M. Saito

Y. Fujiwara

大阪大学
OSAKA UNIVERSITY

国産部品のテストベッド

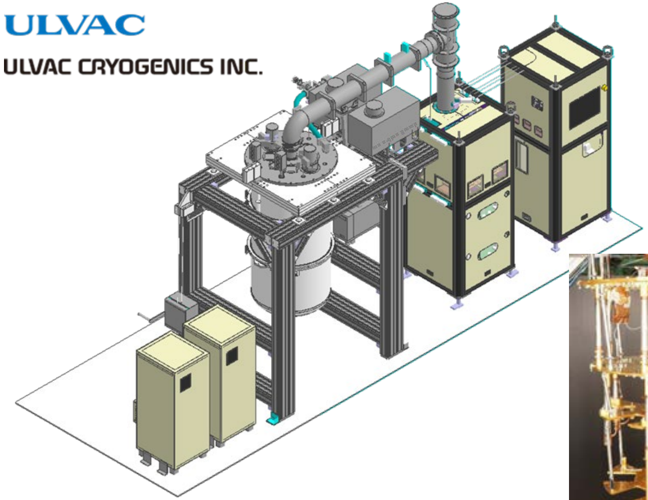


- 低雑音増幅器 日通機
- 超伝導ケーブル コアックス
- 赤外吸収体 川島製作所
- 磁気シールド オータマ
- 冷凍機 ブルーフォース
- 低温ケーブル コアックス
- 制御装置 キュエル
- 量子ビット
- 超伝導増幅器 理研
- 低雑音電源 NF回路
- 計測装置 アンリツ
- チップパッケージ 精研

十分な計算性能が発揮することを確認

出典：大阪大学QIQB根来グループ

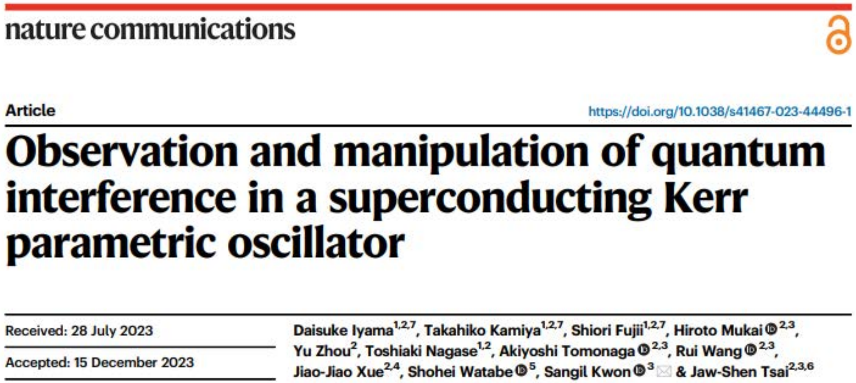
ULVAC
ULVAC CRYOGENICS INC.



2025年度上期稼働開始予定
クライオエレ等開発技術検証＆インテグレート

© NEC Corporation 2024
\Orchestrating a brighter world NEC

カーパラメトリック発振器における量子干渉の観測とゲート操作


nature communications

Article
https://doi.org/10.1038/s41467-023-44496-1

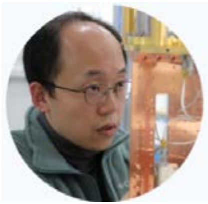
Observation and manipulation of quantum interference in a superconducting Kerr parametric oscillator

Received: 28 July 2023

Accepted: 15 December 2023

Daisuke Iyama[1,2,7], Takahiko Kamiya[1,2,7], Shiori Fujii[1,2,7], Hiroto Mukai[2,3], Yu Zhou[2], Toshiaki Nagase[1,2], Akiyoshi Tomonaga[2,3], Rui Wang[2,3], Jiao-Jiao Xue[2,4], Shohei Watabe[5], Sangil Kwon[3] & Jaw-Shen Tsai[2,3,6]

TOKYO UNIVERSITY OF SCIENCE


S. Kwon


J. S. Tsai

Hardware-efficient FTQC using Kerr cat qubit

- Theory of Kerr cat qubit
  - P. T. Cochrane et al., Phys. Rev. A **59**, 2631 (1999).
  - H. Goto, Phys. Rev. A **93**, 050301 (2016).
  - S. Puri et al., npj Quantum Info. **3**, 18 (2017).
- High-fidelity gate operation
  - T. Kanao et al., Phys. Rev. Appl. **18**, 014019 (2022).
  - H. Chono et al., Phys. Rev. Res. **4**, 043054 (2022).
- Proposal of bias preserving gate
  - S. Puri et al., Sci. Adv. 6, eaay5901 (2020).
- Error-correction code with high error threshold
  - A. S. Darmawan et al., PRX Quantum 2, 030345 (2021).
- Experiments
  - Z. Wang et al., Phys. Rev. X **9**, 021049 (2019).
  - A. Grimm et al., Nature **584**, 205 (2020).
  - N. E. Frattini et al., arXiv:2209.03934.
  - J. Venkatraman et al., arXiv:2211.04605.

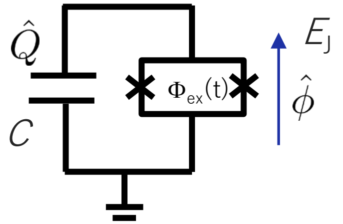
Goto, PRA 2016

Darmawan et al.,
PRX Quantum 2021

© NEC Corporation 2024
\Orchestrating a brighter world NEC

Generation of Schrodinger's cat state

P. T. Cochrane et al., Phys. Rev. A **59**, 2631 (1999).
H. Goto, Sci. Rep. **6**, 21686 (2016).
S. Puri et al., npj Quantum Info. **3**, 18 (2017).



flux modulation:

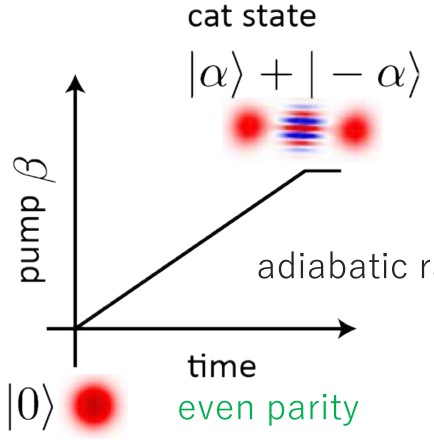
$$E_J(t) = E_J + \delta E_J \cos 2\omega_0 t$$

$$\begin{aligned} K &= e^2/2C \\ \beta &= \frac{\omega_0}{4}\frac{\delta E_J}{E_J} \\ \hat{\phi} &= \left(\frac{2E_c}{E_J}\right)^{1/4}(a^\dagger + a) \\ \hat{Q} &= \mathrm{i}\left(\frac{E_J}{2E_c}\right)^{1/4}(a^\dagger - a) \end{aligned}$$

$$\begin{aligned} \mathcal{H}_{KPO}/\hbar &= -\frac{K}{2}a^\dagger a^\dagger a a + \frac{\beta}{2}({a^\dagger}^2 + a^2) \\ &= -K\left({a^\dagger}^2 - \frac{\beta}{K}\right)\left(a^2 - \frac{\beta}{K}\right) + \frac{\beta^2}{K} \end{aligned}$$

Coherent state is an eigenstate of annihilation operator a, $a|\alpha\rangle = \alpha|\alpha\rangle$

H_{KPO} has degenerate eigenstates of $|\pm\alpha\rangle$, where $\alpha = \sqrt{\frac{\beta}{K}}$

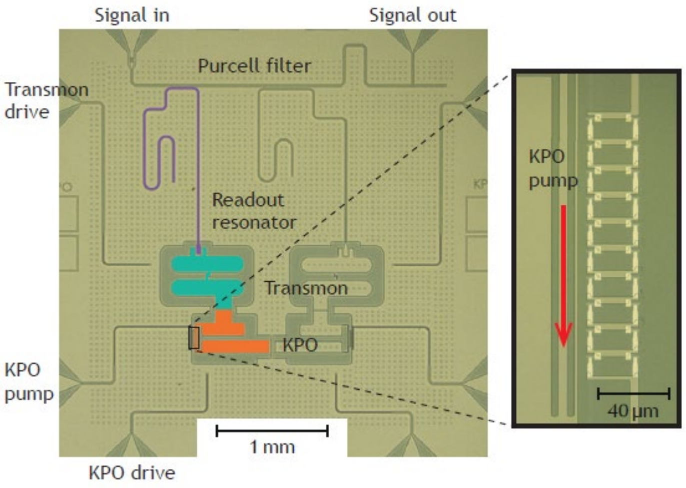


parity conservation

© NEC Corporation 2024
\Orchestrating a brighter world NEC

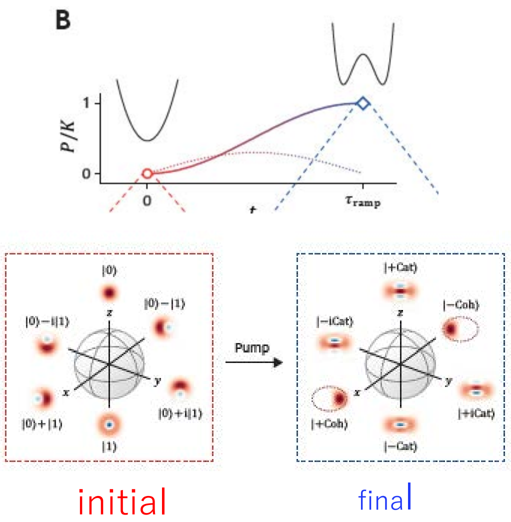
Generation of Kerr cat qubit

Device picture



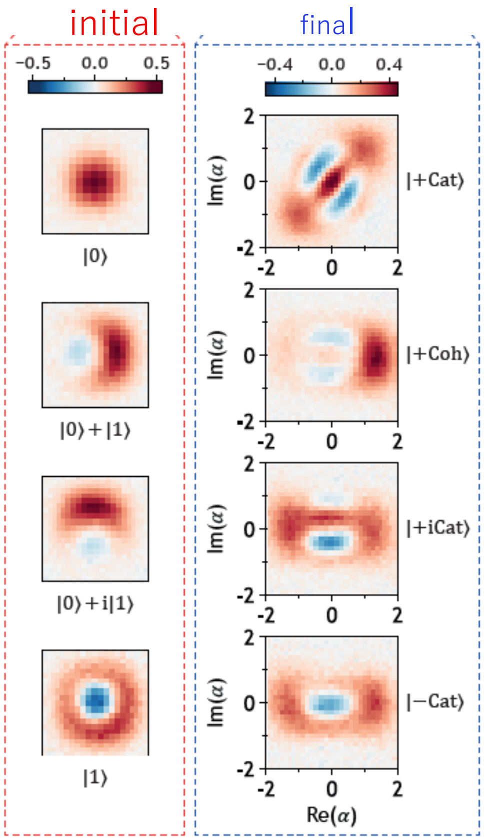
Iyama et al., Nature Commun. **15**, 86 (2024).

adiabatic pumping
(with counter diabatic pump)



c.f.
Z. Wang et al., Phys. Rev. X **9**, 021049 (2019).
A. Grimm *et al.*, Nature **584**, 205 (2020).

Wigner tomography

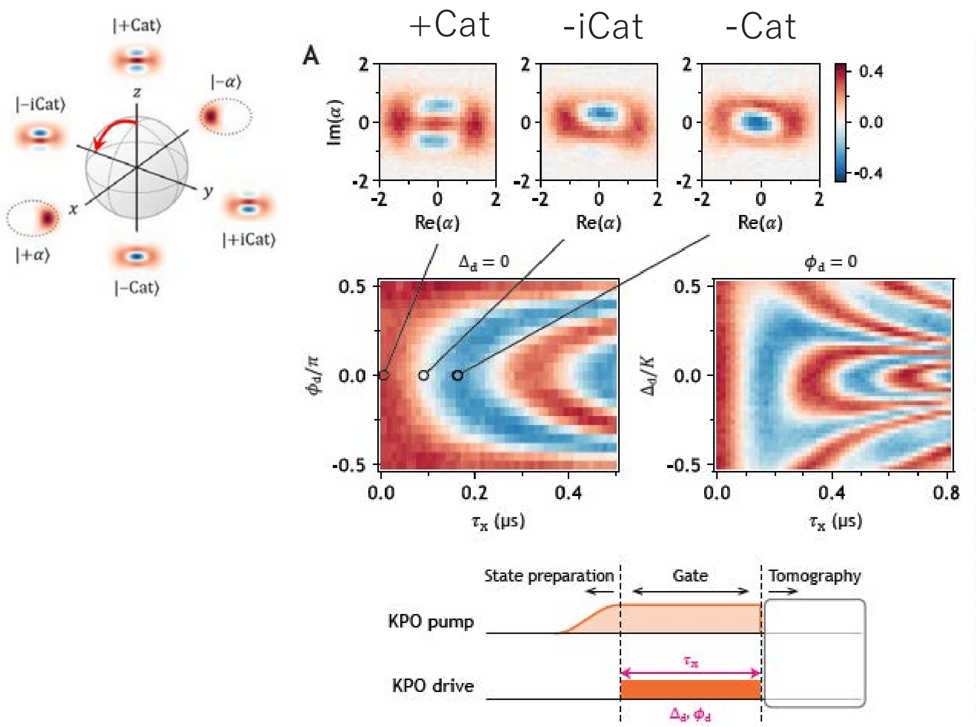


© NEC Corporation 2024
\Orchestrating a brighter world NEC

R_x and R_z gate operations

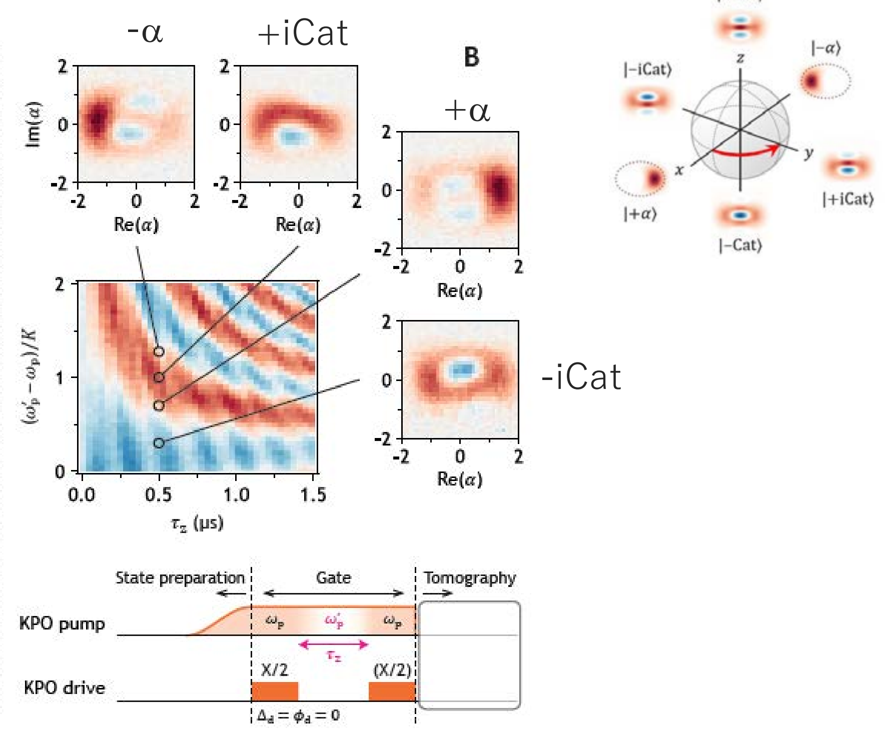
Iyama et al., Nature Commun. **15**, 86 (2024).

X rotation



process fidelity for $R_x(\pi/2) = 0.844$

Z rotation



process fidelity for $R_z(\pi/2) = 0.794$

© NEC Corporation 2024
\Orchestrating a brighter world NEC

Entangled cat state generation from Bell-Fock state

D. Hoshi, T. Nagase et al.,
APS March Meeting 2024

© NEC Corporation 2024
\Orchestrating a brighter world NEC

2-qubit gate on Kerr cat qubits

D. Hoshi, T. Nagase et al.,
APS March Meeting 2024

© NEC Corporation 2024
\Orchestrating a brighter world NEC

システムレベルでの量子コンピュータアーキテクチャの探索：QAOAを例として

IEEE COMPUTER ARCHITECTURE LETTERS, VOL. 23, NO. 1, JANUARY-JUNE 2024 9

Inter-Temperature Bandwidth Reduction in Cryogenic QAOA Machines

Yosuke Ueno, Yuna Tomida, Teruo Tanimoto, Masamitsu Tanaka, Yutaka Tabuchi, Koji Inoue, and Hiroshi Nakamura


Y. Ueno

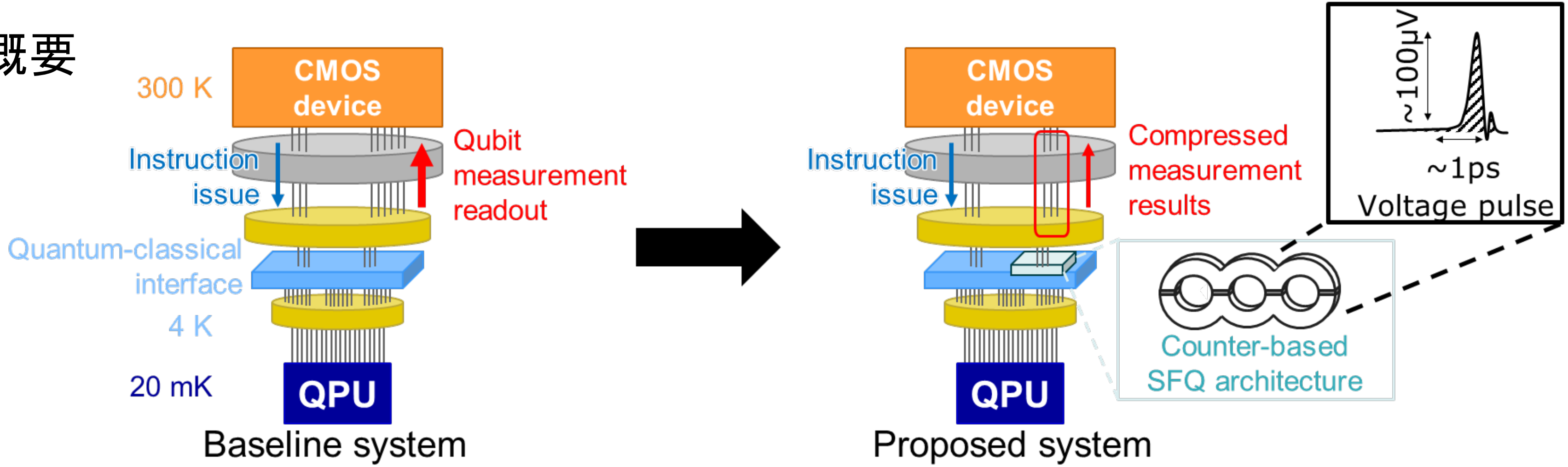

K. Inoue

RIKEN KYUSHU UNIVERSITY NAGOYA UNIVERSITY

\Orchestrating a brighter world NEC

NISQアルゴリズム向け量子コンピュータ・システムの設計

概要



超伝導量子コンピュータの冷凍機内の温度ステージ間配線に着目

– ハードウェア量、ケーブルの熱流入や周辺機器の発熱による熱散逸が問題

QAOAでは、**量子ビット読み出し**に必要な通信が支配的

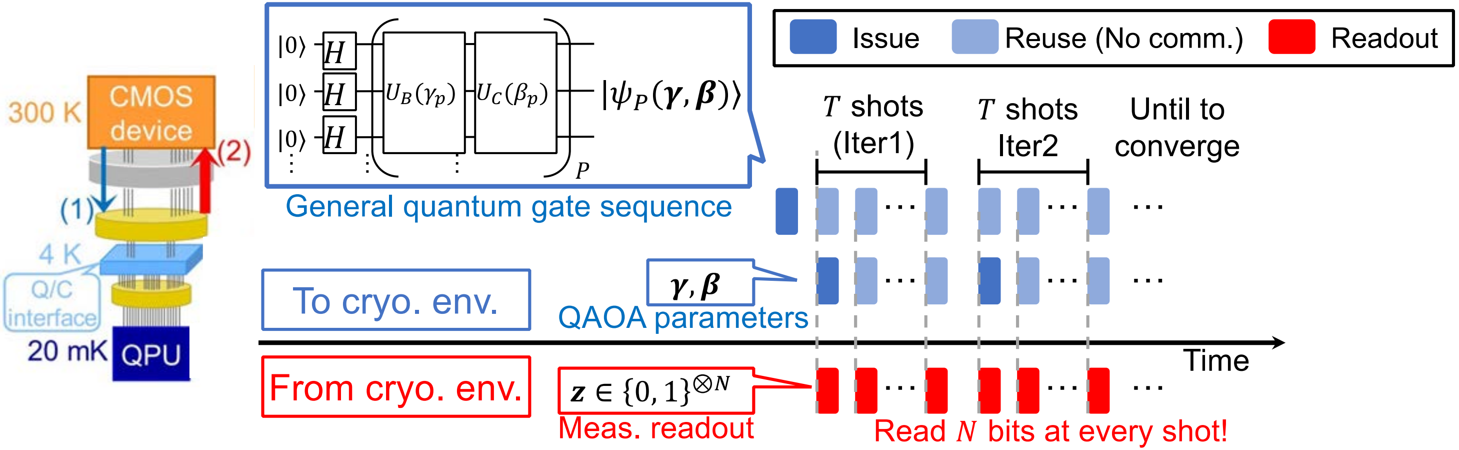
SFQカウンタ・アーキテクチャにより必要バンド幅を削減

© NEC Corporation 2024
\Orchestrating a brighter world NEC

NISQアルゴリズム向け量子コンピュータ・システムの設計

◆ QAOAにおける通信パターンの解析

- 同じ量子回路を繰り返し実行 → 同じ命令列を**再利用**
- 回路パラメータ（γ, β）をTショット毎に更新
- 通信量の大部分は量子ビット観測データ → **ボトルネック！**

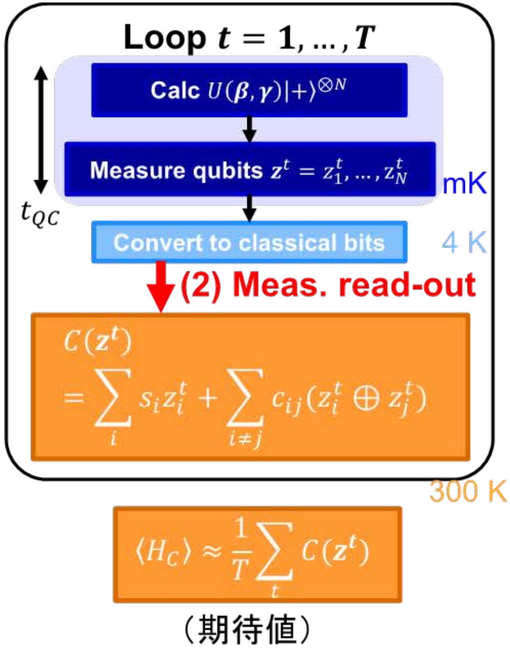


© NEC Corporation 2024

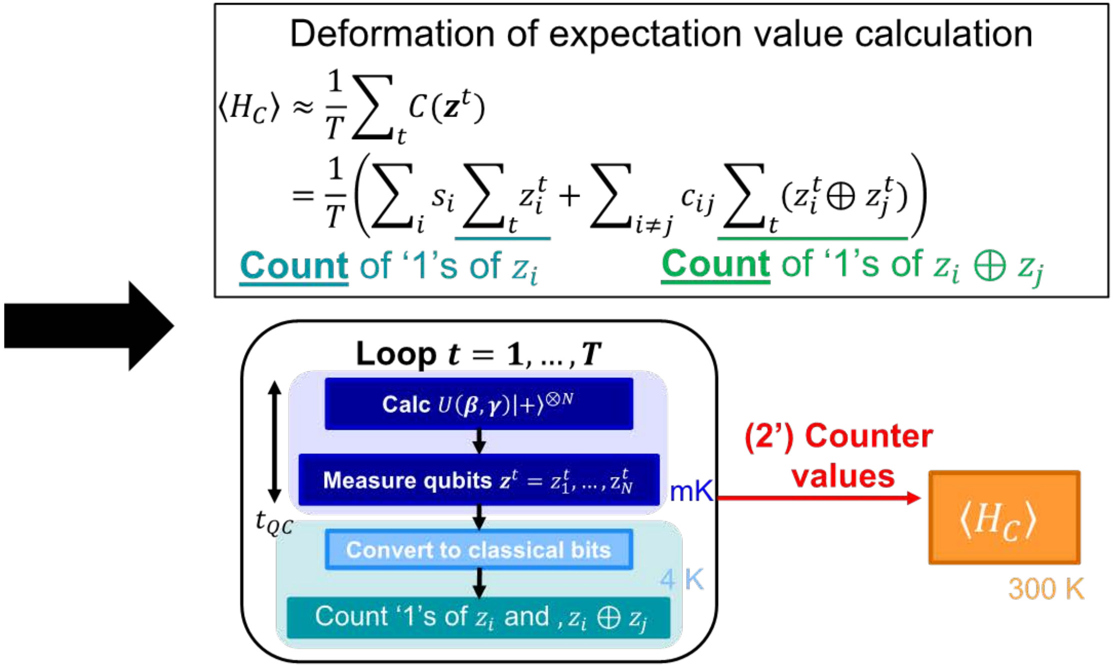
NISQアルゴリズム向け量子コンピュータ・システムの設計

◆ カウンタを用いたQAOA期待値計算

元の期待値計算



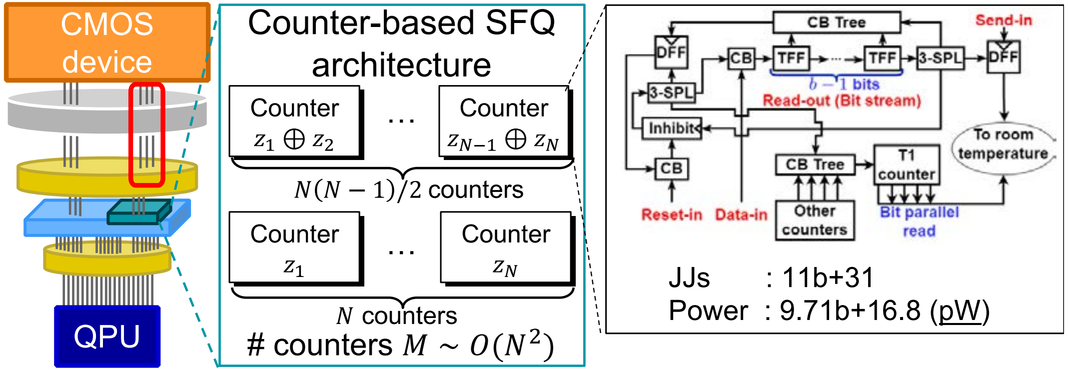
カウンタを使った計算

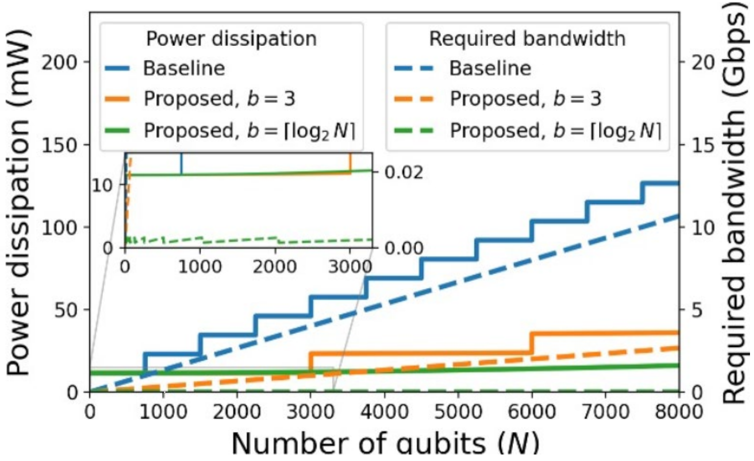


© NEC Corporation 2024
\Orchestrating a brighter world NEC

NISQアルゴリズム向け量子コンピュータ・システムの設計

- ◆ QAOAにおける期待値計算を冷凍機の中でSFQカウンタにより部分的に先行実行
- ◆ カウンタのビット幅bに対して指数的なバンド幅削減効果





Y. Ueno et al., IEEE Comput. Archit. Lett. **23**, 9 (2024).

© NEC Corporation 2024
\Orchestrating a brighter world NEC

量子ビット高強度読出しの解析のための効率的数値計算手法の開発

PHYSICAL REVIEW A **108**, 033722 (2023)

Efficient numerical approach for the simulations of high-power dispersive readout with time-dependent unitary transformation

Shimpei Goto* and Kazuki Koshino†
College of Liberal Arts and Sciences, Tokyo Medical and Dental University, Ichikawa, Chiba 272-0827, Japan

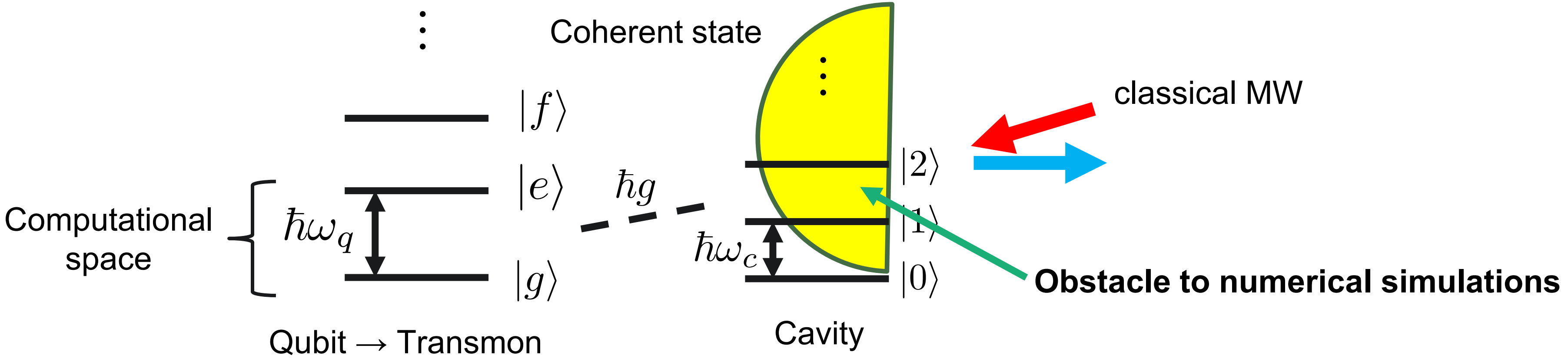
TMDU
TOKYO MEDICAL AND DENTAL UNIVERSITY

S. Goto

K. Koshino

Towards fast dispersive readout

How about using high-power input MW to shorten readout time?

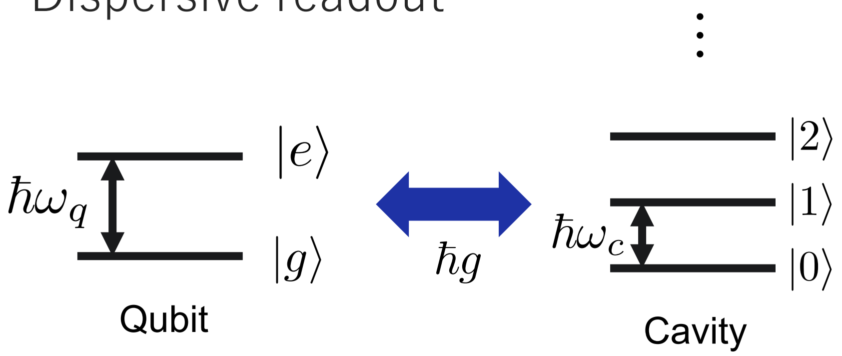


- For large |*n*>, nonlinearity of cavity becomes apparent (critical photon number, n_c)
- Possibility of the excitation to the outer space of computational space

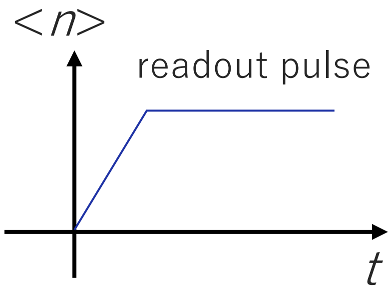
© NEC Corporation 2024

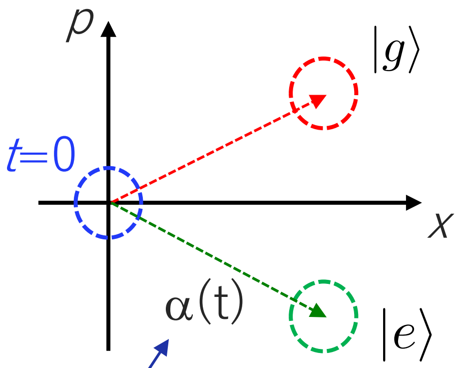
Basic idea

Dispersive readout



$$\frac{\hbar\omega_q}{2}\hat{Z} + \hbar\omega_c\hat{c}^\dagger\hat{c} + \hbar g(\hat{\sigma}^\dagger\hat{c} + \hat{\sigma}\hat{c}^\dagger)$$





Problematic for numerical simulations for large |α|

Lindblad master equation

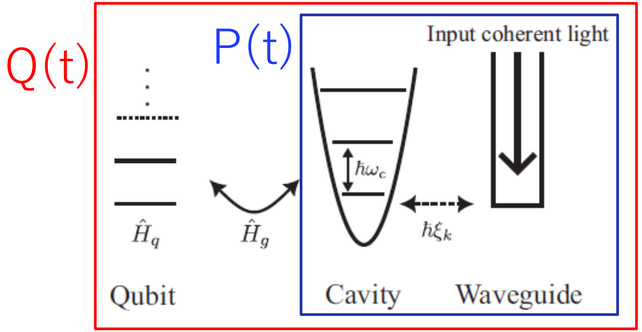
$$\frac{\partial}{\partial t}\hat{\rho}(t) = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}(t)] + \sum_i \gamma_i \left(\hat{L}_i\hat{\rho}(t)\hat{L}_i^\dagger - \frac{1}{2}\left\{\hat{L}_i^\dagger\hat{L}_i, \hat{\rho}(t)\right\}\right)$$

Apply time-dependent unitary transformation $\hat{D}^{-1}[\alpha(t)]$ so that $\langle\hat{c}(t)\rangle$ in displaced frame is small.

© NEC Corporation 2024

Choices of displacement

- Driving frame P(t) : previous method
  - Determine α (t) so that the driving field is absent → Coefficient of $\hat{c}$ is set to zero
  - Adopted in previous works: Phys. Rev. A 75, 032309 (2007) etc.
  - $\langle \hat{c}(t) \rangle_U$ is not necessarily zero because of finite qubit-resonator coupling



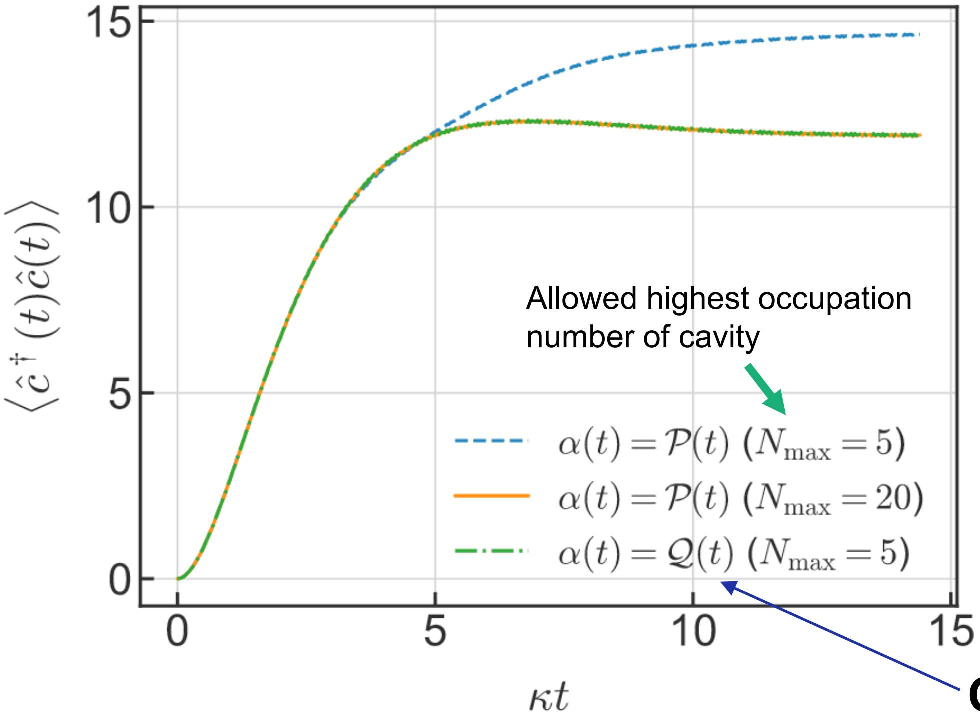
- Absence frame Q(t) : our method
  - Determine α (t) so that $\langle \hat{c}(t) \rangle_U$ does not change from $\langle \hat{c}(0) \rangle_U = 0$

$$\frac{d}{dt}\langle \hat{c}(t) \rangle_U = \frac{i}{\hbar}\left\langle [\hat{H}_U(t), \hat{c}(t)] \right\rangle_U + \sum_i \gamma_i \left(\left\langle \hat{L}^\dagger_{U,i}(t)\hat{c}(t)\hat{L}_{U,i}(t) \right\rangle_U - \frac{1}{2}\left\langle \left\{ \hat{L}^\dagger_{U,i}(t)\hat{L}_{U,i}(t), \hat{c}(t) \right\} \right\rangle_U \right)$$

$$= 0$$

© NEC Corporation 2024
\Orchestrating a brighter world

Comparison of the frames



$$\hat{H} = \frac{\hbar\omega_q}{2}\hat{Z} + \hbar\omega_c \hat{c}^\dagger \hat{c} + \hbar g \hat{X}(\hat{c} + \hat{c}^\dagger) + E e^{-i\omega_c t}(\hat{c}^\dagger + \hat{c})$$

$$\hat{L} = \hat{c} \quad \gamma = \kappa$$

$$\omega_q/\omega_c = 0.75 \qquad g/\omega_c = 3.0 \times 10^{-2}$$

$$\kappa/\omega_c = 7.2 \times 10^{-3}$$

$$E/\omega_c = 1.0 \times 10^{-2}$$

Our proposed frame can reproduce the dynamics with fewer states

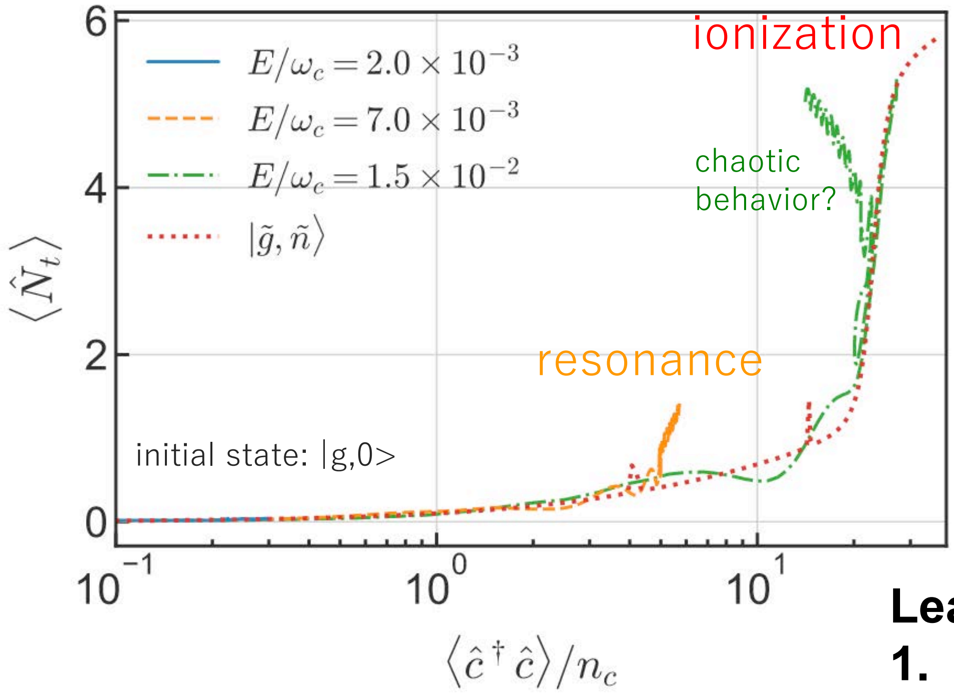
S. Goto and K. Koshino, Phys. Rev. A **108**, 033722 (2023).

© NEC Corporation 2024

\Orchestrating a brighter world NEC

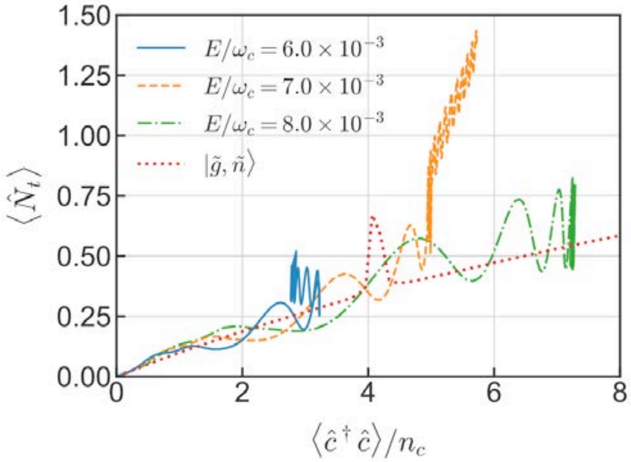
Transmon dynamics during readout

transmon occupation number



i-th excited state of transmon

$$\hat{N}_t = \sum_i i \, |i\rangle \langle i|$$



S. Goto and K. Koshino, Phys. Rev. A **108**, 033722 (2023).

Leakage occurs

1. **in high-occupation number region**
2. **in region close to resonant points**

© NEC Corporation 2024
\Orchestrating a brighter world NEC

プロジェクト活動紹介記事＆ビデオ

nature portfolio

ADVERTISEMENT FEATURE Advertiser retains sole responsibility for the content of this article

Realizing practical quantum computers based on superconductors

By using superconductors, researchers in Japan are seeking to make quantum computers large enough to tackle real-life problems.

Produced by

nature research custom media   MOONSHOT RESEARCH & DEVELOPMENT PROGRAM

A section of a quantum computer based on superconductors. Researchers at NEC are exploring such quantum computers. Credit: Bartlomiej Wroblewski/iSatock/Getty

Toward the Realization of a Superconducting Fault-Tolerant Quantum Computer - Moonshot Goal 6 (NEC) - You...

To achieve a fault-tolerant quantum computer, a significantly large number of physical qubits is required. However, many of the techniques presently utilized...

www.youtube.com

[Toward the Realization of a Superconducting Fault-Tolerant Quantum Computer - Moonshot Goal 6 (NEC) (youtube.com)]

[Realizing practical quantum computers based on superconductors (nature.com)]

\Orchestrating a brighter world

NECは、安全・安心・公平・効率という社会価値を創造し、

誰もが人間性を十分に発揮できる持続可能な社会の実現を目指します。

\Orchestrating a brighter world

NEC