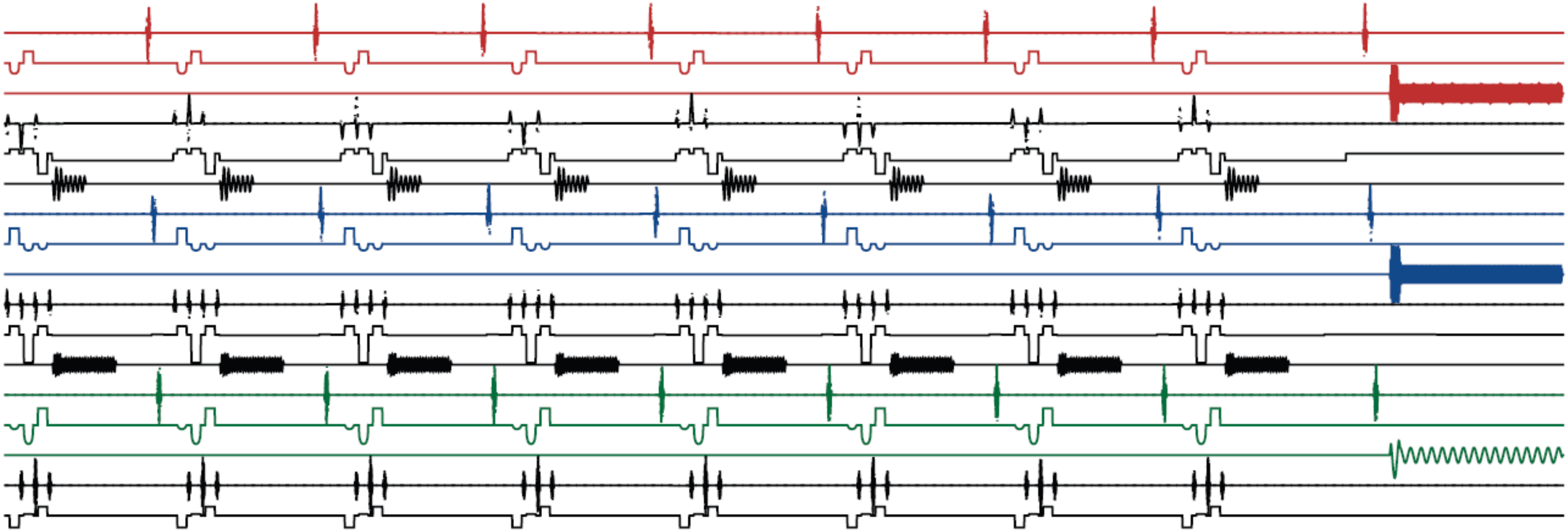
ETH zürich



Error Correction in Superconducting Circuits

Adrian Beckert

Lars Kristiansen

Motivation

- Decoherence/Environmental influences
- Dephasing
- Gate operations and quantum computing need time

Outline

- Theory
  - Classical error correction
  - Quantum error correction
  - Error supresssion factor Λ
- Experiment
  - Setup
  - Measurement procedure
- Results

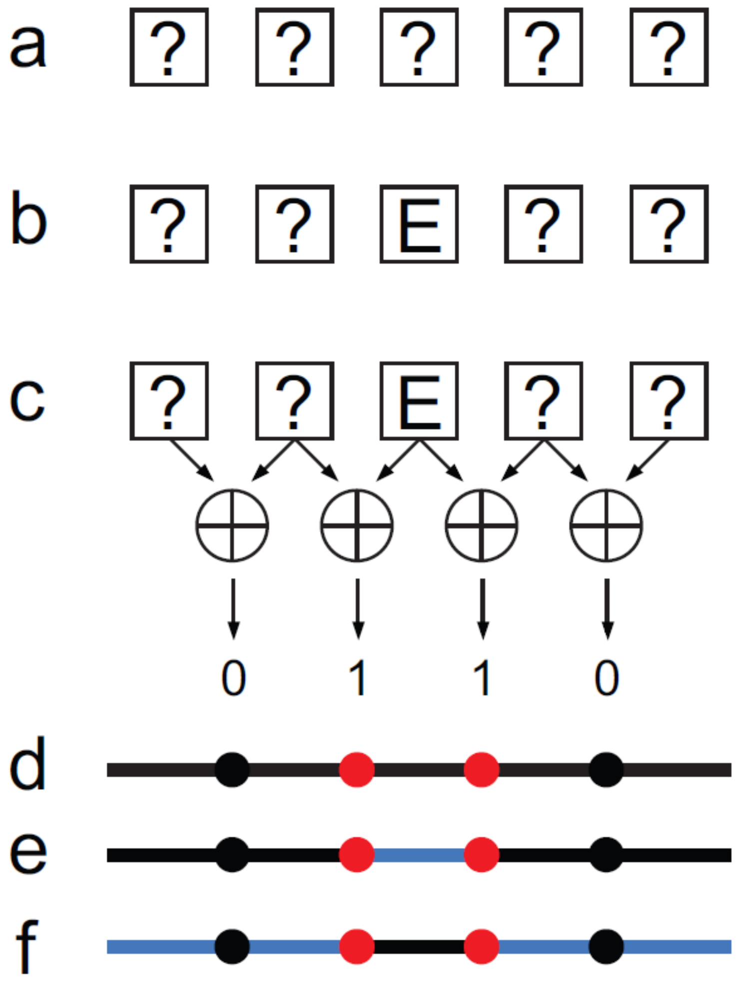
Classical Repetition Code

Improve error tolerance by storing multiple copies of a bit.

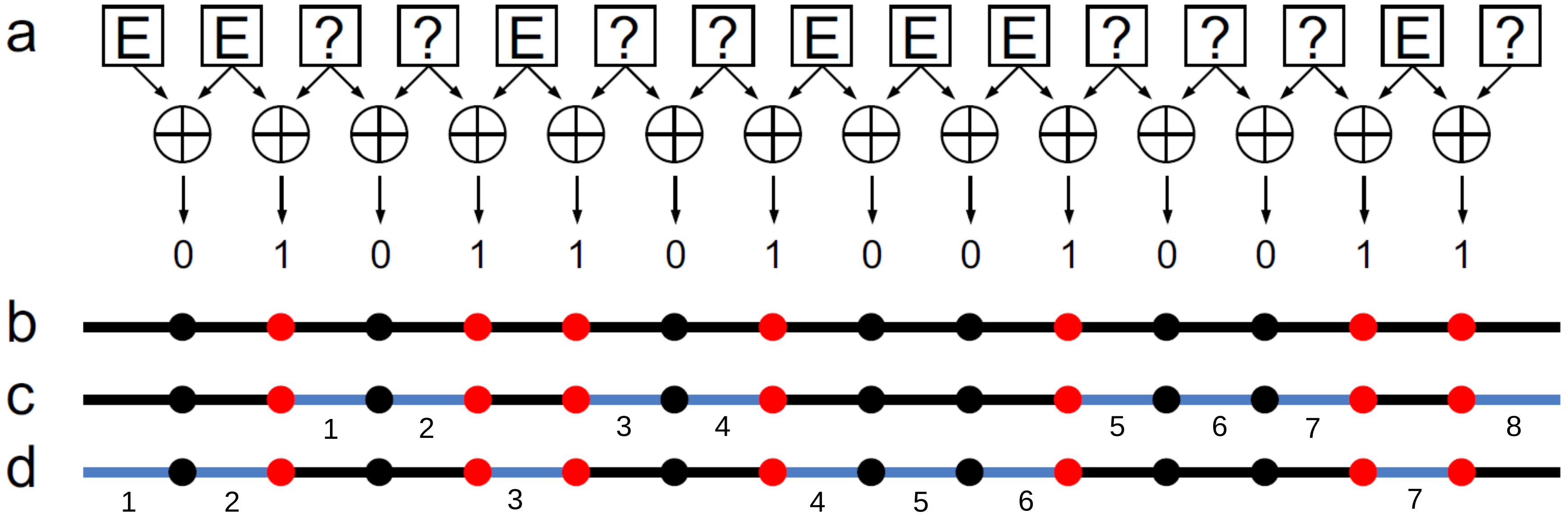
Assumption: independent errors.

Correction method: Majority voting.

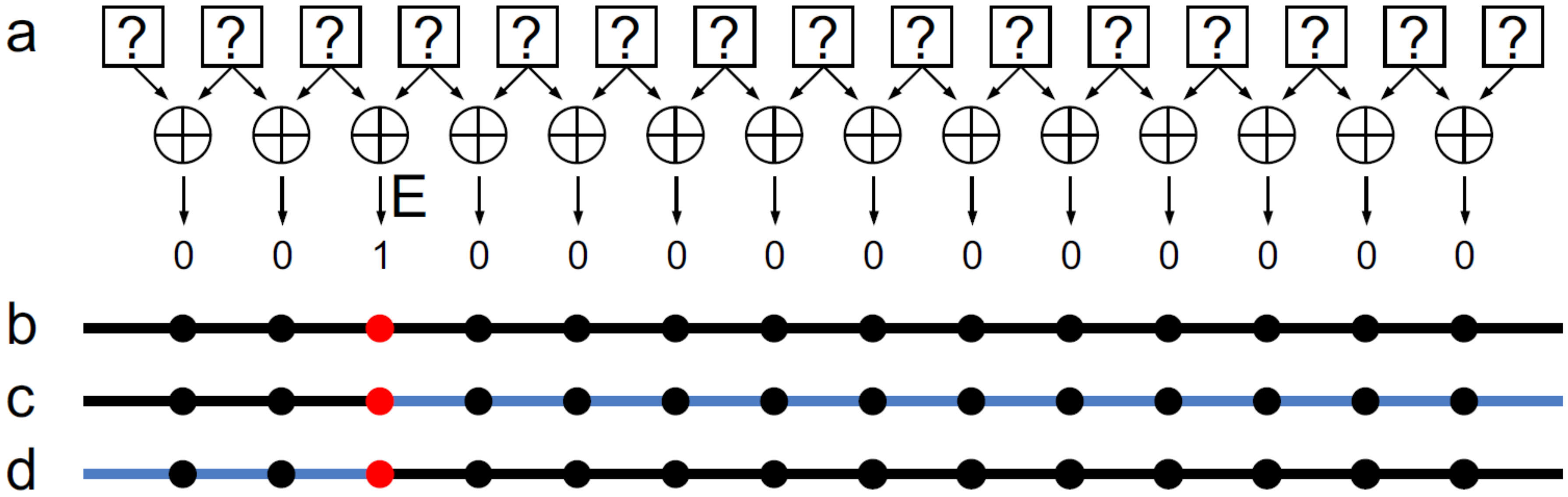
Parity information is sufficient.



An Example



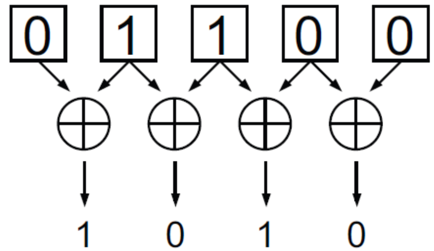
Parity Measurement Errors



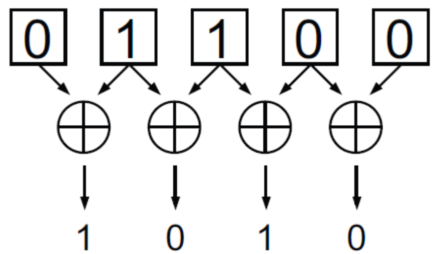
Correction method does not work for measurement errors.

Another Example

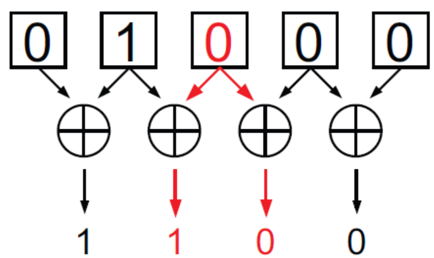
t=0



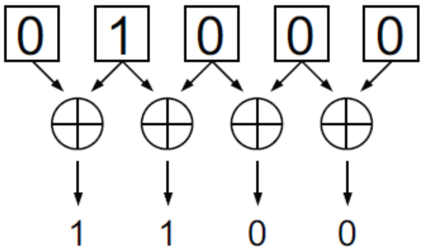
t=1
All parities identical,
no detection events.



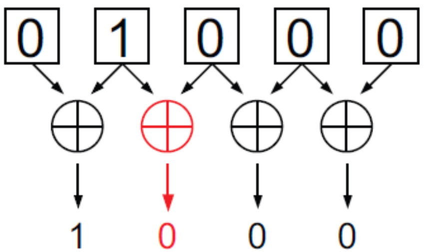
t=2
Two parities differ,
two detection events.



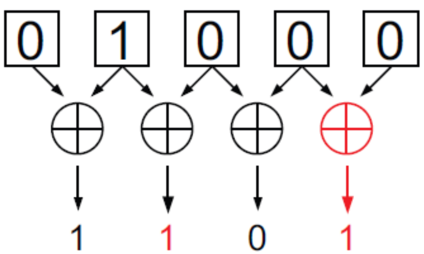
t=3
All parities identical,
no detection events.



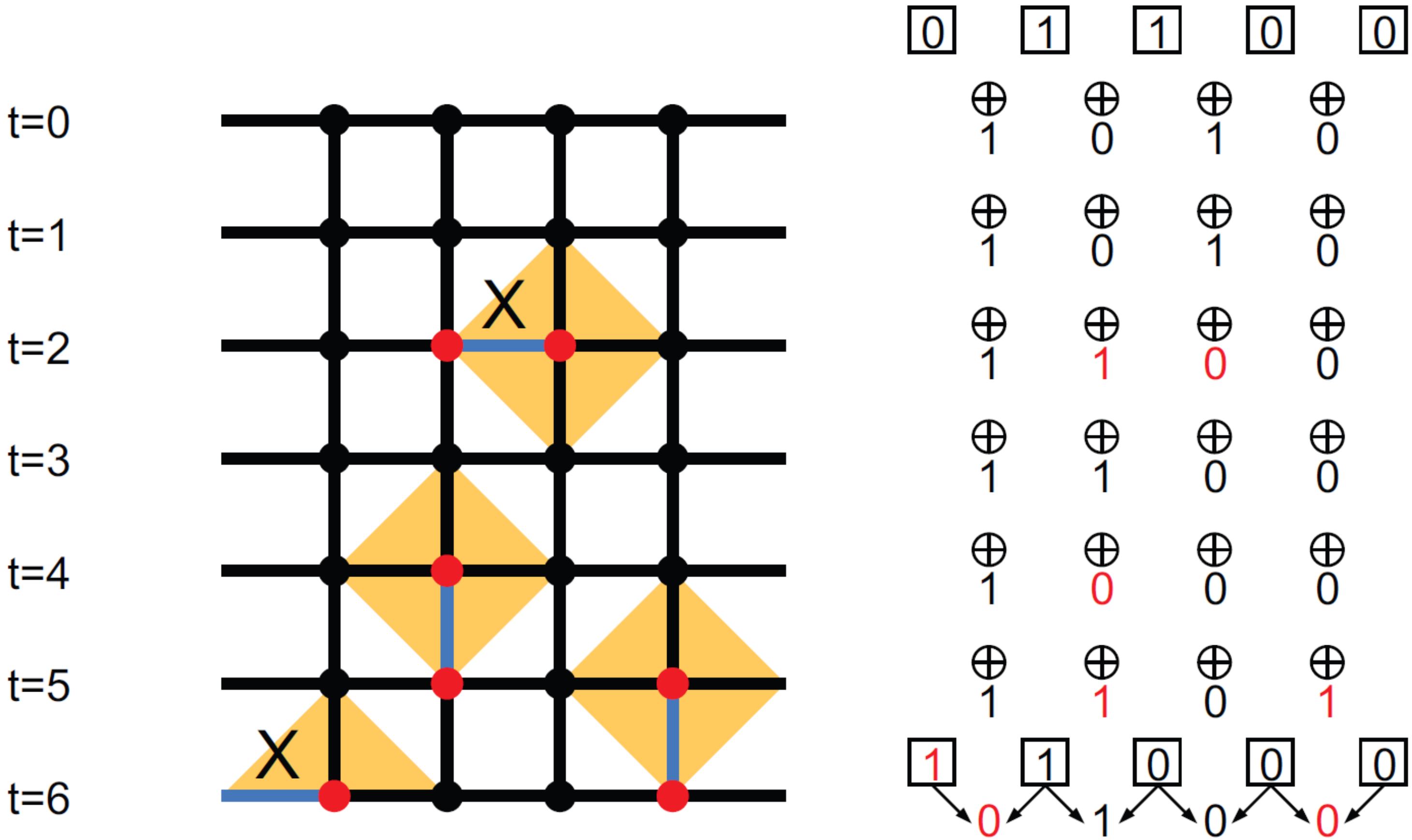
t=4
One parity differs,
one detection event.



t=5
Two parities differ,
two detection events.



Error Connectivity Graph



Quantum Repetition Code

Goal: Make qubits less susceptible to errors by using multiple qubits to store the state.

Bit-flip (X) and phase-flip (Z) errors

Logical states for repetition code with m qubits.

$$|0_L\rangle = |0..0\rangle \qquad |1_L\rangle = |1..1\rangle$$

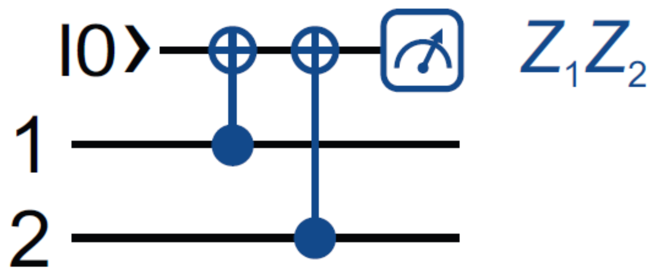
*n*th-order fault tolerance is defined to mean that any combination of *n* errors is tolerable. (n < [m/2])

How to measure the parity of qubits?

The $\hat{Z}\hat{Z}$ operator measures the parity of two qubits because

$$\hat{Z}\hat{Z}|00\rangle = +|00\rangle \qquad \hat{Z}\hat{Z}|01\rangle = -|01\rangle$$
$$\hat{Z}\hat{Z}|11\rangle = +|11\rangle \qquad \hat{Z}\hat{Z}|10\rangle = -|10\rangle$$

Implement this by introducing an ancilla measurement qubit to CNOT gates.



$|00\rangle$ and $|11\rangle$ give $|0\rangle$ for the ancilla qubit state

$|01\rangle$ and $|10\rangle$ give $|1\rangle$ for the ancilla qubit state

An example.

Initial state: $|\Psi\rangle = (\alpha\,|00\rangle_\mathrm{D} + \beta\,|11\rangle_\mathrm{D}) \otimes |0\rangle_\mathrm{A}$

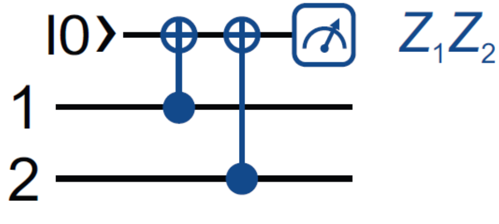
Rotate qubit 1 around the x-axis: $|\Psi'\rangle = [\gamma(\alpha\,|00\rangle_\mathrm{D} + \beta\,|11\rangle_\mathrm{D}) + \delta(\alpha\,|10\rangle_\mathrm{D} + \beta\,|01\rangle_\mathrm{D})] \otimes |0\rangle_\mathrm{A}$

Apply the CNOT gates: $|\Psi''\rangle = \gamma(\alpha\,|00\rangle_\mathrm{D} + \beta\,|11\rangle_\mathrm{D}) \otimes |0\rangle_\mathrm{A} + \delta(\alpha\,|10\rangle_\mathrm{D} + \beta\,|01\rangle_\mathrm{D}) \otimes |1\rangle_\mathrm{A}$

After measurement:

$$|\Psi\rangle = (\alpha\,|00\rangle_\mathrm{D} + \beta\,|11\rangle_\mathrm{D}) \otimes |0\rangle_\mathrm{A}$$

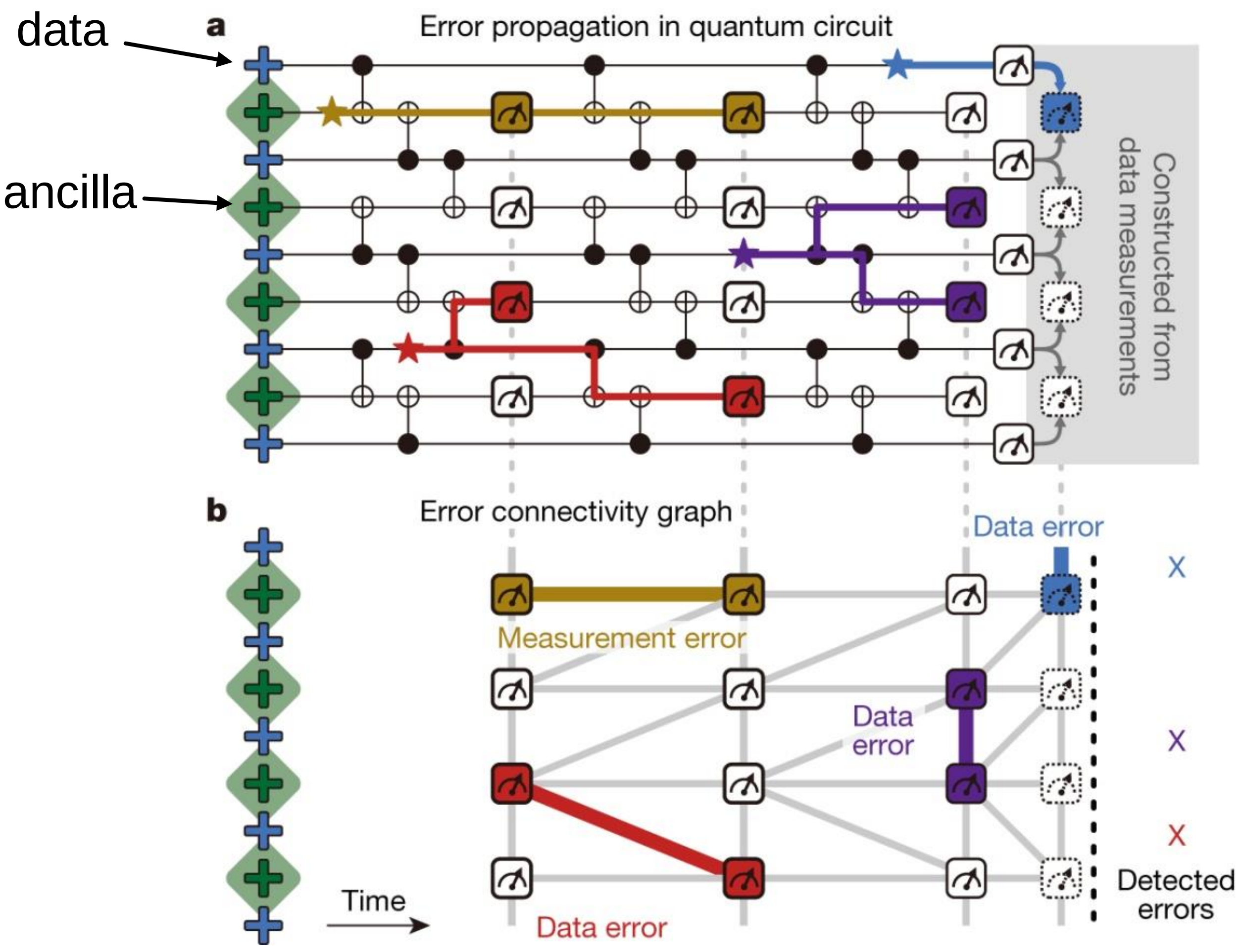
$$|\Phi\rangle = (\alpha\,|10\rangle_\mathrm{D} + \beta\,|01\rangle_\mathrm{D}) \otimes |1\rangle_\mathrm{A}$$



Correction: $|\Psi\rangle = \mathrm{X}_1\,|\Phi\rangle$

Parity measurement does not change the state of the data qubits!

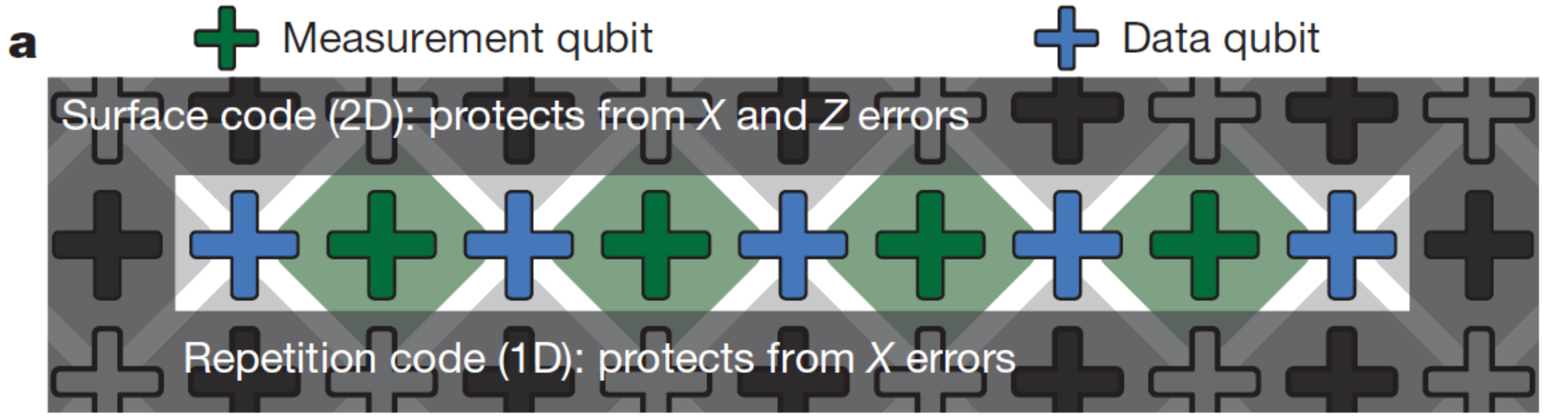
Error propagation and identification.



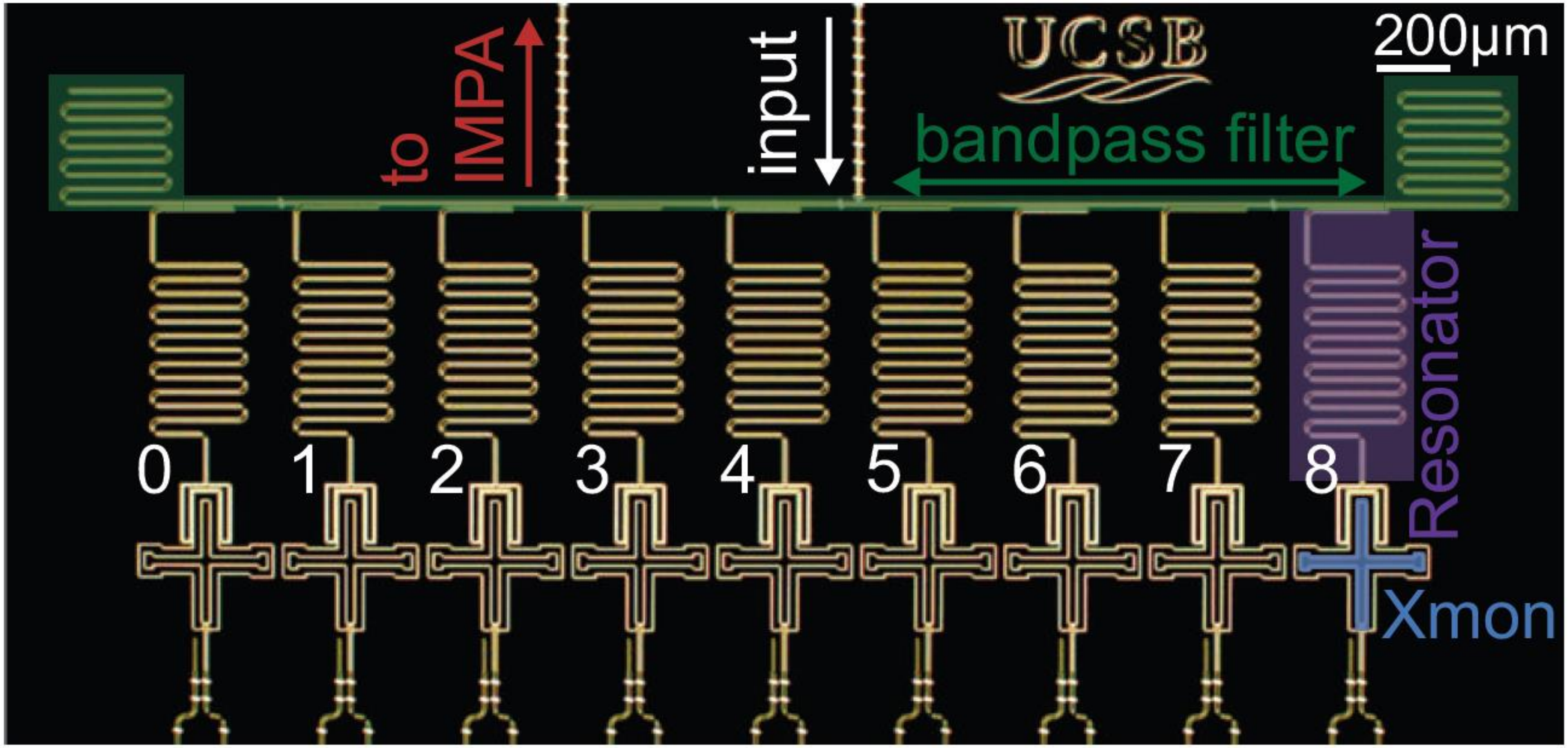
Error supression factor Λ and Fidelity

- A measure of how far below the threshold error rate a system is
- Logical error rate $\varepsilon \propto \frac{1}{\Lambda^{n+1}}$ $\Lambda > 1$ with n-th order fault tolerance n
- The "Fidelity" is a measure of closeness of two quantum states

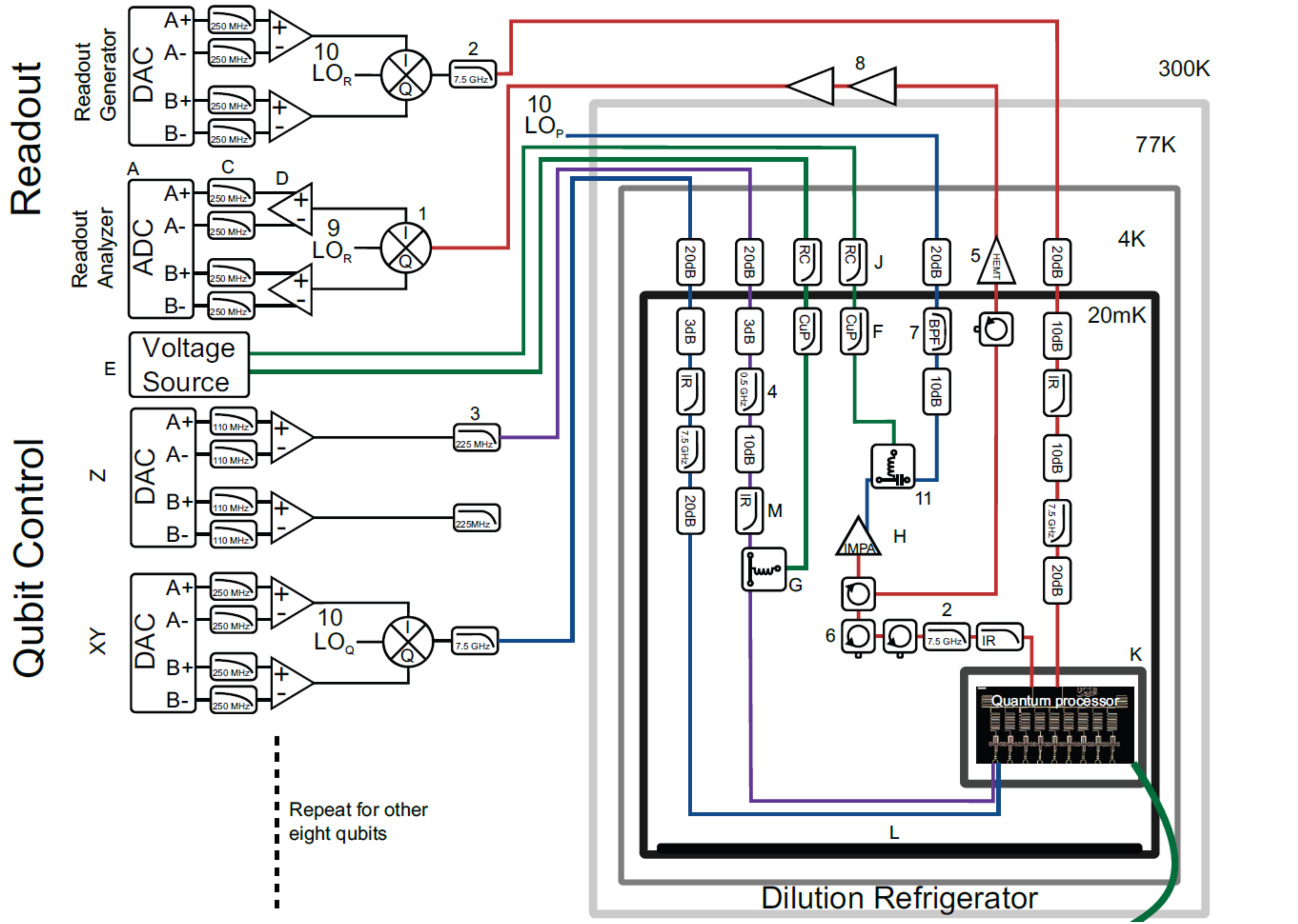
Setup


a
Measurement qubit
Data qubit
Surface code (2D): protects from X and Z errors
Repetition code (1D): protects from X errors

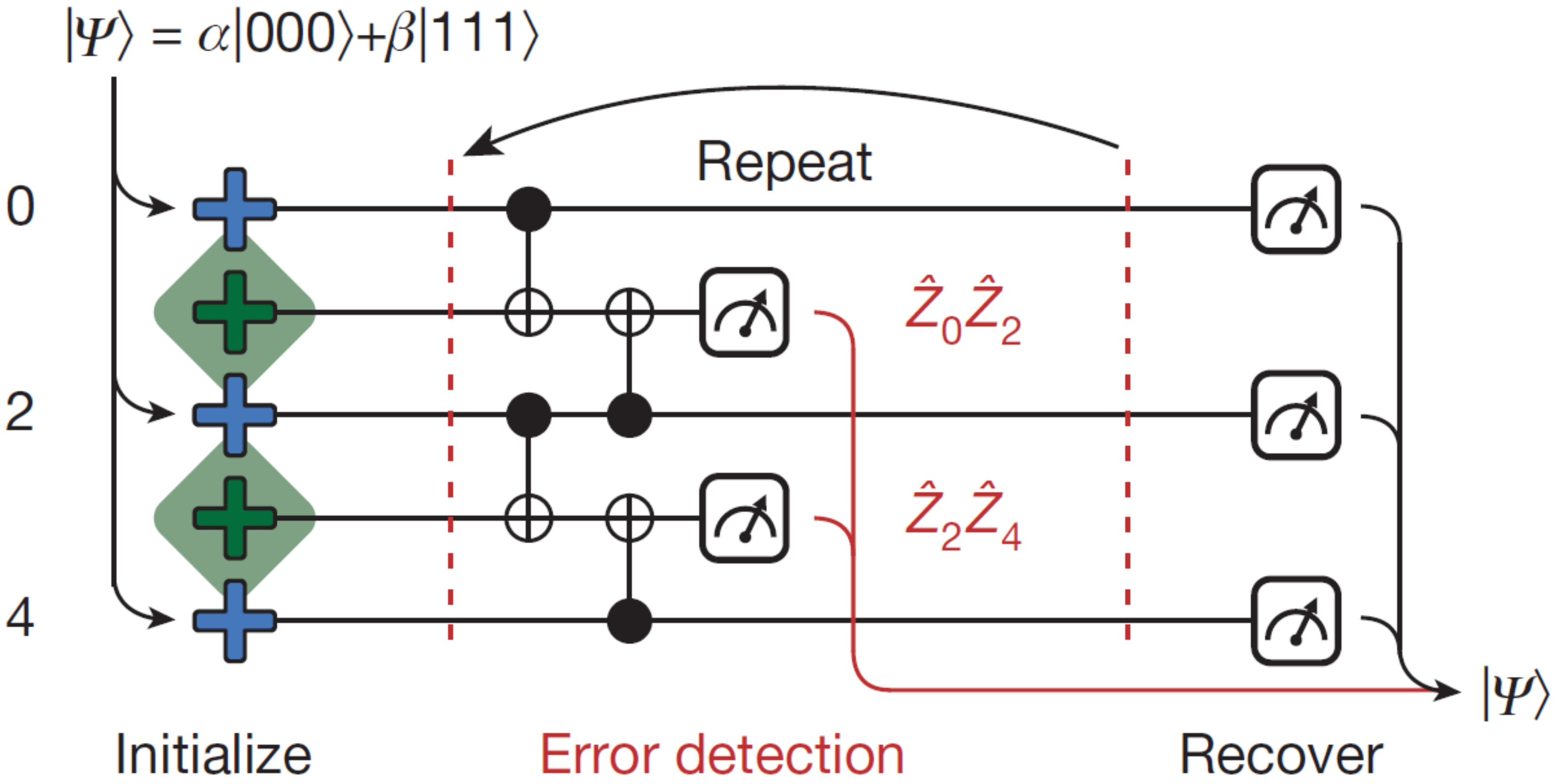
Chip architecture - components



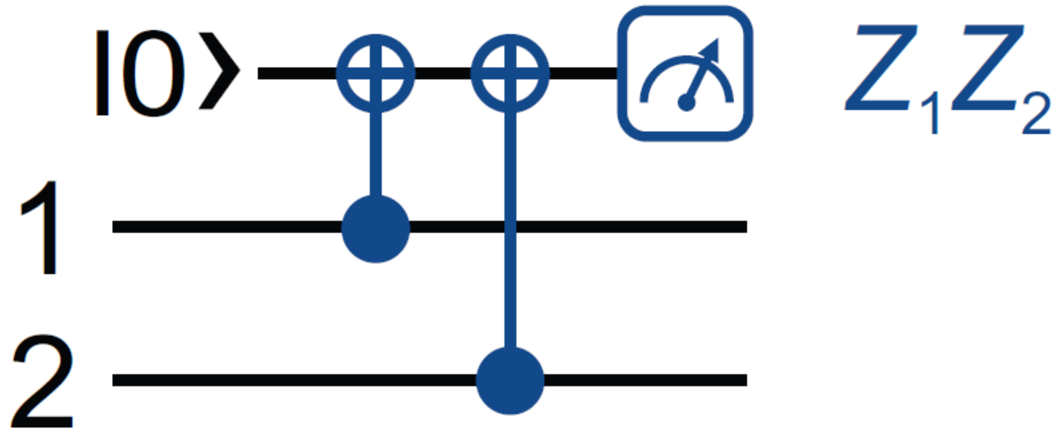
ETH zürich

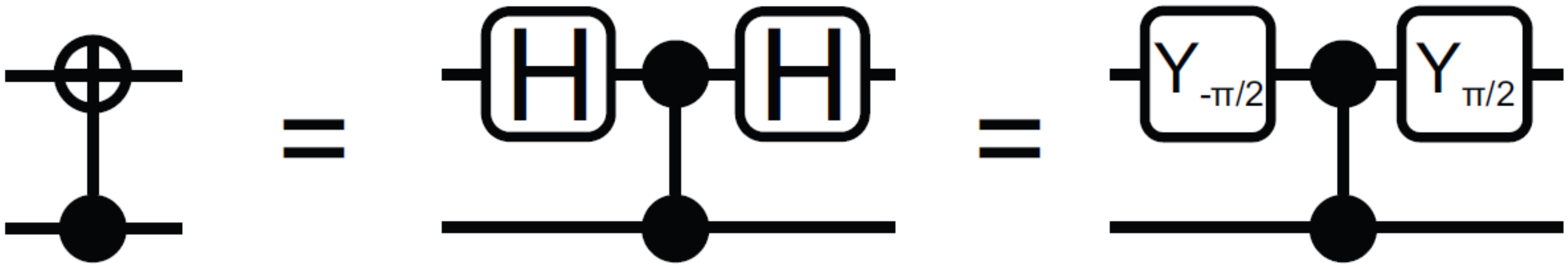

Readout
Readout Generator
DAC
A+
A-
B+
B-
250 MHz
10
LO_R
I
Q
2
7.5 GHz
Readout Analyzer
ADC
A
C
D
1
9
E
Voltage Source
Qubit Control
Z
110 MHz
3
225 MHz
225MHz
XY
LO_Q
Repeat for other eight qubits
300K
77K
4K
20mK
10
LO_P
8
20dB
3dB
10dB
IR
7.5 GHz
0.5 GHz
4
RC
CuP
J
F
BPF
7
5
HEMT
11
M
G
H
IMPA
6
K
Quantum processor
L
Dilution Refrigerator

Measurement procedure

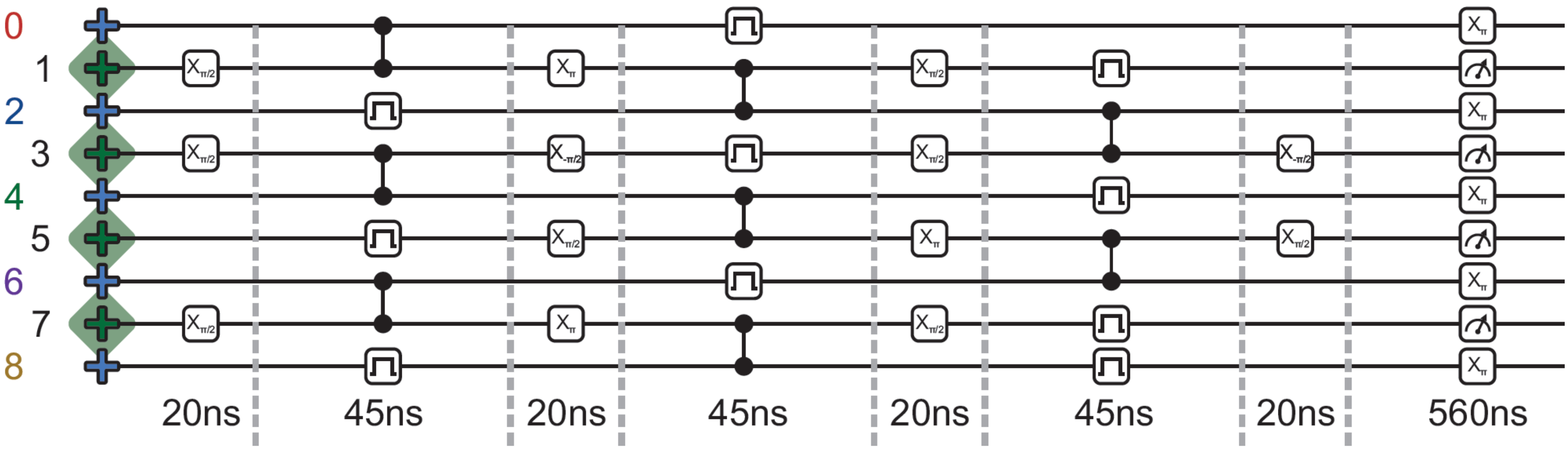


Decomposition of CNOT gate

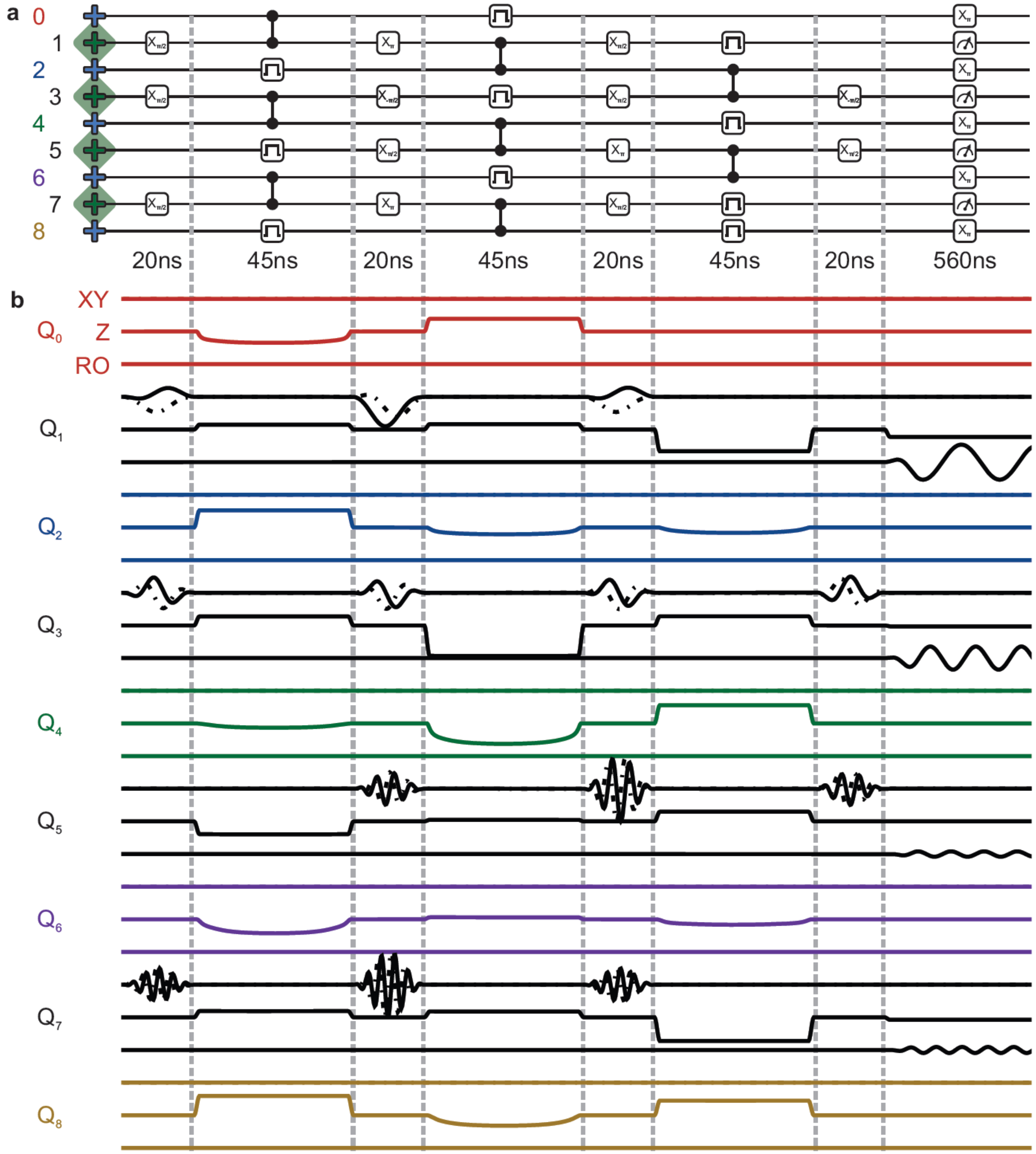




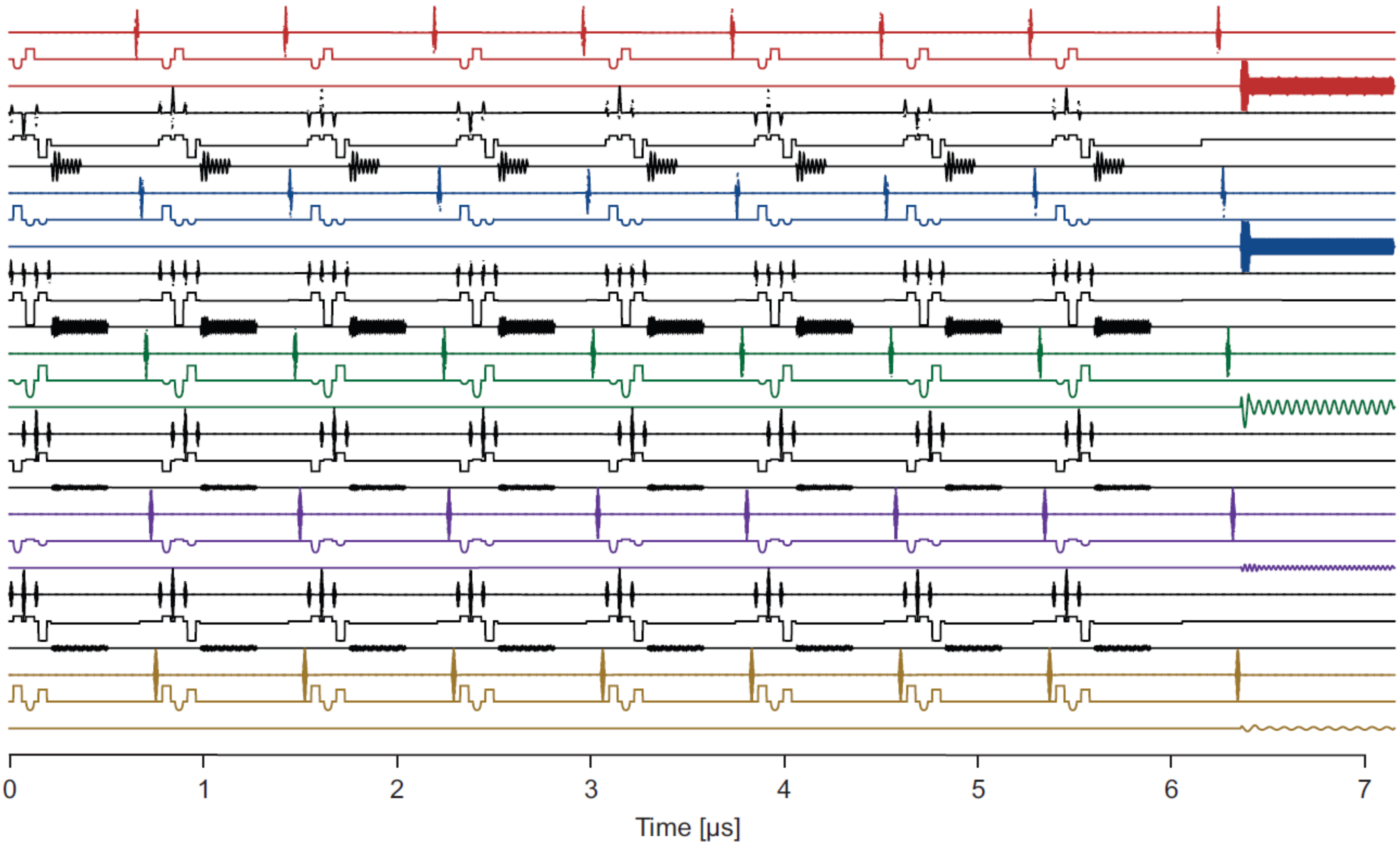
Single repetition code implementation



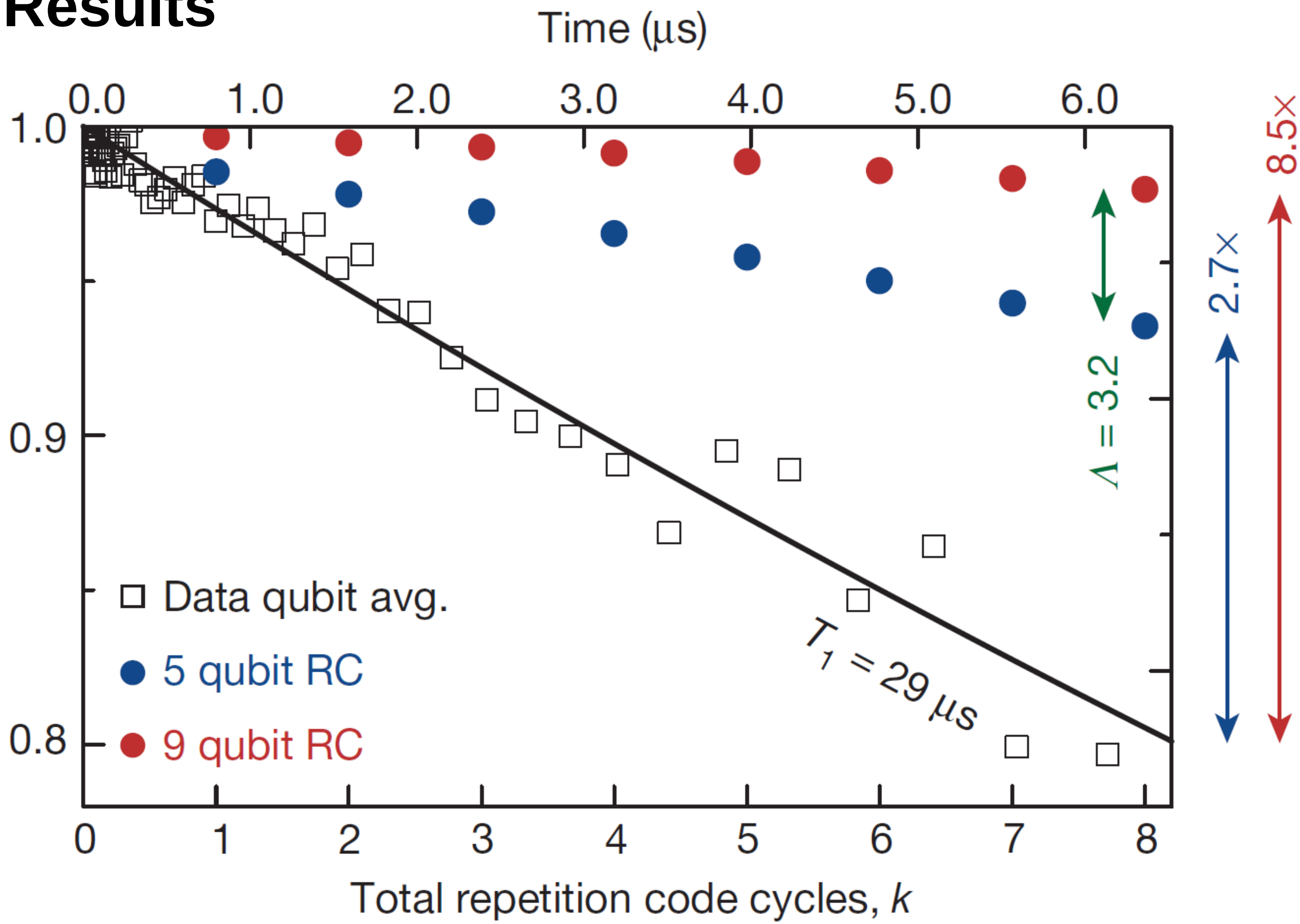
waveform data for 1 cycle



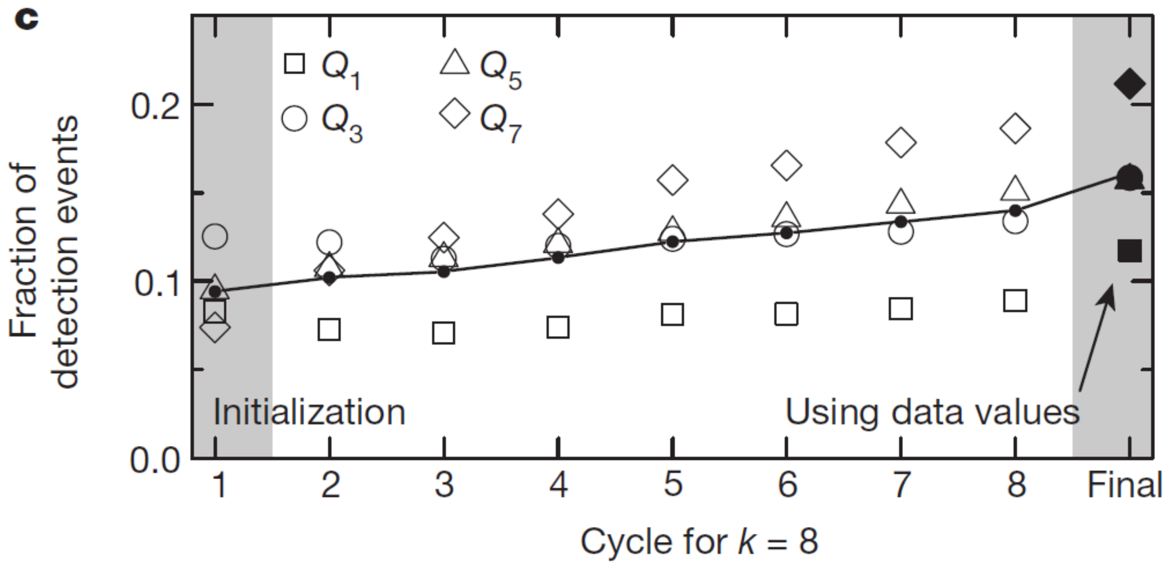
Waveform data for 8 cycles

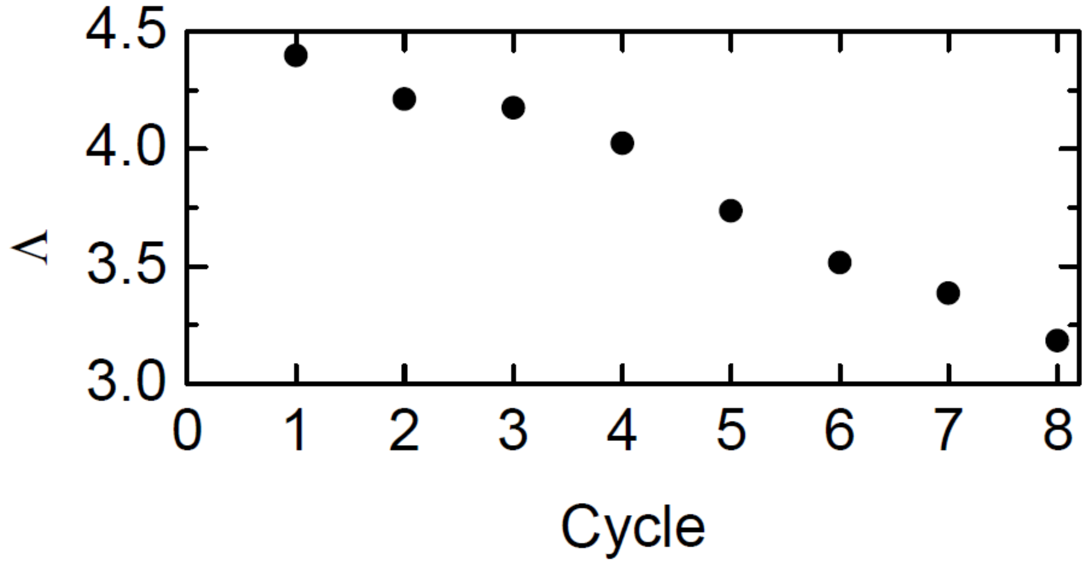


Results


Time (µs)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
1.0
0.9
0.8
0
1
2
3
4
5
6
7
8
Total repetition code cycles, k
Data qubit avg.
5 qubit RC
9 qubit RC
T1 = 29 µs
Λ = 3.2
2.7×
8.5×

Logical error rate and Λ





$$\varepsilon \propto \frac{1}{\Lambda^{n+1}}$$

Acknowledgements & References

Acknowledgements

to Dr. Abdulfarrukh Abdumalikov

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Reference

J. Kelly et al.,State preservation by repetitive error detection in a superconducting quantum circuit, Nature **519**, 66-69 (2015)

Final Slide – Questions?