Tunable coupler to fully decouple and maximally localize superconducting qubits

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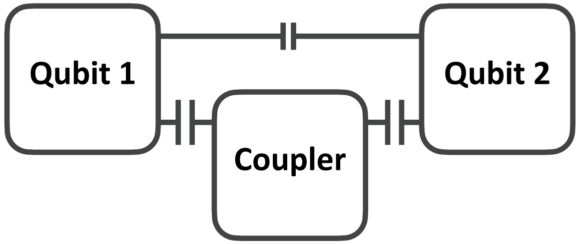
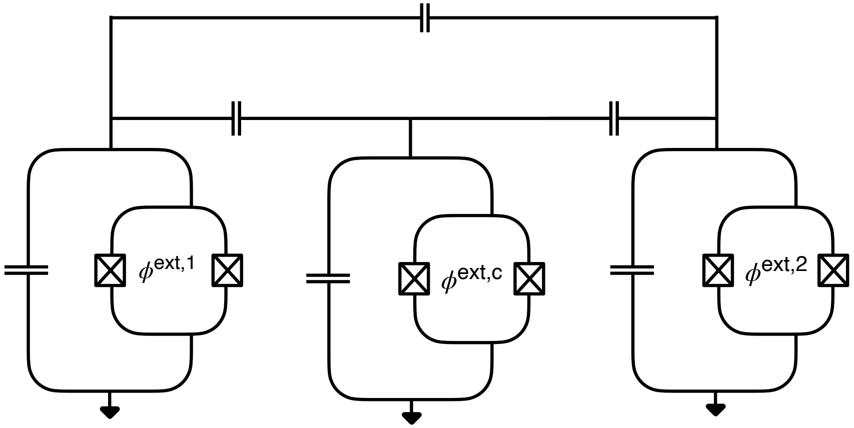
Introduction

Tunable coupler circuits

- Use an additional qubit as coupling element
- Two coupling channels interfere to switch between regimes of large coupling and zero coupling





Main question addressed in this paper:

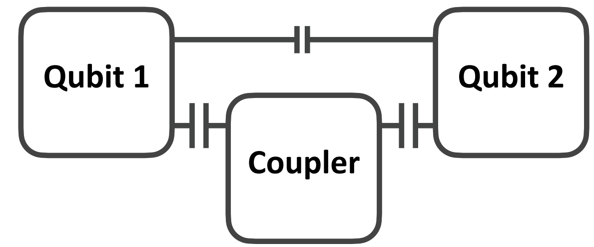
What are these parasitic interactions?

How can we suppress them?

Perturbation theory

Two qubit system with tunable Coupler

$$H = \sum_{i=1,c,2} \omega_i b_i^\dagger b_i + \frac{U_i}{2} b_i^\dagger b_i^\dagger b_i b_i + \sum_{i\neq j} g_{ij} \left(b_i^\dagger b_j + b_j^\dagger b_i \right)$$



State delocalization

$$\epsilon = \max \left(\left| \langle \widetilde{100} \,|\, 001 \rangle \right|^2 , \left| \langle \widetilde{001} \,|\, 100 \rangle \right|^2 \right)$$

- Perturbatively calculate state corrections
- Qubit delocalization minimized for

$$0 = g_{12} + \frac{g_{1c} g_{2c}}{2} \left(\frac{1}{\Delta_{1c}} + \frac{1}{\Delta_{2c}} \right)$$

$$\Delta_{ij} = \omega_i - \omega_j$$

ZZ-crosstalk

$$\zeta = E_{101} - E_{100} - E_{001} + E_{000}$$

- Perturbatively calculate energy corrections up to fourth order

$$\zeta = g_{12}^2 \cdot \mathrm{A} + g_{12} g_{1c} g_{2c} \cdot \mathrm{B} + g_{1c}^2 g_{2c}^2 \cdot \mathrm{C}$$

Restrict coupler anharmonicity

$$U_c = -\frac{U}{2} \cdot \left(1 - \frac{U^2}{\Delta_{12}^2} - \frac{U}{2(\Delta_{1c} + \Delta_{2c})} \right)^{-1}$$

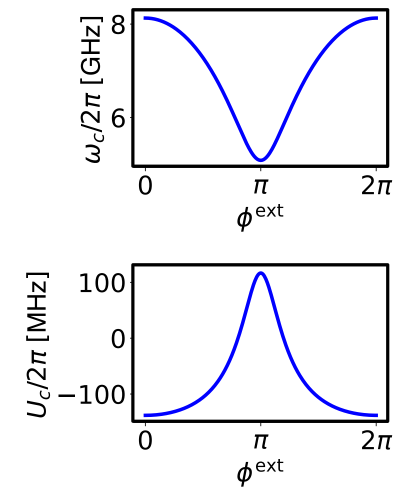
C-shunt flux coupler

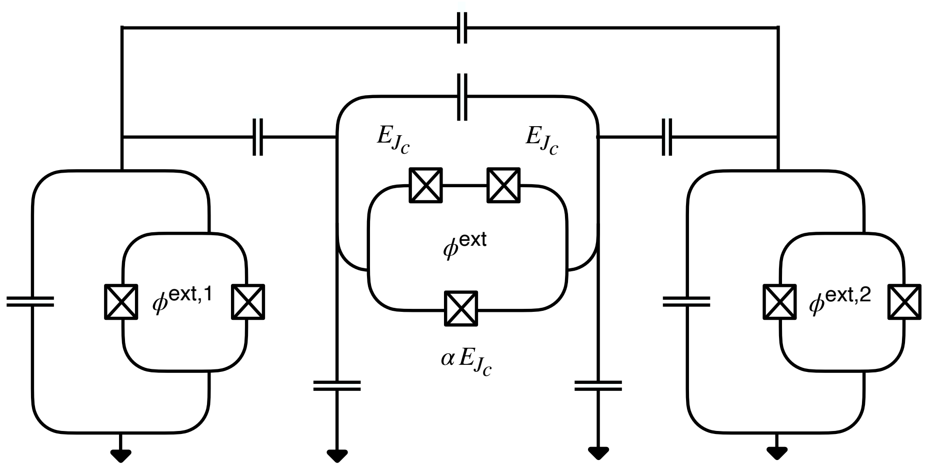
Coupler with positive anharmonicity

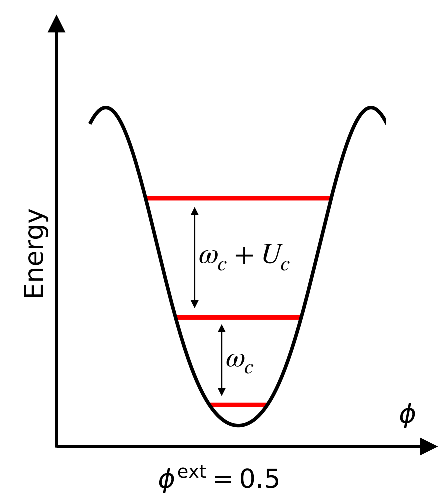
- C-shunt flux qubit has positive anharmonicity

$$V = -2E_{J,c}\cos\left(\frac{\phi_c}{\sqrt{2}}\right) - \alpha E_{J,c}\cos\left(\sqrt{2}\phi_c + \phi^{\text{ext}}\right)$$

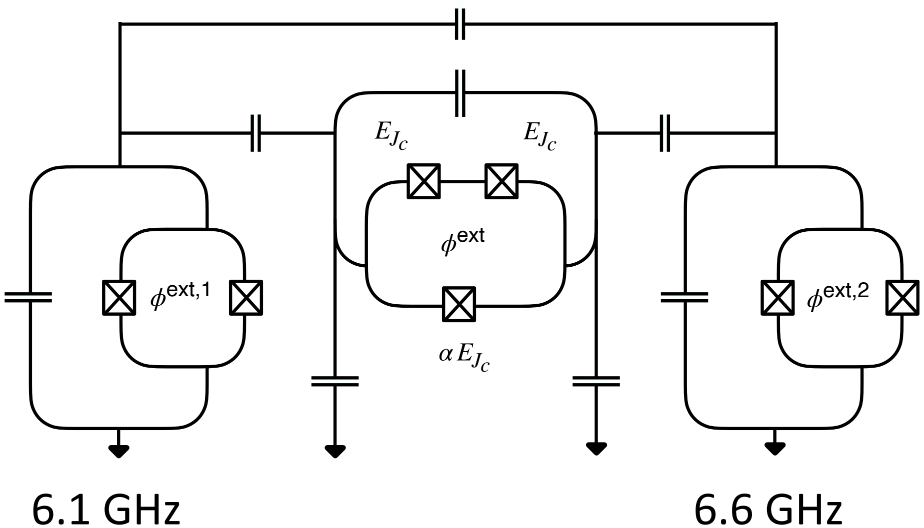
- Regime: $1/8 < \alpha < 1/2$ and $\phi^{\text{ext}} = \pi$

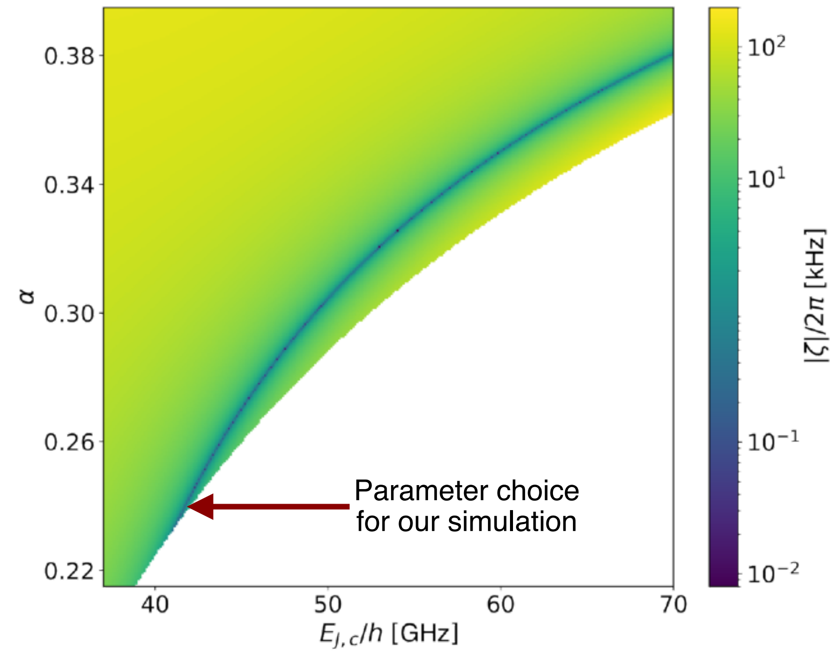






Full decoupling of Transmons





System Hamiltonian

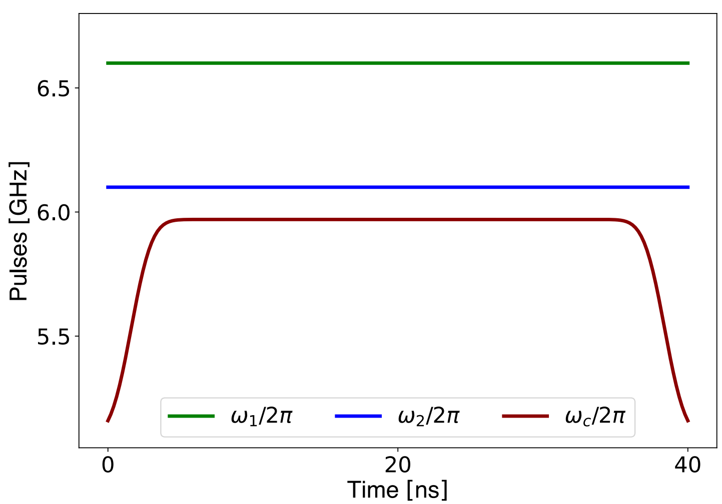
$$H = \sum_{i=1,c,2} \omega_i b_i^\dagger b_i + \frac{U_i}{2} b_i^\dagger b_i^\dagger b_i b_i + K_c \left(b_c^\dagger b_c^\dagger b_c + b_c^\dagger b_c b_c \right) + \sum_{i \neq j} g_{ij} \left(b_i^\dagger - b_i \right) \left(b_j^\dagger - b_j \right)$$

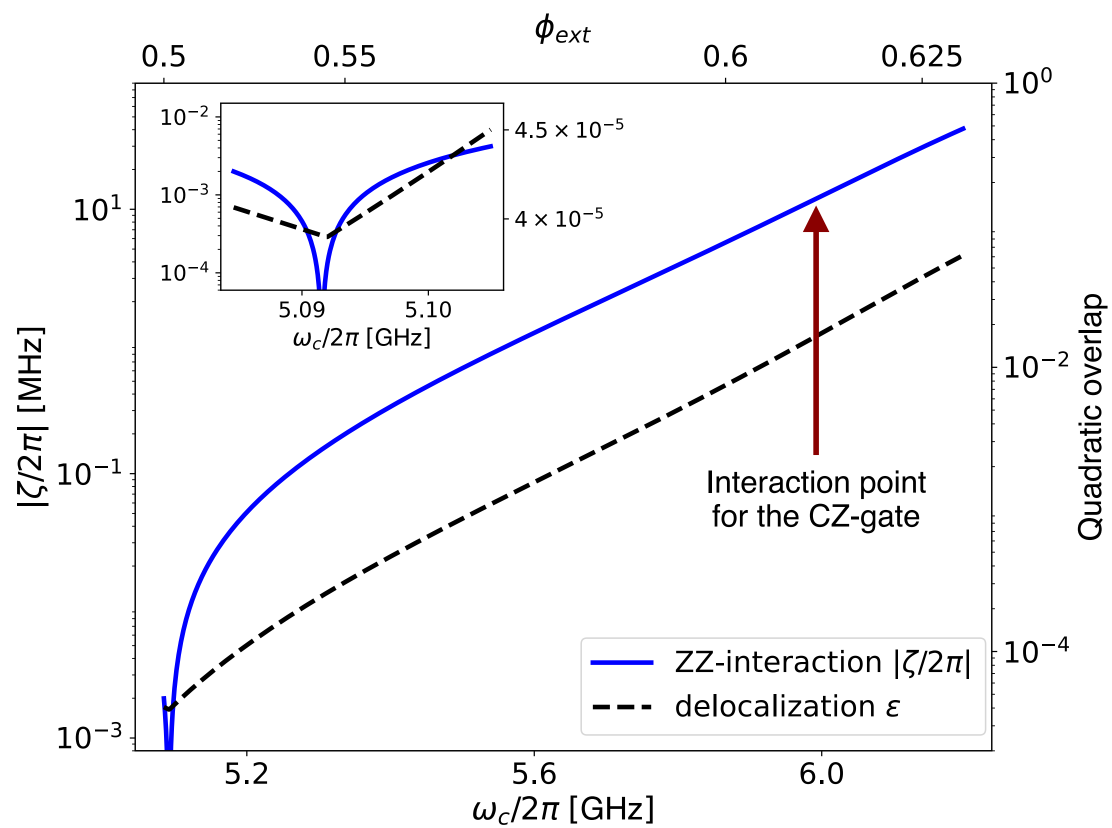
CZ-gate simulation

CZ-gate

- Use large tuning range of ZZ-coupling
- Wait until $|101\rangle$ collects a phase $\pi = \zeta \cdot t$
- Suppress leakage population by using rounded pulse shapes

$t_{\mathrm{gate}} = 40\,\mathrm{ns}$ $\epsilon \approx 2.2 \cdot 10^{-4}$

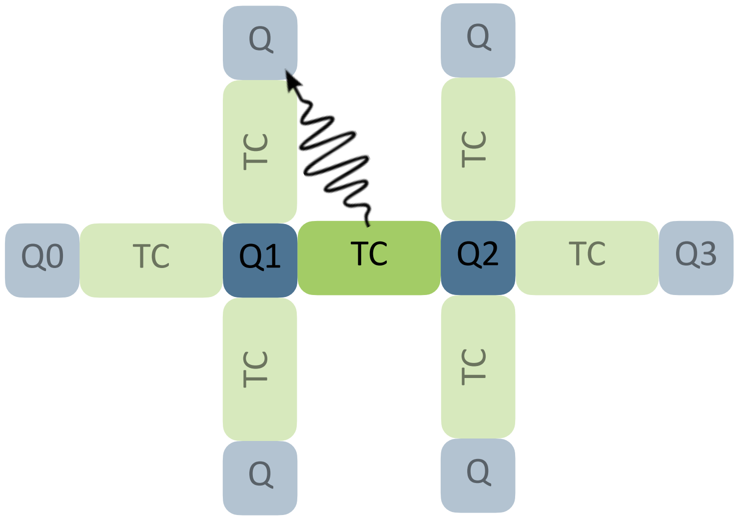


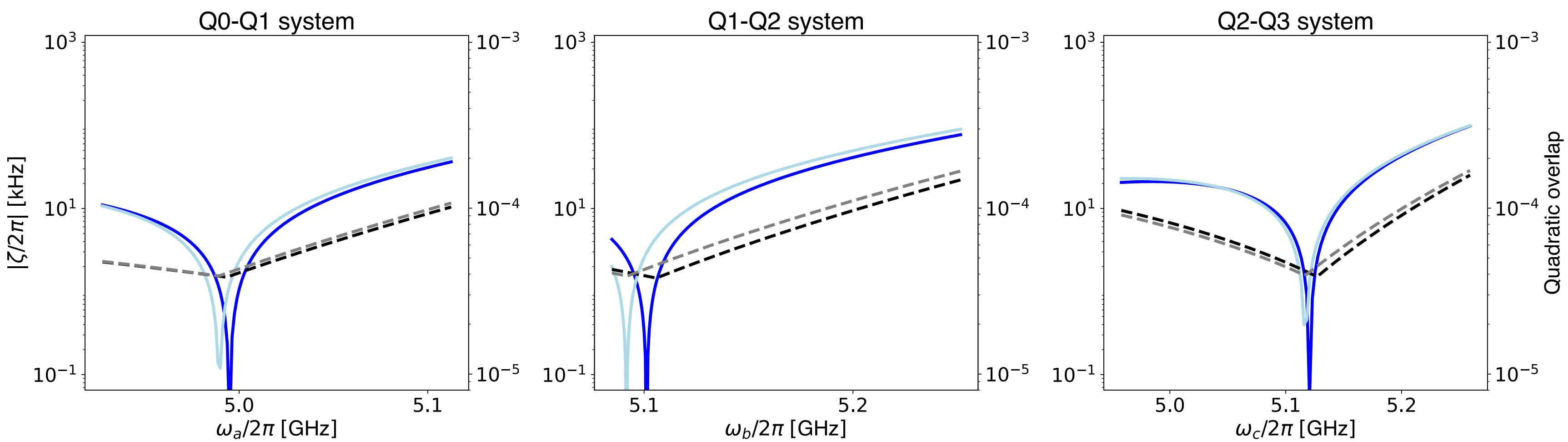


Behaviour in larger systems

Influence of spectator qubits

- Reduce gate fidelity in larger quantum chips compared to isolated qubit dimers
- Perturbatively calculated formulas to fully decouple qubits do not change in the presence of spectator qubits up to leading order
- Can easily use our approach to build larger clusters





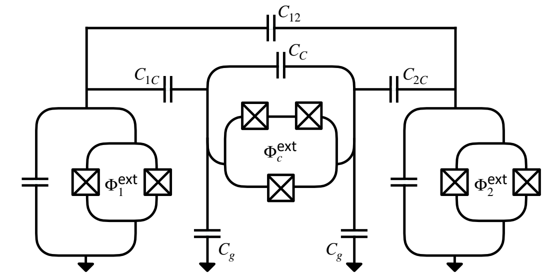
Conclusion

- Two universal formulas to determine the Coupler properties at the idle point of a two-qubit system

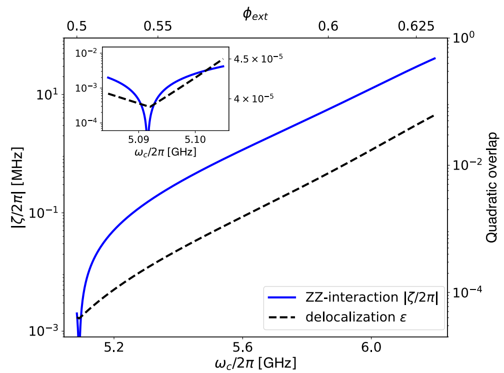
$$g_{\text{eff}} = g_{12} + \frac{g_{1c}g_{2c}}{2}\left(\frac{1}{\Delta_{1c}} + \frac{1}{\Delta_{2c}}\right)$$

$$U_c = -\frac{U}{2}\cdot\left(1 - \frac{U^2}{\Delta_{12}^2} - \frac{U}{2(\Delta_{1c}+\Delta_{2c})}\right)^{-1}$$

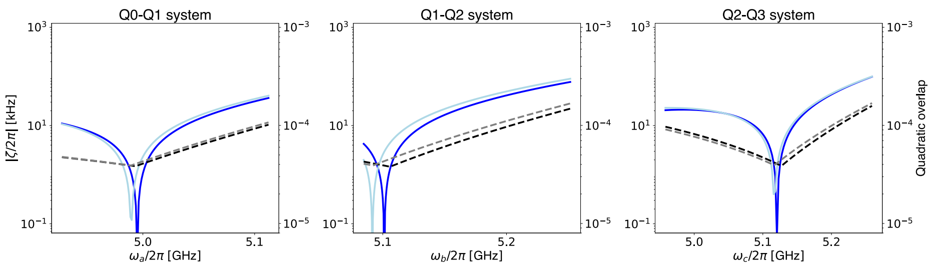
- Coupler proposal to reach zero ZZ-interactions while maintaining maximally localized states



- Opposite sign anharmonicity of qubits and coupler leads to a simultaneous suppression of longitudinal and transversal couplings

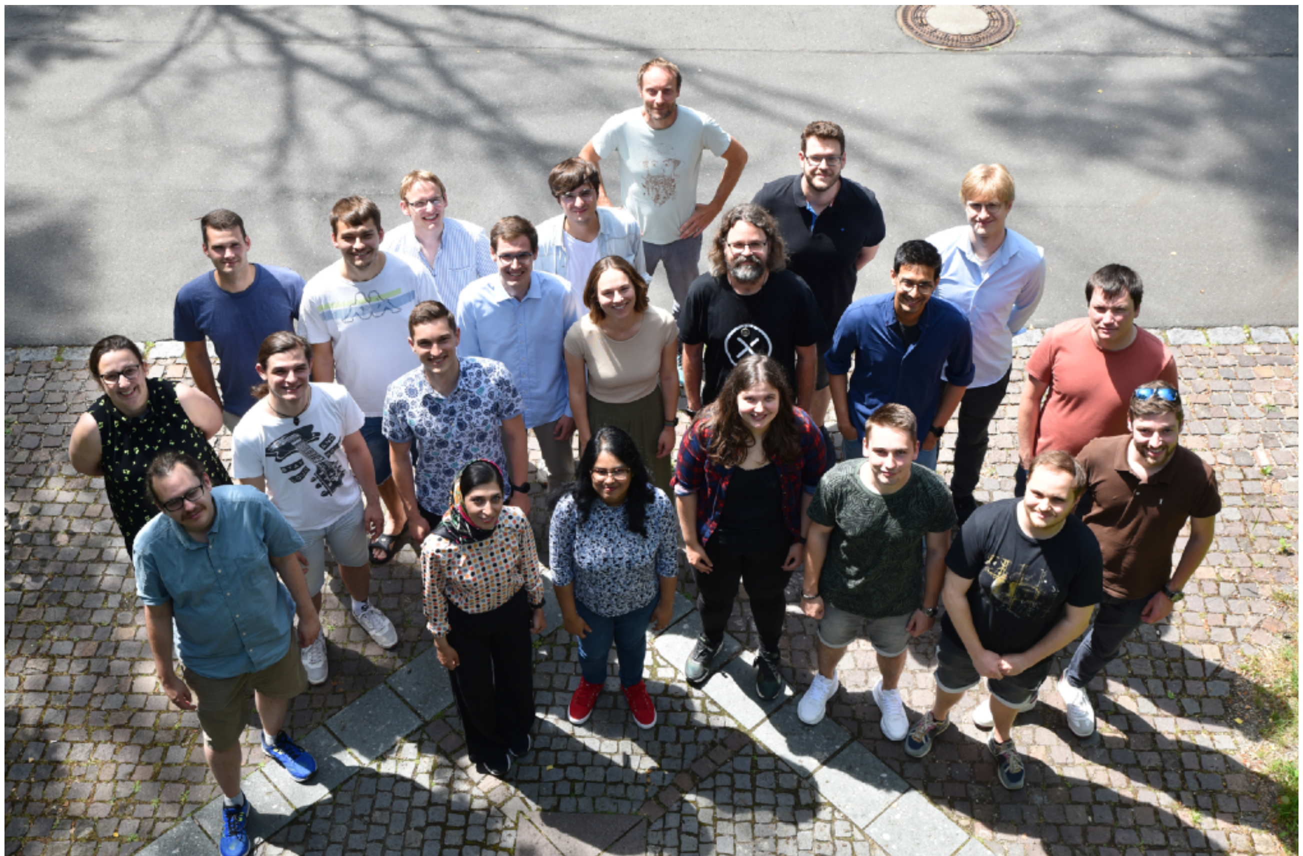


- Simulation of a fast and high fidelity CZ gate that is robust when integrating the qubits into a larger chip



My group

FAU



GeQCoS

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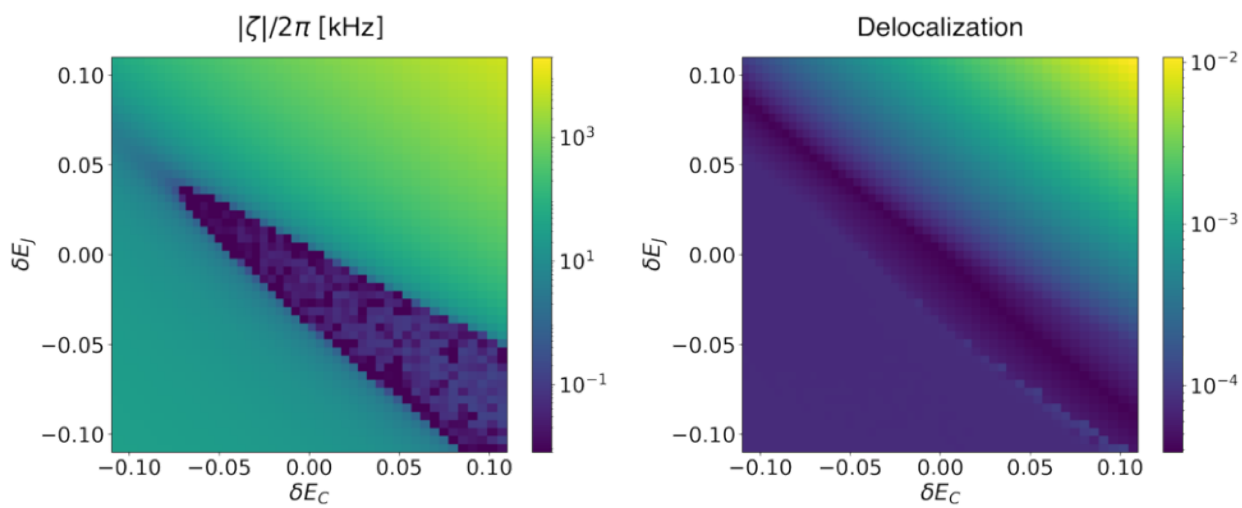
Thank you for your attention!

Lukas Heunisch

Introduction



How to be robust against fabrication inaccuracies:

- Use weakly tunable Transmons as qubits to shift the qubit frequencies to the decoupling point
- Use a flux-tunable junction in the coupler