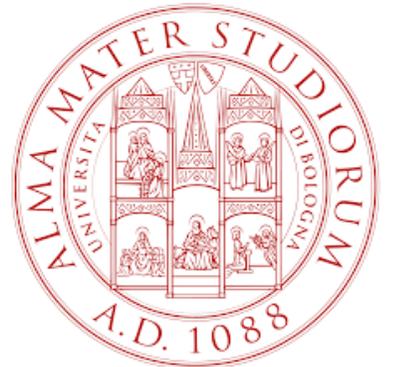# COMPACT PURCELL FILTER DESIGN FOR SUPERCONDUCTING QUBIT READOUT
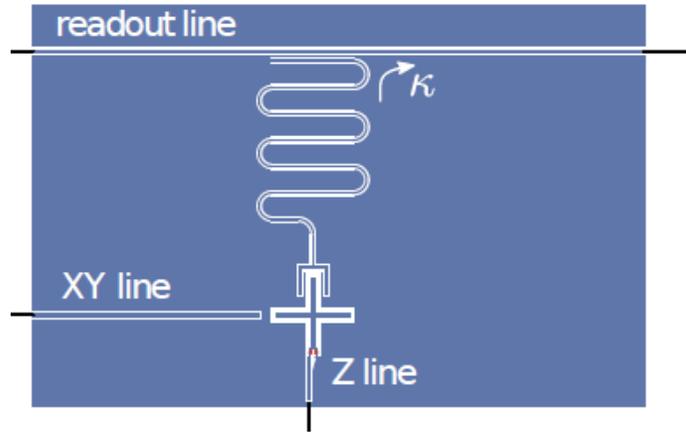
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Istituto Nazionale di Fisica Nucleare

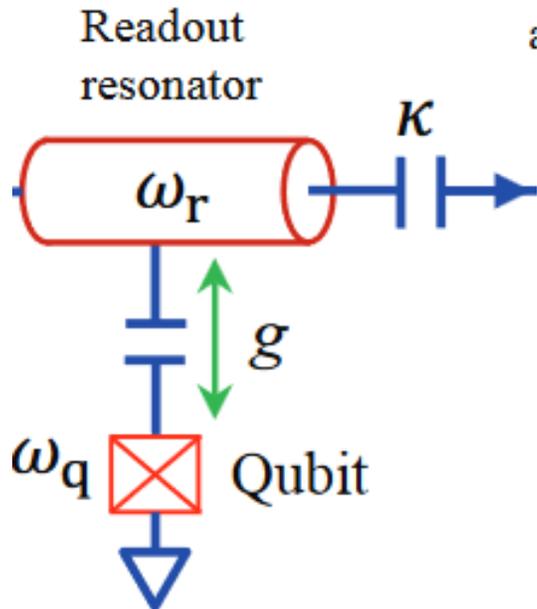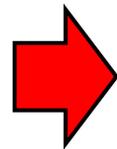DEI, Università di Bologna

THE PROBLEM OF QUBIT MEASUREMENT

readout line

κ

XY line

Z line

Readout resonator

ω_r

κ

g

ω_q Qubit

- The state of the qubit is inferred from the measured frequency of the resonator, coupled with the qubit in the dispersive regime

$$\hat{H}_{\mathrm{disp}} \approx \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z$$

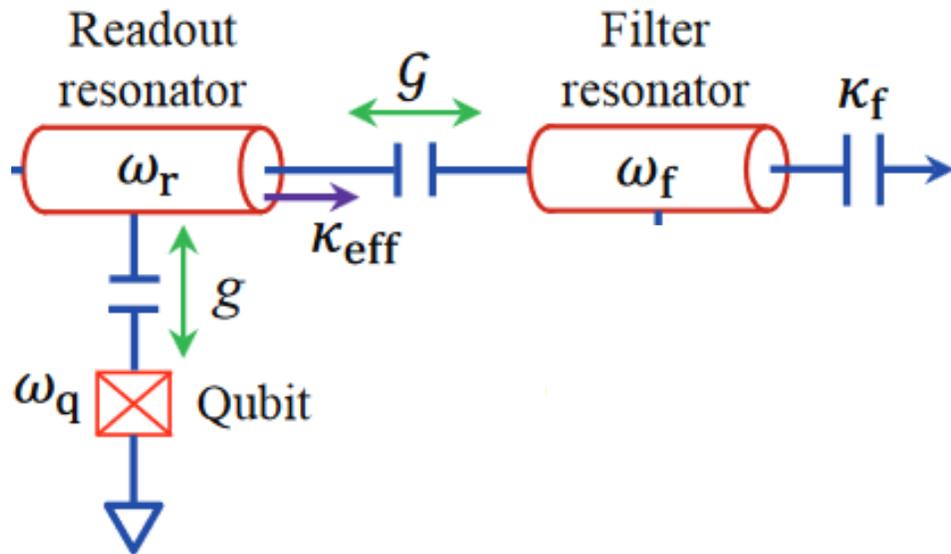- There is additional leakage of the qubit energy into the transmission line (Purcell effect)

$$\Gamma = \left(\frac{g}{\Delta}\right)^2 \kappa(\omega_q) \qquad \Delta = \left|\omega_q - \omega_r\right|$$

Trade-off between qubit decay and readout measurement time

PURCELL FILTER

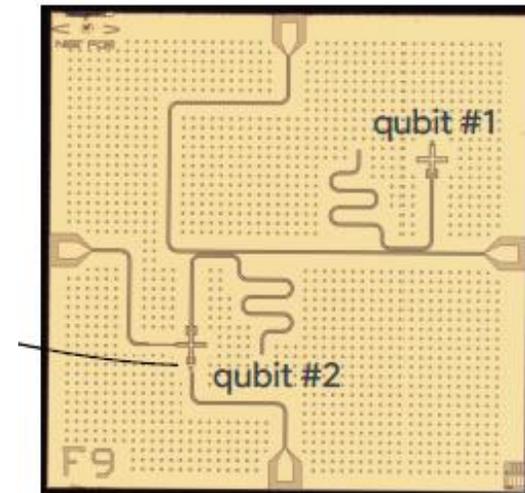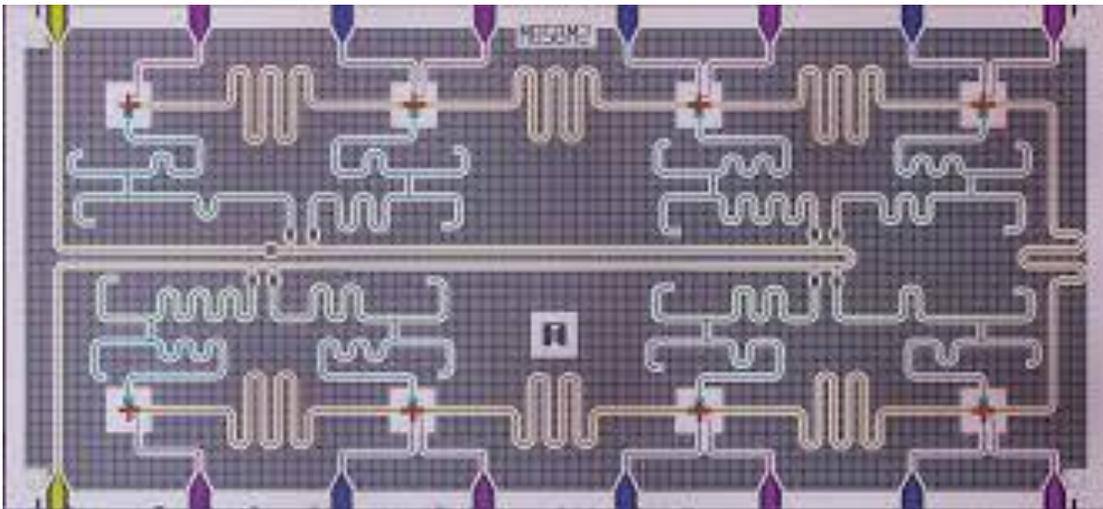**Solution:** Add a filter to reduce the qubit decay at the qubit frequency

$$\Gamma = \left(\frac{g}{\Delta}\right)^2 \kappa_{\text{eff}}(\omega_q)$$
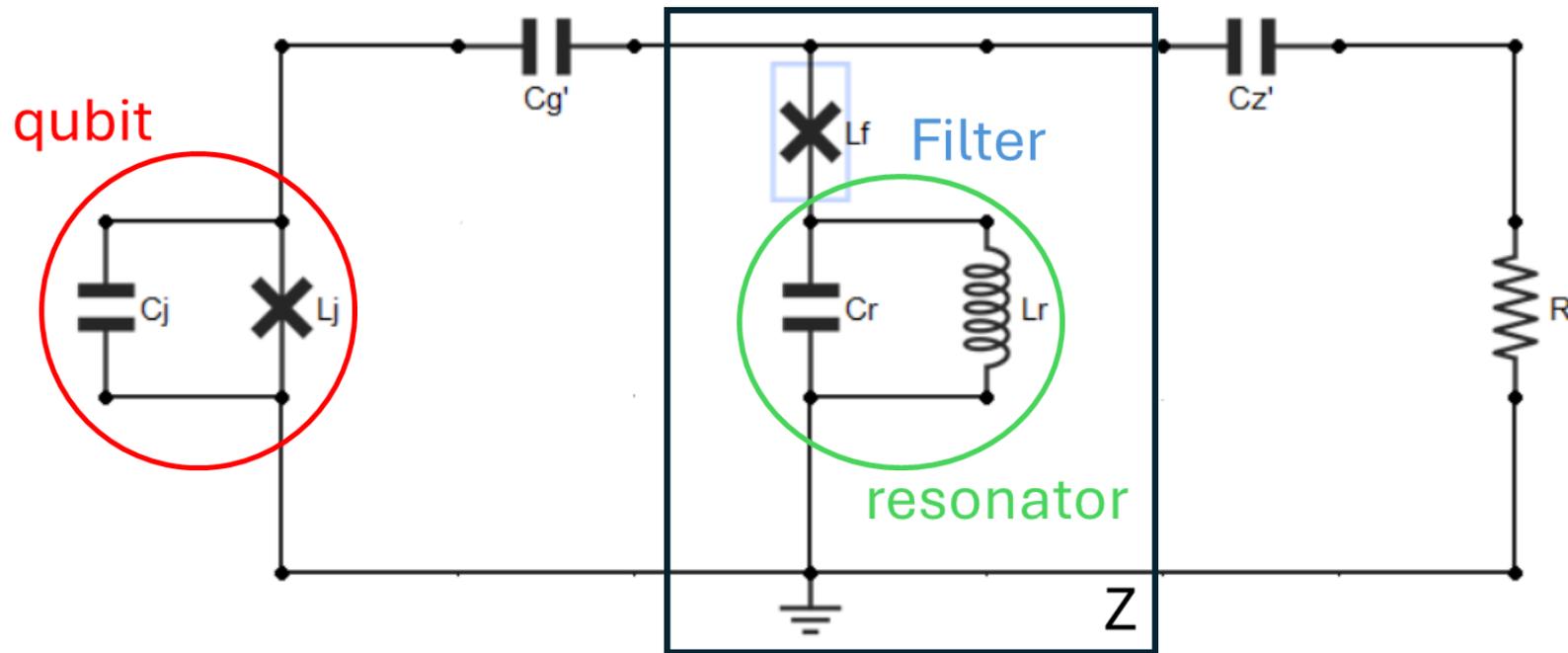
PURCELL FILTER

- Standard designs of Purcell filters use CPW resonators
- CPW resonators need cm-long lines

POSSIBLE PROPOSAL

- Compact architectures adopting a lumped element approach for the readout resonator and/or the Purcell filter by using inductors made of JJ chains
- Indeed, the non-linearity of a JJ chain of N junctions is proportional to $\frac{1}{N^2}$

CIRCUIT EXAMPLE: notch Purcell filter with JJs

- L_f implemented with JJ arrays
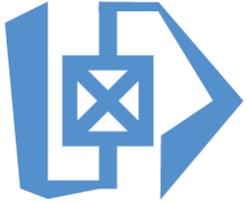
- Notch band very narrow:
  TUNING OF L_f REQUIRED !!

L_f is sized such that Z(ω_q)=0

$$L_f = -\frac{L_r}{1 - \frac{\omega_q^2}{\omega_r^2}}$$
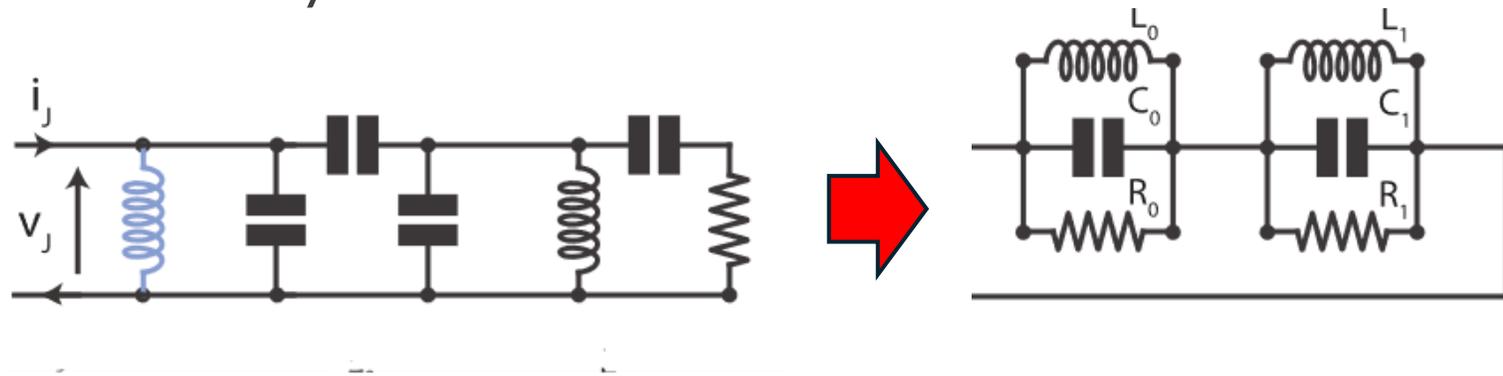
Qubit mode

$\omega_r^2 = 1/\sqrt{L_r \times C_r}$

$\omega_q > \omega_r$

MODELING TOOLS

QuCAT: Quantum Circuit Analyzer Tool

- It's based on **Foster theorem:**

- It provides mode frequencies, mode dissipations, mode anharmonicities, and cross-Kerr parameters

- **Originally it doesn't support JJ arrays**: we have modified QuCAT core in order to make the simulation of JJ chains possible

mode	freq.	diss.	anha.
0	4.08 GHz	18 MHz	1.03 MHz
1	6.44 GHz	8.43 Hz	127 MHz
2	9.1 GHz	148 MHz	24.3 MHz

Kerr coefficients (diagonal = Kerr, off-diagonal = cross-Kerr)

mode	0	1	2
0	1.03 MHz		
1	11.3 MHz	127 MHz	
2	6.31 MHz	73 MHz	24.3 MHz

DESIGN TOOLS

Qiskit Metal: an open-source framework and library for designing superconducting quantum chips and device

Ansys: A platform for performing electromagnetic simulations of quantum chips. With Q3D it is possible to extract capacitance matrix by performing electrostatic simulation. With HFSS it is possible to find the modes of the system

DESIGN METHODOLOGY

Step 1: Search for capacitance and inductance values that satisfy the following constraints by using an optimizer
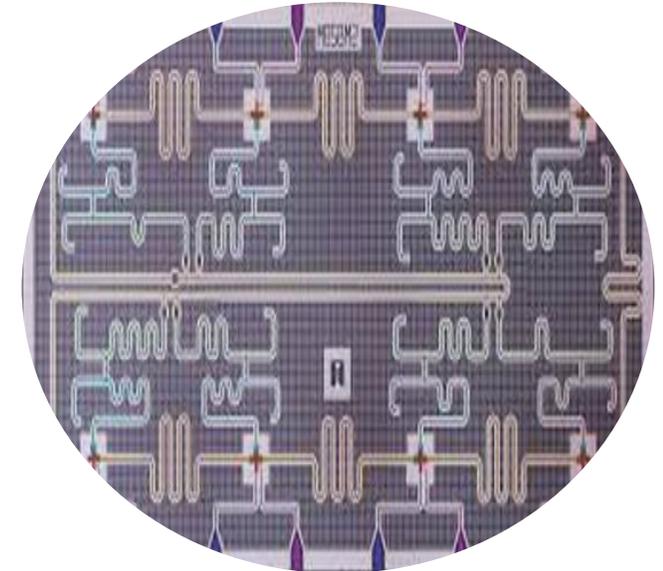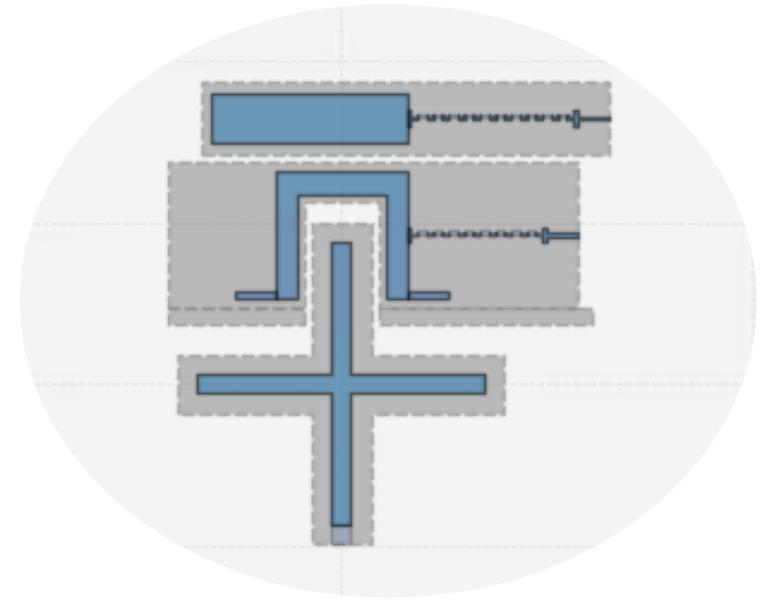
- $\dfrac{g}{\Delta} \ll 1$ DISPERSIVE REGIME

- $\alpha_r n_{crit} \ll \kappa_r$ HARMONIC CONDITION FOR THE RESONATOR (ONLY FOR A LUMPED REALIZATION)

- $\chi \approx \kappa_r$ BEST CONDITION IN TERMS OF SNR

- $\dfrac{1}{\Gamma} = T_p \geq T_{p,min}$

- $\kappa_r \geq \kappa_{r,min}$

DESIGN METHODOLOGY

Step 2: Design the circuit by using QiskitMetal

Step 3: Extract the capacitance matrix using Ansys Q3D and calculate the characteristic parameters with QuCAT

Step 3: Repeat step 2 and step 3 until the desired values are reached

DESIGN EXAMPLE FOR THE NOTCH PURCELL FILTER

- Cj=75.7 fF
- Lj=6.4 nH
- Cr=114 fF
- Lr=8.5 nH (10 JJs of 0.85nH each)
- Cg=19.8 fF
- Cz=17.4 fF
- Lf=14.5 nH (5 JJs of 2.9nH each)

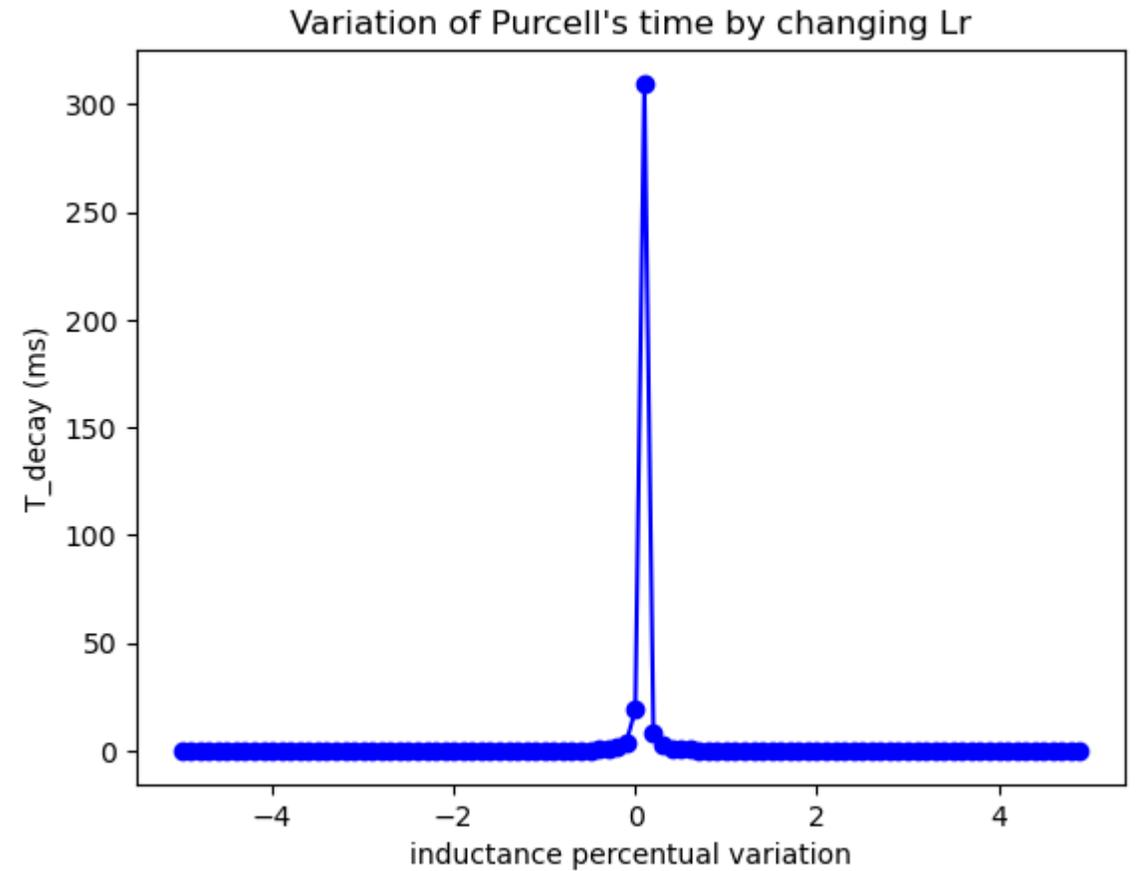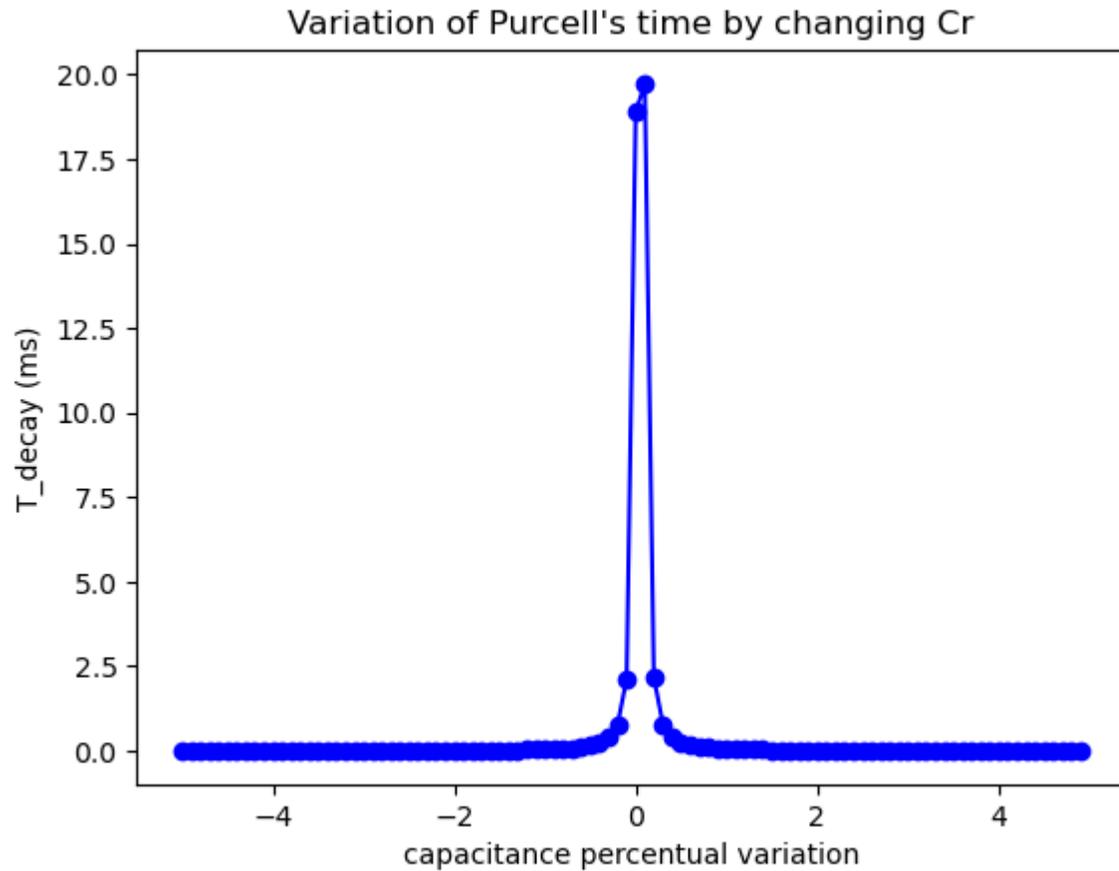|	mode	freq.	diss.	anha.
resonator	0	4.08 GHz	18 MHz	1.03 MHz
qubit	1	6.44 GHz	8.43 Hz	127 MHz
Filter	2	9.1 GHz	148 MHz	24.3 MHz

Kerr coefficients (diagonal = Kerr, off-diagonal = cross-Kerr)

mode	0	1	2
0	1.03 MHz		
1	11.3 MHz	127 MHz	
2	6.31 MHz	73 MHz	24.3 MHz

$$T1 = 18.8 \ ms$$

PROBLEM: high sensitivity to parameter variations

- Tuning of Lf is required
- By tuning Lf it is possible to achieve acceptable Purcell decay

CONCLUSIONS

- Design of Purcell filter to improve the qubit T1

- Proposals for compact designs exploiting a lumped element approach based on JJ arrays

- Simulation results relative to an example design show that a high T1 can be achieved

- Problem of high sensitivity can be solved with the tuning of the JJs

- **Discussion with partners involved in the design of the overall chip and fabrication**