

# SET readout using RF reflectometry and kinetic inductance nonlinearity

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## Abstract

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## 1 Introduction (talk about different types of spin qubits)

## 2 Theoretical background

### 2.1 The SET for charge sensing

Hola Fernando, creo que he terminado de entender lo suficientemente bien como para escribir esta seccion el Coulomb blockade y el SET. El problema es que estoy escribiendo esto a las 18:06, asi que voy a escribirlo primero a grandes rasgos para que me puedas decir si conceptualmente lo entiendo bien, y una vez que eso este subido iré añadiendo las cosas de forma mas rigurosa.

Let's imagine a conducting island on capacitance  $C$  and without excess charges. Due to it's capacitance, some energy will be required to add a charge to this island, and due to Coulomb repulsion each additional charge will require even more energy than the last. Since this additional energy is also proportional to  $1/C$ , with a small enough island and with small enough thermal energy, the energy spectrum of these charges will be discretized, blocking all charges from entrance unless they have enough energy to arrive to the next empty energy state. It's like the quantization of the energy spectra of the 1D infinite square well, but from classical properties.

A SET is a conducting island connected to 2 voltages via tunnel junctions and to a third one via a capacitor. The tunnel junctions are modeled via a capacitor, to simulate the charge accumulation at the walls of the tunnel junction, and a resistance in parallel to simulate the current flowing due to tunneling. This resistance must be high enough so that each tunneling event is well defined, and the way to ensure that is to plug the energy required to introduce an electron to the capacitor, and the RC time of the tunnel junction (in other context the RC time of a circuit is the time it takes to charge a capacitor through a resistance, but in this one would be the average time it takes a charge to tunnel through the barrier). By doing this we get that  $R \gg 4.1\text{k}\Omega$ , but a more careful analysis with tunneling rates[REFERENCE HERE] gives us a more restrictive condition  $R \gg 25.8\text{k}\Omega$ . The voltage connected via a capacitor (the gate voltage) would increase and decrease the electrostatic energy of the island, allowing us to move the next available energy state inside it. The idea is to have a small enough voltage difference between the voltages connected via tunnel barrier, such that we can add a gate voltage that will let a current flow by encouraging a single electron transport from one voltage to the next through the island, but that a small variation of the gate voltage breaks this electron transmission and cuts the conductance of the SET (being right above the edges of the Coulomb diamonds). This charge sensing can be turned into spin sensing by making the source of the gate voltage be an electron (or the lack of one) in another quantum dot, and making the existence (or lack of) an electron in said quantum dot dependent on it's spin.

### 2.2 RF reflectometry

Radio frequency reflectometry is a method to measure change in an impedance connected to a transmission line via the reflection of a radio signal.

Usual lumped element treatment of AC circuits assumes that the size of the circuit is small with respect to the wavelength of the voltage, but with radio frequency voltages we can't do that. The main consequences for us are that now voltage and current are dependent on how far along the circuit you are due to how fast it changes with respect to the size of the circuit itself

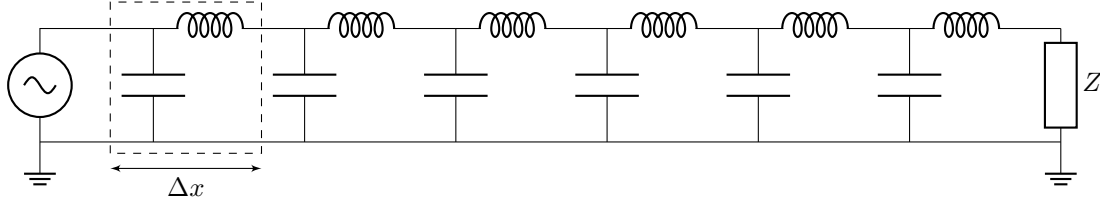


Figure 1: Lumped element model of a lossless transmission line connected to a generic impedance  $Z$ . In order to model the relevant impedance per unit length of the transmission line at radio frequencies, we represent it via sections with inductors in series and capacitors in parallel. Each periodic section like the one inside the dashed rectangle represents a segment of length  $\Delta x$  of the transmission line.

$(V(t), I(t) \rightarrow V(x, t), I(x, t))$  and that the intrinsic inductance and capacitance per unit length of a long connection cannot be ignored. In such cases those connections are made with what is known as a transmission line, which is a cable designed to minimize the radiation of power via that inductance and capacitance, and includes a signal and a ground connection in one package. One example of a transmission line would be a coaxial cable, in which the central conductor is the signal and the outer jacket ground.

Even though a transmission line minimizes that radiation of power, it doesn't erase it, and we need to take it into account in our calculations. To model this inductance and capacitance per unit length ( $L_l$  and  $C_l$  respectively), we will discretize it via a lumped element representation like in figure 1, ignoring the lossess by not including any resistance in our circuit. Each pair inductor-capacitor will occur along a length  $\Delta x$  of the transmission line, so their inductance and capacitance in that stretch will be  $L = \Delta x \cdot L_l$  and  $C = \Delta x \cdot C_l$ . Applying Kirchhoff at a point  $x$  in the transmission line and the limit  $\Delta x \rightarrow 0$  gives us the telegraph equations for a lossless transmission line

$$\begin{aligned} \frac{\partial V}{\partial x} &= -L_l \frac{\partial I}{\partial t} \\ \frac{\partial I}{\partial x} &= -C_l \frac{\partial V}{\partial t} \end{aligned} \quad (2.1)$$

Their solution is

$$\begin{aligned} V(x, t) &= V_+(t - x/v_p) + V_-(t + x/v_p) \\ I(x, t) &= \frac{1}{Z_0} (V_+(t - x/v_p) - V_-(t + x/v_p)) \end{aligned} \quad (2.2)$$

Where  $v_p = \frac{1}{\sqrt{L_l C_l}}$  is the phase velocity of the wave,  $Z_0 = \sqrt{\frac{L_l}{C_l}}$  is the characteristic impedance of the line and  $V_+$  and  $V_-$  are generic functions that describe a right and left traveling wave respectively. Since we'll be choosing our reference frame such that our signal will be always traveling from left to right, the appearance of  $V_-$  in our calculations will mean a reflection.

If we add a generic impedance  $Z$  at the end of the transmission line, we add the boundary condition

$$\frac{V(x_{\text{End}}, \omega)}{I(x_{\text{End}}, \omega)} = Z(\omega) \quad (2.3)$$

With  $V(x, \omega)$  and  $I(x, \omega)$  being the time Fourier transforms of  $V(x, t)$  and  $I(x, t)$  respectively. Choosing  $x = x_{\text{End}} = 0$  to simplify and using the time Fourier transforms of expressions 2.1, we get

$$\frac{V(0, \omega)}{I(0, \omega)} = Z_0 \frac{V_+(\omega) + V_-(\omega)}{V_+(\omega) - V_-(\omega)} = Z(\omega) \quad (2.4)$$

As we can see, the only way in which  $Z_0 = Z(\omega)$  is if  $V_-, (\omega) = 0$ , or in other words, the only way to not get a reflection is to match  $Z_0$  to  $Z(\omega)$ . A useful parameter to define is the reflection coefficient  $\Gamma = \frac{V_-(\omega)}{V_+(\omega)}$ , and with equality 2.4 has the form

$$\Gamma = \frac{Z(\omega) - Z_0}{Z(\omega) + Z_0} \quad (2.5)$$

Through this is how we are going to measure  $Z(\omega)$ , in our case  $R_{\text{SET}}$ , since there is a 1 to 1 mapping between  $\Gamma$  and  $Z(\omega)$ .

The quality of our measurement will be determined by the signal-to-noise ratio (SNR) of the measurement

$$\text{SNR} = |\Delta\Gamma|^2 \frac{P_0}{P_N} \quad (2.6)$$

With  $P_0$  and  $P_N$  the power of the signal and noise respectively and  $\Delta\Gamma = \Gamma_B - \Gamma_A$  the difference in reflection coefficients between the two states to measure. Its modulus is what we will call the contrast and our objective will be first to optimize it by designing a matching network<sup>1</sup> for our SET, and then try to improve it by adding a kinetic inductor, whose inductance changes with the current that goes through it.

### 2.3 Kinetic inductance and his nonlinearity

Due to the high mobility of the charge carriers in a super conductor, a phenomenon known as kinetic inductance emerges. This name comes from the fact that as opposed to a usual inductor, which functions by storing energy in the magnetic field generated by the charge carriers, it is stored as the kinetic energy of the charge carriers themselves.

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<sup>1</sup>A circuit build around our impedance with the objective of increasing the sensibility to its changes. We will talk more about it in section 3

With this simple definition of the kinetic inductance and a little bit of Drude and Ginzburg-Landau theory, we have all we need to derive the property that interests us the most: it's nonlinearity.

The energy stored by an inductor of inductance  $L$  is

$$E = \frac{1}{2}LI^2 \quad (2.7)$$

So, in the case of the kinetic inductance of length  $l$  and cross-section  $S$

$$E_k = \frac{1}{2}L_k I^2 = \frac{1}{2}m(nlS)v^2 \quad (2.8)$$

With  $n$ ,  $m$  and  $v$  the volumetric density, the mass and the speed of the charge carriers. By solving for  $L_k$  and defining the volumetric current density as  $j = nqv$  with  $q$  the charge of the charge carriers we arrive at the following expression

$$L_k = \frac{mlj^2}{nq^2Sj^2} = \frac{ml}{q^2S} \frac{1}{n} \quad (2.9)$$

Now, using the Ginzburg-Landau expression for the volumetric density of supercharge carriers

$$n(v) = |\Psi|^2 = \frac{1}{\beta} \left[ |\alpha| - \frac{1}{2}mv^2 \right] \quad (2.10)$$

And doing a second order approximation of  $L_k$  at  $v \approx 0$ , we arrive at our desired expression

$$L_k = L_{k0} \left( 1 + \frac{j^2}{j_*^2} + \dots \right) \quad (2.11)$$

With  $L_{k0} = \frac{ml}{q^2Sn(v=0)}$  and  $j_*^2 = \frac{2q^2|\alpha|^3}{m\beta^2}$ . If we compare  $j_*$  to the critical current  $j_c$ , which is the maximum current that the system can withstand and can be calculated by obtaining the maximum of  $j$  with respect to  $v$ , we get that

$$j_* = \sqrt{\frac{27}{4}} j_c \quad (2.12)$$

With this we can not only see that the kinetic inductance has a quadratic dependence with the current, but that the sensibility of that dependence it's given by the critical current of the material. And these properties are the ones that we want to use to improve the reading quality for our qubits.

But, to read the qubits with RF reflectometry we send an AC pulse to the resonator, and in that case our kinetic inductance would be varying constantly. How can we use the kinetic inductor then?

The solution is to introduce a DC bias to the circuit, with an intensity much greater than the maximum of the AC current, but still small enough to not break superconductivity and to use an AC current much smaller than the critical current. With it, we can have an inductor that changes inductance along with the resistance of the SET, since the effects of the AC current can be ignored.

$$\begin{aligned}
L_k &= L_{k0} \left( 1 + \frac{(j_{AC} + j_{DC})^2}{j_*^2} + \dots \right) \\
&= L_{k0} \left( 1 + \frac{j_{DC}^2}{j_*^2} + \frac{j_{DC}j_{AC}}{j_*^2} + \frac{j_{AC}^2}{j_*^2} + \dots \right) \\
&= L_{k0} \left( 1 + \frac{j_{DC}^2}{j_*^2} + \left( \frac{j_{DC}}{j_*} + \frac{j_{AC}}{j_*} \right) \frac{j_{AC}}{j_*} + \dots \right) \\
&= L_{k0} \left( 1 + \frac{j_{DC}^2}{j_*^2} + \dots \right) \text{ since } j_{DC} < j_c \text{ and } j_{AC} \ll j_c
\end{aligned} \tag{2.13}$$



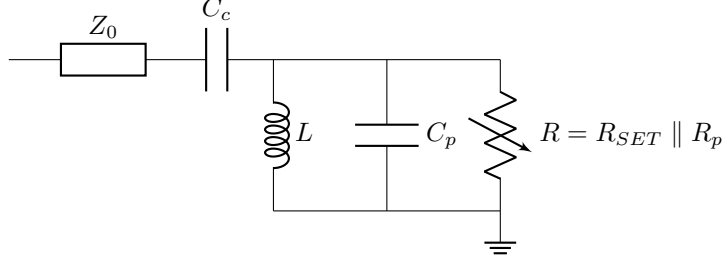


Figure 2: Topology of the resonator that we are going to use.  $C_p$  and  $R_p$  are a virtual capacitor and resistance used to model losses in the circuit, while  $R_{SET}$  is the resistance of the SET in any state. That leaves  $C_c$  and  $L$  as the degrees of freedom in our system.

### 3 The parallel RLC resonator

Now that we have a good theoretical context of all the parts of the problem, we will start by analyzing the resonator with a non-kinetic inductance.

#### 3.1 Resonant frequency and effective impedance

Our analysis begins with obtaining expressions for the resonant frequency and the effective impedance of our resonator. It's easy to see that the impedance of our resonator in figure 2 is

$$Z = \frac{1}{j\omega C_p + \frac{1}{j\omega L} + \frac{1}{R}} + \frac{1}{j\omega C_c} \quad (3.1)$$

Which after a little massaging turns into

$$Z = \frac{\omega^2 L^2 R}{R^2(1 - \omega^2 C_p L)^2 + \omega^2 L^2} + j \left( \frac{\omega L R^2(1 - \omega^2 C_p L)}{R^2(1 - \omega^2 C_p L)^2 + \omega^2 L^2} - \frac{1}{\omega C_c} \right) \quad (3.2)$$

The resonant frequency  $\omega_r$  that makes  $\text{Im } Z = 0$  is

$$\omega_r^2 = \frac{1}{L(C_c + C_p)} \left( 1 + \frac{C_c}{2C_p} - \frac{L}{2R^2 C_p} \pm \sqrt{\left( 1 + \frac{C_c}{2C_p} - \frac{L}{2R^2 C_p} \right)^2 - 1 - \frac{C_c}{C_p}} \right) \quad (3.3)$$

Choosing  $C_c$  and  $L$  such that  $\frac{C_c}{C_p}, \frac{L}{R^2 C_p} \ll 1$ , leaves us with the approximate expression for the resonant frequency

$$\omega_r \approx \frac{1}{\sqrt{L(C_c + C_p)}} \quad (3.4)$$

Finally, to obtain the effective impedance we use this expression in  $\text{Re } Z$

$$Z_{eff} = \text{Re } Z(\omega_r) = \frac{\omega_r^2 L^2 R}{R^2(1 - \omega_r^2 C_p L)^2 + \omega_r^2 L^2} \approx \frac{L(C_c + C_p)}{RC_c^2} \left(1 + \frac{L(C_c + C_p)}{R^2 C_c^2}\right)^{-1} \quad (3.5)$$

And by, again, choosing  $L$  and  $C_c$  such that  $\frac{L(C_c + C_p)}{R^2 C_c^2} \ll 1$  we arrive to our expression for the effective impedance

$$Z_{eff} \approx \frac{L(C_c + C_p)}{RC_c^2} \quad (3.6)$$

In future sections we will be using quite a lot of expressions obtained via approximations in non-approximated systems, only to do more approximations with them. Due to this, it is really important to have a clear picture of the regimes we are working in to ensure that our results work in the state-of-the-art technology, and that's why after each result we are going to recontextualize our approximations.

In this case, the approximations to obtain  $\omega_r$  are clear and straight forward:

$$\frac{C_c}{C_p} \ll 1 \quad (3.7)$$

$$\frac{L}{R^2 C_p} \ll 1 \quad (3.8)$$

But the approximation for  $Z_{eff}$  needs a little bit of extra work. If we multiply  $(C_c/C_p)^2$  in both sides, it turns into

$$\frac{L}{R^2 C_p} \left(1 + \frac{C_c}{C_p}\right) \ll \left(\frac{C_c}{C_p}\right)^2 \quad (3.9)$$

And since we used equation 3.4 to arrive here, it must hold the approximation 3.7, turning the previous expression into

$$\frac{L}{R^2 C_p} \ll \left(\frac{C_c}{C_p}\right)^2 \quad (3.10)$$

While approximations 3.7 and 3.8 impose a **general condition** in our degrees of freedom, approximation 3.10 imposes a **relative condition** between the previous two.

For checking that our results are correct, we can graph the modulus of the reflection coefficient  $\Gamma$  (equation 2.5) as a function of the voltage frequency  $\omega$ . With the standard impedance for a transmission line  $Z_0 = 50\Omega$ , a parasitic capacitance  $C_p = 500\text{fF}$  and a resistance  $R = 50\text{k}\Omega$  (2

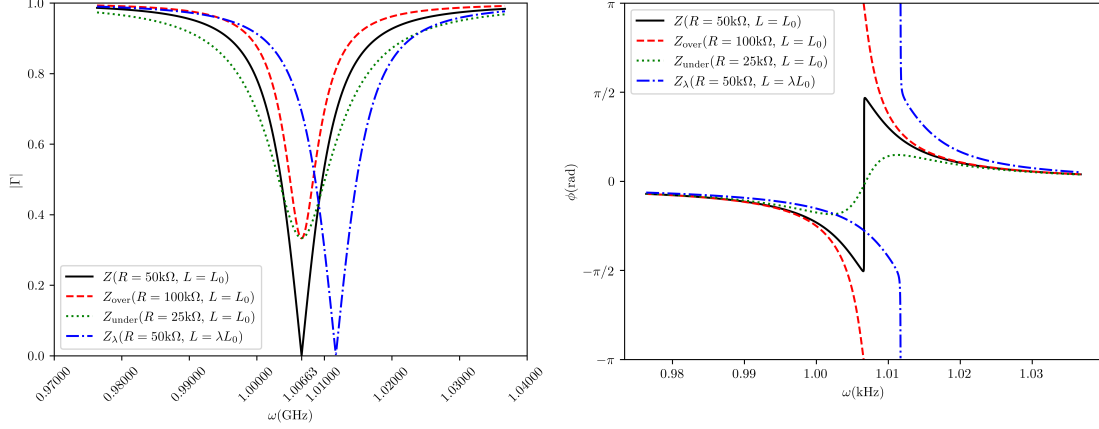


Figure 3: Modulus and phase of  $\Gamma$  in multiple configurations

times the quantum of resistance), we need to choose a  $C_c$  and a  $L$  such that the conditions 3.7, 3.8 and 3.10 are met and  $Z_{\text{eff}} = Z_0$ . With this in mind, we choose  $C_c = 100\text{fF}$  and  $L = 41.67\text{nH}$  (these values are also on the ballpark of real values used in the lab **REFERENCE NEEDED**), which means that we should see  $|\Gamma|$  dip to zero at a frequency of  $1.00654\text{GHz}$ , which is what we see in the black line figure 3.

In addition to this configuration, we have also graphed an over and an under coupled system, and one with a slight variation of the inductance ( $\lambda = 0.99$ ).

### 3.2 Contrast and it's optimization

With an expression for the effective impedance of the system in resonance and (more importantly) an expression for the resonant frequency, now we ask ourselves the question: What are the values of  $L$  and  $C_c$  that maximize the contrast  $|\Delta\Gamma| = |\Gamma(R_{\text{Off}}) - \Gamma(R_{\text{On}})|$ ?

Since on the lab the sizes of  $L$  and  $C_p$  are on the order of the ones used to produce figure 3, is easy to see that  $\omega_r$  will be a lot more sensible to changes in  $L$  than to changes in  $C_c$ , and thus we will use  $C_c$  to optimize the contrast, while we will use  $L$  to ensure that we stay in an acceptable frequency of operation.

With this in mind, we begin obtaining a workable expression of the contrast by plugging expression 3.4 into 3.1 without considering any of the approximations related to 3.4:

$$\begin{aligned}
Z &= \frac{1}{j\omega C_p + \frac{1}{j\omega L} + \frac{1}{R}} + \frac{1}{j\omega C_c} \\
&= \frac{\omega RL}{R(1 - \omega^2 LC_p) + j\omega L} + \frac{1}{j\omega C_c} \\
&= \frac{\frac{jRL}{\sqrt{L(C_c + C_p)}}}{R \left(1 - \frac{\cancel{L}C_p}{\cancel{L}(C_c + C_p)}\right) + \frac{jL}{\sqrt{L(C_c + C_p)}}} + \frac{\sqrt{L(C_c + C_p)}}{jC_c} \\
&= \frac{jRL}{R\sqrt{L(C_c + C_p)} \left(\frac{C_c}{C_c + C_p}\right) + jL} + \frac{\sqrt{L(C_c + C_p)}}{jC_c} \\
&= \frac{jR\cancel{L}}{R\frac{\cancel{L}(C_c + C_p)}{\sqrt{L(C_c + C_p)}} \left(\frac{C_c}{\cancel{C_c} + \cancel{C_p}}\right) + j\cancel{L}} + \frac{\sqrt{L(C_c + C_p)}}{jC_c} \\
&= \frac{jR}{RS + j} + \frac{1}{jS} = \frac{\cancel{RS} + \cancel{RS} + j}{jRS^2 - S} = \frac{1}{RS^2 + jS} \text{ with } S = \frac{C_c}{\sqrt{L(C_c + C_p)}}
\end{aligned} \tag{3.11}$$

Then we use this expression of the impedance to obtain the reflection coefficient, but using the admittance of the transmission line instead of the impedance ( $Y_0 = 1/Z_0$ )

$$\begin{aligned}
\Gamma &= \frac{Z - Z_0}{Z + Z_0} = \frac{Y_0 - 1/Z}{Y_0 + 1/Z} \\
&= \frac{2Y_0}{Y_0 + 1/Z} - 1 = \frac{2Y_0}{RS^2 + Y_0 + jS} - 1 \\
&= 2Y_0 \frac{RS^2 + Y_0 - jS}{(RS^2 + Y_0)^2 + S^2} - 1
\end{aligned} \tag{3.12}$$

Since  $\frac{1}{\sqrt{L(C_c + C_p)}} \approx \omega_r$  then  $\text{Im } Z \approx 0$  and by extension  $\text{Im } \Gamma \approx 0$ , so

$$\Gamma \approx 2Y_0 \frac{RS^2 + Y_0}{(RS^2 + Y_0)^2 + S^2} - 1 \tag{3.13}$$

Next, using the parameters utilized for figure 3 to get a sense of the scale, it is safe to assume that the following approximation is correct

$$(RS^2 + Y_0)^2 \gg S^2 \tag{3.14}$$

Which leaves us with the following expression for the reflection coefficient

$$\Gamma \approx \frac{2Y_0}{RS^2 + Y_0} - 1 \tag{3.15}$$

And this one for the contrast

$$|\Delta\Gamma| = |\Gamma(R = R_{\text{Off}}) - \Gamma(R = R_{\text{On}})| \approx 2Y_0 \left| \frac{1}{R_{\text{Off}}S^2 + Y_0} - \frac{1}{R_{\text{On}}S^2 + Y_0} \right| \quad (3.16)$$

Now, thanks to this simplified form of the contrast, to obtain the optimum value for  $C_c$  we don't need any fancy tricks, just to derive with respect to  $C_c$  and equate to 0. Doing this we arrive at the equation

$$S^2 = \frac{Y_0}{\sqrt{R_{\text{Off}}R_{\text{On}}}} \quad (3.17)$$

And solving it for  $C_c$ , we get the single solution (for  $R_{\text{On}}, R_{\text{Off}}, Y_0, L, C_p, C_c \geq 0$ )

$$C_{c\text{Max}} = \frac{LY_0}{2\sqrt{R_{\text{Off}}R_{\text{On}}}} \left( 1 + \sqrt{1 + 4C_p \frac{\sqrt{R_{\text{Off}}R_{\text{On}}}}{LY_0}} \right) \quad (3.18)$$

We could simply plug this result into a simulation and call it a day, but with a little bit more digging we can extract some interesting results.

First off, by the way the resistances appear in 3.17 and 3.18 it leads really naturally to defining a ratio parameter

$$\rho = \frac{R_{\text{Off}}}{R_{\text{On}}} \quad (3.19)$$

With it our expressions 3.17 and 3.18 turn to

$$S^2 = \frac{Y_0}{\sqrt{\rho}R_{\text{On}}} \quad (3.20)$$

$$C_{c\text{Max}} = \frac{LY_0}{2\sqrt{\rho}R_{\text{On}}} \left( 1 + \sqrt{1 + 4C_p \frac{\sqrt{\rho}R_{\text{On}}}{LY_0}} \right) \quad (3.21)$$

Then, by using the definition of  $S$  from 3.11 and using impedance, we can rearrange 3.20 to

$$Z_0 = \frac{L(C_c + C_p)}{\sqrt{\rho}R_{\text{On}}C_c^2} \quad (3.22)$$

This might remind you of the expression 3.10, and it's easy to see the parallelisms: In the previous case, given a resistance  $R$  we can find a  $L$  and  $C_c$  (in the confines that the restrictions 3.8, 3.7 and 3.9 allow) that will make 3.10 equal to  $Z_0$  and make  $\Gamma$  equal to 0. For the contrast

is the exact same, except that for that given  $R$  it maximizes it instead of making it 0, and that we have 2 values of  $R$ ,  $R_{\text{On}}$  and  $R_{\text{Off}} = \rho R_{\text{On}}$ , so which one do we use? Well it turns out that neither is the correct choice, it is  $\sqrt{R_{\text{Off}} R_{\text{On}}} = \sqrt{\rho} R_{\text{On}}$ , the geometric mean of the resistances.

In addition to this insight, we can also use 3.20 in our approximation for the contrast (3.14) to see that, when optimized, it only depends on the ratio of the resistances, and that has a maximum value of 2, which is expected:

$$|\Delta\Gamma| \approx 2Y_0 \left| \frac{1}{R_{\text{Off}}S^2 + Y_0} - \frac{1}{R_{\text{On}}S^2 + Y_0} \right| = 2 \left| \frac{1}{\sqrt{\rho} + 1} - \frac{\sqrt{\rho}}{1 + \sqrt{\rho}} \right| = 2 \left| \frac{1 - \sqrt{\rho}}{1 + \sqrt{\rho}} \right| \quad (3.23)$$

After these results it seems appropriate to analyze with more detail the approximations used, so we can contextualize the regime in which this works. The first approximation done was  $\omega \approx \omega_r$ , which boils down to 3.8 and 3.7. The second approximation was 3.14, so let's see if with the optimum  $C_c$  it holds. Using 3.20 we have

$$(RS^2 + Y_0)^2 \gg S^2 \rightarrow \left( \frac{RY_0}{\sqrt{\rho}R_{\text{On}}} + Y_0 \right)^2 \gg \frac{Y_0}{\sqrt{\rho}R_{\text{On}}} \quad (3.24)$$

Now, considering  $R = R_{\text{On}}$  since it's the worst case scenario and returning to the use of impedance instead of admittance, the condition turns to

$$\left( \frac{1}{\sqrt{\rho}} + 1 \right)^2 \gg \frac{Z_0}{\sqrt{\rho}R_{\text{On}}} \quad (3.25)$$

Since by definition  $\rho \leq 1$ , we can take a stricter version for this approximation but still achievable

$$R_{\text{On}} \gg Z_0 \quad (3.26)$$

This is clearly true in our case. In theory. Because you see, we've been ignoring something up until now for the sake of simplicity, something that was mentioned at the beginning of this section: the parasitic resistance  $R_p$ . As was said in the description of figure 2,  $R_p$  is a virtual resistance added in parallel with  $R_{\text{testSET}}$  to model losses in the circuit, and it can make  $R < 50\text{k}\Omega$ , so it is important that we keep it in mind.

Thankfully is easy to add it back retroactively (that's why we've ignored it up until now): we just need to do the following substitutions

$$\begin{aligned}
R_{\text{On}} \rightarrow R'_{\text{On}} &= R_{\text{On}} \parallel R_p = \frac{R_{\text{On}} R_p}{R_{\text{On}} + R_p} \\
R_{\text{Off}} \rightarrow R'_{\text{Off}} &= R_{\text{Off}} \parallel R_p = \frac{R_{\text{Off}} R_p}{R_{\text{Off}} + R_p} \\
\rho \rightarrow \rho' &= \frac{R'_{\text{Off}}}{R'_{\text{On}}}
\end{aligned}$$

If we give the same treatment to  $R_p$  as to  $R_{\text{Off}}$  by introducing a ratio parameter

$$\pi = \frac{R_p}{R_{\text{On}}} \quad (3.27)$$

Then the substitutions are

$$\begin{aligned}
R_{\text{On}} \rightarrow R'_{\text{On}} &= \frac{\pi}{1 + \pi} R_{\text{On}} \\
R_{\text{Off}} \rightarrow R'_{\text{Off}} &= \frac{\rho\pi}{\rho + \pi} R_{\text{On}} \\
\rho \rightarrow \rho' &= \frac{\rho(1 + \pi)}{\rho + \pi}
\end{aligned}$$

Taking this even further beyond with the fact that in an SET  $\rho \approx \infty$  (in the Off state, no electrons are travelling through), the substitutions are

$$\begin{aligned}
R_{\text{On}} \rightarrow R'_{\text{On}} &= \frac{\pi}{1 + \pi} R_{\text{On}} \\
R_{\text{Off}} \rightarrow R'_{\text{Off}} &= \pi R_{\text{On}} \\
\rho \rightarrow \rho' &= 1 + \pi
\end{aligned}$$

The introduction of the parasitic resistance and an infinite  $R_{\text{Off}}$  doesn't change much, in the sense that for most of the expressions is better to simply use the prime versions of  $\rho$  and  $R_{\text{On}}$  for clarity. Most. Because for two results in specific it helps: in [3.23](#)

$$|\Delta\Gamma| \approx 2 \left| \frac{1 - \sqrt{1 + \pi}}{1 + \sqrt{1 + \pi}} \right| \quad (3.28)$$

And in [3.26](#)

$$\frac{\pi}{1 + \pi} R_{\text{On}} \gg Z_0 \rightarrow \pi \gg \frac{Z_0}{R_{\text{On}} - Z_0} \quad (3.29)$$

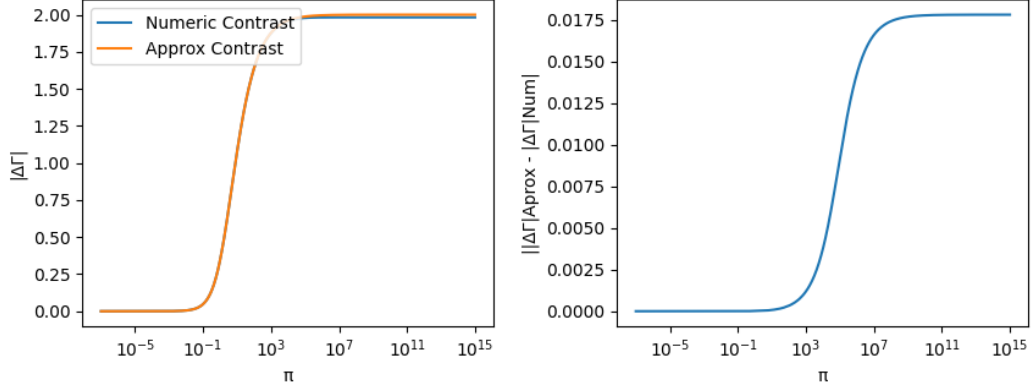


Figure 4: Numerical optimum contrast and our formula (3.28) with the difference between them.  $L = 180\text{nH}$ ,  $C_p = 500\text{fF}$ ,  $Z_0 = 50\Omega$ ,  $R_{\text{On}} = 50\text{k}\Omega$ ,  $\rho = 2 \cdot 10^{-6}$ .

Using the values of  $Z_0$  and  $R_{\text{On}}$  that we have been considering up until now ( $50\Omega$  and  $50\text{k}\Omega$  respectively) we can see that for 3.26 to work in a worse case scenario,  $\pi$  must be a lot greater than  $10^{-3}$ . It probably would be, given that for a  $\pi$  100 times greater,  $|\Delta\Gamma| \approx 0.0477$ , which isn't a good contrast to aim for.

Finally, we check our results by comparing them against the numerically calculated optimum contrast via a simulation that searches the optimum value of  $C_c$  for a given value of  $\pi$ .

As we can see in figure 4, even though the approximation gets worse for greater  $\pi$ , it caps off to a difference of 0.0175, which still makes it a pretty good approximation.

Next, we'll try to do the same analysis to a system with a variable inductance via a kinetic inductor.



## 4 The parallel kinetic RLC resonator

Now that we have familiarized ourselves with the way a parallel RLC resonator behaves and how we can optimize it for the best possible contrast, we are going to analyze how the inclusion of a variable  $L$  via a kinetic inductor will affect the contrast of our circuit.

Like with the resistance, the measure of the qubit in the state 1 will be linked with an inductance  $L_{\text{On}}$ , and an inductance  $L_{\text{Off}}$  with the state 0. Taking a page out of the previous section, we are going to introduce a parameter  $\lambda$  defined as

$$\lambda = \frac{L_{\text{Off}}}{L_{\text{On}}} \quad (4.1)$$

It's important to denote that  $0 < \lambda \leq 1$ , unlike  $\rho$ . This is due to  $R_{\text{On}} < R_{\text{Off}}$  and that the voltage is constant, so  $I_{\text{On}} > I_{\text{Off}}$ .

One more thing we need to cover before trying to get a usable expression for the optimum contrast is a new problem that comes with a variable inductance: which one do we use? Since we don't know which one is best, we'll introduce the parameter  $1 \leq \lambda_t \leq \lambda$  such that  $\omega = \frac{1}{\sqrt{\lambda_t L_{\text{On}}(C_c + C_p)}}$ . This parameter will determine the tuning we will be using, which will boil down to 3:

- $L_{\text{On}}$  tuning ( $\lambda_t = 1$ )
- $L_{\text{Off}}$  tuning ( $\lambda_t = \lambda$ )
- Middle tuning ( $1 < \lambda_t < \lambda$ )

We won't consider the outside of this interval of frequencies because as we shall see it's objectively worse than any of these 3 options.

### 4.1 Analysis of the effect on kinetic inductance on the contrast

We start in the same way as in 3.11: with the most generic expression for the inductance and little by little we start to specify more and more (for example, with an expression for  $\omega$ ).

$$\begin{aligned}
Z &= \frac{1}{j\omega(\lambda_t)C_p + \frac{1}{j\omega(\lambda_t)\lambda L_{\text{On}}} + \frac{1}{R}} + \frac{1}{j\omega(\lambda_t)C_c} \\
&= \frac{\omega(\lambda_t)R\lambda L_{\text{On}}}{R(1 - \omega(\lambda_t)^2\lambda L_{\text{On}}C_p) + j\omega(\lambda_t)\lambda L_{\text{On}}} + \frac{1}{j\omega(\lambda_t)C_c} \\
&= \frac{R\lambda L_{\text{On}}}{\frac{R}{\omega(\lambda_t)}(1 - \omega(\lambda_t)^2\lambda L_{\text{On}}C_p) + j\lambda L_{\text{On}}} + \frac{1}{j\omega(\lambda_t)C_c} \\
&= \frac{jR\lambda L_{\text{On}}}{\frac{R\omega(\lambda_t)}{\omega(\lambda_t)^2} \left(1 - \frac{\lambda L_{\text{On}}C_p}{\lambda L_{\text{On}}(C_c + C_p)}\right) + j\lambda L_{\text{On}}} + \frac{1}{j\omega(\lambda_t)C_c} \\
&= \frac{jR\lambda L_{\text{On}}}{R\omega(\lambda_t)\cancel{L_{\text{On}}}(C_c + \cancel{C_p}) \left(\frac{\lambda_t(C_c + C_p) - \lambda C_p}{\cancel{\lambda_t}(C_c + C_p)}\right) + j\lambda L_{\text{On}}} + \frac{1}{j\omega(\lambda_t)C_c} \\
&= \frac{jR\cancel{\lambda}L_{\text{On}}}{R\omega(\lambda_t)\cancel{L_{\text{On}}}\cancel{\lambda} \left(\frac{\lambda_t}{\lambda}(C_c + C_p) - C_p\right) + j\cancel{\lambda}L_{\text{On}}} + \frac{1}{j\omega(\lambda_t)C_c} \\
&= \frac{jR}{R\omega(\lambda_t) \left(\frac{\lambda_t}{\lambda}(C_c + C_p) - C_p\right) + j} + \frac{1}{j\omega(\lambda_t)C_c}
\end{aligned} \tag{4.2}$$

As you can see, since the inductance of  $Z$  interacts with the one inside  $\omega$ , I've written directly  $\lambda L_{\text{On}}$  instead of  $L$  to then swap it, like with  $R$ . So to get  $Z_{\text{On}}$  the substitutions needed are  $R = R_{\text{On}}$  and  $\lambda = 1$ , and for  $Z_{\text{Off}}$  is just  $R_{\text{Off}}$ .

With that detail out of the way we can see that, as opposed to the previous section, we can't wrap neatly  $C_c$ ,  $C_p$  and  $L$  in a parameter like  $S$ . Due to this, I believe that to obtain an expression like the one for the non-kinetic resonator it would be necessary to do an analysis on a case by case bases with more context about the application to better choose the correct approximations, if arriving at a nice and practical expression is even possible that is. Since the objective of this master's thesis is a theoretical proof of concept for the use of kinetic inductors to improve readout for silicon spin qubits, simulations and their analysis will be the methodology used.

## 4.2 Simulation of the effect on kinetic inductance on the contrast

In a simulation you have supreme control over what is simulated, how is simulated and what and how results are shown. A great deal of time was spent deciding these things, and the final decisions and their reasoning are the following:

The main value we are going to calculate and graph is  $\Delta\Gamma(Z_0, \rho, R_{\text{On}}, C_p, L_{\text{On}}, \lambda_t, \pi, C_c, \lambda)$ .

Due to the high number of inputs, we need to fix some of them in order to analyze in the best way possible how does  $\Delta\Gamma$  behave. Taking inspiration from the non-kinetic case, in which for the optimum value of  $C_c$  the only parameter that affected the contrast was  $\pi$ , we will fix the following variable with the following values

$Z_0$	$\rho$	$R_{\text{On}}$	$C_p$	$L_{\text{On}}$
$50\Omega$	$2 \cdot 10^6$	$50\text{k}\Omega$	$500\text{fF}$	$180\text{nH}$

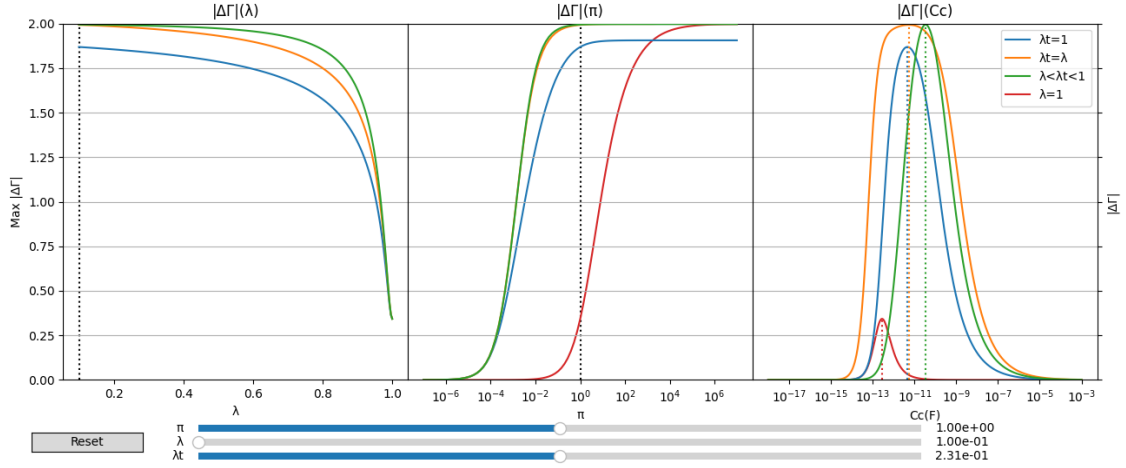


Figure 5: Multiple representations of the contrast with sliders to control their parameters. Right:  $|\Delta\Gamma_{\text{Opt}}(\lambda)|$ . Center  $|\Delta\Gamma_{\text{Opt}}(\pi)|$ . Left:  $|\Delta\Gamma(C_c)|$

So, what we will graph is  $\Delta\Gamma(\lambda_t, \pi, C_c, \lambda)$ , which only depends on  $\pi$ ,  $C_c$  (since we'll need to find the optimal value numerically), and all the new variables associated with the introduction of a variable inductance. This still leaves us with a 4 variable function, and the best way to plot it that I could think of can be seen in figure 5

In the left and central plot we have the modulus of  $\Delta\Gamma_{\text{Opt}}$ , which is  $\Delta\Gamma$  with the value of  $C_c$  that maximizes the modulus, as a function of  $\lambda$  and  $\pi$  respectively, and the left plot is  $|\Delta\Gamma(C_c)|$ . In each there are multiple lines: 3 with a different value of  $\lambda_t$  and one with  $\lambda = 1$  to act as reference for the non-kinetic case (for the left plot it didn't make sense to add the reference line). Finally, we have 3 sliders to control the plots in real time:

- $\pi$  slider controls the value of  $\pi$  for the left and right plot, and the dotted black line in the center plot
- $\lambda$  slider controls the value of  $\lambda$  for the center and right plot, and the dotted black line in the left plot
- $\lambda_t$  slider controls the value of  $\lambda_t$  for the plot with  $\lambda < \lambda_t < 1$

The range of the  $\lambda$  and  $\pi$  sliders is the same as the domain of the respective plots ( $\lambda \in [0.1, 1]$ ,  $\pi \in [10^{-7}, 10^7]$ ), and the range of the  $\lambda_t$  slider is  $\lambda_t \in [\lambda, 1]$  (the edges were included, so it could be seen how it morphs into the other two plots). The domain of the right plot is  $C_c \in [10^{-18}, 10^{-3}]$  fF, and it was chosen such that for any combination of  $\lambda$  and  $\pi$  the maxima was in it, since it is also the range in which the simulation search for the optimum  $C_c$ .

The main observations, both in relevance and notoriety, can be seen directly with figure 5

- A smaller  $\lambda$  is always better in order to improve the contrast
- $\lambda_t$  and  $\lambda < \lambda_t < 1$  are objectively better than the non-kinetic case, with the main difference being that with an intermediate  $\lambda_t$  the optimum  $C_c$  is greater

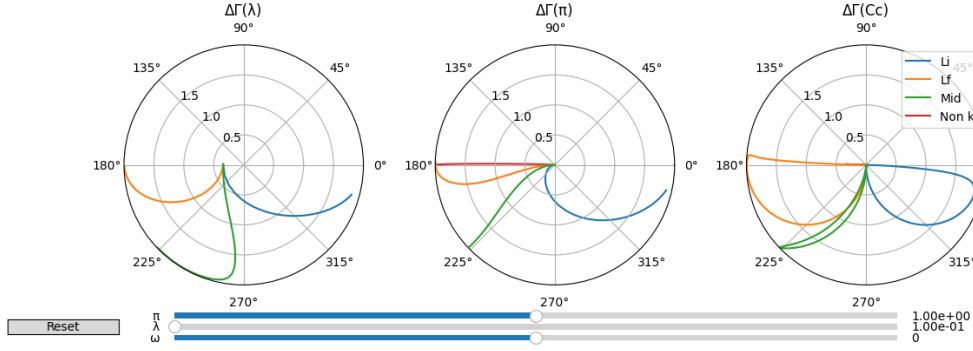


Figure 6: Multiple representations of the contrast with sliders to control their parameters. Right:  $\Delta\Gamma_{\text{Opt}}(\lambda)$ . Center  $\Delta\Gamma_{\text{Opt}}(\pi)$ . Left:  $\Delta\Gamma(C_c)$

- $\lambda_t = 1$  hits a ceiling that causes that, for a high enough value of  $\pi$ , the introduction of a kinetic inductor is actually worse than a non-kinetic one. With the  $\pi$  slider can be seen that this ceiling depends on  $\lambda$ , but modifying the non-variable parameters shows that it also depends on them. To be more specific,  $|\Delta\Gamma(\lambda_t = 1)| \propto R_{\text{On}}, C_p, 1/L_{\text{On}}$ , with  $R_{\text{On}}$  being the more sensible of the 3 by a margin.

Thanks to the sliders a more thorough analysis of the simulation can be made, but nothing besides the previous points can be seen except for some quirky behavior not drastic enough to necessitate images, but curious enough to talk about it and encourage playing with the simulation to see it.

This behavior boils down to 3 quirks that appear on the plots, one for each, at high enough values of  $\pi$ . These oddities are, from left to right

- A local minimum appears in the left plot on all lines as early as  $\pi = 3.09$  near  $\lambda = 1$
- At  $\pi \approx 1526$ , the central plot with  $\lambda_t = \lambda$  gets a sudden but small jump, caused by the next point in the list
- A second local maximum appears in the right plot with  $\lambda_t = \lambda$ , and at  $\pi \approx 1526$  it surpasses the previous global maximum

We can easily find an explanation by looking at  $\Delta\Gamma$  instead of  $|\Delta\Gamma|$ . When increasing  $\pi$ , the origin of the lines in the left plot of figure 6 shifts to the left, while the ends stay relatively similar, making the path curve to the center of the complex plane. Similarly, the closed path with  $\lambda_t = \lambda$  in the right plot crosses over itself at  $\pi \approx 66$ , causing the second maximum to appear and at  $\pi \approx 1526$ , it surpasses the previous and causes the sudden rise in  $|\Delta\Gamma(\pi)|$ .

## 5 Conclusions

## 6 Outlook