Electromagnetic simulations for near Field GHz spectrometer

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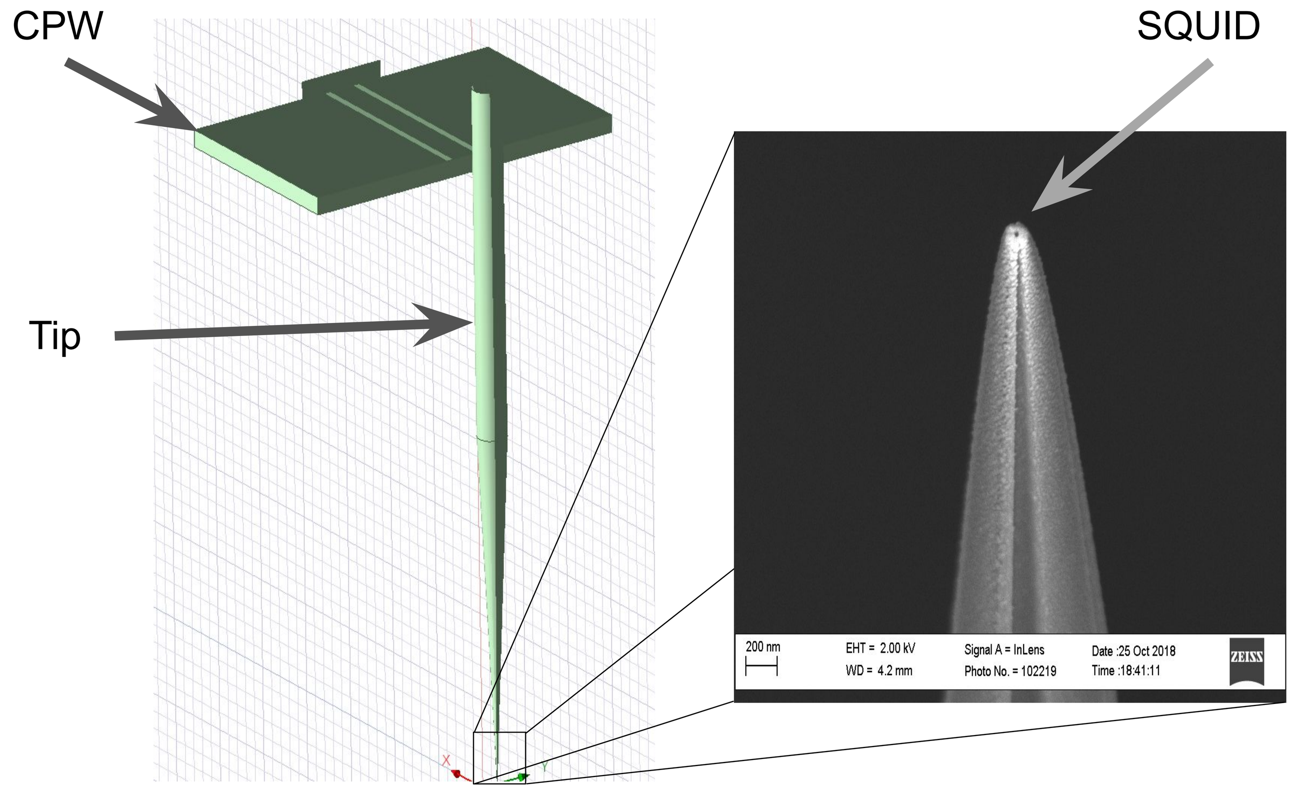
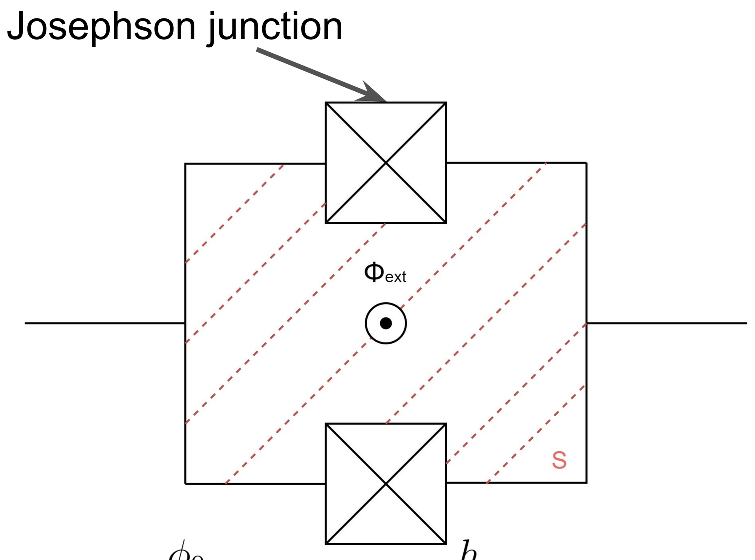
Abstract

The goal of the internship was to simulate a near-field GHz spectrometer with the shape of a tip on which a thin coat of NbN is deposited. A SQUID at the end of the tip allows to detect magnetic field variation. By modelling the system's behavior as an LC resonator with the SQUID acting as an ifield-dependant inductance. We can determine its variation very precisely by following the resonance frequency. We used Ansys' HFSS Software to simulate the tip frequency and coupling to a waveguide. We managed to study the behavior of the tip while modifying its geometry (ex : tip distance to the waveguide).
However we have faced some challenges. Simulating a model with a large aspect ratio can be difficult and require many techniques to mesh properly. Moreover, ensuring the validity of the model is essential, especially with software simulations. Several tests are needed to check the robustness of the model against the theory.

Spectrometer 3D Model



SQUID structure

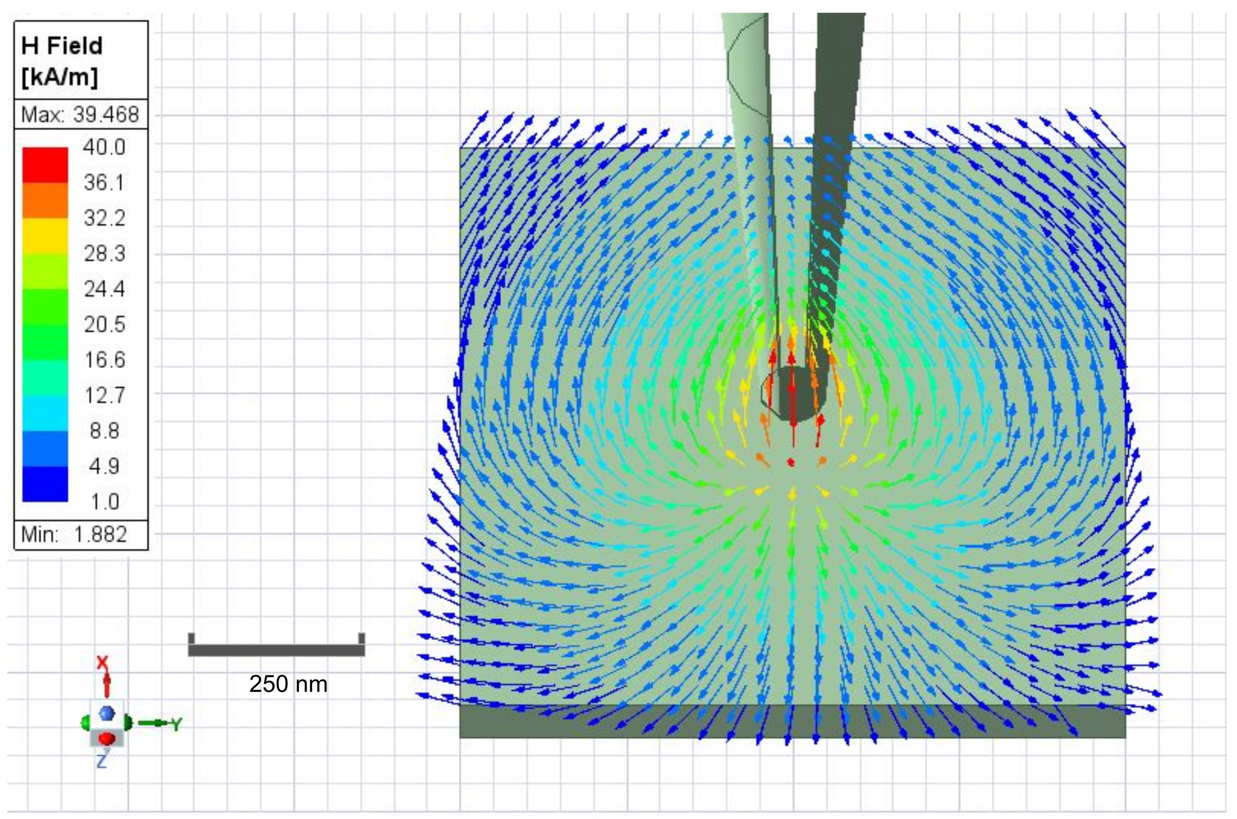


$L_J = \frac{\phi_0}{I(\phi_{ext})}$ with $\phi_0 = \frac{h}{2e}$

The SQUID inductance depends on the magnetic field in S : $\phi_{ext} = B_{ext}.S$

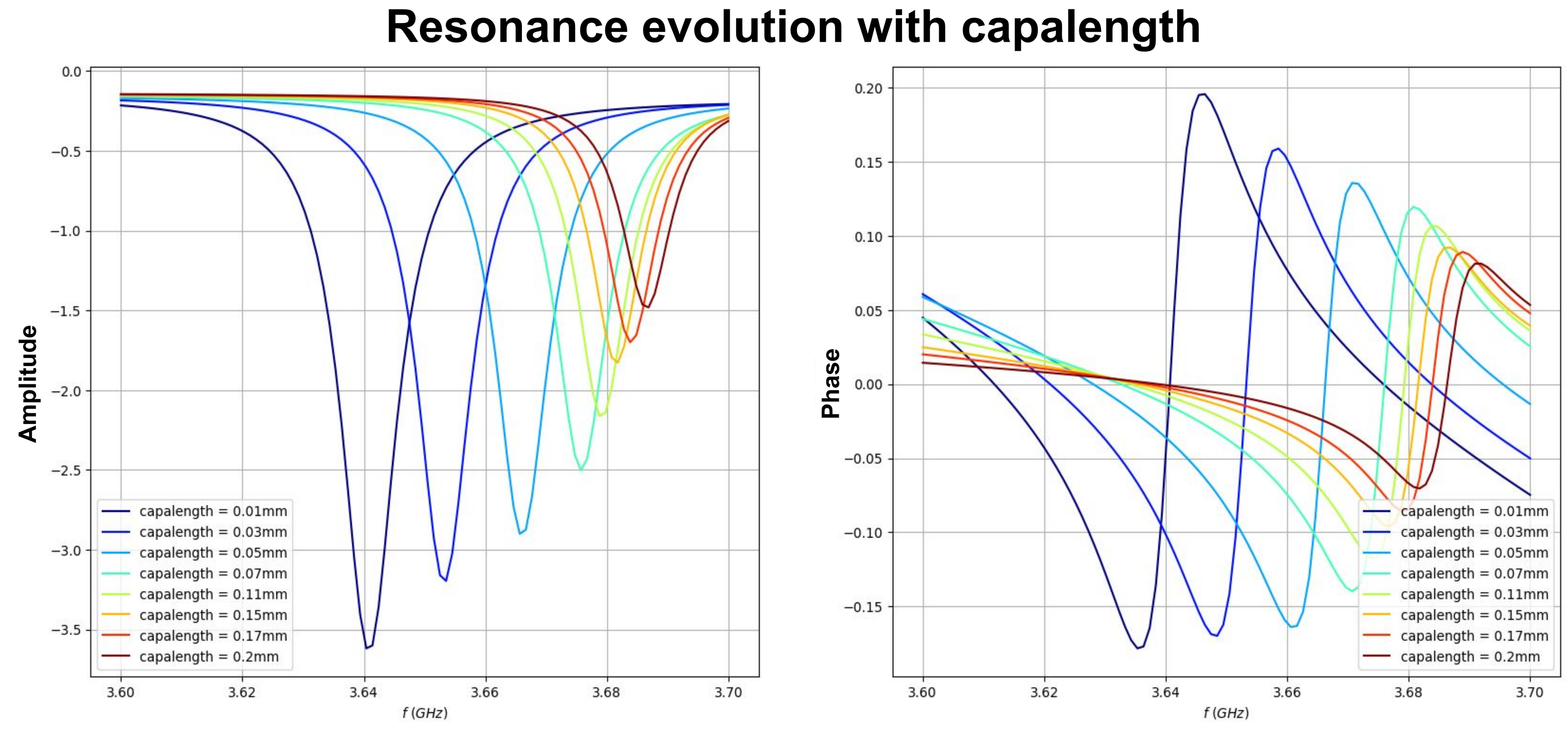
We have : $L_J \approx 10pH$

H Field on the tip



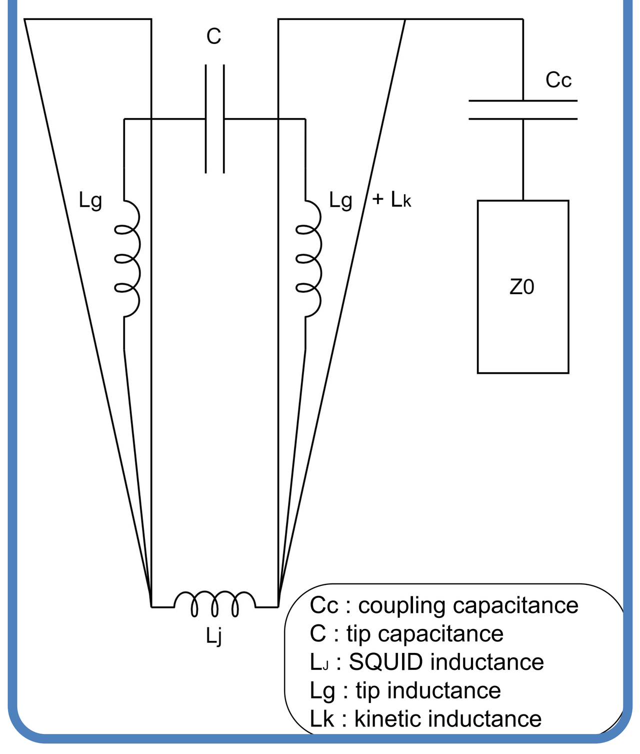
The vast majority of the H field at resonance is at the edge of the tip, which is important for spatial resolution.

Resonance evolution with capalength



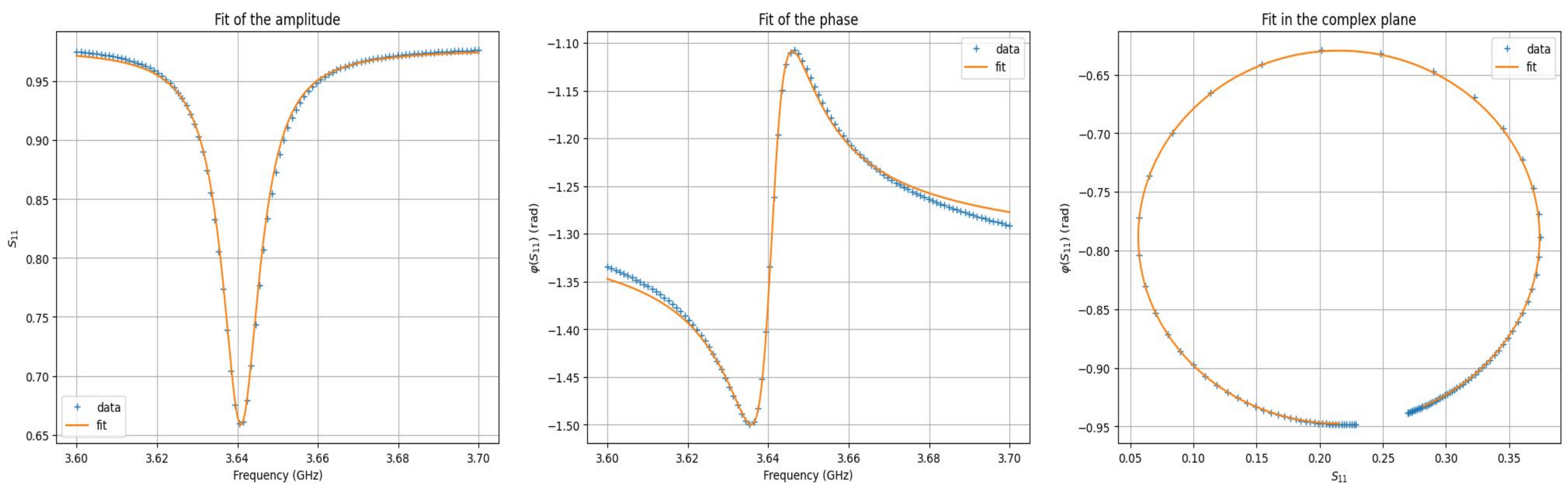
HFSS simulations scanning frequencies for the reflection factor, variation of capalength : distance between the CPW and the tip. We observe an increase in the resonance frequency and a decrease in the total quality factor. The increase in frequency is due to the reduction of coupling capacity between the CPW and the tip. The resonance frequency given by the simulations is in the range measurable by standard electronic equipment.

Equivalent circuit

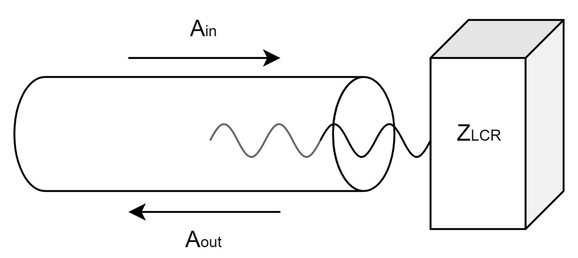


Fit of the resonator frequency response

To obtain the parameters of the tip we realized a fit of the data given by the simulation using a simple model of a Fresnel reflection factor with a LCR resonator.
The fit was done simultaneously on the amplitude and on the phase using Python.



Acquisition method



We proceed by measuring the reflection coefficient for the signal sent to the tip. If the tip resonate |S11| value drops.

Tip impedance and reflexion coefficient :

$$Z_{LCR} = \frac{1}{i\omega C_k} + \left(\frac{1}{i\omega L} + i\omega C + \frac{1}{R}\right)^{-1}$$

$$S_{11} = \frac{A_{out}}{A_{in}} = A\frac{Z_{LCR} - Z_0}{Z_{LCR} + Z_0}$$

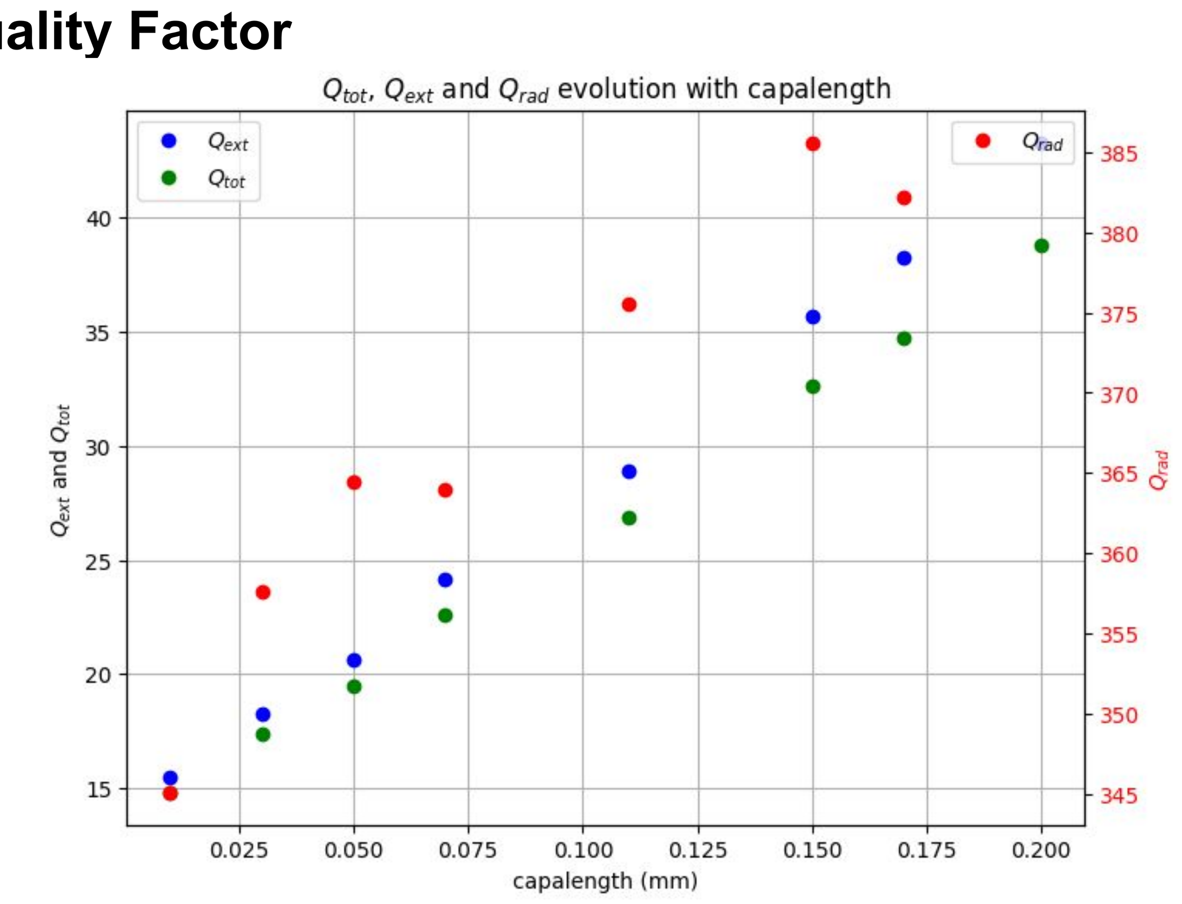
Quality Factor

Norton resistor and Quality factors :

$$R^* = \frac{1 + \omega_{res}^2 C_k^2 R^2}{\omega_n^2 C_k^2 R^2}$$

we have : $Q_{rad} = \omega_{res} RC$ and $Q_{ext} = \frac{\omega_{res} R^* C}{2}$

then $\frac{1}{Q_{tot}} = \frac{1}{Q_{rad}} + \frac{1}{Q_{ext}}$



This figure shows the quality factors of the simulation following the variation of capalength. The quality factor (Qrad) depends directly on the tip's radiative losses, it characterizes the coupling between the tip and the surrounding vacuum, thus describes the photons emitted into free space. The external factor characterises the coupling to the CPW line. The larger it is, the less the spike is coupled. Qext is expected to depend linearly on the coupling capacitance Cc which is what we obtain numerically. In practice we will also have losses in the superconductor, but those can not be simulated with HFSS.

References and acknowledgement

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(2) S. Probst, F. B. Song, P. A. Bushev et al . *Rev. Sci. Instrum.* 86 (2015)
(3) M. Tinkham, Introduction to Superconductivity (1996)

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Conclusions and perspectives

Conclusions:

- The tip in its final geometry appears to resonate at around 3.6 GHz, which means that the complete device can be made with standard electronic devices.
- The radiation is non negligible with this geometry. Further simulation need to be done to control this parameter.

Perspectives:

- The tip could be used to measure the magnetic field variation on the surface of materials. For example It could be used to detect spin with a good spatial resolution. By modifying the tip geometry we can alter its resonance frequency and detect it with standard reflectometry techniques.