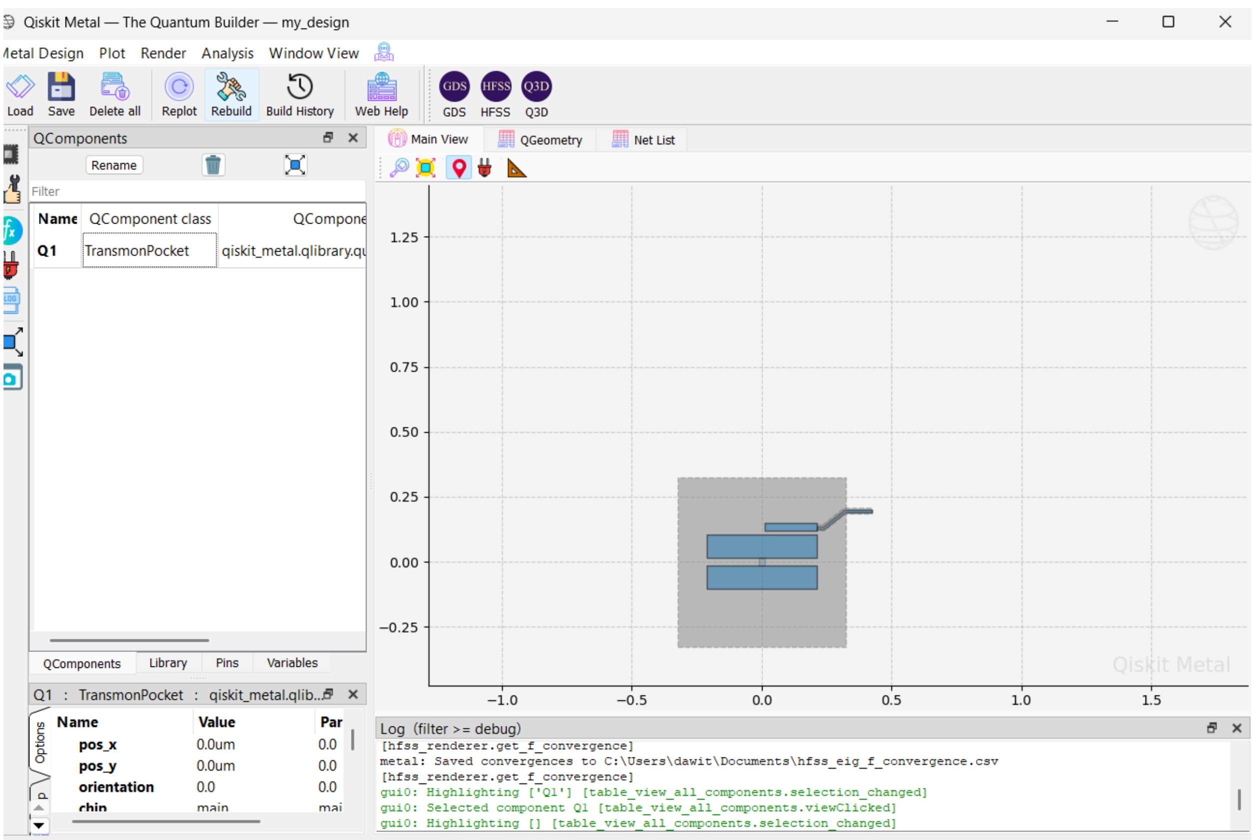
Introduction

This report documents the EE 274 project assigned by Dr. Wong. The primary objective is to gain practical familiarity with the Qiskit Metal and Ansys HFSS workflow used in superconducting circuit design and analysis. Through the lab overview and associated exercises, this report demonstrates my understanding of the course concepts by walking through the full simulation pipeline—from environment setup to eigenmode simulation and energy participation ratio (EPR) analysis.

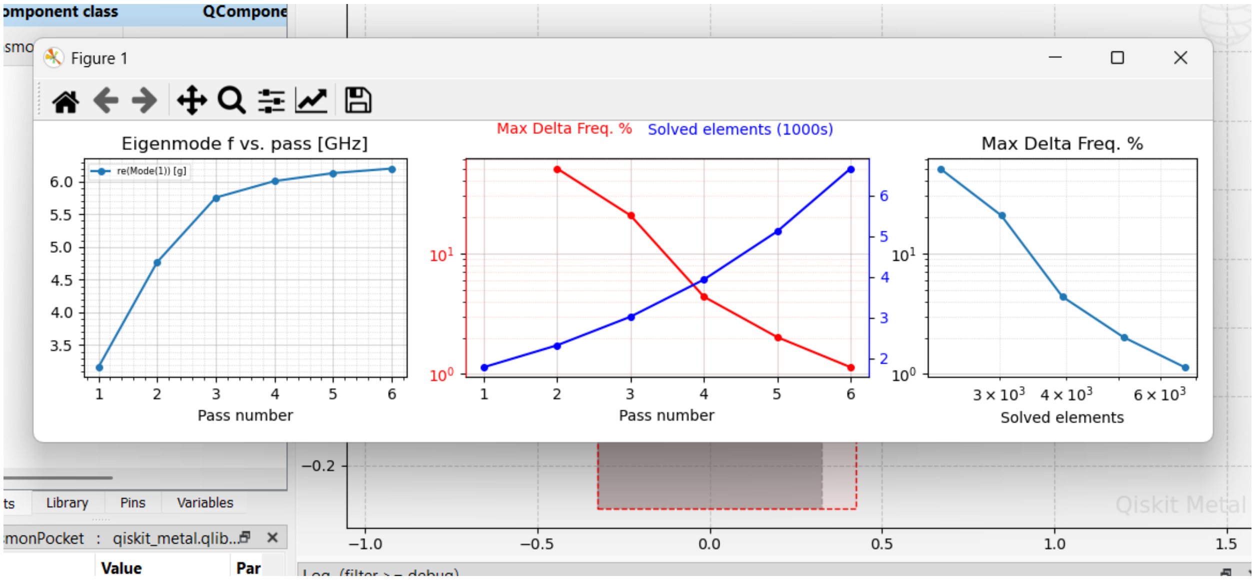
To prepare the toolchain, I installed Anaconda and configured Jupyter Notebook to run Qiskit Metal. I also installed Ansys HFSS using the software access instructions provided with the project. Using the example Eigenmode and EPR analysis notebooks available through the Qiskit documentation, I imported the required files into Jupyter and executed the workflow to generate simulation results. The remainder of this report presents the step-by-step procedure I followed and the key outputs obtained from running the eigenmode and EPR analyses.

Import and run all the necessary libraries.

Create a chip with 2mm-by-2mm dimensions and Qiskit metal interface showed up.

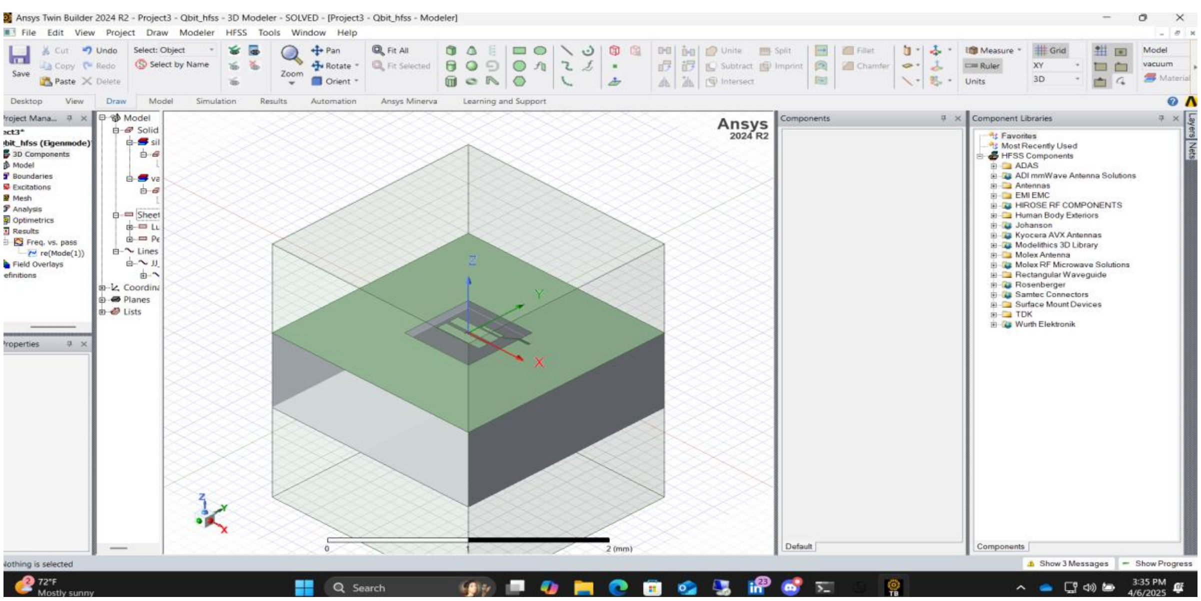


The image in the GUI is transmone qubit with the capacitor. Create a single transmon with one readout resonator and move it to the center of the chip previously defined. The data attached below shows the qubit eigenmode frequency vs pass simulation .

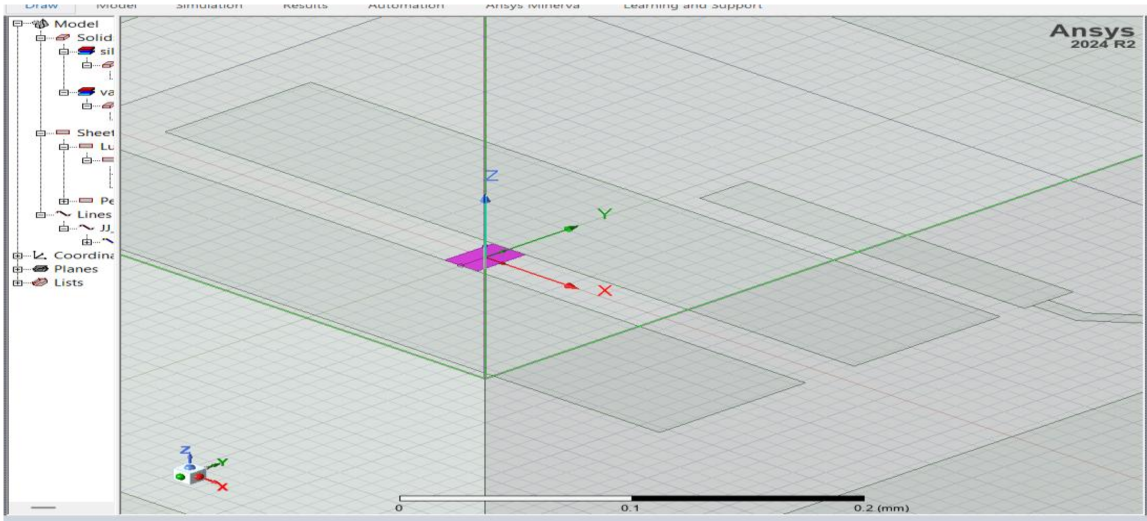


Next go through EPR (energy participation ratio analysis) and set up some parameters. Execute simulation and verify convergence and EM field. And this line of code opens HFSS “eig_qb.sim.run(name="Qbit", components=['Q1'], open_terminations=[], box_plus_buffer = False) eig_qb.sim.plot_convergences()”

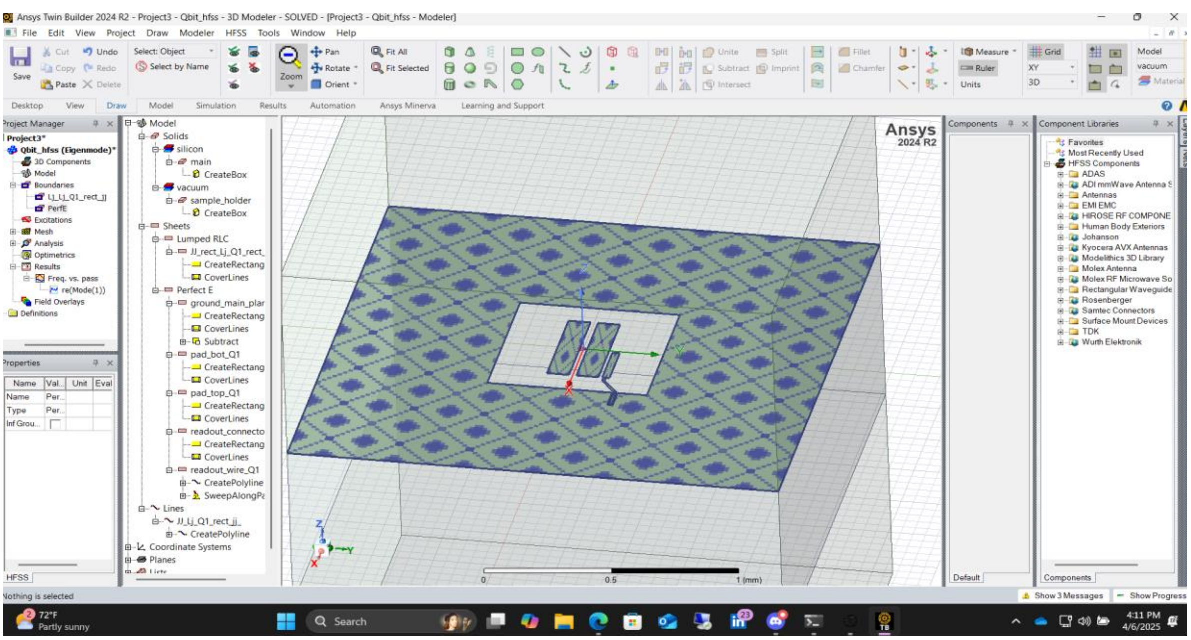
- the 3D structure simulation shows up in HFSS



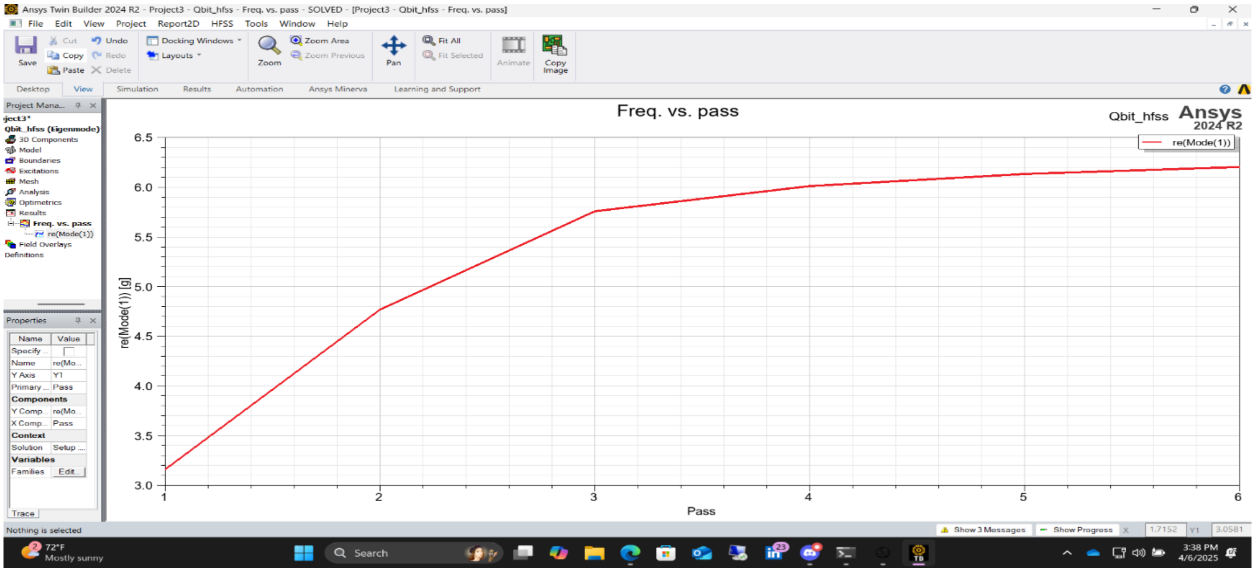
What I got out from the above 3D simulation object is that if I zoom it out, I can see the Josephson junctions which is the transoms qubits. Shunt capacitor in between, and the junction is aluminum oxide sandwiched between two niobium, which are superconductors.



The picture below with the blue and gray Ish shows that it's perfectly superconducting, there is no resistance at all.

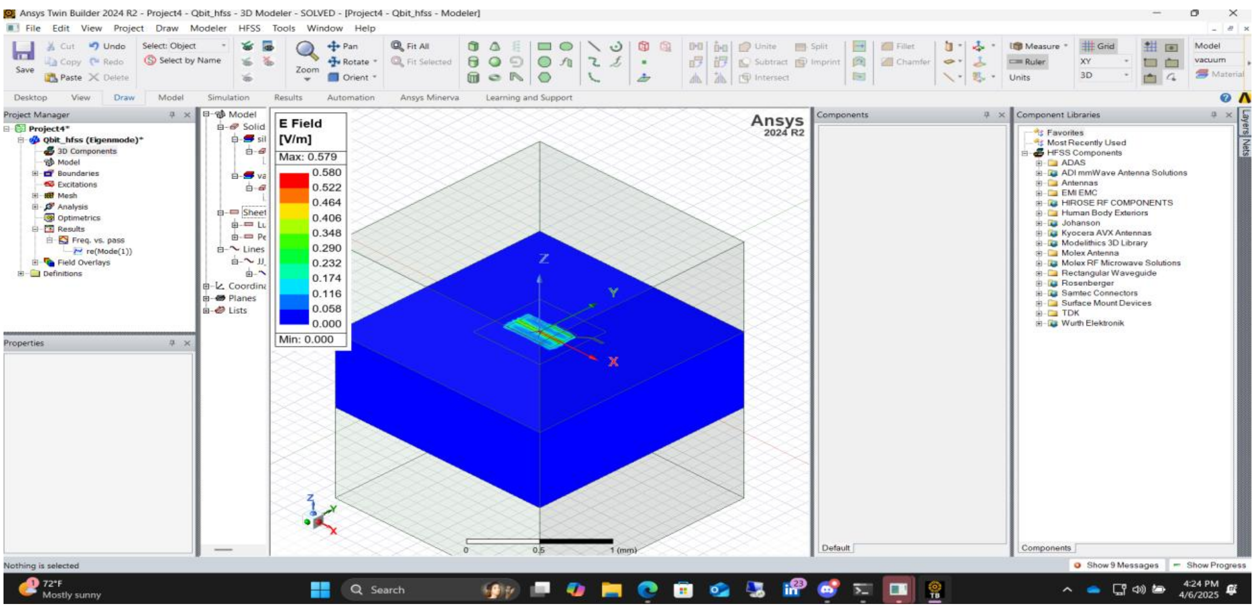


And the circuit is a 2D plane as we can see it below:



- The above 2D picture Freq. Vs. Pass shows that different pass determines whether it’s converged after some consecutive pass.

Eigenmode simulation shows below



Basically, this rendering is useful to see the electromagnetic distribution and energy calculation to do something useful for superconducting qubits.

EPR Analysis

We will now run EPR as a single step. On screen you will observe various information in this order:

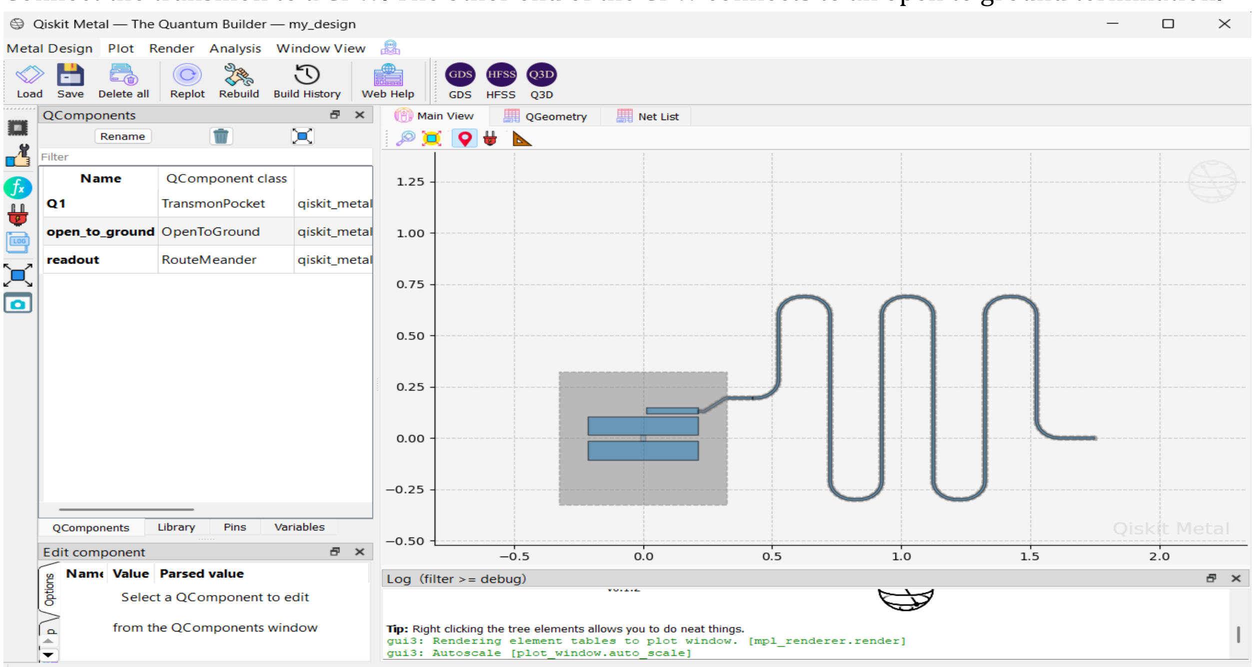
- stored energy = Electric and magnetic energy stored in the substrate and the system as a whole.
- EPR analysis results for all modes/variations.
- Spectrum analysis.
- Hamiltonian report.

Identify the non-linear (Josephson) junctions in the model. You will need to list the junctions in the EPR setup.

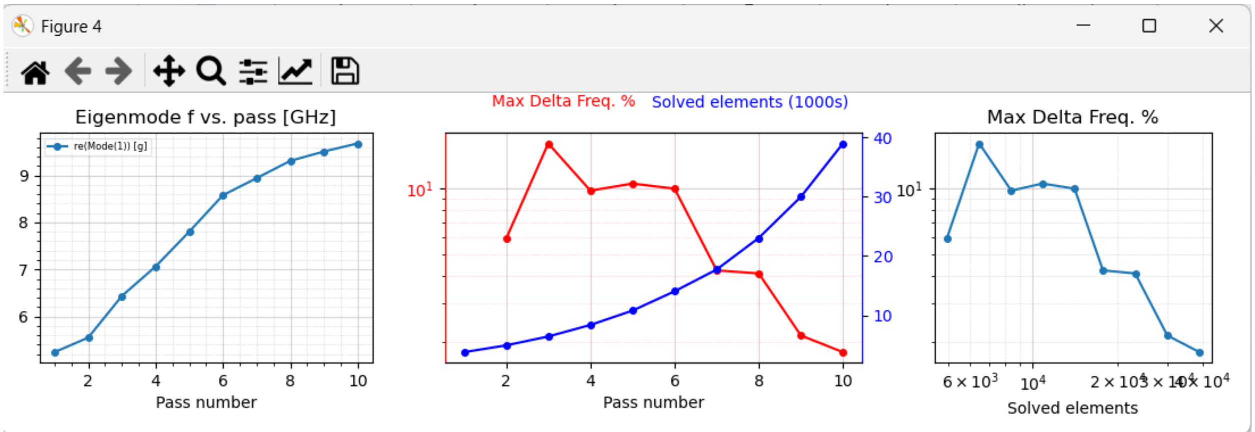
In the qiskitmetal code there are two important quantities for EPR analysis which are rectangele “'JJ_rect_Lj_Q1_rect_jj'” and line “'JJ_Lj_Q1_rect_jj_'”

Analyze the CPW resonator

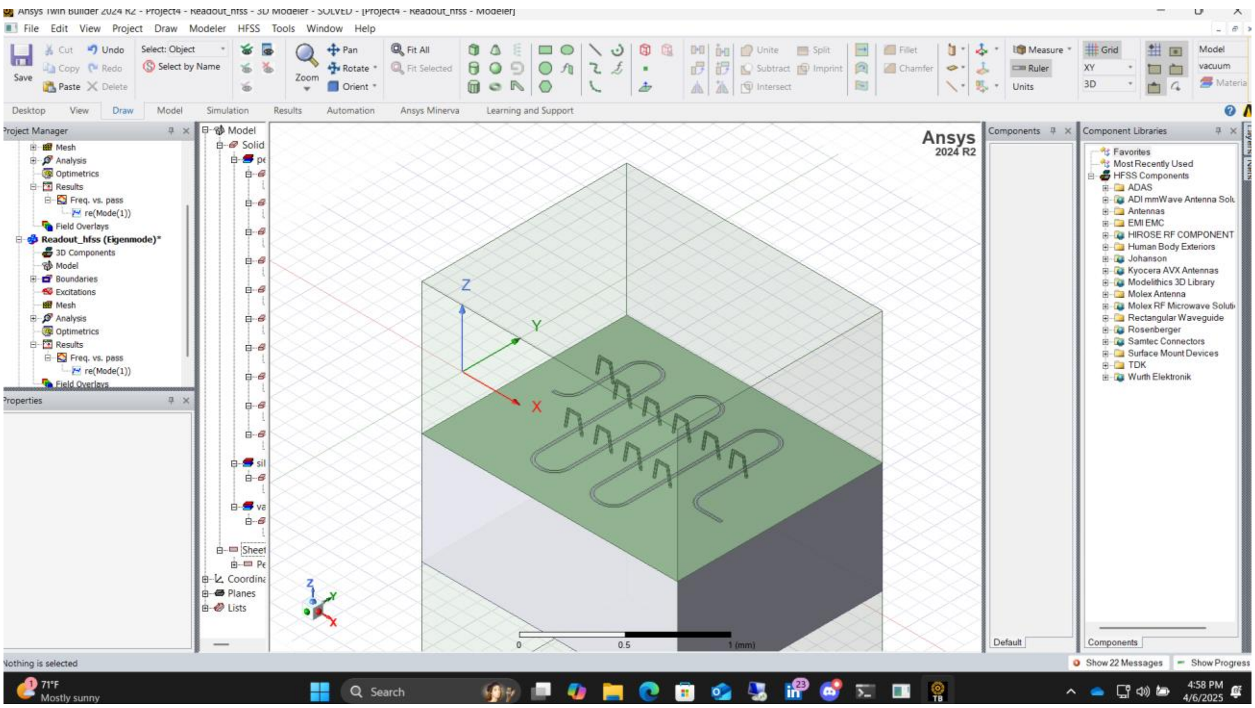
Now, the picture below shows that we build the wave guide which acts as a resonator. Connect the transmon to a CPW. The other end of the CPW connects to an open to ground termination.



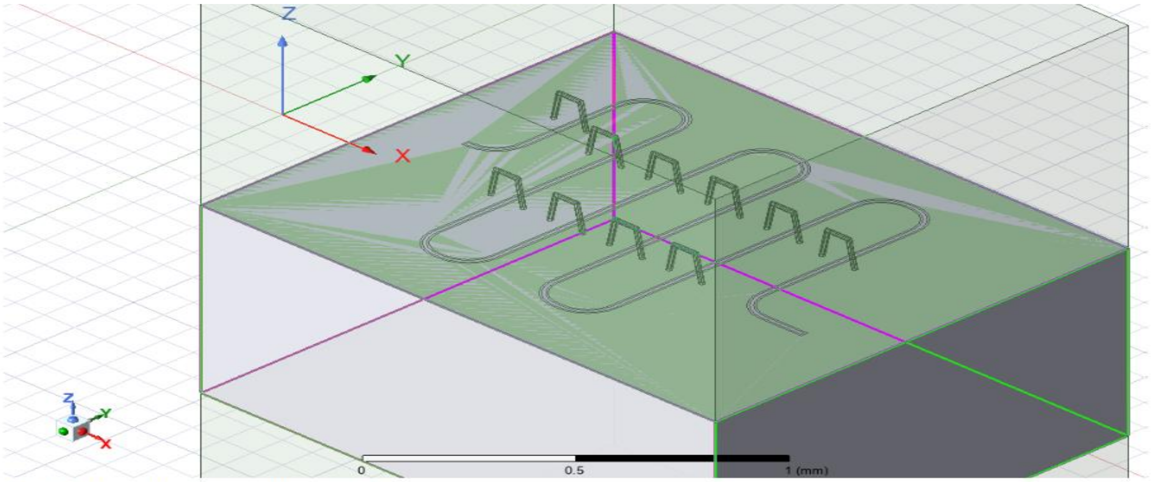
- For the resonator analysis we will use the default setup and Execute simulation and verify convergence and EM field.
- Artificial atoms and cavity share energy, and they will affect each other.



And ofcourse when we ran our code on qiskit, we see the simulation in 3D on HFSS as the picture shared below



Below the simulation ran and it shows also the resonator frequency about 9.67 GHz




```
[73]: WindowsPath('C:/Users/dawit/Downloads/ansys.png')
```

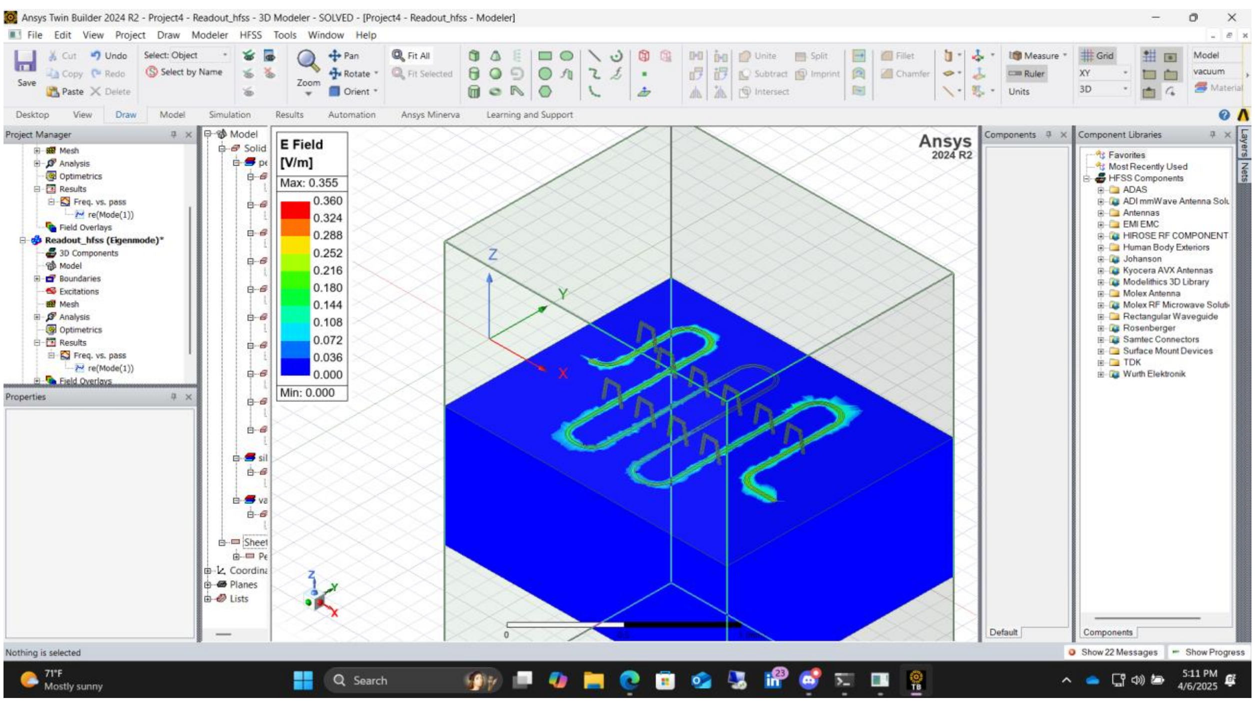
Recover eigenmode frequencies for each variation.

```
[74]: eig_rd.get_frequencies()

Design "Readout_hfss" info:
        # eigenmodes    1
        # variations    1
Design "Readout_hfss" info:
        # eigenmodes    1
        # variations    1
```

[74]:

variation	mode	Freq. (GHz)	Quality Factor
0	0	9.679603	inf

Again, here is the electromagnetic field distribution



Eventually, we do EPR analysis. The reason why we are interested in EPR analysis is to find the electric and magnetic energy stored in the readout system. What we want to see is, with this qubit, how is it going to change the resonance frequency of the cavity.

When the qubit spins up and down, the effect is approximately equal to the cross curve and it's going to affect the resonator frequency differently.

Here is the result we get as shown below:

```
[77]: WindowsPath('C:/users/dawit/Downloads/ansys.png')
```

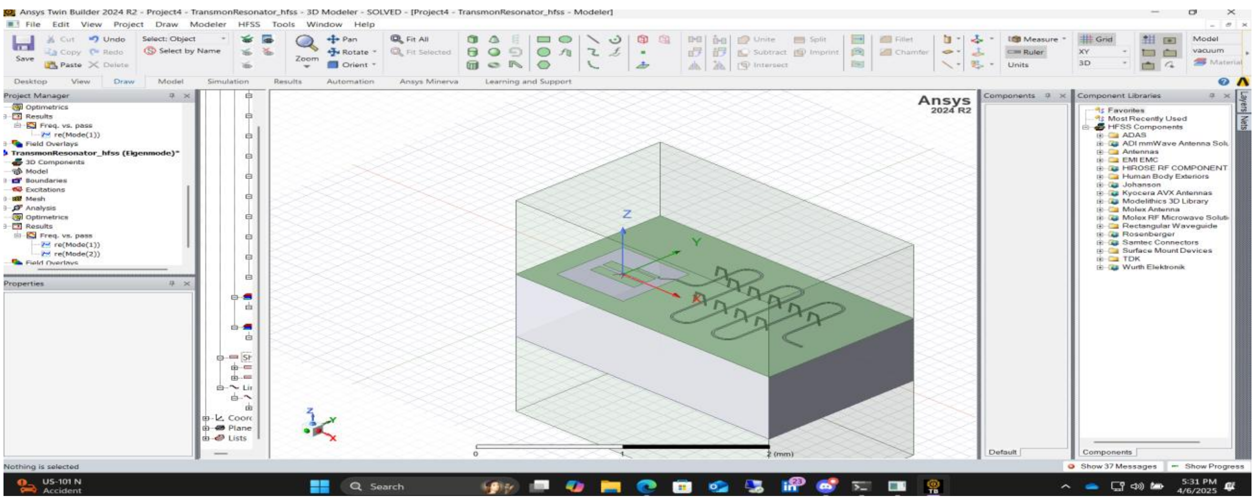
EPR Analysis ¶

Find the electric and magnetic energy stored in the readout system.

```
[78]: eig_rd.run_epr(no_junctions = True)

Design "Readout_hfss" info:
        # eigenmodes    1
        # variations    1
Design "Readout_hfss" info:
        # eigenmodes    1
        # variations    1

        energy_elec_all       = 1.72954229010017e-24
        energy_elec_substrate = 1.58260880511112e-24
        EPR of substrate = 91.5%

        energy_mag    = 1.72954985433982e-24
        energy_mag % of energy_elec_all  = 100.0%
```

Analyze the combined transmon + CPW resonator system:

transmonresonetor HFSS simulation



As it has shown in the picture above, what we are doing is combining transom qubits with the resonator we designed.

Below, shows that 2D analysis of both the qubits and the resonator.as we can see the red is converging to a frequency 6 GHz. However, the green surface line converges about 9.5 GHz frequency. Meaning, now we are integrating the qubit and resonator combined frequency is higher.

Conclusion

In this lab, I explored the electromagnetic properties of a transmon qubit-resonator system using Ansys HFSS and the pyEPR (Energy Participation Ratio) framework. The goal was to compute eigenmodes of the qubit and extract participation ratios to estimate key quantum parameters. After constructing the geometry in HFSS, I performed eigenmode analysis to identify resonant frequencies and field distributions. The pyEPR analysis allowed me to estimate qubit anharmonicity, coupling strengths, and dispersive shifts by analyzing how energy is shared among the system's components. This lab provided hands-on experience in connecting finite-element simulation with quantum circuit modeling, bridging electromagnetic design with superconducting qubit theory.

3D Cavity Design on HFF

By following the instructions on the video, I have created the 3D cavity. The steps were straight forwards I just used the same values and parameters for the design as the Lab video. Here are the design parameters I used as shown in the picture blew.

Properties: 3Dcavity_transmon - HFSSDesign1

Local Variables

(•) Value ( ) Optimization / Design of Experiments ( ) Tuning ( ) Sensitivity ( ) Statistics

Name	Value	Unit	Evaluated V...	Type	Description	Read-only	Hidden	Sweep
Xmax	30	mm	30mm	Design		☐	☐	☑
Ymax	50	mm	50mm	Design		☐	☐	☑
Zmax	30	mm	30mm	Design		☐	☐	☑
thickness	5	mm	5mm	Design		☐	☐	☑
Xmaxthickn...	40	mm	40mm	Design		☐	☐	☑
radious	2	mm	2mm	Design		☐	☐	☑
offset	10	mm	10mm	Design		☐	☐	☑
shiftport	25	mm	25mm	Design		☐	☐	☑
radius1	1	mm	1mm	Design		☐	☐	☑
radius	2	mm	2mm	Design		☐	☐	☑

☑ Show Hidden

Add... | Add Array... | Edit... | Remove | Export... | Import...

OK | Cancel | Apply

Properties: 3Dcavity_transmon - HFSSDesign1

Local Variables

(•) Value ( ) Optimization / Design of Experiments ( ) Tuning ( ) Sensitivity ( ) Statistics

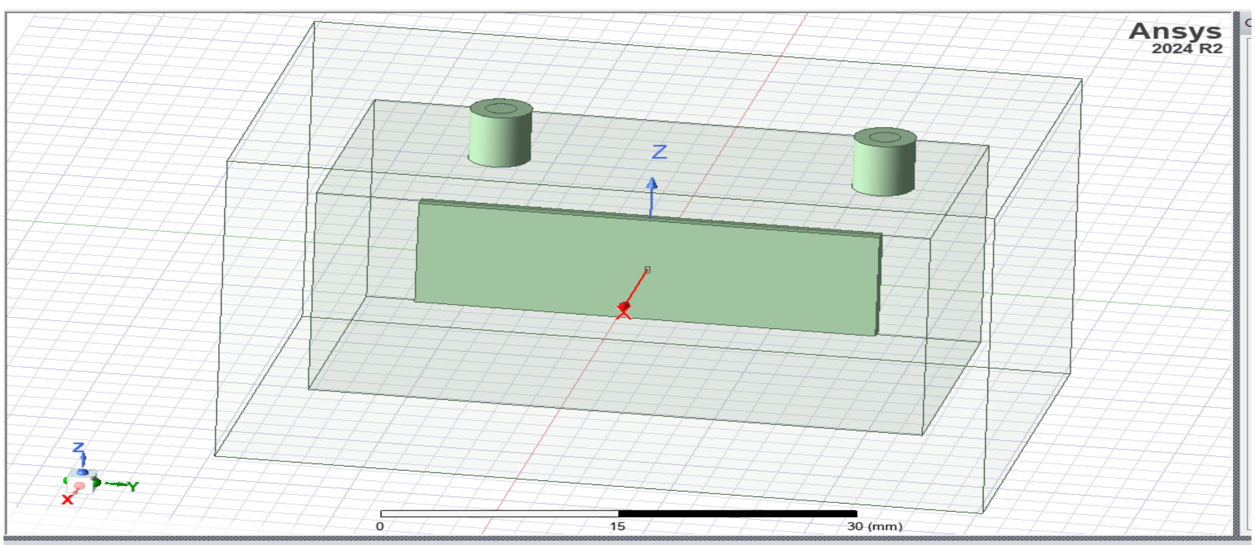
Name	Value	Unit	Evaluated V...	Type	Description	Read-only	Hidden	Sweep
shiftport	25	mm	25mm	Design		☐	☐	☑
radius1	1	mm	1mm	Design		☐	☐	☑
radius	2	mm	2mm	Design		☐	☐	☑
Sub	1	mm	1mm	Design		☐	☐	☑
Sub_Xmax	1	mm	1mm	Design		☐	☐	☑
Pad_Y	0.3	mm	0.3mm	Design		☐	☐	☑
Pad_Z	0.3	mm	0.3mm	Design		☐	☐	☑
L_JJ	0.05	mm	0.05mm	Design		☐	☐	☑
Lj	12	nH	12nH	Design		☐	☐	☑

☑ Show Hidden

Add... | Add Array... | Edit... | Remove | Export... | Import...

OK | Cancel | Apply

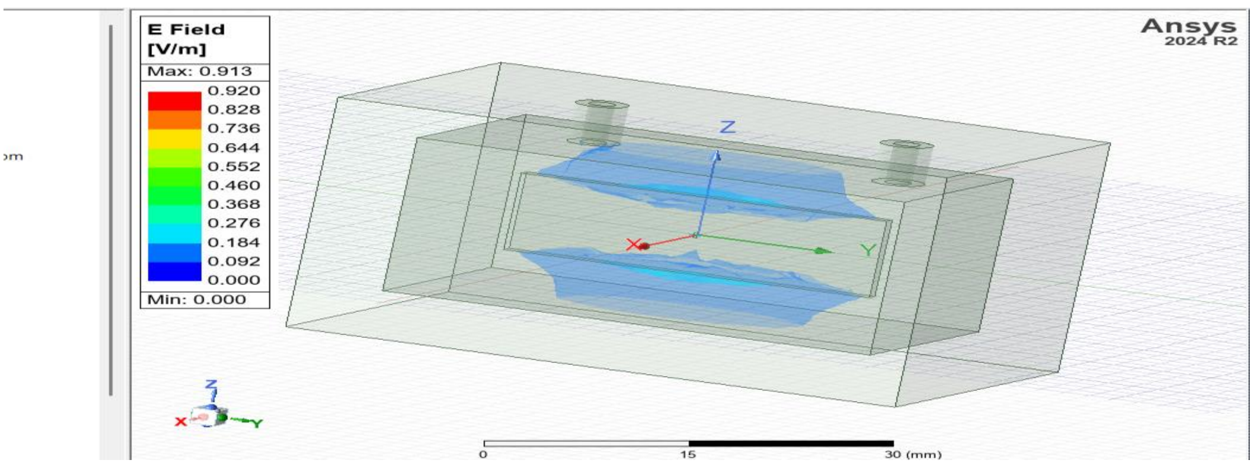
below here is the 3D cavity design by using the design parameters that I attached above



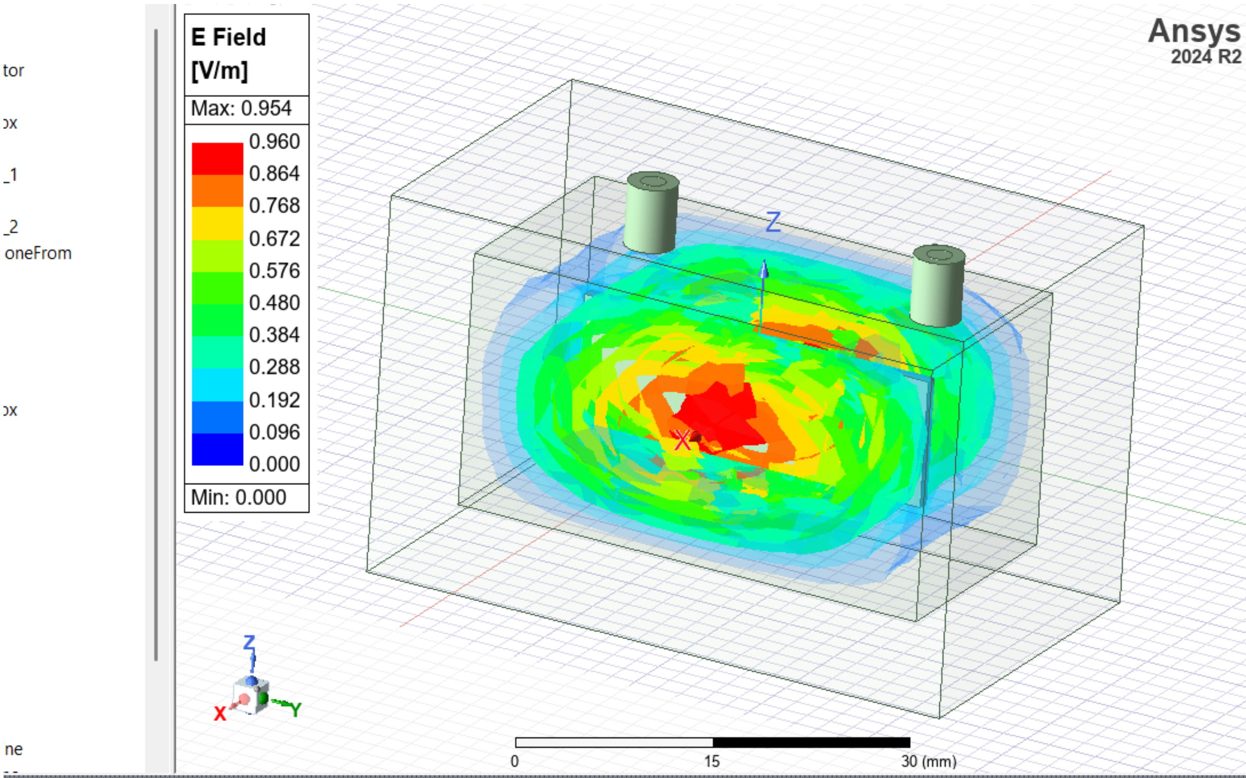
I simulated the eigen mode and these is the value i got, look the picture below.

This simulation is based on Lj 12nH.

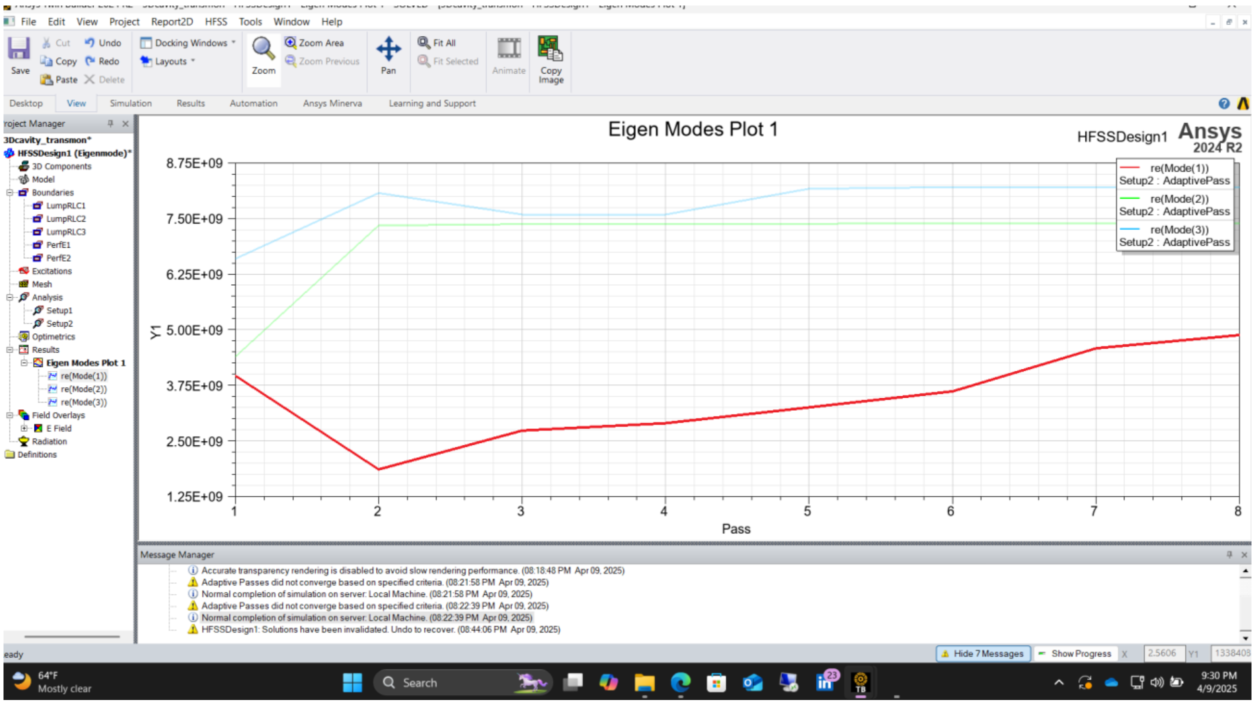
Next, I want to simulate the electric field of the vacuum transmone qubit inside, here is the simulation result below for the first mode.



Below is the third Efield mode



Now let’s see the plot of eigenvalue mode based on Lj= 12nH and the plot is attached below.



I have included the Qiskit 3D cavity code used during the lab session. After modifying it as needed, I imported the design into HFSS and ran the simulations through Qiskit Metal. I've attached both the code I executed, and the simulation results obtained so far.

Conclusion

In this project, I followed a tutorial provided by Dr.Wong that demonstrated how to design a 3D superconducting cavity in Ansys HFSS and integrate it with Qiskit. The objective was to simulate a cavity–transmon system and analyze parameters relevant to quantum computing, such as cross-Kerr coupling.

The process began with creating the 3D cavity structure in HFSS, carefully defining dimensions, material properties, and boundary conditions to support resonant electromagnetic modes. I then ran eigenmode simulations in HFSS to extract resonant frequencies and visualize the electric field distribution across different modes. Observing how the field interacts with the transmon helped me understand mode participation and energy confinement. The Josephson junction was modeled as a lumped element to capture its nonlinear inductance, a key factor in calculating cross-Kerr interactions.

Through this process, I learned how electromagnetic simulation tools and quantum design frameworks can be combined to prototype superconducting quantum circuits and analyze qubit-cavity dynamics at a detailed level.