EE274-Project 2 Report

Introduction

In Project 1, I was still getting familiar with HFSS, so my initial 3D cavity design and simulation weren't done correctly. Because of that, I had to go back and start from scratch. After redoing the setup properly, I was able to get meaningful results. Now, I'm moving forward with Project 2 and will use this document to carefully document each step of my progress.

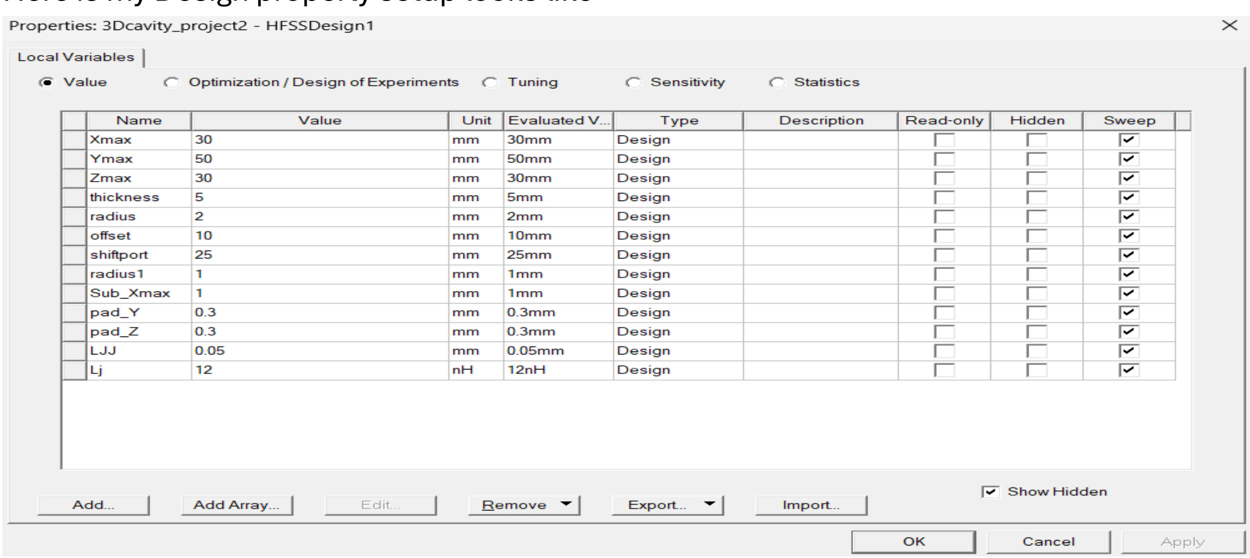
In project 2

As I mentioned in the introduction, I simulated the eigenmode structure with the following setup:

1. Minimum frequency: 1 GHz
2. Number of modes: 3 (though my focus is specifically on Mode 1 and Mode 2, which I will analyze and include results for)
3. Accuracy: 1%
4. Maximum passes: 10 (as originally instructed)

However, I ran into some issues — the simulation did not converge properly within 10 passes and produced errors. To troubleshoot, I increased the maximum passes to 15, and that led to better results: the simulation converged on the real frequency without errors. Despite this improvement, I continued my analysis using the 10-pass data as required. Throughout the simulation, I kept the Josephson inductance LJ =12nH fixed.

Here is my Design property setup looks like



Properties: 3Dcavity_project2 - HFSSDesign1

Local Variables

Value | Optimization / Design of Experiments | Tuning | Sensitivity | Statistics

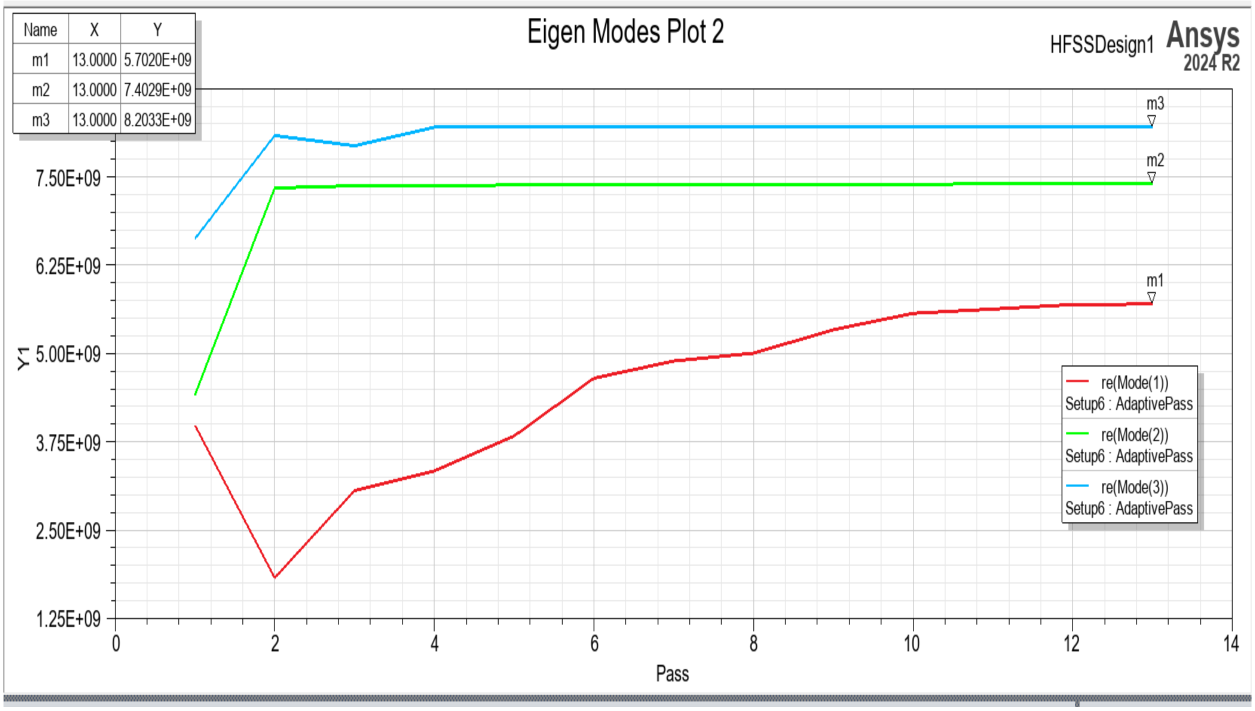
Name	Value	Unit	Evaluated V...	Type	Description	Read-only	Hidden	Sweep
Xmax	30	mm	30mm	Design		☐	☐	☑
Ymax	50	mm	50mm	Design		☐	☐	☑
Zmax	30	mm	30mm	Design		☐	☐	☑
thickness	5	mm	5mm	Design		☐	☐	☑
radius	2	mm	2mm	Design		☐	☐	☑
offset	10	mm	10mm	Design		☐	☐	☑
shiftport	25	mm	25mm	Design		☐	☐	☑
radius1	1	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		☐	☐	☑
LJJ	0.05	mm	0.05mm	Design		☐	☐	☑
Lj	12	nH	12nH	Design		☐	☐	☑

Show Hidden

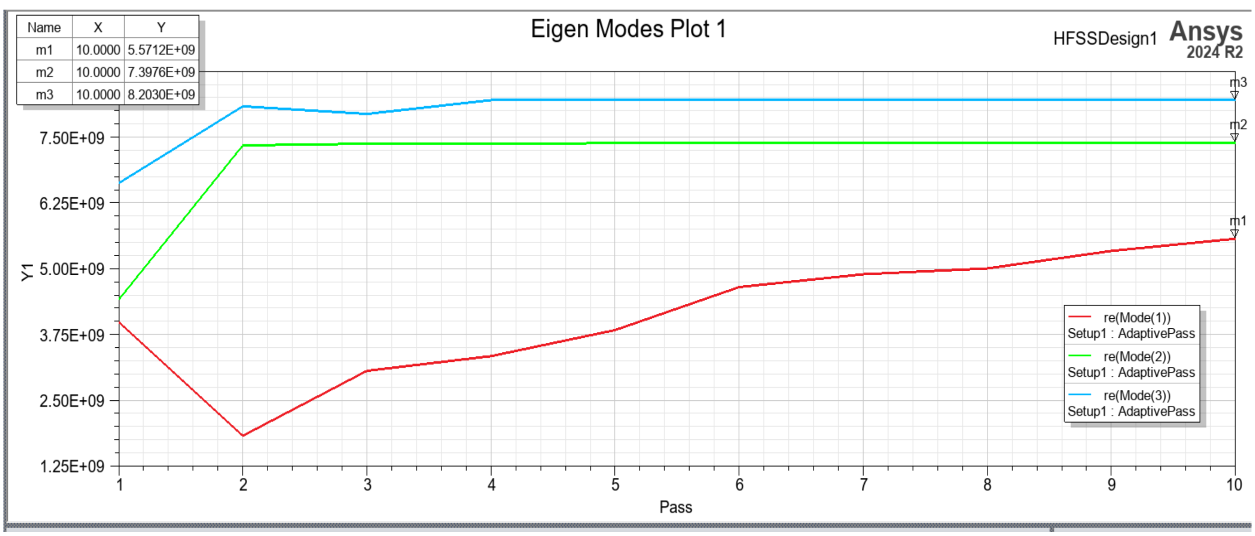
Add... | Add Array... | Edit... | Remove | Export... | Import...

OK | Cancel | Apply

Here is an Eigenmode plot based on 15 passes



and here is an Eigen mode plot based on 10 passes



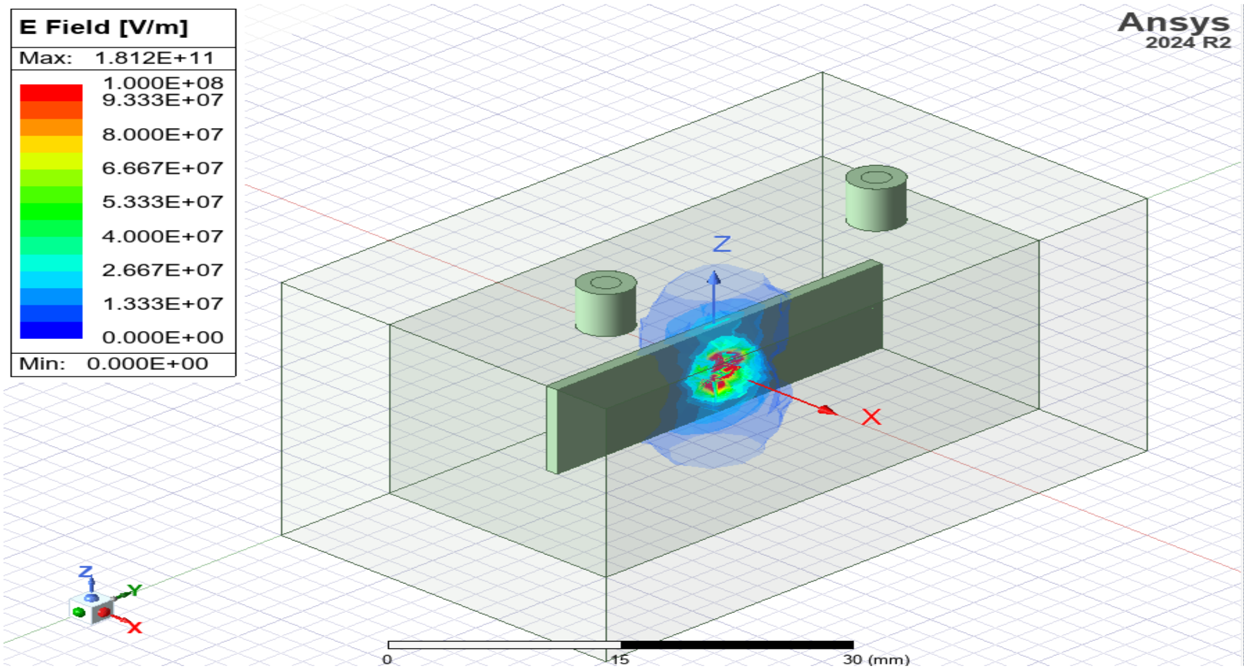
Study of Mode 1 and 2 without Change the location of the Sapphire and the JJ

1st mode = about 5.571 GHz

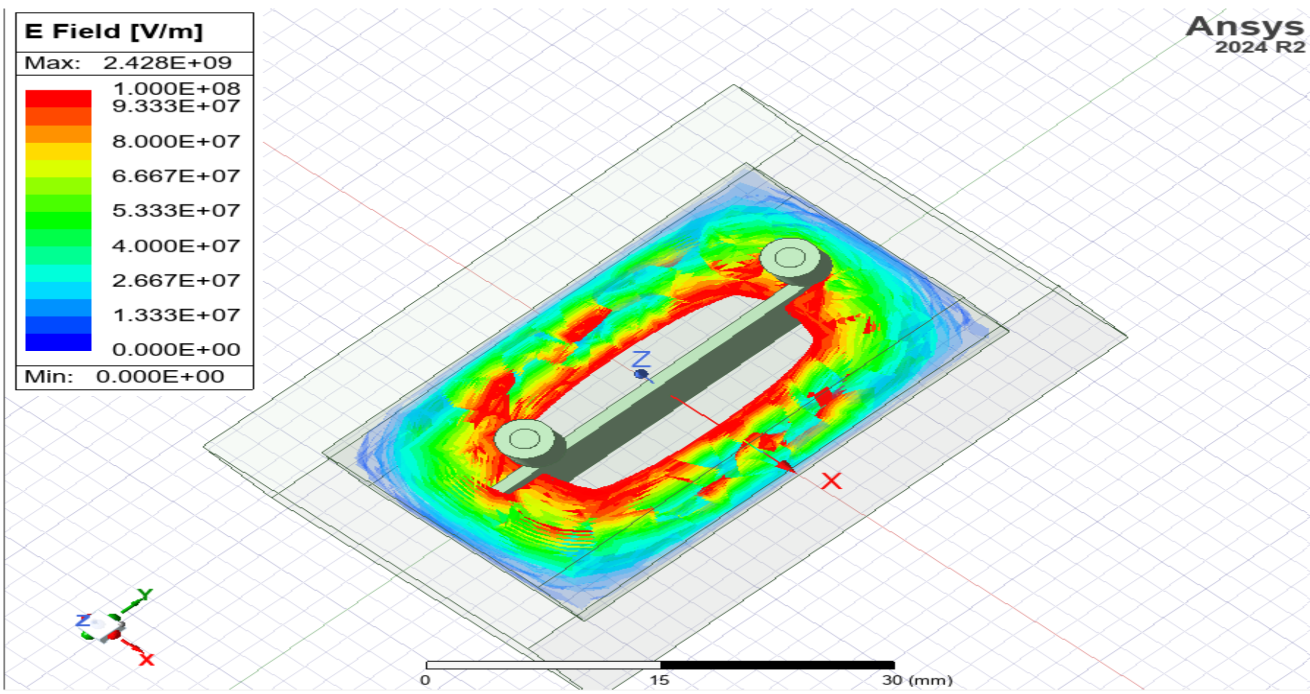
2nd mode = about 7.397 GHz

Since i don't know what it means I'm going to see the electric field distribution simulation

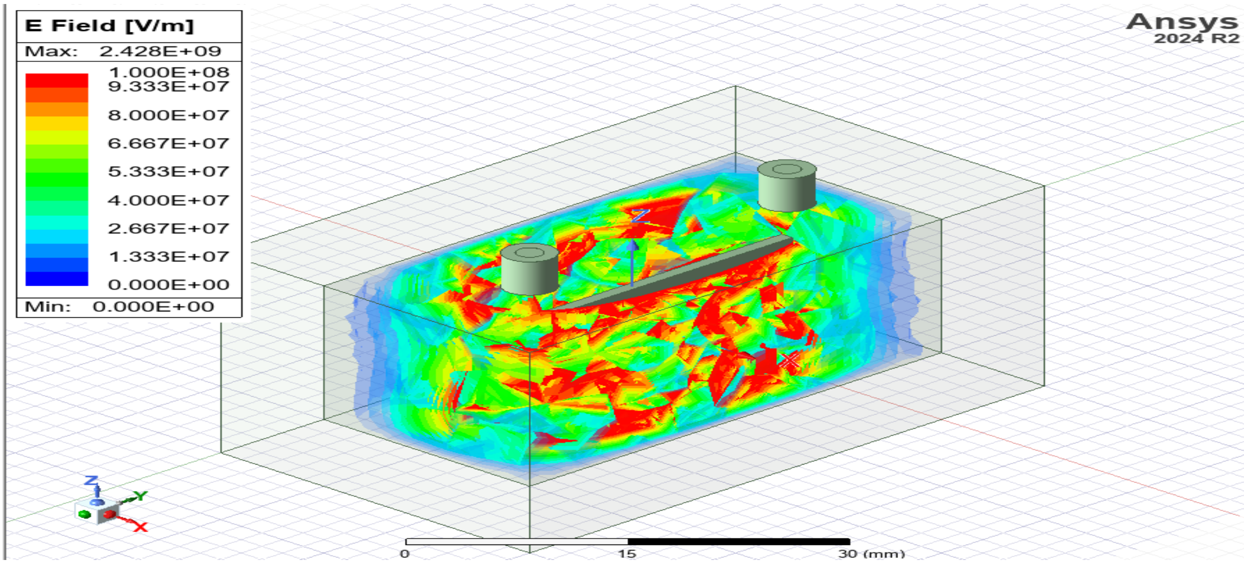
This is Mode 1, electric field.



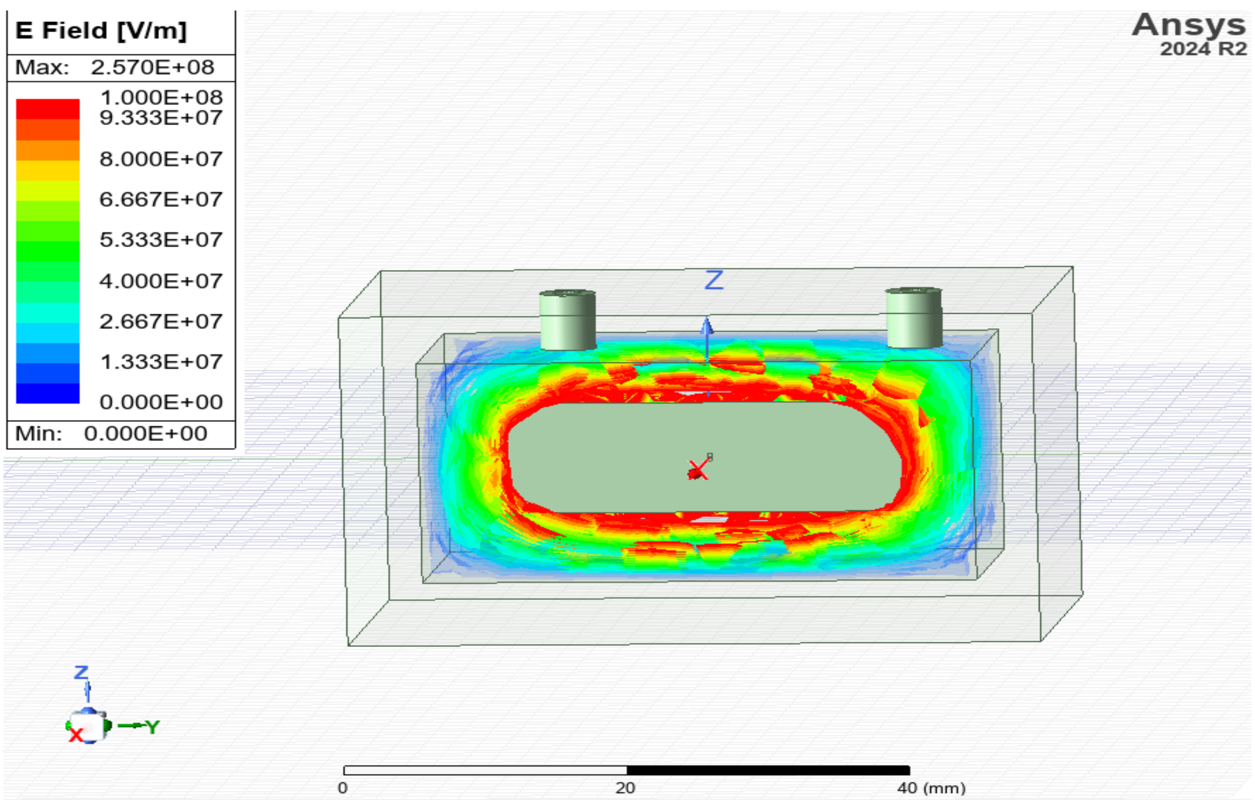
Here is the electric field of mode 2 of the cavity, top view.



Here is the side view.



And last, here is the mode 3 electric field



My conclusion based on these data for project one without Change the location of the Sapphire and the JJ

The electric field distribution across the first three cavity eigenmodes reveals a progression in spatial complexity as the mode number increases. Mode 1, resonating around 5.571 GHz, displays a relatively simple and symmetric electric field pattern, consistent with the fundamental mode of the cavity. Mode 2, at approximately 7.397 GHz, exhibits a more complex field distribution, as seen in both the top and side views, indicating the presence of additional field nodes and higher spatial variation. Mode 3 further increases in complexity, with multiple field lobes and intricate electric field regions, characteristic of a higher-order mode. These results align with expectations from cavity resonator theory, where higher modes correspond to more intricate field structures and higher resonant frequencies. Understanding these field patterns is crucial for optimizing design parameters in applications such as qubit coupling and cavity-QED systems.

Project 2

In this project, based on the project 1 structure I have I'm going to study mode 1 and mode 2 cavity eigenmodes based on Change the location of the Sapphire and the JJ and, I will study:

i. Cross-Kerr

ii. Q

iii. Resonant Frequency.

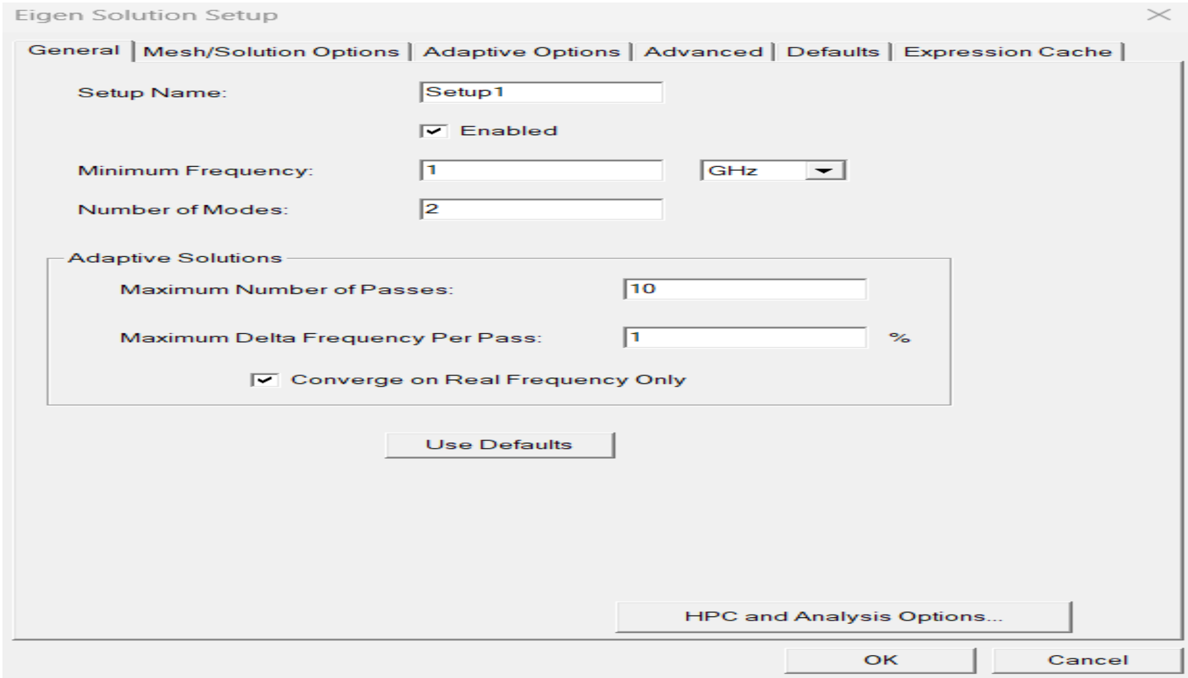
I changed the position of Sapphire and JJ. I set the position of the JJ lumped RLC to this: Sub_Xmax -LJJ/2 ,-LJJ/2 , . Perfect E which is rectangle 1 and its duplicate moved to: Sub_Xmax ,-pad_Y/2 ,-pad_Z-LJJ/2.

The Sapphire location has moved to the position, here I attached the screen shoot:

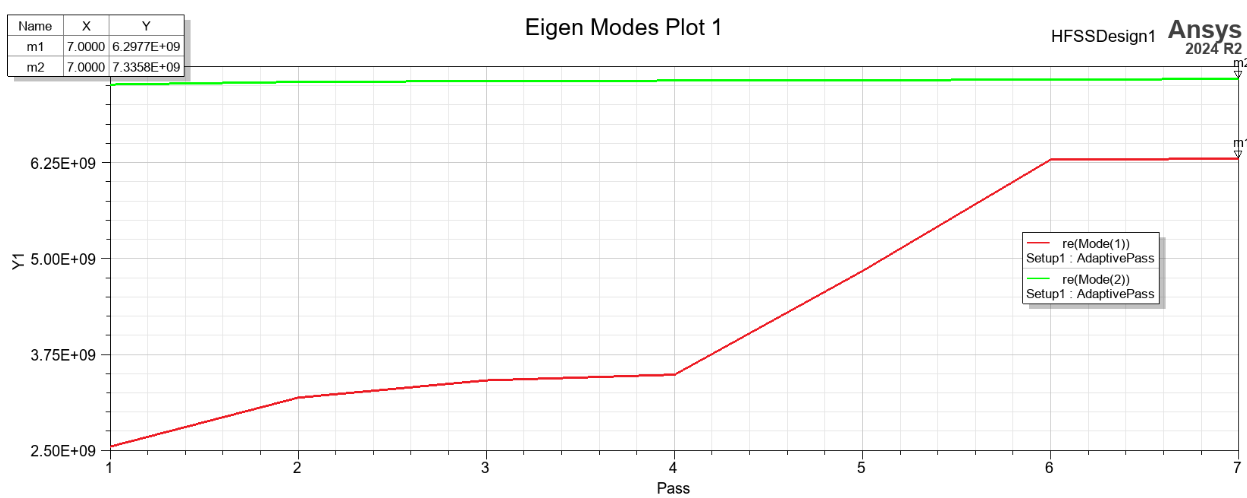
Name	Value	Unit	Evaluated V...	Description
Command	CreateBox			
Coordinate ...	Global			
Position	-Sub_Xmax/2 ,-(Ymax-2*thickness-5mm)/2 ,-(Zmax-2*thickness-5mm)/2		-0.5mm , -17....	
XSize	Sub_Xmax		1mm	
YSize	Ymax-2*thickness-5mm		35mm	
ZSize	Zmax-2*thickness-2*5mm		10mm	

JJ position also moved accordingly.

Here is the eigen solution setup, based on this I'm going to simulate the cavity.



I run the simulation based on the set up i have provide above. Below, I will document the simulation results plots and electric field distribution to each eigenmode.

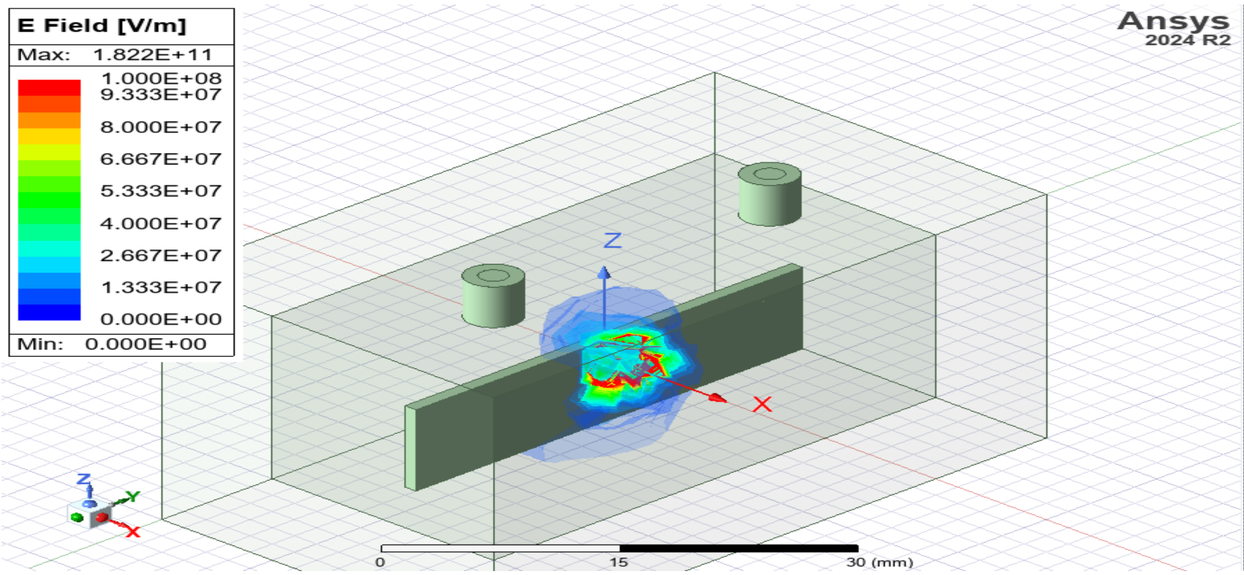


As you can see, the Eigen mode plots for two modes, thier resonant frequency is different from project one Eigenmode plots.

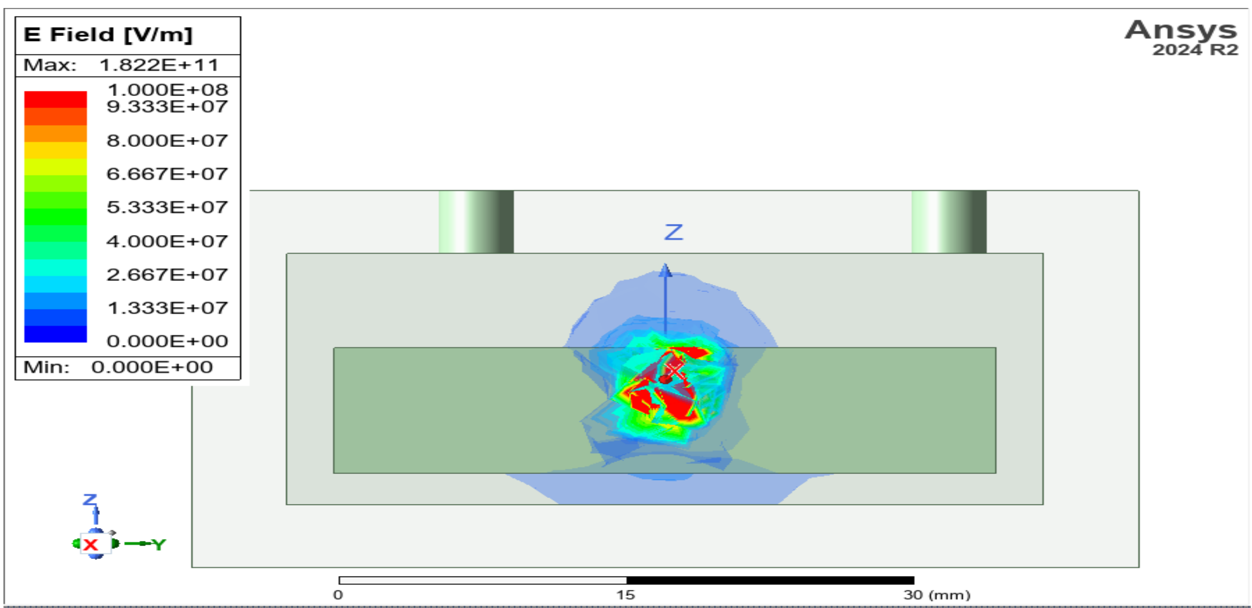
Comparison table for project 1 and project 2 Eigenmode plot resonant frequency plot.

Eigenmodes	For project 1	Project 2	Difference
1st mode	about 5.571 GHz	About 6.97 GHz	Project 2 is bigger
2nd mode	about 7.397 GHz	About 7.33 GHz	Almost the same

Here is the electric field simulation for cavity mode 1.

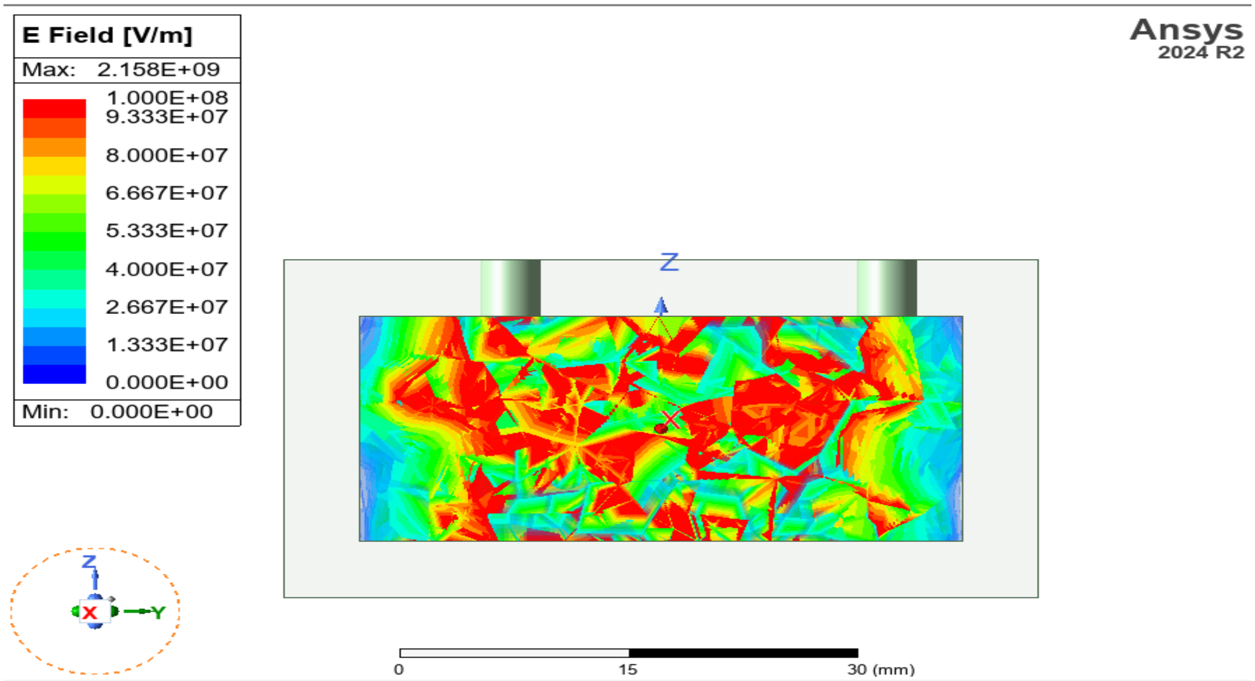


And here is the side view of the same cavity mode 1

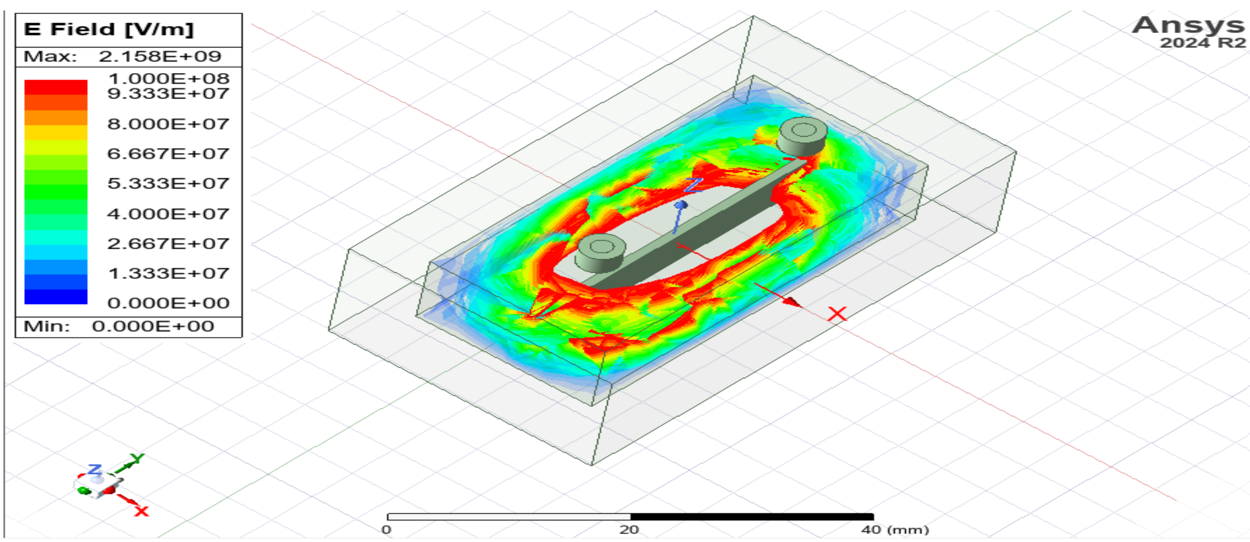


As clearly shows that the cavity mode 1 simulation results in the pictures, there is a concentrated high electric field on the qubits which is the Josephson Junctions. The qubit has a very high frequency in cavity mode 1.

Next, here we are going to see the electric field distribution plot/simulation of the 2nd cavity mode. Attached are the side view of cavity mode 2 and the top view of cavity mode 2 electric field simulations.



Top view below,



Before I move on to Analize these:

i. Cross-Kerr

ii. Q

iii. Resonant Frequency

I want to understand what each term means. therefore, I want to start with:

I. Cross-Kerr

Cross-Kerr is how much the frequency of one mode shifts when the other is excited. It's like how one vibrating string affects the pitch of another when they’re coupled. It's a key ingredient in making qubits "talk" to each other in a quantum circuit.

ii. Q

Q is a measure of how well my quantum device holds onto energy. The higher the Q, the less energy it loses and the better it is for keeping qubit states stable. In short, Q factor means that measures how "sharp" and "clean" a resonance is, or how little energy it loses.

In a Quantum circuit:

High Q	**Low Q**
Energy stays in the system longer	Energy leaks out quickly
Great for storing quantum	Better for fast readout or
information	coupling
Like a good violin string	Like a rubber band

Real-world analogy:

- A high-Q qubit holds information like a safe with thick walls.
- A low-Q resonator is like a doorbell: it lets energy in and out fast so you can "hear" it.

iii. Resonant Frequency

Resonant frequency is the natural pitch or vibration of my system and the frequency it “likes” to operate at.

Now, Interpretation and Study of the simulation results: Below I have shown the table of Eigen mode frequency table

Eigen Modes Table 2 HFSSDesign1 Ansys 2024 R

	Pass	re(Mode(1)) Setup1 : AdaptivePass	re(Mode(2)) Setup1 : AdaptivePass
1	1.000000	2557014664.807100	7261826166.034400
2	2.000000	3193925558.052590	7296563763.459720
3	3.000000	3418552130.209990	7306744153.875580
4	4.000000	3492472278.915410	7312814975.729740
5	5.000000	4841526398.519900	7318246325.300770
6	6.000000	6289126323.806090	7326586248.227230
7	7.000000	6297661671.256490	7335786759.136710
8	8.000000	nan	nan
9	9.000000	nan	nan
10	10.000000	nan	nan

At Pass 7 the frequency and of each mode.

Modes	Frequency (GHz) at Pass 7
Mode 1	6.2977 GHz
Mode 2	7.3358 GHz

This confirms: These are my two resonant modes.

And Q factors from Eigen Q

Eigen Q Table 1 HFSSDesign1 Ansys 2024 R2

	Pass	Q(1) Setup1 : AdaptivePass	Q(2) Setup1 : AdaptivePass
1	1.000000	4497071087.743507	13685.590085
2	2.000000	23096706037.900688	14408.530100
3	3.000000	15556381178.788477	13471.420911
4	4.000000	6920570208.244492	10752.583321
5	5.000000	1349704933.535155	13563.196190
6	6.000000	73399227.779164	11989.822252
7	7.000000	84094304.456692	9838.957718
8	8.000000	nan	nan
9	9.000000	nan	nan
10	10.000000	nan	nan

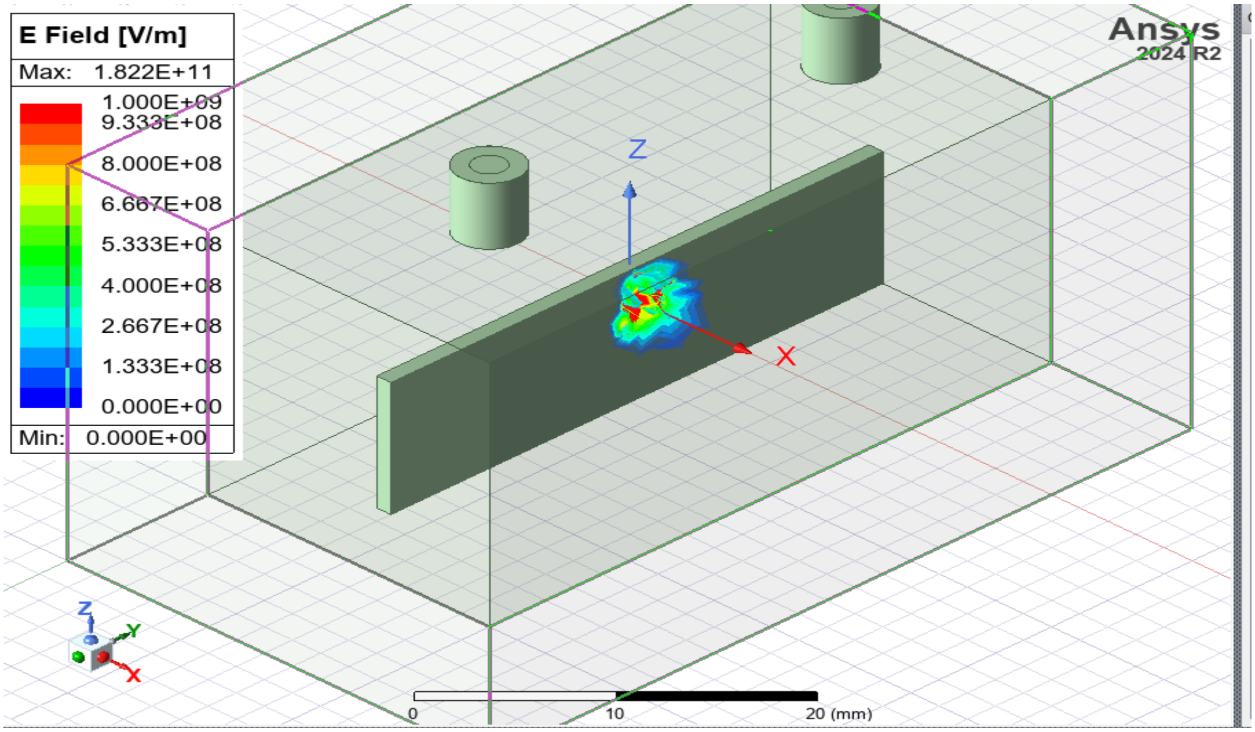
Q Factors from Eigen Q table at pass 7

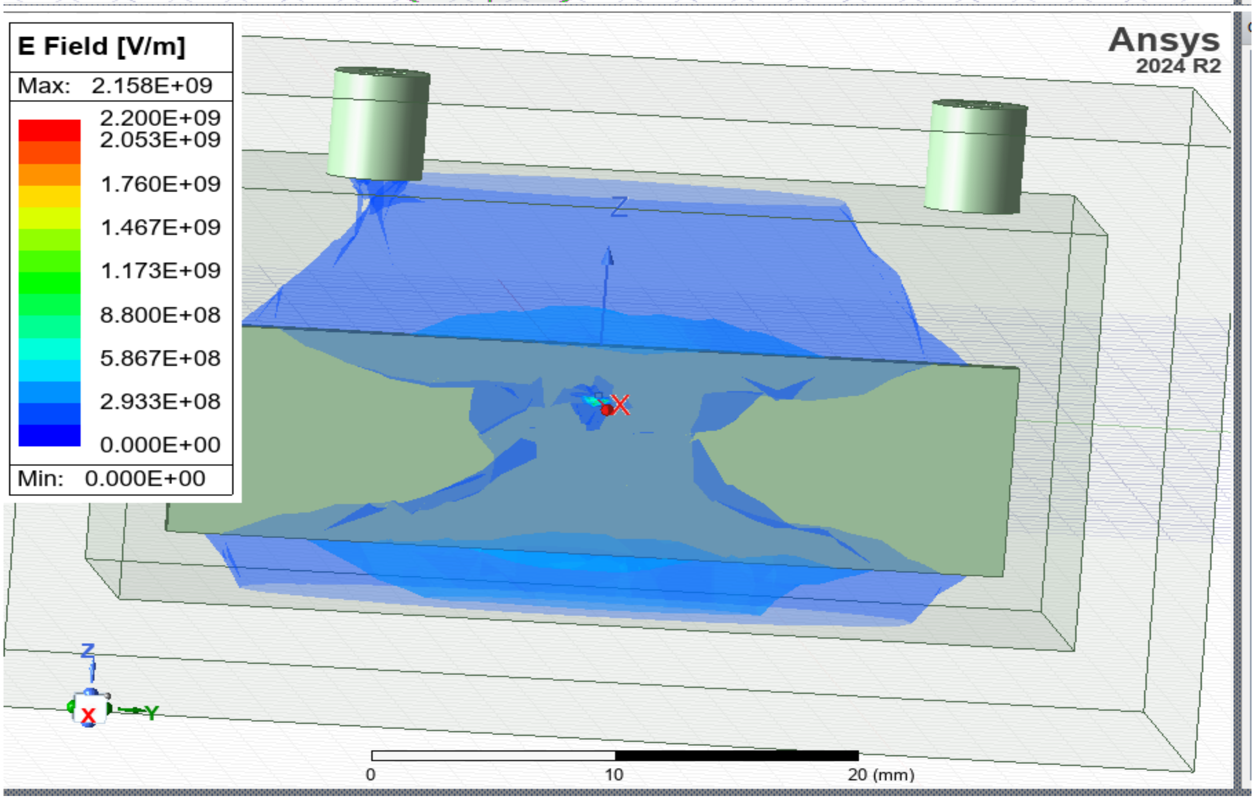
Modes	Q Factor at Pass 7
Mode 1	8.4×10^7 (very high Q cavity mode)
Mode 2	~9840 (readout-like, lossy mode)

This confirms:

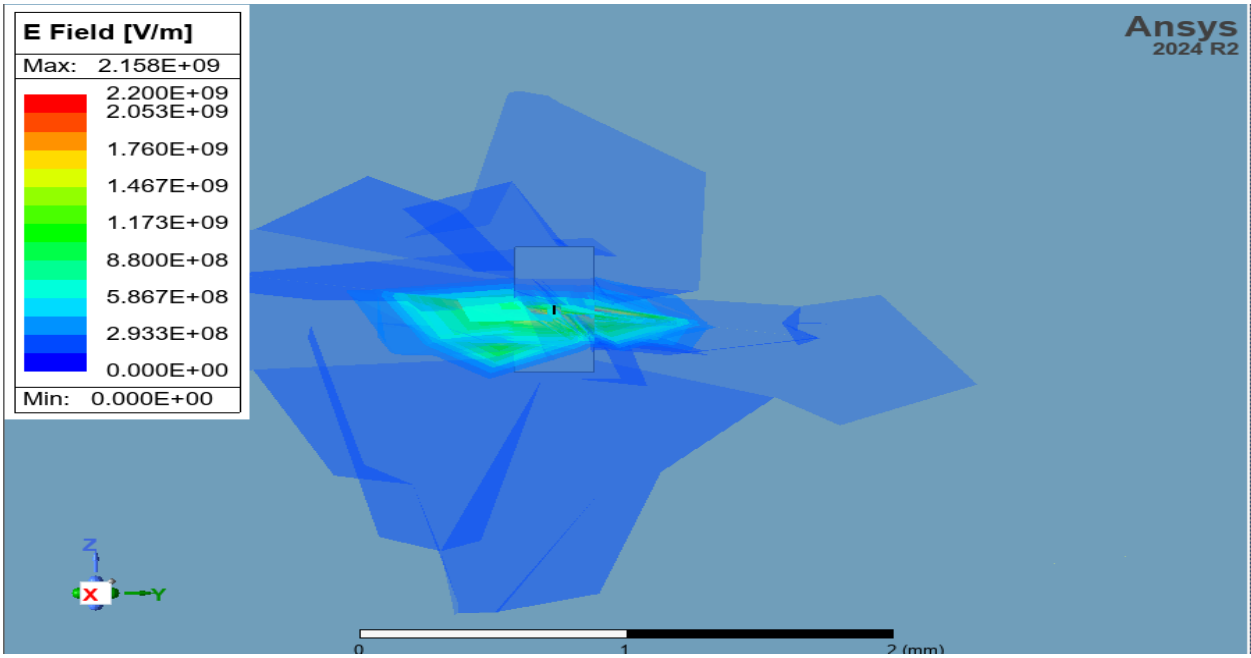
- Mode 1 is likely the qubit-like mode (non-radiative, low-loss)
- Mode 2 is likely the readout-like mode (coupled, more lossy)

Next, I'm going to focus on Cross-kerr:





here is the closer view



The energy is concentrated at the center of Josephson Junction. It shows that electromagnetic field is high where the qubit is located.

Cross-Kerl analysis summary (Personal Reflection)

I initially set out to estimate the cross-Kerr coupling using both HFSS and Qiskit Metal, but unfortunately, Qiskit Metal stopped working on my machine. I spent about two full days troubleshooting the installation, trying different Python versions, dependencies, and environments but I couldn't get it running again. So instead, I decided to present what I could do from HFSS and share my understanding and observations.

What I have learned about Cross-Kerr

From my reading and tests, I learned that cross-Kerr coupling strongly depends on the qubit's position relative to other components in the cavity. In this project, I modified the geometry by shifting the sapphire and qubit slightly farther apart compared to the setup I used in Project 1. This change reduced the mode overlap, which in turn weakened the cross-Kerr interaction.

I also experimented with different values of the Josephson inductance (LJ) — trying 7 nH and 5 nH instead of a fixed 12 nH. I noticed that decreasing LJ caused the qubit frequency to increase, while the cavity frequency stayed mostly unchanged. This also had the effect of increasing the estimated cross-Kerr coupling, likely because the system became more nonlinear as LJ decreased.

However, since HFSS doesn't directly compute cross-Kerr in a linear eigenmode simulation, I noted that The ~1 GHz separation between modes may imply weak cross-Kerr coupling under linear conditions, although this could be enhanced by non-linear elements such as a Josephson junction. To estimate Cross-Kerr coupling (χ) between modes, we usually need a nonlinear simulation (e.g., using a Josephson nonlinearity or perturbation theory).However, from linear eigenmodes I can at least check how close the two modes are, which influences the strength of Kerr.

Estimating Cross-Kerr from HFSS

Since HFSS is a linear simulator, it doesn't directly calculate Kerr or cross-Kerr couplings. However, you can still estimate how strong the Kerr effect might be based on the frequency spacing between modes. The idea is that:

$\Delta f = f2\text{-}f1 = 7.3358\text{GHz} - 6.2977\text{GHz} = 1.0381\text{GHz}$

Because the two modes are spaced about 1 GHz apart, they are not very close in frequency, which suggests the Kerr coupling is relatively weak in this configuration unless it's enhanced by a nonlinear element like a Josephson junction.

Final Thoughts

Even though I couldn't extract a precise numerical value for χ due to Qiskit Metal not working, this process helped me understand what affects cross-Kerr interaction including mode spacing, field overlap, and nonlinear elements like Josephson junctions. I plan to revisit this once I can get Qiskit Metal and pyEPR running again.