

Modeling Kinetic Inductance in Superconductors: A Practical Guide

Superconducting Circuit Design and Simulation in Keysight ADS

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Overview

Accurate superconductor modeling is essential for microwave circuit design in quantum computing and quantum sensing. Superconducting materials introduce **temperature-dependent kinetic inductance**, which directly affects resonant frequency, impedance, and overall circuit performance.

In Keysight ADS, superconductors are modeled using **material-based definitions** that specify critical temperature and London penetration depth. This approach automatically computes **kinetic inductance and surface impedance in both circuit and electromagnetic (EM) simulation**.

This application note shows how to:

- Model superconducting circuits in ADS using material-based definitions
- Capture kinetic inductance effects at both circuit and EM levels
- Evaluate temperature-driven frequency shifts using a CPW resonator example

Key Takeaways

- ADS models superconductors using **material definitions** rather than manual impedance tuning.
- Key material inputs are **critical temperature (T_c)**, **London penetration depth ($\lambda_L(0)$)**, and **normal-state conductivity or sheet resistance (σ_n / R_s)**.
- **Kinetic inductance can dominate when $t \leq \lambda_L(T)$** and may account for 50–80% of total inductance in thin films.
- Temperature can shift resonant frequency significantly, often by several gigahertz.
- Use **circuit simulation** for fast design exploration and **EM simulation in QuantumPro** for geometry-accurate prediction.

Impact of Kinetic Inductance

Origin

Kinetic inductance arises from the inertia of Cooper pairs in a superconducting film and plays a central role in microwave circuit behavior. Its effect becomes especially important when the conductor thickness approaches the London penetration depth, making temperature-dependent modeling essential for predicting frequency shifts and optimizing design.

In normal conductors, high-frequency field penetration is governed by skin depth, a dissipative effect that increases effective resistance with frequency. In superconductors, dissipation is suppressed and penetration is instead set by the London penetration depth, which reflects Cooper-pair inertia rather than resistive loss. When the film thickness is comparable to this penetration depth, kinetic inductance becomes a significant part of the total inductance and can shift resonance without adding dissipation.

Relevance of Film Thickness

Kinetic inductance is a distributed effect that appears in superconducting microwave circuits when the conductivity becomes predominantly imaginary below T_c . It is especially important in applications such as kinetic inductance detectors, traveling-wave parametric amplifiers, and superconducting nanowires.

► **Design Tip:** Kinetic inductance is not a small correction — it can **dominate** the total inductance. Its effect is strong when $t \leq \lambda_L(T)$ and is often 50–80% of the total inductance in thin films. **When** $t \gg \lambda_L(T)$, its contribution becomes small. It is helpful to compare film thickness with penetration depth early in the design process.

The effect of the kinetic inductance per square ($L_{k,\square}$) is highly dependent on the superconducting film thickness (t)¹ and can be expressed as:

$$L_{k,\square} = \mu_0 \lambda_L(T) \coth\left(\frac{t}{\lambda_L(T)}\right)$$

where μ_0 is the permeability of free space, $\lambda_L(T)$ is the temperature-dependent London penetration depth, t is the thickness of the superconducting film, and T_c is the critical temperature.

- It is pronounced when the superconducting film thickness is comparable to or smaller than the London penetration depth.
- It is negligible when $t \gg \lambda_L(T)$.

¹ A. R. Kerr, "Surface Impedance of Superconductors and Normal Conductors in EM Simulators," NRAO Electronics Division Internal Report No. 302, Feb. 19, 1996.

PEC Approximation

Approximating a superconductor as a PEC can produce significant errors, especially when the film thickness is comparable to or smaller than the London penetration depth. As shown in Figure 1, modeling a coplanar waveguide resonator as a PEC instead of a superconducting material can shift the resonance frequency by several gigahertz.

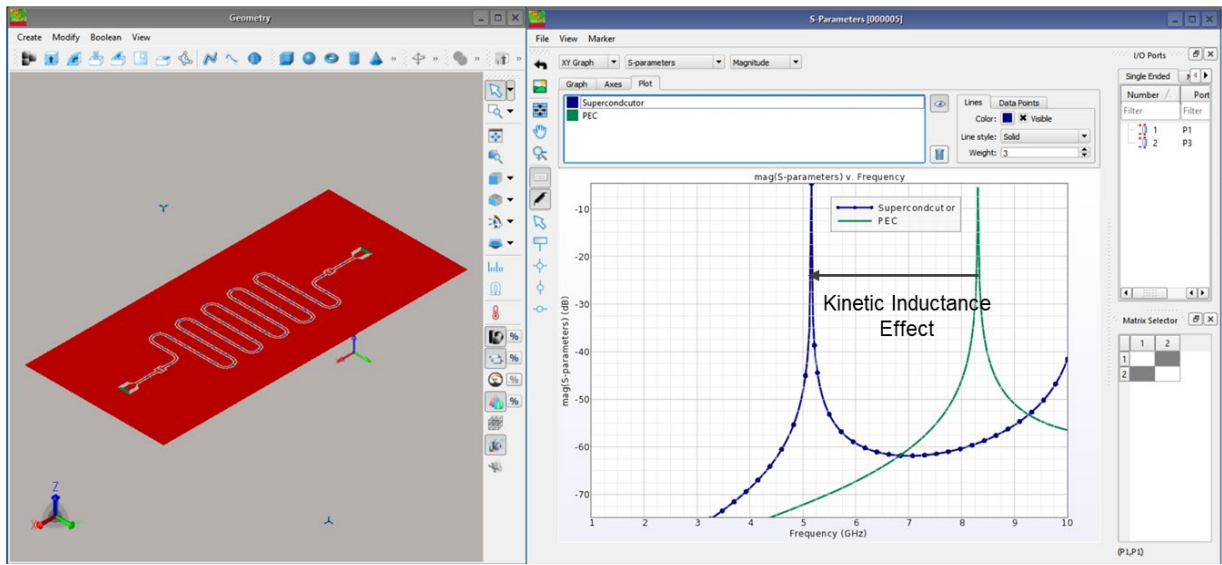


Figure 1. Modeling a superconducting resonator as a PEC produces multi-GHz frequency error—revealing the critical impact of kinetic inductance.

⚠ Important: A superconductor should not be modeled as a PEC.

This removes kinetic inductance, underestimates total inductance, and can produce large resonance-frequency errors, including multi-gigahertz shifts in resonators. Use material-based superconductor definitions instead.

Modeling Frameworks

Superconducting microwave circuits can be modeled at several levels of fidelity, each with different tradeoffs in physical detail, runtime, and workflow complexity.

1. Lumped-element and transmission-line models.

These models represent superconducting structures with modified RLC networks or transmission lines that include kinetic inductance and reduced surface resistance analytically.

When to use: **Early design studies, compact resonators, parametric structures, and fast design-space exploration.**

2. Surface-impedance and complex-conductivity EM models (BCS-based)

These full-wave models use surface-impedance or complex-conductivity boundary conditions derived from BCS-based formalisms such as Mattis–Bardeen or Zimmermann. They capture frequency- and temperature-dependent material response without explicitly resolving microscopic physics.

When to use: **Accurate prediction of loss, penetration depth, and quality factor in planar or 3D superconducting structures.**

3. Hybrid EM–circuit co-simulation models

Passive superconducting structures are first analyzed with EM solvers to extract distributed behavior or S-parameters, then combined with nonlinear Josephson-junction models at the circuit level.

When to use: **Large superconducting and quantum circuits that require both distributed EM effects and nonlinear junction dynamics.**

4. Fully coupled multiphysics superconducting models

These models couple electromagnetic fields directly to superconducting material physics to capture temperature dependence, nonequilibrium effects, and time-dependent loss mechanisms.

When to use: **Research-focused analysis where thermal, dynamic, or nonequilibrium effects are central and computational cost is secondary.**

These approaches are also important in quantum sensing applications such as parametric amplifiers, delay lines, and phase shifters, where kinetic inductance is used for sensitivity enhancement and dispersion engineering.

Keysight ADS provides an integrated environment for superconducting microwave design, with material-based models that automatically include kinetic inductance and temperature dependence in both circuit and full-wave EM simulation.

This application note uses a superconducting resonator to show how ADS and QuantumPro capture kinetic inductance and the resulting temperature-dependent frequency shift. It also compares superconducting and PEC-based models to show why superconducting material behavior must be included when film thickness is comparable to or smaller than the London penetration depth. ADS supports lumped-element, surface-impedance EM, and hybrid EM–circuit workflows; fully coupled multiphysics modeling is outside the scope of standard design flows.

Implementation Methods

Superconducting microwave circuits depend strongly on both frequency and temperature because penetration depth, kinetic inductance, and surface resistance all vary with operating conditions. Modeling methods differ in how well they capture these effects, so understanding their tradeoffs is important when choosing the right approach for each stage of design.

In practice, three main implementation techniques are commonly used:

1. **Surface-impedance boundary conditions**

This method represents the superconductor with a surface-impedance boundary condition based on the film's complex surface impedance. It can model electromagnetic behavior accurately, but the impedance changes with both frequency and temperature. That means the model must be parameterized and maintained across operating conditions, which adds complexity — especially for broad sweeps.

2. **Sheet-inductance models**

Instead of specifying surface impedance directly, this method assigns an effective sheet inductance to the superconducting film. It captures frequency-dependent behavior, but not temperature dependence. To analyze different temperatures, the sheet inductance must be updated for each case, which makes the approach less practical for multi-temperature studies.

3. **Material-based superconductor models**

In this method, the superconductor is defined as a material using physical parameters such as London penetration depth, critical temperature, and normal-state conductivity. The solver then computes surface impedance automatically as a function of frequency and temperature. This removes the need for manual updates or auxiliary models and provides a more consistent, physics-based representation across operating conditions.

► **Recommended Approach:** Material-based modeling is the only method that captures **both frequency and temperature dependence** automatically. It avoids manual re-parameterization, keeps circuit and EM simulation consistent, and is the **recommended workflow for superconducting design in ADS**.

The following section shows how this material-based workflow is implemented in ADS and EMPro / QuantumPro.

Superconducting Materials in ADS and EMPro / QuantumPro

In ADS and EMPro / QuantumPro, superconductors are defined as materials using a small set of physical parameters that determine their temperature- and frequency-dependent behavior:

- **Critical temperature (T_c)**, the temperature below which the material enters the superconducting state and its DC resistivity drops to zero.
- **London penetration depth (λ_L)**, the distance over which magnetic field decays inside a superconductor to 1/e of its surface value. In the material definition, ADS uses the value at 0 K, $\lambda_L(0)$, and computes the effective penetration depth at temperature T using ²

$$\lambda_L(T) = \frac{\lambda_L(0)}{\sqrt{1 - \left(\frac{T}{T_c}\right)^4}}$$

- **Room-temperature DC conductivity or sheet resistance.** You can specify either the normal-state conductivity σ_n directly or the sheet resistance R_s , from which conductivity is calculated as shown below using the superconducting film thickness t .

ADS supports superconducting modeling in both circuit and EM environments, as shown in Figure 2.

In the schematic editor, the ADS 2026 **Superconductors** library provides microstrip and coplanar components that are compatible with superconducting CPW and microstrip substrates.

Conductors Dielectrics Semiconductors Superconductors Surface Roughness							
Material		Loss Parameters		Superconductivity		Permeability (MUR)	
Material Name	Library	Parameter Type	Real	London Depth (0K)	Critical Temp	Real	Imaginary
Nb	Superconducti...	Conductivity	6.7e6 Siemens/m	40 nm	9.25 °K	1	
NbN	Superconducti...	Resistance	0 Ohm/Sq	250 nm	14 °K	1	

Add Superconductor Add From Database... Remove Superconductor

² J. Delayen, "Surface Impedance," in RF Superconductivity: Physics, Technology, and Applications, USPAS course materials, University of Maryland, June 2008. Accessed Mar. 2, 2026. Available: uspas.fnal.gov/materials/08UMD/Surface_Impedance.pdf.

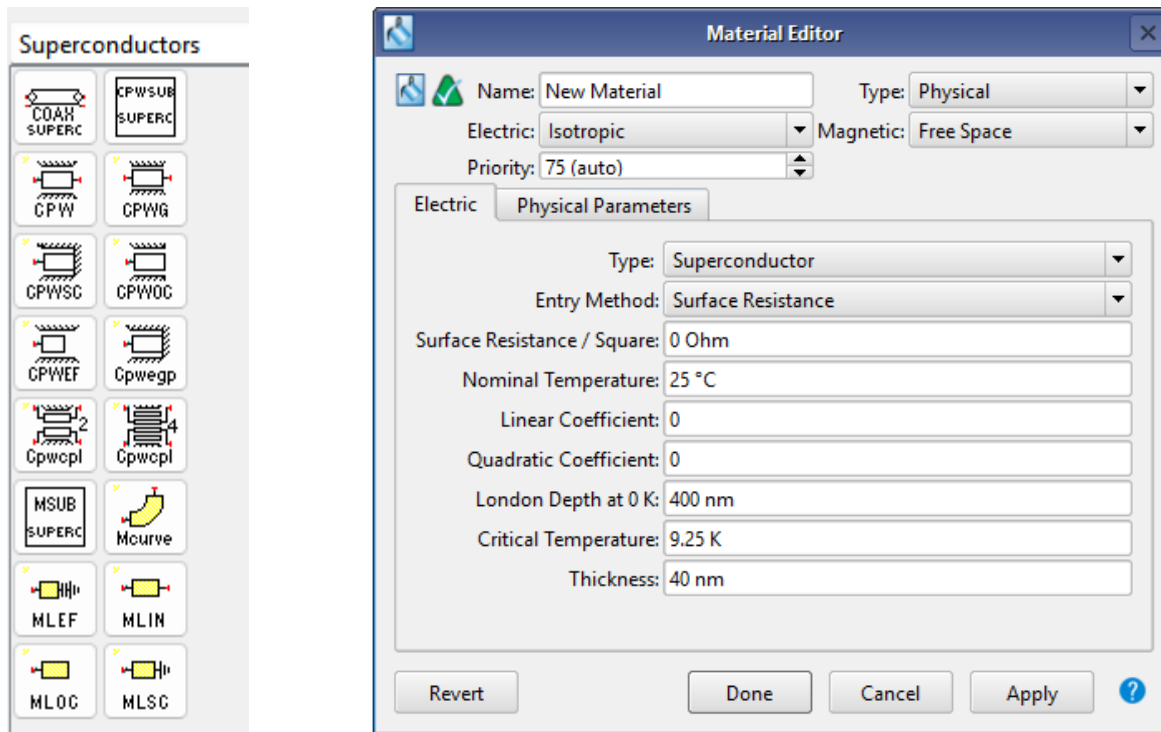


Figure 2. Superconductor definition across Keysight ADS tools. (a) ADS Material Definition. (b) ADS Circuit Environment. (c) EMPro / QuantumPro Material Editor.

In ADS Layout, a material is marked as superconducting in the material definition and assigned the required properties using either bulk conductivity or sheet resistance.

Material Model

Kinetic inductance can be represented in several ways, including sheet-inductance models, impedance boundary conditions, and material-based definitions using London penetration depth. In ADS, the material-based superconducting model uses **London penetration depth** because it enables automatic **temperature-dependent** behavior. Sheet inductance can then be derived from that definition when needed.

Ambient temperature determines whether the material is treated as normal-conducting or superconducting. For $T \geq T_c$, the material is modeled in its normal-conducting state. For $T < T_c$, it is modeled as a superconductor with conductivity based on the London penetration depth and the normal-state conductivity, as defined by the material model.

When a superconductor is defined by sheet resistance in FEM Gen2 analysis, the corresponding room-temperature DC conductivity $\sigma_n = 1/(R_s \cdot t)$ is constrained. In practice, FEM limits this value to the room-temperature conductivity of aluminum, $3.7 \times 10^7 \text{ S/m}$. This should be kept in mind when interpreting simulations based on very low sheet resistance.

If the sheet resistance R_s is set to zero, the simulation assumes no resistive loss. For $T \geq T_c$, the material is then treated as a PEC in the normal-conducting state. For $T < T_c$, the superconductor is modeled as lossless, so the simulation captures kinetic inductance without resistive dissipation.

► **Design Tip:** Setting $R_s = 0$ creates a **lossless model**. This setting is most useful when the goal is to isolate **kinetic-inductance-driven frequency shift**. To study linewidth, insertion loss, or Q degradation, use a **nonzero sheet resistance** or normal-state conductivity.

Example: Superconducting CPW Resonator

This section uses a superconducting CPW resonator to show how temperature-dependent kinetic inductance shifts resonance frequency. It compares operation below and above the critical temperature to illustrate the transition between superconducting and normal-conducting behavior. The goal is to demonstrate the modeling workflow and resulting frequency response, not quantum-parameter extraction such as energy levels or coherence times.

The example demonstrates temperature-dependent kinetic inductance using:

1. A superconducting coplanar waveguide substrate in the ADS circuit environment.
2. A superconducting material definition in QuantumPro.

ADS Circuit Environment

Circuit Model

With the superconducting CPW substrate and an **S-Parameters** block, ADS captures kinetic inductance and evaluates resonator behavior below and above the critical temperature.

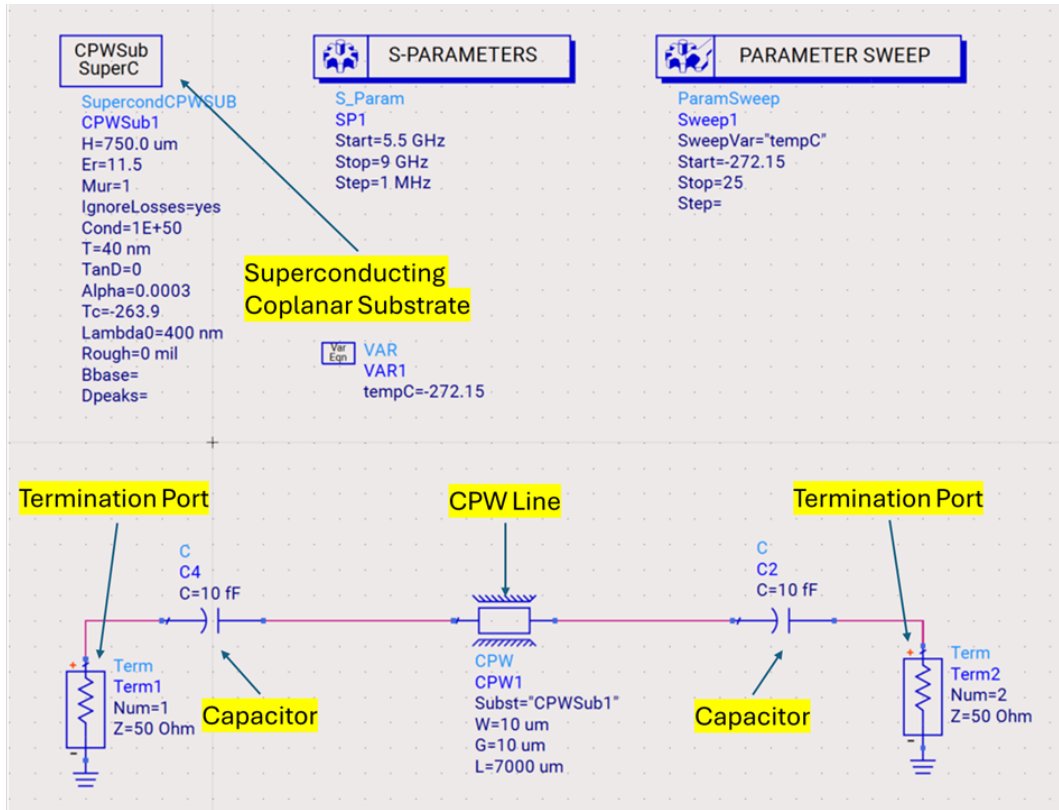


Figure 3. ADS schematic of the superconducting resonator using standard circuit components and a superconducting CPW substrate.

As shown in Figure 3, the resonator consists of a CPW line connected to a capacitor on each side, with 50 Ω terminations at both ports. The **SupercondCPWSub** component from the **Superconductors** palette enables superconducting modeling of the CPW line. The CPW length sets the nominal resonant frequency, while ambient temperature changes kinetic inductance and shifts resonance.

Substrate

The **SupercondCPWSub** substrate is defined by the following superconducting properties:

- Critical temperature, T_c
- London penetration depth at 0 K, $\lambda_L(0)$

Descriptions of the **SupercondCPWSub** parameters are available in the component documentation.

In this example, the superconducting film thickness is much smaller than the London penetration depth, so kinetic inductance has a strong effect on the resonator response.

At room temperature, the normal-conducting case can be approximated as a lossless conductor by assigning very high conductivity or setting the film thickness to zero.

Temperature Setup

In ADS circuit simulation, background temperature is set through the CPW component properties. In this example, the variable **tempC** is swept to evaluate temperature-dependent circuit behavior.

Frequency Setup

The **S-Parameters** block uses an adaptive sweep from 5.5 to 9 GHz, with additional linear points spaced at 1 MHz for improved resolution.

Results

Before reviewing the simulated response, it is helpful to relate the resonance shift to the resonator's total inductance.

Total inductance in a superconducting resonator is the sum of geometrical and kinetic contributions, i.e.,

$$L_{total} = L_{geom} + L_k$$

Comparison at 1 K:

- For Aluminum ($\lambda \approx 50$ nm at 1 K): With film thickness $t = 20$ nm, $L_k/L_{total} \approx 0.5$
- For Niobium ($\lambda \approx 90$ nm at 1 K): With $t = 20$ nm, $L_k/L_{total} \approx 0.7$ – 0.8

At low temperature, kinetic inductance is a major contributor to total inductance—especially for niobium, where it can dominate. As film thickness decreases or penetration depth increases, L_k rises rapidly relative to L_{geom} , making it a key design parameter for superconducting resonators.

As temperature increases from 1 K (-272.15 °C) to room temperature (25 °C), the resonant frequency shifts from about 5.868 GHz to about 8.408 GHz. Because resistive loss is not included in this example, the peak amplitude and width remain nearly unchanged.

► **Design Tip:** This example is intentionally lossless. Sheet resistance is set to zero so the simulation isolates the effect of **temperature-dependent kinetic inductance** on resonance frequency. As a result, **peak width and Q remain nearly unchanged**, and the example is best interpreted as a frequency-shift study rather than a dissipation or loss analysis.

Figure 4 compares the transmission spectra at the two temperature points, and the peak frequencies are summarized below.

Temperature	Peak Frequency
1 K (-272.15 °C)	5.868 GHz
Room temperature (25 °C)	8.408 GHz

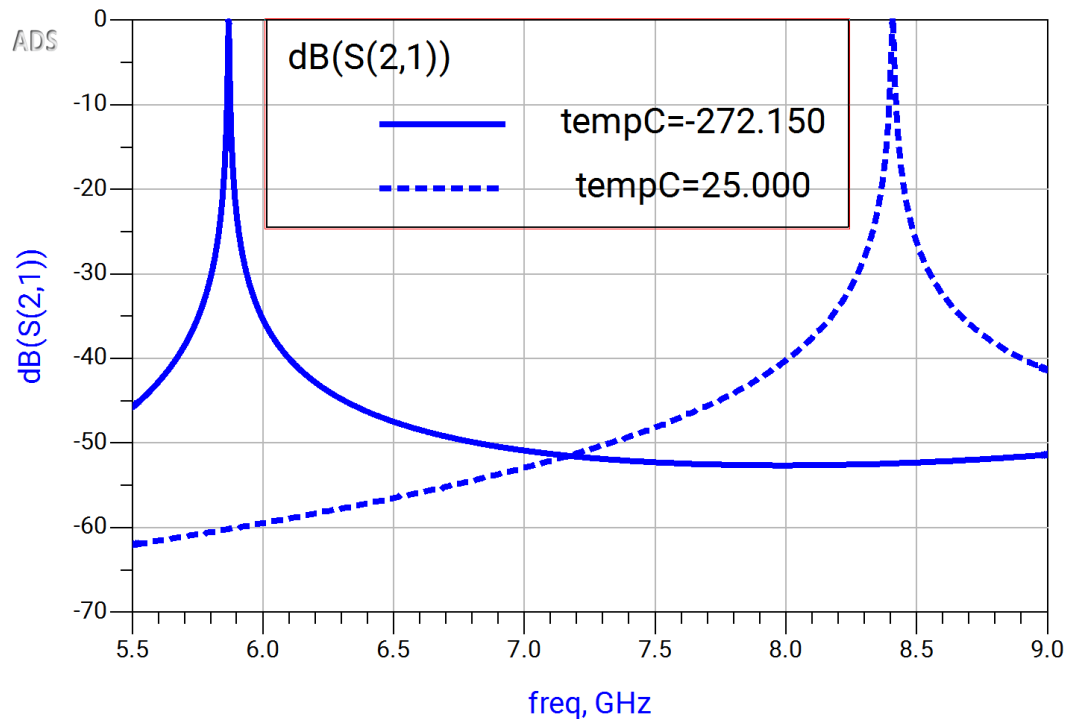


Figure 4. Resonance shift due to kinetic inductance between room temperature and 1 K. Resistive losses are ignored, so the quality factor remains largely unchanged.

QuantumPro EM Environment

In QuantumPro, both **Full EM Analysis** and **Energy Participation Analysis** can be used to evaluate how temperature-dependent kinetic inductance affects resonator response. Changing the background temperature relative to the critical temperature shifts both the resonant frequency and the eigenfrequency.

Substrate

The example starts in a quantum technology workspace, where the substrate stack and predefined layers are already configured for superconducting circuit design.

Superconductor

The resonator's superconducting material properties are defined in ADS through **Options > Technology > Material Definitions**.

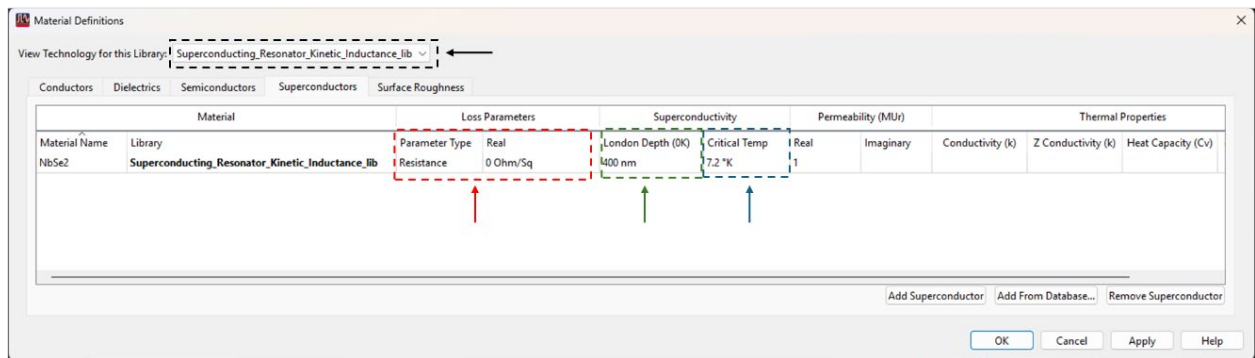


Figure 5. NbSe2 superconducting material definition to be used in the resonator. The superconductor is defined by a zero sheet resistance (neglecting the resistive losses), a relatively large London penetration depth of 400 nm, and a critical temperature of 7.2 K.

In this setup, the library view is *Superconducting_resonator_kinetic_inductance_lib*. Under **Loss Parameters**, the material uses **Resistance** with **Real** = 0 Ω/sq . Under **Superconductivity**, the key inputs are **London Depth** = 400 nm and **Critical Temp** = 7.2 K.

In this example, the 40 nm film thickness is much smaller than the 400 nm London penetration depth, so kinetic inductance strongly influences the resonator response.

Schematic

The resonator schematic is created in Quantum Artwork using the following elements:

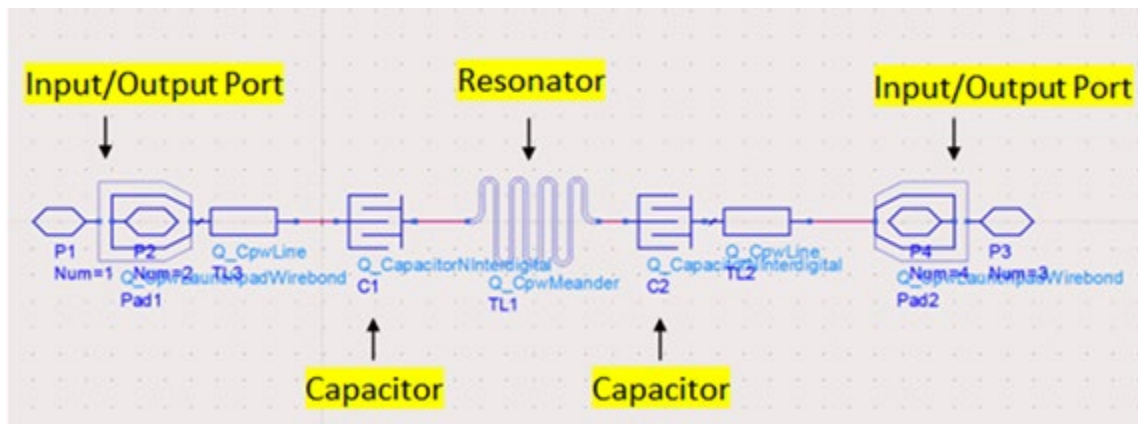


Figure 6. ADS schematic of the superconducting resonator created using Quantum Artwork.

The schematic diagram includes the following components:

- The I/O ports are arranged as follows:
 - P1 and P2 are located on the left
 - P3 and P4 are located on the right
- The half-wavelength resonator uses a central meander line terminated by capacitors C1 and C2.

Layout

The layout is generated from the schematic through **Layout > Generate/Update Layout**.

A **boundary box** in the **boundary:drawing** layer defines the ground fill used in the EM simulation.

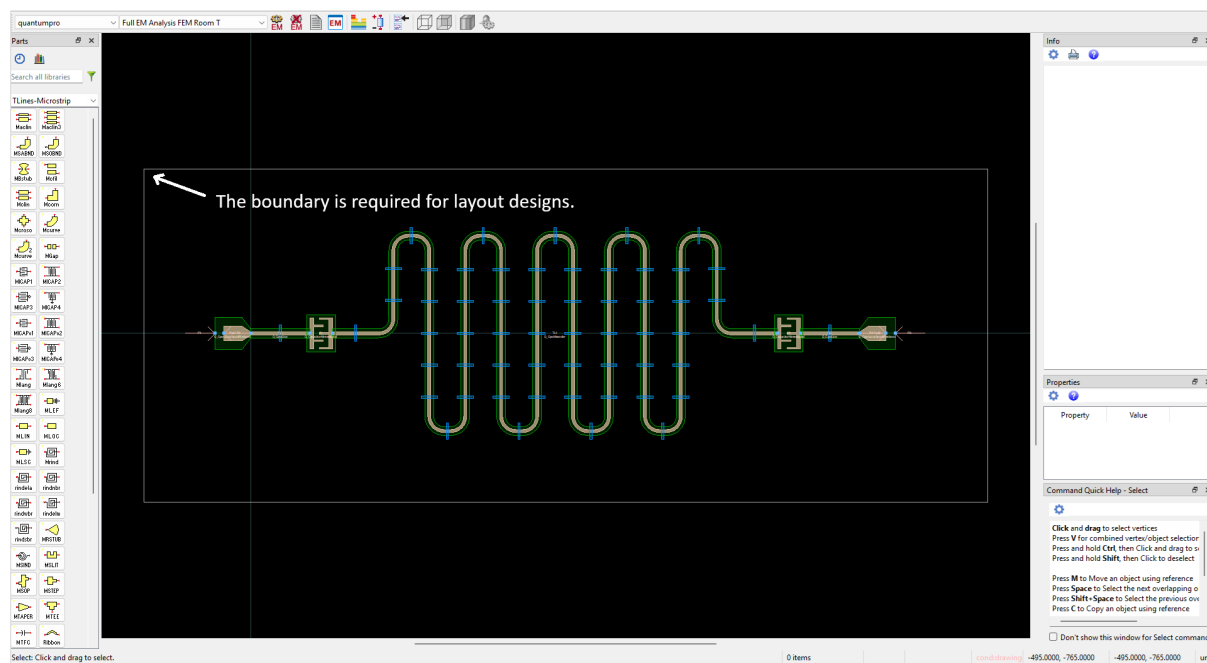


Figure 7. ADS layout of the superconducting resonator generated from the schematic.

The layout includes:

- The layout reflects the schematic, and updating the schematic propagates the corresponding changes to the layout.
- The layout view for this circuit shows:
 - two Q_CpwLine's (identical parts)
 - two Q_CpwLaunchpadWirebond's (identical parts)
 - two Q_CapacitorNInterdigital's (identical parts)
 - a Q_CpwMeander
- The pins (pink arrows) are required to define the simulation ports. The circuit has four pins in total:
 - Pins 1 and 2 - placed at the left I/O Port
 - Pins 3 and 4 - placed at the right I/O Port

Some components use default settings, while others require modified parameter values.

The table below summarizes the customized parameters used in this example

Part Name	Customized Parameters
Q_CpwMeander	<ul style="list-style-type: none">• L = 7000.0 μm• Radius = 50.0 μm• LeadLength = 200.0 μm• XOffset = 1500.0 μm• BridgeGap = 100.0 μm
Q_CpwLaunchpadWirebond	<ul style="list-style-type: none">• PadGap = 30.0 μm
Q_CpwLine	<ul style="list-style-type: none">• BridgeGap = 100 μm
Q_CapacitorNInterdigital	<ul style="list-style-type: none">• InterdigitalGap = 20.0 μm• FingerEndGap = 20.0 μm

EM Simulation in QuantumPro

After the layout is complete, QuantumPro is used to configure the EM simulation.

1. QuantumPro is launched from **Tools > QuantumPro > Open**, which loads the layout and generated ground fill for EM analysis.
2. The analysis setup follows the single-qubit workflow ³, including nets, ports, meshing, and frequency planning.

Field storage is not required in this example because quantum parameters are not being extracted.

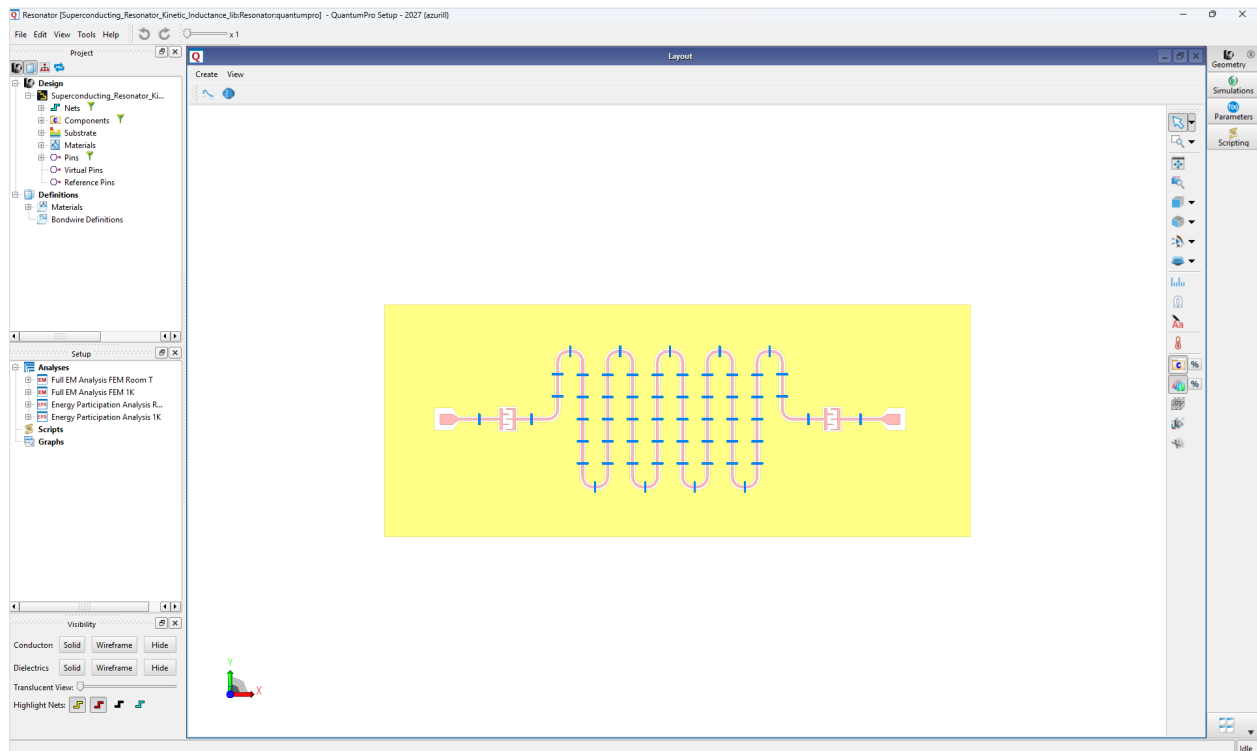


Figure 8. Superconducting resonator in the QuantumPro electromagnetic environment.

Temperature Setup

In QuantumPro, background temperature is defined under **Analyses > Options**, with a separate analysis used for each temperature point in the comparison.

³ Keysight Technologies, "Designing for Superconducting Qubit Circuits," Application Note, Available: <https://www.keysight.com/us/en/assets/3123-1286/application-notes/Designing-for-Superconducting-Qubit-Circuits.pdf>.

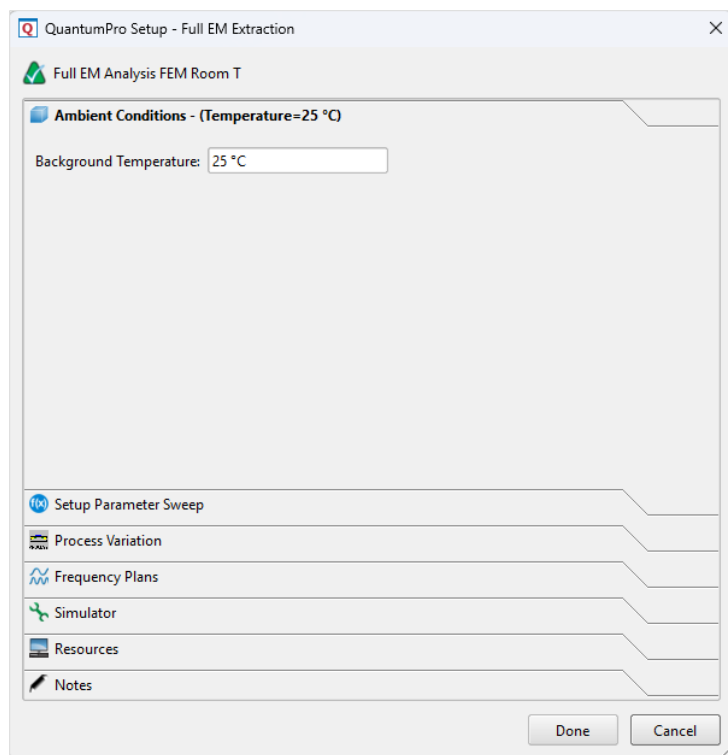


Figure 9. QuantumPro simulation setup for the superconducting resonator.

EM Analysis Types

Full EM Analysis and Energy Participation Analysis setups can be duplicated and renamed to organize simulations for different temperatures or design conditions.

This example uses four analyses: Full EM and Energy Participation at both 1 K and room temperature.

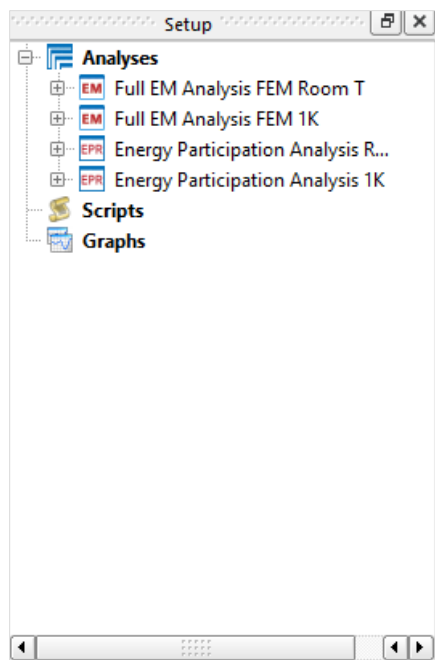


Figure 10. QuantumPro EM analysis setup for the superconducting resonator.

Frequency Setup

For **Full EM Analysis**, the example uses an adaptive sweep from 4 to 10 GHz with 13 additional linear sampling points for improved resolution.

Adaptive sweeps are usually more reliable than purely linear or logarithmic sweeps. If a fixed-step sweep is used, the frequency step should be chosen based on the expected resonances and quality factors.

► **Design Tip:** Combine adaptive and coarse linear sweeps for efficient resonator analysis. High-Q, narrow resonances can be missed or poorly resolved with fixed-step sweeps unless the frequency spacing is chosen carefully.

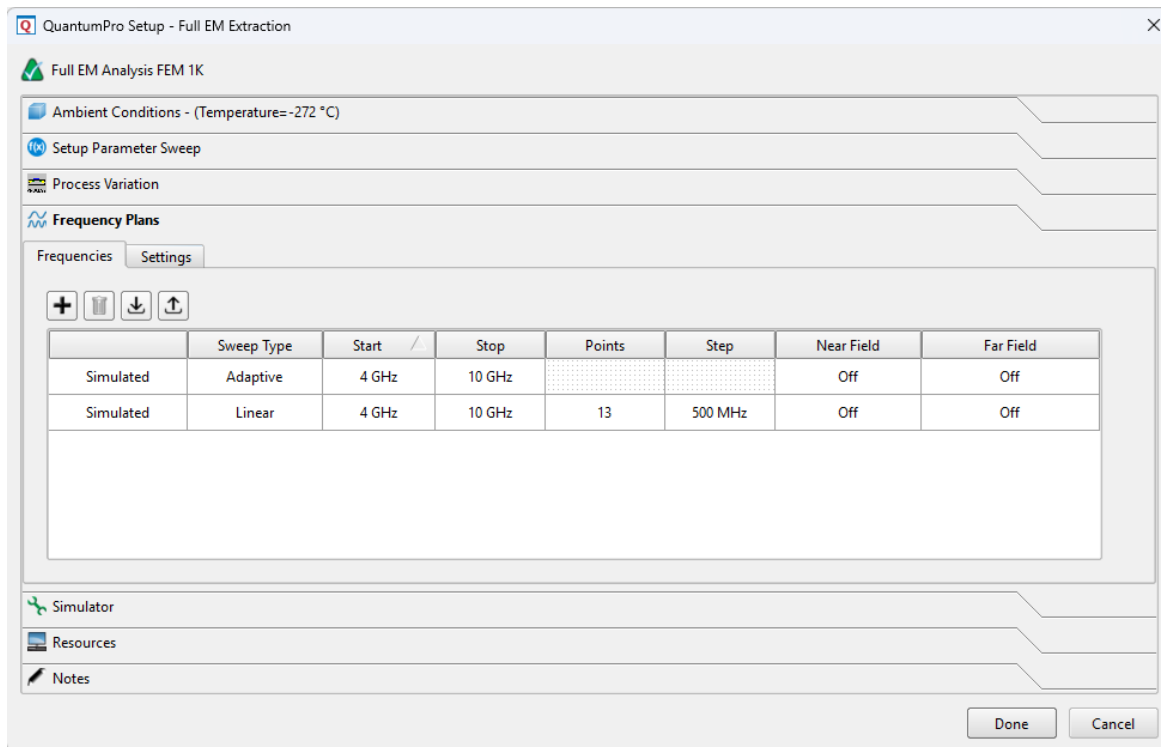


Figure 11. Frequency-plan setup in QuantumPro.

For **Energy Participation Analysis**, the frequency range is defined under the *Options* tab. In this example, the start and stop frequencies are 1 GHz and 10 GHz, and near-field data are not required.

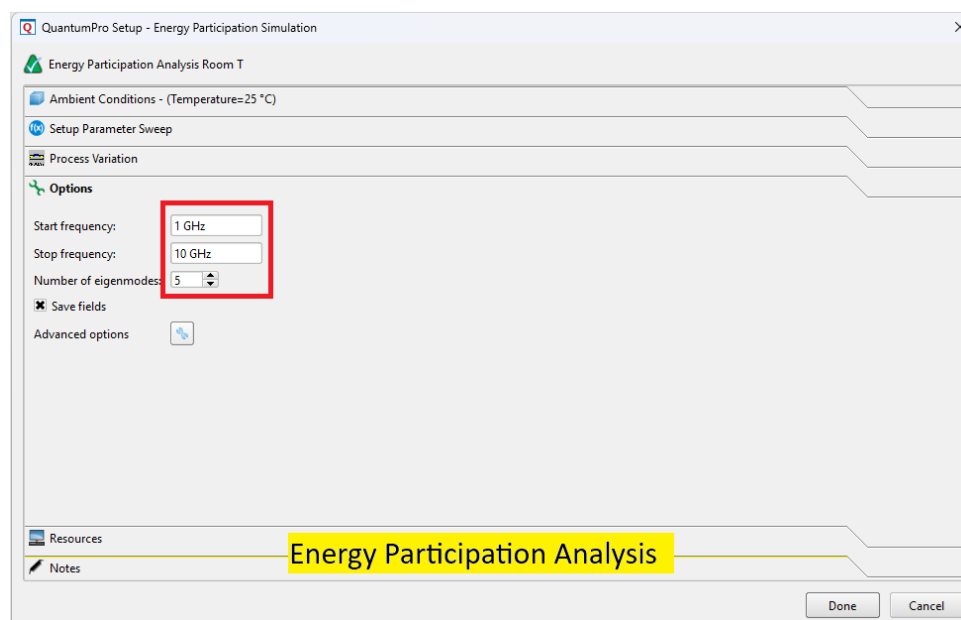


Figure 12. Options setup for Energy Participation Analysis in QuantumPro.

Mesh Setup

Superconducting CPW structures require careful meshing to resolve narrow features accurately.

Use the following mesh settings:

1. Mesh options are defined under Full EM Analysis > Options or Energy Participation Analysis > Options.
2. Under Simulator, the example uses FEM with Advanced Simulator Setup. Momentum Microwave can also be used if the CPW mesh is tightened appropriately, which can reduce runtime.
3. Under Initial Mesh > Target Mesh Size, the Global setting remains Automatic, and conductor cond (1) is overridden to 5 μm , providing about two mesh elements across the CPW strip.

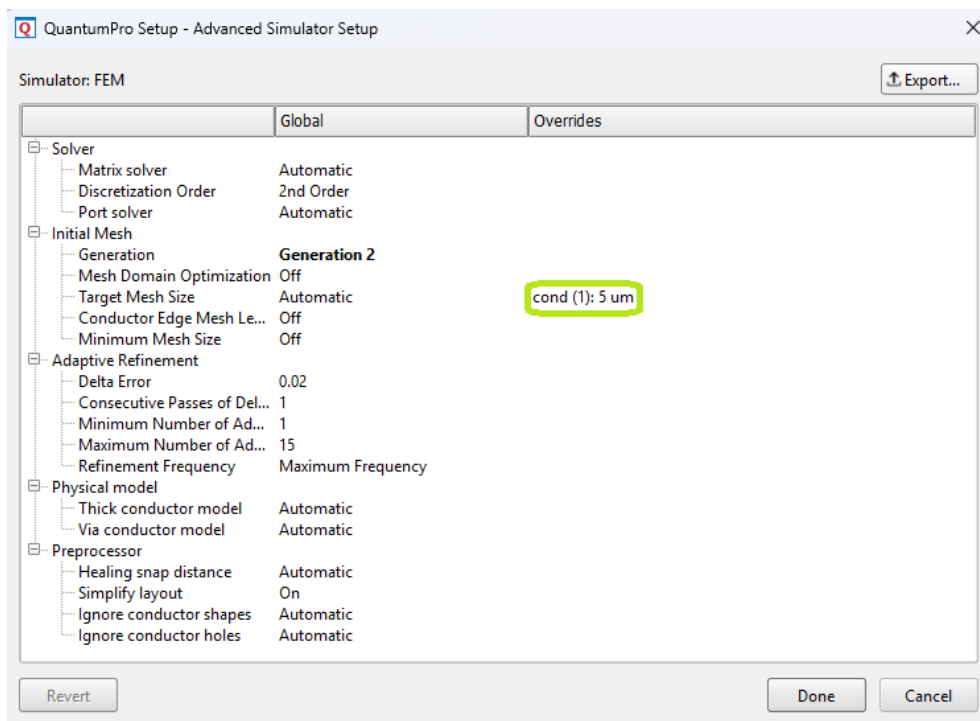


Figure 13. Advanced simulator setup for Energy Participation Analysis in QuantumPro.

The resulting mesh concentrates elements near the resonator center conductor, transmission lines, and pads.

► **Design Tip: Refine the mesh on narrow CPW conductors.** A coarse mesh can under-resolve strip geometry and distort resonant frequency. A local conductor override is more effective than globally tightening the entire mesh.

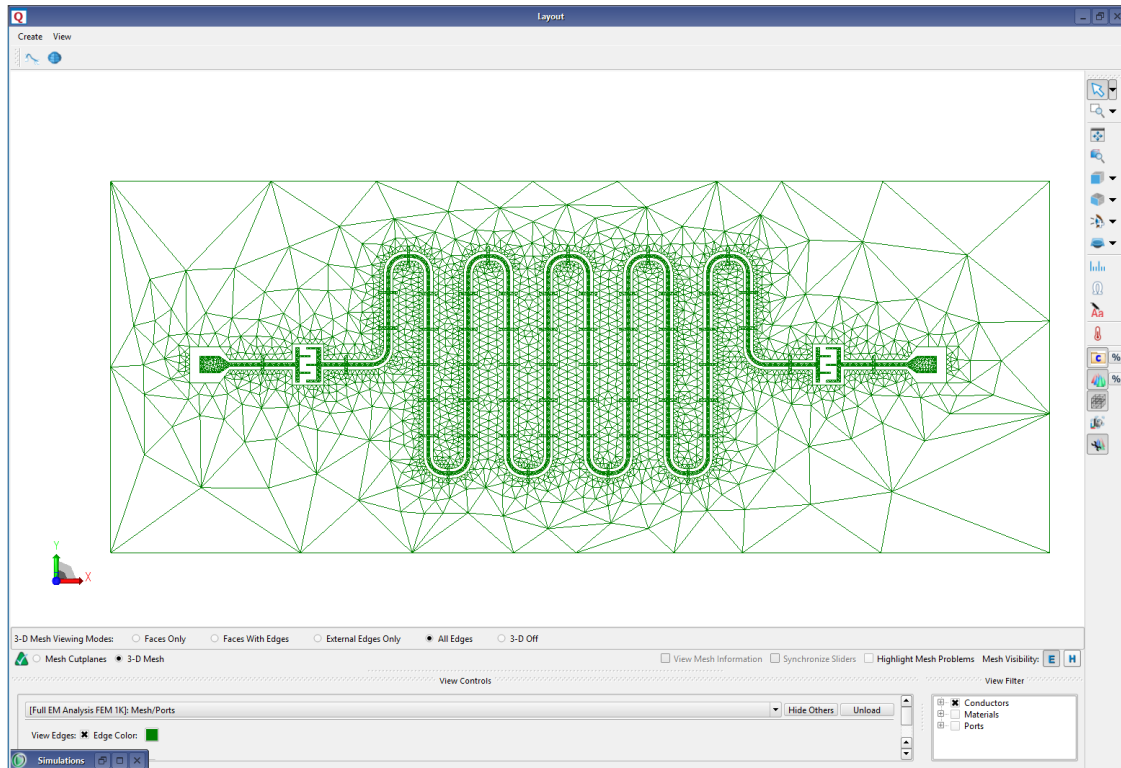


Figure 14. Meshed geometry for Energy Participation Analysis in QuantumPro.

Results

As temperature changes from 1 K to room temperature, the resonant frequency shifts from about 5.2 GHz to about 8.1 GHz. Because loss is not included in this example, the peak amplitude and width remain nearly unchanged. Figure 15 shows the Full EM transmission spectra at the two temperature points.

► **Design Tip:** This QuantumPro example is also intentionally lossless. A nonzero sheet resistance is appropriate when studying linewidth, insertion loss, or Q degradation.

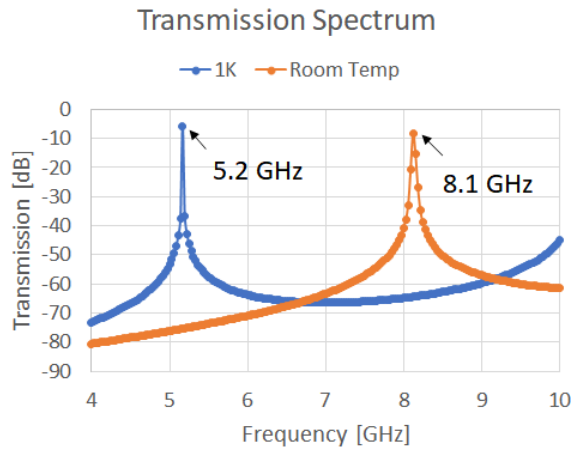


Figure 15. Frequency response of the resonator at room temperature and 1 K, showing the frequency shift caused by the significant contribution of kinetic inductance. Resistive losses are ignored, so the quality factor remains largely unchanged.

The results are summarized below.

Temperature	Eigenfrequency (Energy Participation Analysis)	Peak Frequency (EM)	Q Factor (Energy Participation Analysis)
1 K (-272.15 °C)	5.1667 GHz	5.2936 GHz	109706
Room Temperature (25 °C)	8.1250 GHz	8.1936 GHz	109725

Conclusion

Keysight ADS provides an integrated, material-based workflow for modeling superconductors across both circuit and full-wave EM simulation. By defining physical parameters such as T_c , $\lambda_L(0)$, and σ_n or R_s , the simulator automatically captures kinetic inductance and its temperature dependence.

This application note showed how the same superconducting resonator can be analyzed in ADS circuit simulation and in QuantumPro using both Full EM and Energy Participation Analysis. The example demonstrated that temperature-dependent kinetic inductance can shift resonant frequency by several gigahertz, making accurate material modeling essential.

Together, ADS and QuantumPro provide a unified workflow for accurate superconducting circuit design from schematic to full-wave EM analysis.

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