Navigating the Design Challenges of Superconducting Quantum Chips

Mohamed Hassan, Quantum Solutions Planning Lead

Agenda

- Superconducting Quantum Systems
  - Major Components
  - Design Challenges
- EDA Solutions for Superconducting Quantum Chips
  - Quantum Layout
  - QuantumPro
  - Quantum Circuit Simulation
- Takeaways

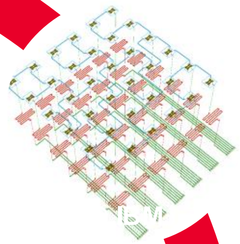
Objective: Explore and address key design challenges of superconducting qubits and quantum amplifiers

Superconducting Quantum Systems

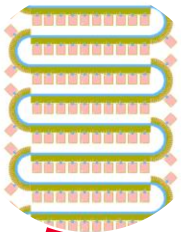
Major components

Superconducting quantum computer

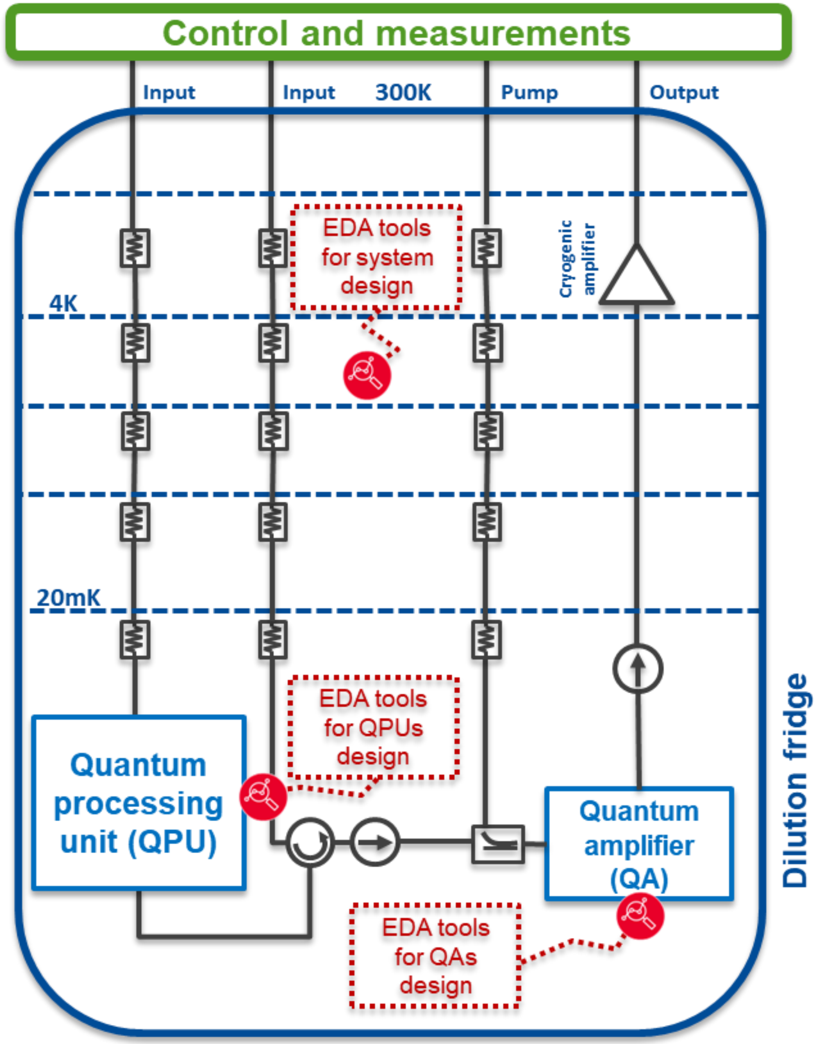
Quantum processing unit



Quantum amplifier



Cryogenic microwave system

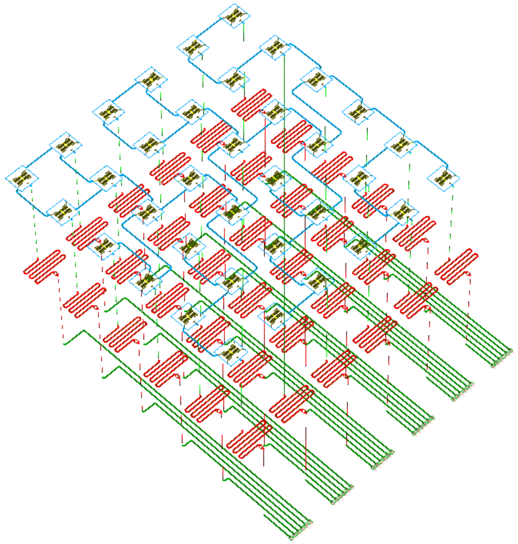


Design Challenges for Superconducting Quantum Systems

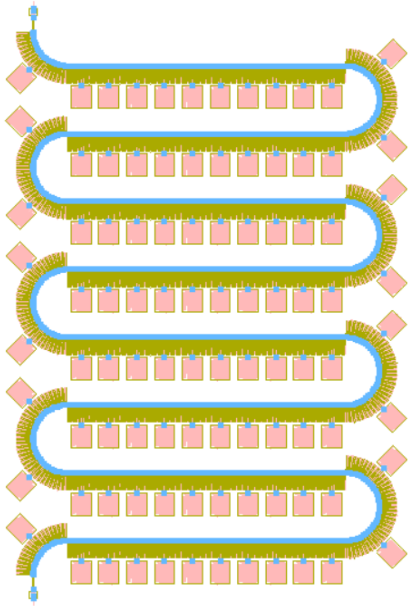
The bottlenecks

- Long, costly development cycles of superconducting quantum chips.
  - Design complexity rapidly increases with the number of qubits / junctions in quantum chips.
  - Problems with prototypes meeting design requirements.
  - Repeated testing to get a working prototype.
- Steep knowledge barrier for microwave engineers to jump into the quantum field.

QPU Example



QA Example

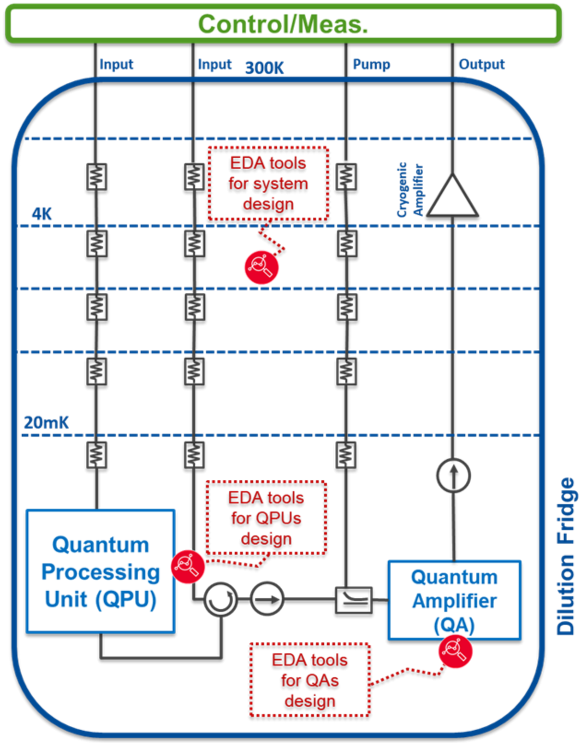


EDA Specific Challenges

- Minute CPW features
- Complex layout
- Electrically large structures
- Cross-talk

EDA Solutions for Superconducting Quantum Systems

What is under the hood?

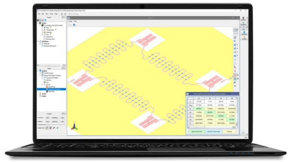


Components of a Superconducting Quantum Computer

1. Quantum Processing Unit (QPU)
2. Quantum Amplifier (QA)
3. Cryogenic Microwave System

	Under the hood	Design
Supercond. Qubits	Coplanar waveguide resonance circuits	Adjust frequencies, coupling etc.
Quantum Amplifiers	Nonlinear parametric microwave circuits	Adjust gain, noise with a pump etc.

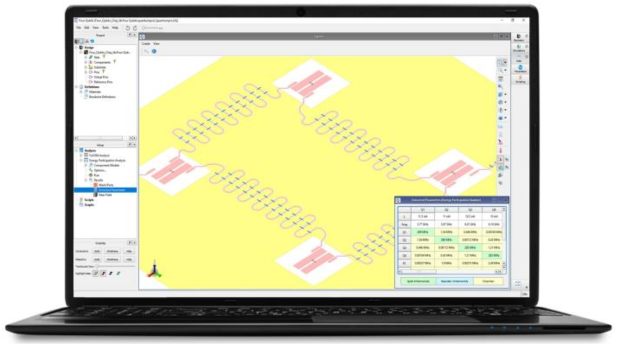
Theme	**Quantum Layout**	**EM for Quantum**	**Quantum Circuit**	**Quantum System**
Needs	Versatile and robust quantum layout	Faster design cycle for quantum chips	Gaining insights into complex quantum amplifiers	Gaining insights into quantum experimental setup
Specifics	• Wide range of quantum components • Single and multilayers • Easy circuit buildup	• Multiple solvers (MoM, FEM) • Multiple analysis (freq domain and eigenmode) • Automated quantum extraction	• Robust nonlinear analysis that can handle 1000s JJs • Flux quantization	• Noise analysis • Pulsed system response • What if troubleshooting
Product	ADS Layout	QuantumPro	Quantum Ckt Sim	In the Roadmap!


Great News

- Keysight provides best in-call Quantum EDA solutions
- Unlike the next best alternatives, Keysight has an integrated workflow
- Keysight is providing an integrated solution of great value for the design of superconducting Qubits and Quantum amplifiers

Quantum Layout



QuantumPro

Quantum Circuit Simulation

The Value of an Integrated Solutions

Faster development while saving money and time

Collection of point tools
$$$$
+ the hassle of integration and maintenance

- Layout (Solution1)
- EM tool (Solution2)
- Quasistatic (Solution3)
- Quantum Parameter Extraction (Solution4)
- Quantum Circuit Analysis (Solution5)
- Kinetic Inductance (Solution6)

W3706B

- QuantumPro (EM+Quasistatic)
- Quantum Ckt Sim
- Quantum Parameter Extraction
- Quantum Layout
- Supercond. Kinetic Inductance

Integrated solution of a great value

- Unlike the competition or homegrown solutions, we are putting together an integrated workflow
- W3706B is an attractive alternative to six different solutions saving you money and time

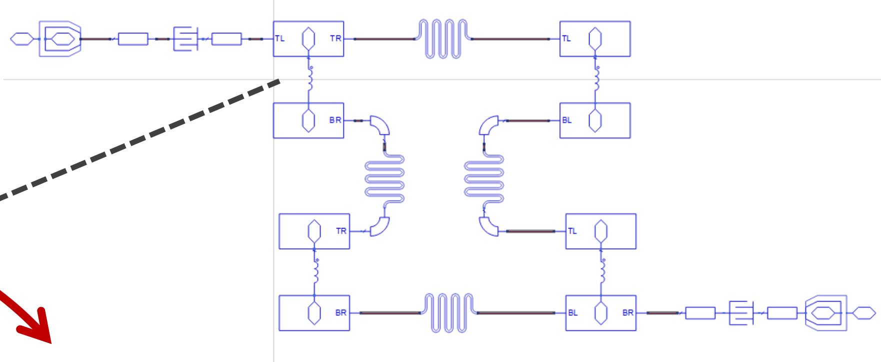
Workflow for Superconducting Quantum Chips

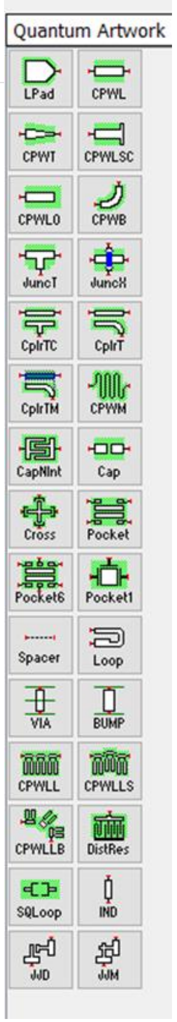
Faster design cycle for Quantum chips with an integrated solution

Extracted Parameters

	Q1	Q2	Q3	Q4	R1	R2	R3	R4
L	11.5 nH	11 nH	10.5 nH	10 nH				
Freq	5.95 GHz	6.1 GHz	6.3 GHz	6.44 GHz	8.65 GHz	8.92 GHz	9.41 GHz	9.67 GHz
Q1	311 MHz					1.22 MHz		0.865 MHz
Q2		313 MHz			1.49 MHz			1.01 MHz
Q3			319 MHz			1.62 MHz	1.21 MHz	
Q4				317 MHz	2.12 MHz		1.27 MHz	
R1		1.49 MHz		2.12 MHz	10.6 kHz			
R2	1.22 MHz		1.62 MHz			6.48 kHz		
R3			1.21 MHz	1.27 MHz			4.84 kHz	
R4	0.865 MHz	1.01 MHz						2.83 kHz

Qubit Anharmonicity | Resonator Anharmonicity | Cross-Kerr





Quantum Circuit

Quantum Parameters

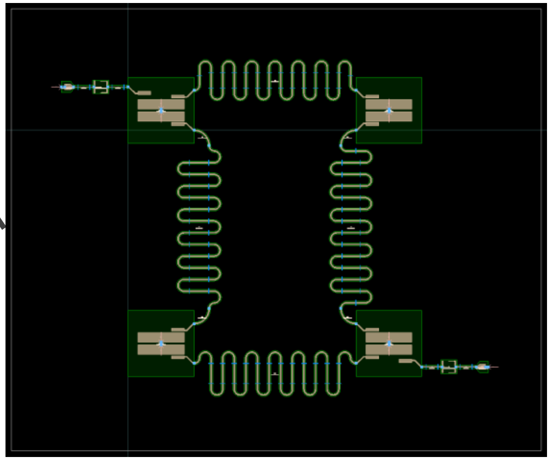
Quantum Layout

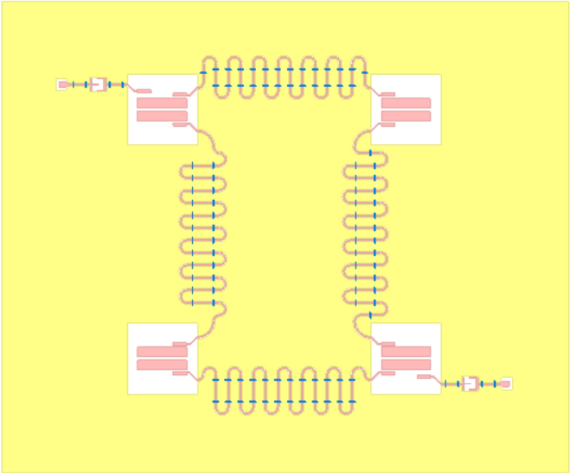
Automation enablement through Python APIs

EM Setup

EM Solution

MoM, FEM





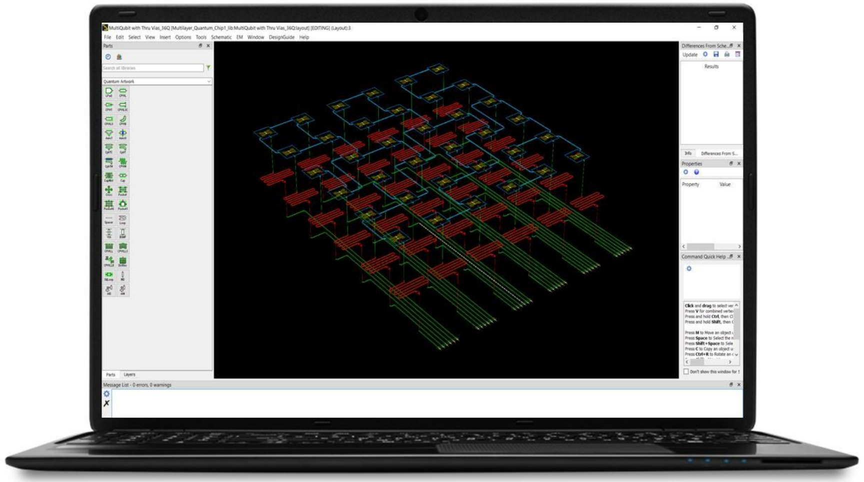
+ Kinetic Inductance

Quantum Layout

The layout solution for Quantum design

"Build your Quantum Chip with Ease" with

- An extended library of **quantum layout** components including:
  1. Resonators and qubits – to enable building Quantum Processing Units (QPUs)
  2. Common Coplanar Waveguide CPW components – to allow building peripheral circuits
  3. Distributed Loaded CPW components – to facilitate building Quantum Amplifiers (QAs)
- Preset Quantum technology to jump-start development
- Automatic airbridges are added o save you the hassle of dealing with unwanted modes of the CPW line
- Multilayer technology to scale up the number of Qubits



Build your Quantum Chip Easily in ADS

Saving time in building the layout of Quantum chips

An extended library of **quantum layout** components including:

1. Resonators and qubits – to enable building Quantum Processing Units (QPUs)
2. Common Coplanar Waveguide CPW components – to allow building peripheral circuits
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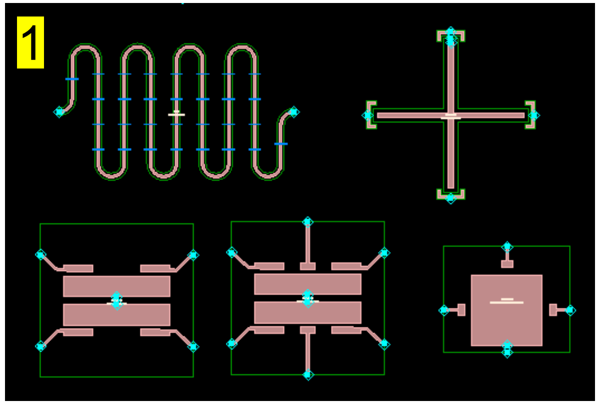
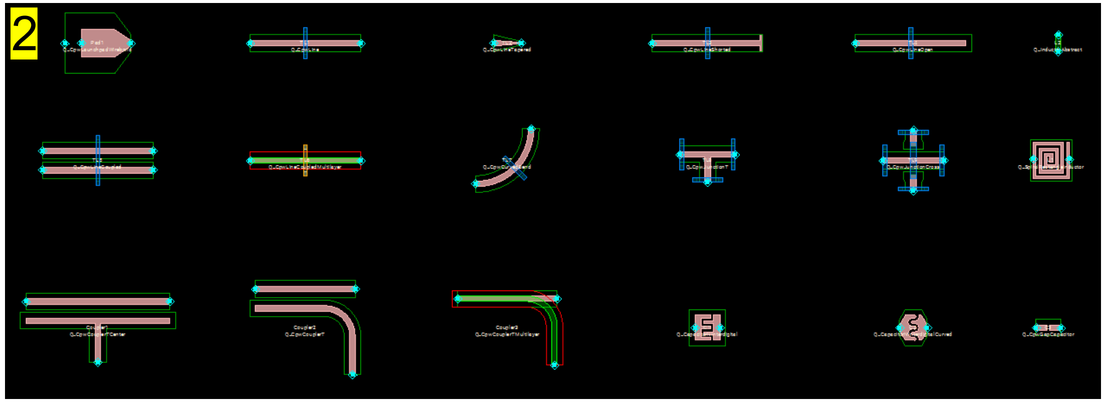
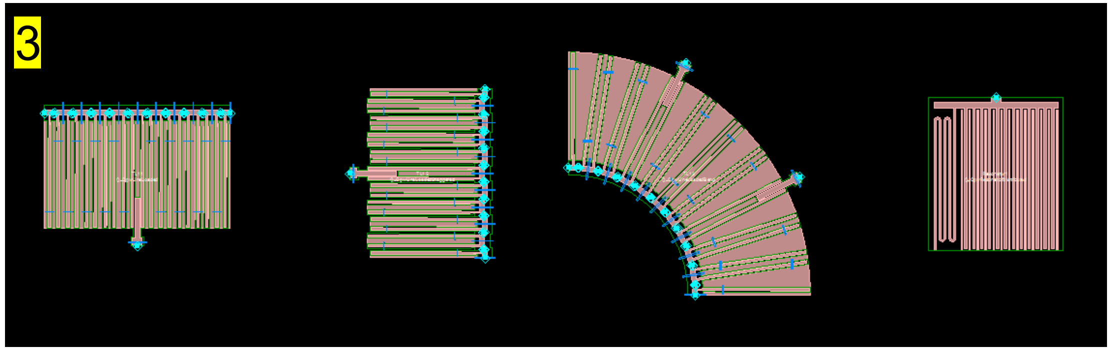




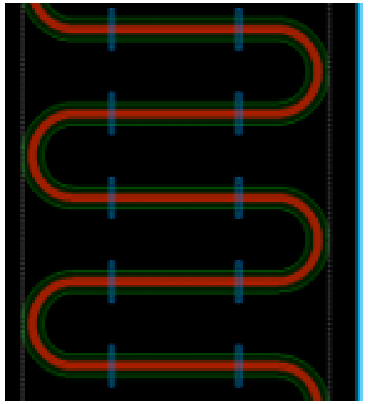


Quantum Layout Palette

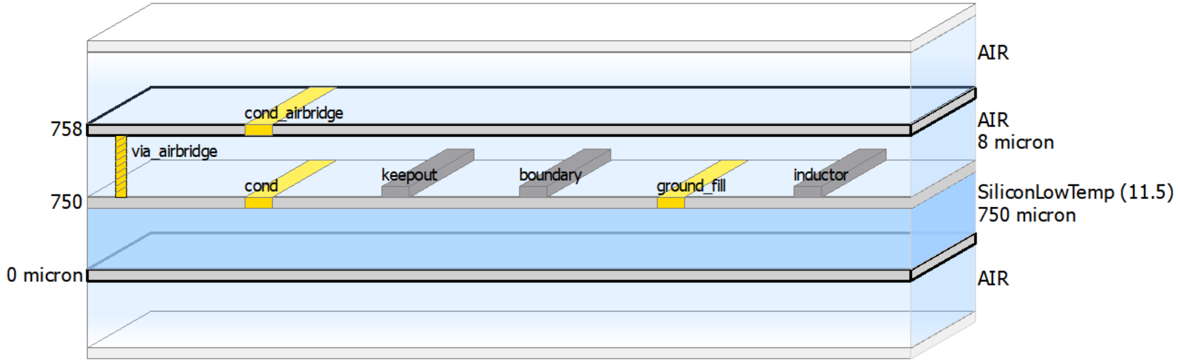
Build your Quantum Chip Easily in ADS Cont.

Jump-starting development with the preset Quantum technology

- Preset Quantum technology to jump-start development
- Automatic airbridges are added to the CPW lines, including meander-lines, to save you the hassle of dealing with unwanted modes of the CPW lines
- Quantum technology is added to the layout technology wizard for new workspaces



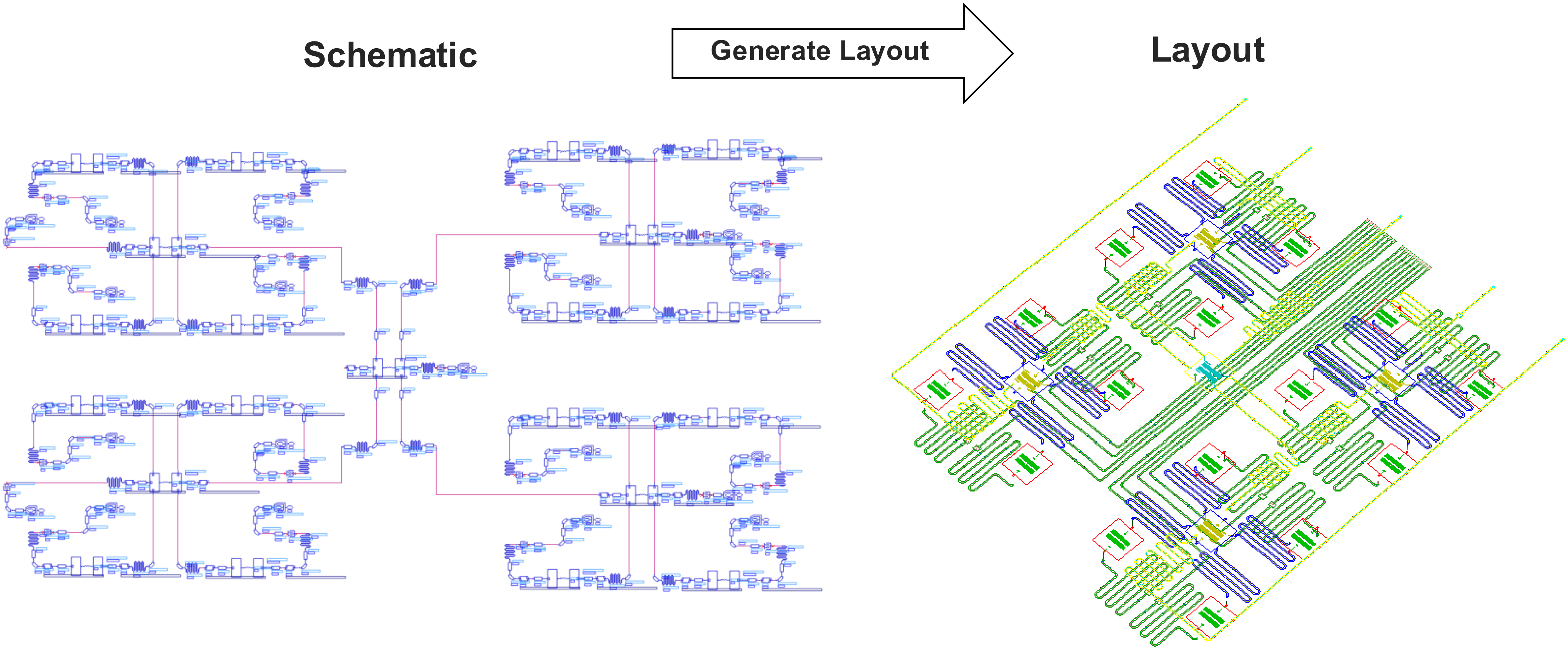
Automated Airbridges



Preset Quantum Technology

Driving Layout from Schematic

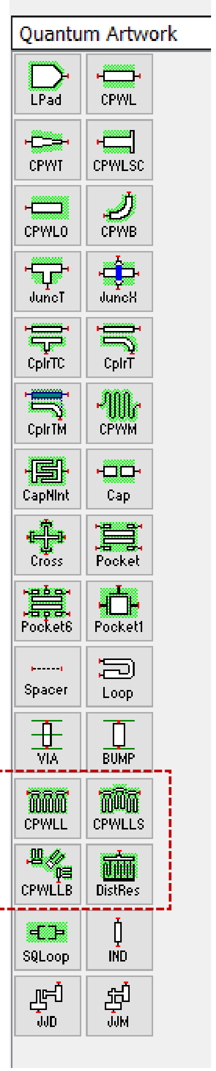
Abstracting the chip complexity



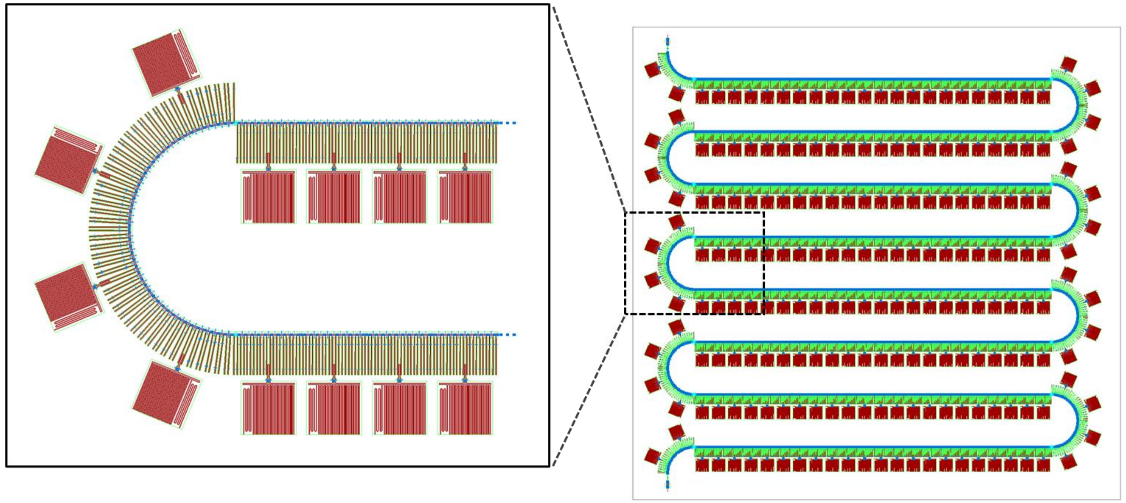
JTWPA Artwork

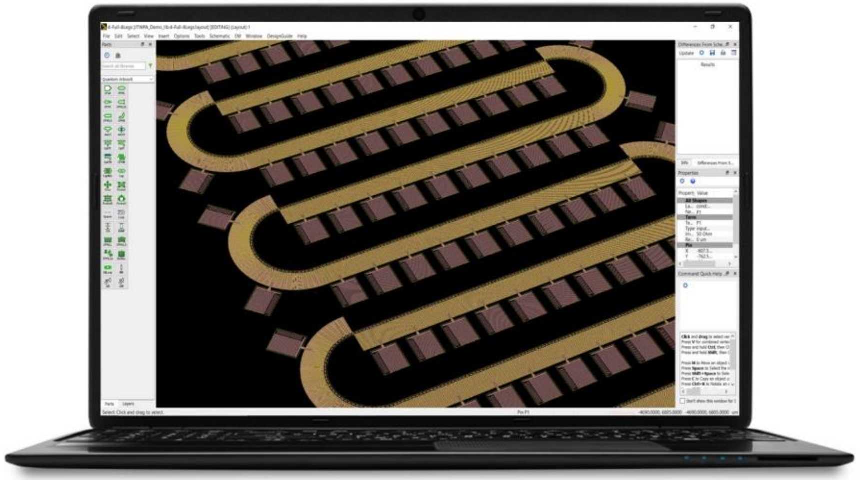
Building complex Quantum amplifiers

Quantum artwork includes **distributed loaded coplanar waveguide artworks** that can be utilized in the development of **traveling wave quantum structures** such as the Josephson Traveling Wave Parametric Amplifiers **(JTWPAs)**



Example for a JTWPA built with the new features in ADS



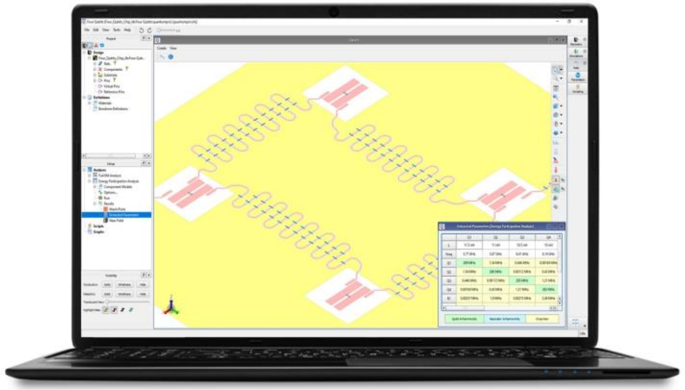


QuantumPro

The EM solution for Quantum design

- First to the quantum market with an **integrated solution**
- **“Faster development cycle of quantum chips” with** five different key features in one platform:
  1. **Quantum Layout**: Library of commonly used quantum artwork -- fully parametrized
  2. **Electromagnetic**: Full EM solution in both frequency domain and eigenmode (with kinetic inductance)
  3. **Quantum Parameters**: Automatic extraction using the three standard methods, black box quantization, EPR, and quasi-static.
  4. **Nonlinear Circuit**: Market-leading harmonic balance
  5. **Nonlinear Co-Sim**: Ability to inspect the power-dependent response of the quantum chip by combining the EM and nonlinear circuit flows

> “We selected Keysight QuantumPro because it provides a complete workflow from design entry through layout, analysis, and extraction. The tool is easy to use and gives us everything we need to develop our forthcoming chips.”
>
> Albert Solana, Chief Business Officer, Qilimanjaro Quantum Tech



Solving the Superconducting Qubits Problem in QPro

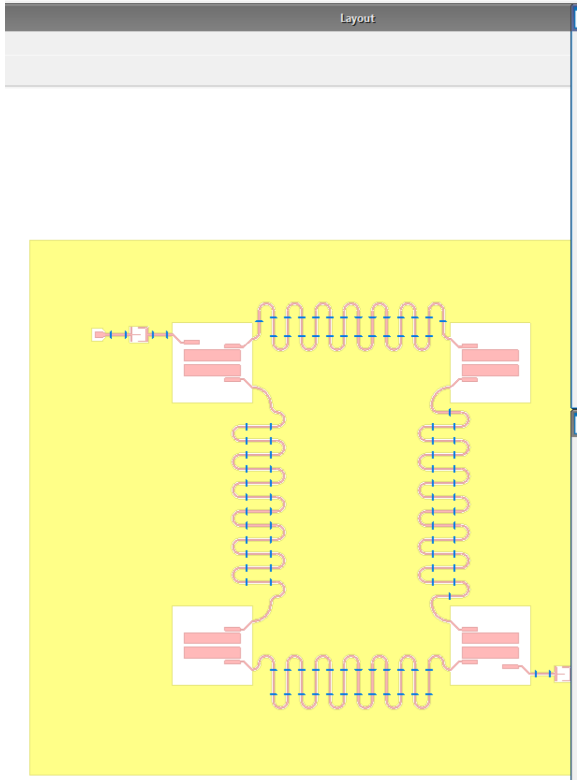
Cross-checking Quantum parameter extraction using multiple methods

Analysis	Full EM Analysis			Energy Participation Analysis
Solution Domain	Quasi-Static Frequency Domain	Frequency Domain	Frequency Domain	Eigenmode
Solver	Momentum RF	Momentum Microwave	FEM	FEM
Quantum Parameter Extraction Method	Quasi-Static Blackbox Quantization	Blackbox Quantization	Blackbox Quantization	Energy Participation Ratio (EPR)
Computational Complexity	Low	Medium	High	Medium

QuantumPro provides access to various EM methods in one interface

Automated Quantum Parameter Extraction

Lowering the Knowledge Barrier for Microwave Engineers



Extracted Parameters

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Qubit Anharmonicity | Resonator Anharmonicity | Cross-Kerr

Extracted Parameters

	Q1	Q2	Q3	Q4	R1	R2	R3	R4
L	11.5 nH	11 nH	10.5 nH	10 nH				
Freq	5.75 GHz	5.86 GHz	6.01 GHz	6.13 GHz	8.43 GHz	8.67 GHz	9.14 GHz	9.46 GHz
Q1	287 MHz	1.18 MHz	0.333 MHz	0.000831 MHz	0.00191 MHz	1.55 MHz	0.00111 MHz	1.05 MHz
Q2	1.18 MHz	285 MHz	0.001 MHz	0.402 MHz	1.78 MHz	0.00189 MHz	0.000773 MHz	1.16 MHz
Q3	0.333 MHz	0.001 MHz	286 MHz	1.48 MHz	0.00315 MHz	1.85 MHz	1.38 MHz	0.000602 MHz
Q4	0.000831 MHz	0.402 MHz	1.48 MHz	283 MHz	2.34 MHz	0.00316 MHz	1.48 MHz	0.000618 MHz
R1	0.00191 MHz	1.78 MHz	0.00315 MHz	2.34 MHz	7.6 kHz	4.61e-06 MHz	0.0061 MHz	0.00362 MHz
R2	1.55 MHz	0.00189 MHz	1.85 MHz	0.00316 MHz	4.61e-06 MHz	5.08 kHz	0.00445 MHz	0.00285 MHz
R3	0.00111 MHz	0.000773 MHz	1.38 MHz	1.48 MHz	0.0061 MHz	0.00445 MHz	3.59 kHz	3.05e-06 MHz
R4	1.05 MHz	1.16 MHz	0.000602 MHz	0.000618 MHz	0.00362 MHz	0.00285 MHz	3.05e-06 MHz	2.14 kHz
Q Factor	1.09e+06	1.09e+06	1.09e+06	1.09e+06	1.09e+06	1.09e+06	1.09e+06	1.09e+06
T1	30.1 us	29.5 us	28.8 us	28.2 us	20.6 us	20 us	19 us	18.3 us

Qubit Anharmonicity | Resonator Anharmonicity | Cross-Kerr

Freq-Domain Extraction

- Will show the coupling terms only between neighboring qubits and resonators

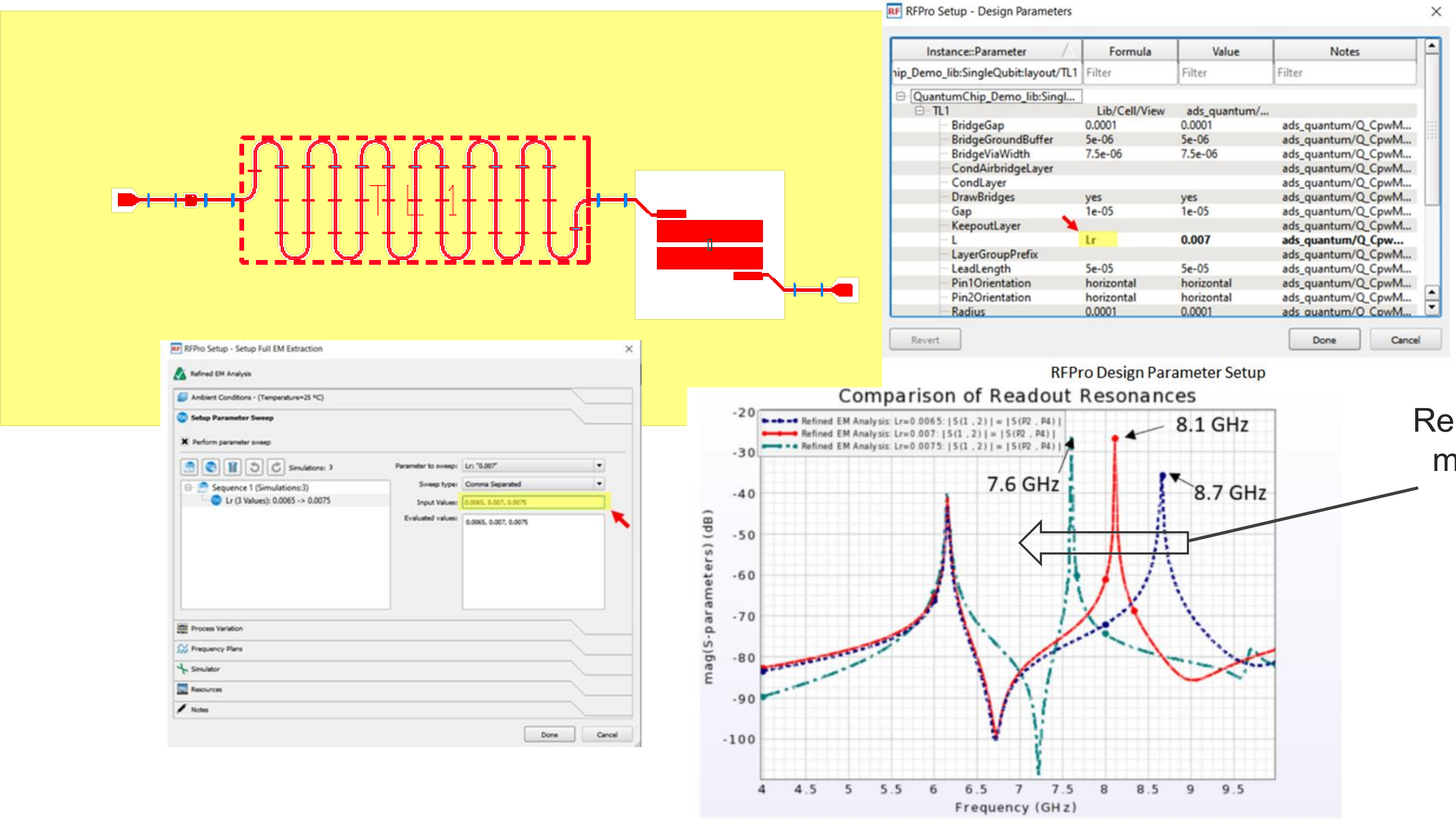
Eigenmode Extraction

- Will show the coupling terms even between distant qubits and resonators

Quantum Parameter Extraction with a "Double Click" – No need to manually program the extraction

Tune the Parameters of your Quantum Chip Effortlessly

Faster iteration on the Quantum design with parametric analysis

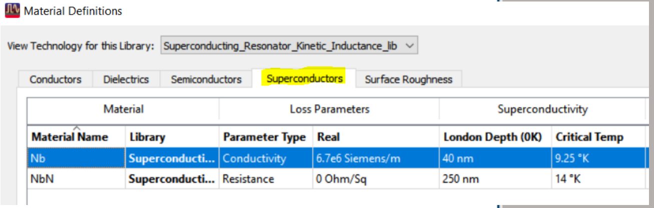


Resonator frequency moves lower upon increasing Lr

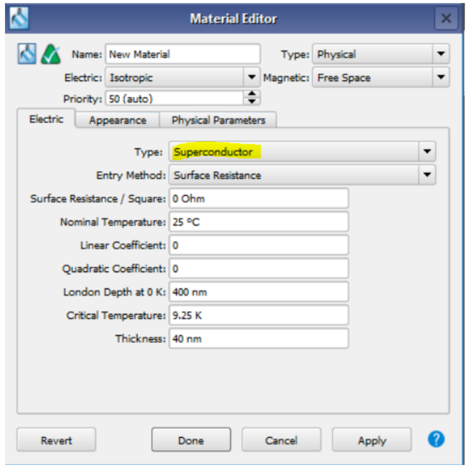
Model the Effect of Kinetic Inductance

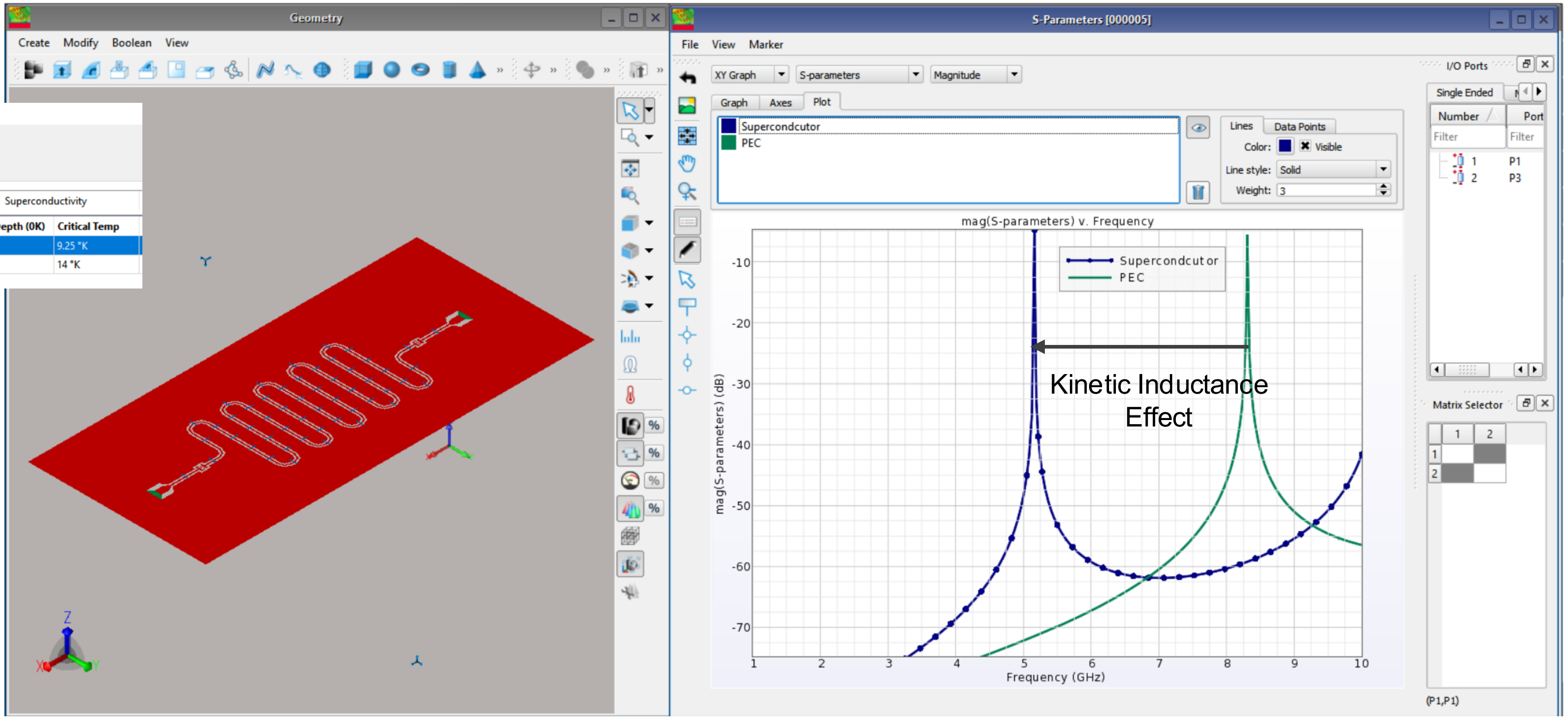
Predicting the Shift in Frequency Due to Kinetic Inductance in Superconductors

Superconductors in ADS



Superconductors in EMPro





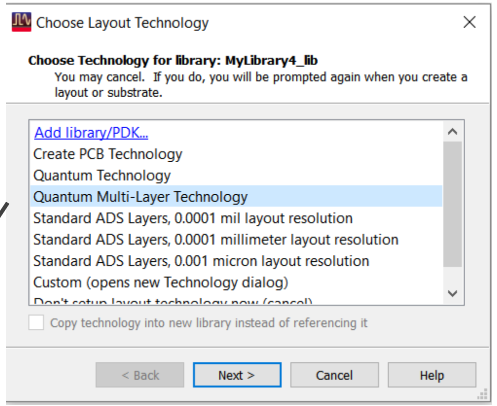
Easily model superconductors in ADS

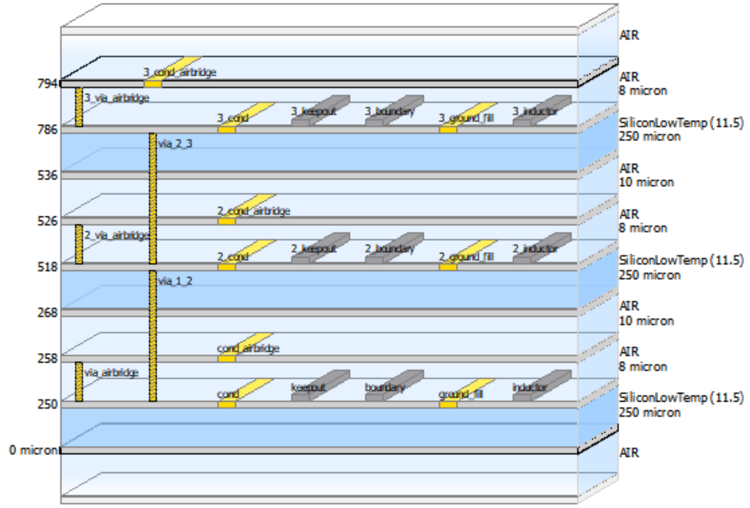
- 7mm resonator, London depth=400nm, film thickness 40nm
  fres (PEC)=8.26 GHz, fres (superconductor)=5.10 GHz
- Kinetic Inductance Effect=-38.3%

Multi-Layer Quantum Technology

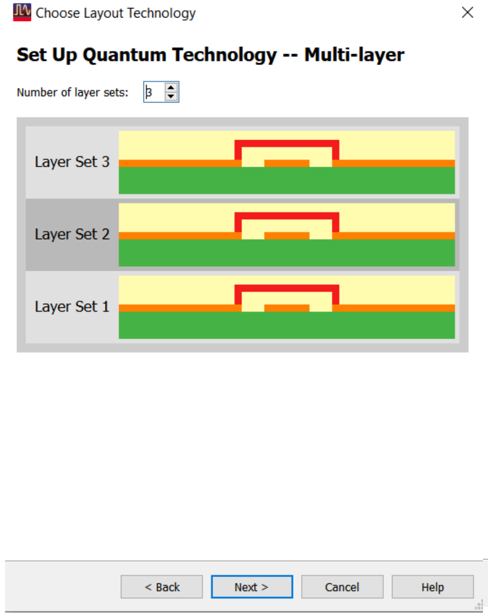
Scaling-up the number of Qubits

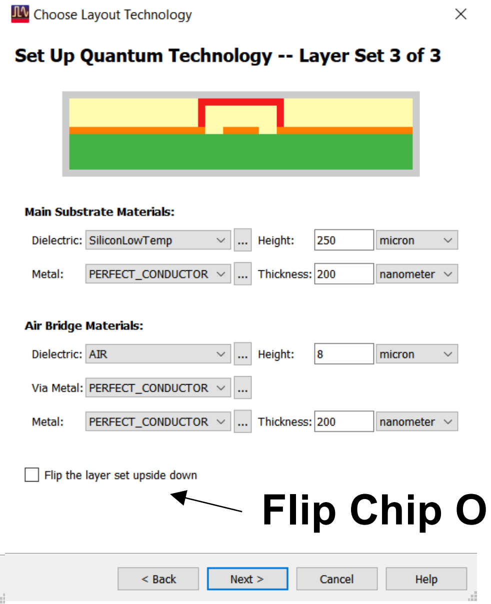
Enables building chips consisting of a large # of qubits



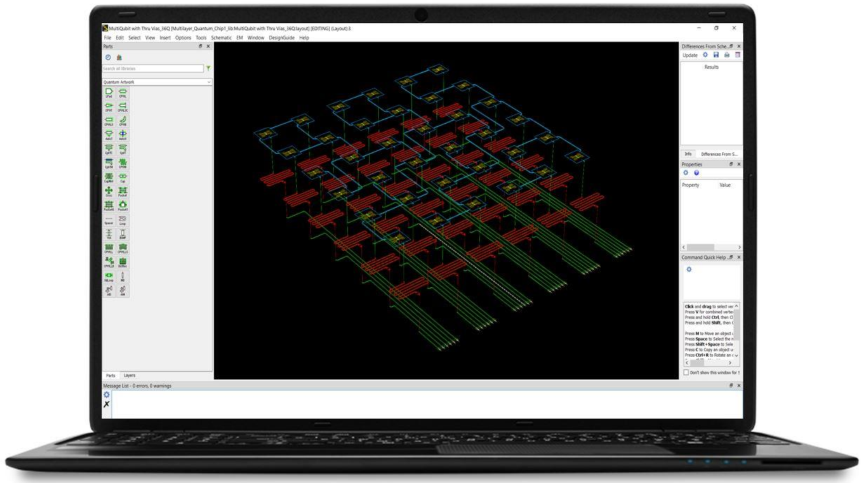


Multilayer Qubit Chip built with ADS!





Flip Chip Option

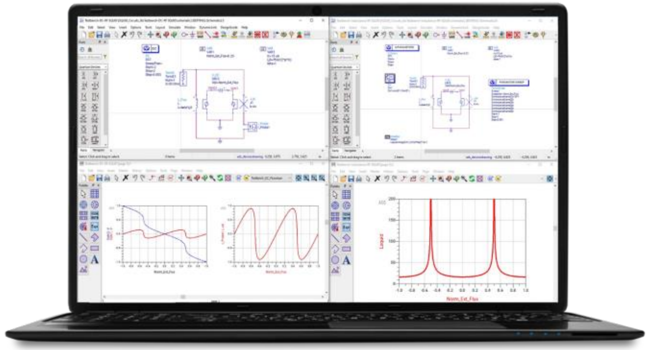


Quantum Circuit Simulation

The circuit solution for Quantum design

- The industry's most capable and accurate analysis with flux quantization for large, highly nonlinear quantum circuits.
- **“Faster development of large, highly nonlinear parametric quantum circuits” with:**
  1. A library of quantum devices encompassing RF/DC SQUIDs, SNAILs, FLUXONIUMs, and SNAKEs.
  2. A comprehensive circuit design environment with Harmonic balance, Transient / convolution, Circuit envelope, and X-parameters.
  3. Ability to drive superconducting circuits with external flux.
  4. Simplified workflow for the design of parametric quantum circuits including quantum amplifiers

> **“Using Quantum Ckt Sim, it is now possible to enforce flux quantization conditions in ADS frequency-domain simulations of superconducting devices. This is a critical capability whose absence thus far limited the usability of modern EDA tools in microwave superconducting circuit design.”**
>
> **Ofer Naaman**
> Research Scientist, Google Quantum AI



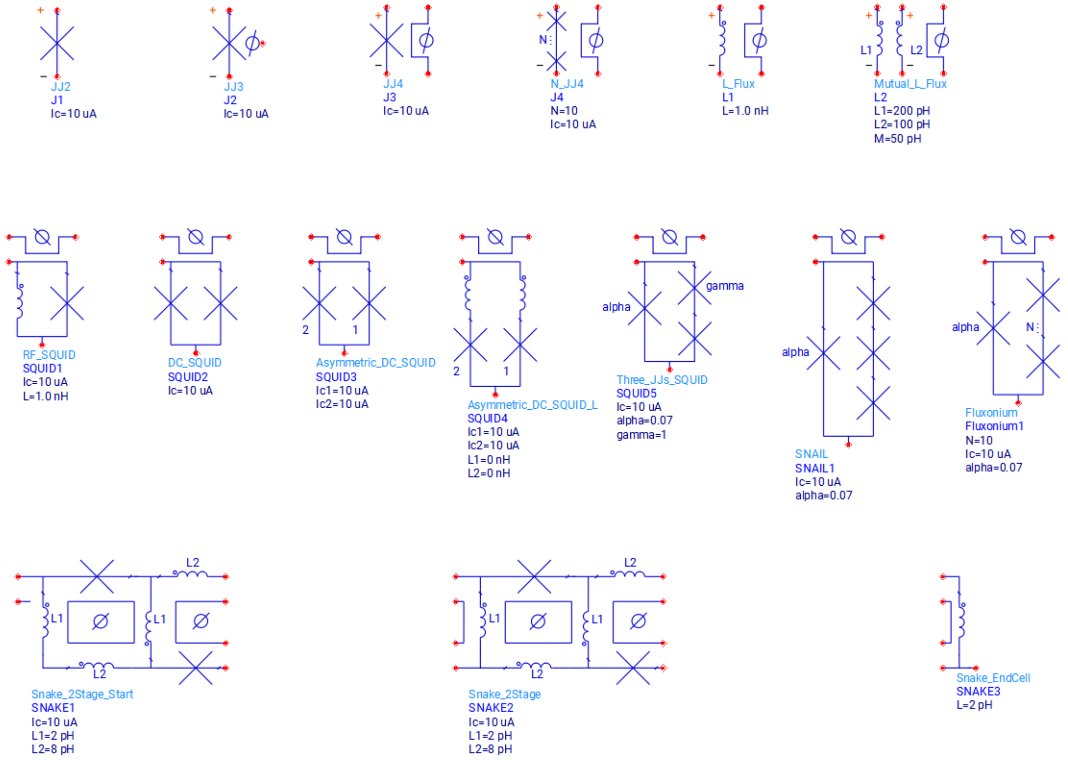
Success Story

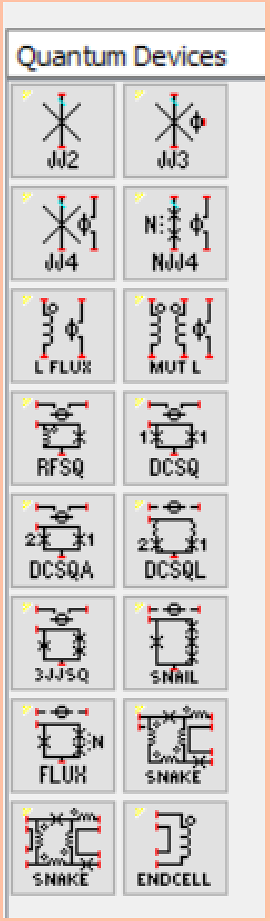
Ofer Naaman, Ted White, Mohamed Awida Hassan, Derek Slater, Sean Mcilvane, Edwin Yeung, and Philip Krantz. "Modeling flux-quantizing Josephson junction circuits in Keysight ADS." *arXiv preprint arXiv:2408.07861* (2024).

Build your Quantum Circuit Easily in ADS

Saving time in building Quantum circuits

- Extended library of Quantum devices including **SQUIDs, SNAIL, and Snake,** which can be utilized in the development of parametric quantum circuits

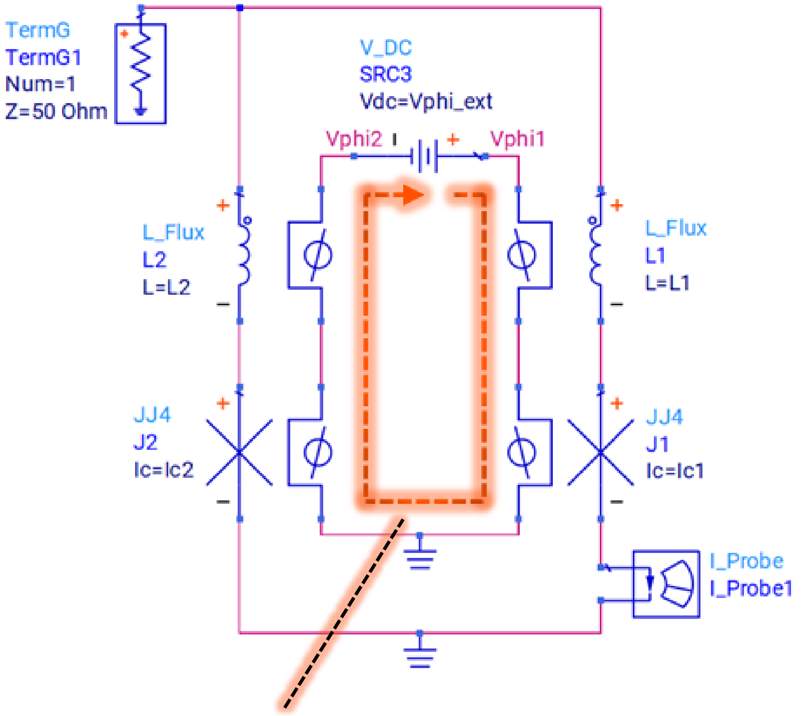




Flux Quantization in Superconducting Loops Cont.

Faster analysis using frequency-domain solvers

- Capturing **flux quantization** in the **time domain** (transient analysis) is **straightforward** because it is inherently represented in the behavioral model of the components
- However, in **frequency domain** analysis, we must enforce the flux quantization condition by another mean
- We came up the idea of mapping the flux quantization condition into **auxiliary voltage loops** that can be recognized with circuit solvers
- This became possible with the inclusion of Josephson junction and inductance models featuring flux nodes (JJ4, N_JJ4, L_Flux, and Mutual_L_Flux) in the library of Quantum devices
- Here is an example of how the flux quantization condition is implemented for a DC SQUID circuit

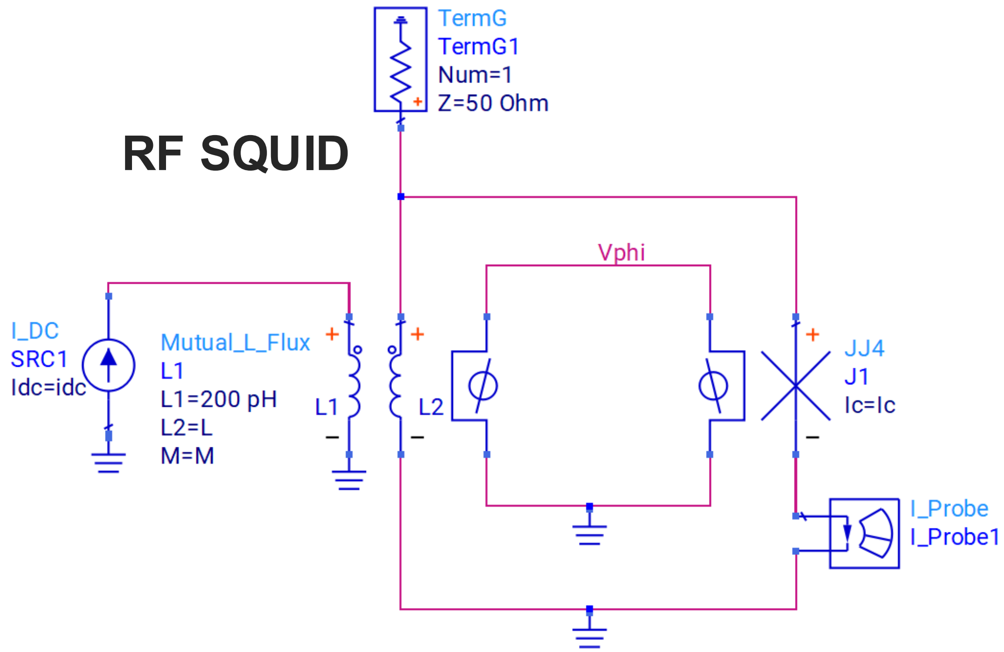


Flux Quantization with auxiliary flux loop!

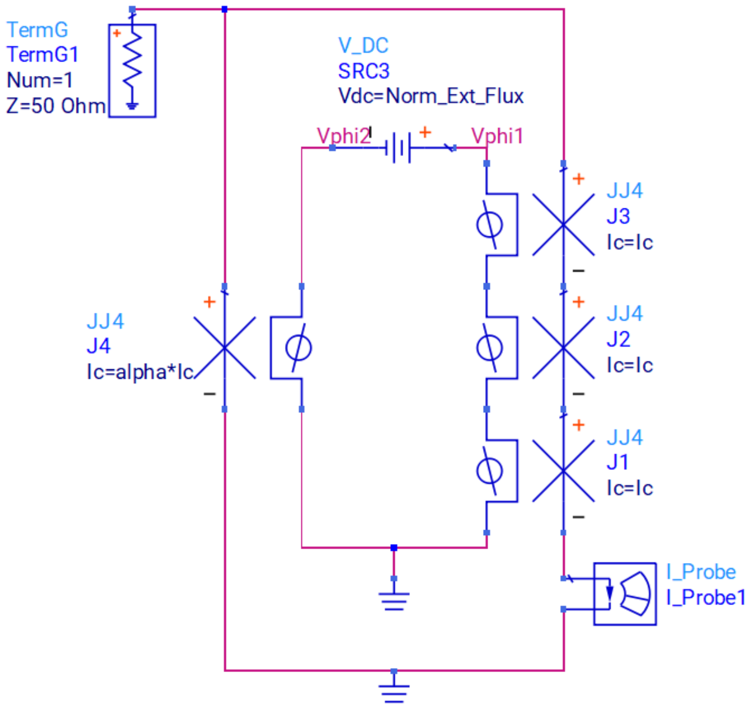
Flux Quantization in the Frequency Domain – More Examples

Handling complex circuits with ease

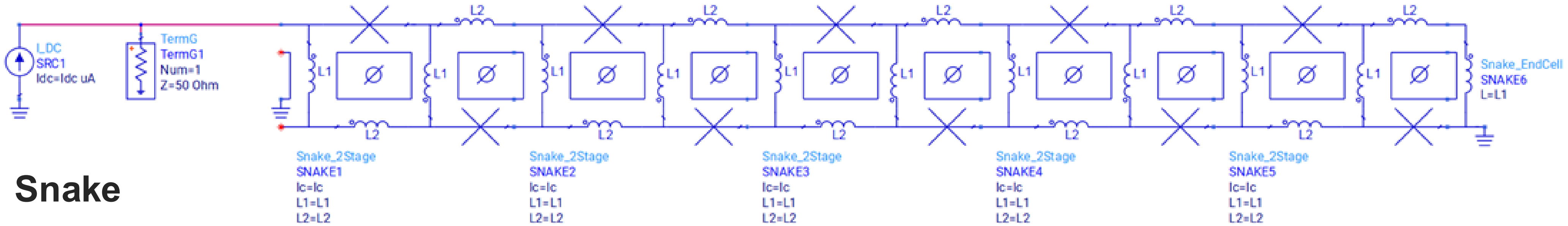
RF SQUID



SNAIL

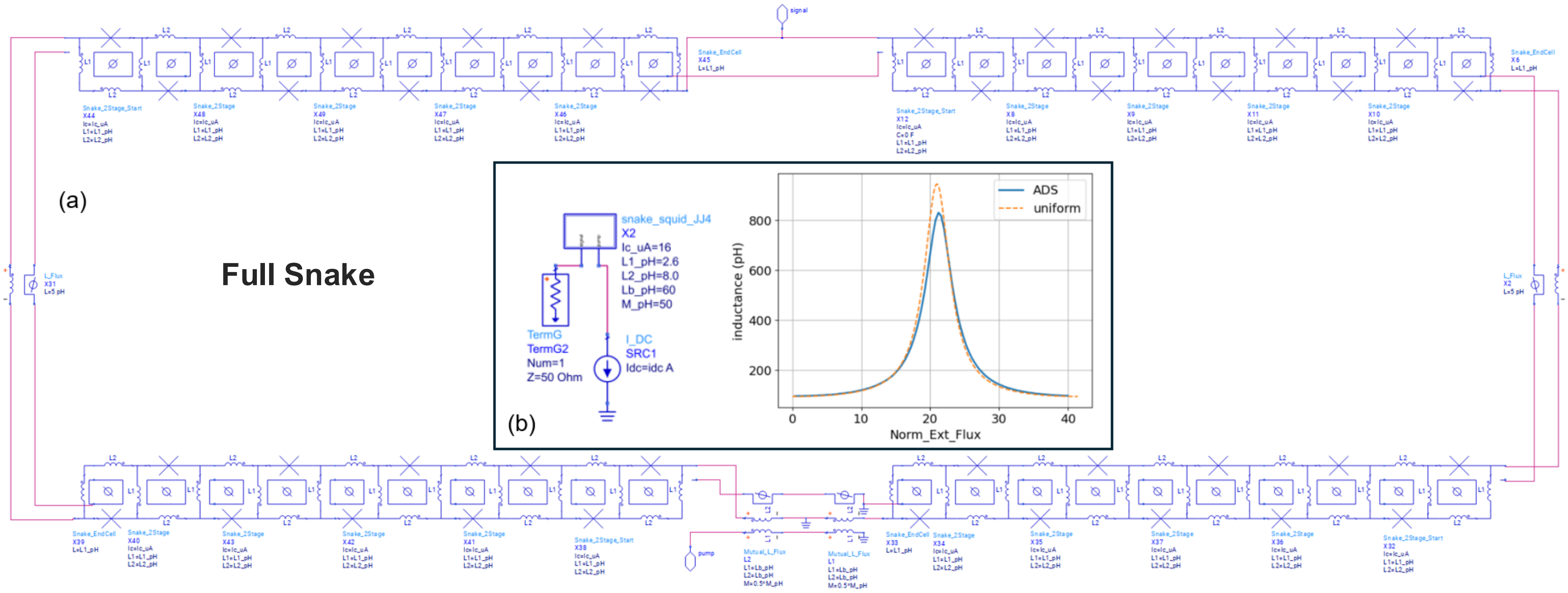


Snake



Flux Quantization in the Frequency Domain – More Examples Cont.

Handling complex circuits with ease



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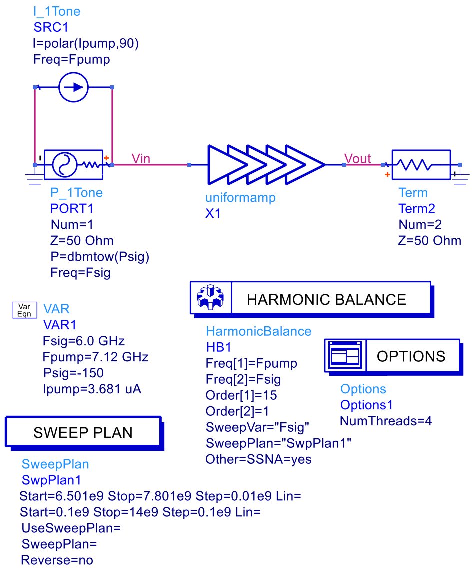
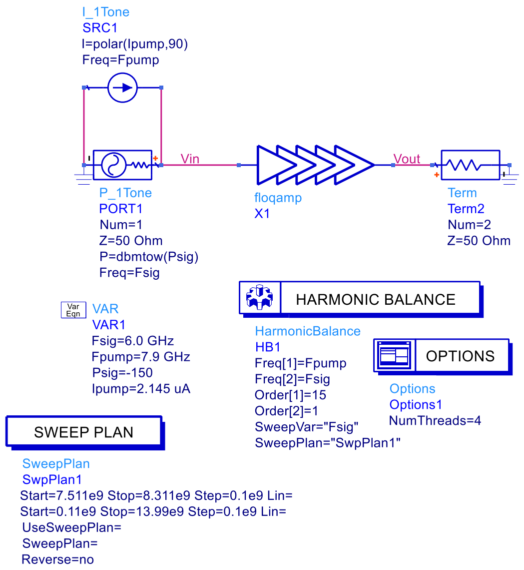
Design and Optimize your Quantum Amplifier with ADS

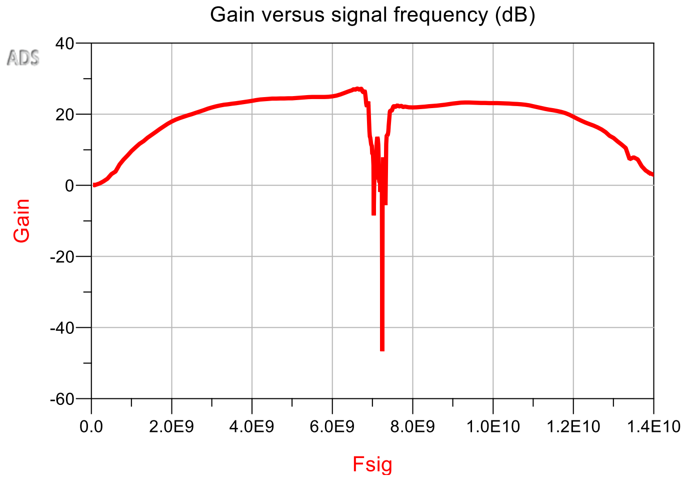
Tackling the Design of Complex Quantum Amplifiers

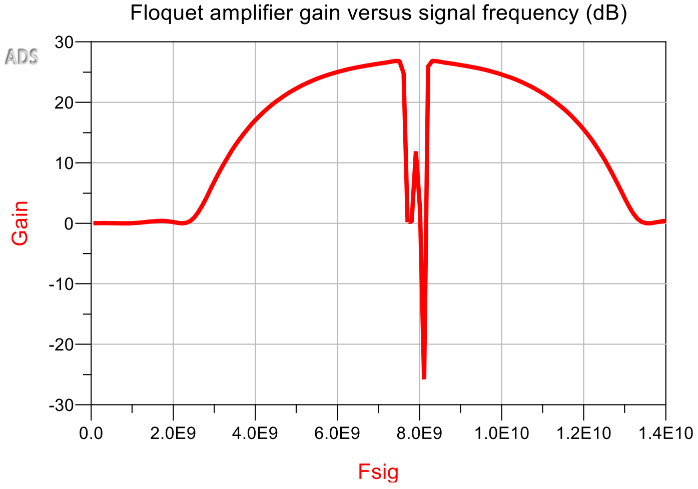
Uniform Design



Floquet Design







Get insights on the amplifier's gain ripples and quantum efficiency

Success Story

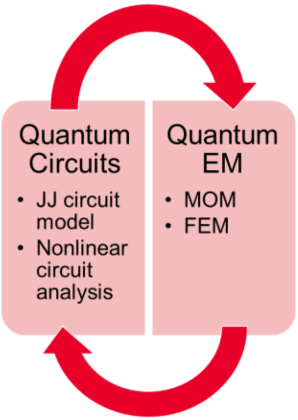
Peng, Kaidong, et al. "X-parameter based design and simulation of Josephson traveling-wave parametric amplifiers for quantum computing applications." *2022 IEEE International Conference on Quantum Computing and Engineering (QCE)*. IEEE, 2022.

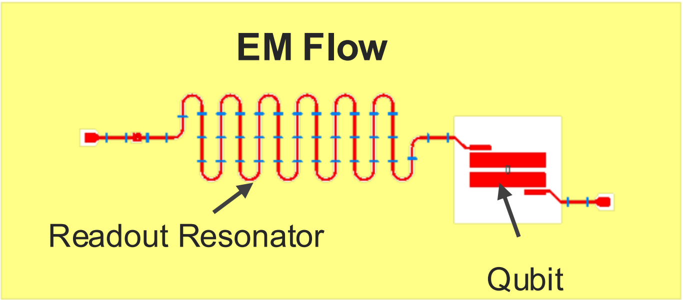
Leverage Co-Sim to Inspect the Power Dependence of your Quantum Chip

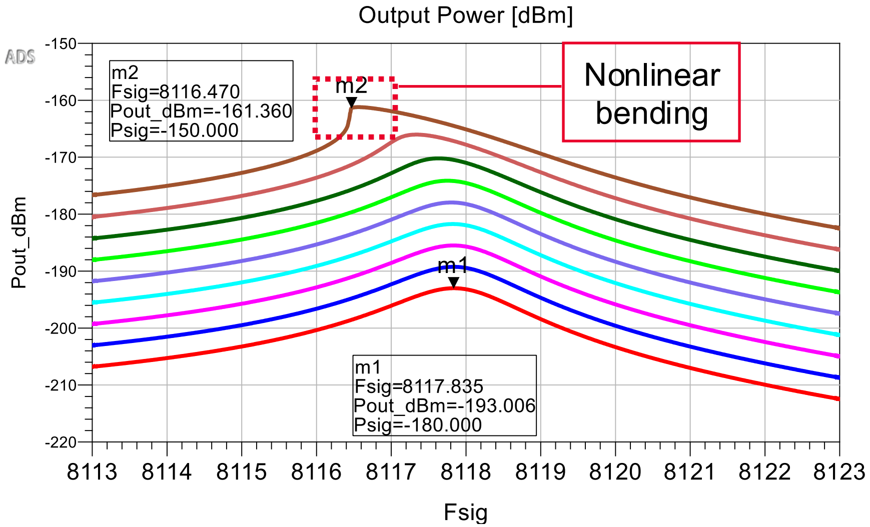
Unmatched Insights on the Response of your Quantum Chips

- Nonlinear co-simulation is where we couple the EM flow with the nonlinear circuit flow through the Josephson junction models to predict the power-dependent response of quantum chips
- Thanks to the integrated EM/circuit flow, that made nonlinear co-simulation possible for quantum chips

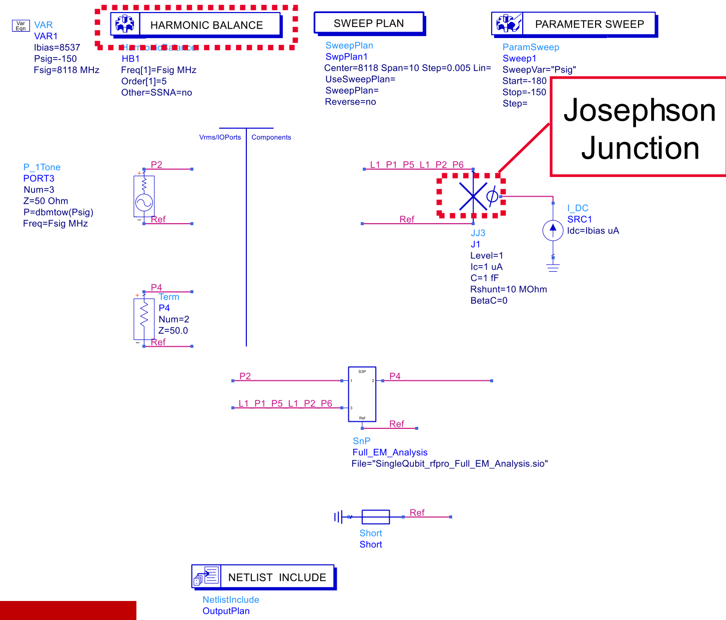
Co-simulation







Nonlinear Circuit Flow

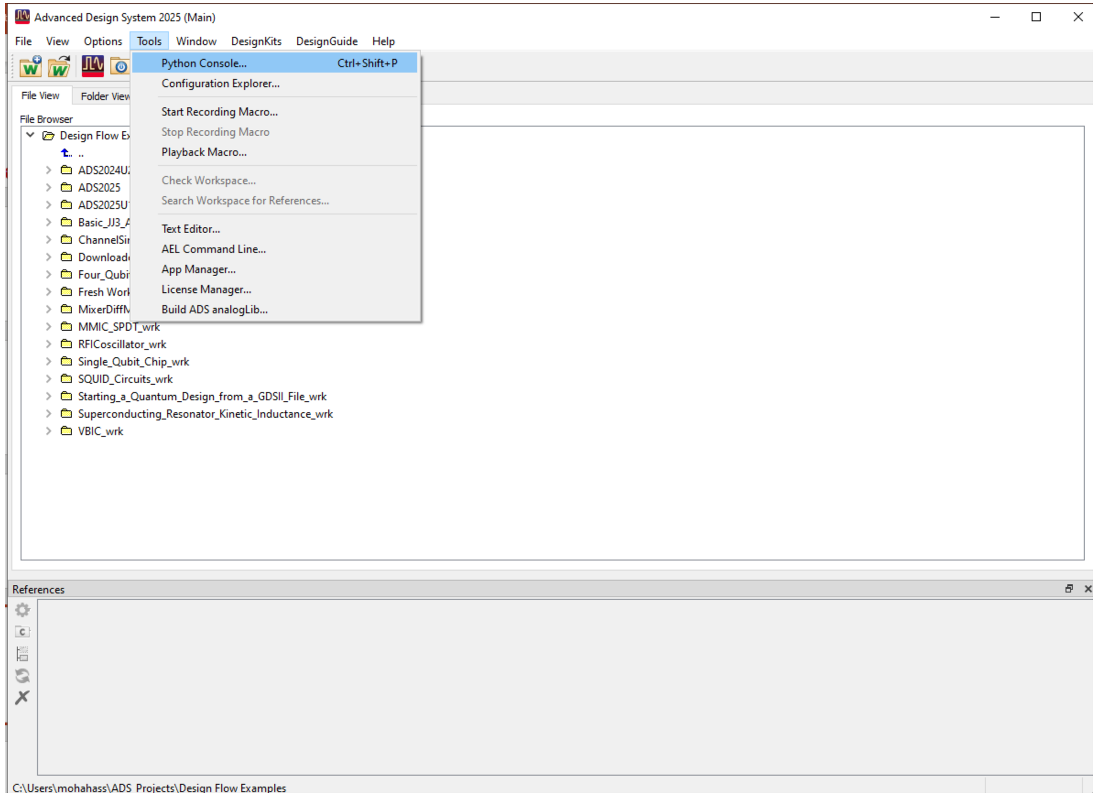


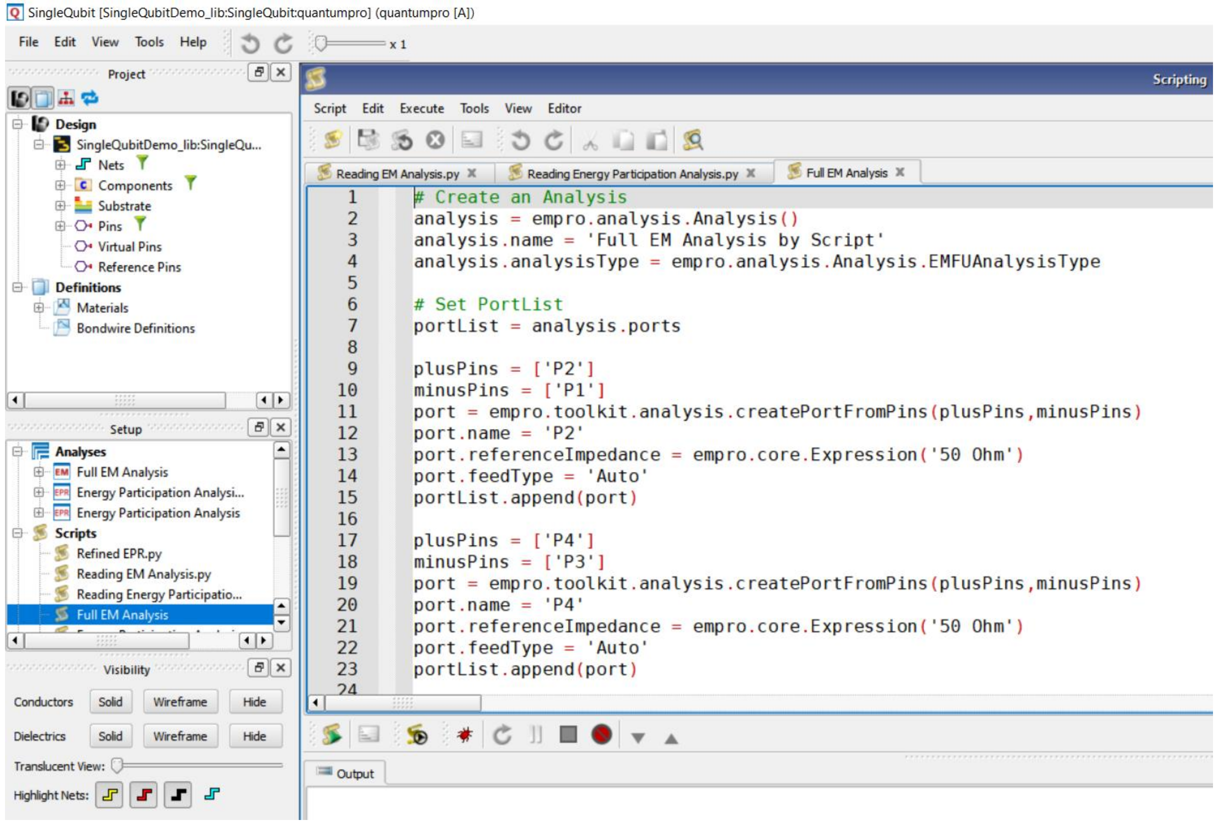
Predicting the dispersive shift of the readout signal as the power is ramped up

Scripting and Automation for Quantum

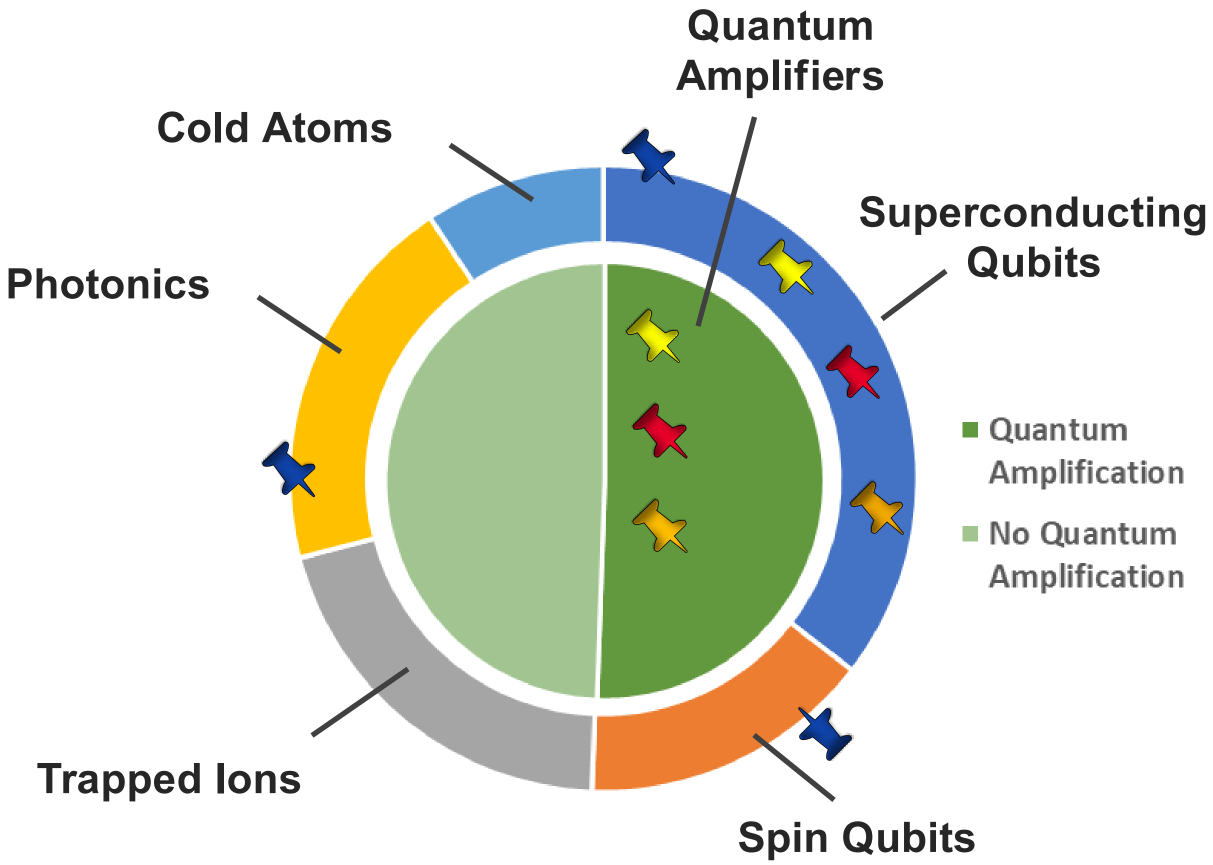
Support of multiple workflow automation using ADS/QPro

- What's more, **ADS2025** includes a release for a Python console that enables users to control workflow, modify workspaces, automate tasks, and customize the user interface to suit their needs.





Market Segmentation and Solutions



https://www.bcg.com/publications/2021/building-quantum-advantage

QPro Quantum Layout Quantum Ckt Sim

ALFNA

Keysight Quantum EDA Solutions

Superc. Qubits	Quantum Amplifiers	Both
W3704B: ADS Core, EM Design, Layout, QPro	**W3703B**: ADS Core, Layout, Q Ckt Sim	**W3706B**: ADS Core, EM Design, Layout, QPro, Q Ckt Sim

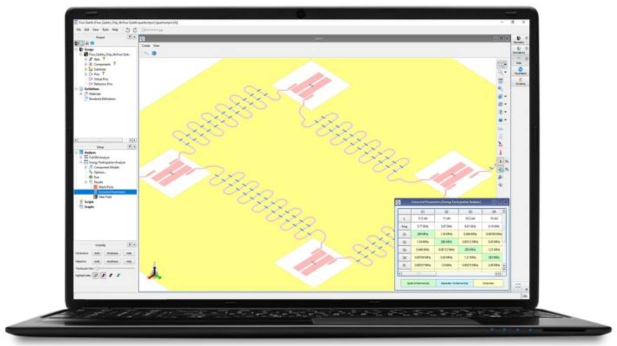
Keysight's Flicker Noise Solutions

E4727B: A-LFNA for 1/f noise characterization in cryogenic electronics for quantum systems

Takeaways

- EDA tools are well-positioned to streamline the design of superconducting quantum systems (for both qubits and amplifiers) and help microwave engineers venture into quantum design overcoming the steep quantum knowledge barrier
- Unlike the competition or homegrown solutions, Keysight offers an integrated workflow
- Keysight provides an integrated solution of great value for the design of superconducting Qubits and Quantum amplifiers

Quantum Layout



QuantumPro

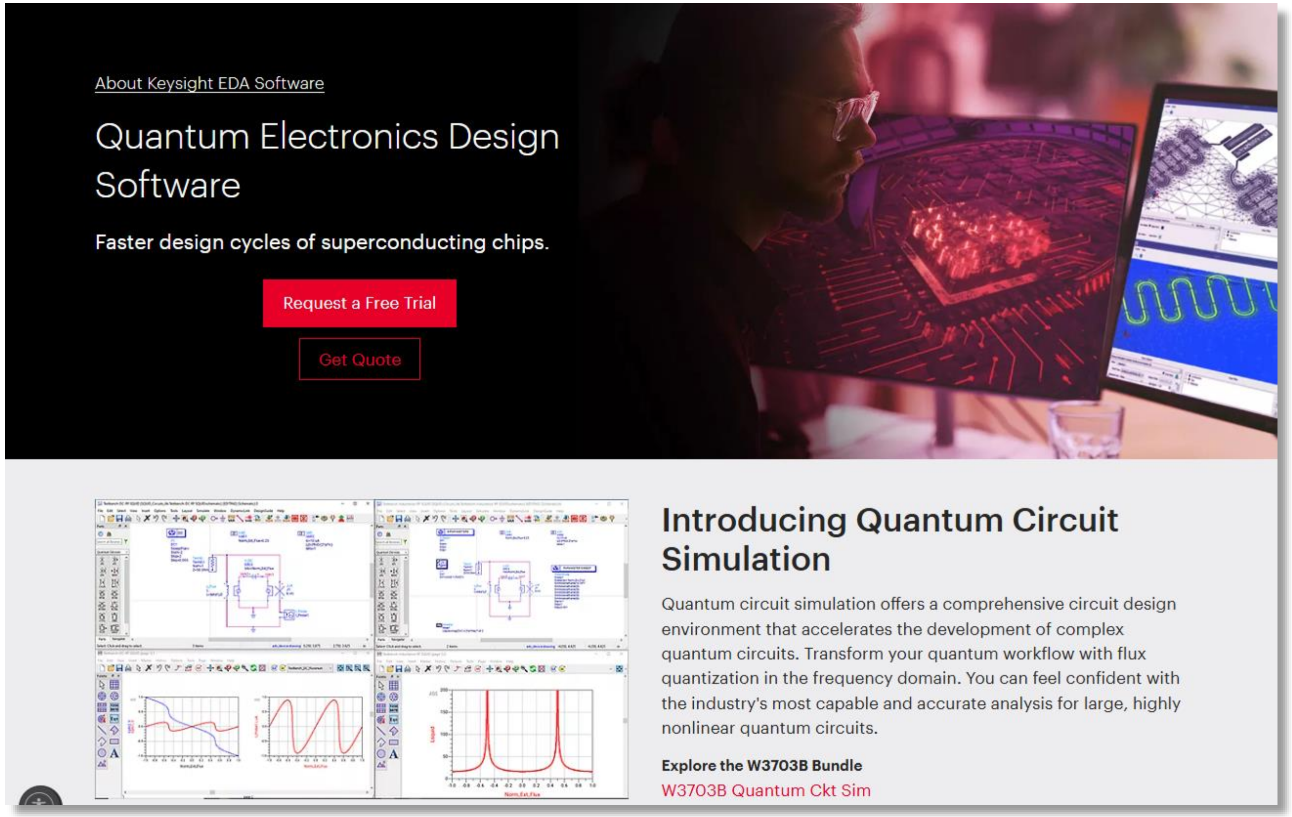
Quantum Circuit Simulation

Take the next step with Keysight Quantum EDA Solutions

- For more information or to request a free trial of Keysight Quantum EDA solutions, visit

  https://www.keysight.com/find/quantum-eda

- Early access is available for specific existing customers



Google “Quantum EDA” and our web page floats to the top!

Thank you