Exploring **FreeFEM** for Superconducting Qubit Chip Modeling

FreeFEM Days

December 18, 2025

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A bit of context

ALICE & BOB

- Quantum computer manufacturer
- Superconducting technology
- Cat qubits
- Focused on FTQC

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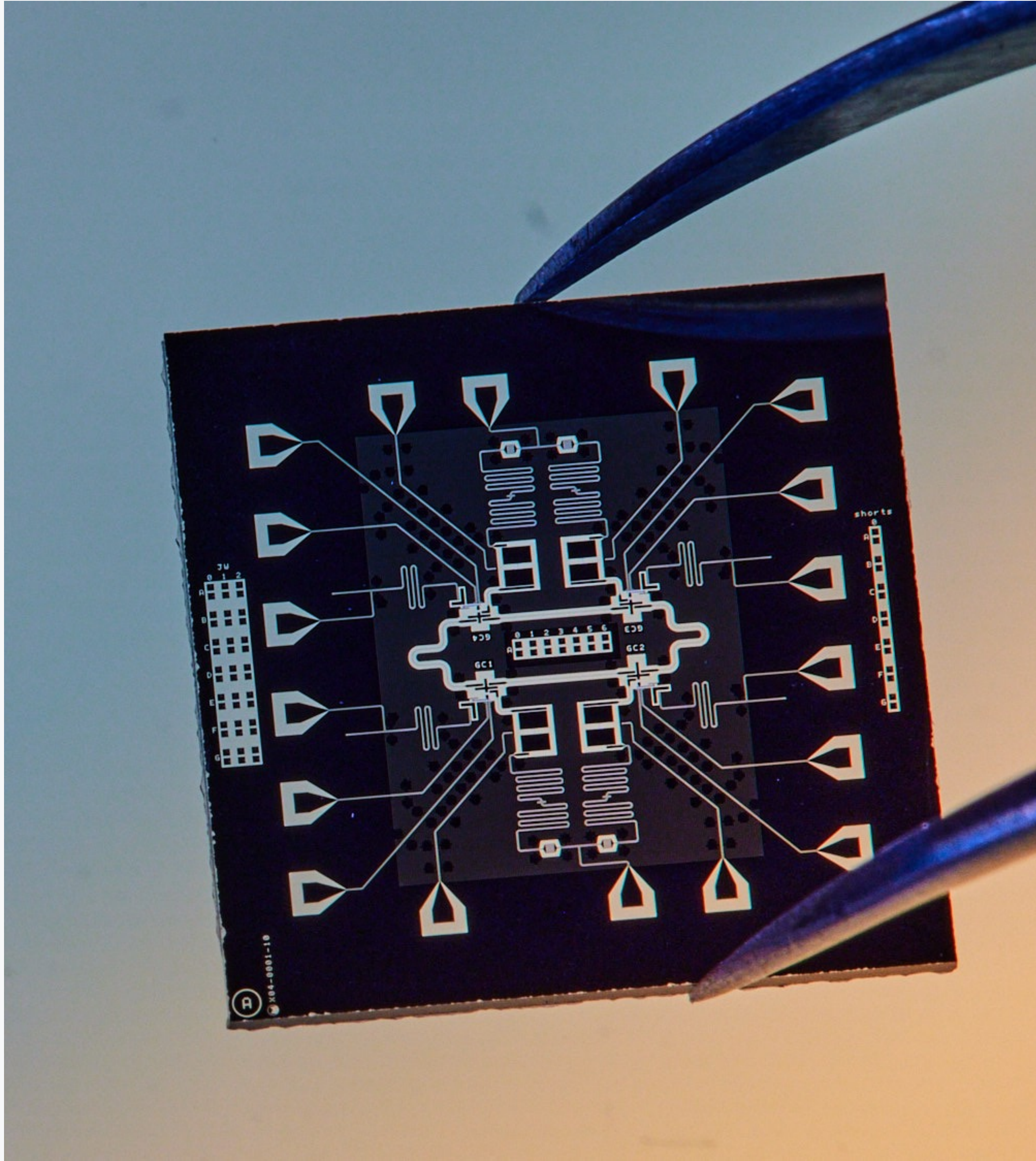
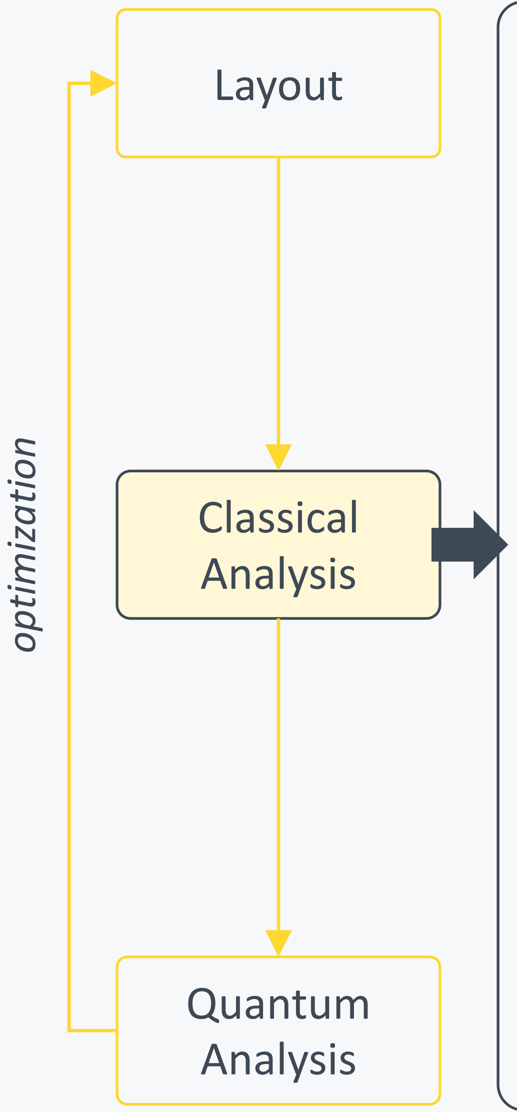
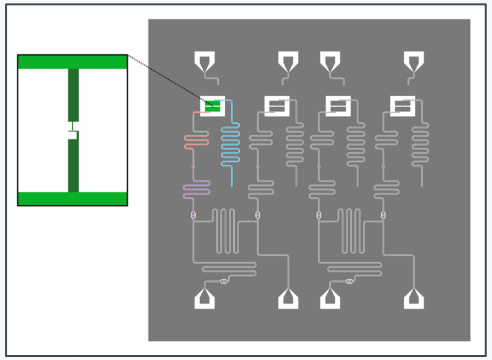
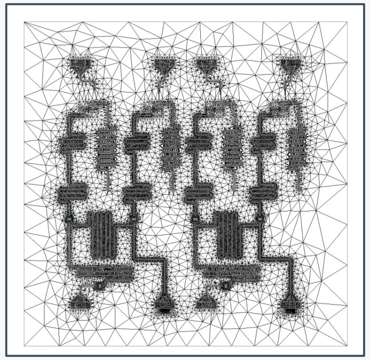


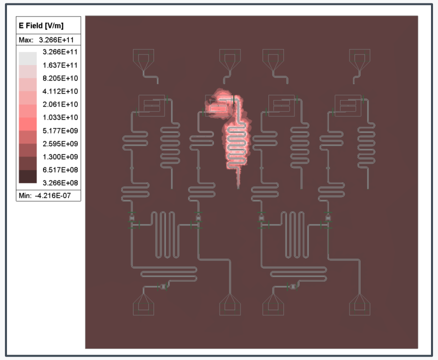
The Chip Design Process Involves EM Simulations

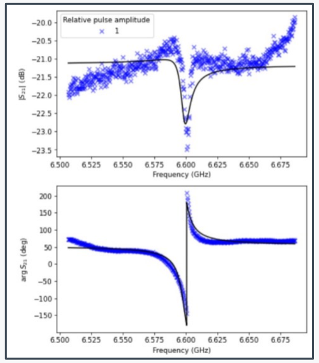


Ansys / HFSS









- **Eigenmode simulation** → resonance frequencies, field distribution, participation ratios, etc.
- **Driven simulation** → scattering parameters, coupling strengths, cross-talks, etc.
- **HFSS limitations**:
  - Prohibitive licensing costs preventing large-scale, massively parallel full-chip simulations and systematic cross-talk analysis
  - Incomplete superconducting material modeling (*e.g.*, London equation)

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FreeFEM Training & Support

- **3-days theoretical + hands-on training program:**
  - FreeFEM fundamentals
  - Variational formulations and FEM for PDEs
  - Meshing, mesh adaptation
  - Direct/iterative solvers, PETSc interface, DDM
  - Visualization
  - Application-driven case studies

- **Follow-up training focused on domain-specific problems:**
  1 hour/week over two months.

- **FreeFEM Team:**
  - Frédéric Hecht, Sorbone Univ.
  - Frédéric Nataf, CNRS
  - Pierre Jolivet, CNRS
  - Pierre-Henri Tournier, CNRS
  - Emile Parolin, Inria

Inria Academy

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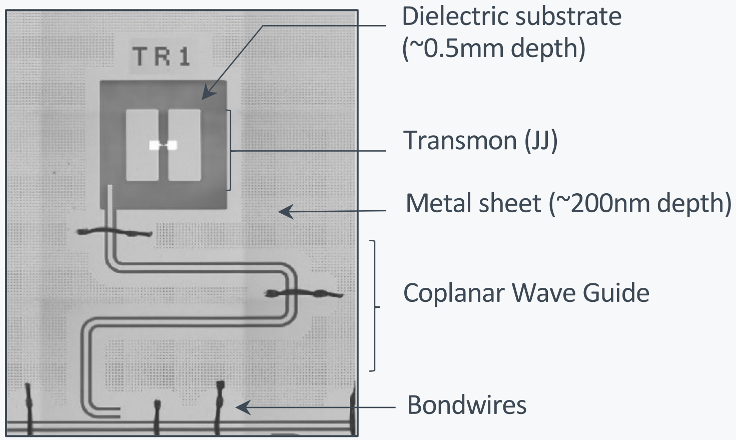
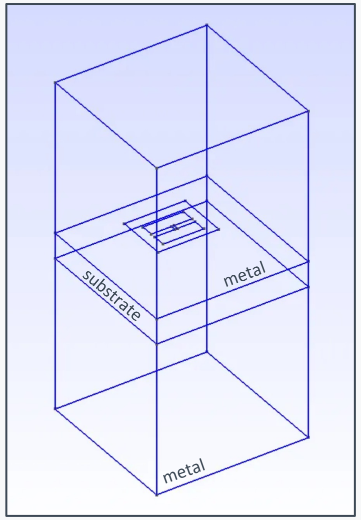
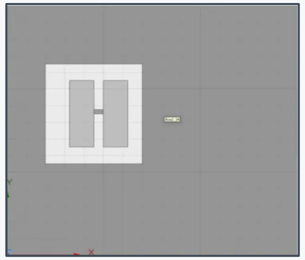
What we did

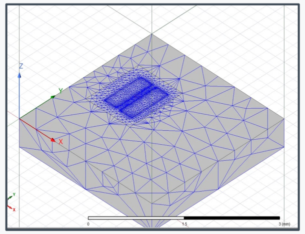
Problems of Interest

Simplified Test-Case









Driven Problem – Solved for $\boldsymbol{E}$

$$
\begin{cases}
\nabla \times \left(\mu_r^{-1} \nabla \times \boldsymbol{E}\right) - k_0^2 \, \varepsilon_r \, \boldsymbol{E} = 0 & \text{in the computational domain } \Omega \\
\boldsymbol{n} \times \boldsymbol{E} = 0 & \text{on PEC sheet} \\
\left[\left[\mu_r^{-1} (\nabla \times \boldsymbol{E}) \times \boldsymbol{n}\right]\right]_{\Gamma_j^p} = i\omega\mu_0 \left(\boldsymbol{J}_{0,j} + \sigma_{s,j} \boldsymbol{E}_T\right) & \text{on ports}
\end{cases}
$$

Eigenmode Problem – Solved for $(k_0, \boldsymbol{E})$

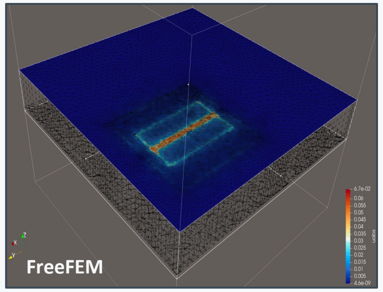
$$
\begin{cases}
\nabla \times \left(\mu_r^{-1} \nabla \times \boldsymbol{E}\right) - k_0^2 \, \varepsilon_r \, \boldsymbol{E} + i \, k_0 \, \zeta \, \boldsymbol{E} = \boldsymbol{0} & \text{in the computational domain } \Omega \\
\boldsymbol{n} \times \boldsymbol{E} = 0 & \text{on PEC sheet and ports}
\end{cases}
$$

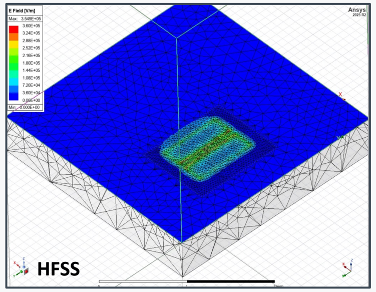
→ **Generalized nonlinear eigenvalue problem.**

Summary of Results

Driven Simulations

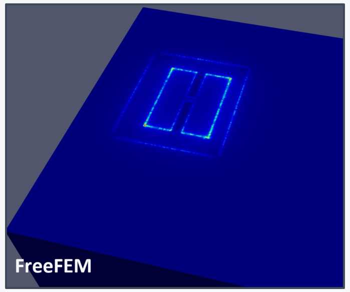
- Good agreement between HFSS & FreeFEM on field distribution and S-parameters (Δ =1e-6 on the same mesh), for both the single and 2-ports problems.

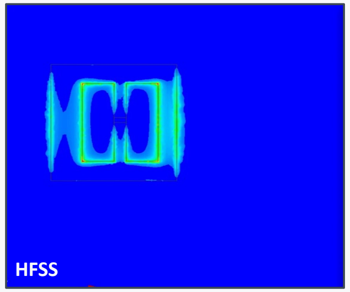




Eigenmode Simulations

- Good agreement between HFSS & FreeFEM for a simplified lossless cavity (generalized but linear eigenvalue problem).
- Ongoing work to correctly implement the nonlinear problem.

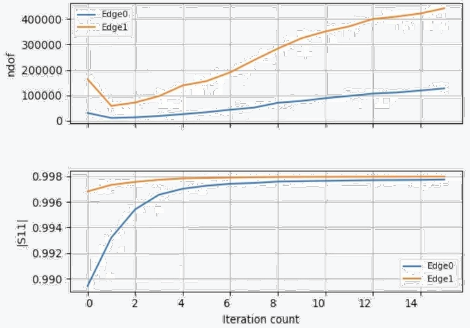


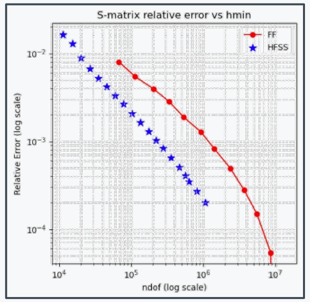


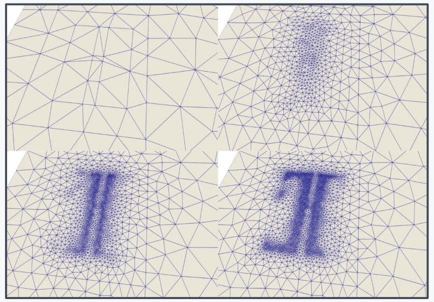
Tested Numerical Methods

- Discretization and solvers:
  - 0th & 1st order H-curl Nédélec elements (3D)
  - Direct sparse solvers (LU / Multifrontal)
  - Krylov subspace methods (GMRES/FGMRES)
  - Domain Decomposition Methods (ASM)
  - EigenValue, EPSSolve, Kikuchi mixed formulation
- Post-processing
  - Computation of S-param from port integrals
  - Export of fields & eigenmodes to VTK/Paraview

- Automated mesh adaptation :
  - Metric-based using *mshmet+mmg3D* (loop: *solve* → *estimate* → *adapt*)
  - Heuristic-based (edge mesh guided by a 1D heat equation)







Takeaways

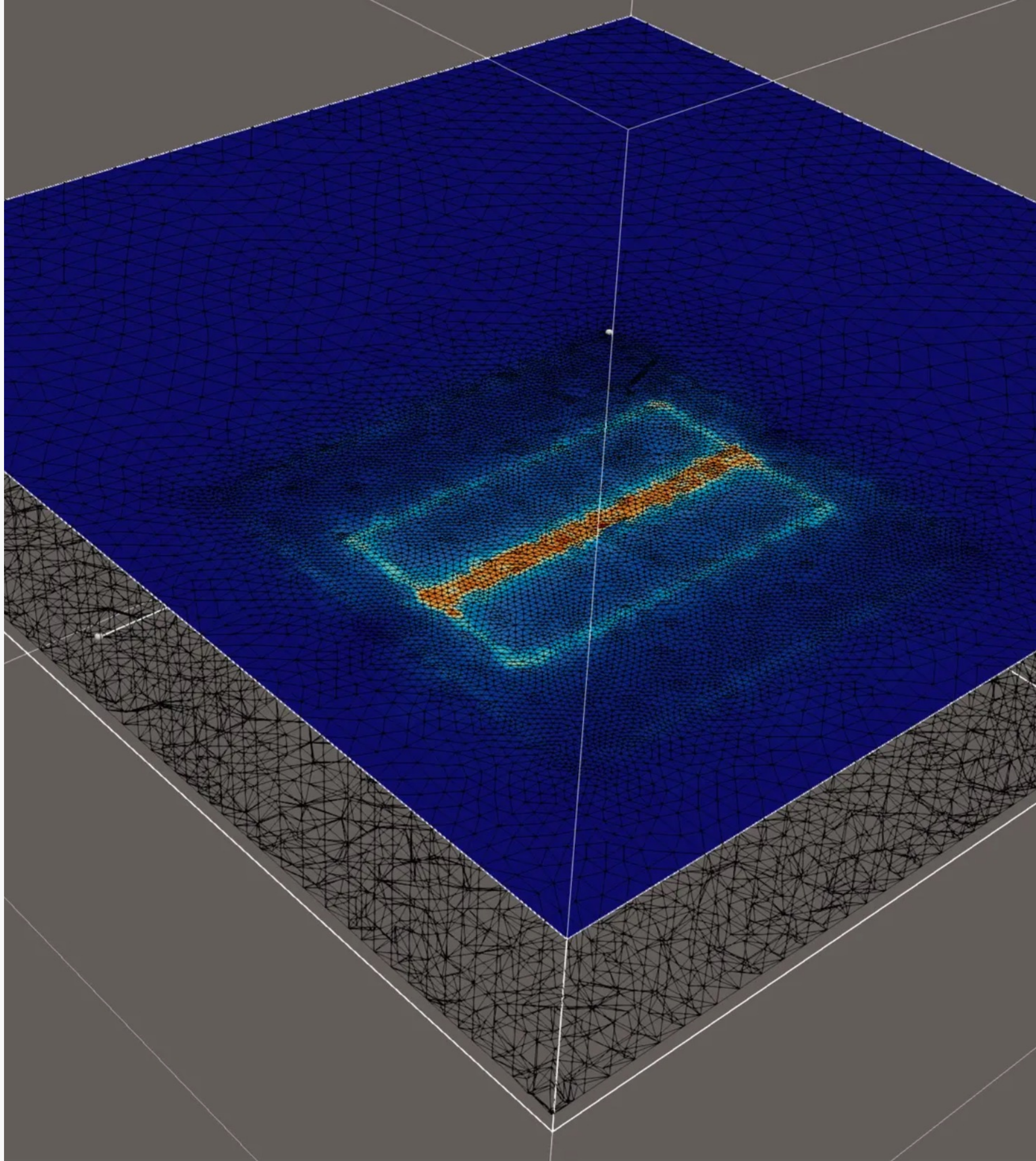
Outcome & Future work

- **First exploratory assessment with limited scope, not a thorough quality/performance benchmarking.**

- **Strengths observed:**
  - Validated against HFSS results for the considered test-cases
  - Highly flexible, broad numerical method support with strong PETSc ecosystem integration
  - Active expert community and extensive example base

- **Main challenges:**
  - Steep learning curve (variational formulations, solver choices, etc.)
  - No turnkey solution for generalized linear & nonlinear EVP

- **Next steps:**
  - Nonlinear EVP with lossy JJ inductance sheets
  - Bondwires handling
  - Performance and scalability for large-scale simulations
  - Anisotropic material properties
  - Participation ratio computation



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THANK YOU.