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Fast, highly accurate, full-FEM Surface Acoustic Wave (SAW) simulation

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OVERVIEW

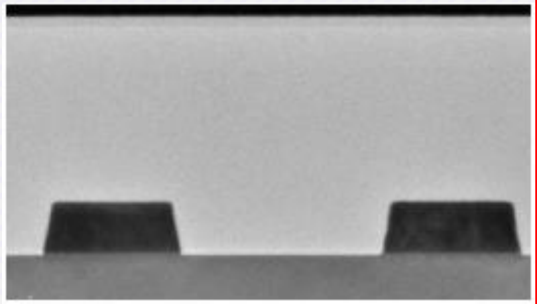
- Introduction
- Quick Review of Hierarchical Cascading FEM background
- Examples
- The Problem At Scale
- Introducing The Web Platform
- Examples
- Summary
- References and Acknowledgements

Introduction

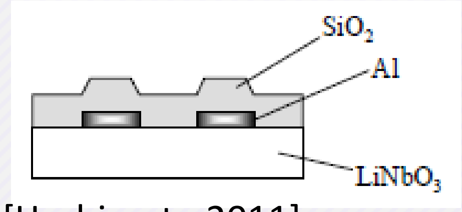
- Highly accurate and fast simulations tools are needed for high performance SAW filter design
- Higher accuracy required by:
  - More complex applications with stringent performance requirements
  - More complex thin-film processes and devices (TCSAW, IHP)
- Can't rely only on approximate solutions as provided by COM/P-matrix based approaches for every stage of design

Sources of images in [brackets].

TCSAW

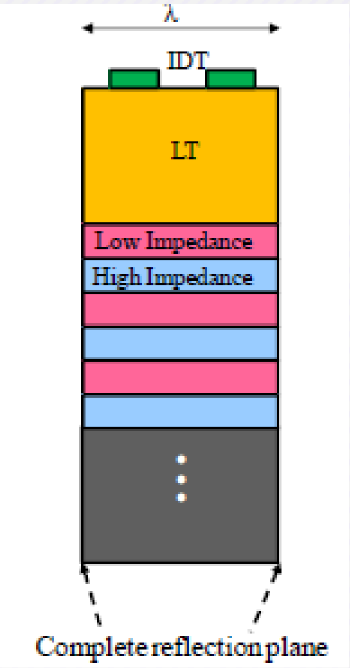


[Abbott Chiba 2015]



[Hashimoto 2011]

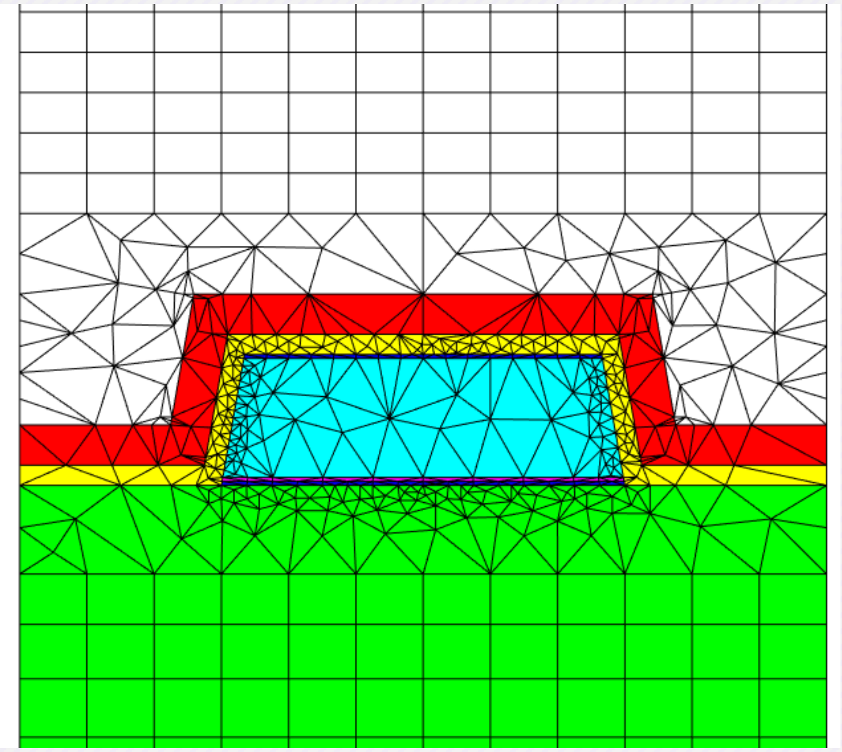
IHP



[Takai IUS2016]

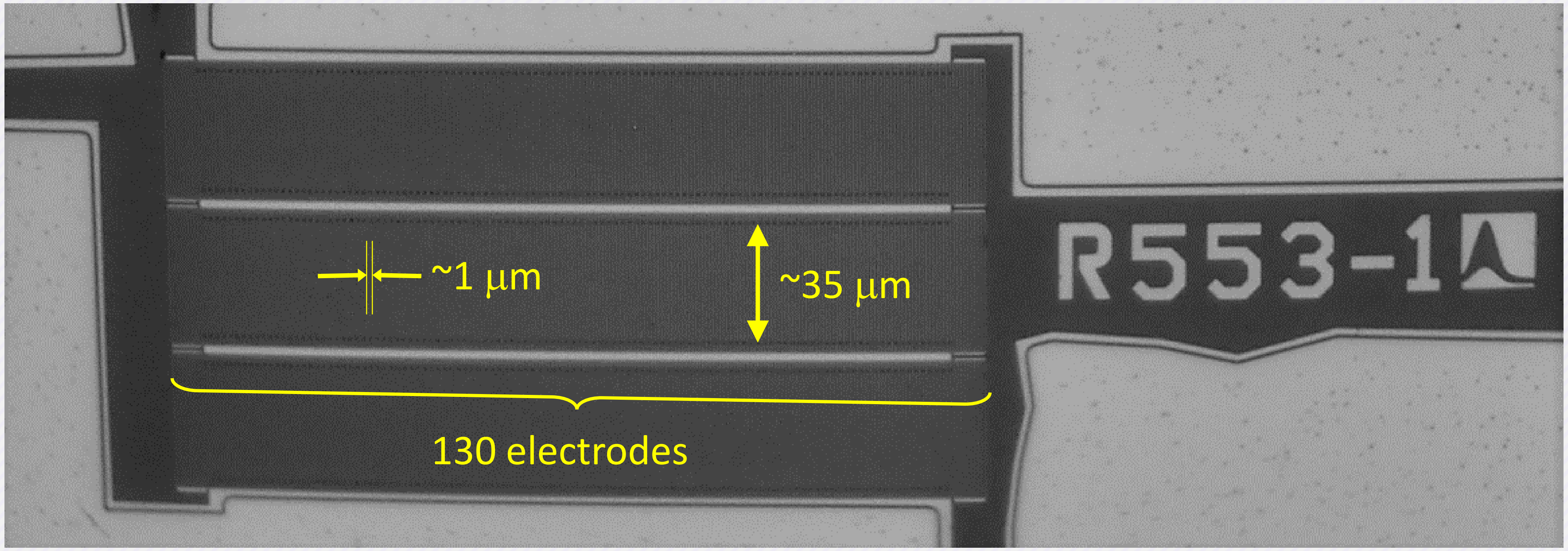
FEM + SAW ?

- Finite-Element Method (FEM) is astonishingly versatile.
  - arbitrary materials and crystal cuts
  - complex electrode shapes
  - multilayered structures with several dielectrics or metals
  - well established numerically, available commercially
- Historically, two major obstacles
  - The difficulty with open boundary conditions
  - High accuracy = many degrees-of-freedom (DOF)
    - Large RAM requirement, long computation times
- Today, these are largely solved for 2D simulation, by perfectly matched layers and hierarchical cascading.
- Augmented by the use of High Performance Computing (HPC) infrastructure in the cloud.



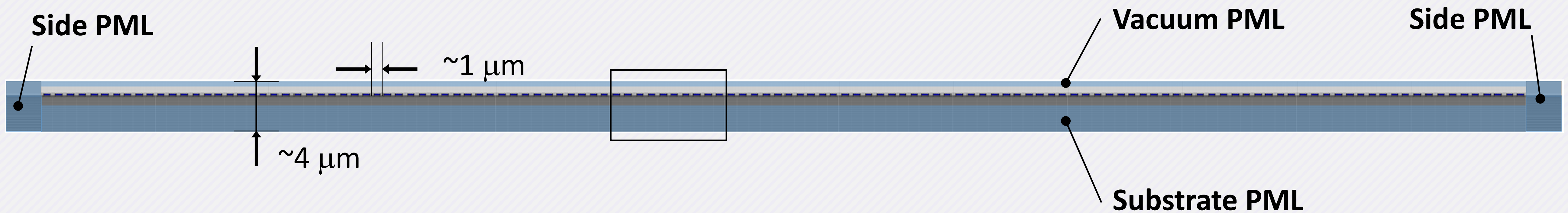
Example: LSAW Resonator

3x 2 GHz resonator on 42°YX-cut $LiTaO_3$ (from LTE B1/B3 quadplexer)



EXAMPLE: LSAW RESONATOR

2D FEM Mesh of the Full Device



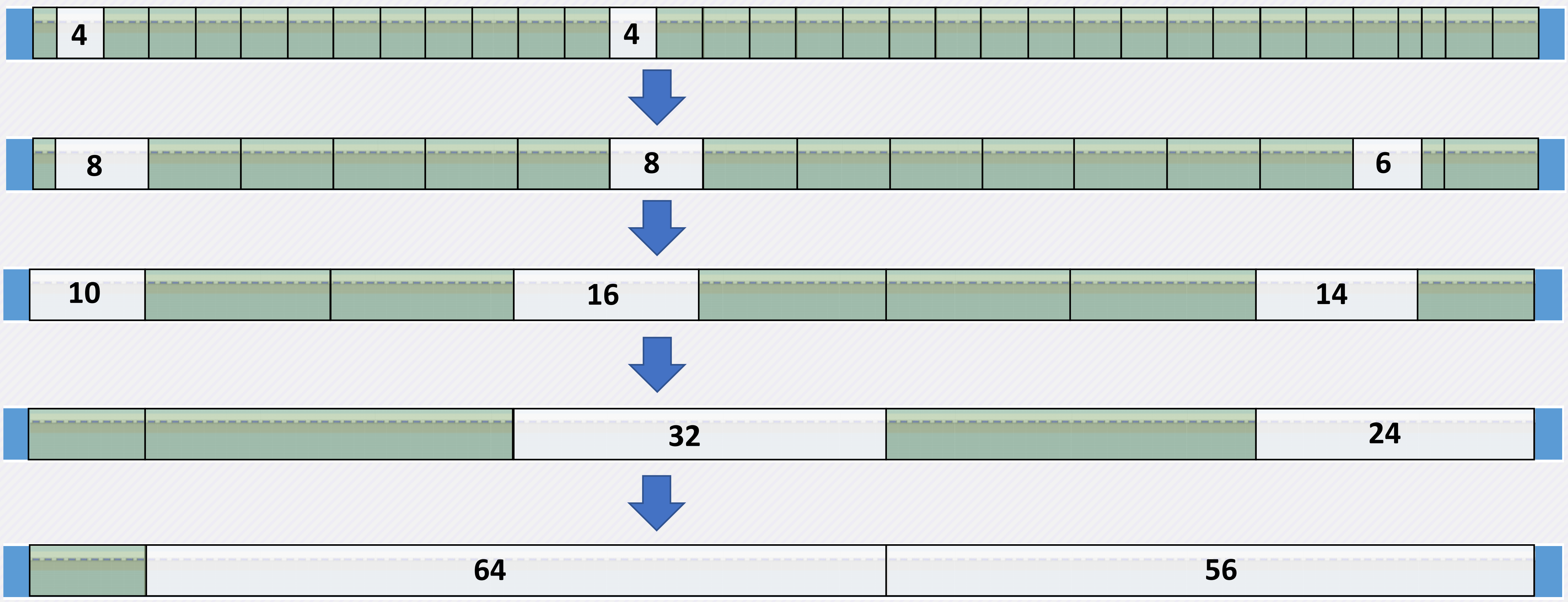
”General purpose FEM software”

Frequency domain analysis

Desired accuracy ~1 ppm: 20-40 nodes / wavelength

Total ~900 000 DOFs : not practical.

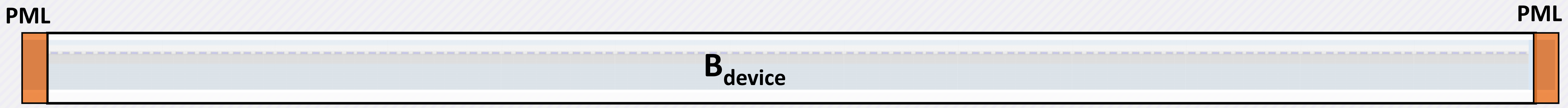
Example: LSAW Resonator



EXAMPLE: LSAW RESONATOR

- Entire device is modeled.
- Equivalent with full FEM simulation.
- Full solution can be recovered with inverse cascading.

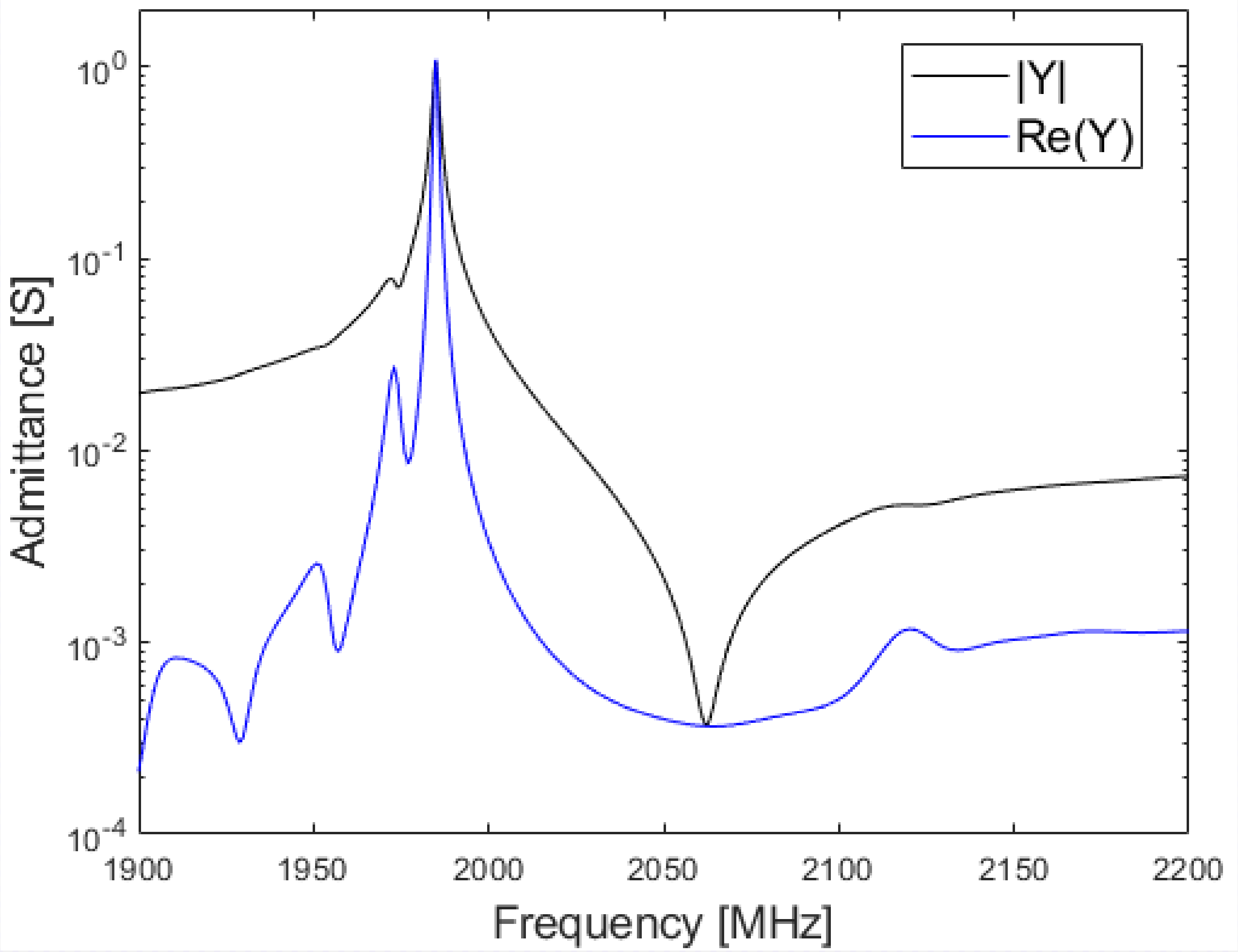
2D Full Device B-matrix Model



EXAMPLE: LSAW RESONATOR

42°YX-cut $LiTaO_3$, 8% Al electrodes
p = 1 µm, a/p = 0.48, Nt = 110, Ng = 10

- Matlab platform, 64-bit Windows
- CPU i7-2600k, 3.4 GHz, 32GB RAM
- Optimized unit block mesh
  - quadratic elements
  - 6462 internal DoFs/period
  - 208 DOFs per boundary
  - 907 140 DOFs in total
- Computation time 2.3 s / frequency
  - Easily reduced to ~< 1s on faster hardware



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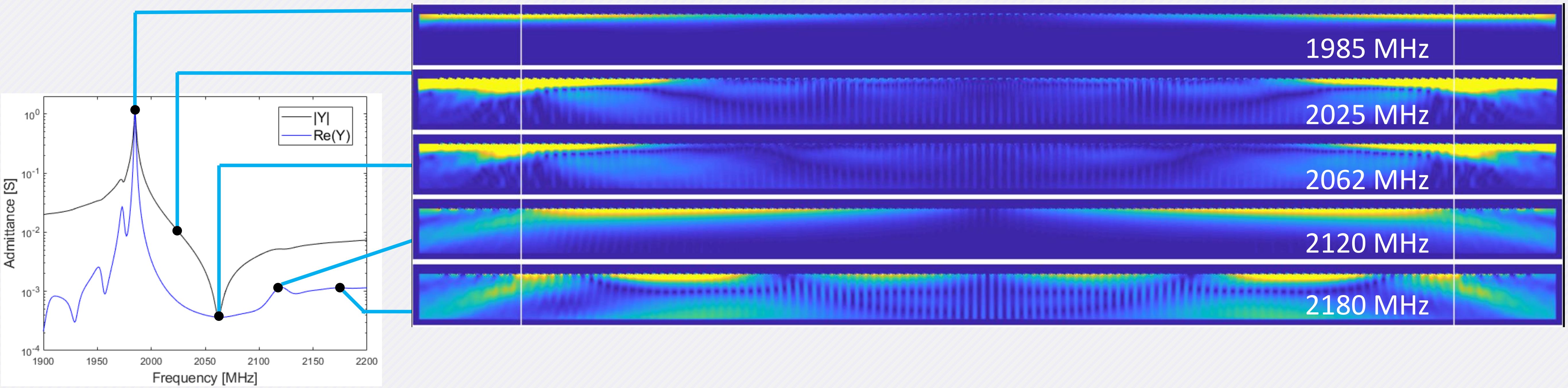
Synchronous Resonator

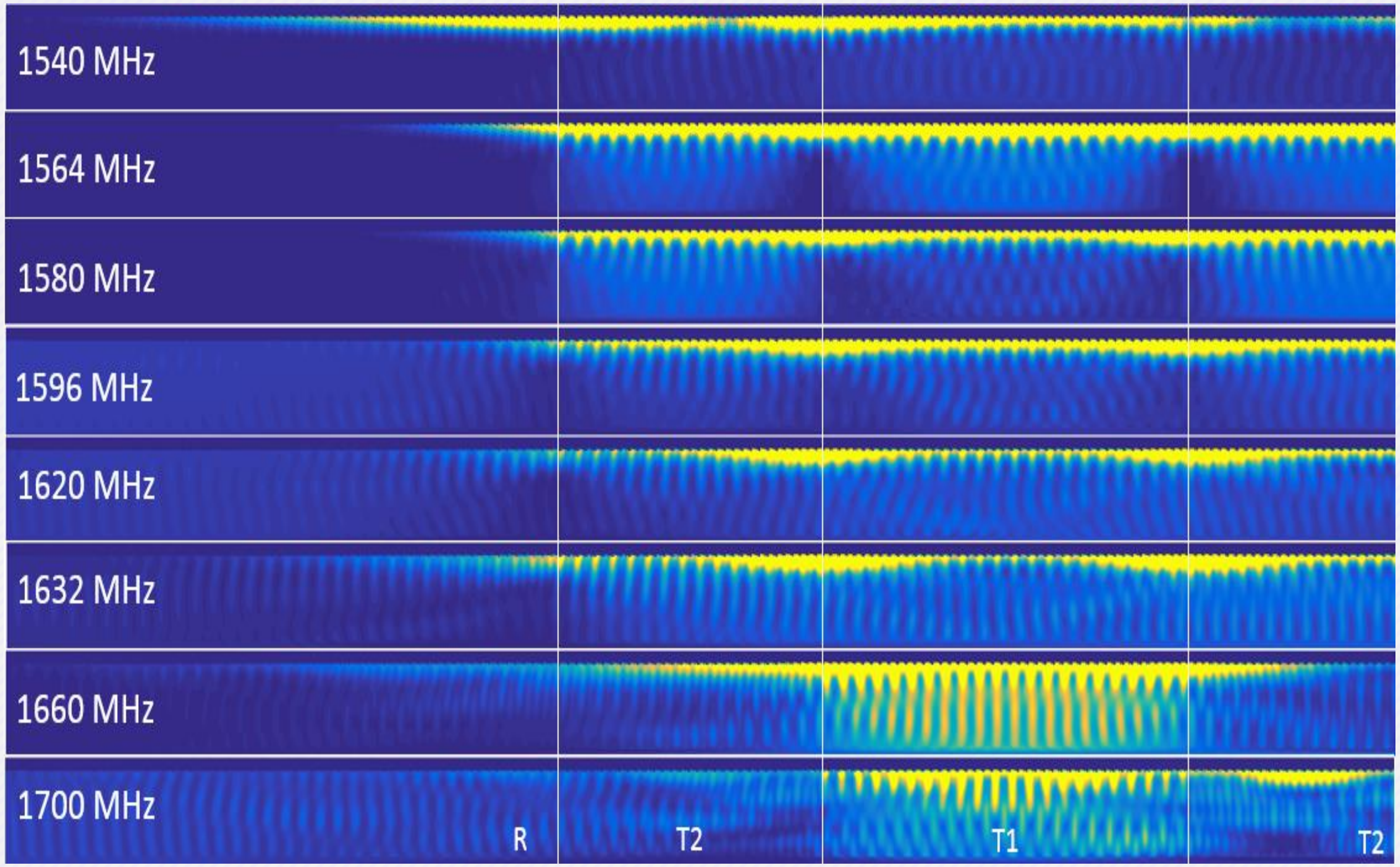
- J. Koskela IUS 2018

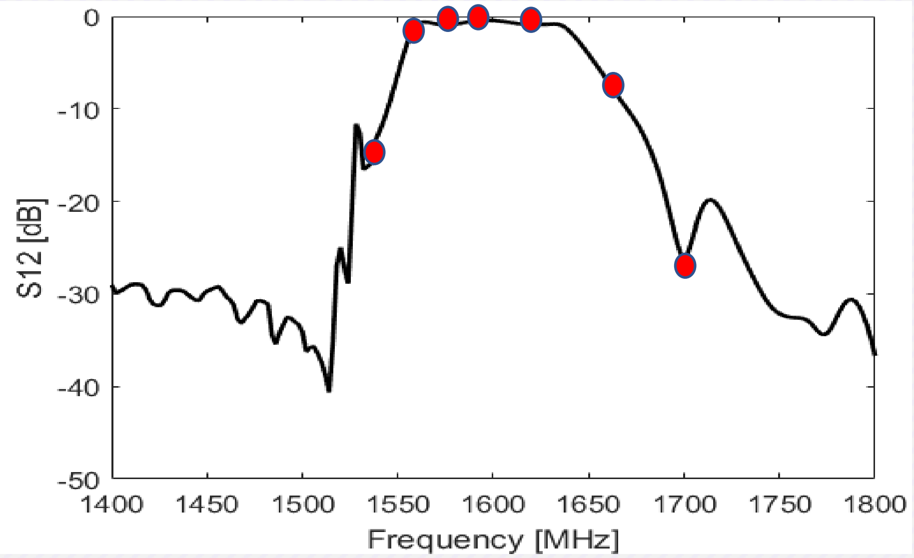
Absolute power flow $|\vec{P}|$ at various frequencies.



ACCUMULATED ENERGY, CRF5 ON LITHIUM TANTALATE

- V.P. Plessky [IUS 2017]





Energy density in the 5-IDT CRF at selected frequencies below, within, and above the stopband. Only one (left) half of the (symmetric) device is shown

HIERARCHICAL CASCADING ALGORITHM

Analysis phase

1. Search for periodic patterns *on all levels*.
2. Identify unique **unit blocks** and model them with FEM.
3. Present the device as a series of cascading operations.

Evaluation phase

1. FEM system matrix $\rightarrow$ B-matrix
2. Cascade B-matrices until the whole device is covered.
3. Terminate with side PMLs and solve for the excitations.
4. (*Optional*) Inverse cascading and postprocessing

Remarks

1. Efficiency depends on the extent of periodicity.
    - For IEs and CRFs, typically **drastic memory gains and speed-up**.
    - In synchronous resonators, complexity increases logarithmically with length.
    - Applicable also to **platelet** and **membrane** structures, and **BAW** devices.
2. The computational complexity is largely decoupled from the geometry fidelity of the computational mesh.
3. Batch analysis: many geometries with similar block structure can be simulated in same run, with very significant gains in computational complexity.

THE 3D CHALLENGE

Hierarchical cascading is highly efficient in 2D. How about 3D?

- It can be done.

IEEE IUS 2017

Full 3D simulation of SAW resonators using hierarchical cascading FEM

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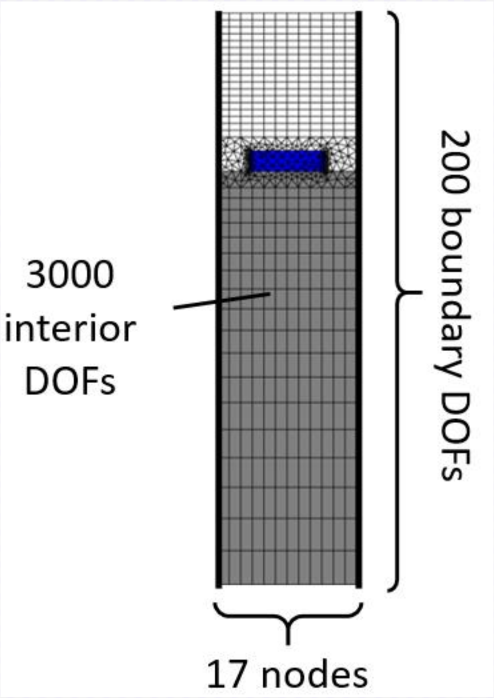
  - 42°YX-$LiTaO_3$, aperture 15λ, N_t= 200, N_g = 50
  - Transducer unit cell 39,242 nodes, reflector unit cell 19,196 nodes; 15M+ DOFs total
  - 10 min / frequency point using 40 processor cores

- Generally, 3D simulation remains very computation-intensive.

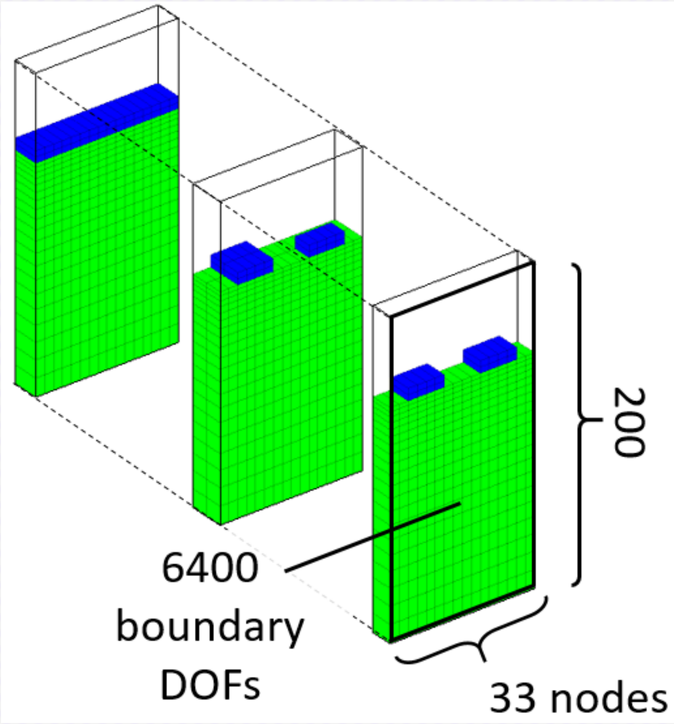
THE 3D CHALLENGE

- RAM usage and complexity and determined by number of boundary DOFs.
- Consider stress test scenarios with **high accuracy requirement**

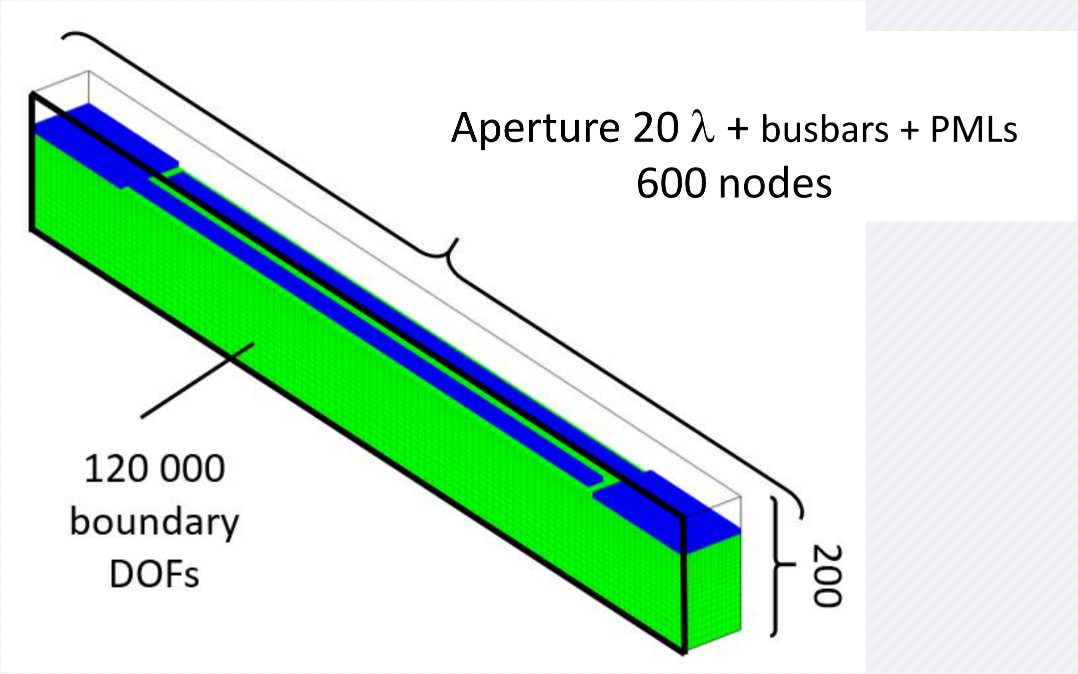
2D Finite Device



3D Periodic Array

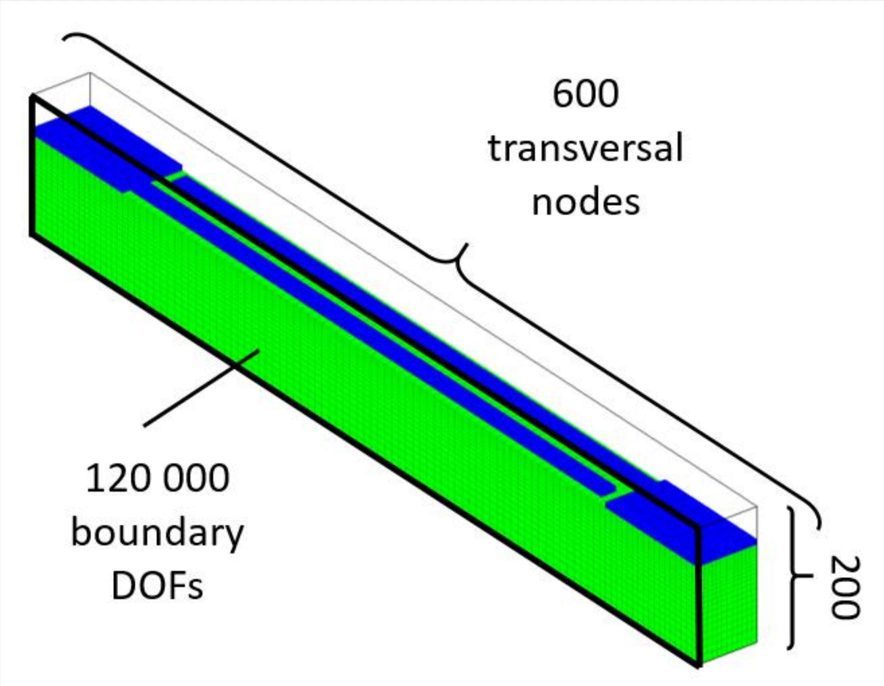


3D Finite Device



THE 3D CHALLENGE

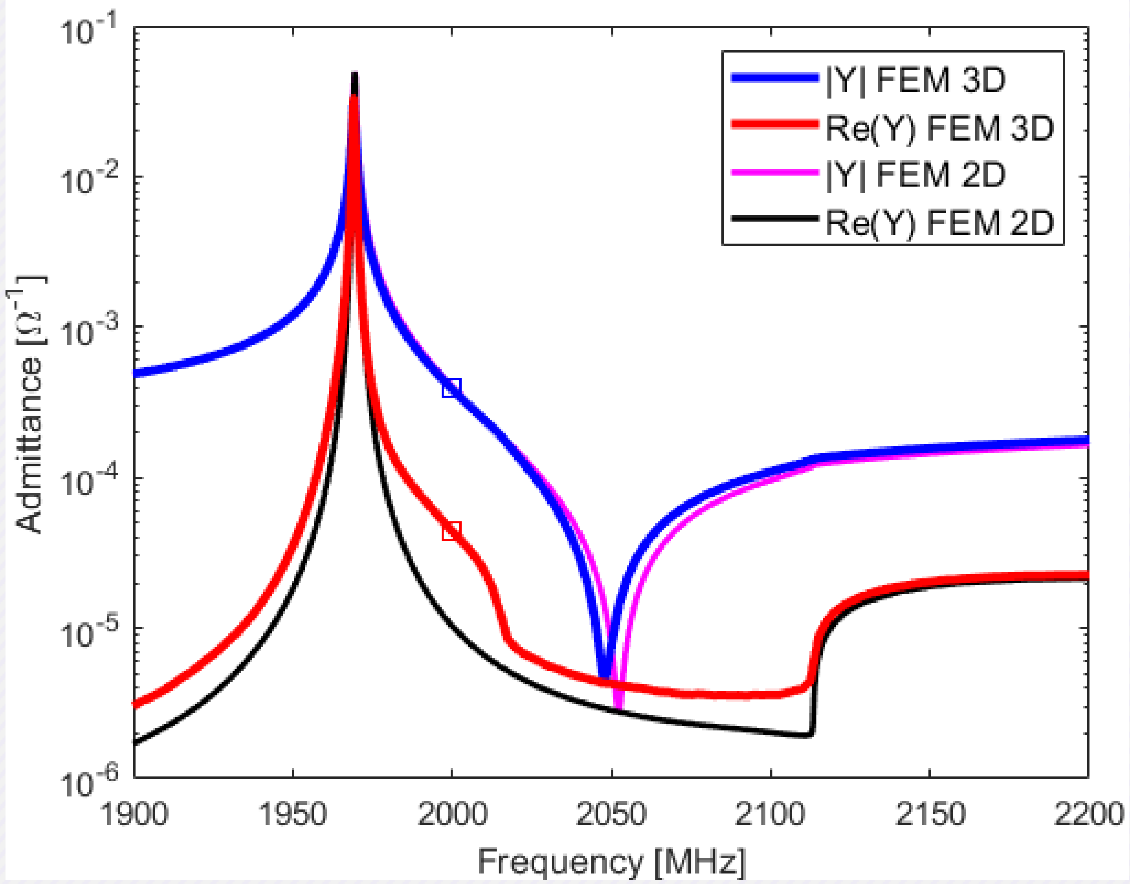
- 3D Stress test scenario with high accuracy requirement
  - N_{DOF}=120 000 **boundary DOFs**
  - **RAM** required to store a single B-matrix $m \sim (N_{\mathrm{DOF}})^2$ ~ 2 TB
  - **Complexity** of a cascading operation $\mathrm{O}\left((N_{\mathrm{DOF}})^3\right) \sim 3 \cdot 10^{11}$
  - Naïve scaling from 2D: cascading time ~25 days



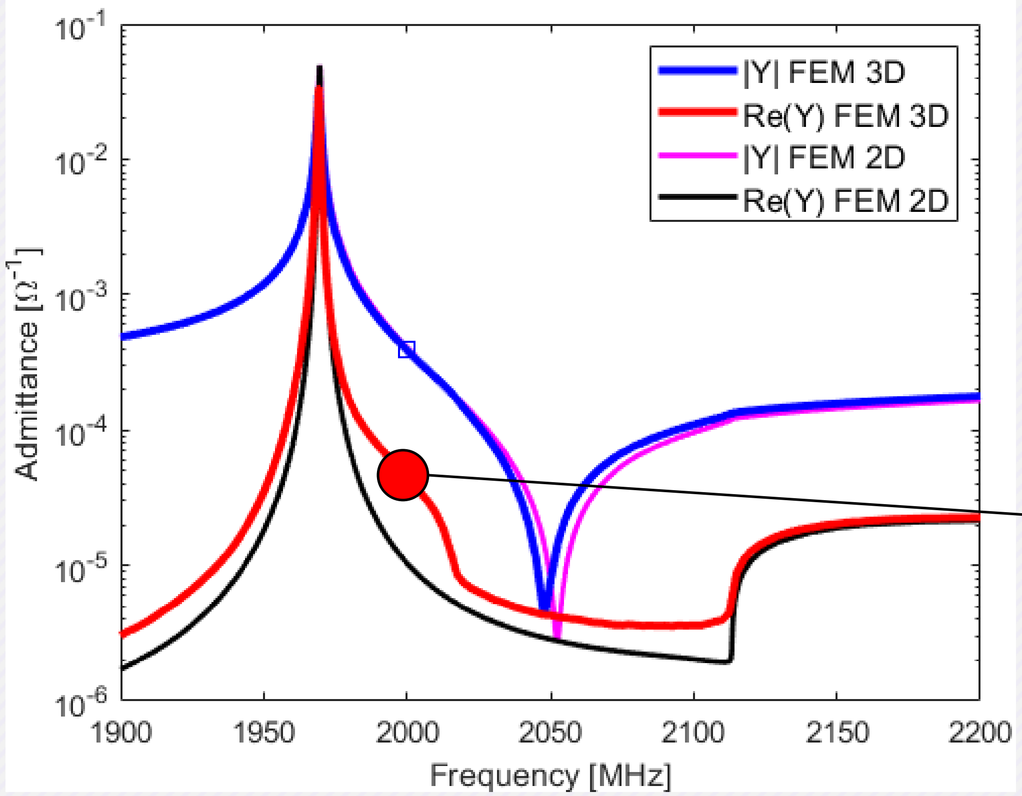
3D Periodic Array on 42°YX-cut LiTaO3

42°YX-cut $LiTaO_3$, 8% Al electrodes
p = 1 µm, a/p = 0.55, W = 40 µm
Gaps 0.5 µm, no dummy fingers

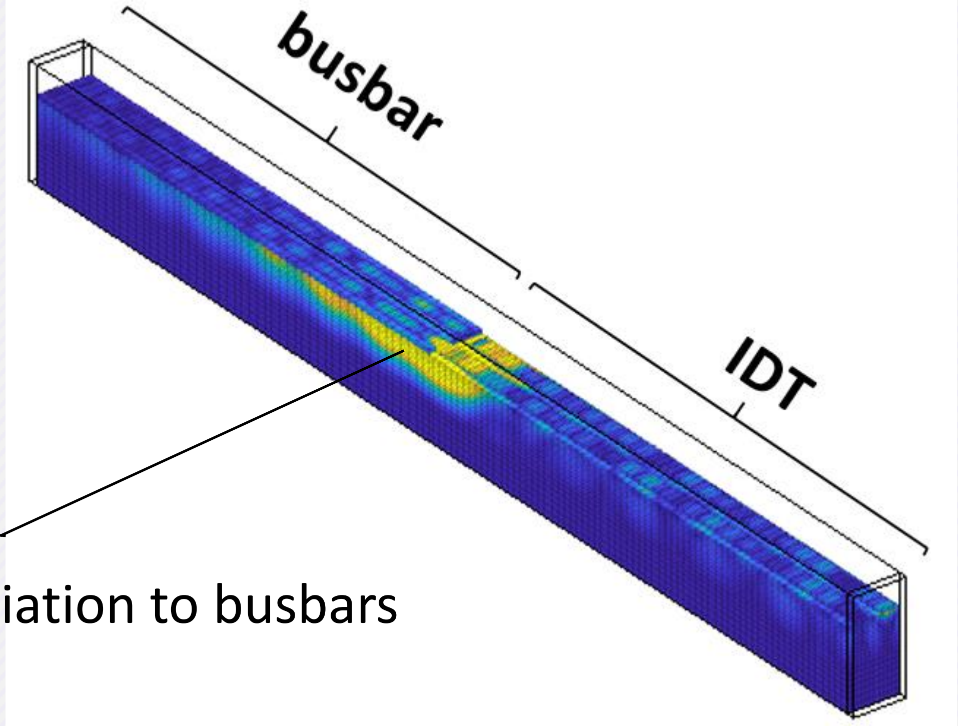
- 3.7M DOFs
- 50-100 iterations
- 10-30 min / frequency
- Reference simulation with direct cascading: 80 min / frequency



3D Periodic Array on 42°YX-cut LiTaO3



Absolute power flow $|\vec{P}|$

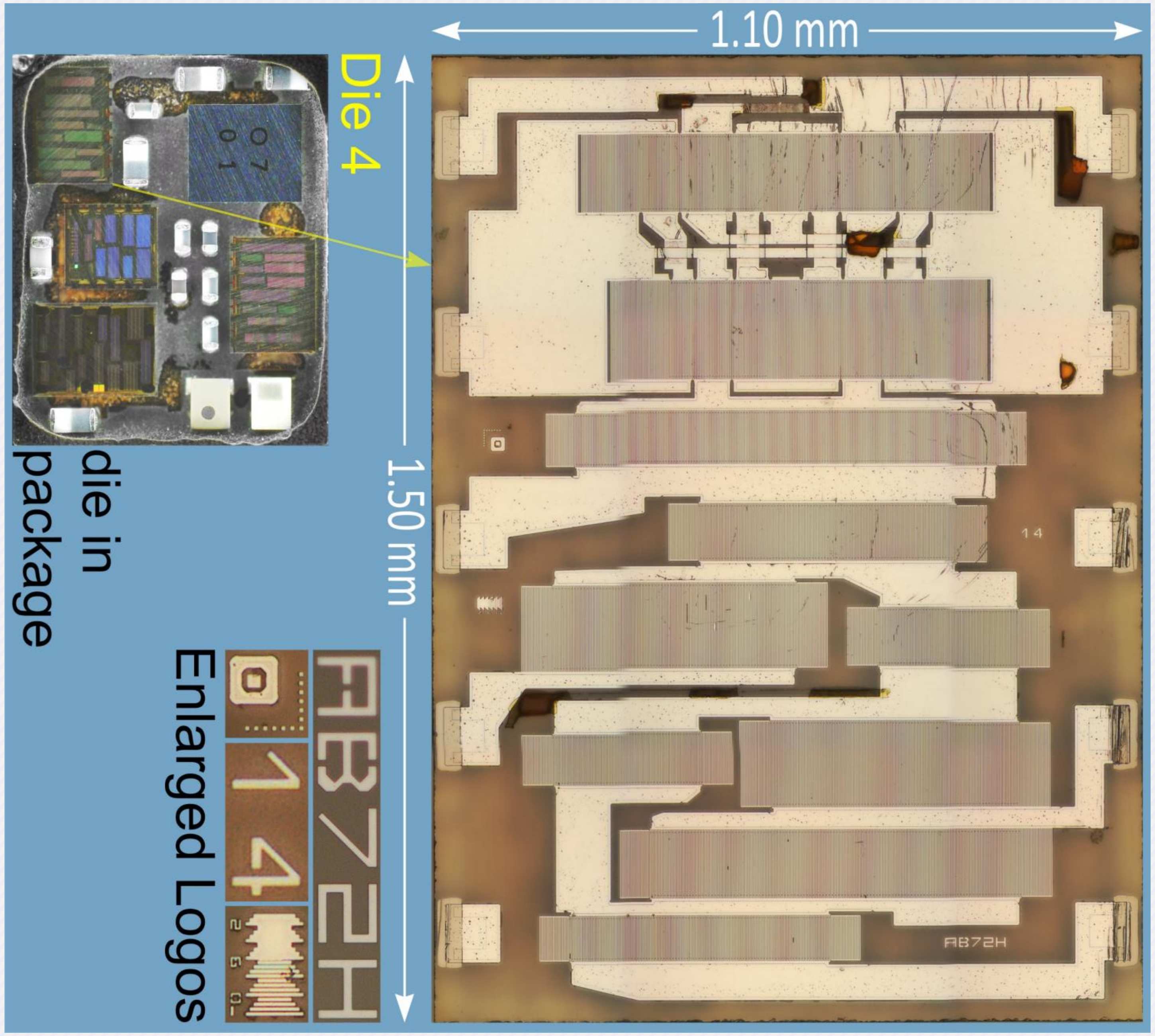


LSAW radiation to busbars

Hierarchical Cascading Method

- *Efficient* tool for 2D simulation of finite SAW and BAW devices.
  - the full power of conventional FEM
  - drastically reduced **memory usage**
  - improved **computational speed**
  - device analysis: power flow, stored energy, Q-factor
- *Accurate*: enables high fidelity computational meshes.
- PML / damping layer according to the **crystal anisotropy**!
- 3D simulation remains numerically demanding.
  - Modal approach, iterative cascading?

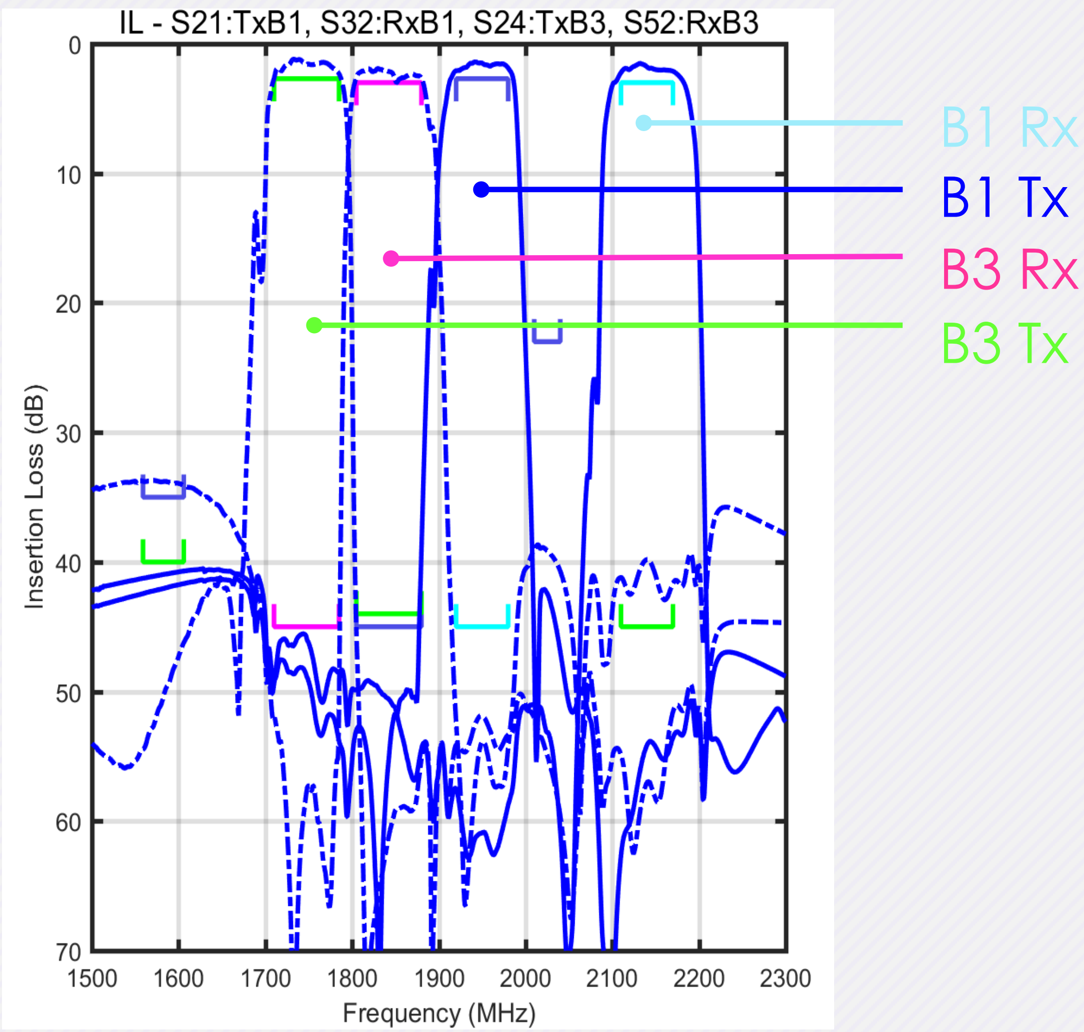
SAW Multiplexers – The Problem Of Scale

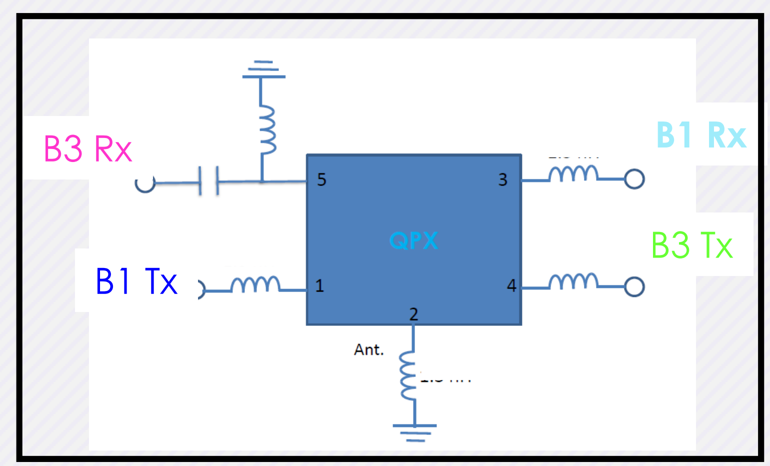


- High performance SAW multiplexers include many (dozens) of acoustic devices
- Optimization of the design is tightly coupled and highly constrained
  - Each iteration requires updates to many devices to compensate for changes in the other devices.
- These can generally be simulated in parallel to enable quick feedback to the designer

A Specific Example - Resonant 2520 QPX 1/3

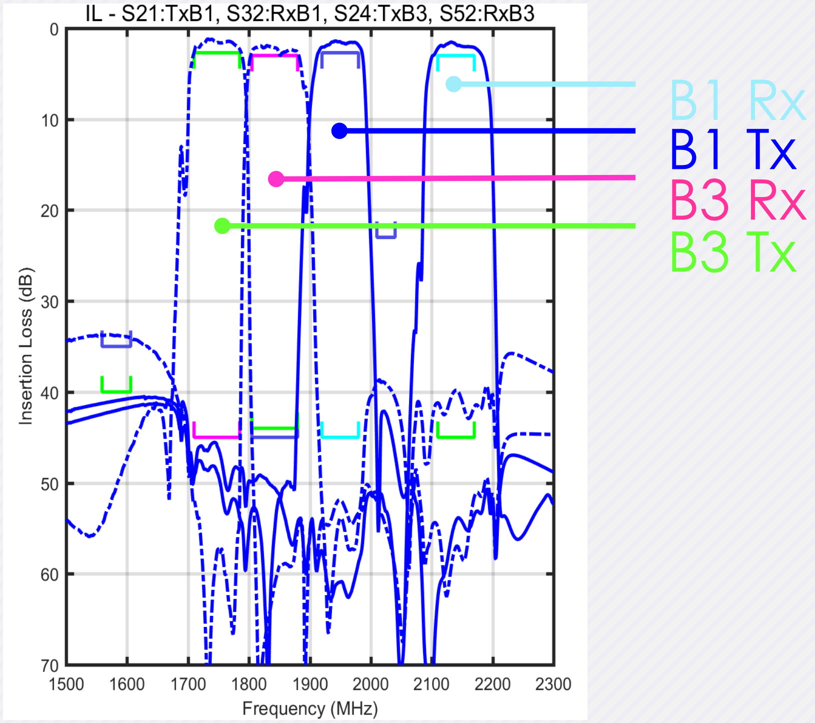
- Competitive IL in low-cost SAW
- Prefab model is accurate
- Designs at multiple foundries now





A SPECIFIC EXAMPLE - RESONANT 2520 QPX 1/3

- A typical recent quadplexer (QPX) design from Resonant contains 32 unique SAW resonators.
- Detailed simulation requires a wide, and high resolution frequency sweep, e.g. 700 MHz at 0.5 MHz increments (1401 frequency points)
- With a typical time per frequency point for a single device of 1 second a complete quadplexer simulation would require: 32x1401x1 second = 44,832 seconds = **12.45 hours** of simulation time.
- Clearly, this is impractical at all stages of design!
- However, with the right infrastructure and code structure in place, we can distribute this calculation over several computers in a High Performance Computing (HPC) cluster

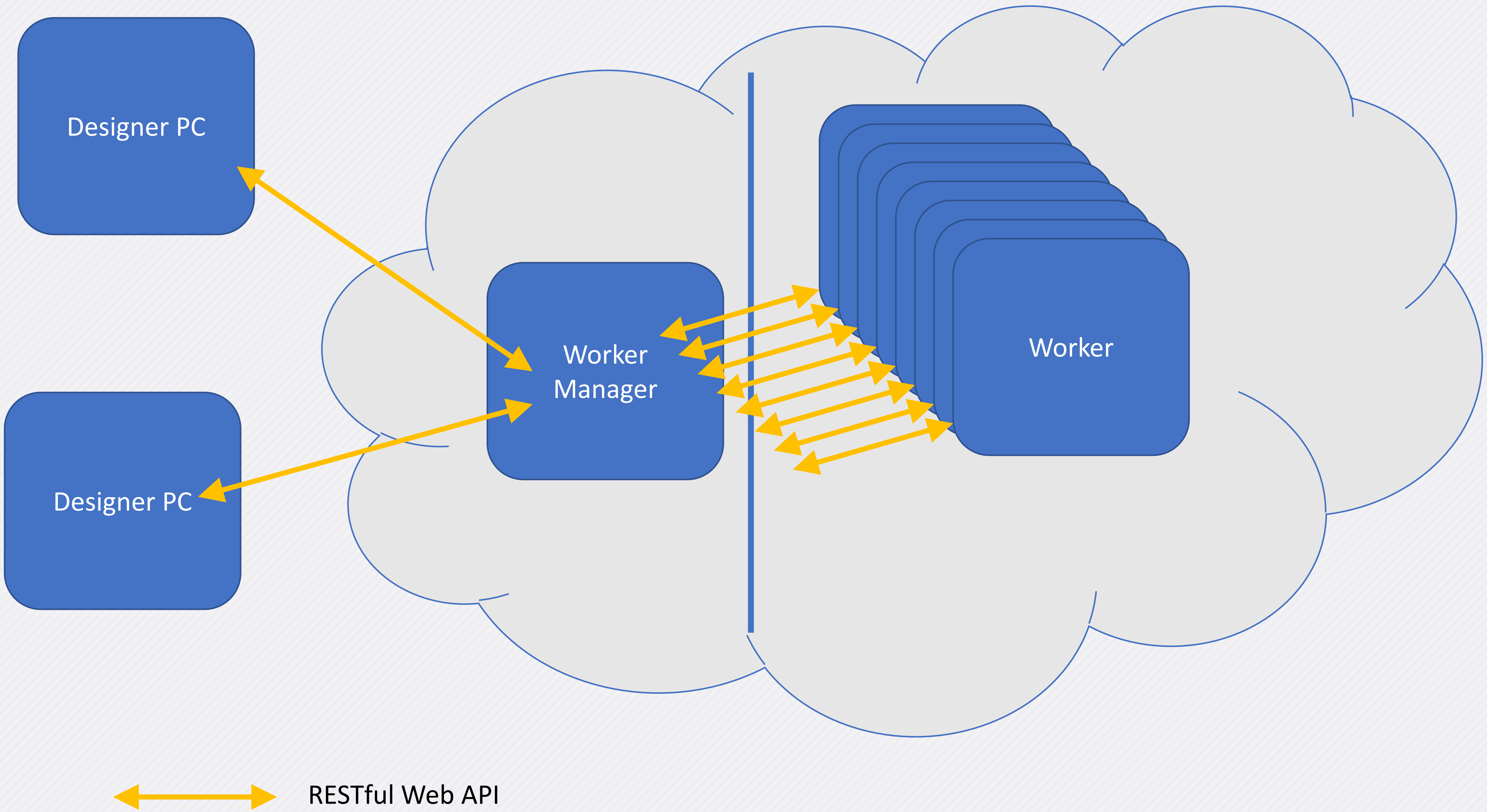


On premises vs. Cloud

- An on-premises cluster must be sized for peak throughput
  - You need to purchase and maintain enough machines to support the maximum throughput needed by your team of designers.
- Hardware is fixed, performance is determined at the time of purchase

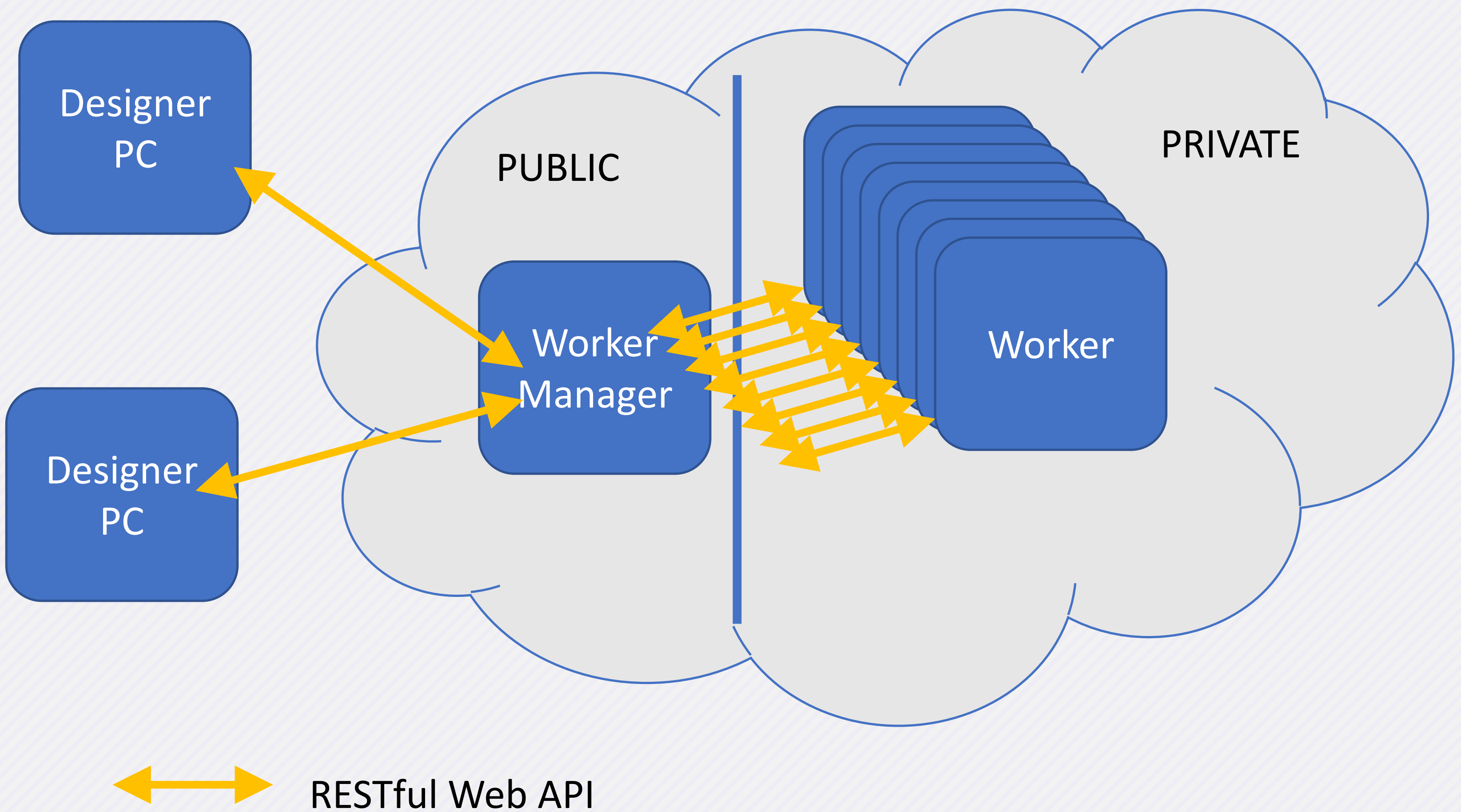
- Cloud throughput scales up to the number of workers that are available from the cloud provider
  - More flexible trade-off of cost / capacity/ performance / time to finished simulation
- Hardware is updated regularly by the cloud provider
  - Performance per worker increases as new technology is made available
  - Cost/performance be scaled appropriately for different problems
  - $0.10 - $40/hour depending on machine properties

Our Approach

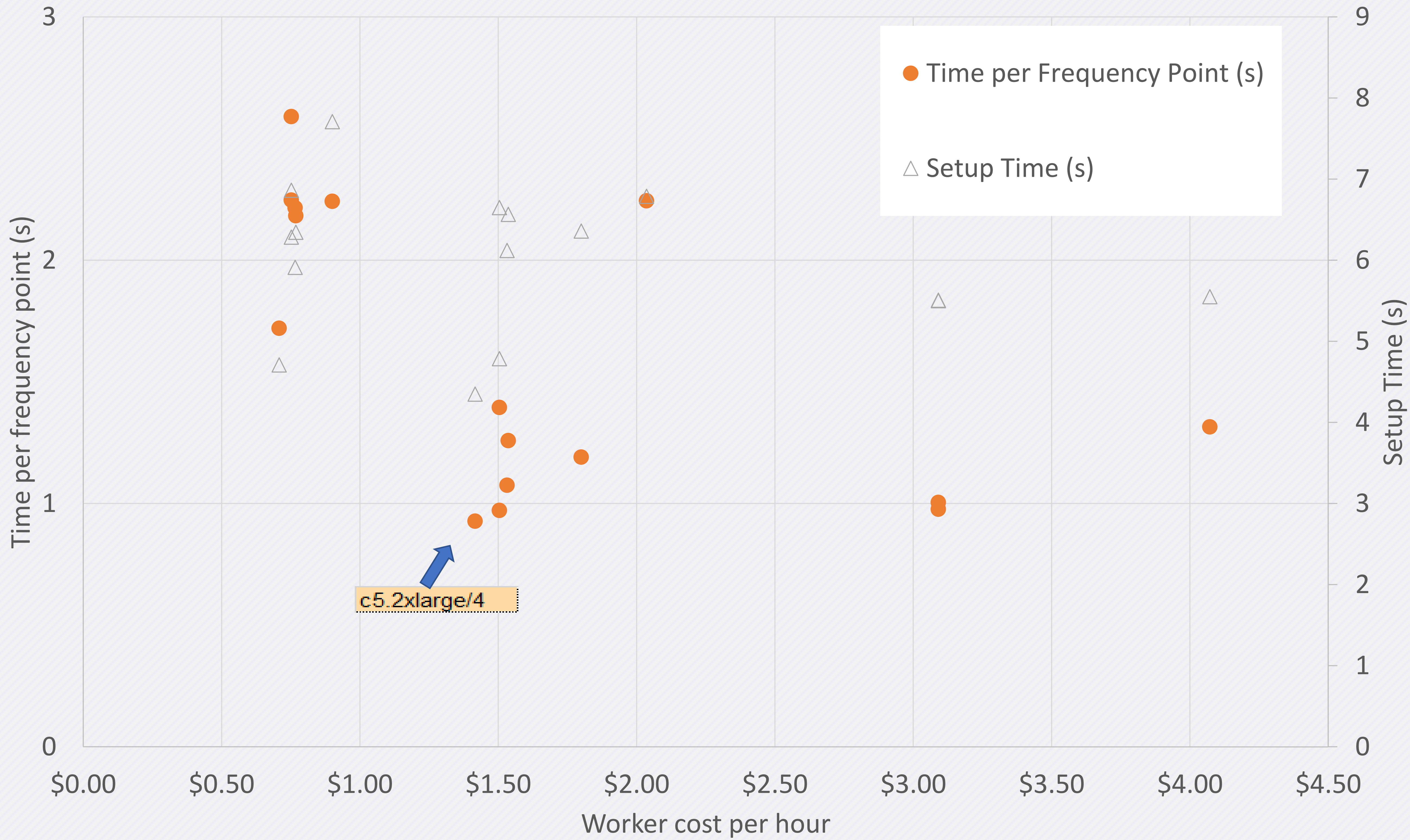


Our Approach II

- A designer can submit a job to the worker manager over the public web either through a web browser or, via web API (automation) directly from the design tool
- The worker manager decides if it already has workers available to handle the new requests. If not, it starts up the needed number of workers to support the request.
- The job is processed by the workers on the private cloud and results are returned to the worker manager



TRADEOFF EXAMPLE – COST VS. PERFORMANCE



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SUMMARY

- We have developed a series of full Finite Element Analysis (FEM) tools using a hierarchical cascading approach that allows us to make simulations very rapidly (< ~1 second per frequency point)
- These tools can be applied to a wide variety of devices and applications
- We have also developed a web based framework that allows us to leverage the power of cloud computing to provide low cost, scalable throughput for extensive calculations to be managed in parallel.
  - We have deployed other tools besides the FEM tool using the web based framework

Acknowledgements

- The work presented here was a team effort with key contributions from the following individuals at Resonant.
  - Julius Koskela
  - Victor Plessky
  - Patrick Turner
  - Bob Hammond
  - Neal Fenzi
  - Dejan Nenov
  - Nick Parker
  - Sotiria Lampoudi
  - Filip Iliev
  - Bryant Garcia
  - Sean McHugh
- And many more ,,,

Recent References

- “Hierarchical Cascading Algorithm for 2-D FEM Simulation of Finite SAW Devices” J. Koskela et al. IEEE Trans. UFFC Vol.65, p. 1933 (2018)
- “Leaky SAW devices with Beryllium electrodes” V. Plessky, et al. IUS 2018.
- “FEM Modeling of an Entire 5-IDT CRF/DMS Filter” V. Plessky et al. IUS 2017
- “Acoustic Radiation from Ends of IDT in Synchronous Resonators” V. Plessky et al. IUS 2017
- “Rapid 2D FEM Simulation of Advanced SAW Devices” J. Koskela et al., IMS 2017


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