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Free-Shape Optimization of VHF Air-Core Inductors using a Constraint-Aware Genetic Algorithm

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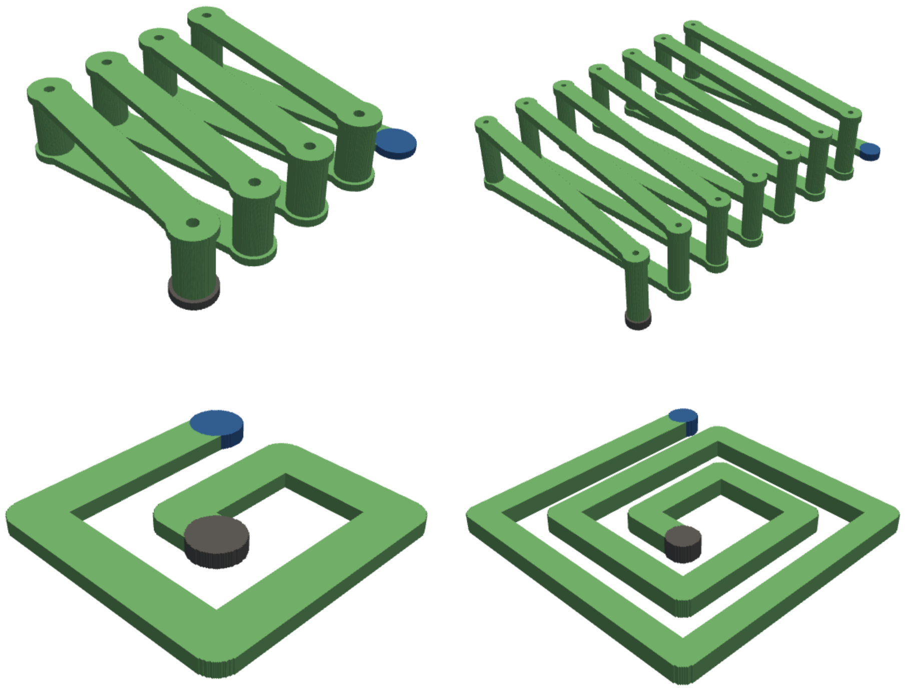
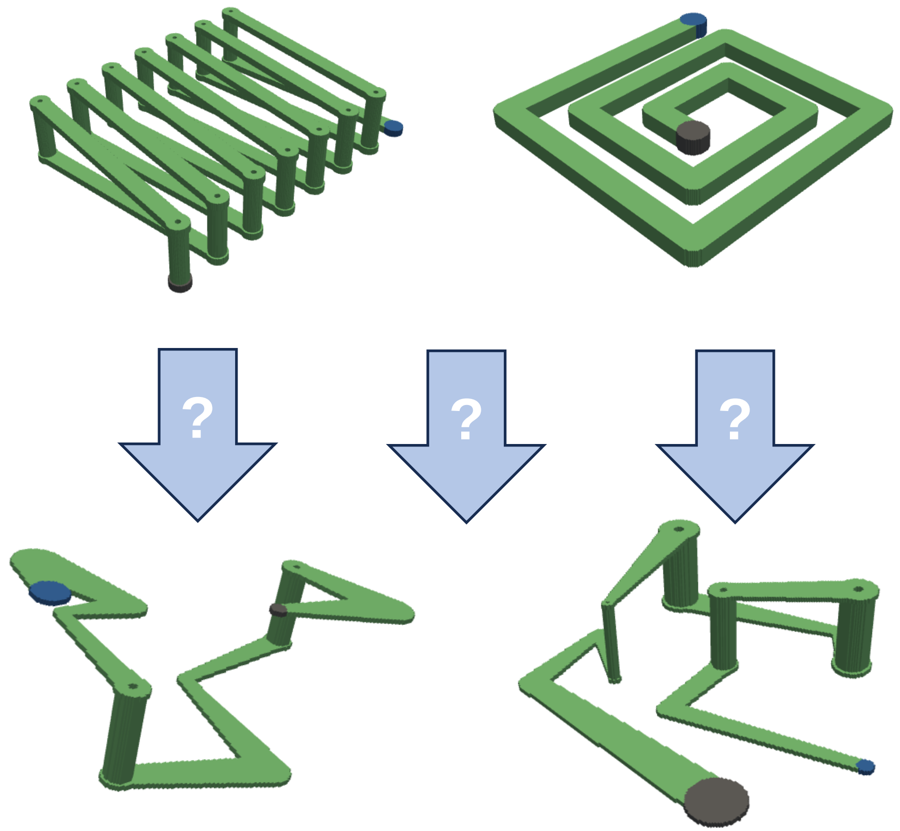
Optimization of Magnetics

- **Magnetics** are often a **bottleneck**
- **Optimizing the materials?**
  - Copper, silver, aluminum, gold, etc.
  - Magnetic material improvements are slow
- **Optimizing the geometry?**
- **Optimal air-core inductor geometries?**
  - Spiral, solenoid, staple
  - Toroid, cylinder



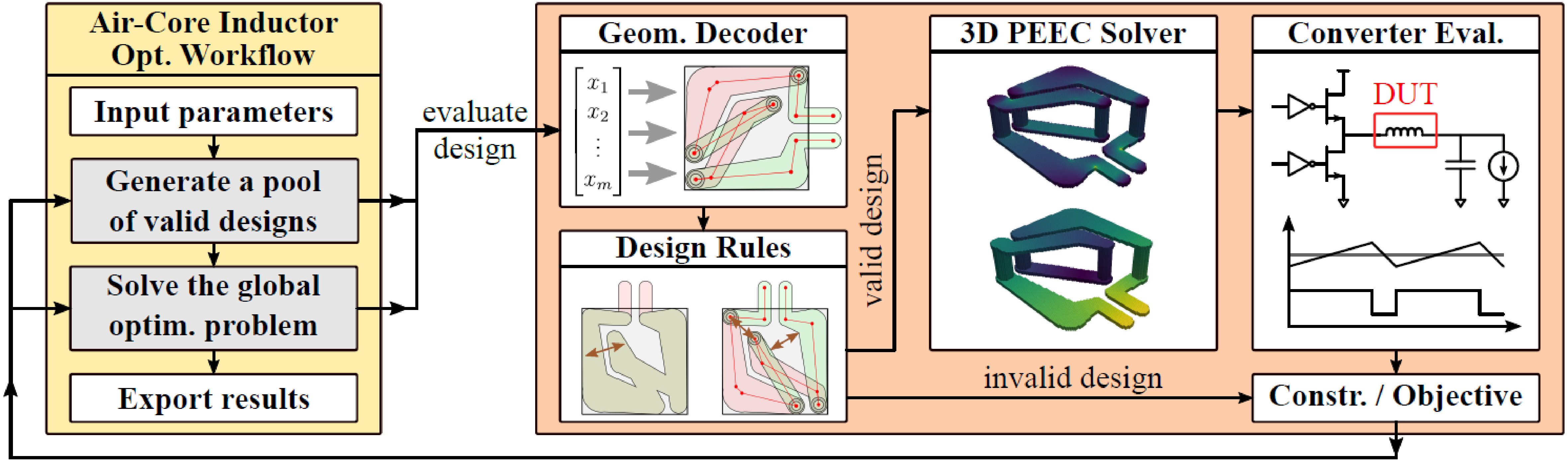
Free-Shape Optimization

- **Topological optimization**
  - Definition of **constraints**
  - Definition of an **objective**
  - Automated shape optimization
- **Common for structural mechanics**
- **Applicability to magnetics**
  - Large computational cost
  - Complex topologies and constraints
  - Discrete variables (e.g. layers)
  - Non-differentiable / discontinuous objective



Optimization Workflow

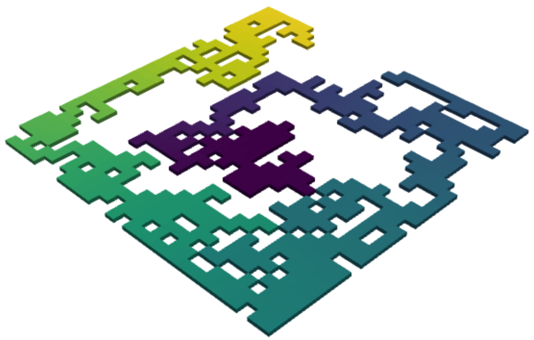
Air-Core Inductor Optimization Workflow

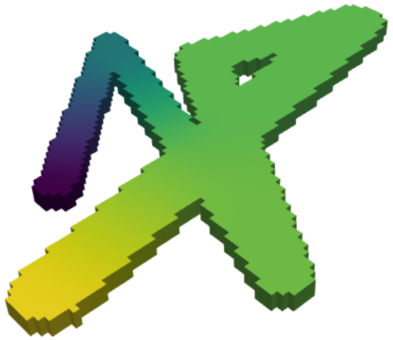


Geometry and Constraints

- **Considered geometries**
  - Multilayer planar process
  - Variable trace width
  - Variable via size
- **Design rules**
  - Clearance, width, footprint, angle, curvature, etc.
  - Complex computational geometry
- **Optimal designs** are often located at the **limit**
- **Optimizers** are very good at **finding loopholes**

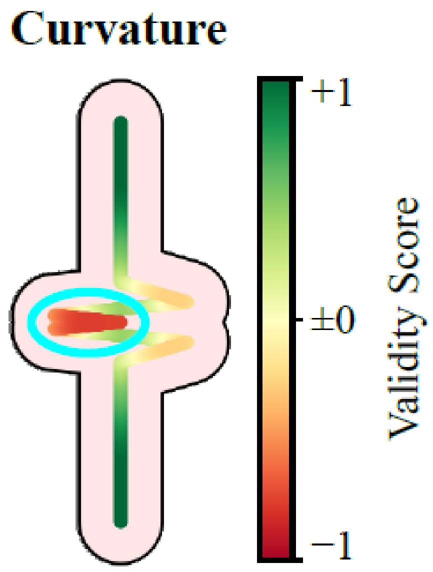
Invalid Geometries

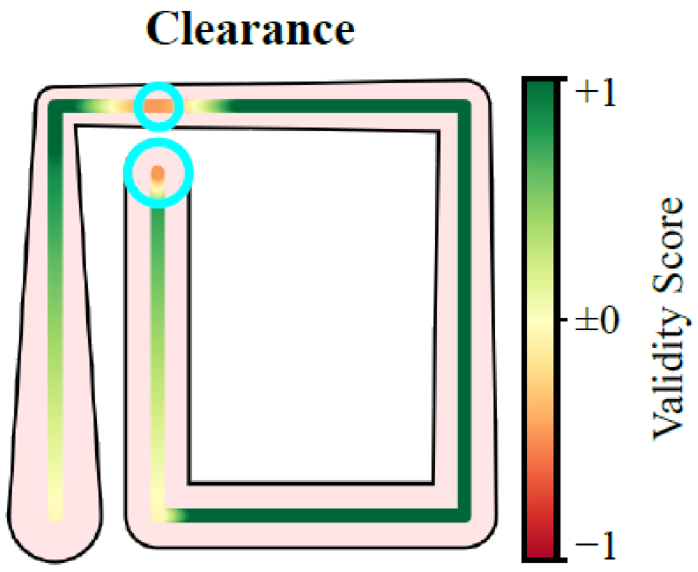


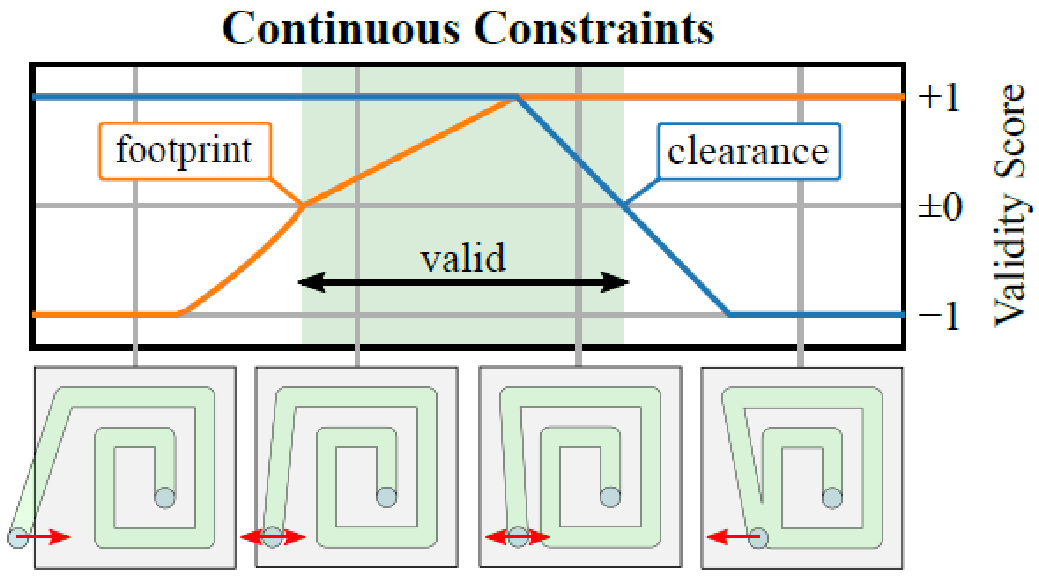


Soft Constraints

- How “close” is a design to become valid/invalid?
- Helpful for the optimizer (as constraints and/or penalty)

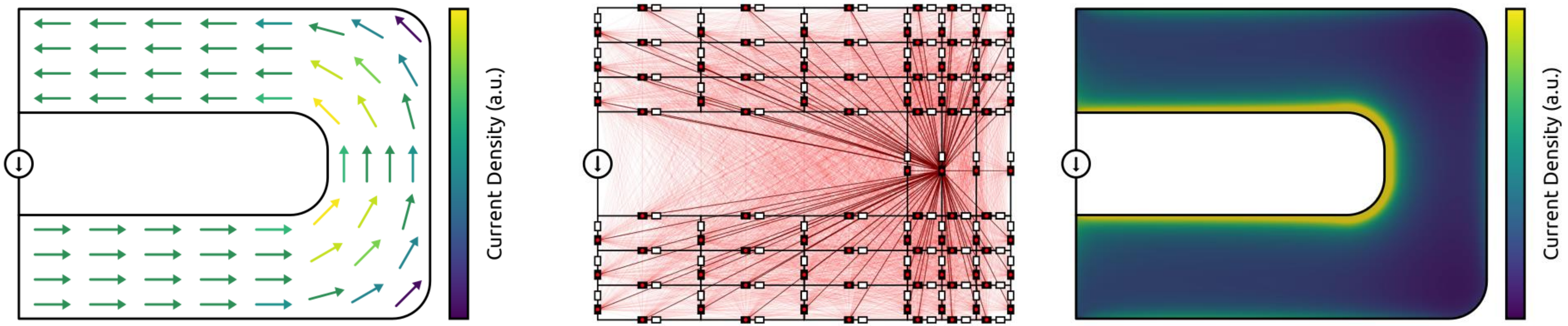






3D PEEC Solver

- **PEEC (Partial Element Equivalent Circuit) method [1970s]**
  - Integral equations method using large equivalent circuit
  - Fast for air-core structures (only the conductors are meshed)
- **Generates large dense matrices**

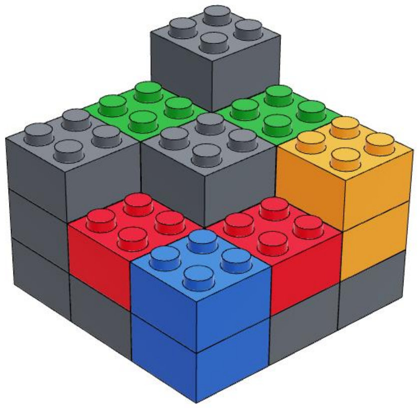


[Ruehli, IEEE TMTT, 1974]

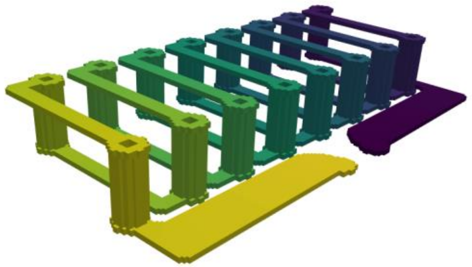
3D PEEC Solver

- **FFT acceleration [2018, 2022]**
  - Using **voxels** to represent the geometries
  - Embedding the matrices in **circulant tensors**
- **Advantages**
  - **Memory** storage: from **$O(n^2)$** to **$O(n)$**
  - Matrix **multiplication**: from **$O(n^2)$** to **$O(n \ln(n))$**
- **PyPEEC** (custom implementation)
  - **3D magnetic solver** (DC and AC)
  - Can handle **arbitrary geometries**
- **Can solve 6.5 designs per seconds**

Voxel Structure



PyPEEC Inductor

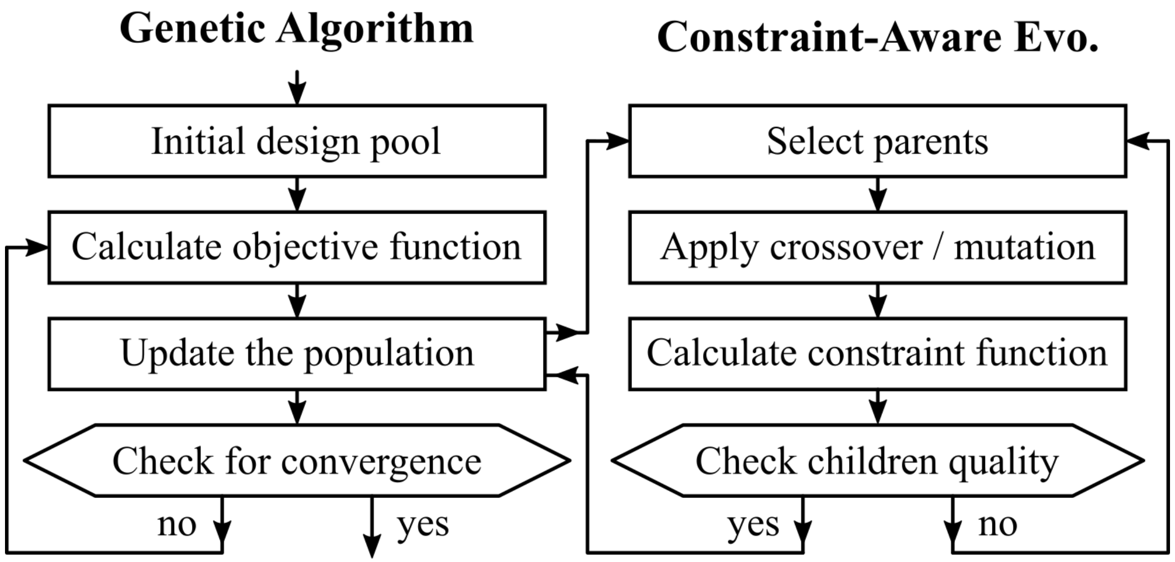


[Yucel, IEEE TMTT, 2018] and [Torchio, IEEE TPEL, 2022] and [Benchmarked with an AMD EPYC 9354 and 75k DoFs]

Global Optimization

- **Gradient-free algorithms:** differential evolution, particle swarm, Parzen estimator, CMA-ES, NgIohTuned, and **genetic algorithm**

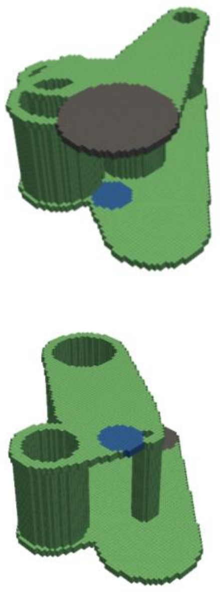
- **The design rules** are extremely **restrictive**
- **Constraint-aware genetic algorithm**
- **Enforce** the design **rules** during the optimization



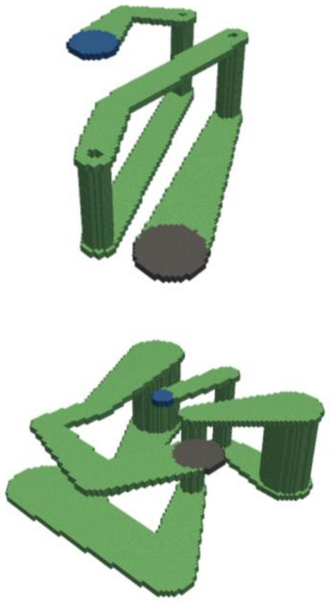
Design Rule Awareness

- **Generation of random designs for the initial population**
  - **Probability** to obtain a **valid** design: below **one in a billion**
  - **Fully random generation is not feasible**
- **A recursive tree algorithm has been developed**

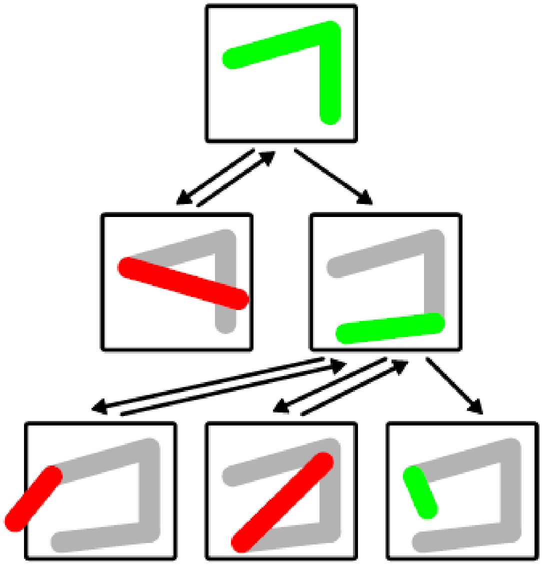
Invalid Designs



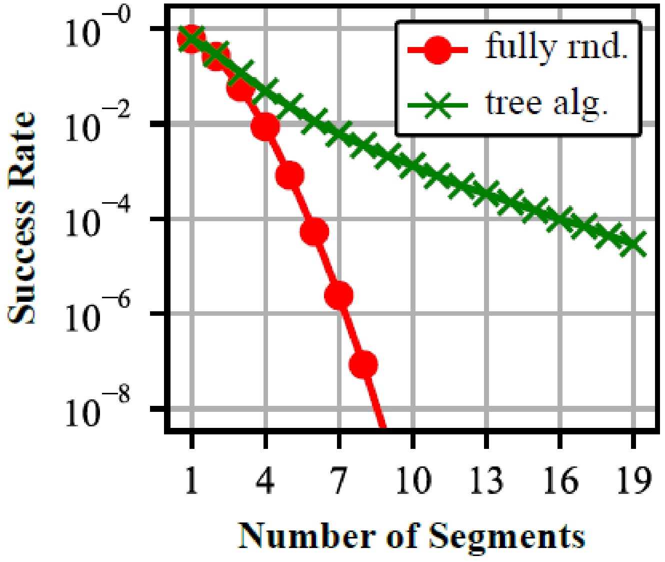
Valid Designs



Recursive Tree Example



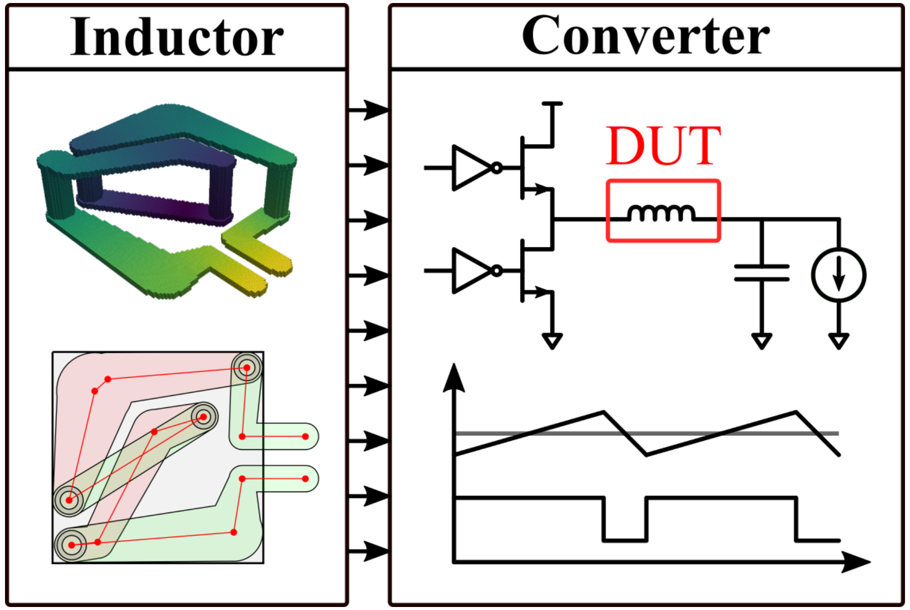
Valid Design Generation



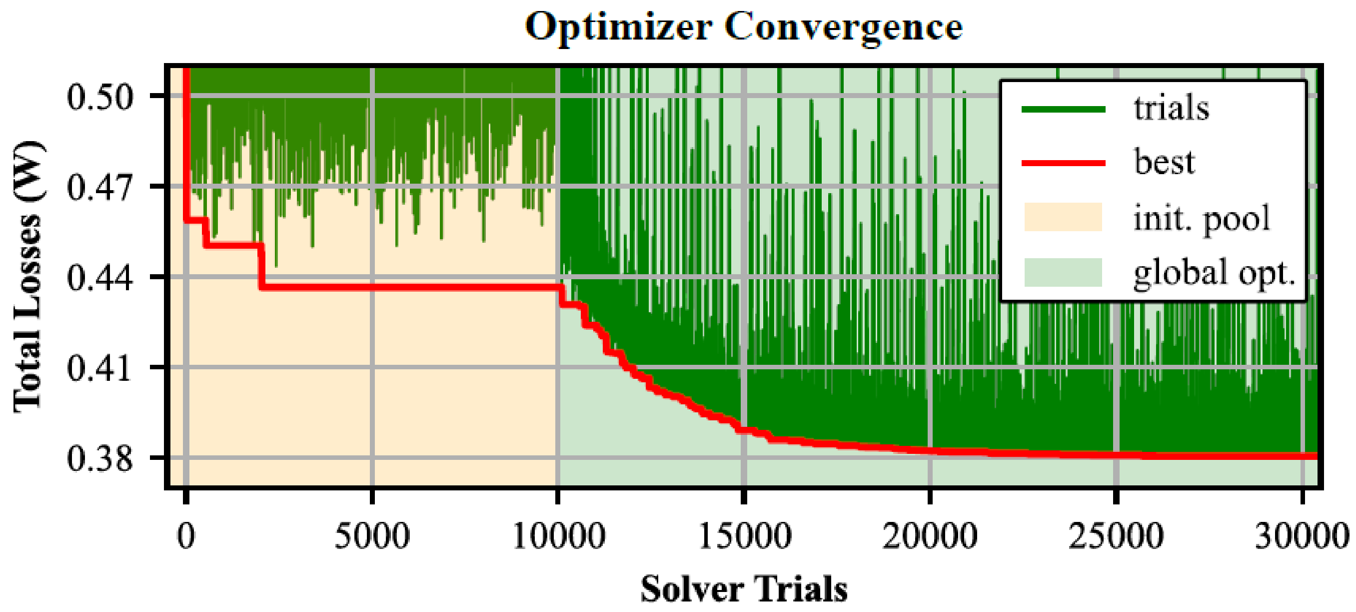
Optimization Results

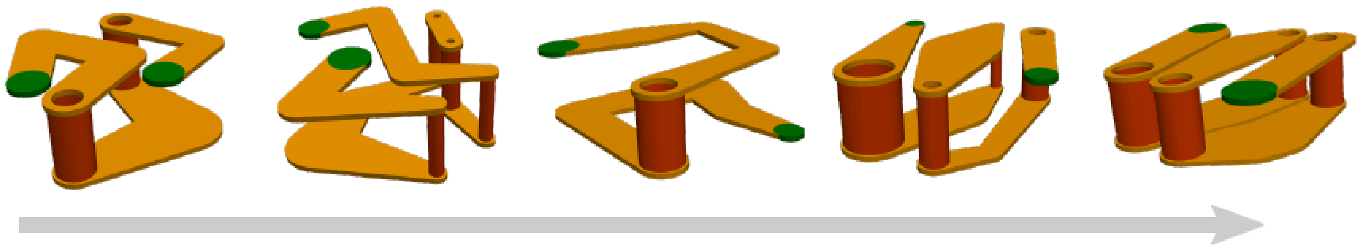
Problem Specifications

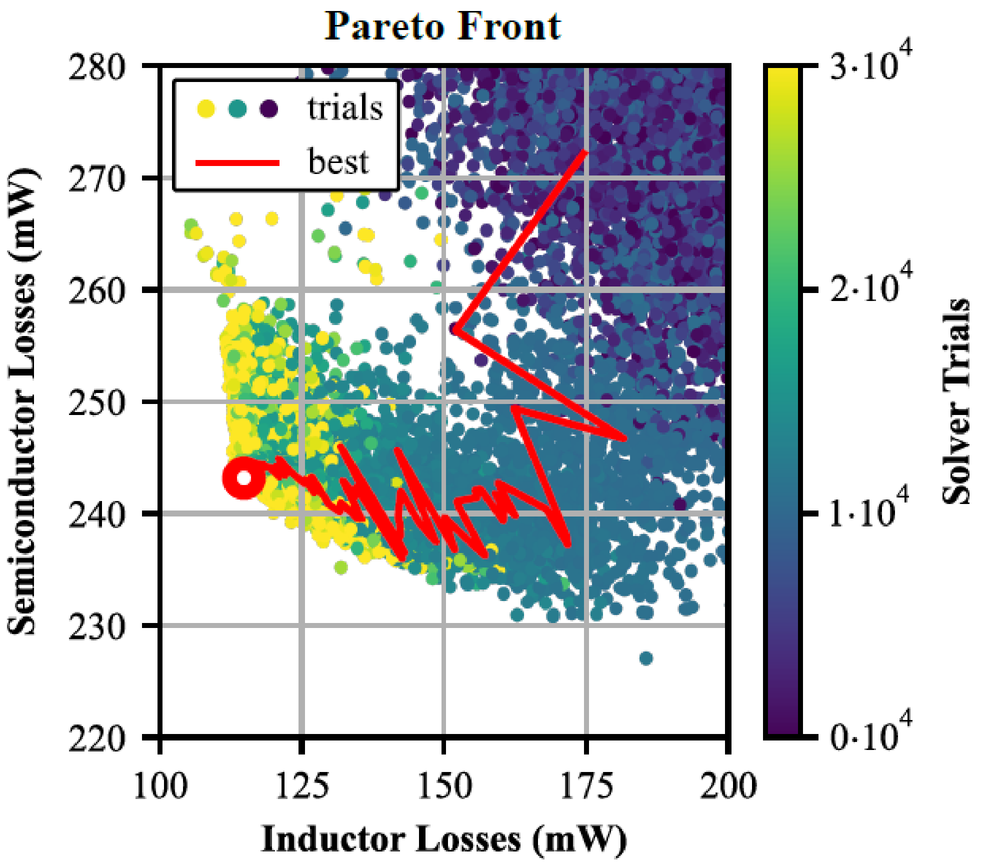
- **Inductor of a DC-DC Buck IVR**
  - **3.3 V to 0.8 V** at **1.6 W**
  - **40.68 MHz** operating frequency
  - **180 nm SOI** switches
- **Design rules**
  - Limited footprint: **1 mm²**
  - **Two-layer** planar inductor
- Minimize **converter losses**



Optimizer Convergence

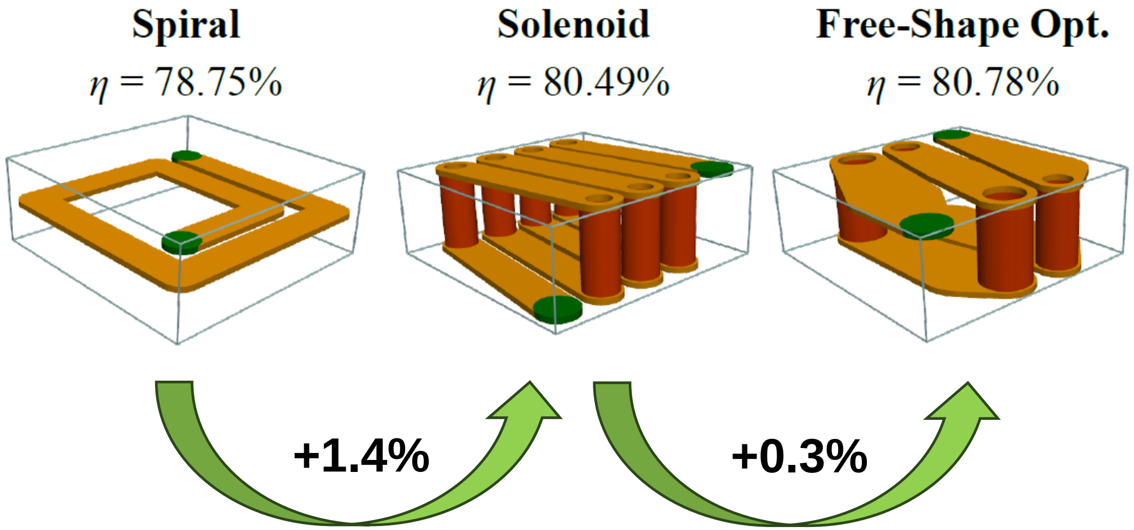






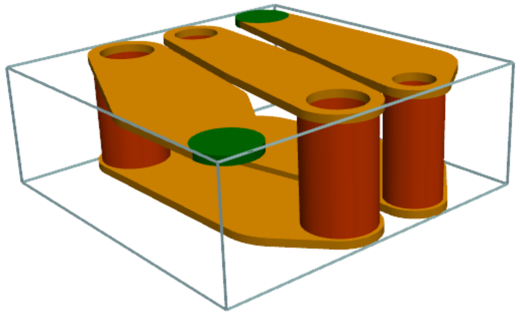
Design Space Diversity

- **Standard geometries**
  - **Spiral** with 1.5 turns
  - **Solenoid** with 4 turns
- **Free-shape design**
  - **Solenoid** with 3 turns
  - **Only 0.3% more efficient**
- **Is shape opt. useless?**
  - Design space diversity
  - Additional constraints

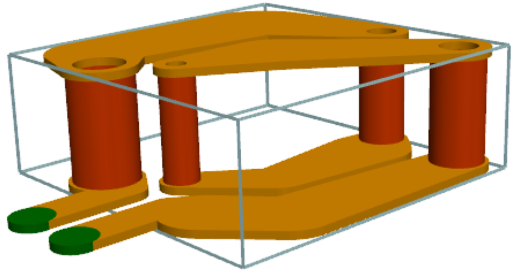


Additional Constraints

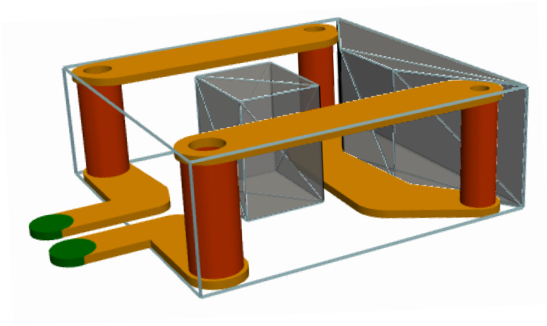
Floating Terminals



Fixed Terminals



Footprint Constraint

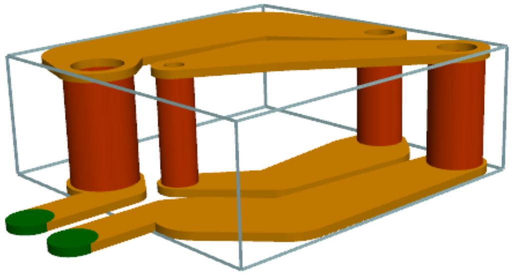


Shape	**Solenoid shaped**		**Solenoid shaped**		**Loop shaped**
Total Efficiency	80.8%	**- 1.8%**	79.0%	**- 1.2%**	77.8%
Inductor Efficiency	93.3%		90.8%		89.7%

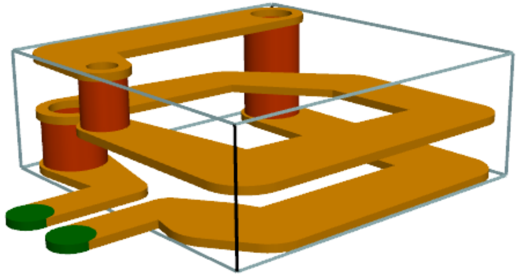
- **Shape optimization can handle complex constraints**
- **Terminals have a non-negligible impact**

Extension of the Design Space

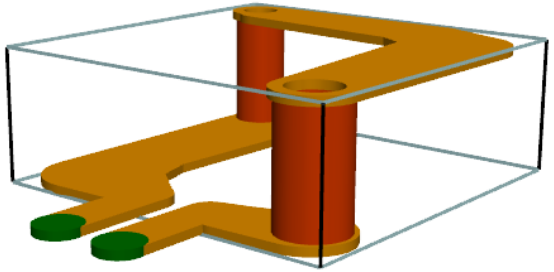
Reference Geometry



Three-Layer Geometry



Three-Level Topology

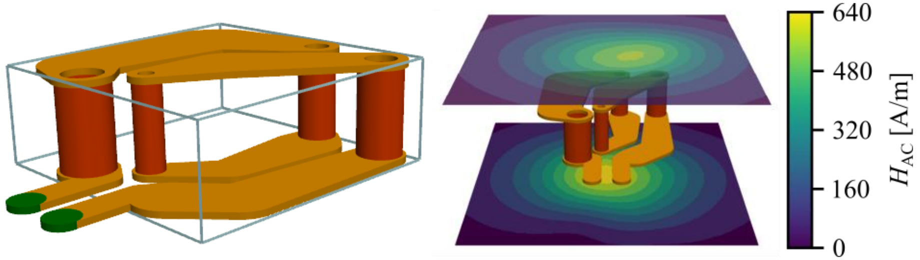


Shape	**Solenoid shaped**		**Loop shaped**		**Loop shaped**
Total Efficiency	**79.0%**	**+ 1.0%**	**80.0%**	**+ 3.8%**	**83.8%**
Resistance Value	**16.9 mΩ**		**21.8 mΩ**		**11.1 mΩ**
Inductance Value	**2.17 nH**		**3.42 nH**		**1.31 nH**

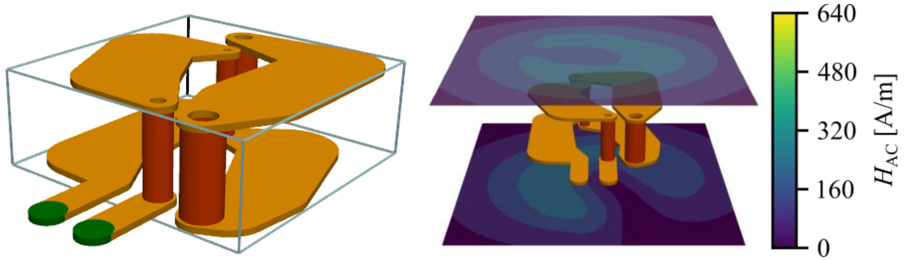
- **Different boundary conditions lead to different shapes**

Near-Field Optimization

Reference Geometry



Near-Field Optimization



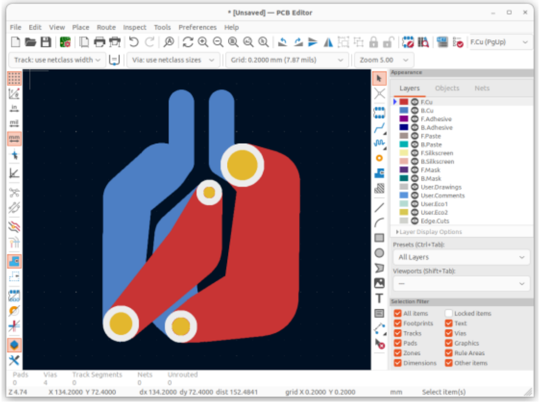
Shape	**Solenoid shaped**		**Non-conventional shape**
Total Efficiency	79.0%	- 0.9%	78.1%
DC Mag. Near Field	771 A/m	÷ 2.5x	288 A/m
AC Mag. Near Field	616 A/m		249 A/m

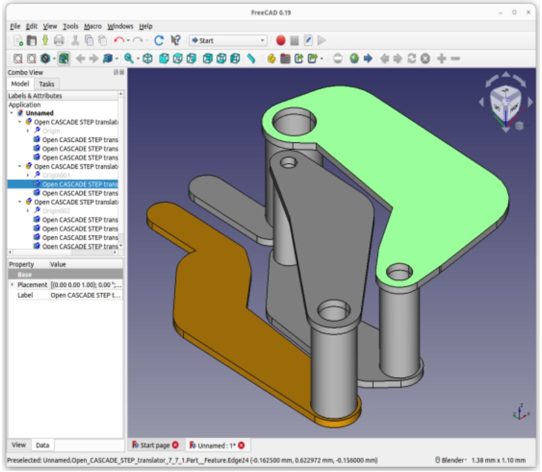
- **Magnetic near-field: eddy-current losses and/or EMI issues**
- **Massive field reduction with marginal impact on the efficiency**

Conclusion

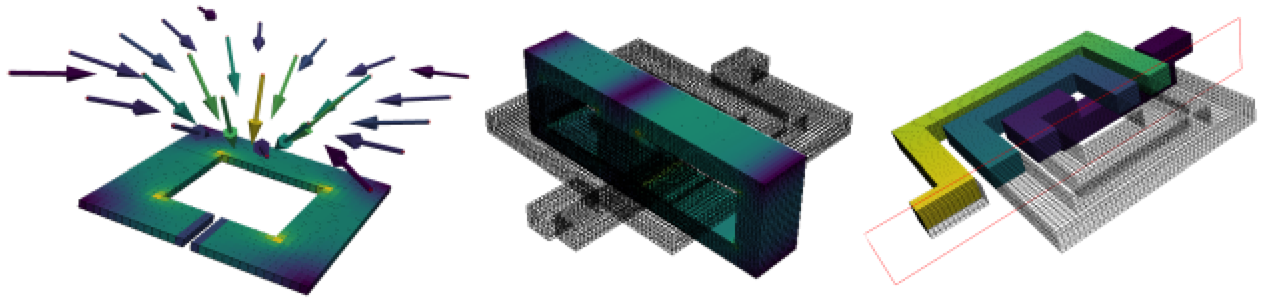
Conclusion and Outlooks

- **Free-shape optimization**
  - Strict **design rule** enforcement
  - Fast **3D** FFT-accelerated **PEEC**
  - **Constraint-aware genetic algorithm**
- **Air-core inductors for IVRs**
  - Classical shapes good for standard problems
  - Shape optimization can handle complex constraints
- **Outlooks**
  - Scaling to more complex problems
  - Gradient-based methods (e.g., auto-diff)
  - Neural networks (e.g., surrogate)





PyPEEC

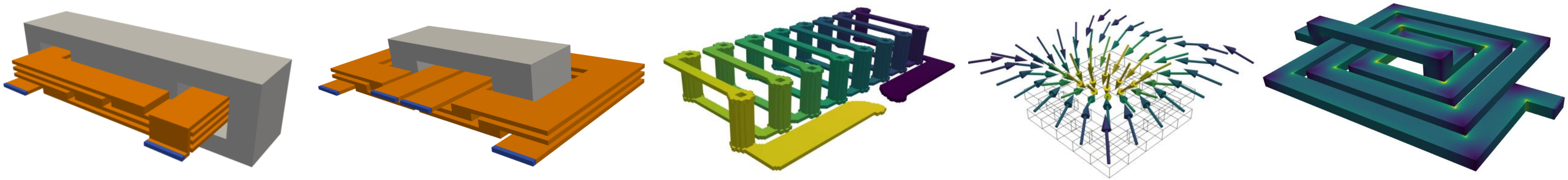


- 3D FFT-accelerated PEEC solver
- DC and AC magnetic problems
- Fully open source Python code

python Package Index

CONDA-FORGE

pypeec.otvam.ch



Shape Opt. Source Code

GitHub

github.com/otvam/pyfreecoil

zenodo

zenodo.org/records/14247697

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Thank you! Questions?

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