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
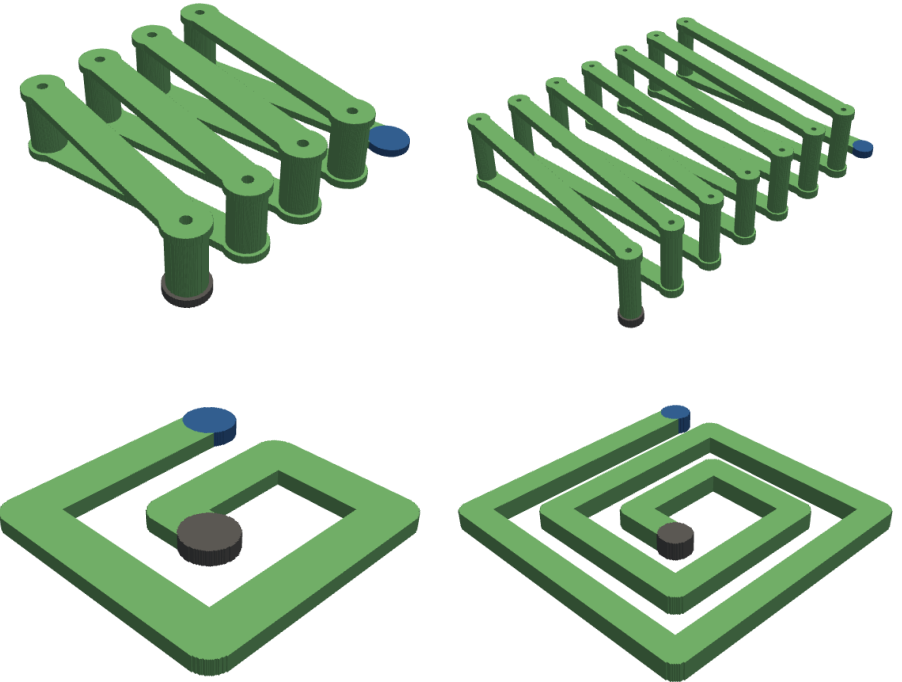
Free-Shape Optimization

- **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
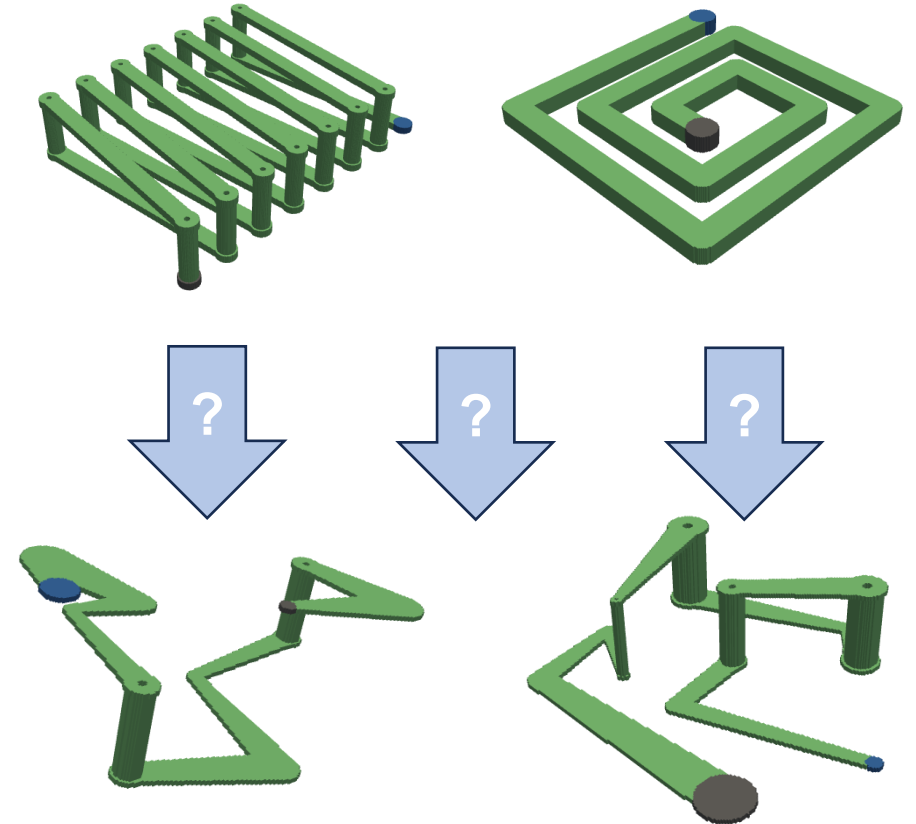
Optimization Workflow

Air-Core Inductor Optimization Workflow
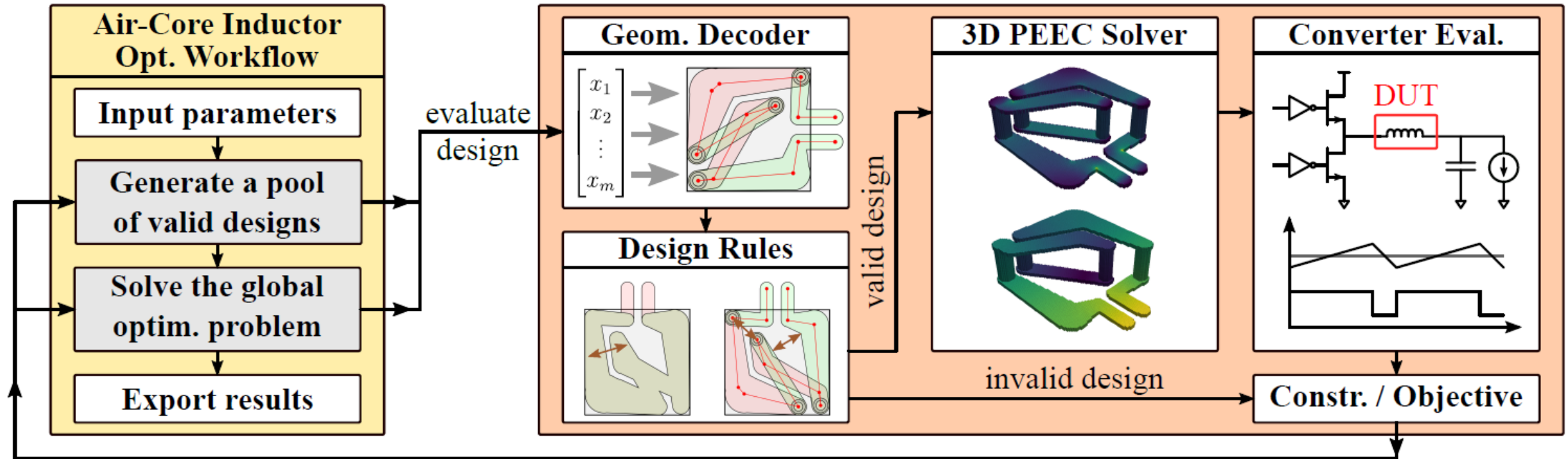
Geometry and Constraints

- **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**

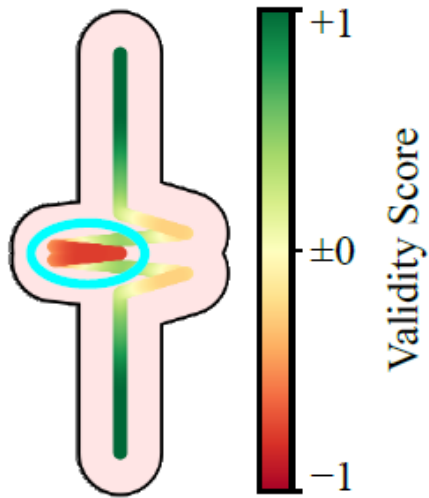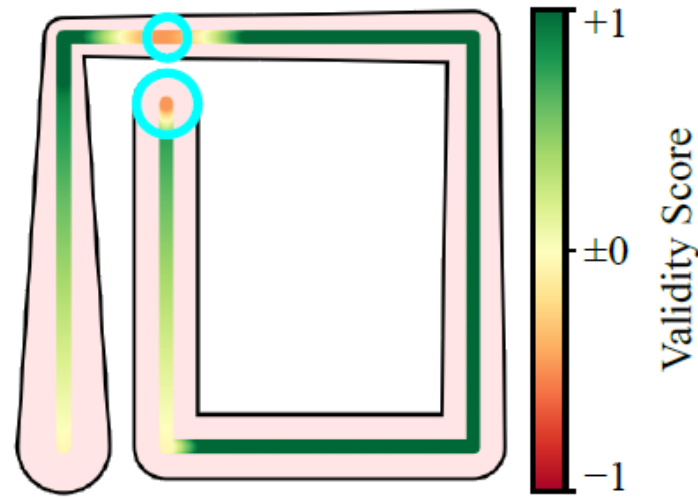- **Optimizers** are very good at **finding loopholes**

Invalid Geometries

Soft Constraints

- **How "close" is a design to become valid/invalid?**
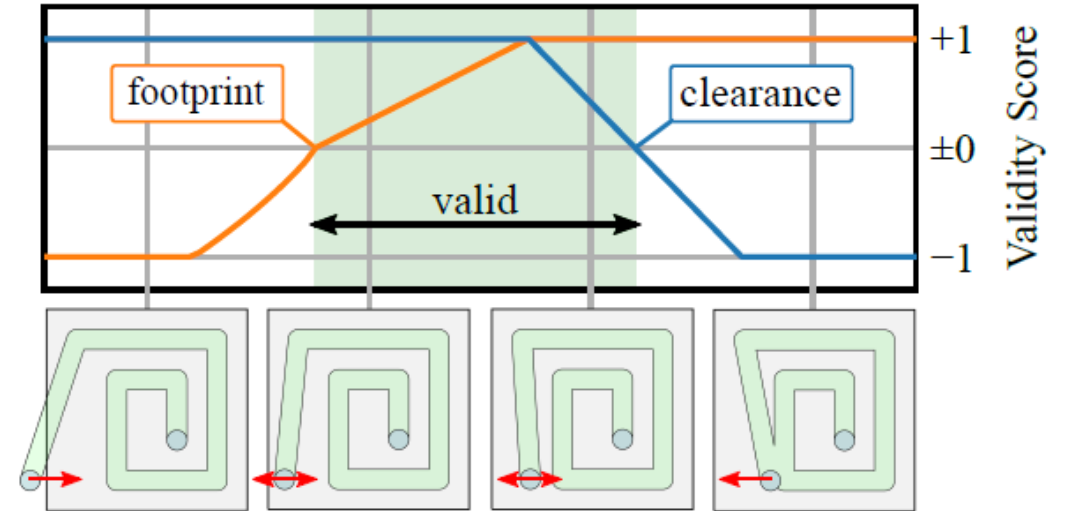- **Helpful for the optimizer (as constraints and/or penalty)**
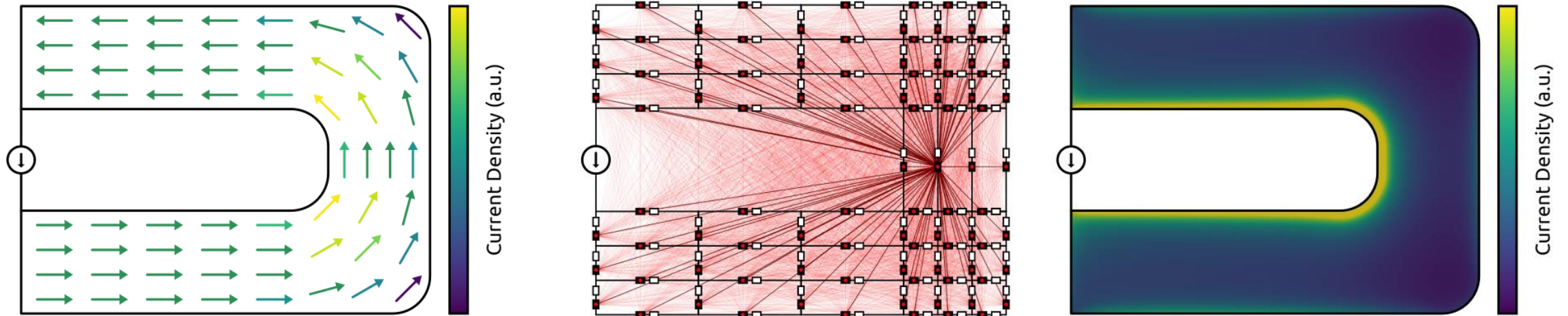
3D PEEC Solver

- **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**
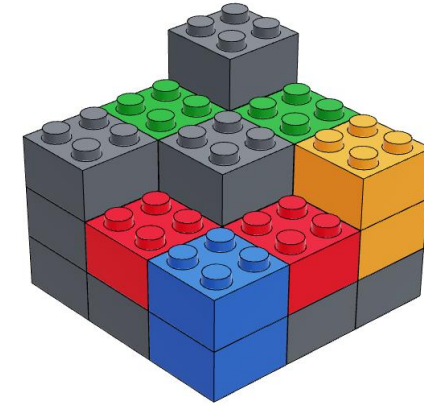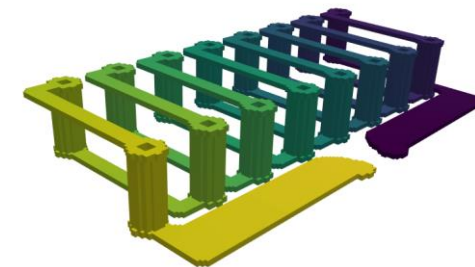

[Ruehli, IEEE TMTT, 1974]

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**

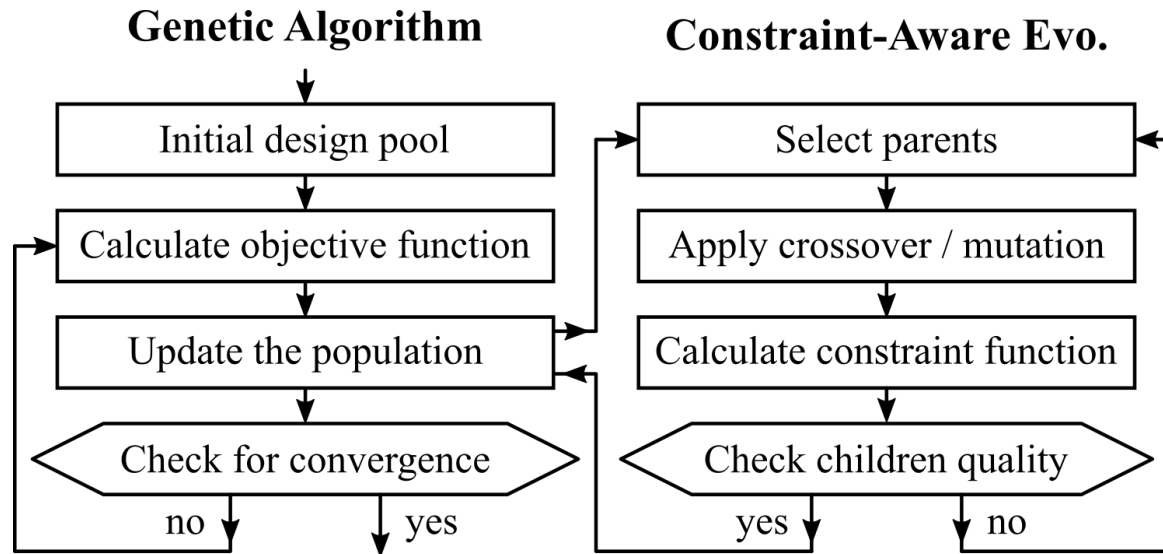- **Can solve 6.5 designs per seconds**

Voxel Structure

PyPEEC Inductor

9

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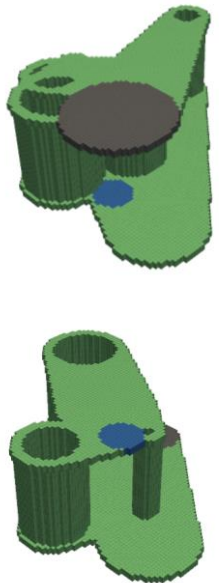
Global Optimization

- **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

Genetic Algorithm

Initial design pool
↓
Calculate objective function
↓
Update the population
↓
Check for convergence
no ↓   ↓ yes

Constraint-Aware Evo.

Select parents
↓
Apply crossover / mutation
↓
Calculate constraint function
↓
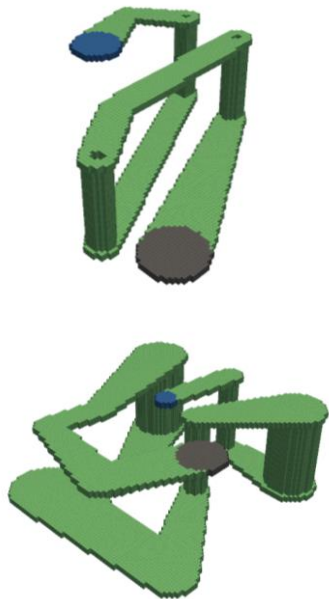Check children quality
yes ↓   ↓ no

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**

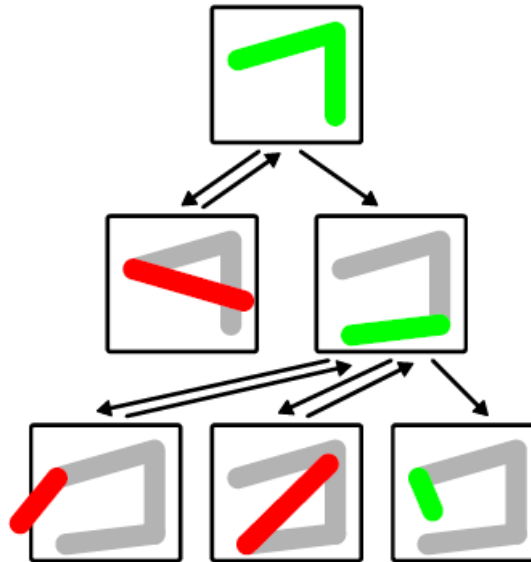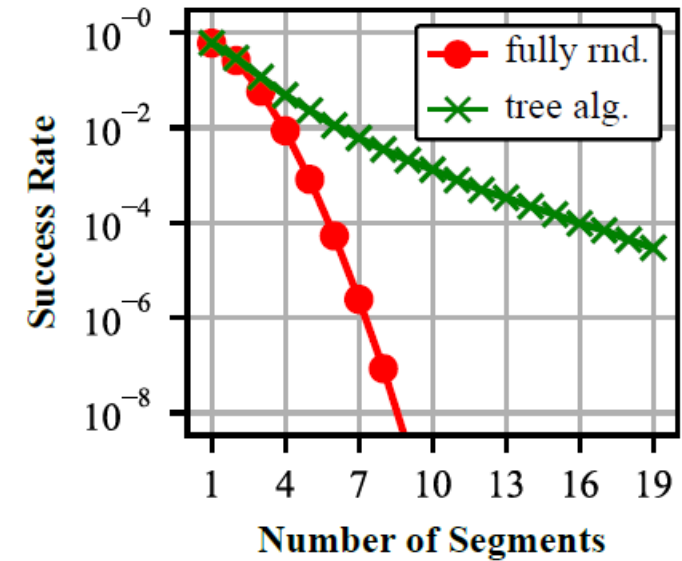- **A recursive tree algorithm has been developed**
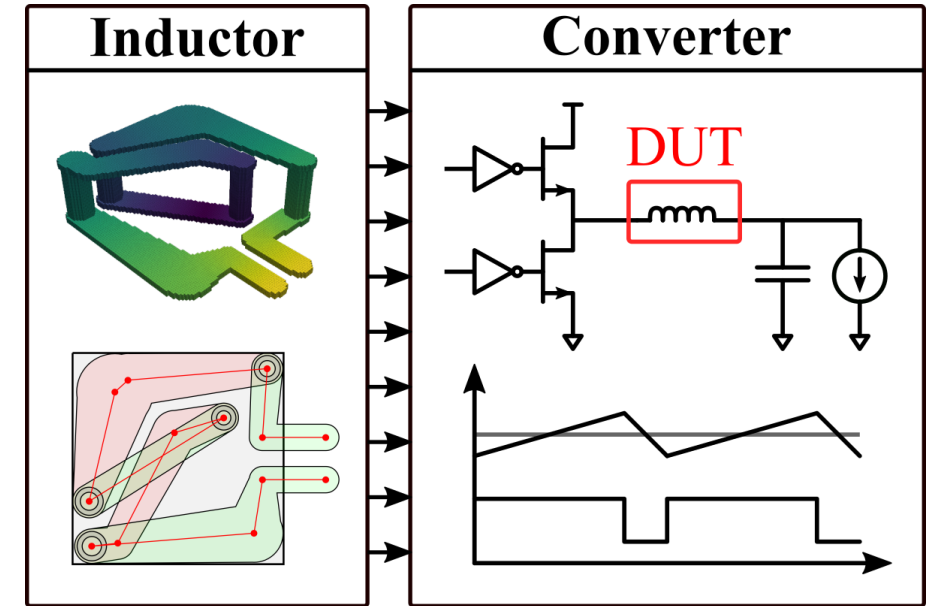
Invalid Designs

Valid Designs

Recursive Tree Example
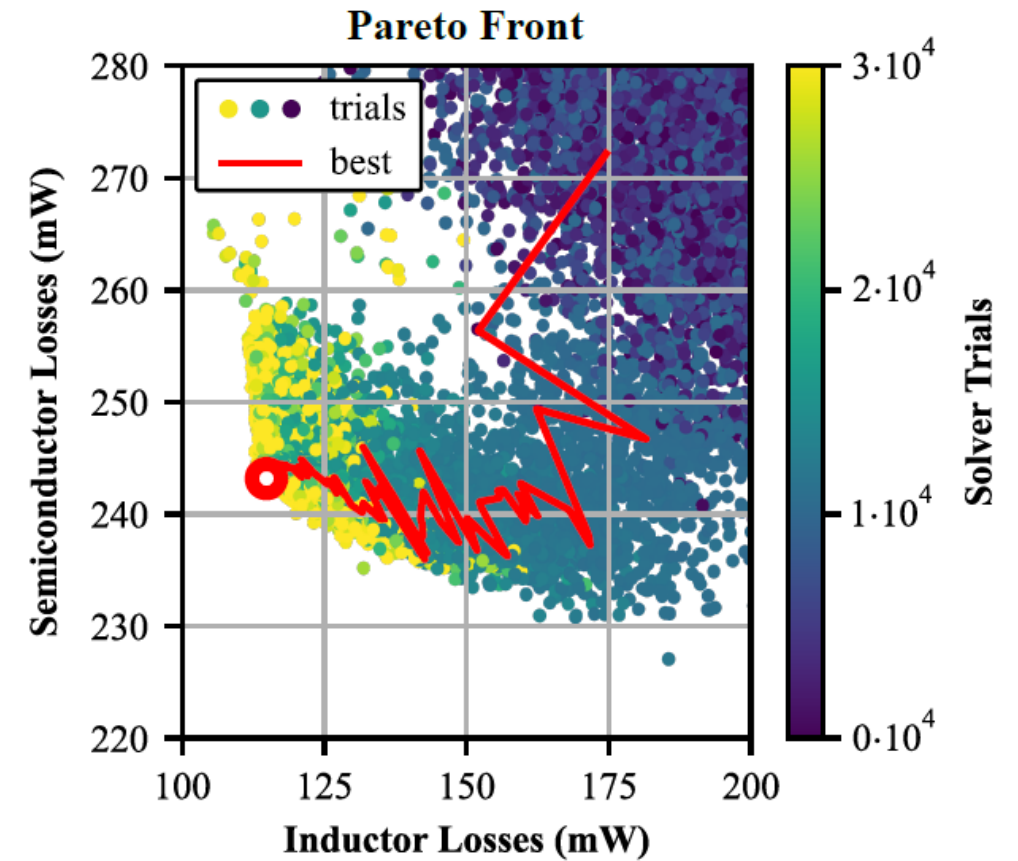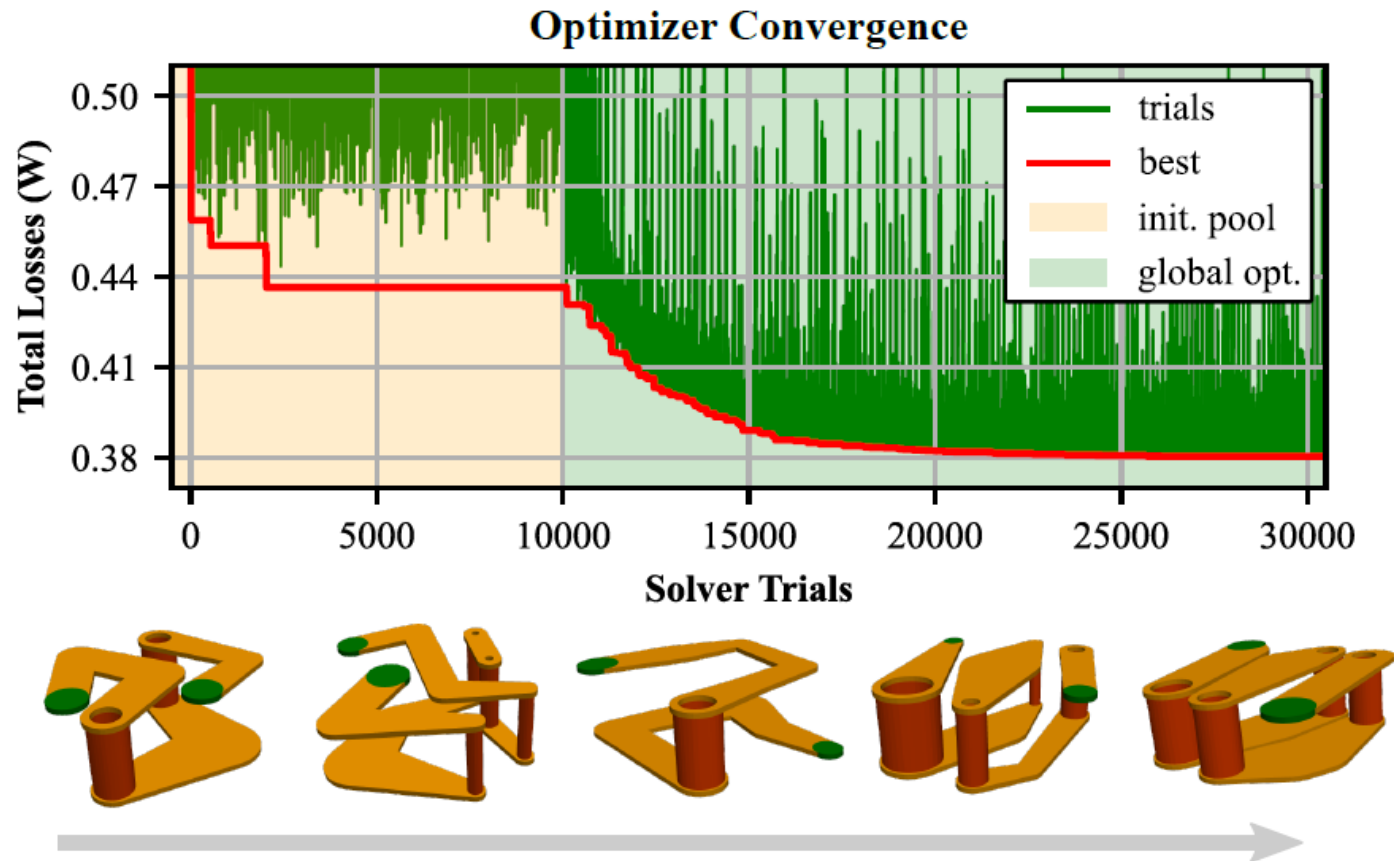
Valid Design Generation

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
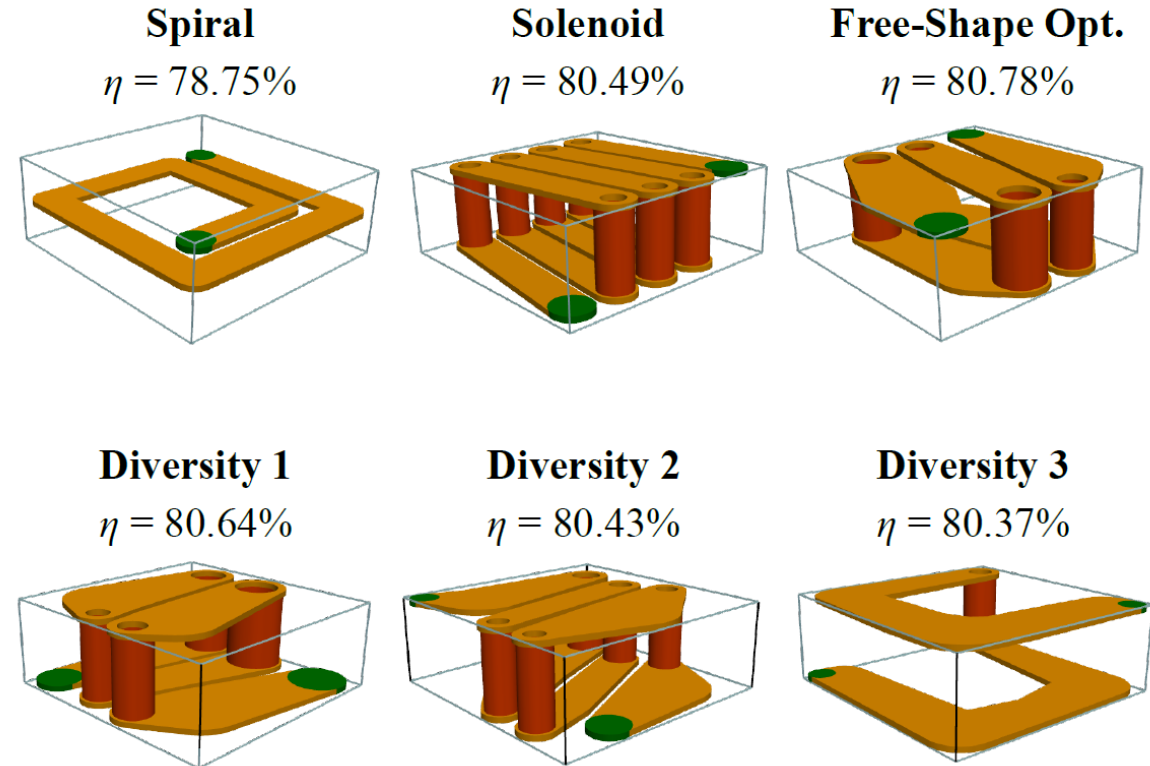
- Minimize **converter losses**
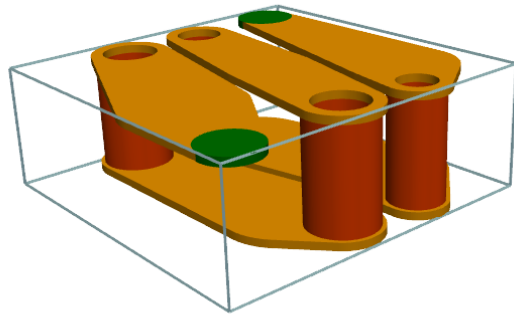
Optimizer Convergence

Design Space Diversity

- **Classical design**
  - ○ **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?**
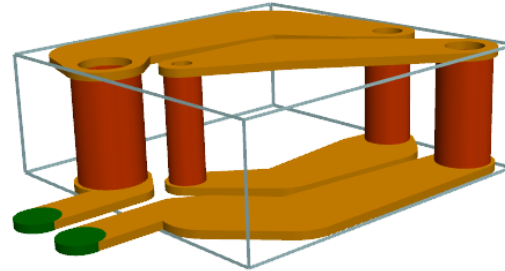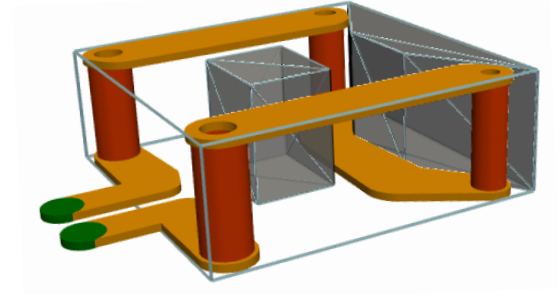 - ○ Design space diversity
  - ○ Additional constraints

Spiral
$\eta = 78.75\%$

Solenoid
$\eta = 80.49\%$

Free-Shape Opt.
$\eta = 80.78\%$

Diversity 1
$\eta = 80.64\%$

Diversity 2
$\eta = 80.43\%$

Diversity 3
$\eta = 80.37\%$

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**
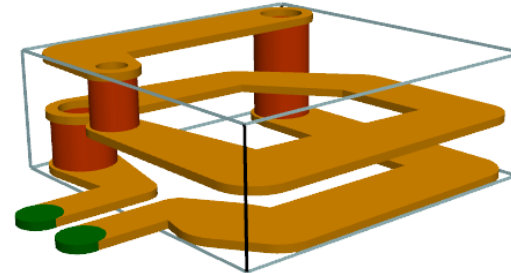- **Terminals have a non-negligible impact**
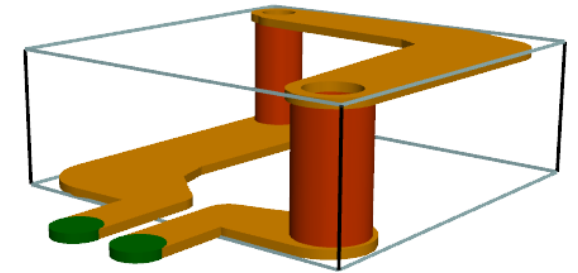
Extension of the Design Space
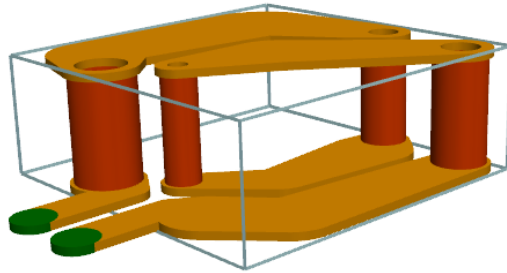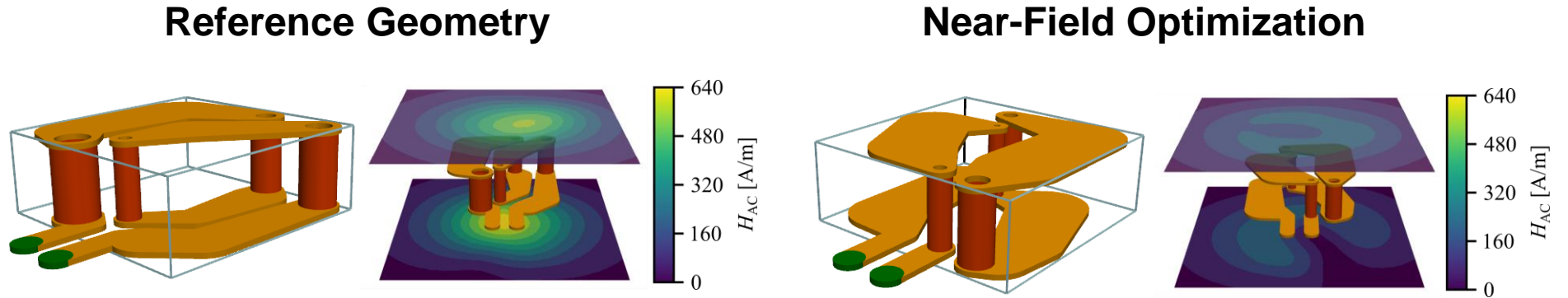
Reference Geometry		Three-Layer Geometry		Three-Level Topology

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		288 A/m
AC Mag. Near Field	616 A/m	÷ 2.5x	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)
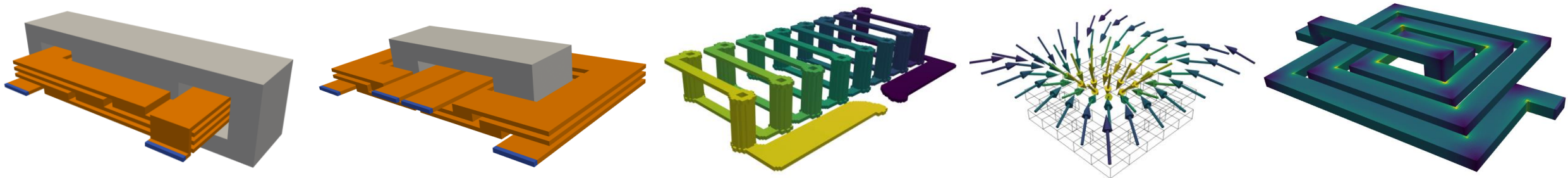 - Neural networks (e.g., surrogate)
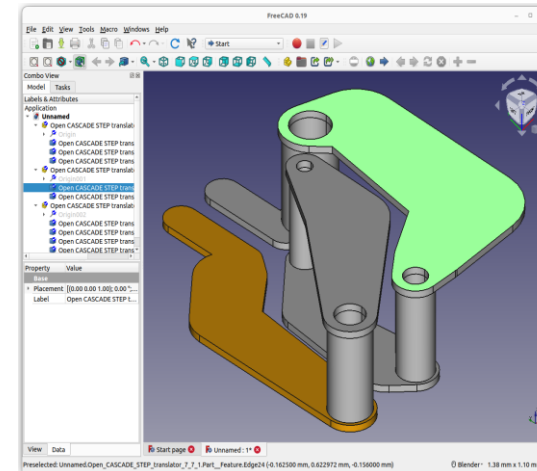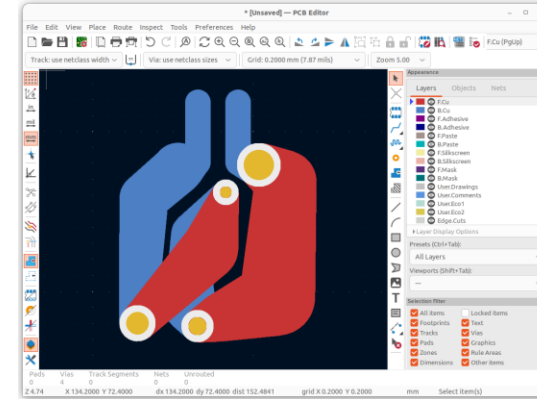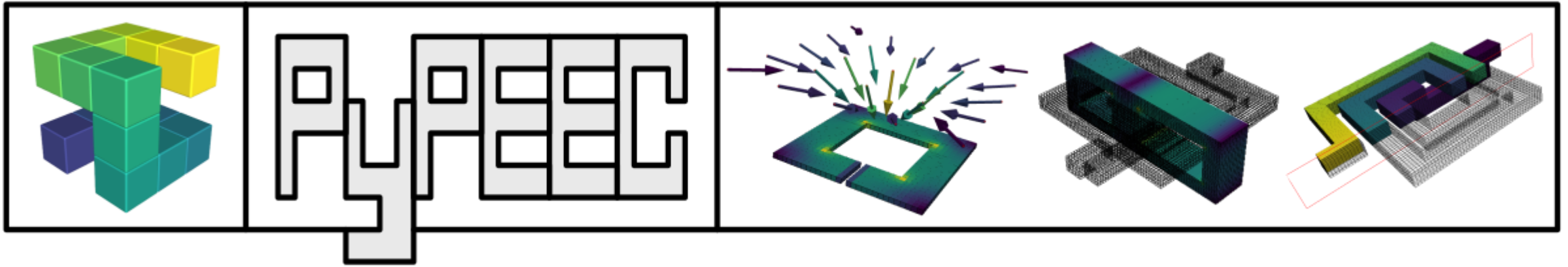
- **3D FFT-accelerated PEEC solver**
- **DC and AC magnetic problems**
- **Fully open source Python code**

pypeec.otvam.ch

Shape Opt. Source Code

GitHub

github.com/otvam/pyfreecoil

zenodo

zenodo.org/records/14247697

APEC 2025

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Thank you! Questions?

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