U.S. DEPARTMENT OF ENERGY
Office of Electricity

Development of Automated Design and Optimization Tools for High Frequency Magnetic Components; Migration to Open Source and High Performance Computing Environments

TRAC Program Review

US Department of Energy, Office of Electricity

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Contents

- Project overview
- The problem being addressed
- State of art approaches
- Uniqueness of the proposed solution
- Significance of the results, if successful
- Specific research questions being addressed
- Technical explanation of the proposed approach
- Project schedule, deliverables, and current status
- Anticipated challenges and risk mitigation strategies
- Broader impact

Project Overview

Project summary :

- Development of a more automatic magnetic design and optimization method using genetic algorithm (GA) and finite element analysis (FEA).
- Migration of the magnetic design tools developed to open source platforms.
- Migration of developed program and co-simulation package of MATLAB/SIMULINK-PLECS-COMSOL to high performance computing.

Total value of award : ~$550k over 3 years

Period of performance : 4/1/2017 – 3/31/2020

Project lead and partners : NETL (lead on overall subtask), Purdue University

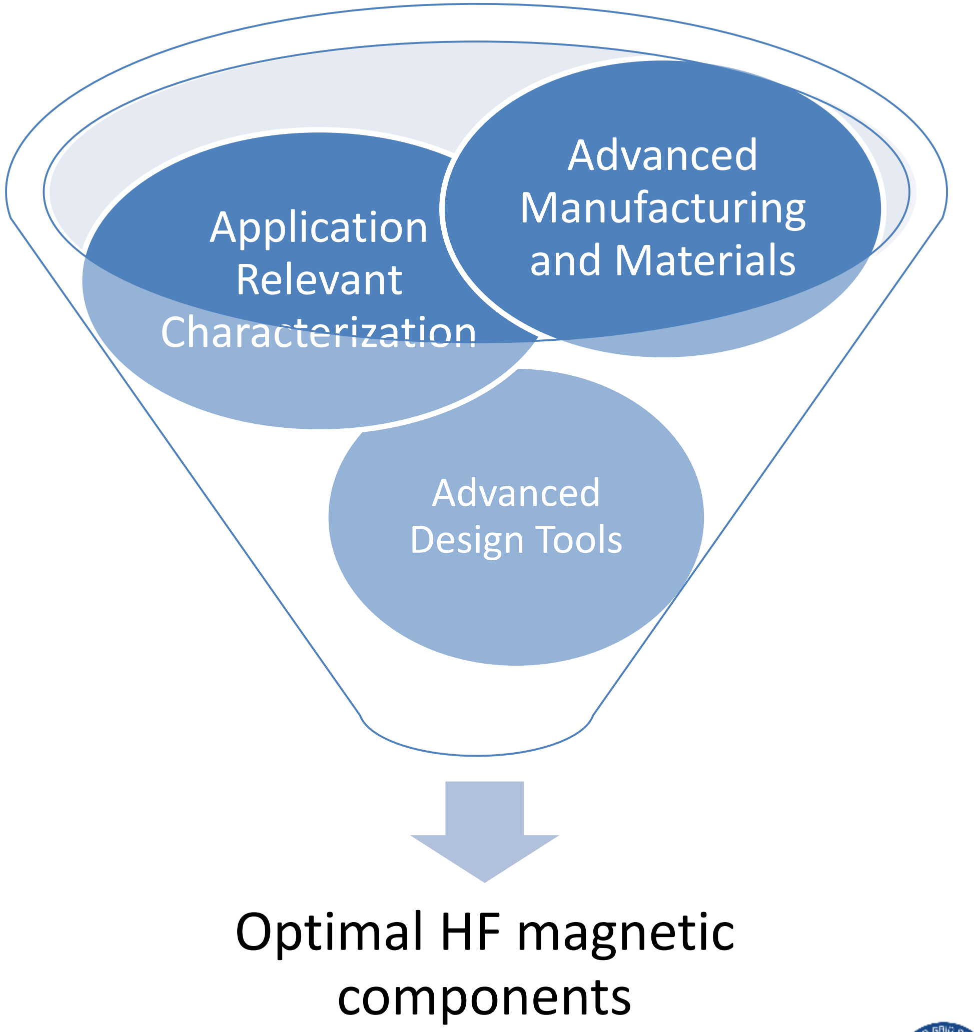
The Problem Being Addressed : Research Motivation

What tools are needed to design high frequency magnetic components?

1. Advanced Manufacturing Processes and Materials

2. Application Relevant Core / Component Characterization – Publication of Data Sheets

3. Advanced Design Tools
   – Multi-Objective Optimization
   – Co-Simulation Methods



The problem being addressed

The need for advanced magnetic design and optimization tools

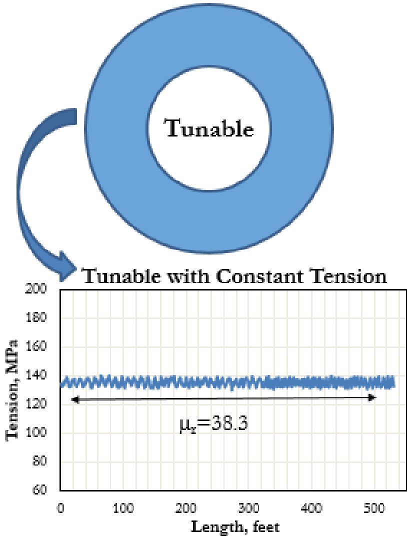
- A need exists to more accurately incorporate magnetic component performance in the context of converter and component operation.

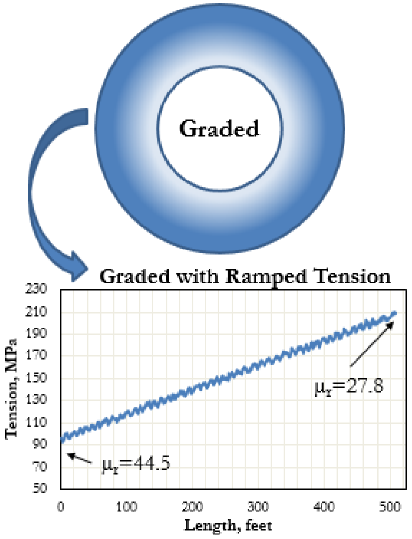
- New materials and manufacturing methods are also opening new design spaces which were not previously possible.

- For example, NETL has developed an advanced material process with unique property of spatial tunable permeability.

- An ability to spatially tune the permeability is an unprecedented degree of freedom in the design process.

- Such advances must be compared with traditional design tools and methods in a consistent framework to reach a full global optimization in the design space.



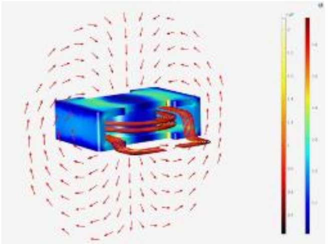


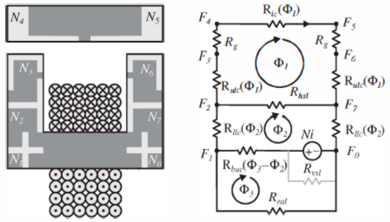
The problem being addressed

The need for advanced magnetic design and optimization tools

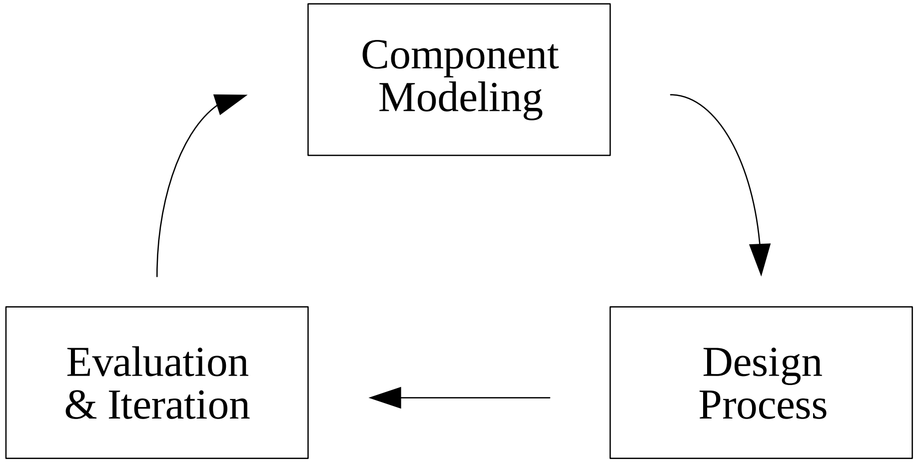
- Aspects of component design
  - Component modeling
    - Magnetic equivalent circuit (MEC)
    - Finite element analysis (FEA)
    - Etc.
  - Design processes
    - Rules of thumb
    - Sensitivity analysis
    - Multi-objective optimization
    - Etc.
  - Evaluation & Iteration

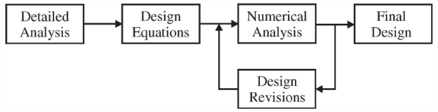
- The project addresses these aspects of design process with a goal of providing a suite of tools that enable more optimized designs for emerging applications of interest to the TRAC program.

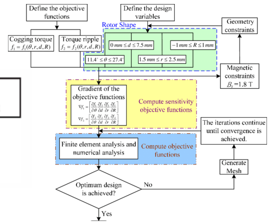


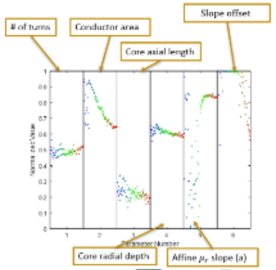


(a) cross section showing nodes (b) magnetic equivalent circuit









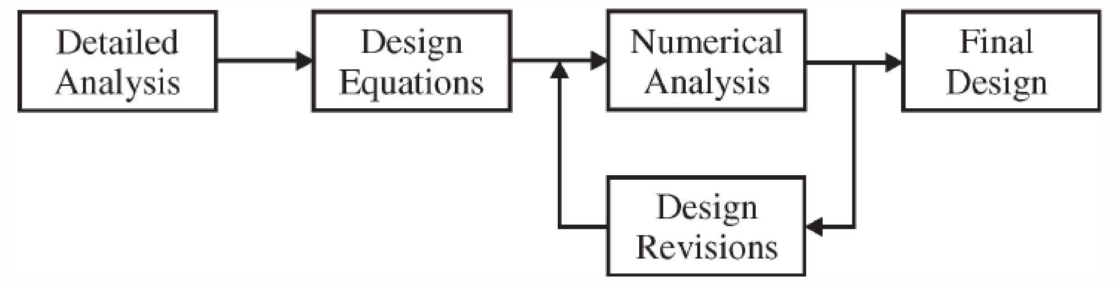
State of the Art Approaches : Conventional design processes

Magnetic component design methods

- Method 1: follow governing design heuristics (“rules of thumb”)
  - It yields a design, but it is typically not the best design
  - Requires significant engineering expertise and time for each design

- Method 2: sweep a small set of variables to which the performance is most sensitive (sensitivity analysis)

- Method 3: employ a full multi-objective optimization.



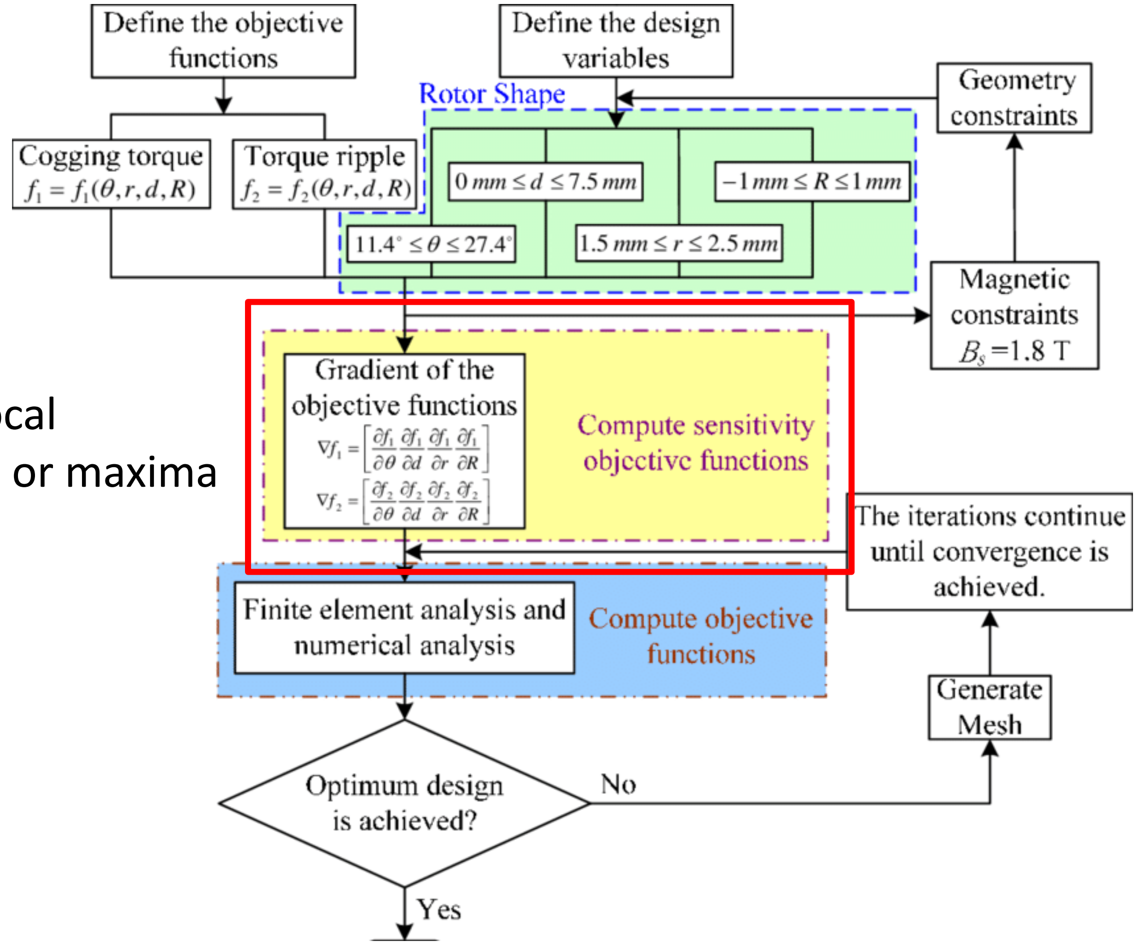
A manual design process

State of the Art Approaches : Conventional design processes

Magnetic component design methods

- Method 1: follow governing design heuristics (“rules of thumb”)
- Method 2: sweep a small set of variables to which the performance is most sensitive (sensitivity analysis)
  - Typically finds local minima or maxima, but not guaranteed to find global best solutions
- Method 3: employ a full multi-objective optimization.

Finds local minima or maxima

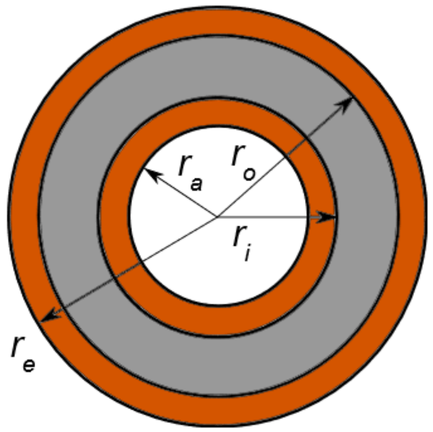


[1] C Hwang, C & M Chang, C & Li, Ping Lun & Liu, Cheng-Tsung. (2011). Design of rotor shape to reduce torque ripple in IPM motors. Journal of Physics: Conference Series. 266. 012068. 10.1088/1742-6596/266/1/012068.

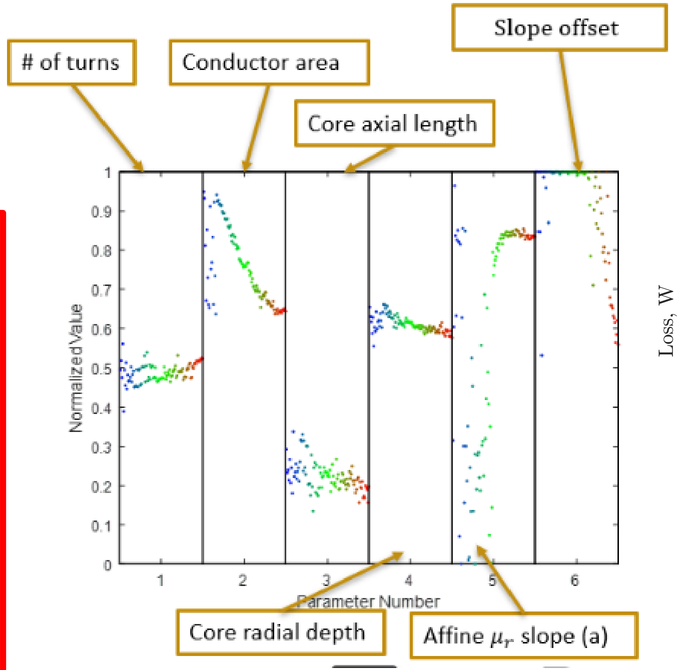
State of the Art Approaches : Multi-objective design process

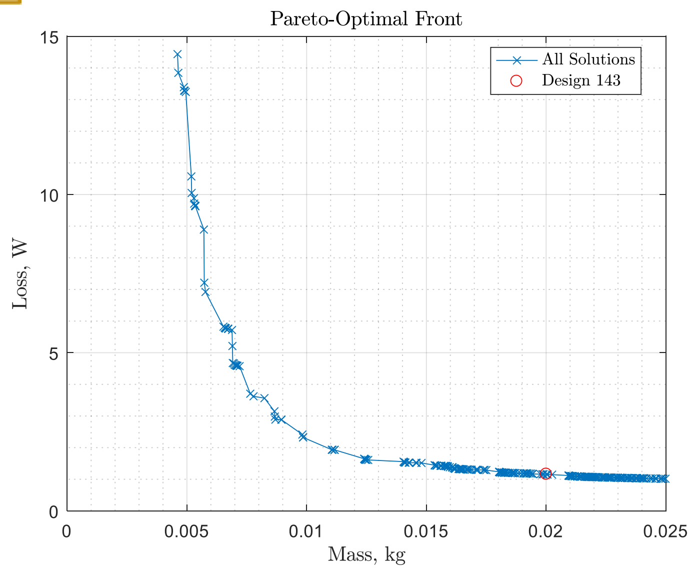
Magnetic component design methods

- Method 1: follow governing design heuristics (“rules of thumb”)
- Method 2: sweep a small set of variables to which the performance is most sensitive (sensitivity analysis)
- Method 3: employ a full multi-objective optimization.
  - Most robust approach to determine global optimal solutions
  - Limited only by the assumptions of possible design modifications



- Consider the following dimensions:
  - r_a: air window radius
  - r_i: core inner radius
  - r_o: core outer radius
  - r_e: external radius
  - l_c: core axial length

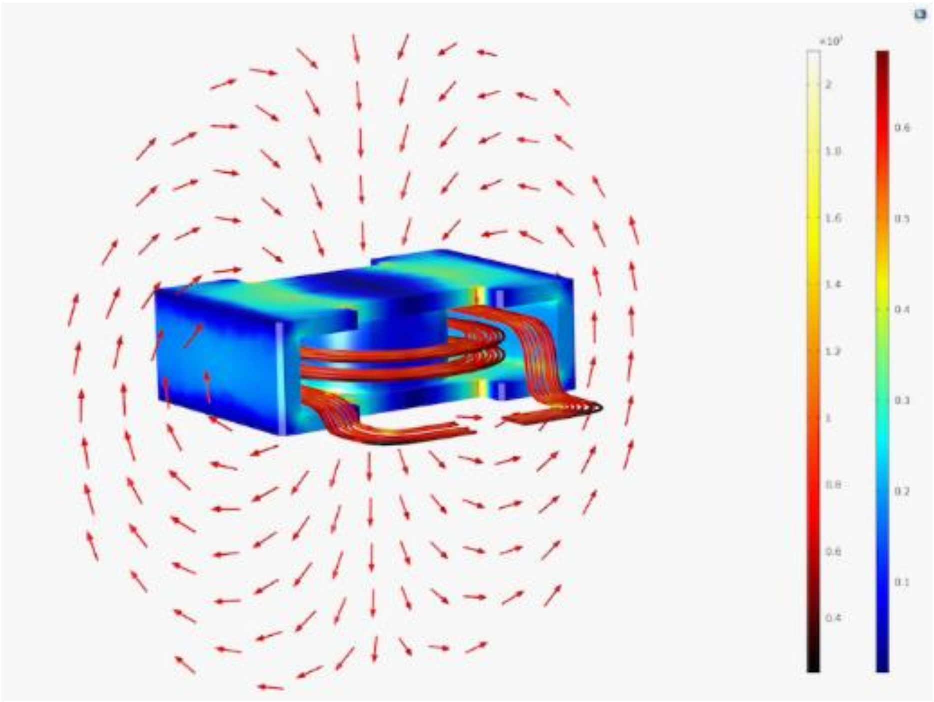




State of the Art Approaches : Component Level Modeling

Finite Element Modeling (FEA)

- FEA Pros
  - Physics can be reproduced accurately including electromagnetic performance, thermals, etc.
  - Robust, quantitative modeling is possible for multi-physics problems using FEA
- FEA Cons
  - User inputs / material models are critical
  - High computational requirements limit the application for “in the loop” design and optimization methods

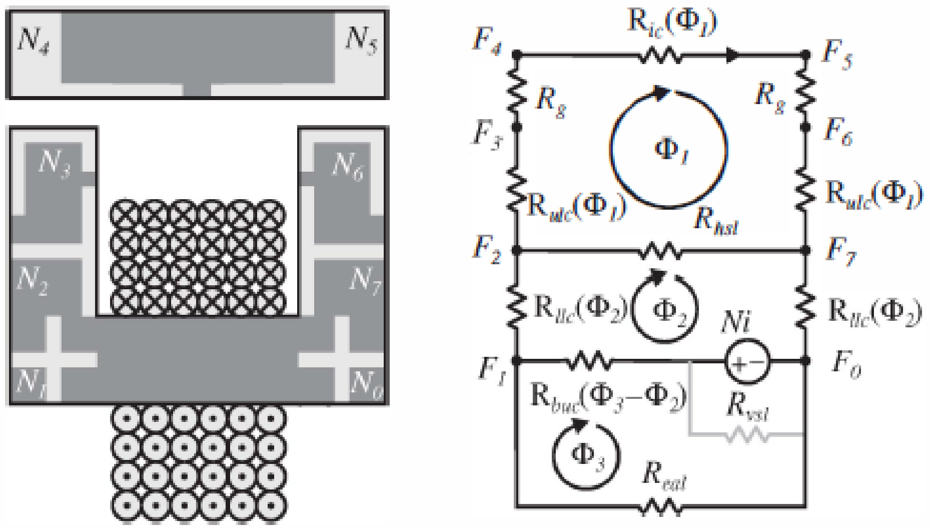


State of the Art Approaches : Component Level Modeling

Magnetic Equivalent Circuit (MEC)

- MEC Pros
    - Simplified models can be leveraged to capture the essential features of a magnetic component for designs
    - Lower computation requirements are compatible with incorporation into multi-objective design methods
    - Physics can be reproduced with reasonable accuracy over the validity range of the developed model

- MEC Cons
    - MEC models are manually derived in terms of elements
    - Detailed analysis, such as thermals, can be difficult
    - Additional elements are added manually by the engineer to improve accuracy for a subset of the design space

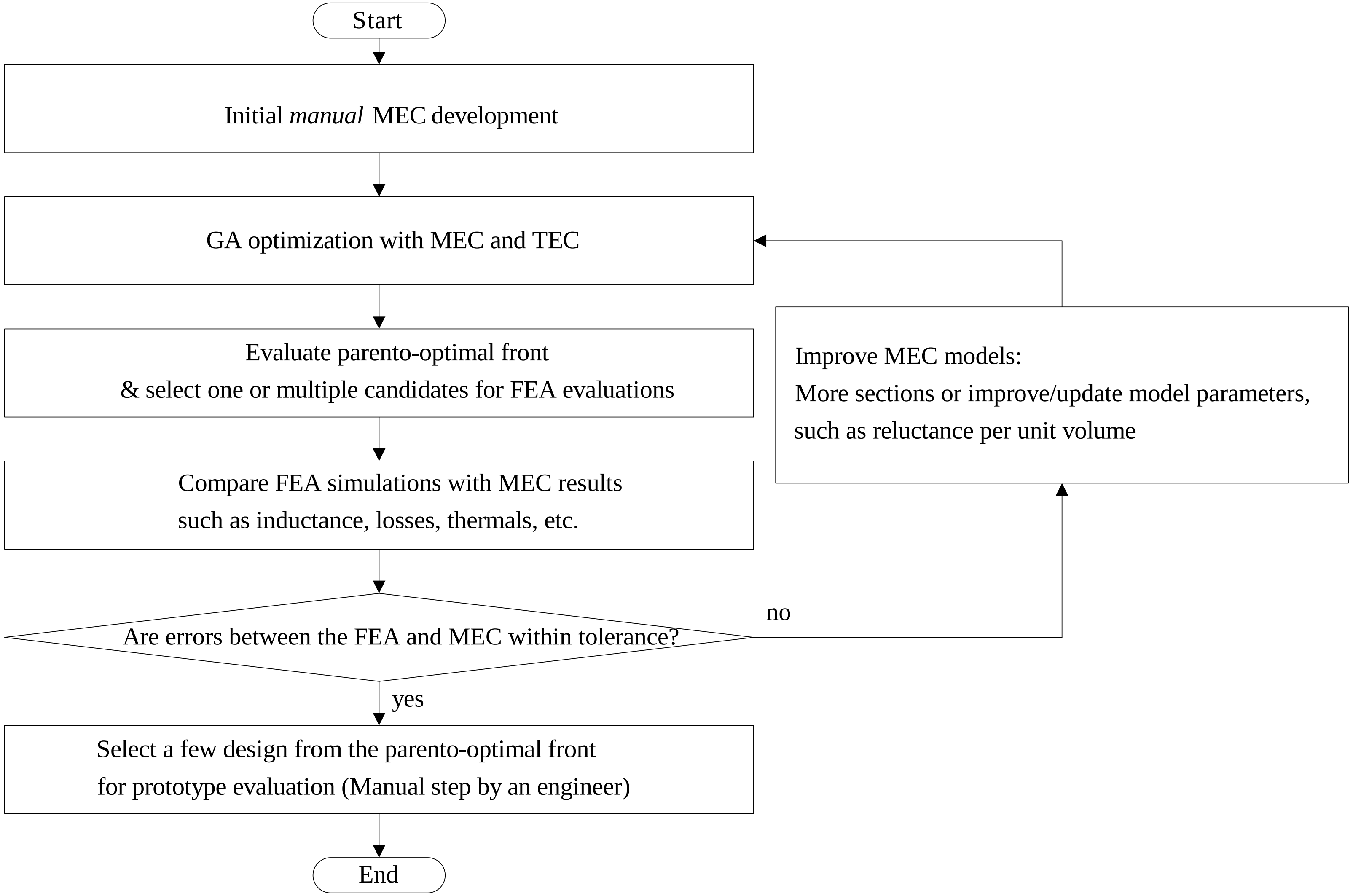


(a) cross section showing nodes (b) magnetic equivalent circuit

State of the Art Approaches : Magnetic Component Designs

Traditional multi-objective optimization

- ***User defined*** MEC models
- Accuracy check with FEA for selected designs from pareto-optimal front
- ***Manual improvements*** of MEC models based on the FEA check



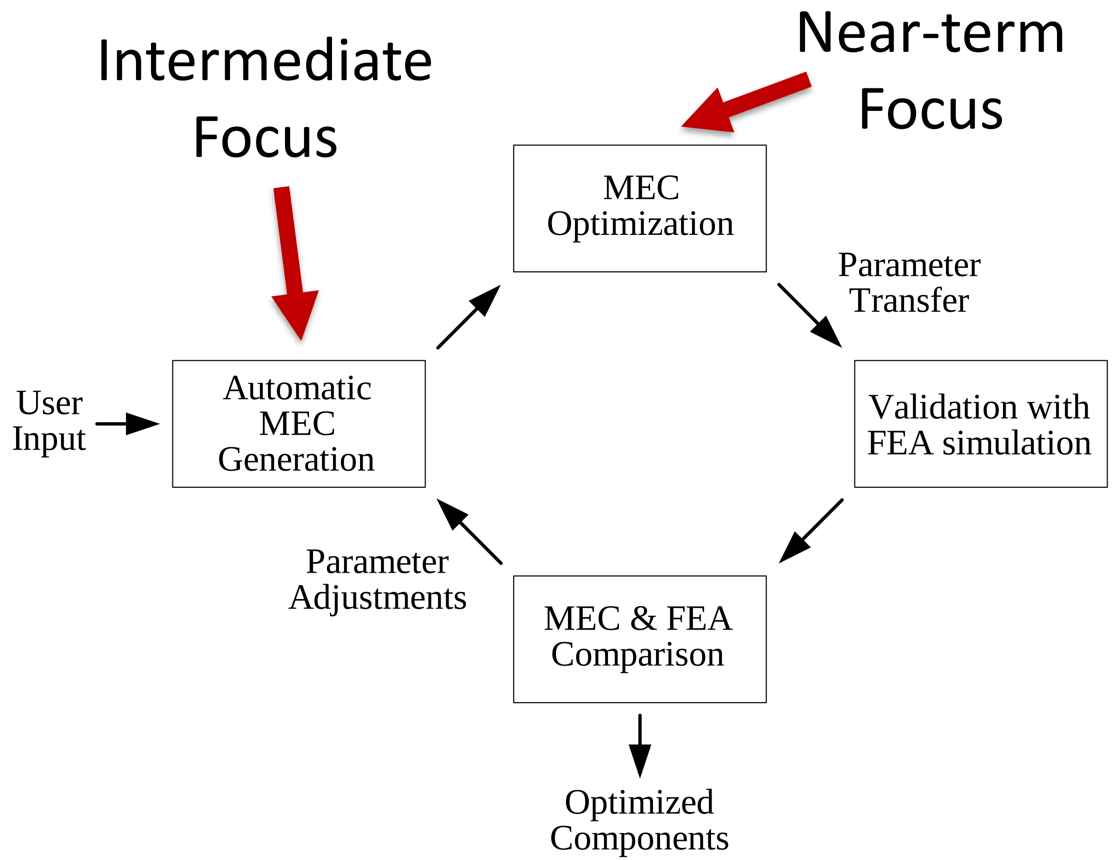
Uniqueness of the Proposed Solution : New Design / Optimization Tools

- Pragmatic, tiered approach to ensure short term value proposition and tangible outcomes while pursuing long-term objectives

- Leverage existing optimization and tool sets previously developed

- Goals are to

1) Reduce needs for user interaction
2) Achieve more globally optimized designs

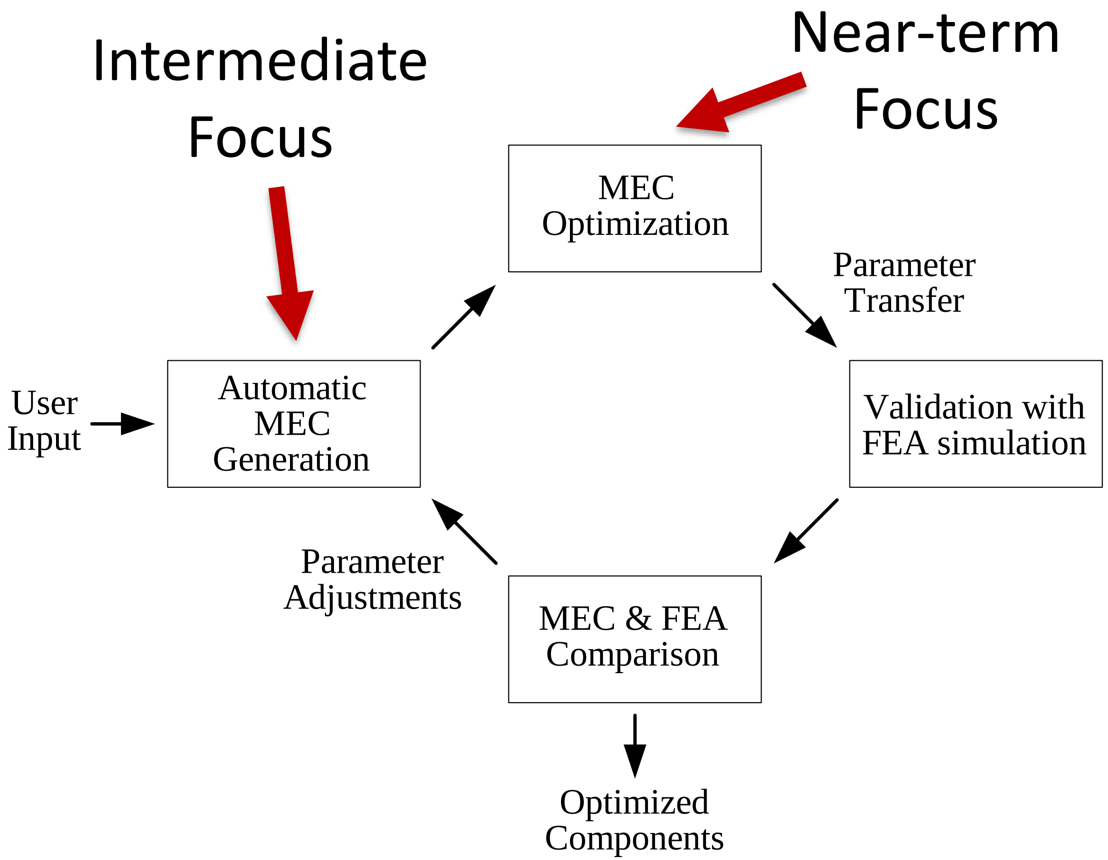


Uniqueness of the Proposed Solution : New Design / Optimization Tools

Near-term: Develop enhanced MEC models to account for spatially varying permeability and also including thermal models.

Intermediate: Develop methods for “automated MEC” development for more automated designs.

Long-Term: Utilize co-simulation methodologies for combined converter / magnetic component designs



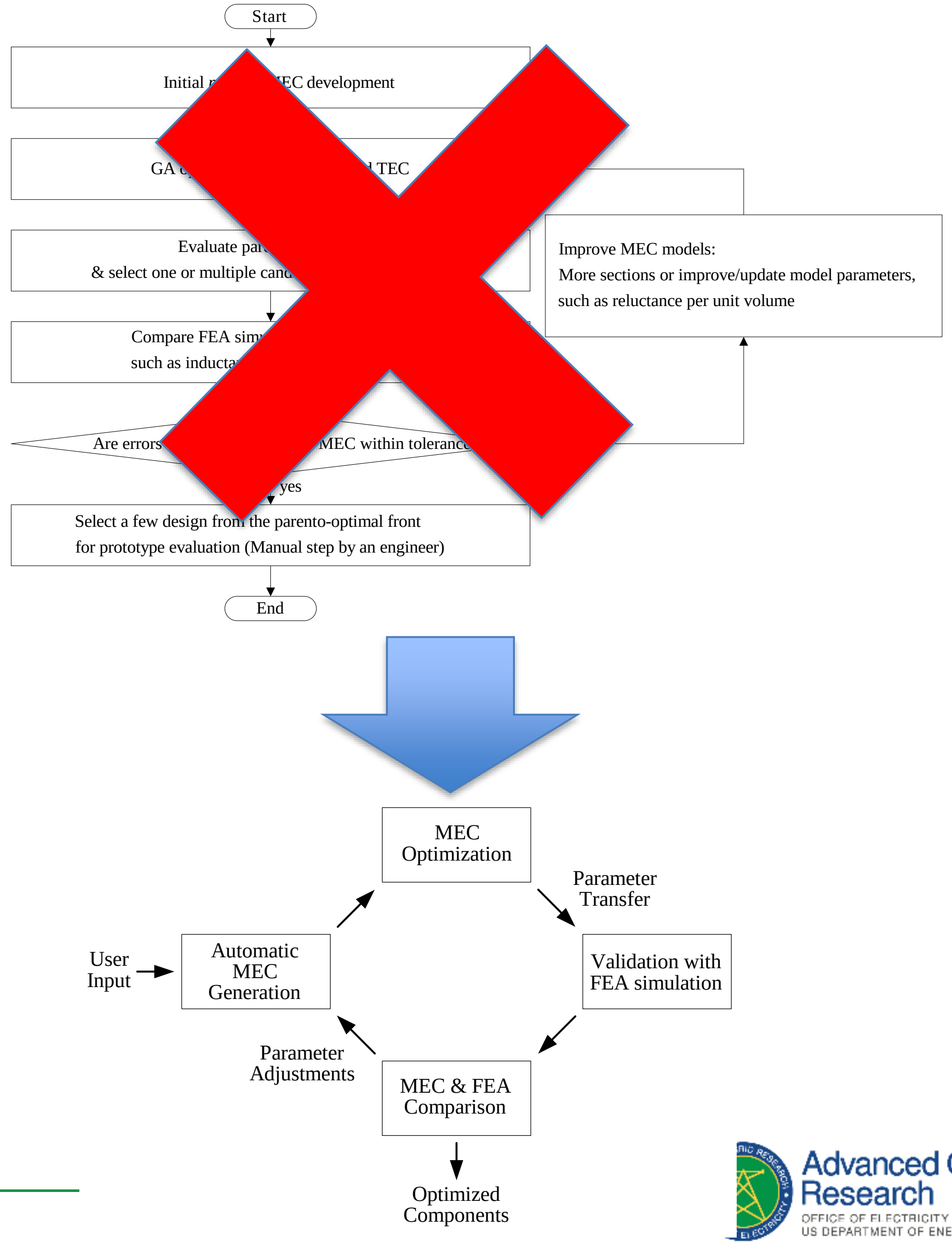
Significance of the results, if successful

- After initial specifications and design constraints, user interaction in the design process would be significantly reduced or eliminated.

- A wide range of possible designs would be explored with accurate models of the magnetic component performance, without the need for user-derived models.

- Advanced materials and processing techniques will be fully incorporated with the new design solutions.

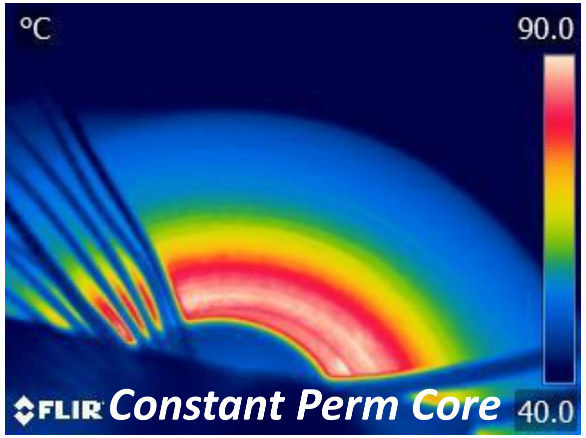
- Newly developed tools will be available to TRAC partners in the form of open source tool-kits and/or on the NETL high performance computing facilities.



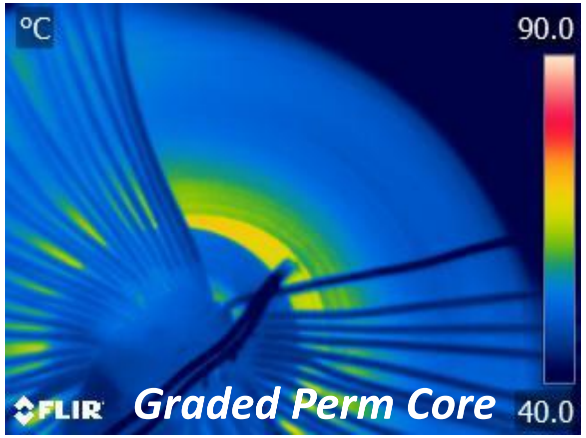
Significance of the results, if successful

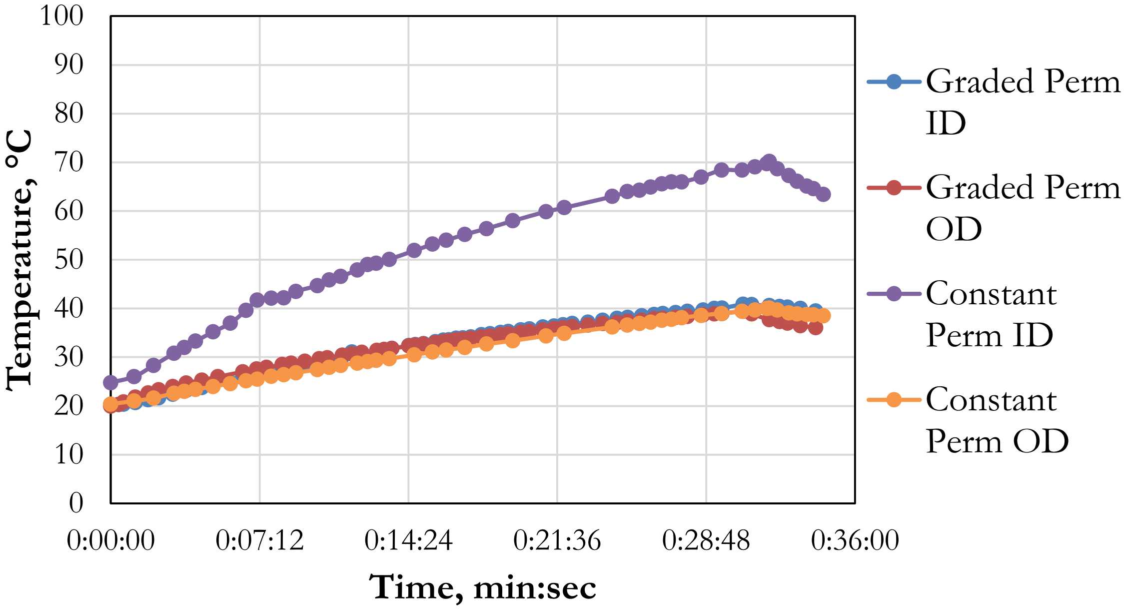
- Use-Case Example: Improved performance of inductors leveraging advanced alloy compositions and strain anneal processing
- Improved combinations of (1) power density, (2) efficiency, and (3) peak temperature rise are realized through the new design tools.

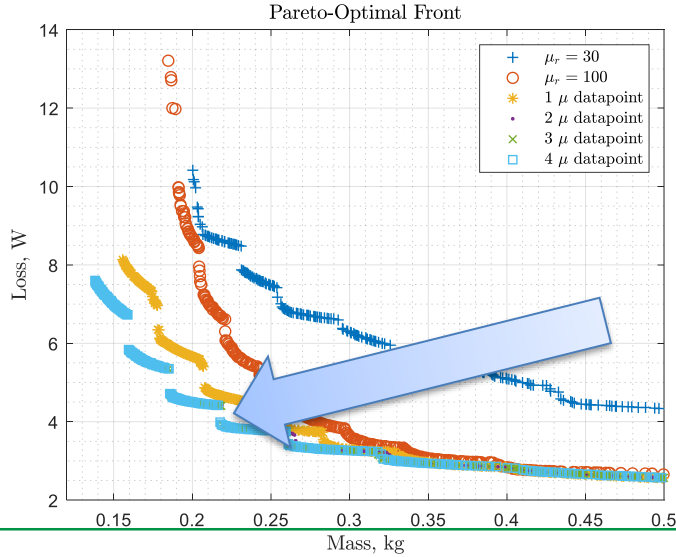
Higher peak temperature



Lower peak temperature



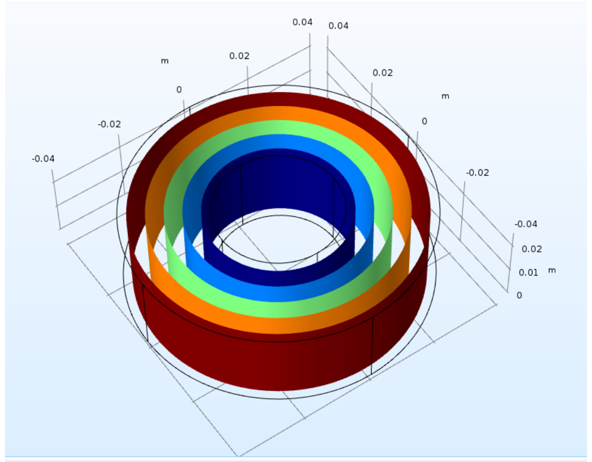


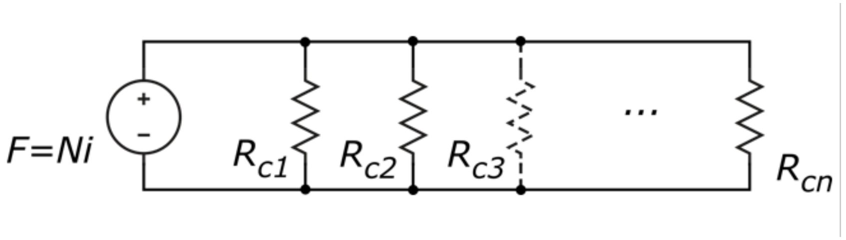


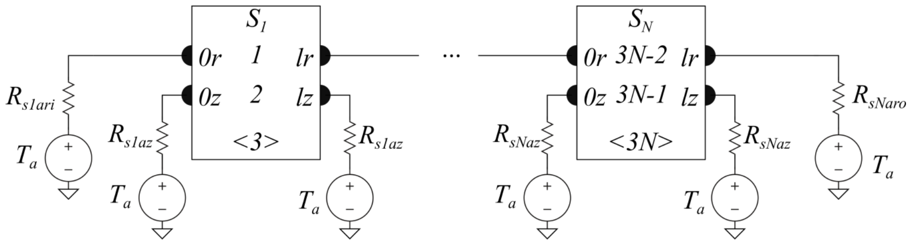
Improvement by "Permeability Engineering" method and multi-objective optimization method

Specific research questions being addressed

- Techniques for practical modeling of thermal, magnetic, and electrical performance of magnetic components through advanced magnetic and thermal equivalent circuit models
- Comparison of various methods and techniques for "automation" of the MEC development process to allow for more automated and generalized designs
- Benchmarking of performance of various models and techniques with both finite element simulations as well as model experimental prototypes to benchmark accuracy
- Methods for optimizing computational efficiency of various techniques



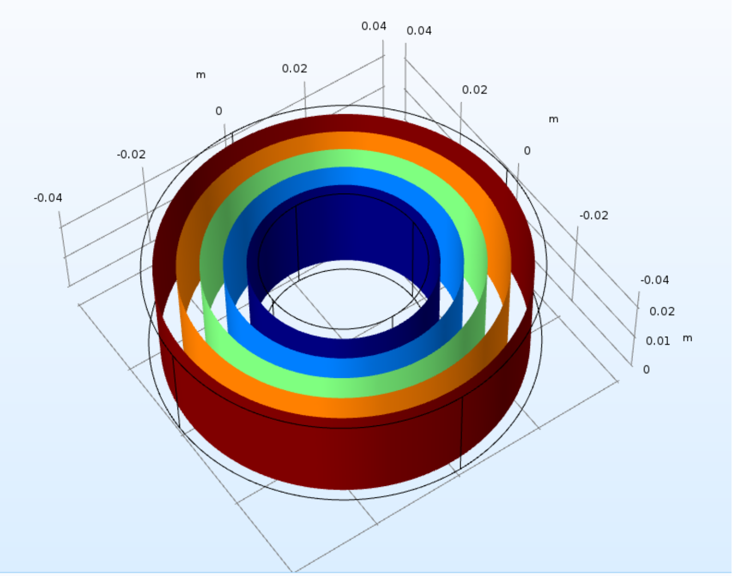


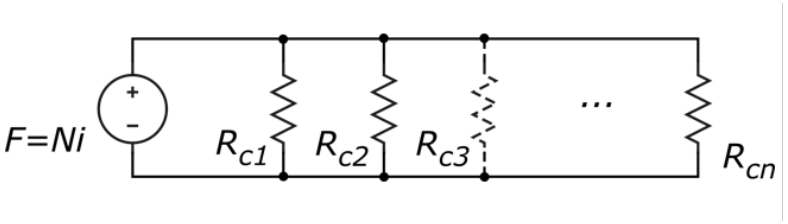


Technical Explanation: Use case "inductor" MEC modeling

Reluctance modeling

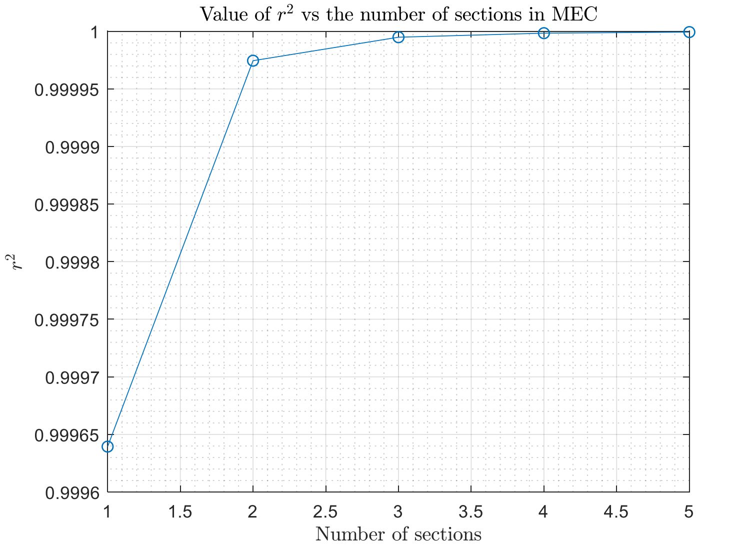
- Spatially varying permeability is captured with parallel reluctance elements.
- With more sections, the MEC models become more accurate.
- Existing MEC algorithms were enhanced to allow for an arbitrarily large number of discrete sections





$$\frac{1}{R_{total}} = \frac{1}{R_{c1}} + \frac{1}{R_{c2}} + \frac{1}{R_{c3}} + \cdots + \frac{1}{R_{cn}}$$

r^2 error as a function of section counts



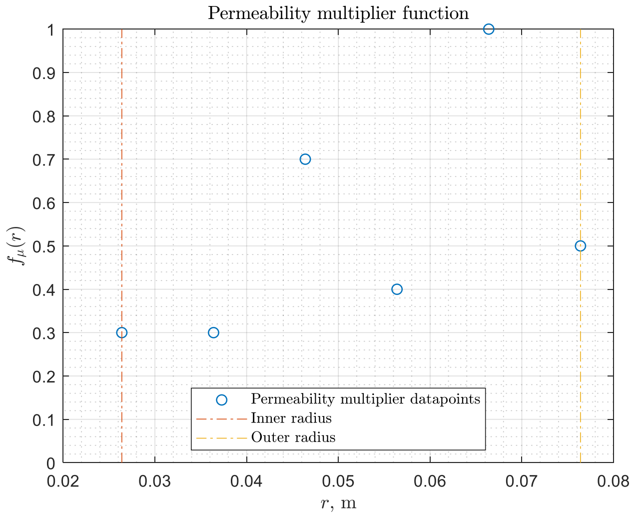
Technical Explanation: Use case “inductor” MEC modeling

Arbitrary permeability modeling

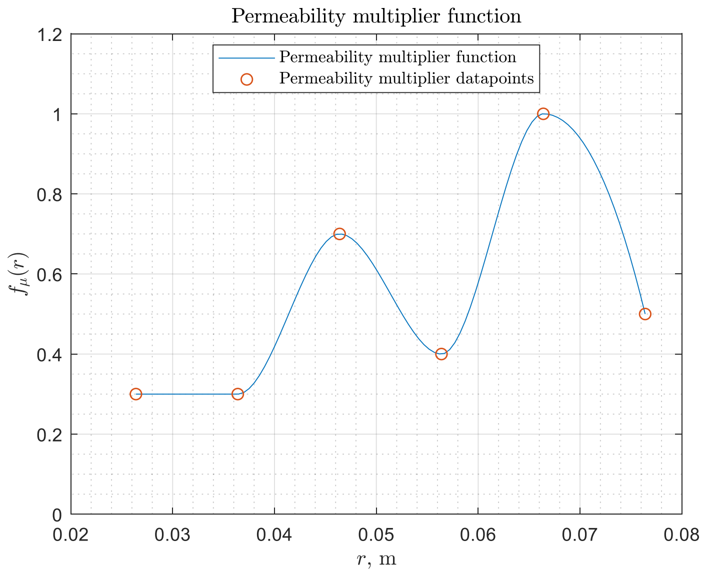
- Data points are utilized to store a profile of an arbitrary permeability.
  - Permeability = data point range from 0 to 1 (normalized) X base relative permeability (e.g. $\mu_r = 100$)

- Continuous permeability is constructed using a piecewise Hermite cubit polynomial

- In purple, the actual flux density solution across the toroid using the permeability data shown in the figure

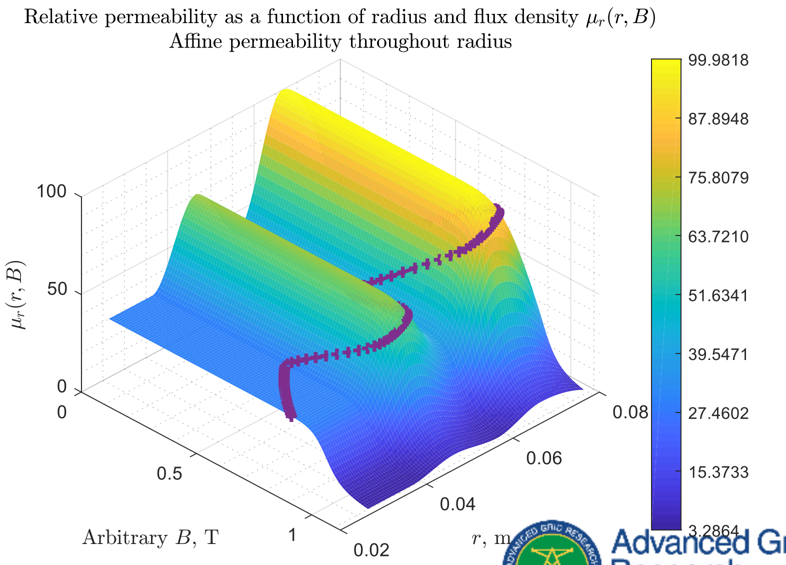


Data points



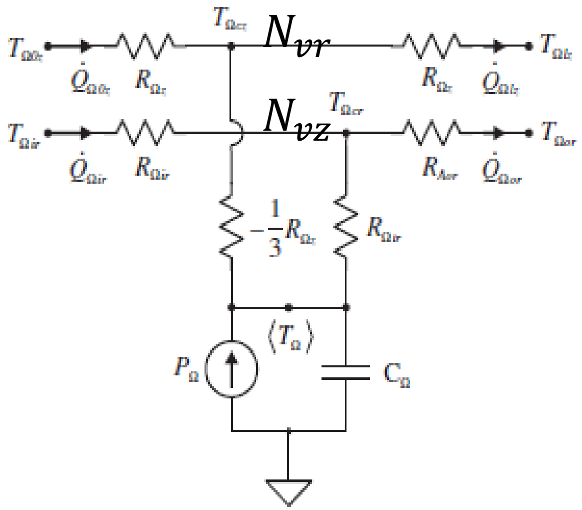
A piecewise Hermite cubic polynomial

Permeability throughout radius of a toroid core

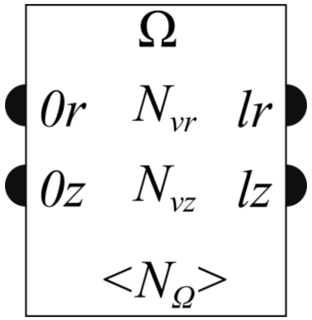


Technical Explanation: Use case "inductor" TEC modeling

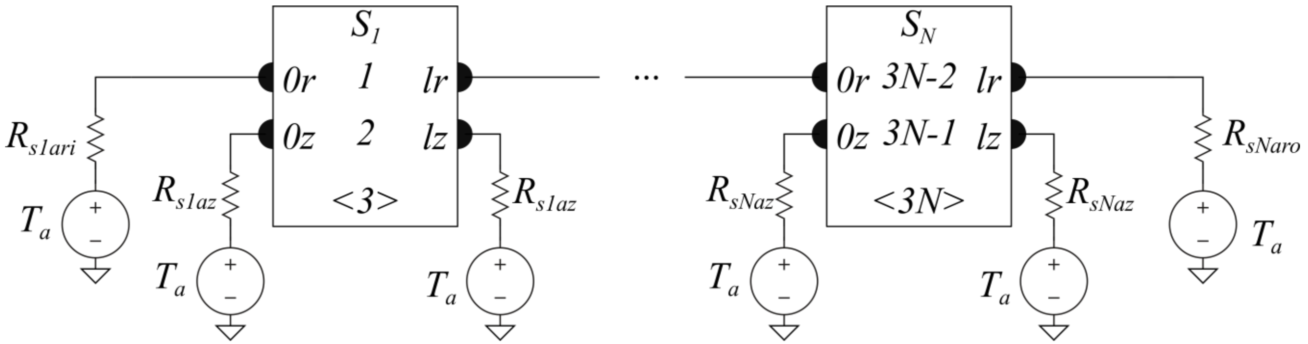
- The thermal equivalent circuit (TEC) modeling is included in the GA optimization
- Each inductor section (MEC element) is coupled with corresponding TEC element.
- TEC elements are connected to each other radially (r variables) and vertically (z variables)



Equivalent thermal model for a toroidal core



Block model with the same internal circuits



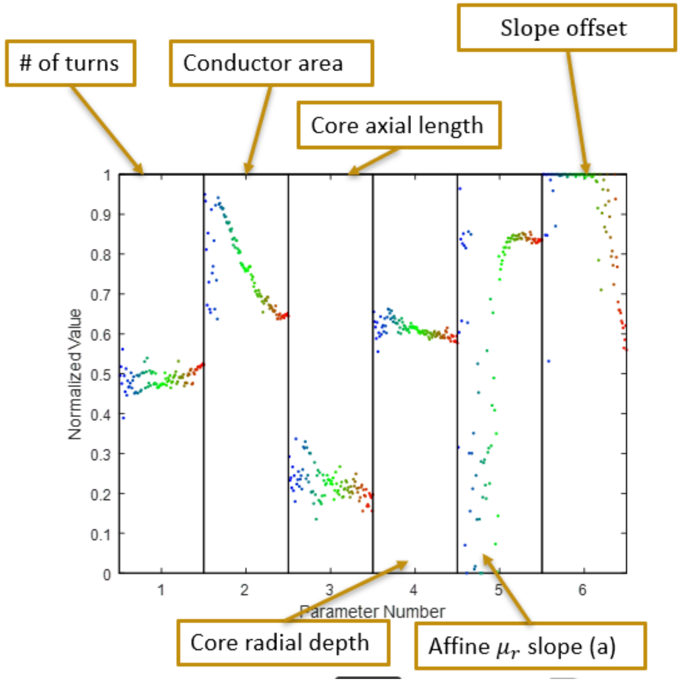
Models of multiple section of core

Technical Explanation: Multi-objective optimization

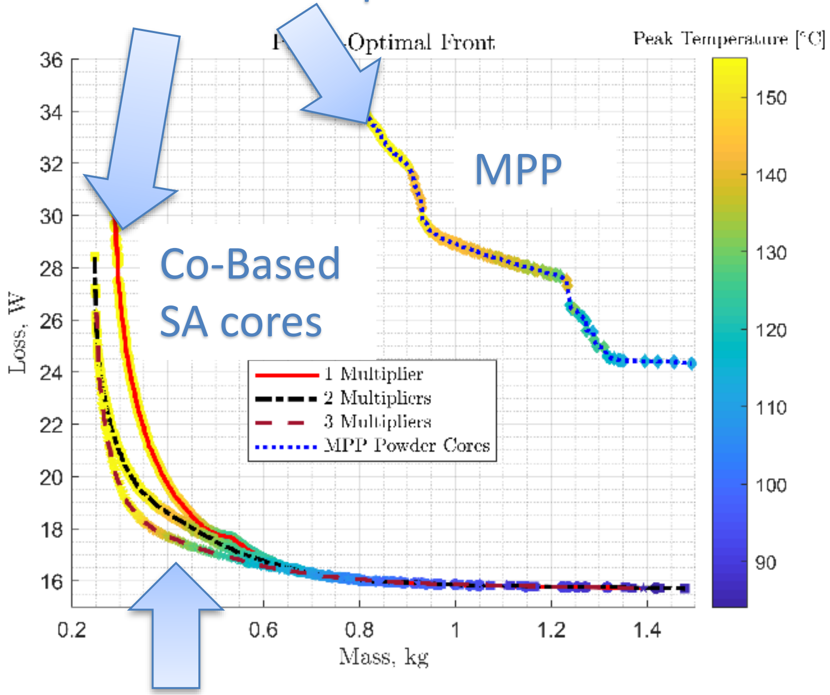
Global Optimization with Genetic Algorithm (GA)

- With multi-objective GA, design spaces are searched to optimize to losses, sizes, peak temperature, permeability profiles, etc.

- A new set of open source tools for component design in this emerging area.



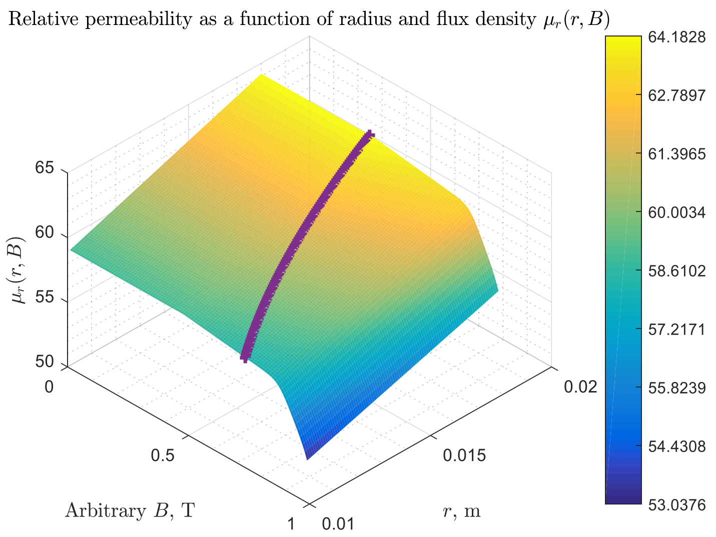
Difference between MPP powder core and NETL developed cores



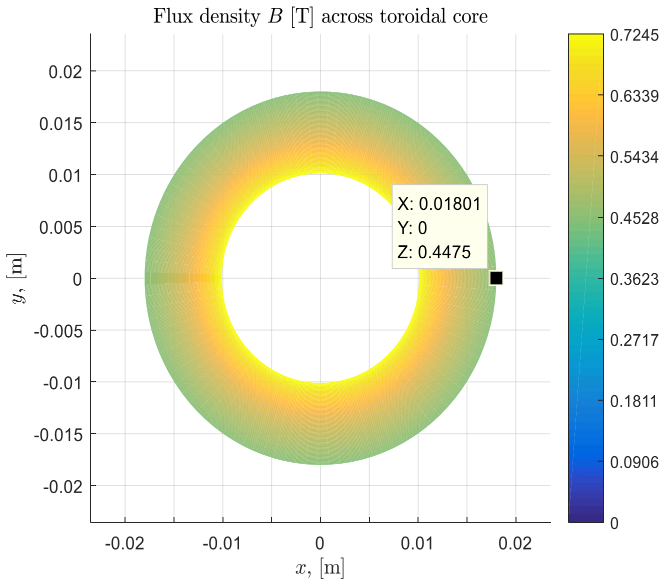
Improvement by “Permeability Engineering” method and multi-objective optimization method

Technical Explanation: Multi-objective optimization

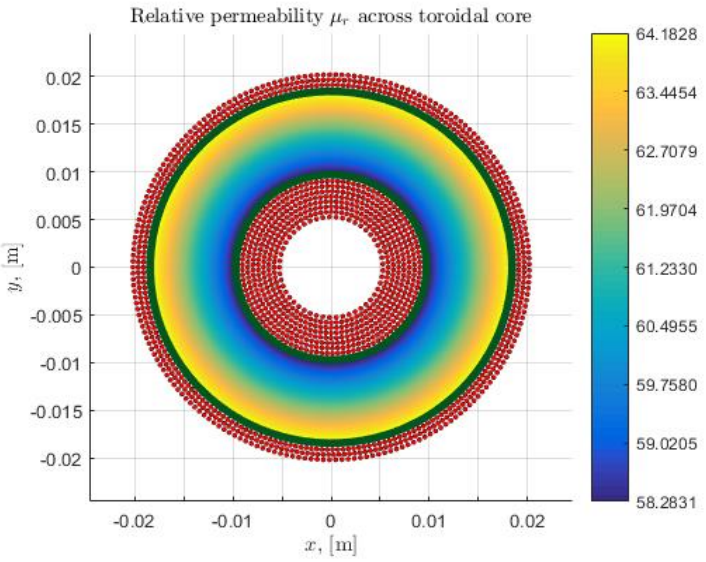
MEC Optimization results



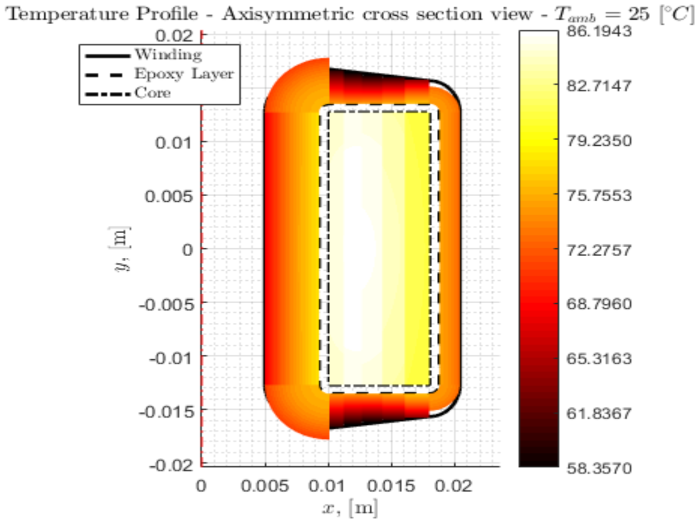
Flux Density



Relative Permeability

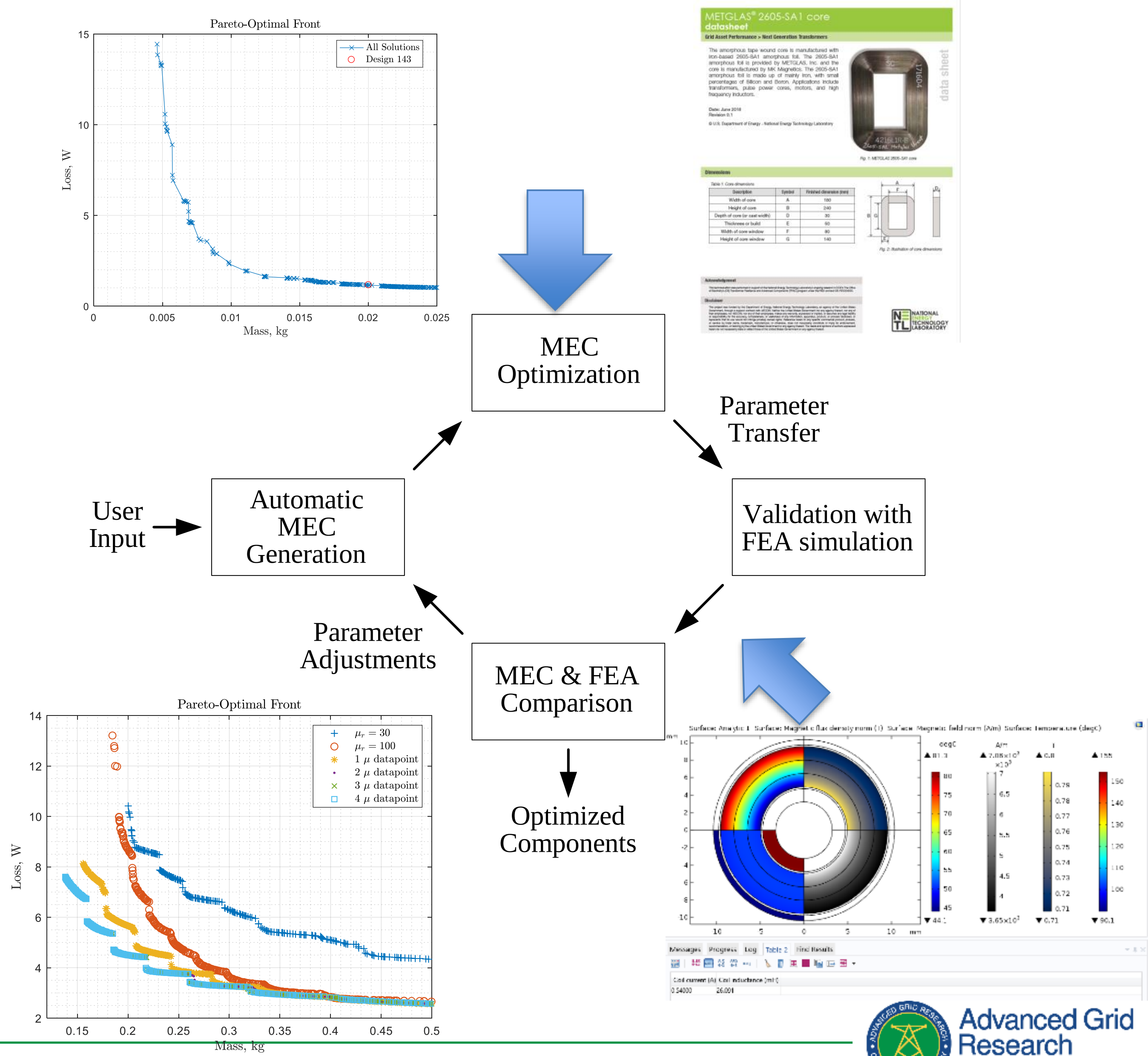


Temperature Profile



Technical Explanation: Automated MEC approaches

- Leveraging the developed MEC optimization program, our intermediate focus of automatic MEC generation is being researched.
- The inductor “use case” is utilized.
- Complexity of the models will be increased incrementally and iteratively.



Advanced Grid Research
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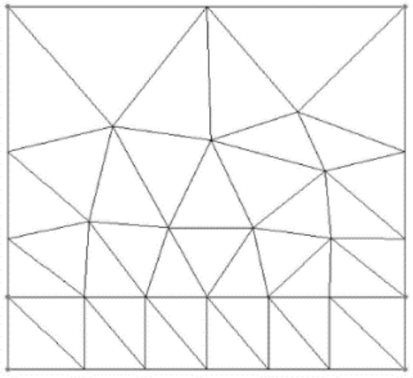
Emerging technology: Semi-automatic MEC designs

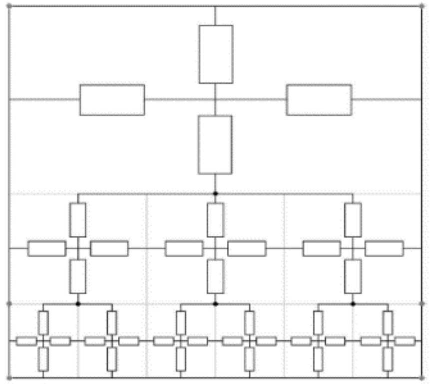
- MEC mesh method
  - Magnetics are divided into many small MEC blocks.
  - Subsequently, constructed MEC mesh is optimized by reducing the orders of the MEC elements and solved.

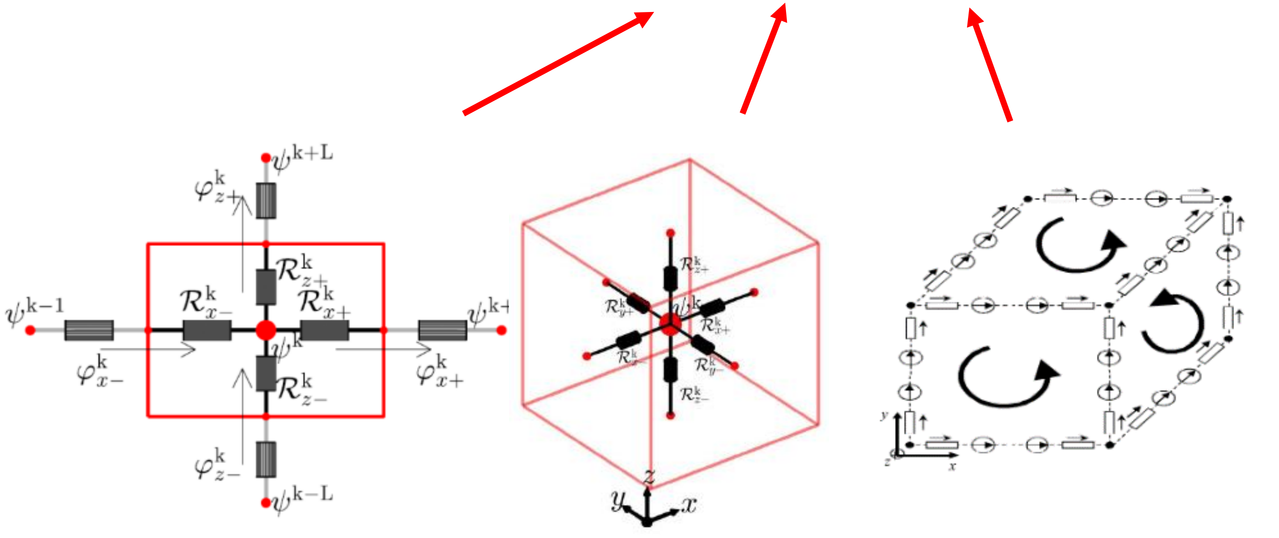
- When compared to a 3D FEA model, an error less than 1% is obtained.
  - But computation time is significant so a trade-off is required in accuracy [1].

Finite Element Analysis (FEA) Mesh



Magnetic Equivalent Circuit (MEC) Mesh



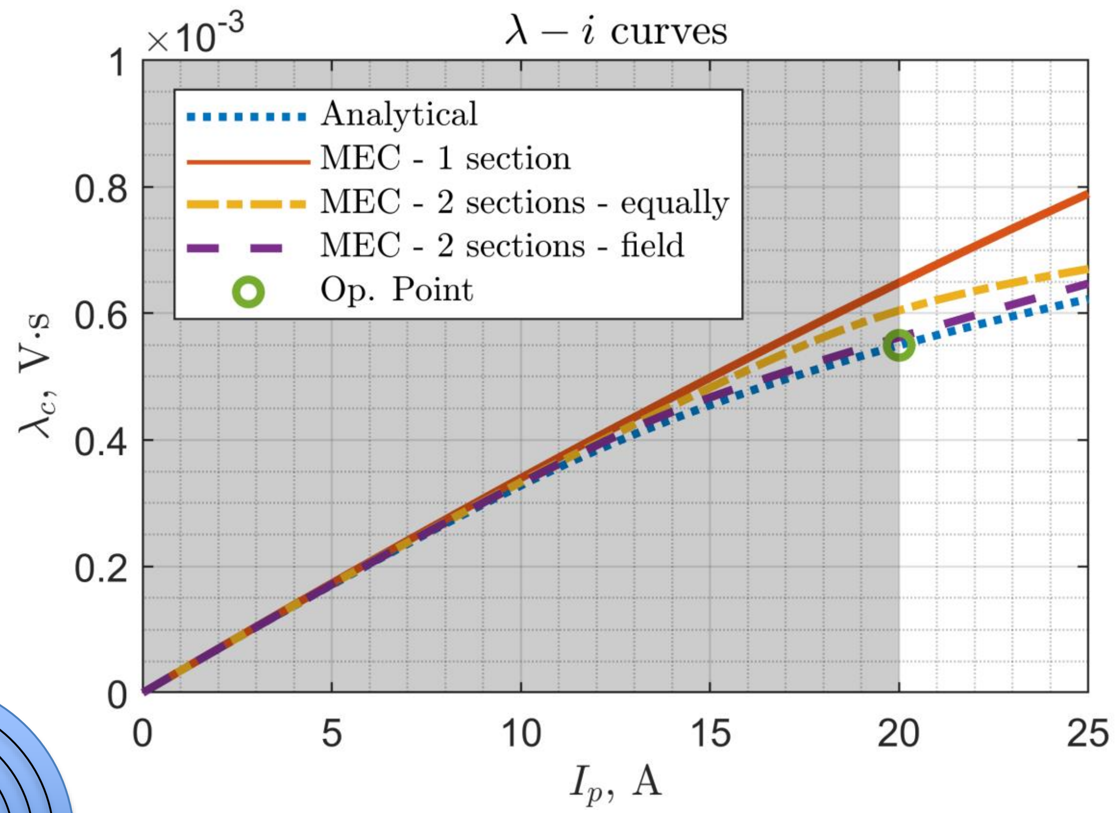


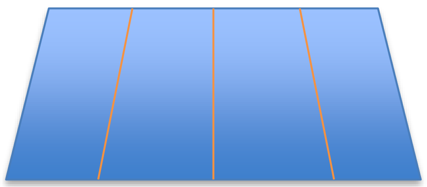
2-D 3-D Hexahedral

[1] K. J. W. Pluk, J. W. Jansen, and E. A. Lomonova, “3-D Hybrid Analytical Modeling: 3-D Fourier Modeling Combined With Mesh-Based 3-D Magnetic Equivalent Circuits,” *IEEE Trans. Magn.*, vol. 51, no. 12, pp. 1–14, Dec. 2015.

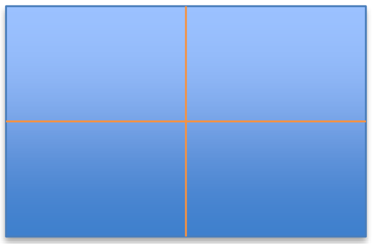
Technical Explanation: Adaptive MEC meshing

- Different automatic MEC generation methods are being searched.
- One approach is adaptive MEC meshing
  - Each element can be subdivided in a number of sections;
  - Previously, the number of subdivisions were derived manually, but we seek to determine the subdivisions automatically.

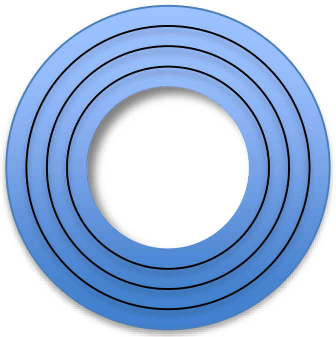




Trapezoidal domain



Rectangular domain

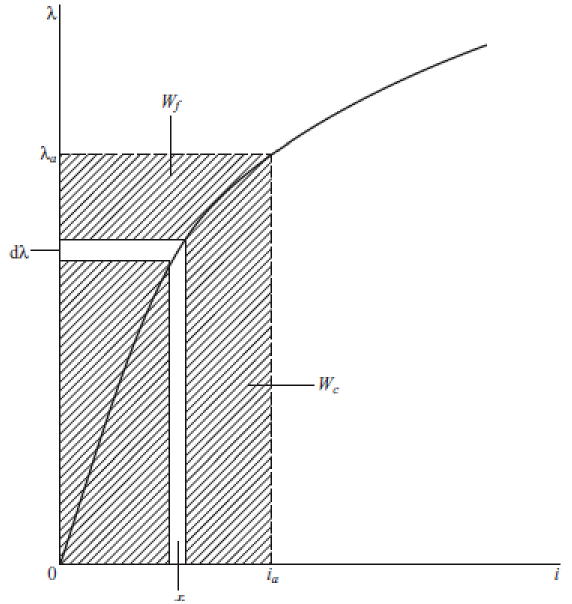


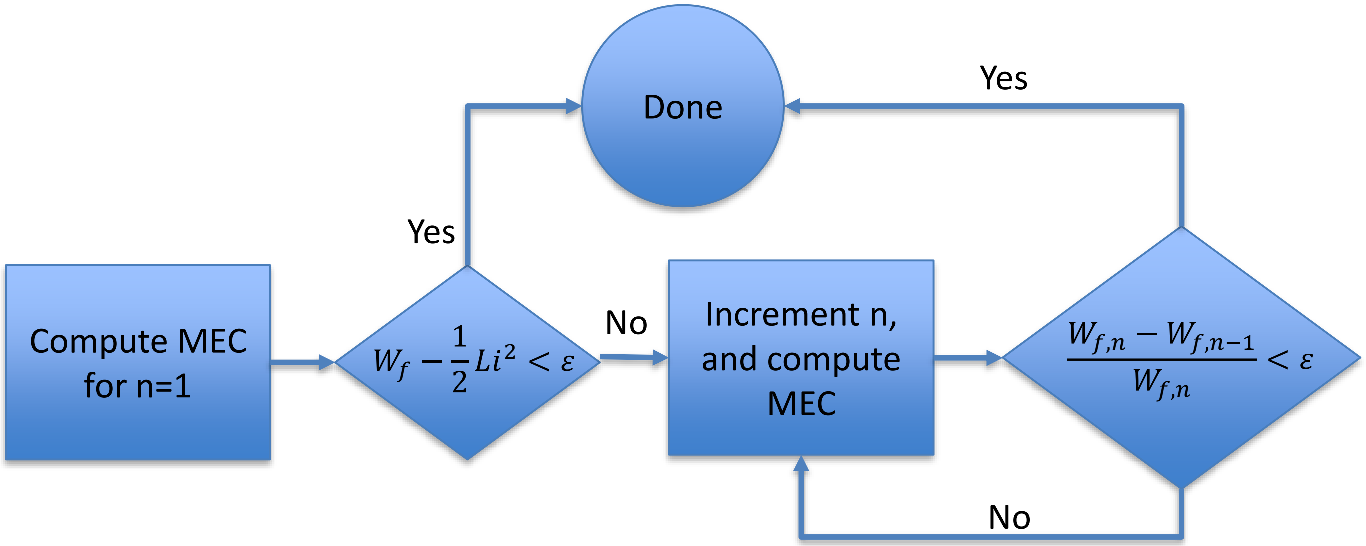
Cylindrical domain

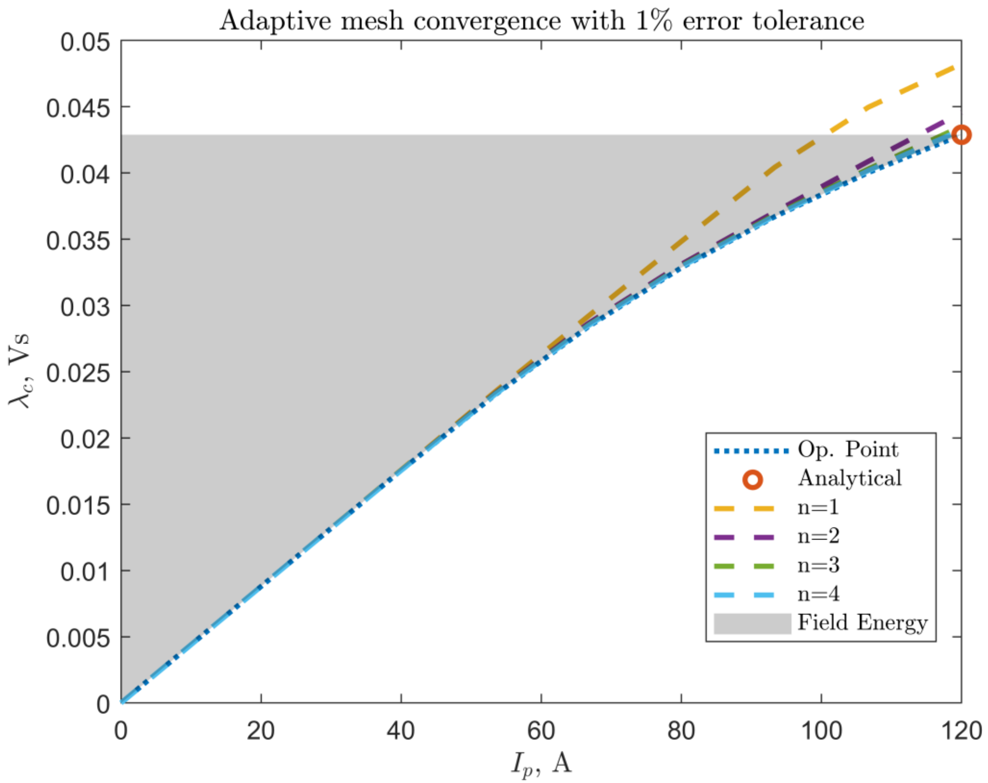
Technical Explanation: Adaptive MEC meshing

- The field energy is utilized as the determining factor of whether the adaptive MEC meshing is adequate.

- MEC meshing continues to evolve until the field energy difference is within the error margin.

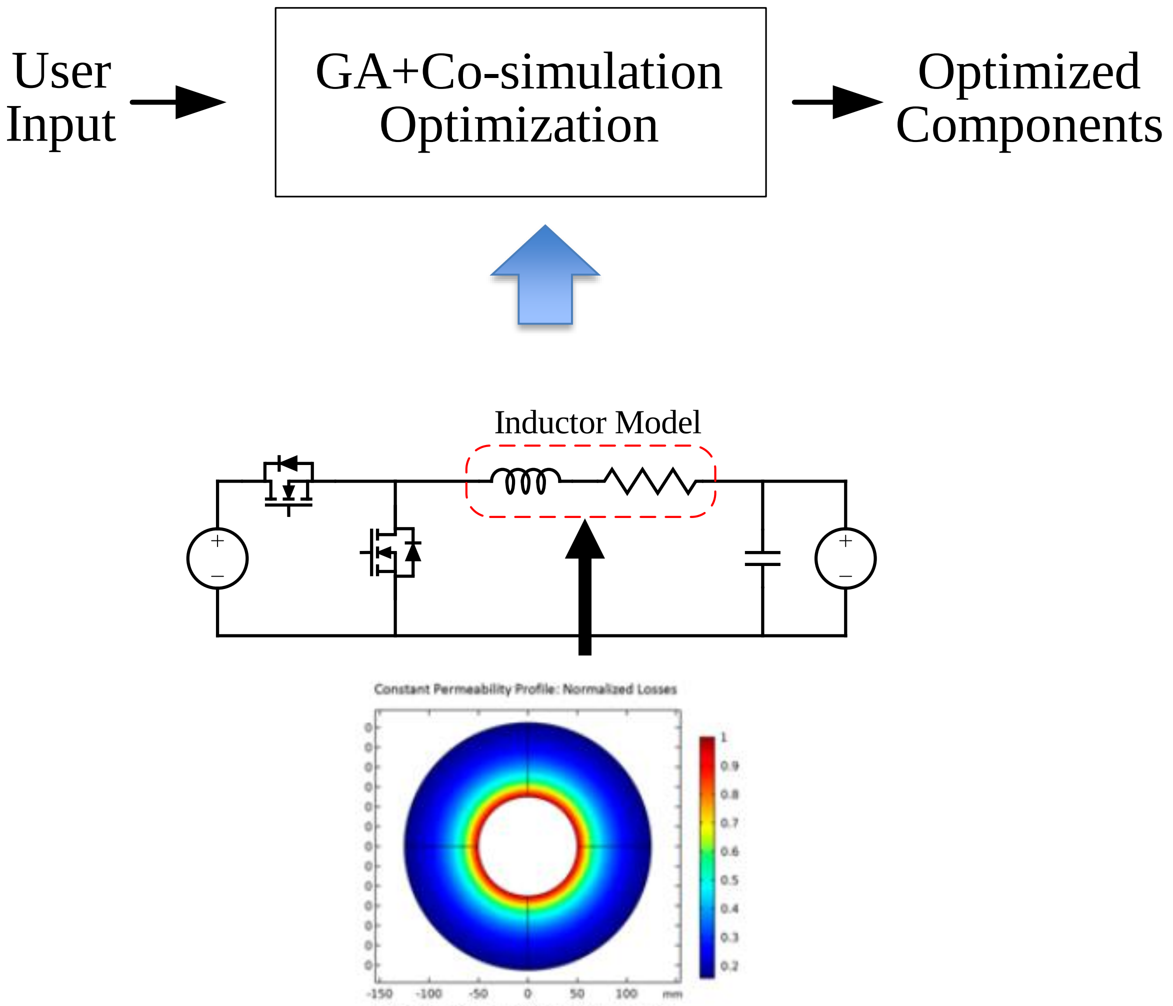






Technical Explanation: Optimization with co-simulation (Long-term)

- Instead of GA optimization with MEC, the GA optimization with co-simulation is being considered as a long-term goal
- Results from co-simulation can be parameterized and used as a design criterion in the GA optimization
- This approach can yield optimized components without iterations, but computation time is a significant practical challenge.
- High performance computing may be a requirement for this approach.



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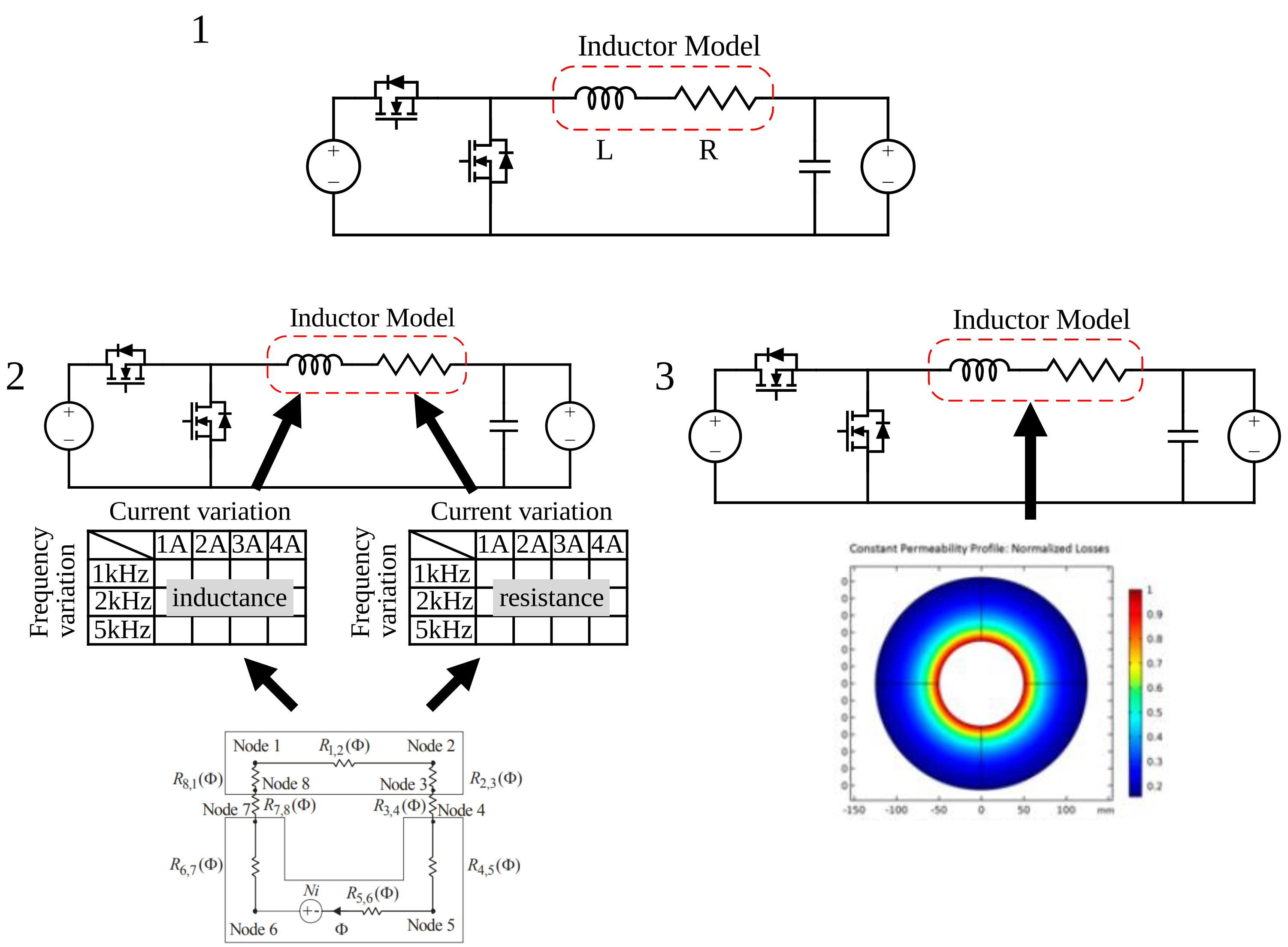
Technical Explanation: Time-domain co-simulation

1. Simple analytic models
2. Lookup table models
   - Lookup table is populated based on other simulations, such as MEC or FEA
3. Co-simulations with Finite Element Analysis models
   - FEA model interacts with circuit simulator to provide accurate results
   - Computation time is prohibitive

Co-simulation with MEC rather than FEA is a potential path forward.

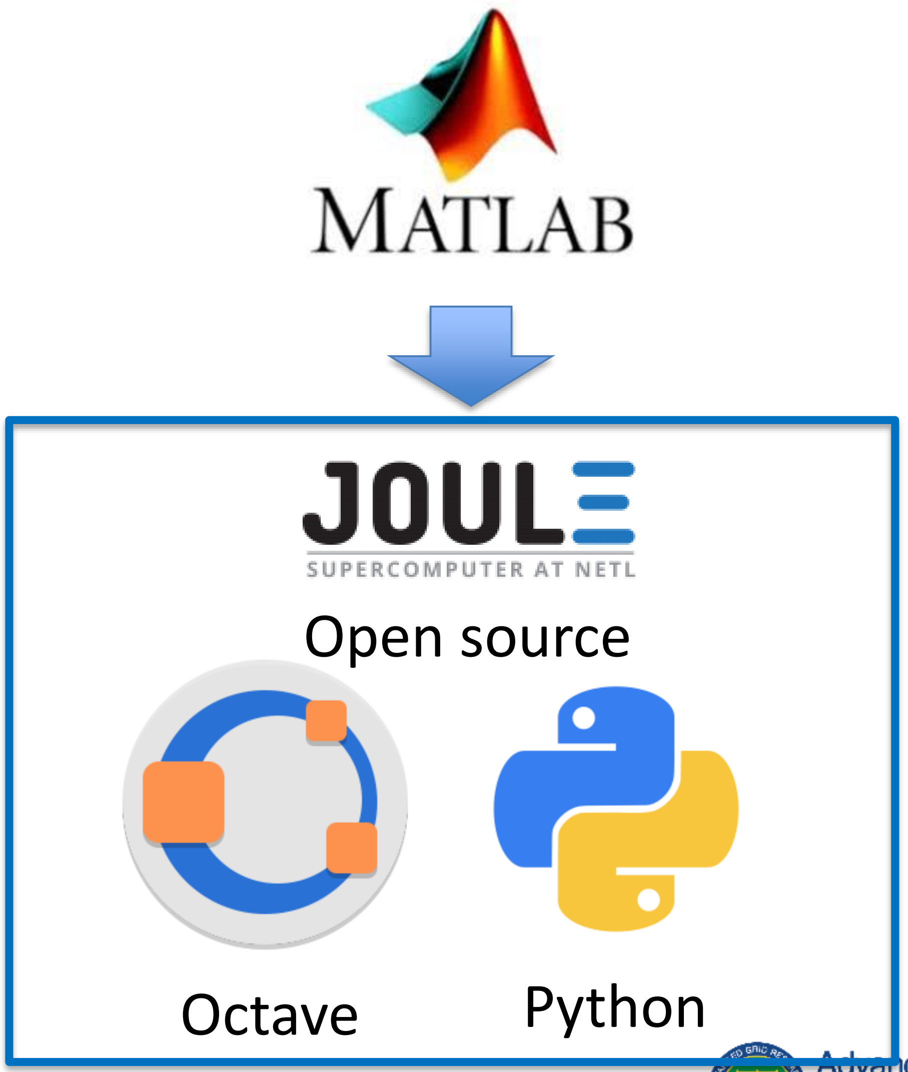


Technical Explanation

Migration to Open Source and High Performance Computing Environments

- MATLAB simulations and optimizations on a personal computer are examined to be imported to a higher computing platform, such as NETL's JOULE supercomputer.
  - MEC optimization program has been successfully imported and tested on the supercomputer.

- Additionally, migration from MATLAB to open-sources, such as Octave and Python, is explored for better accessibility.



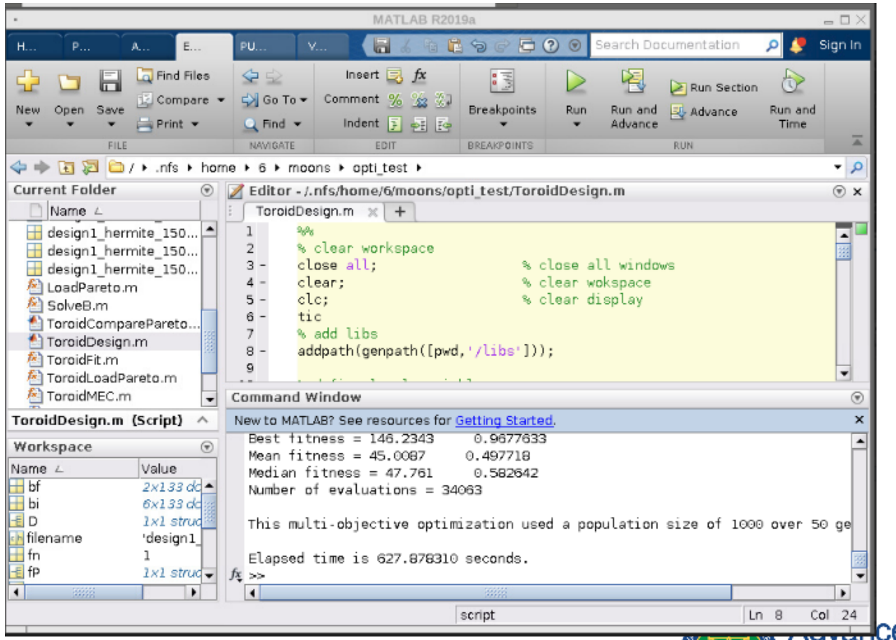
Computing performance comparison

- The GA simulation requires many generations, typically over 1000~2000 generations in the inductor designs, until optimal designs are found.

- Based on the simulation of 50 generations and 1000 populations

- Preliminary comparison suggests the NETL Joule Supercomputer with parallel processing can improve the simulation time by 10x compared to the PC

	50 generation	2000 generation (estimated)	Computation time comparison
Standard PC	999 sec	11.1 hours	100% (base)
Supercomputer without parallel processing	627 sec	6.97 hours	62.7%
Supercomputer with parallel processing (Estimated)	100 sec	1.11 hour	10%



Project Schedules

- Develop and Demonstrate Proof-of-Concept for Integrating Converter Design and Finite Element Based Magnetics Component Simulations in Magnetics Optimization
  - Budget Period 1: Explore Co-Simulation environment (MATLAB/SIMULINK – PLECS – COMSOL) & partially automatic magnetic design processes
  - Budget Period 2: Develop inductor global optimization program with genetic algorithm as a use case (GA)
  - Budget Period 3: Develop automatic inductor design and optimization program using GA and FEA & Migration to open source and high performance computing environment

Project schedule, deliverables, and current status

Milestones:

BP1: Develop and Demonstrate Proof-of-Concept for Integrating Converter Design and Finite Element Based Magnetics Component Simulations in Magnetics Optimization

√ Build converter model in Matlab-Simulink w/ various transformer equivalent circuits

√ Demonstrate successful integration of Comsol and Matlab

√ Perform a parameter variation comparison between standard converter simulations with analytical models and finite element integrated models

BP2: √ Select a "use case" topology for demonstrating advantages of new modeling

√ Build and simulate a model of selected "use case" topology using standard methods and newly developed methods

√ Provide recommendations for scaling computational methods and future approach

BP3: Develop automatic inductor design and optimization program using GA and FEA & Migration to open source and high performance computing environment

√ Literature review and brain-storming on automatic MEC generation method, (3/31/2019) (Complete)

√ Importation of FEA results of "use case" topology to MEC generation domain, (6/30/2019) (Complete)

√Comparison of FEA results with Genetic Algorithm Optimization result to understand requirements and limitations of an automated MEC generation, (6/30/2019) (Complete)

- Demonstrate a first automated MEC algorithm and compare with FEA for benchmarking, (9/30/2019)

- Update and "fine-tune" the parameters of the automatic MEC generation based on the comparison in Q2 and apply to a selected "use case", (12/31/2019)

- Verification of the automatic MEC generated "use case" topology in the multi-physics domain

Deliverables:

- Technical report demonstrating advantages of new methods under development, End of Q4

Milestones On Track

Deliverables On Track

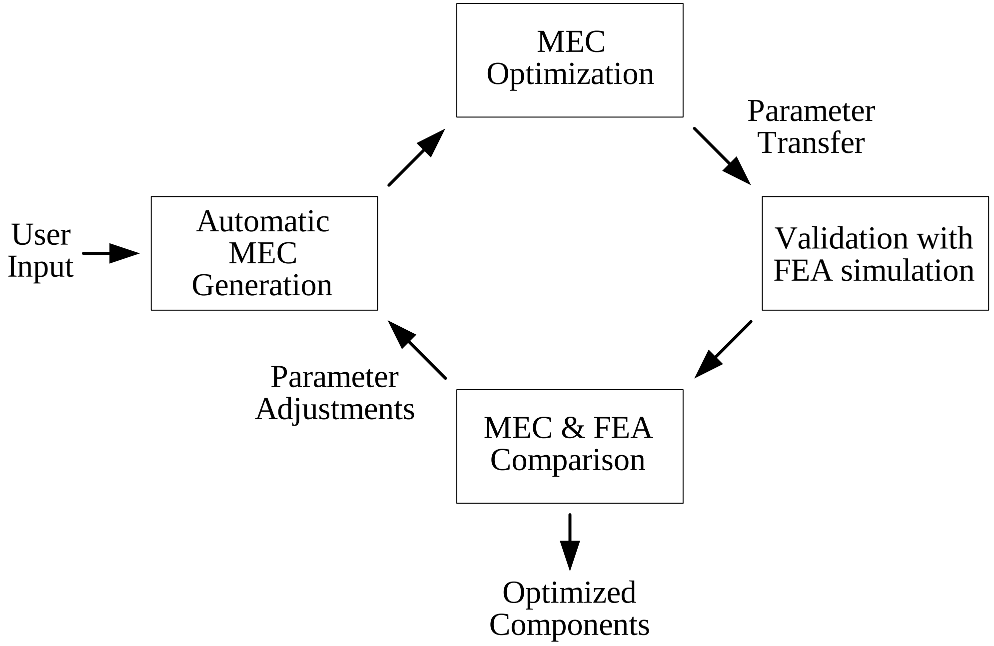
Total Budget = ~$550k
BP3 Budget Remaining = ~$100k
Spending On Track

Anticipated challenges and risk mitigation strategies

Challenges/Risks	Severity	Probability	Mitigation Strategy
New tool development can require significant time and foundational efforts	Medium	High	Leveraging existing methods and tools developed, and build upon them to pursue the project objectives. Engage key university partners developing automated design methodologies.
High computation requirements may preclude tools from being utilized	High	Medium	Pursue a step-wise approach, with a focus on early tool development from established tools that are computationally efficient. Gradually build towards more computationally intensive models and methods.
Commercial licenses may preclude users from leveraging developed tools	Medium	Medium	Seek to transfer developed tools to open source platforms, and develop initial tools with open source platforms ultimately being the target.
TEC model used in GA optimization might not be accurate	Low	Medium	Once the design iteration loop is closed, the comparison and adjustment of TEC with FEA result can improve the TEC results as the number of iteration increases.
Design iteration might not converge to a stable result	Medium	Medium	Currently, a simple factor correction is considered. Alternative convergence algorithms will be pursued as needed to ensure a balance between accuracy, computational efficiency, and convergence.

Next steps

- Research and refine automatic MEC method
- Complete the individual step verification and bring everything together on automatic MEC process (closing the loop)
- Extend the modeling efforts to more complex components, such as EI core inductors and transformers
- Further evaluate feasibility for co-simulation methods to incorporate converter performance within the optimization
- Transition to open source platform
- Further engage with industrial and TRAC program partners to leverage new tools for programmatic impact



Broader Impact: Presentations, papers, and open-source programs

- Past presentations
  - Power Sources Manufacturers Association (PSMA) Magnetic Workshop on March 16, 2019 at Anaheim, CA
  - Applied Power Electronics Conference (APEC) Industry Session: High Frequency Magnetics: New Magnetic Materials on March 19, 2019 at Anaheim, CA
- Future planned presentations
  - 2019 Coil Winding Expo (CWIEME) America, Chicago, IL, Sept 17-18
  - 2019 IEEE Energy Conversion Congress & Expo (ECCE), Baltimore, MD, Sept 20-Oct 3
- Submitted abstracts
  - 2019 MMM Conference – Title: A Multiphysics Assessment on Permeability Tuning Techniques in Power Inductors. Purdue University Submission
  - 2020 TMS Annual – Title: Multi-Objective Design of Permeability Engineered Soft Magnetic Metal Amorphous Nanocomposite Cores. An invited presentation.
- Planned transaction paper
  - Title: Multi-objective Optimization Paradigm of Toroidal Inductors with Spatially Tuned Permeability Using Thermal and Magnetic Equivalent Circuits.
- The developed MEC optimization programs on MATLAB are being transferred to open source platforms. It will be available to TRAC partners in the near future.

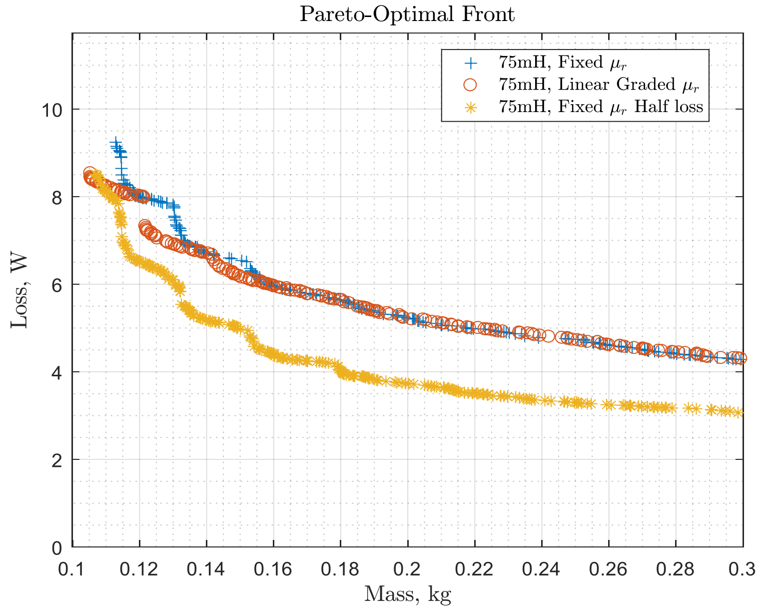
Broader Impact: Industrial collaboration

- Collaboration with Mainstream Engineering

- Development of highly optimized inductors using the developed GA inductor design program

- Lower inductor temperature due to the combinations of better core materials, permeability engineering, and optimizations

Application	#1	#2	#3
Target Inductance (mH)	25	75	8.2
Copper Losses (W)	1.64*	3.19*	2.11*
Core Losses (W)	0.3 @ 10 kHz	1.48 @ 5kHz	4.55 @ 25 kHz
Design Max Peak Winding Temperature (°C)	125	150	150
I_{max} (mA)	540	960	1372
Estimated Max Flux Density (T)	0.72 @ 10 kHz	0.87 @ 5kHz	0.69 @ 25 kHz



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