Virtual Prototyping Project

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Aim

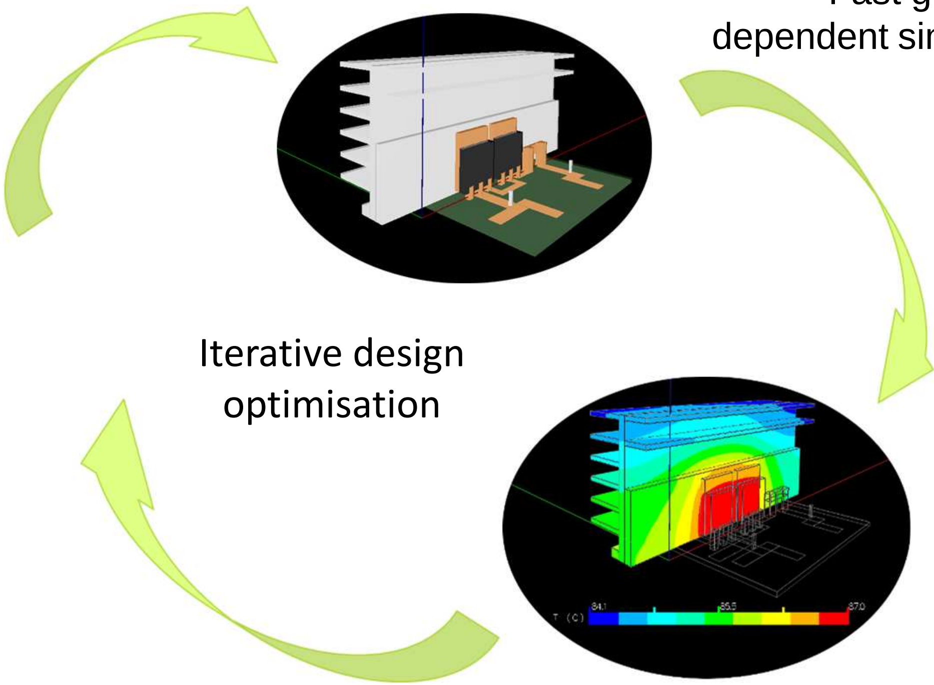
Developing simulation methods and software for iterative design optimisation

Coupled, Multi-Domain Effects

- Semiconductor
- Electrical/Electromagnetic
- Thermal
- Mechanical/Robustness

Targeting:

- Fast simulation
- Tools/techniques that could be used by typical power electronics engineers



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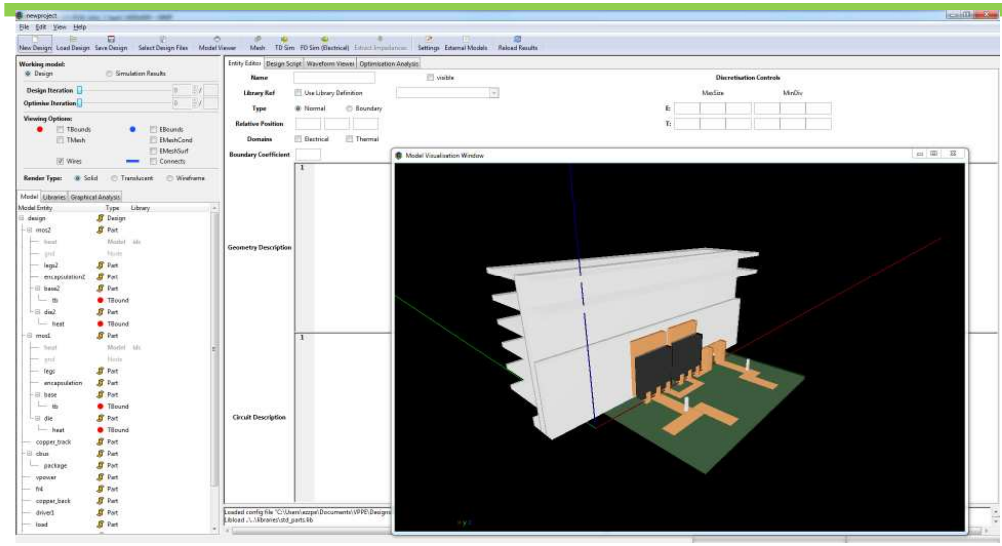
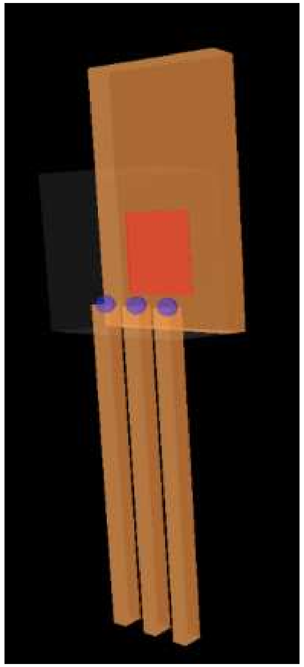
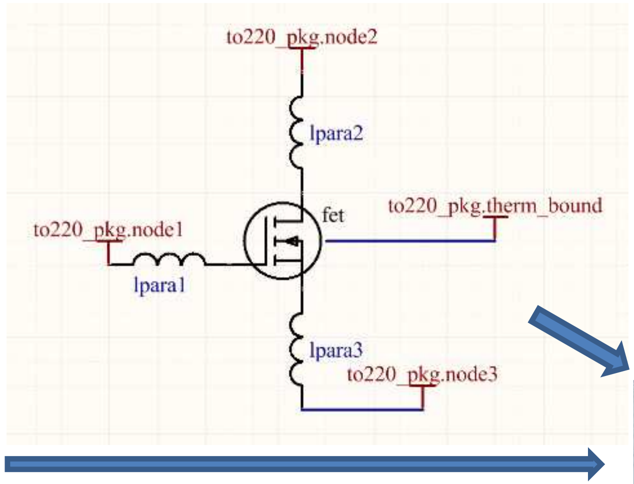
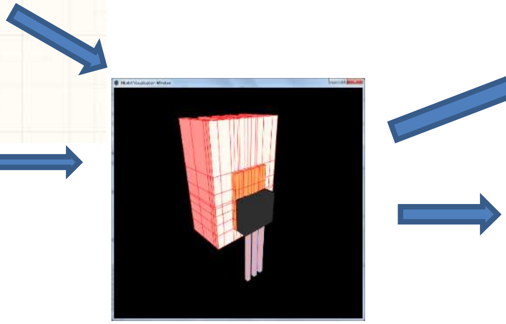
Software

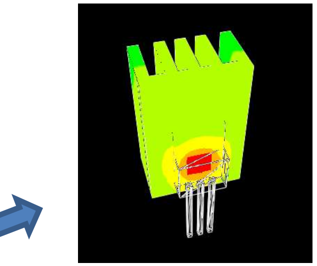


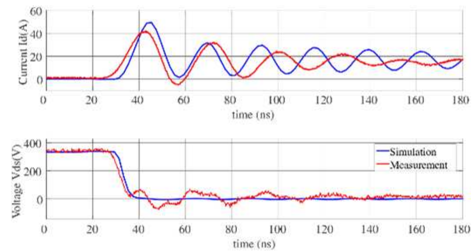
- Dual circuit – geometry description of components
- Numerical methods add equations to simulation to take effect of design geometry into account
- Power electronic circuit simulation drives and influenced by 3D models in co-simulation
- Need fast 3D thermal, electromagnetic, mechanical models











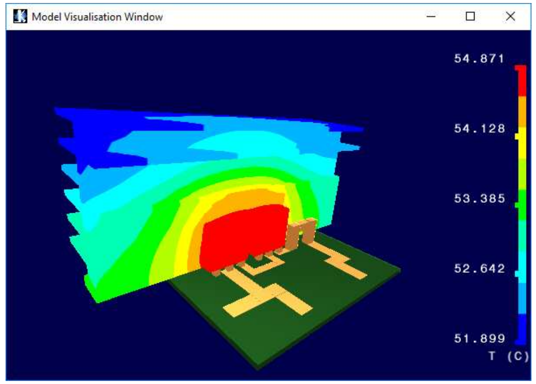
Starting Point

$$[M]\frac{d\vec{x}}{dt} = [K]\vec{x} + [F]\vec{u}$$

Large system of ODEs ($10^3 - 10^5$)

$$\vec{x}_i = [A]^{-1}\vec{b}_i$$

Large matrix solve at each time-step



- The vector u contains the inputs to the system
  - u is usually small – a few current / voltage / heat inputs
- The vector x contains the solution:
  - x is usually very large 1000 – 100,000 – one entry for each mesh node
- At each time step a matrix solve must be performed to obtain x_i
  - [A] is a combination of [M] and [K], b is combination of x_{i-1}, $[F]$, u
- Once x_i has been obtained, the temperature / current density / flux density / etc can be plotted.

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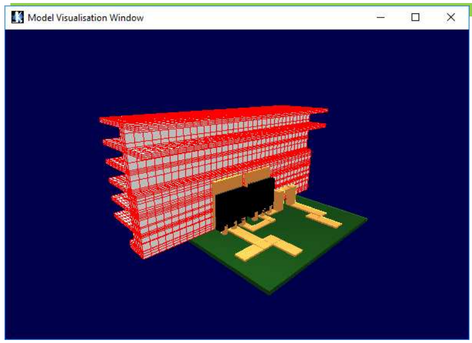
Starting Point

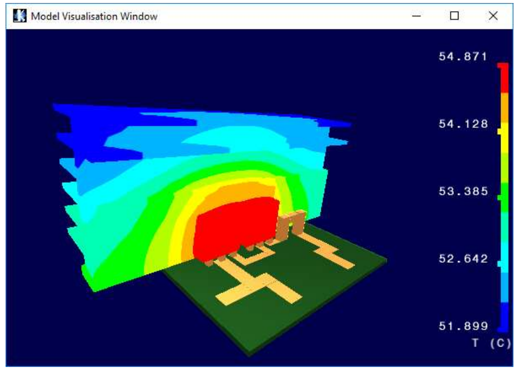


$$[M]\frac{d\vec{x}}{dt} = [K]\vec{x} + [F]\vec{u}$$

Large system of ODEs ($10^3 - 10^5$)

$$\vec{x}_i = [A]^{-1}\vec{b}_i$$

Large matrix solve at each time-step



$$(M_r, K_r, F_r) \leftarrow (M, K, F)$$

Order reduction algorithm transforms system matrices

$$[M_r]\frac{d\vec{x}_r}{dt} = [K_r]\vec{x}_r + [F_r]\vec{u}$$

Small system of ODEs (10-50)

$$\vec{x}_{i_r} = [A_r]^{-1}\vec{b}_{i_r}$$

Small matrix solve at each time-step

$$\vec{x}_i = [V]\vec{x}_{i_r}$$

Reduced order solution can be expanded to approximate all entries in x

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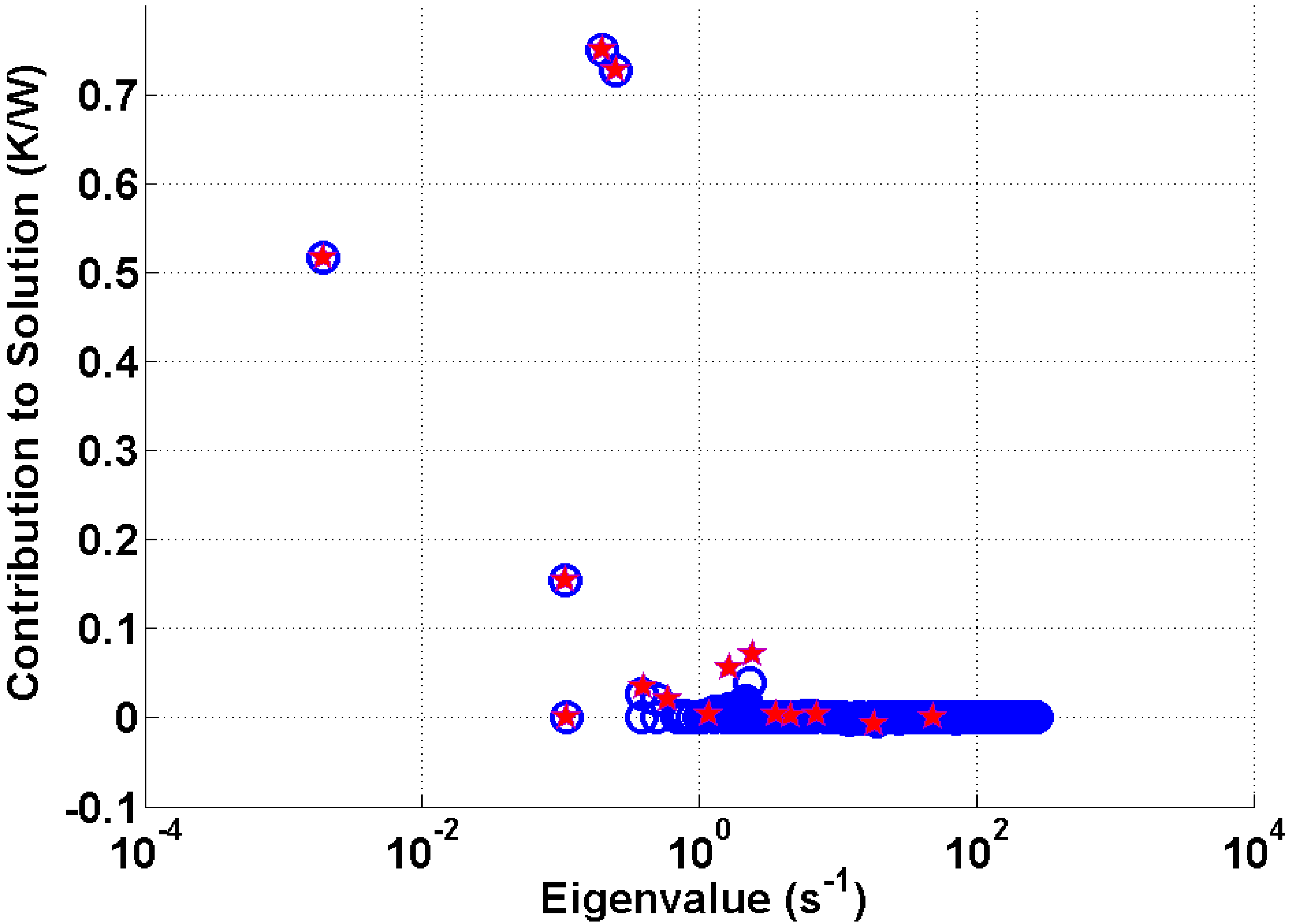
Reduced Order Models - Eigenvalues



Challenges

- Electromagnetic modelling
  - Extending method to account for influence of magnetic cores
  - Losses in magnetic materials
  - Bandwidth of reduced order electromagnetic models

- Semiconductor models
  - Accurate switching behaviour with easy datasheet calibration

- Thermo-mechanical
  - Heat transfer to fluids
  - Mechanical stresses & lifetime

Reduced Order 3D-Electromagnetic Modelling

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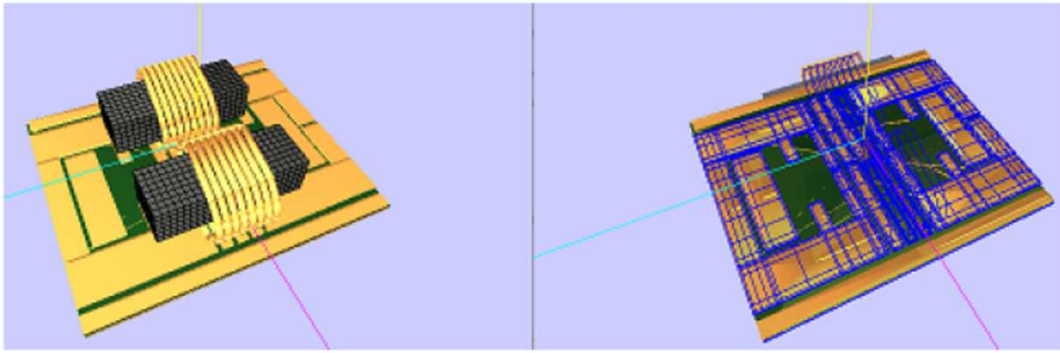
Magnetic Material Modelling

Extension to PEEC method for magnetic materials

Previous work limited to specific core geometries

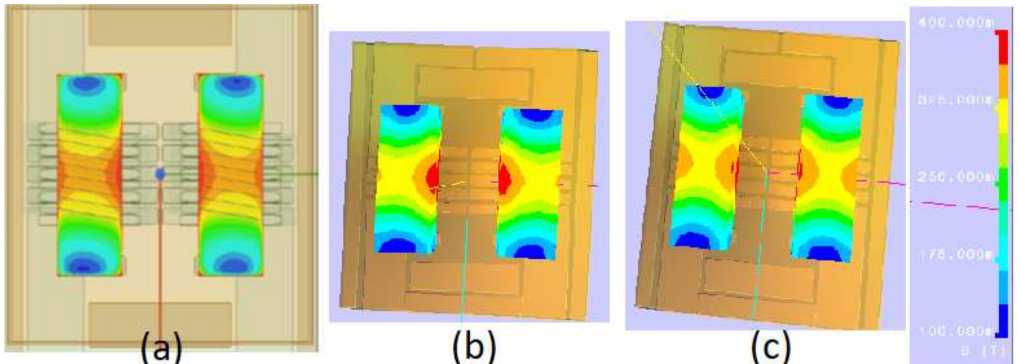


3D visualisation using ROM works for magnetic field and current density if matrix equation formulation modified

$$\begin{bmatrix} P^{-1} & 0 & 0 \\ 0 & L & L_m \\ 0 & 0 & 0 \end{bmatrix} \begin{matrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{i}} \\ \dot{\boldsymbol{m}} \end{matrix} = \begin{bmatrix} 0 & G & 0 \\ G^T & R & 0 \\ 0 & \lambda & \alpha \end{bmatrix} \begin{matrix} \boldsymbol{v} \\ \boldsymbol{i} \\ \boldsymbol{m} \end{matrix} + \begin{bmatrix} D \\ 0 \\ 0 \end{bmatrix} \boldsymbol{v_{in}}$$

$$\begin{bmatrix} P^{-1} & 0 \\ 0 & L - L_m \alpha^{-1} \lambda \end{bmatrix} \begin{matrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{i}} \end{matrix} = \begin{bmatrix} 0 & G \\ G^T & R \end{bmatrix} \begin{matrix} \boldsymbol{v} \\ \boldsymbol{i} \end{matrix} + \begin{bmatrix} D \\ 0 \end{bmatrix} \boldsymbol{v_{in}}$$

Some minor accuracies in ROM but time per step reduced from 0.3s - <<1ms for this model with 0.6s MOR overhead

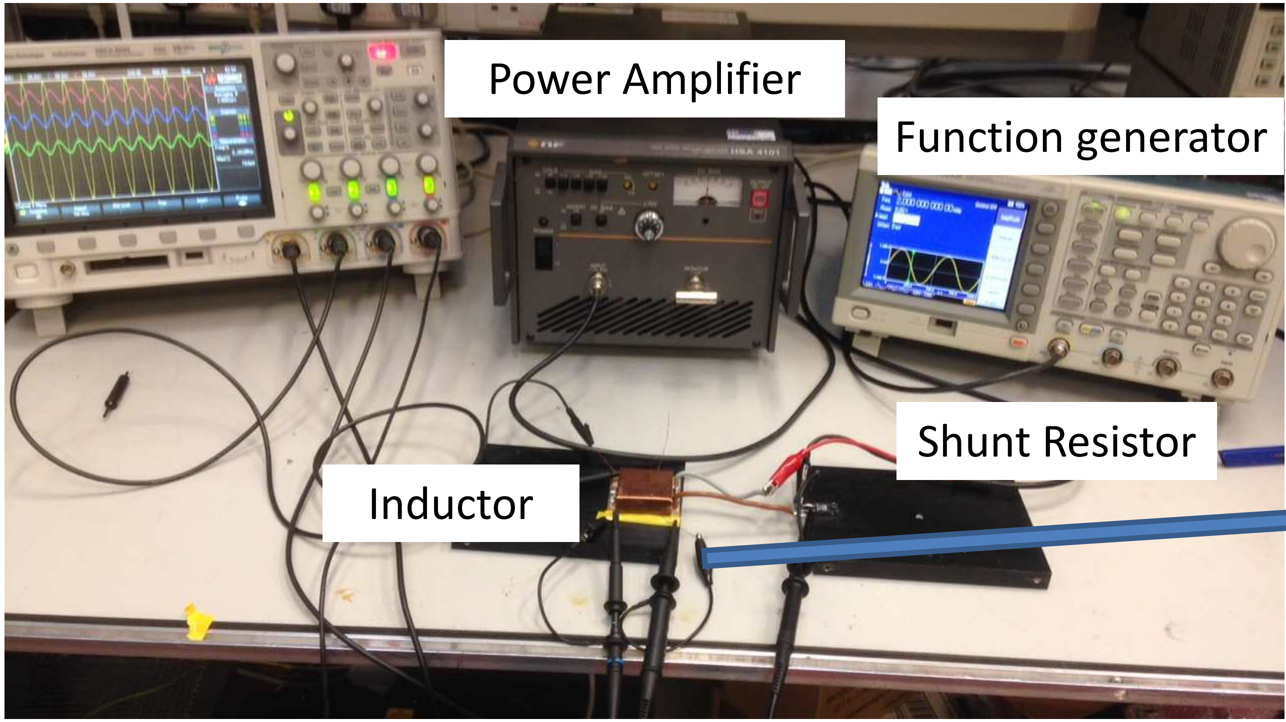


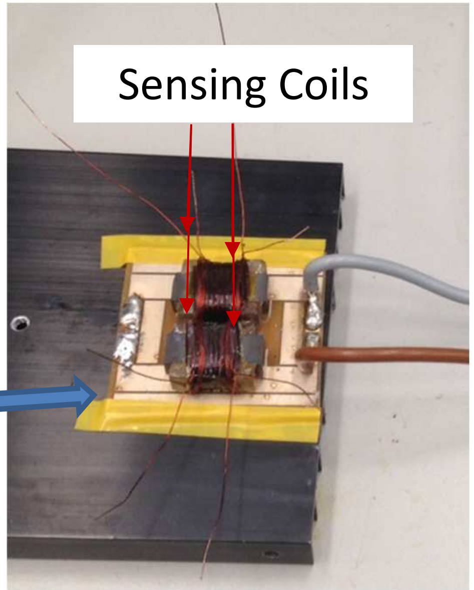
(a) Ansys Maxwell

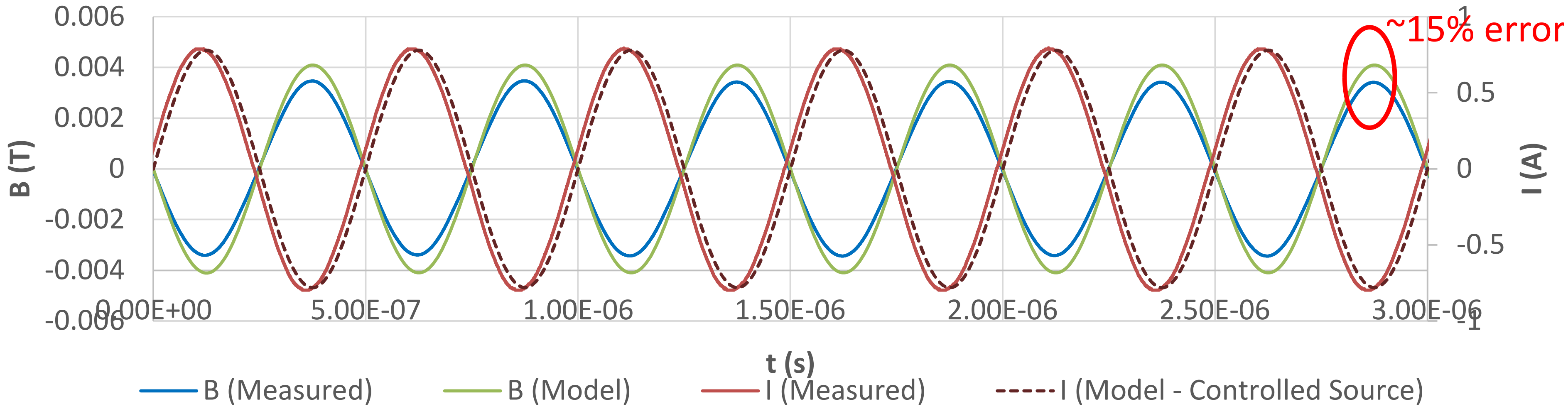
(b) No MOR *Model Size 4184*

(c) MOR *Model Size 52*

Comparison with Measurement

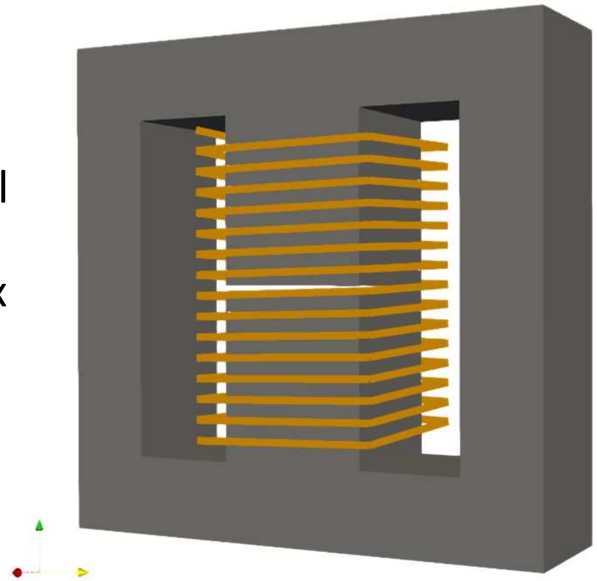




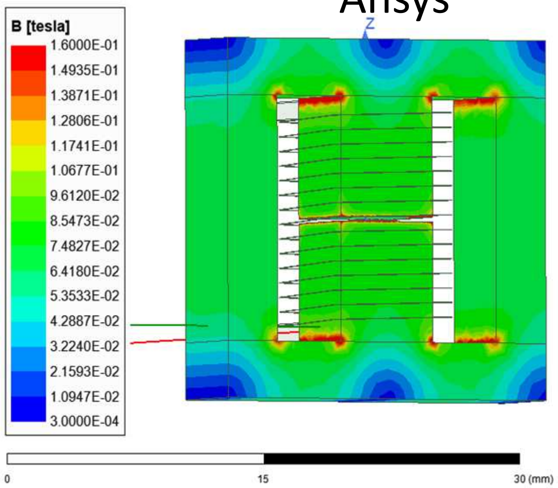


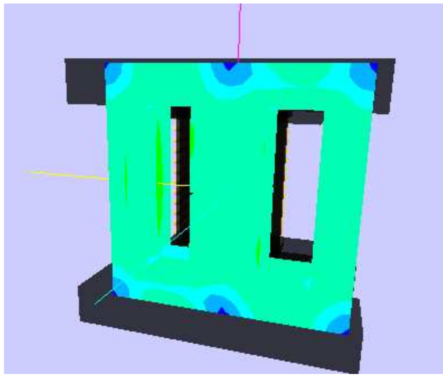
Magnetic Material Modelling

- Extended to E-core for magnetic loss work at Bristol
- High μ, small airgap – increased influence of core model
- Requires solve of a badly condition matrix (α sub-matrix that relates cell magnetisation to B field)

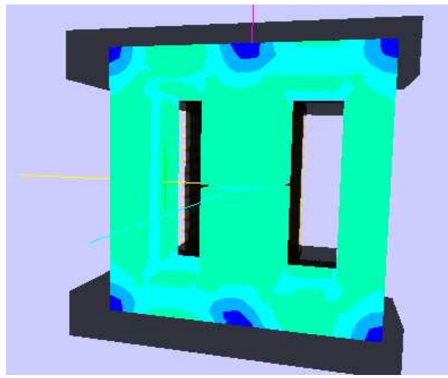


Ansys





No MOR – size ~ 7200



Model size 31

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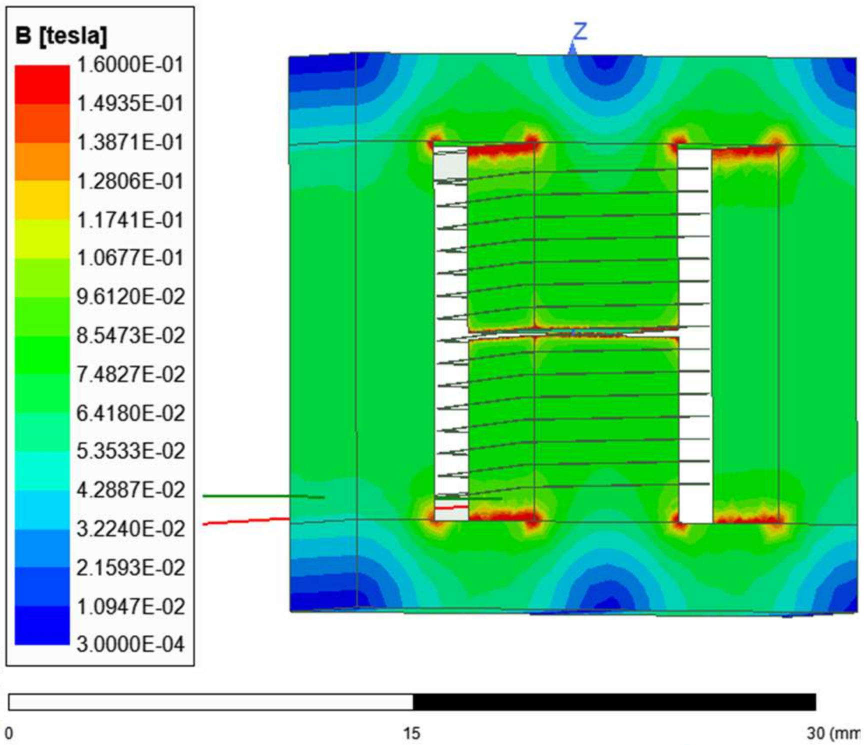
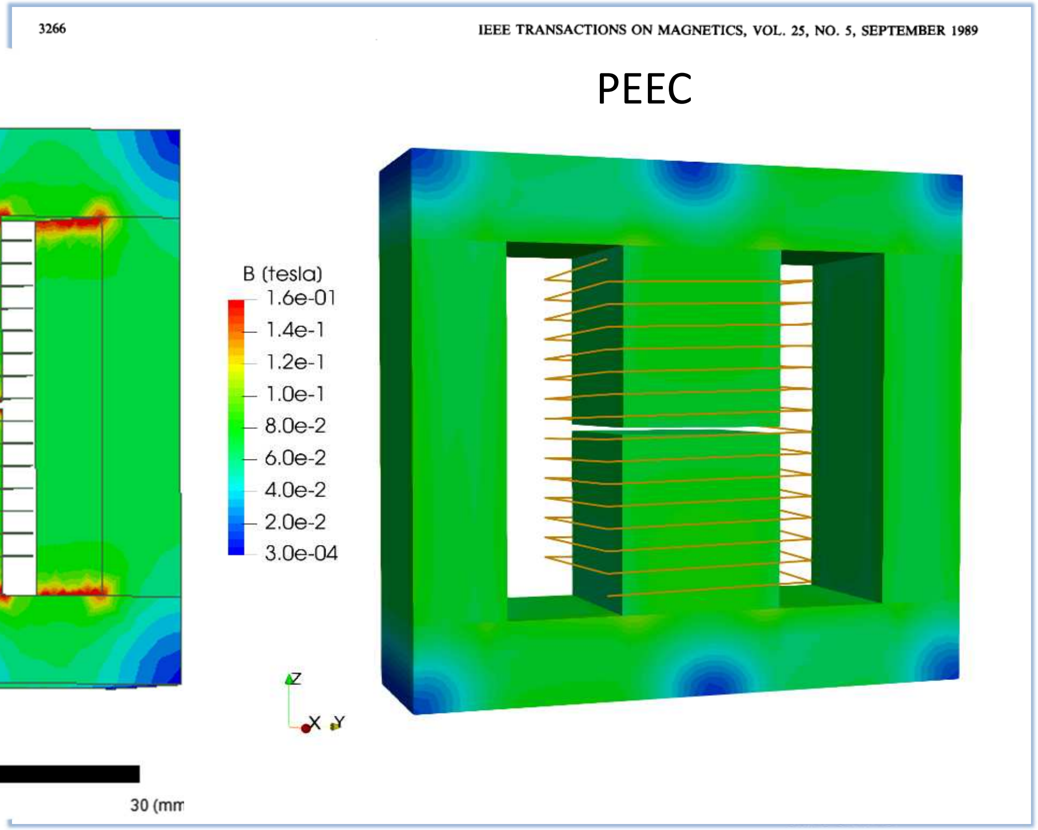
Magnetic Material Modelling

- Developed test environment to find solution
  - Lots of obvious fixes don’t work – standard preconditioners, moving from numerical to exact analytical integration for matrix coefficients
  - Partial solution by applying correction to off-diagonal matrix coefficients and very fine mesh
  - Think full solution by increasing order of basis functions - would allow accurate results with coarse mesh, work ongoing!

Ansys





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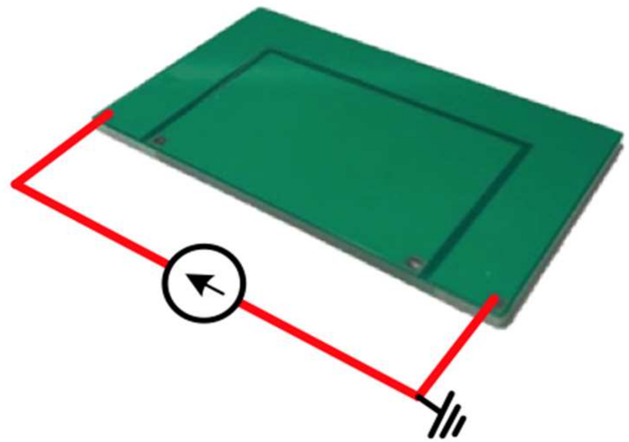
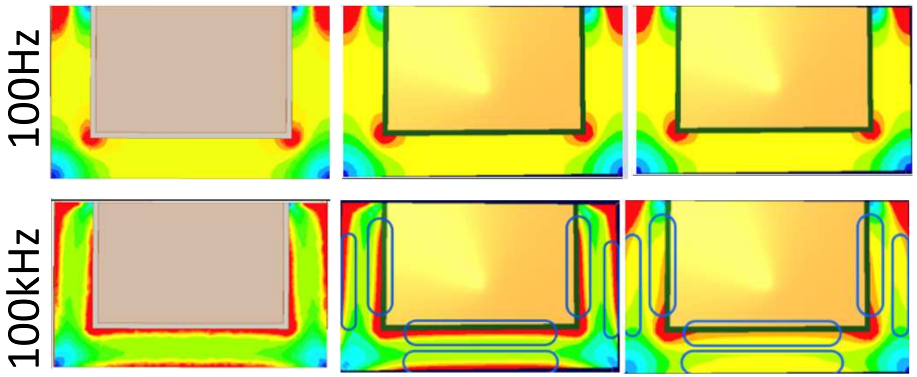
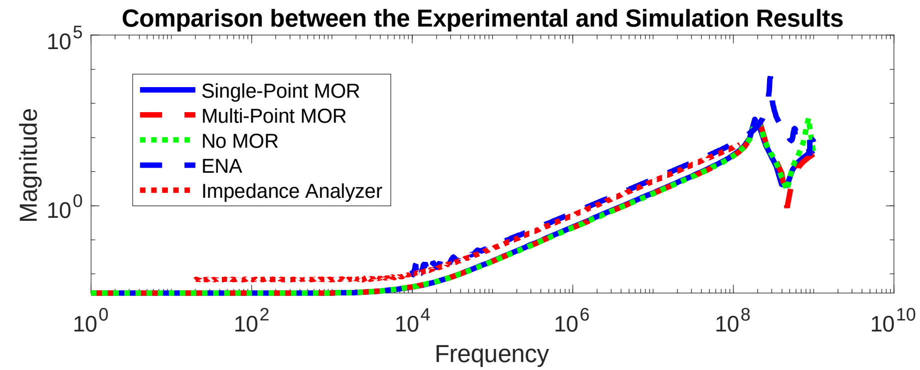
Increasing ROM bandwidth

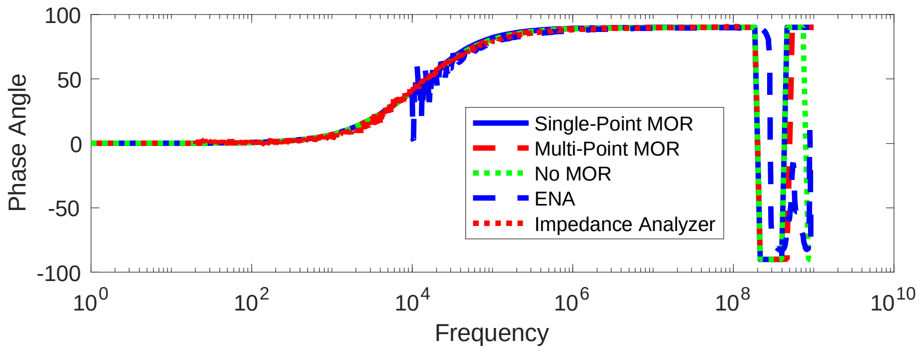
- EM models have significant response at DC and much higher frequencies





Ansys Maxwell | No MOR | Standard MOR





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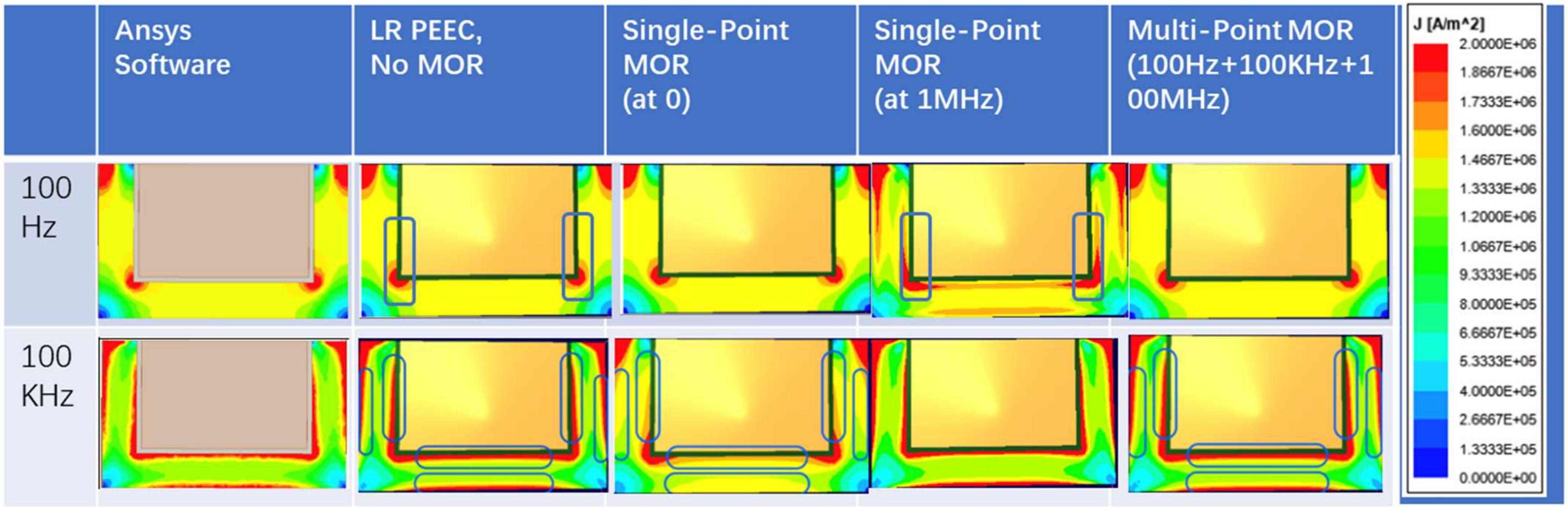
Modified Multiple Shift Algorithm



	PEEC Model Generation	MOR	Model Size	Time/Freq. Stepping	Simulation Time
No MOR	90s	No	6650	244s ×136 steps	33379.6s
Single Point MOR	90s	260s	10	0.015ms × 136 steps	350s
Multi Point MOR	90s	410s	37	0.013ms ×136 steps	503s

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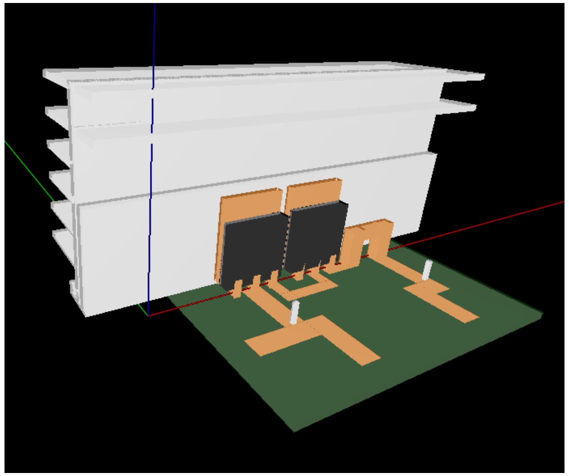
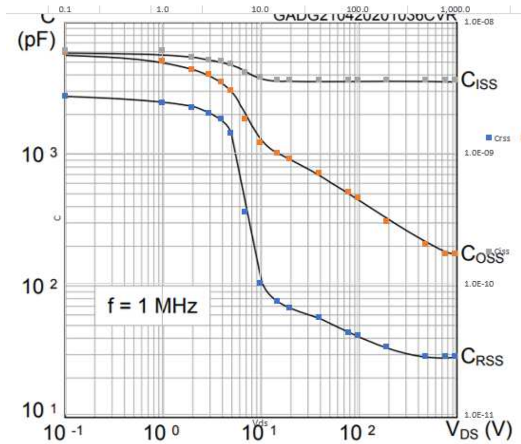
Semiconductor Behaviour Models

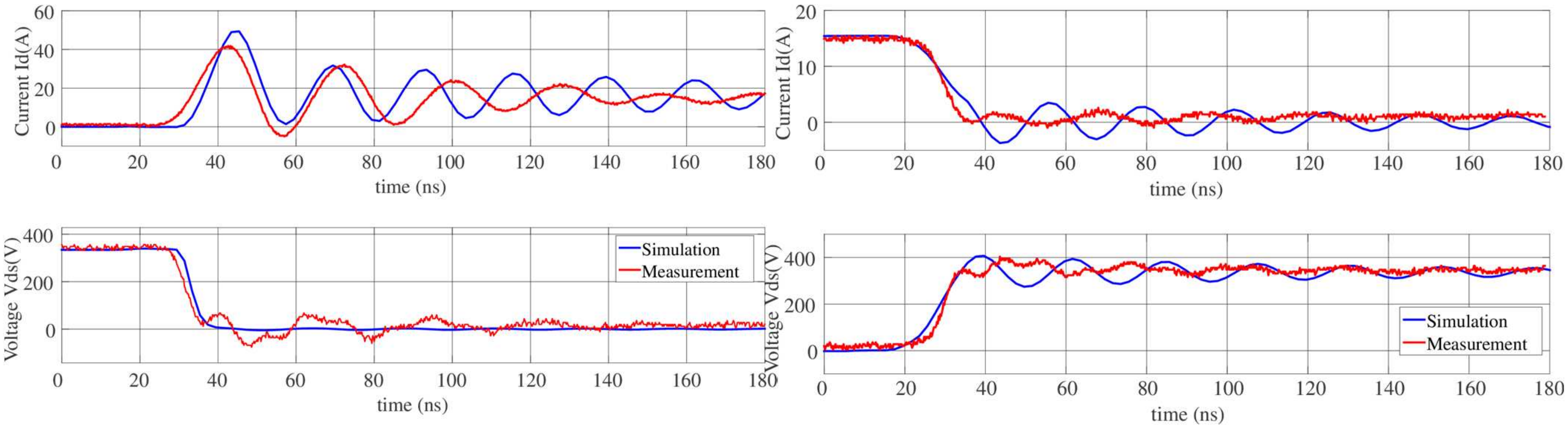


SiC MOSFET Modelling

25s for meshing and generating equations; 17s for MOR; 140s for circuit simulation (415000 time step, 115 equations)

Lookup table based on parameters in datasheet





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Magnetic Component Loss Modelling

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Core Loss Modelling - Modified Steinmetz Equations

The Steinmetz equation may be used to the calculate core power loss density in magnetic components:

$$P_{core} = kf^{\alpha}{B_m}^{\beta}$$

Where f is the frequency, B_m is the AC flux density magnitude. k, α and β are the Steinmetz parameters derived by curve fitting measured data under sinusoidal excitation.

Modified variants of the Steinmetz equation enable core loss calculation under non-sinusoidal excitation.

Model	DC-bias effects	Relaxation effects	Non-sinusoidal waveforms	Accuracy	Number of parameters	Comments
Steinmetz Equation [1]	×	×	×	*	3	Inaccurate
Modified Steinmetz Equation [2]	×	×	✓	**	3	Inaccurate
Generalised Steinmetz Equation [3]	×	×	✓	***	3	Moderate accuracy
Improved Generalised Steinmetz Equation [4]	×	×	✓	****	3	Accurate over a large range of duties and waveforms
Improved Improved Generalised Steinmetz Equation [5]	×	✓	✓	*****	8	Most accurate however experimentally determined parameters required

Improved Generalised Steinmetz Equation (iGSE) selected for its accuracy and readily available parameters provided by manufacturers

iGSE

The iGSE equation:

$$P_v = \sum_i \frac{1}{T}\int_0^T k_i \left|\frac{dB}{dt}\right|^{\alpha} |\Delta B|^{\beta-\alpha} dt$$

Where ΔB is the peak-peak amplitude of the major or minor loop in which the flux density is at the instantaneous time t. k_i is determined by:

$$k_i = \frac{k}{(2\pi)^{\alpha-1}\int_0^{2\pi}|cos\theta|^{\alpha}2^{\beta-1}d\theta}$$

An approximation for the value of k_i has been shown to be accurate to within 0.15% for values of α from 0.5 to 3:

$$k_i \cong \frac{k}{2^{\beta+1}\pi^{\alpha-1}\left(0.2761 + \frac{1.7061}{\alpha + 1.354}\right)}$$

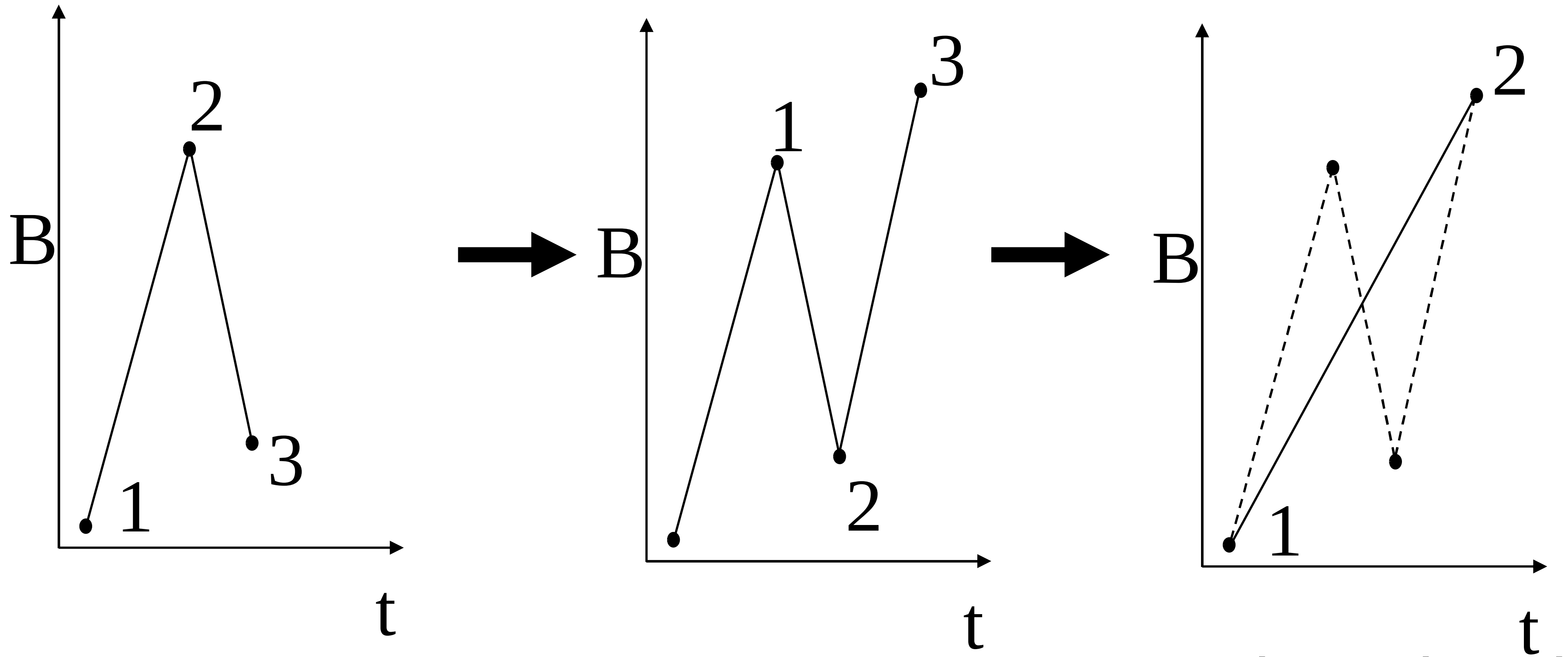
The iGSE can be rewritten for piecewise-linear waveforms:

$$\overline{P_v} = \frac{k_i(\Delta B)^{\beta-\alpha}}{T}\sum_m \left|\frac{B_{m+1}-B_m}{t_{m+1}-t_m}\right|^{\alpha}(t_{m+1}-t_m)$$

Model parameter	Parameter details	Source
Steinmetz coefficients	k,α and β	Manufacturer design tool/ Datasheet
PWL waveform	Flux density vs. time (B(t))	PEEC Software
Component geometry	Volume (V)	PEEC software

Rainflow counting

- Cycle period length is required for the iGSE equation.
- Rainflow counting algorithms identify cycles from PWL data in real-time i.e. period length and amplitude.



No cycle counted

Cycle counted

Cycle extracted – period and amplitude recorded

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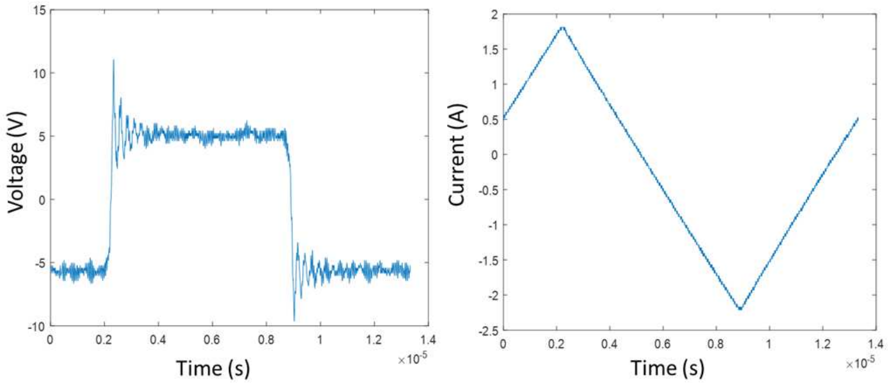
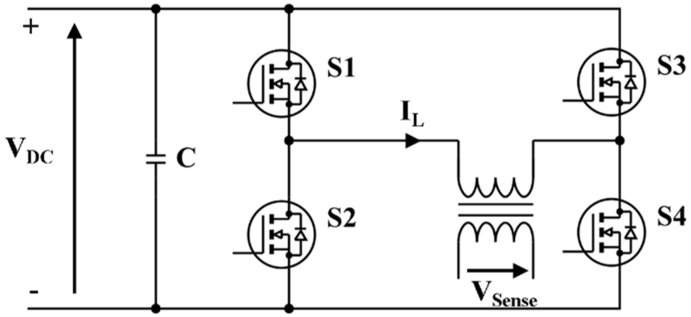
Validation

- Experimental hardware for model validation:
  - H-Bridge inverter – triangular current (I_L) waveform
  - EF20 N87 47uH inductor with sense winding constructed and losses measured:

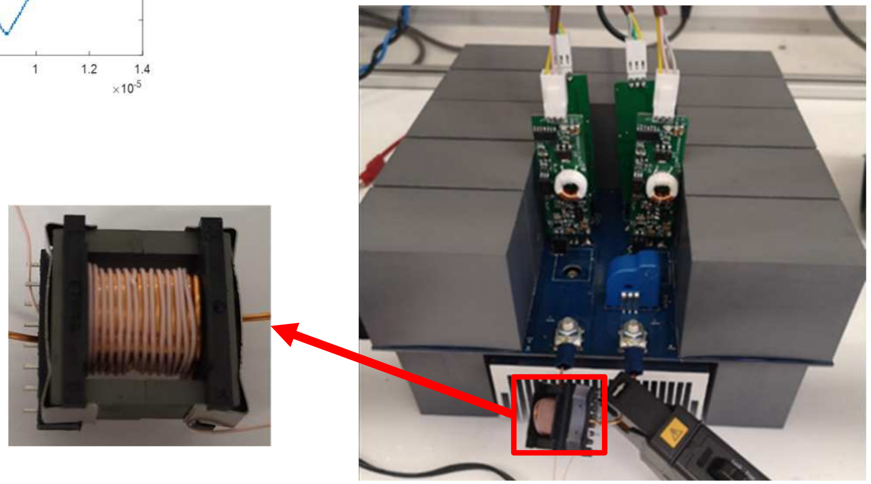




  - Core losses calculated using:

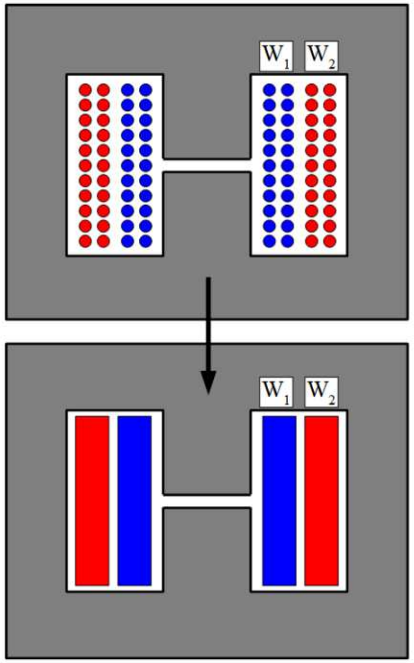
$$\frac{P}{V} = \frac{f \int_0^T i_p(t) \frac{N_1}{N_2} v_2(t) dt}{A_e l_e}$$

  - PEEC core loss model validation is ongoing



Winding Loss Modelling

- Accurate AC winding loss calculations in high-frequency gapped inductors are computationally expensive due to the need for 3D modelling in combination with very fine mesh size requirements.
- To address this, a winding loss calculation approach, based on the Squared Field Derivative (SFD) method is introduced and seamlessly integrated into the multi-physics Virtual Prototyping for Power Electronics software

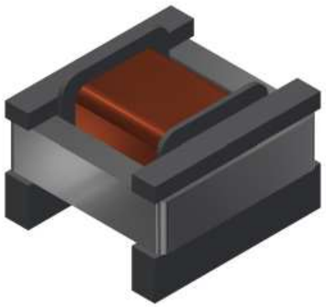


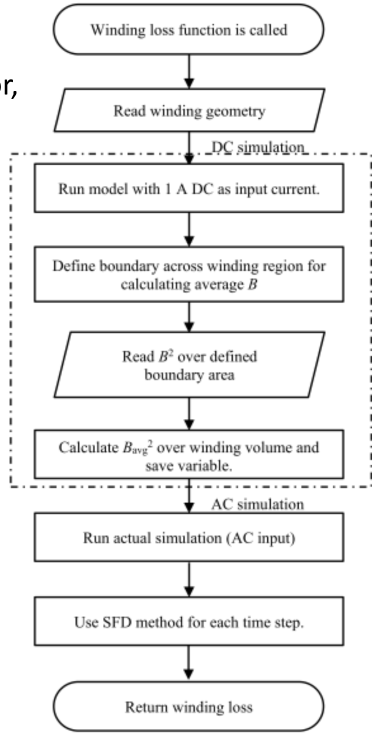
The SFD is based on an analytical loss expression in a single round conductor, assumed small compared to the skin-depth, subject to a uniform field.

$$P_{avg} = \frac{\pi l_m N d_c^4}{64\rho_c}\langle\overline{\left(\frac{dB}{dt}\right)^2}\rangle$$

The field is established through a simple magnetostatic simulation and scaled based on operating ampere-turns at each time-step. Multiple windings can be accounted for through superposition.

The winding is treated as a homogenous region, significantly reducing discretisation requirements yet spatial loss estimation can be calculated to allow high fidelity thermal modelling and identification of hot-spots.





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Validation

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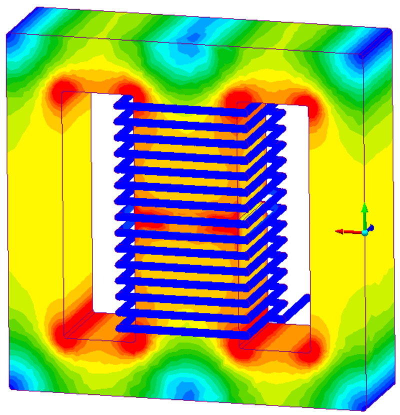
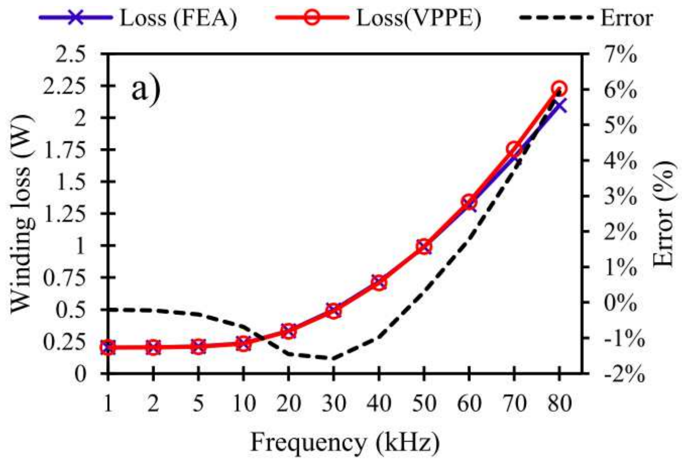
Simple 15 turn low-fill winding

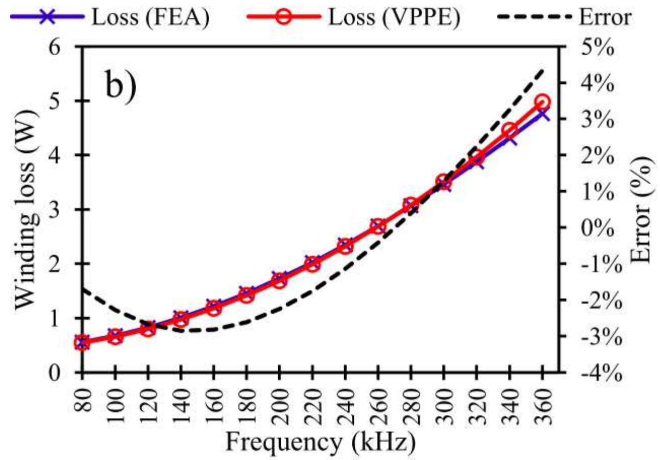
Core



Gapped Inductor Example



60 turns, single strand



60 turns, multi-strand

Air-gap

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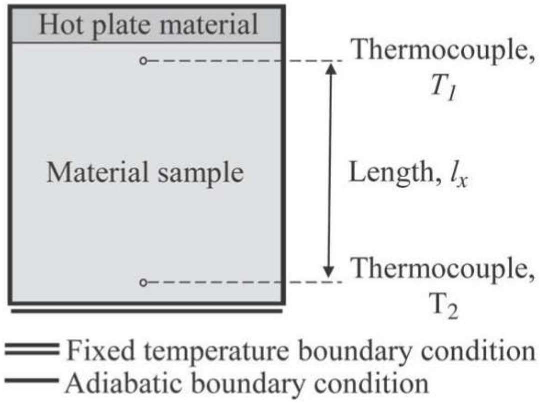
Winding Equivalent Thermal Parameter Modelling

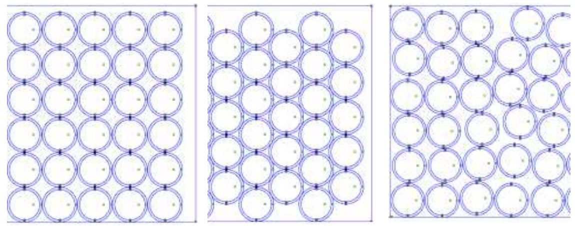
- Accurate thermal modelling requires detailed understanding of the thermal properties of the constituent components – this is particularly challenging for winding regions
- To address this, thermal homogenisation techniques are introduced to reduce the winding amalgam to a lumped material with equivalent thermal properties based on the volume fraction of conductor, insulation and encapsulation

Equivalent thermal conductivity may be found using a numerical heat-flow meter experiment or analytically using a two stage homogenisation based on Hashin and Shtrickman. Round and rectangular conductors are considered.

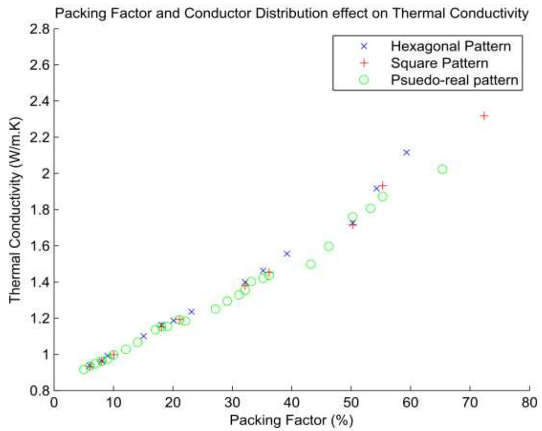


$$k_e = k_a \frac{(1+v_c)k_c + (1-v_c)k_a}{(1-v_c)k_c + (1+v_c)k_a}.$$

Example Conductor Packing patterns



Square Hexagonal Pseudo-real



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Heat Transfer to Fluids

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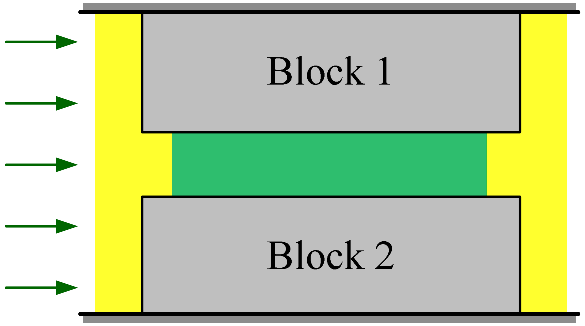
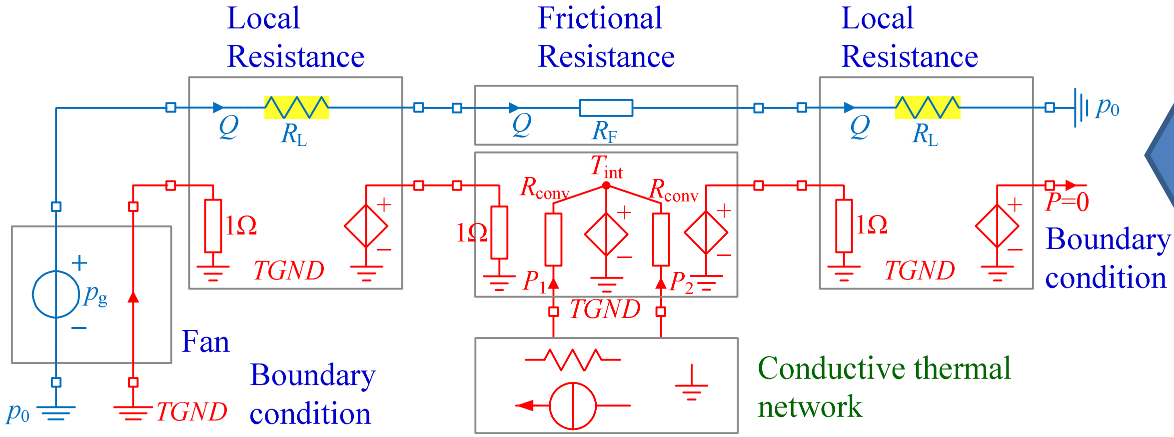
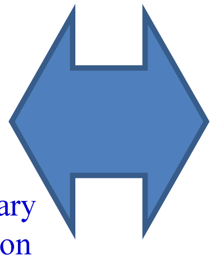
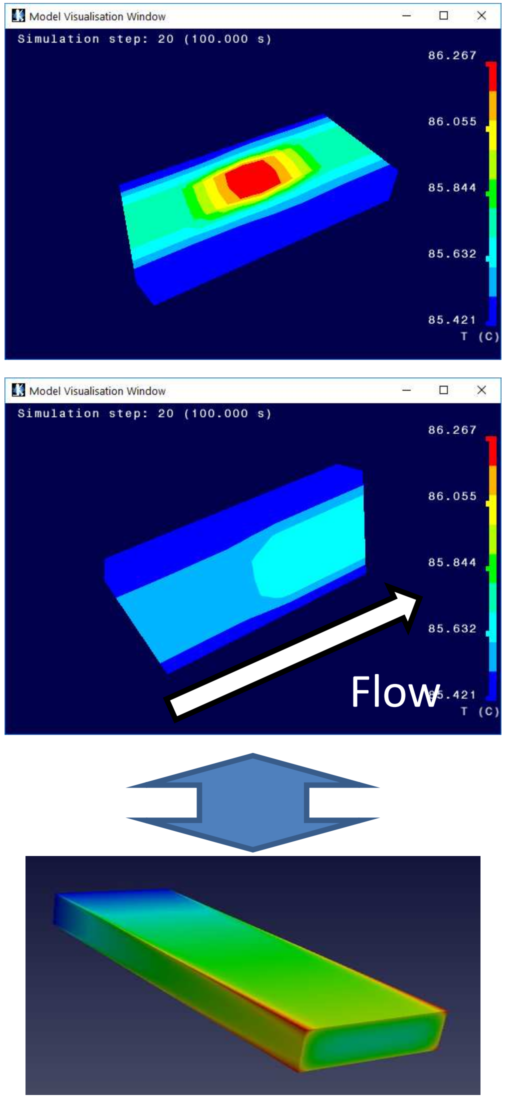
Coupled Flow Network-CFD

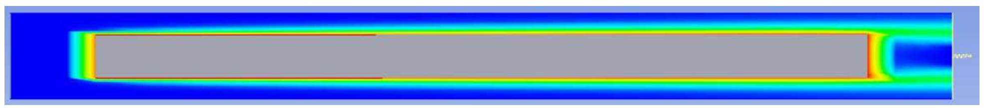




Flow network acts as fluid boundary condition for 3D coldplate model







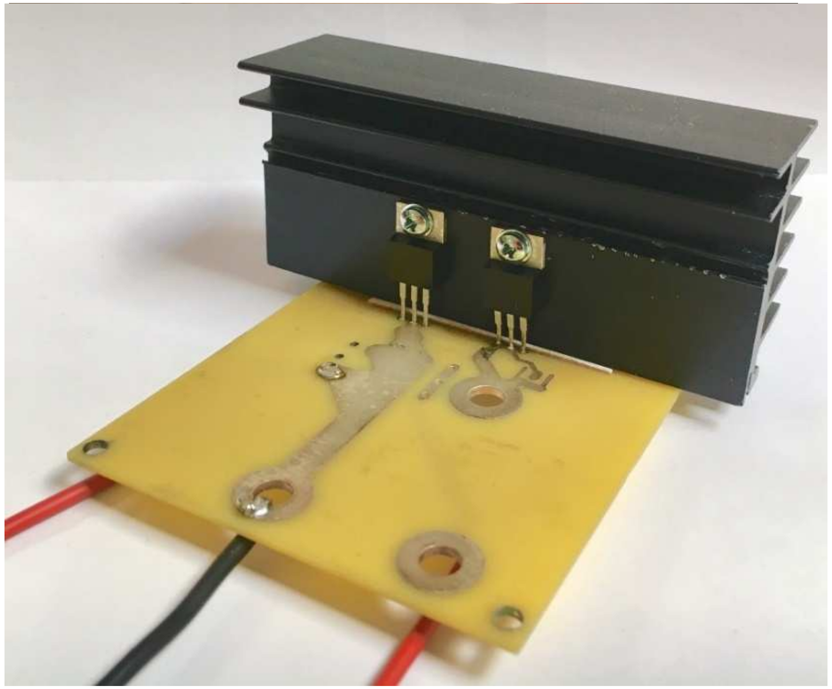
	CFD	VP S/W
Volume flow rate (m^3/s)	0.0002	
Pressure drop (Pa)	31.92	31.77
Wall temp. (° C)	46.5~48.2	45.6~52.5

Pressure-flow and heat transfer characteristics computed by initial CFD solve

Demonstration:
Real-time Simulation

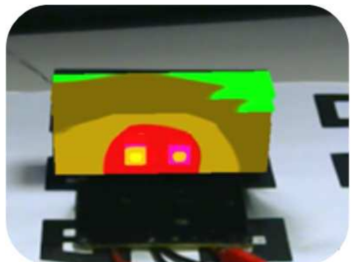
Augmented Reality

- Augmented reality: computer generated effects overlaid onto live video streams
  - Artificial effects are oriented and scaled so that they appear to be part of real word
  - Can be deployed on mobile devices or using mixed reality glasses

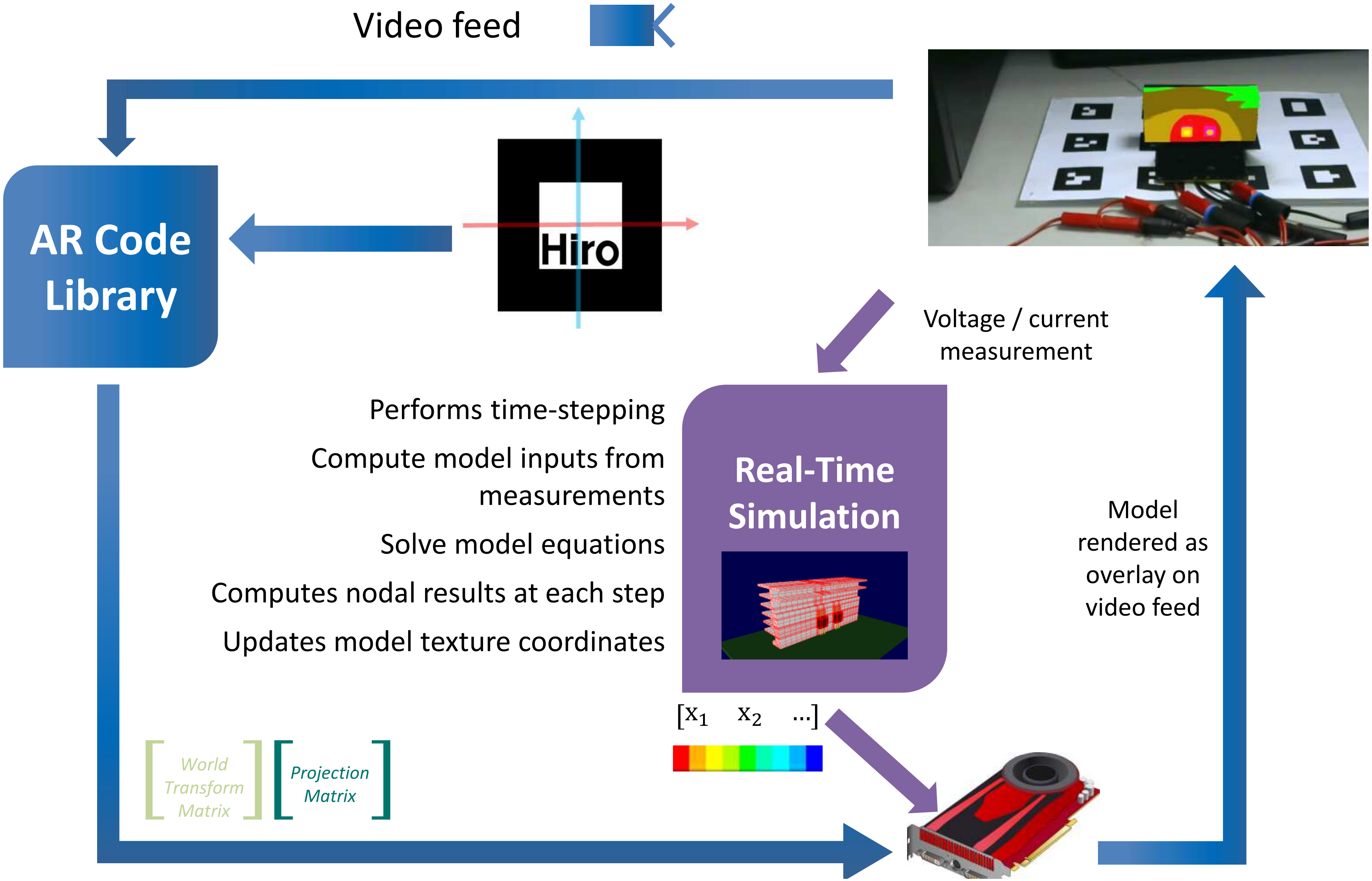


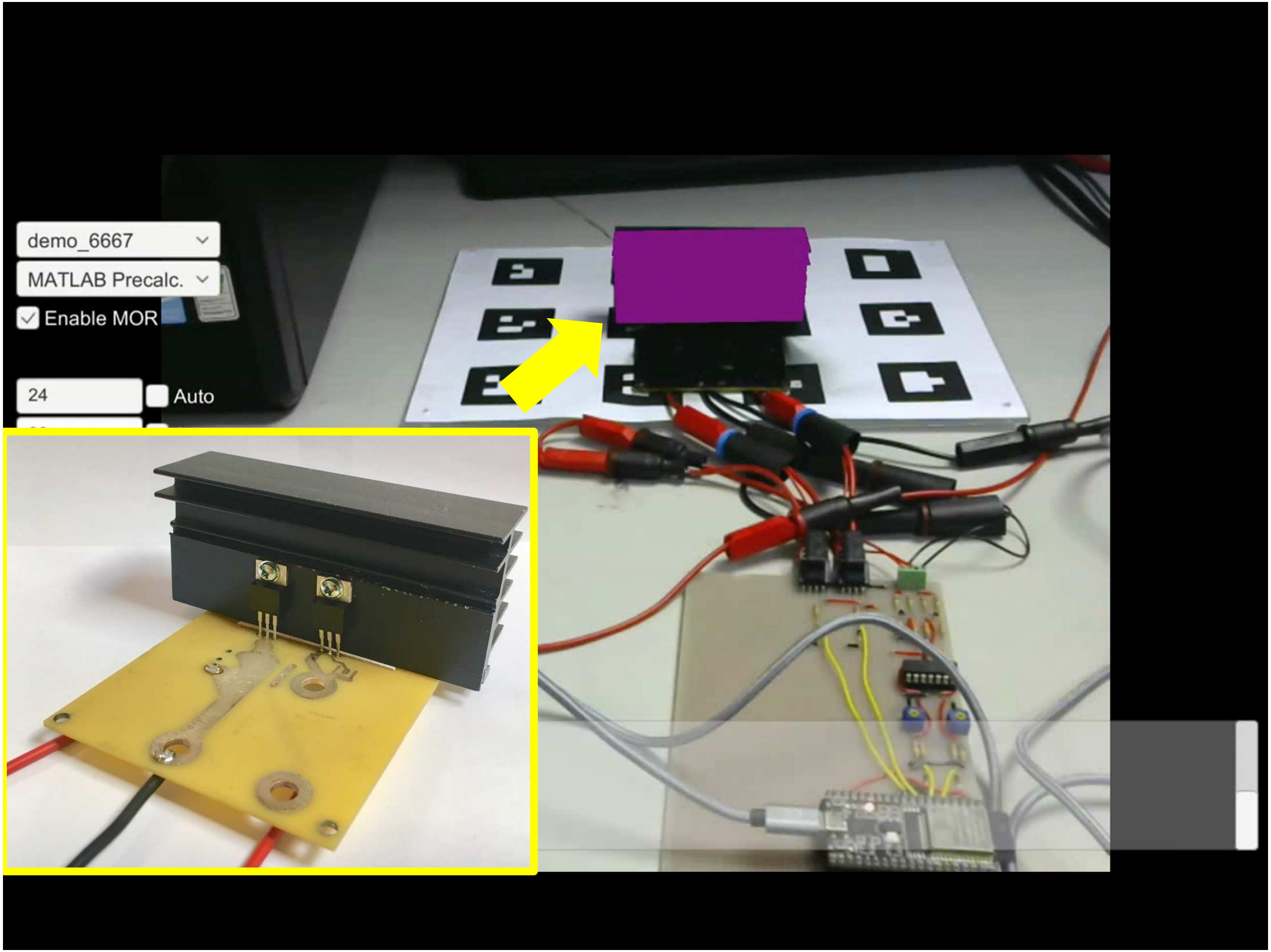
- Overlay real-time simulation results onto live video
  - Visualisation of invisible effects

Measureable Quantities (V,I) → **Real-Time Simulation** → **AR** →



Initial Demo

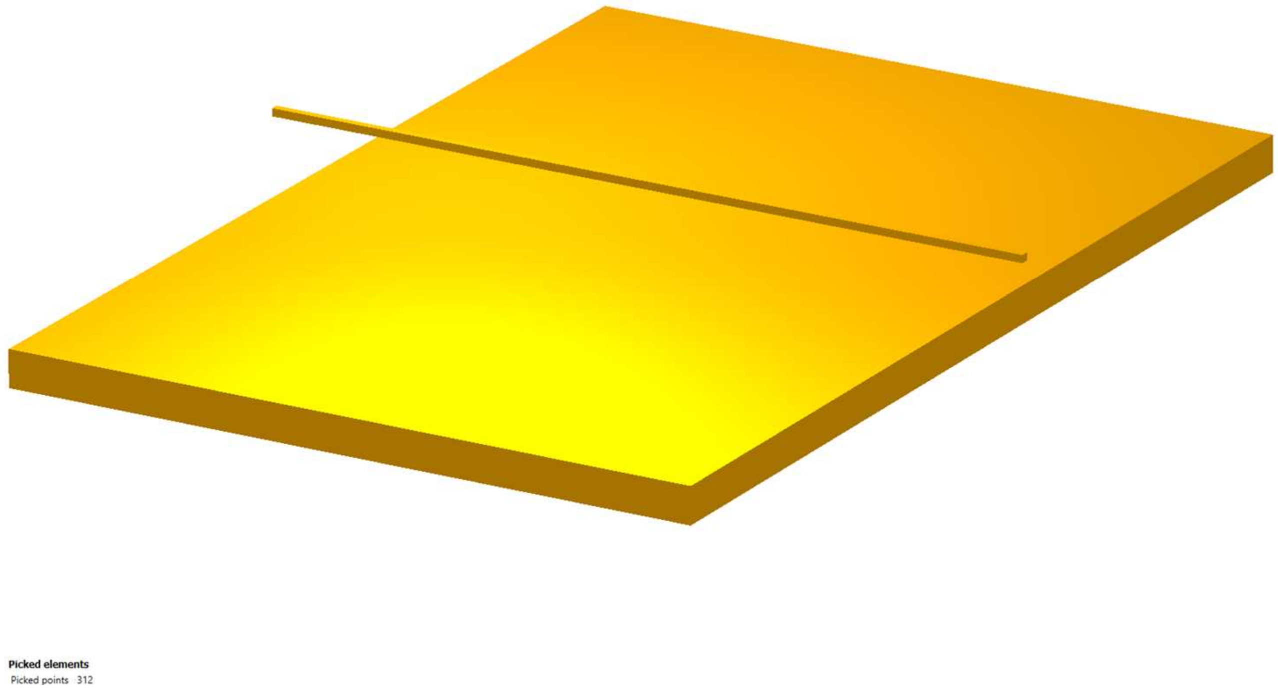



demo_6667
MATLAB Precalc.
Enable MOR
24
Auto

Slightly more interesting application…

- Thermal visualisation easy to validate due to IR imaging – also a bit pointless!
- Electromagnetic implementation using some of techniques discussed earlier

Current carrying wire over ground plane



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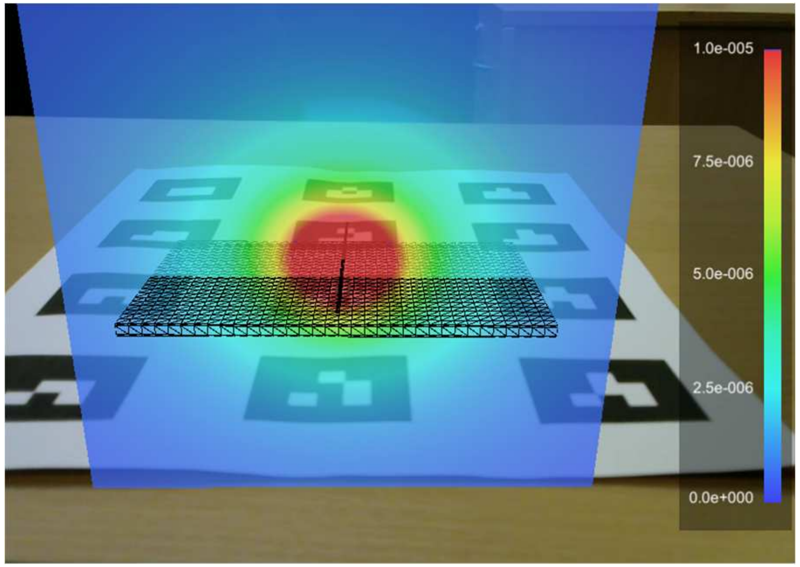
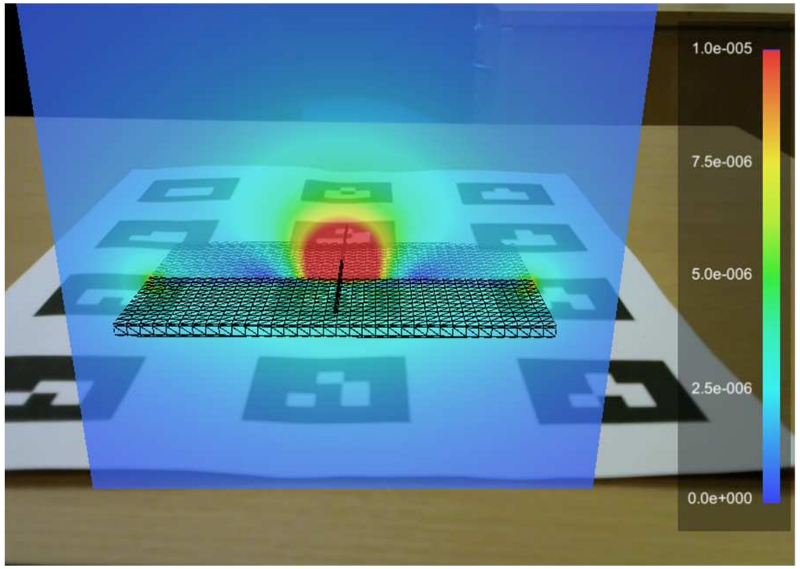
Results with 1Hz (L) and 10kHz (R) excitation

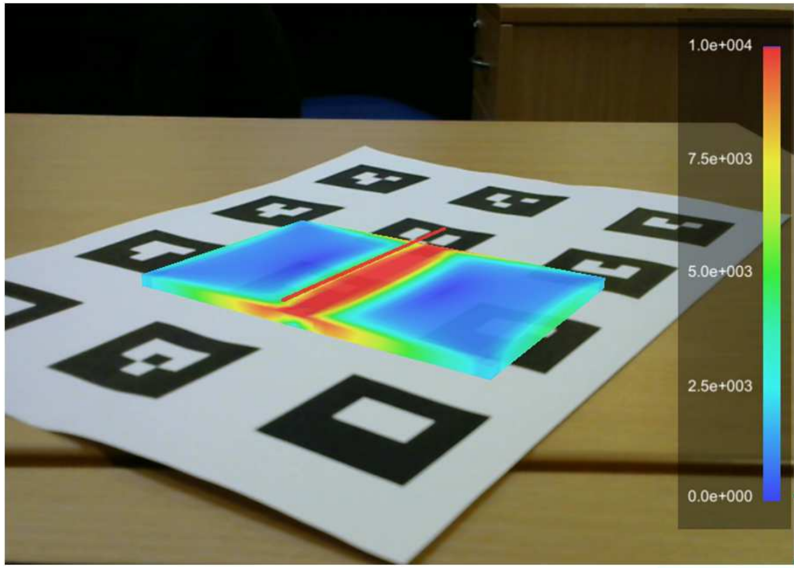




Above – magnetic field, induced ground plane currents distort field at higher frequencies

Right – Visualisation of currents in ground plane

Real-time computation and visualisation of high frequency effects much more difficult!



Thank you

Any questions?

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