Efficient lithium-ion battery pack electro-thermal simulation

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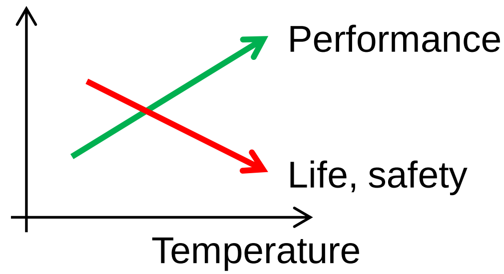
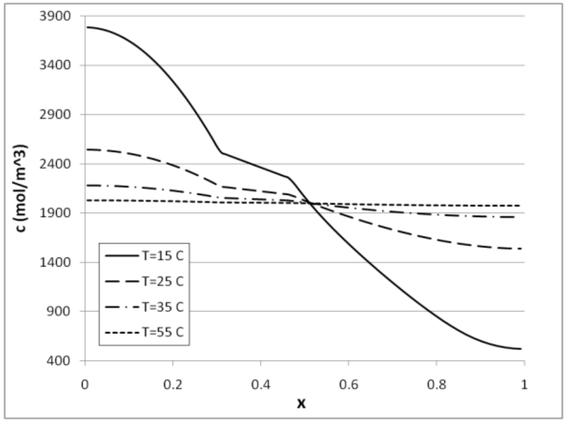
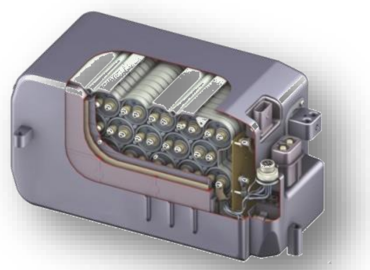
Introduction

- Li-ion batteries are temperature sensitive

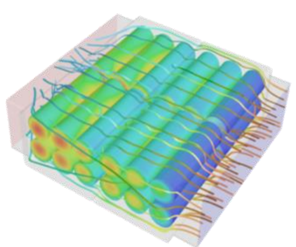


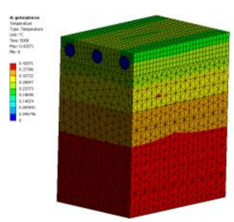


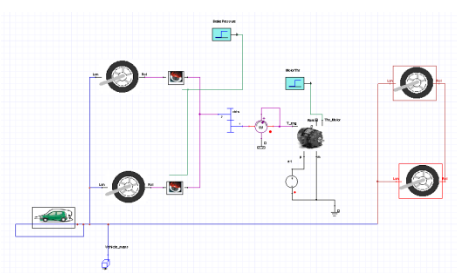
- Battery pack needs active cooling/heating
  - Efficient energy usage
  - Control systems



- Reduce the prototype efforts:
  - **Simulation aided design**







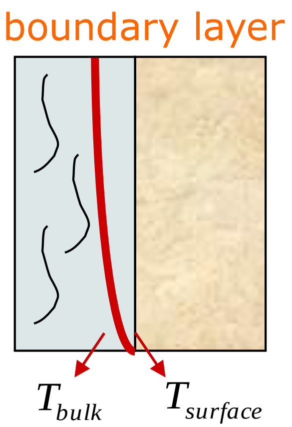
Outline

- Traditional thermal modeling approach
- Efficient simulation with Model Order Reduction
- Electro-thermal battery pack simulation
- Summary

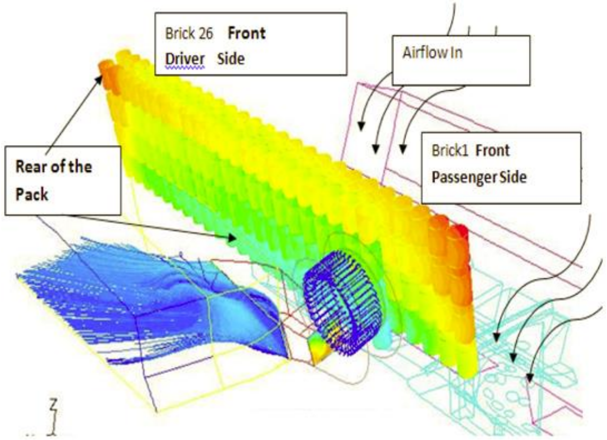
CADFEM

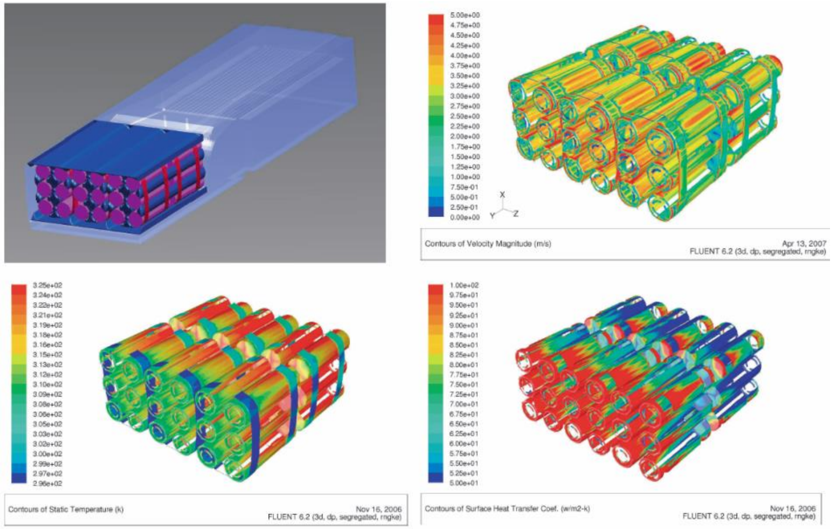
Thermal simulation

- Heat transfer phenomena
  - Heat conduction,
  - Radiation
  - Convection (fluid flow)



- CFD/FEM
  - Standard tool for Industry



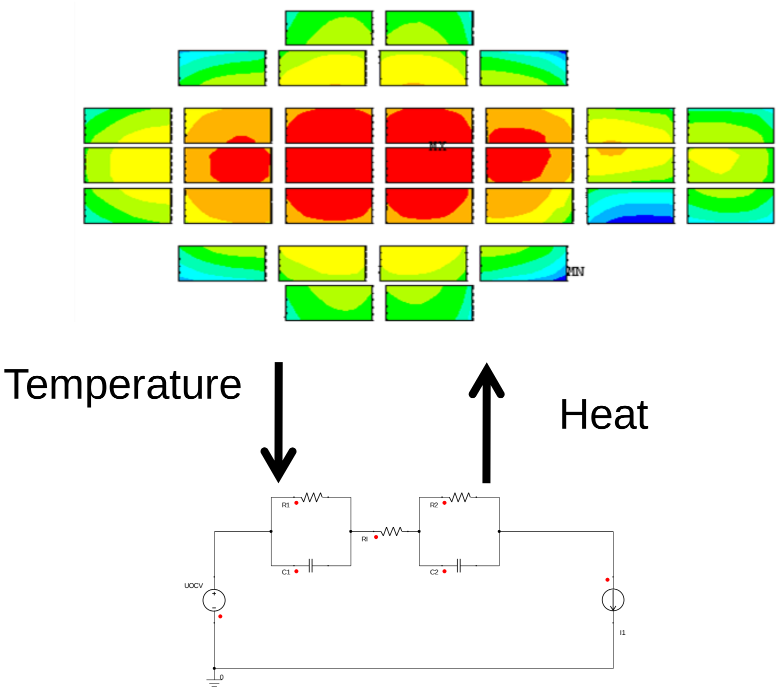


1. D. Ghosh, P. D. Maguire, and D. X. Zhu, " Design and CFD Simulation of a Battery Module for a Hybrid Electric Vehicle Battery Pack," SAE 2009-01-1386
2. D. Ghosh, K. King, B. Schwemmin, D. Zhu, "Full Hybrid Electrical Vehicle Battery Pack System
Design, CFD Simulation and Testing," SAE 2010-01-1080

Drage, P., Kussmann, C., Jagsch, S., " Simulating Thermal Management of Battery Modules for Propulsion of Hybrid Vehicles. EAAC 2007

Battery Thermal Management > Simulation challenge

- FEM transient CPU costs
  - 5 min per time step (1000k nodes) (intel i7, 4 cores)
  - ~1000 time steps = 80hrs!



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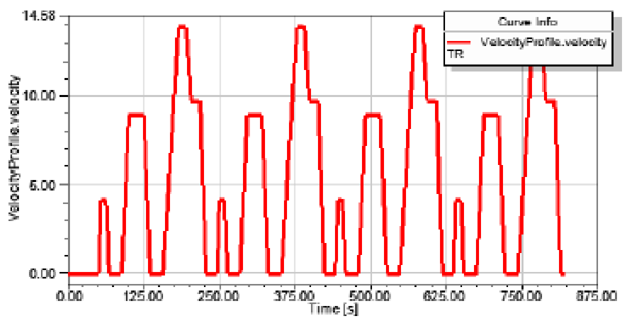
Dynamic loads



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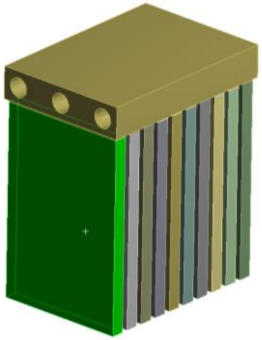
Controller
Vehicle model
…

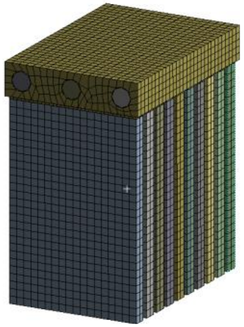
Low CPU cost is needed >Reduced order thermal model

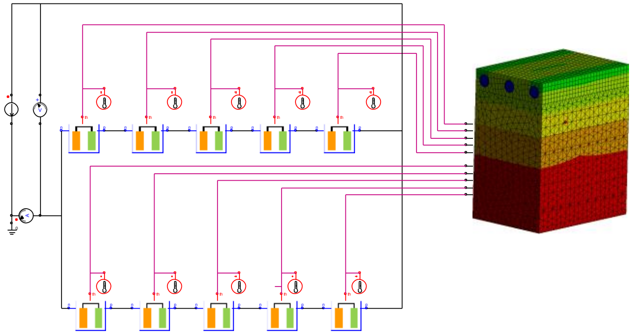
CADFEM

Bring 3D thermal model to system level

CAD battery pack model → 3D FEM model → MOR → Reduced model







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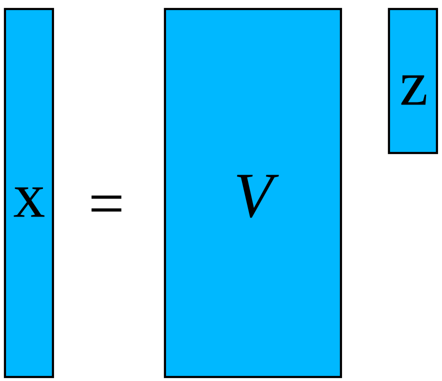
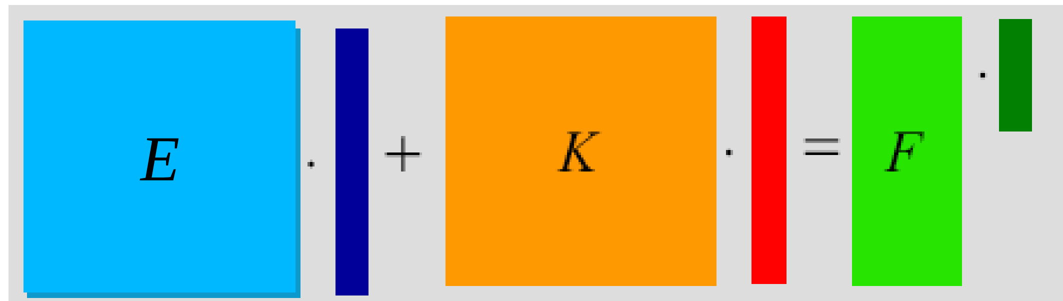
MOR for ANSYS: http://ModelReduction.com

$$E\dot{\mathbf{x}} + K\mathbf{x} = B\mathbf{u}$$

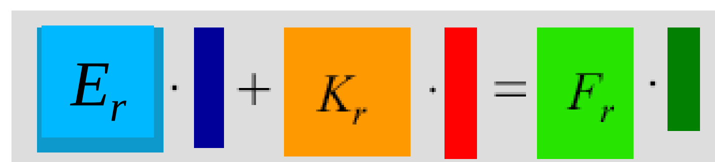
- Projection onto low-dimensional subspace

$$\mathbf{x} = V\mathbf{z} + \varepsilon$$





$$V^T E V\dot{\mathbf{z}} + V^T K V\mathbf{z} = V^T B\mathbf{u}$$



- Advantage:
  - NO transient solution with the original FEM model is necessary
  - Highly accurate (linear systems)
  - As accurate as the original FEM model

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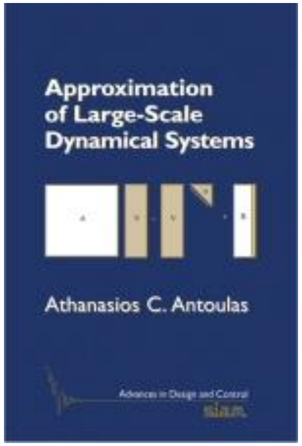
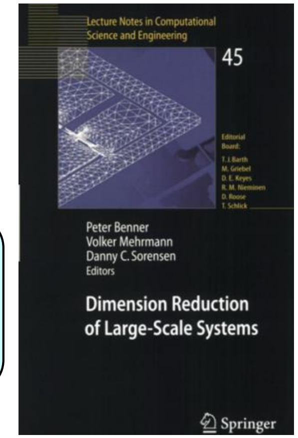
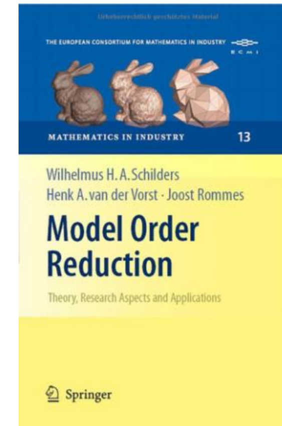
MOR in Modern Mathematics







Linear Dynamic System, ODEs

Control Theory
BTA, HNA, SPA
$O(N^3)$

Moment Matching via **Krylov subspaces**. Iterative, based on matrix vector product.

Low-rank Grammian, SVD-Krylov

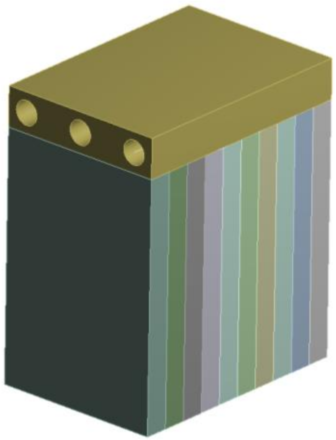
one-side Arnoldi process

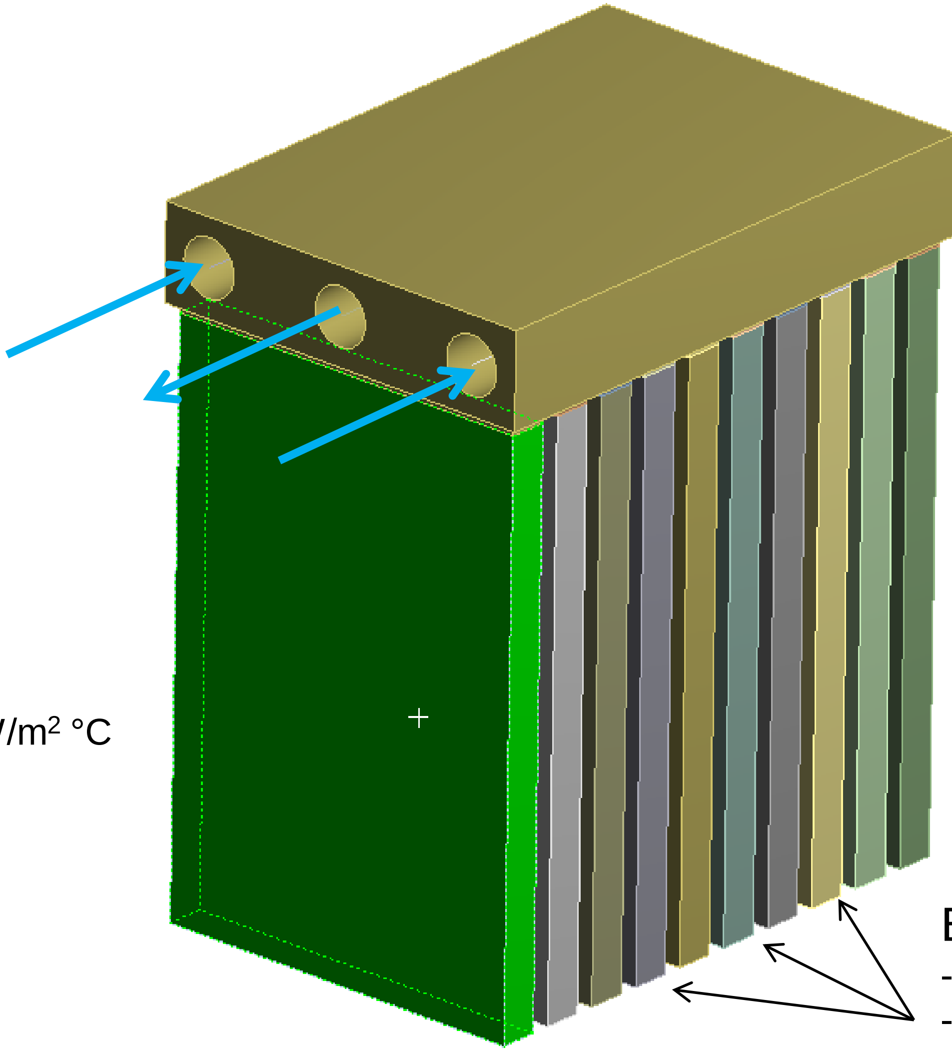
double-side Lancsoz algorithm

MOR for ANSYS

CADFEM

Battery pack FE thermal model in ANSYS WB





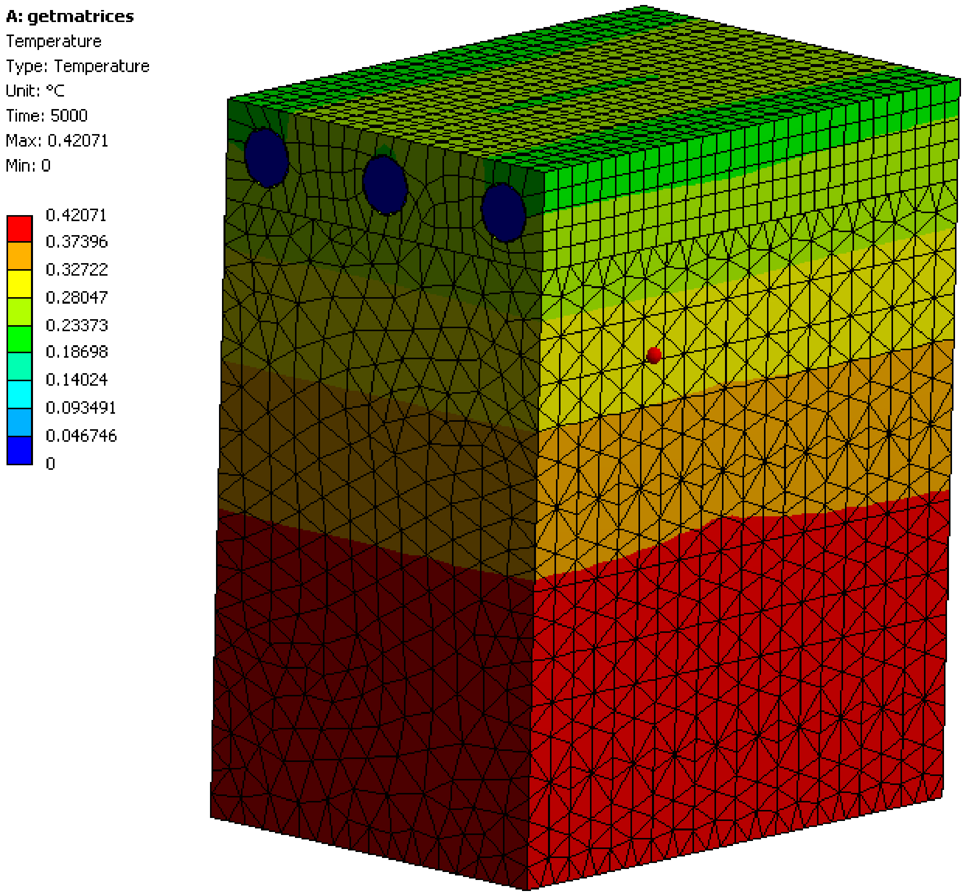
Cooling channels:
- FLUID116
- Mass flow: 0.1 kg/s (water)
- Heat transfer coefficient: 500W/m^2 °C
- Inlet Temperature: 20°C

Battery Cells
- 10 cells
- Orthotropic heat conductivity

FEM analysis

- What one can get?
  - Field of
    - Temperature
    - Heat flux
  - Total heat fluxes…

- CPU costs
  - Mesh:150k nodes
  - CPU cost per time/load step :~31s



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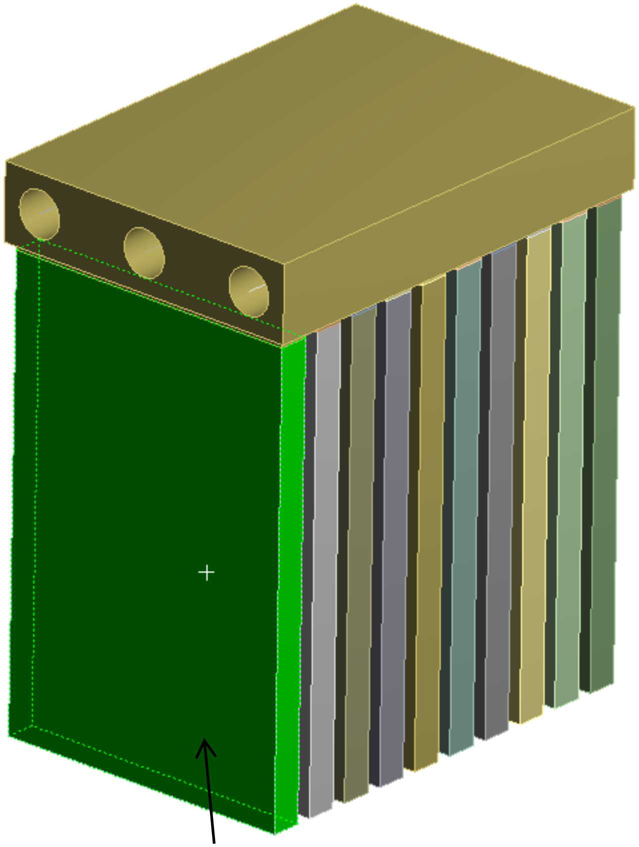
MOR - preparation

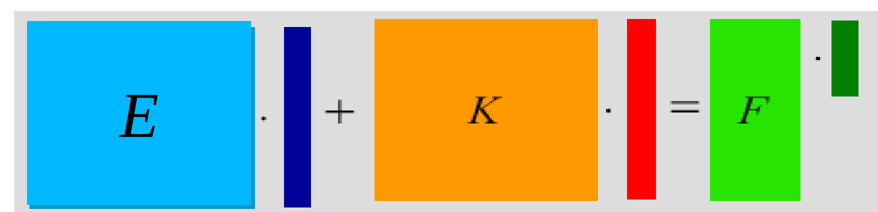
- Terminal concept (IN/OUT)

Outputs:
Temperature at the center of each cell

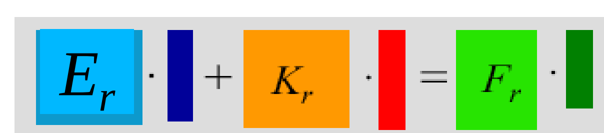


Each cell is one input
(volumetric heat generation)

$$E\dot{\mathbf{x}} + K\mathbf{x} = B\mathbf{u}$$

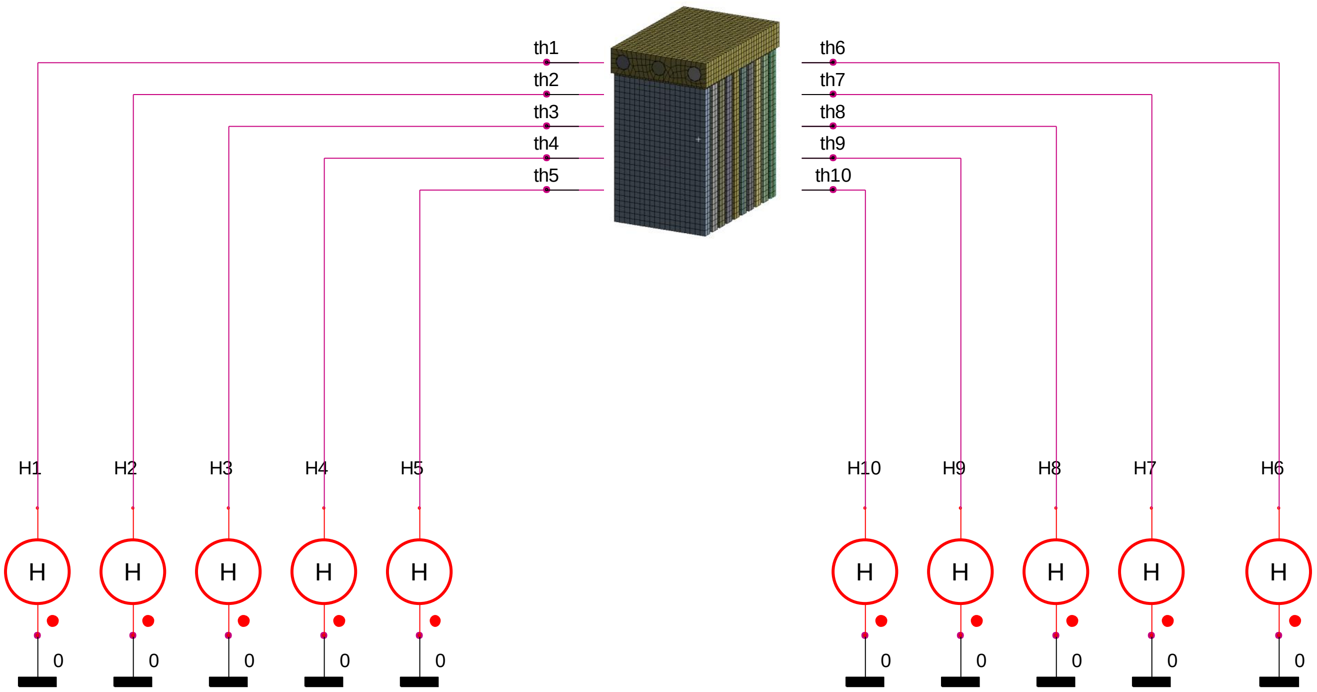


$$V^T E V \dot{\mathbf{z}} + V^T K V \mathbf{z} = V^T B \mathbf{u}$$



Battery reduced order model

- ROM
  - 10 inputs /outputs
  - Dimension : 100 (from original 150.000)
  - Solved in ANSYS Simplorer



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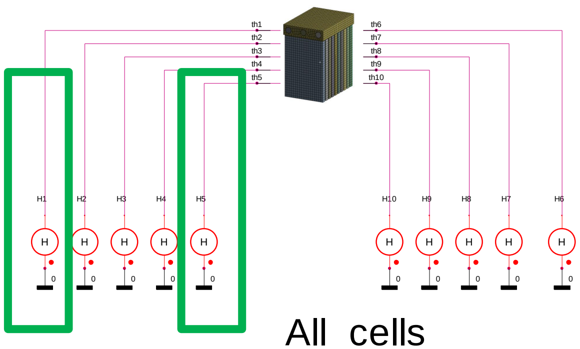
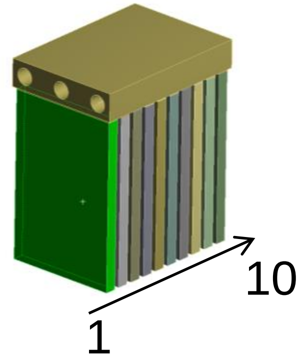
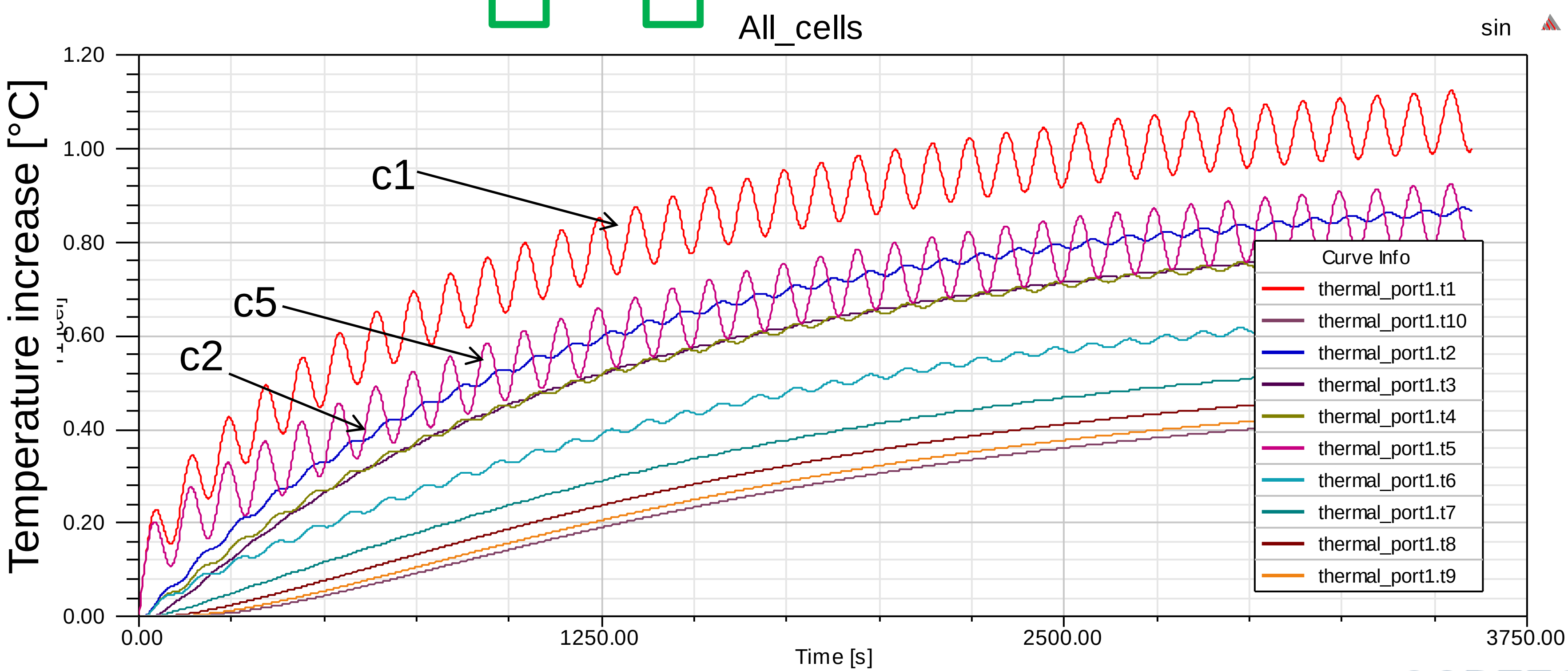
Verification case

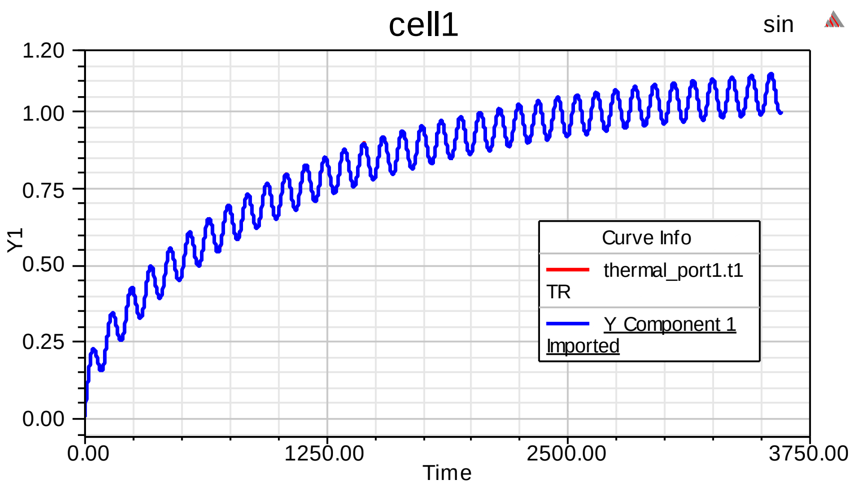
- Sinusoidal power for cells 1 and 5, f=0.01Hz, 20W max power



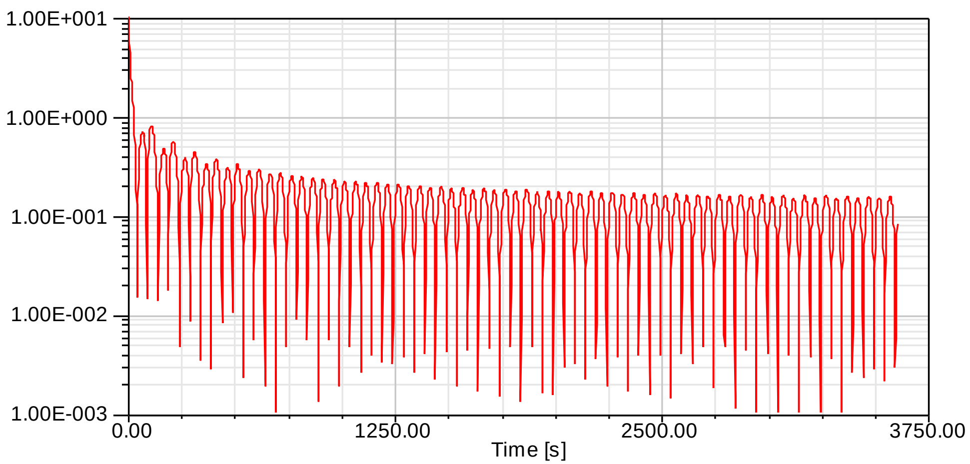




Verification case – ROM vs Full (ANSYS)



Error=abs((y-yref)/yref)*100



Fixed time step: 1s, Total time: 3600s

Full (ANSYS) CPU time: 47750s (13.2hrs)

ROM CPU time: **35.9s**

Speedup solution factor: 1300x faster

Error smaller than 2%

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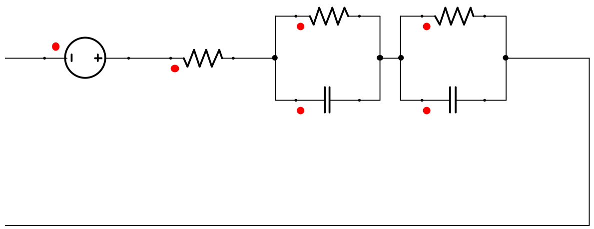
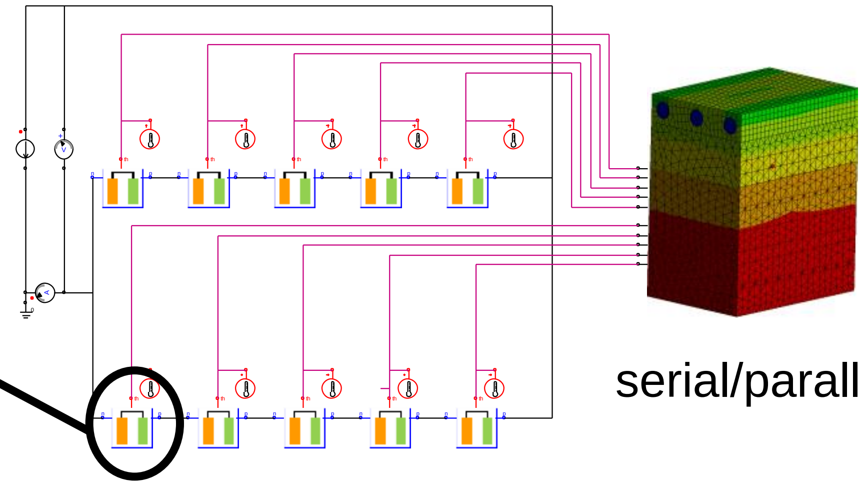
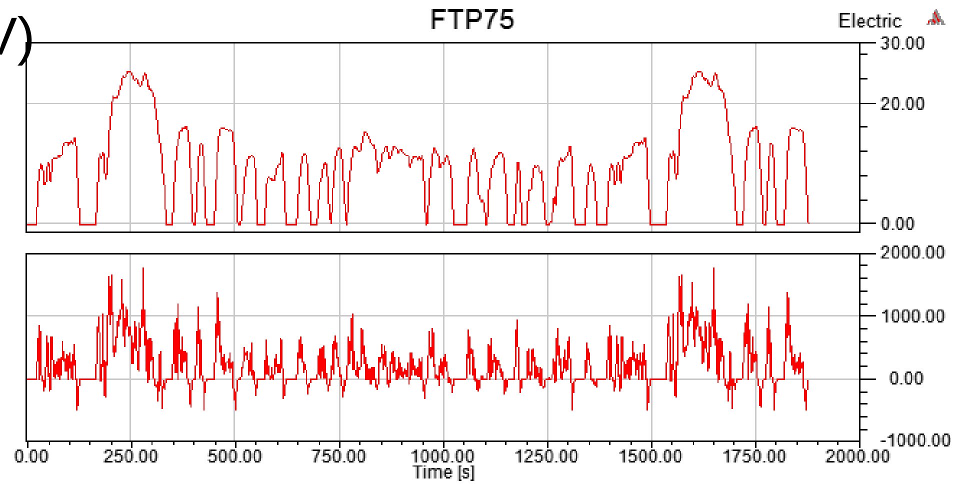
Electro-thermal battery pack model

- Circuit based electrical model
  - 40Ah





- Vehicle Power Train Model (EV)
  - 1150 kg, 42kW motor
  - Drive train model
    - FTP75 drive cycle



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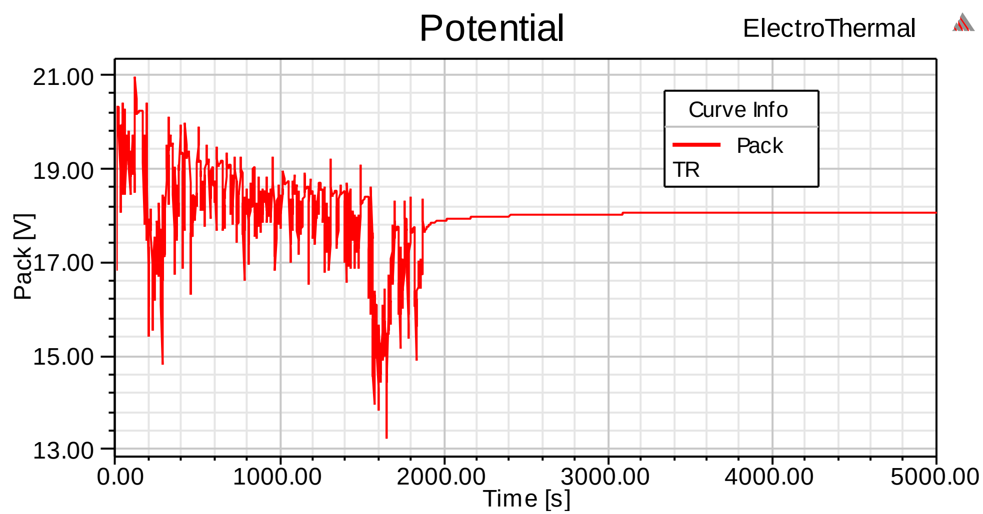
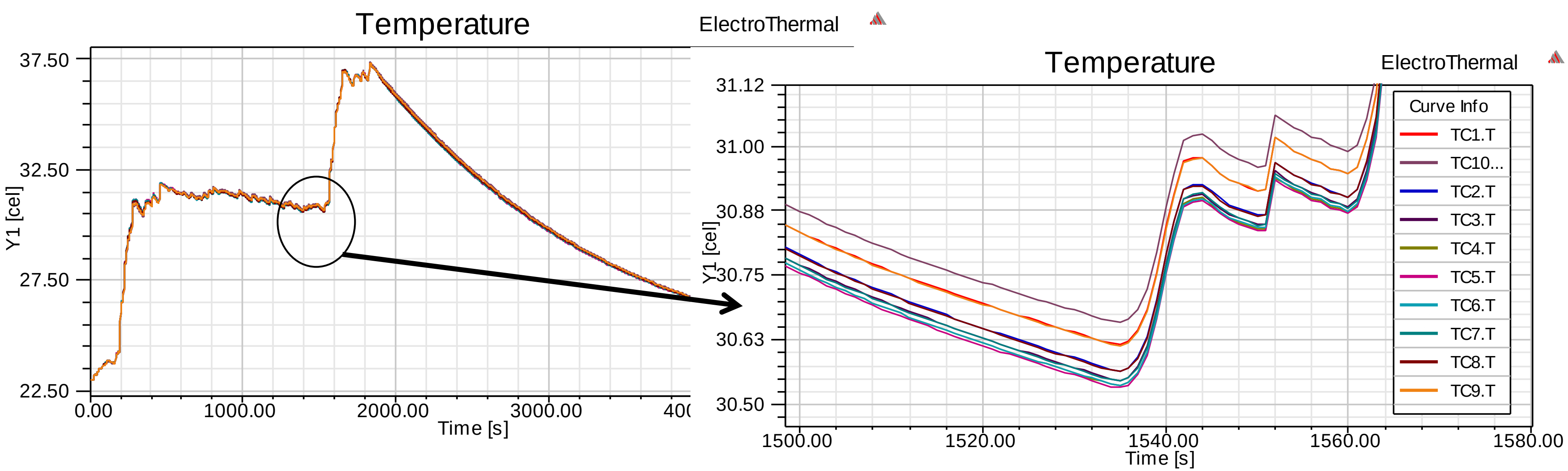
Results over EV onver FTP 75 drive cycle

- Simulation
  - Physical time: 5000s
    - t<1800s (FTP75)
    - Cooling phase
  - CPU time: 166s





CADFEM

Summary

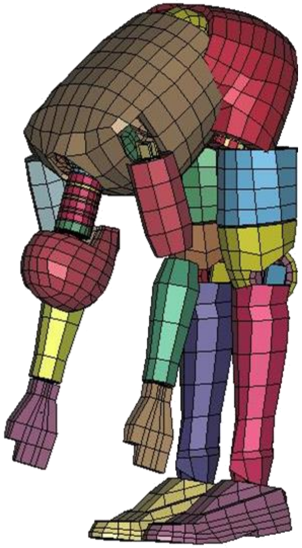
- Projection via Krilov subspaces are efficient and accurate
  - Differences of full (FEM) vs ROM are under 2%
  - Speedup of 1300x

- Battery pack thermal responses in complete drive cycles are simulated in a minute scale

  >Control design and complete simulation

- Method for accurate electro-thermal system level design
  - IGBT’s, MEMS, Sensors, ….

Thank you for your attention



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