

Weakly Coupled Thermo-Electric and MHD Mathematical Models of an Aluminium Electrolysis Cell

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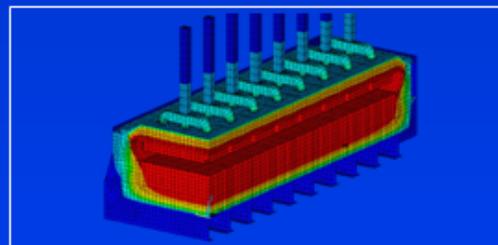
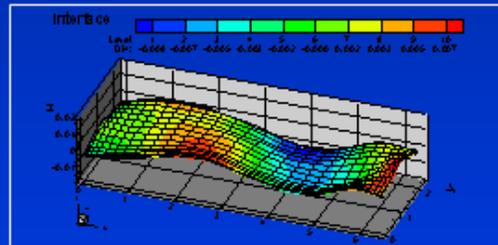
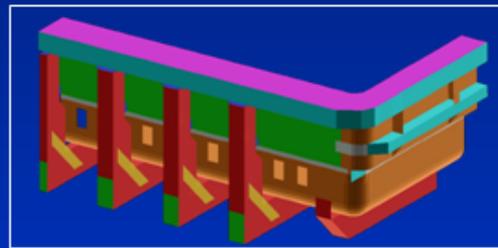
Plan of the Presentation

- **Introduction**
- **Part 1: Dupuis' Thermo-Electric Models**
 - Complete 300 kA Cell Thermo-Electric Model
 - Complete 500 kA Cell Thermo-Electric Model
 - Complete 740 kA Cell Thermo-Electric Model
- **First Weakly Coupled Solution Between T/E Model and MHD Model**
- **Part 1 Conclusions**
- **Part 2: Bojarevics' Cell Stability Model**
 - Initial 500 kA Cell Busbar Design
 - Modified 500 kA Cell Busbar Design
- **Part 2 Conclusions**

Modeling the Hall-Héroult Cell

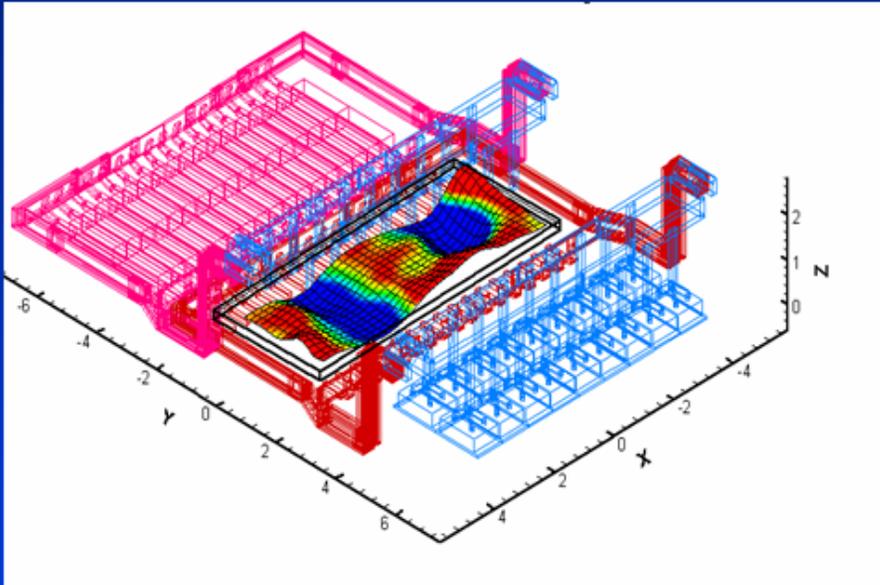
Currently, we can fit Hall-Héroult mathematical models into three broad categories:

- Stress models which are generally associated with cell shell deformation and cathode heaving issues.
- Magneto-hydro-dynamic (MHD) models which are generally associated with the problem of cell stability.
- Thermal-electric models which are generally associated with the problem of cell heat balance.

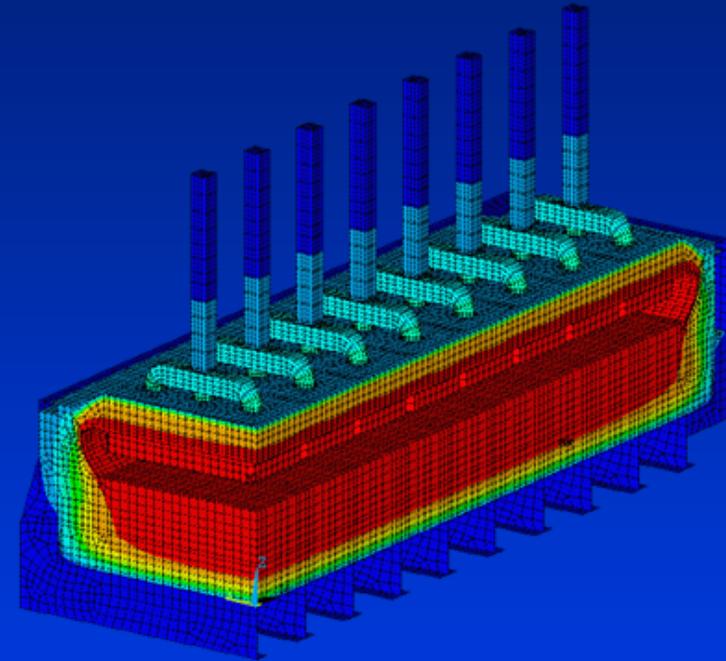


Cell Design

Modeling the Hall-Héroult Cell

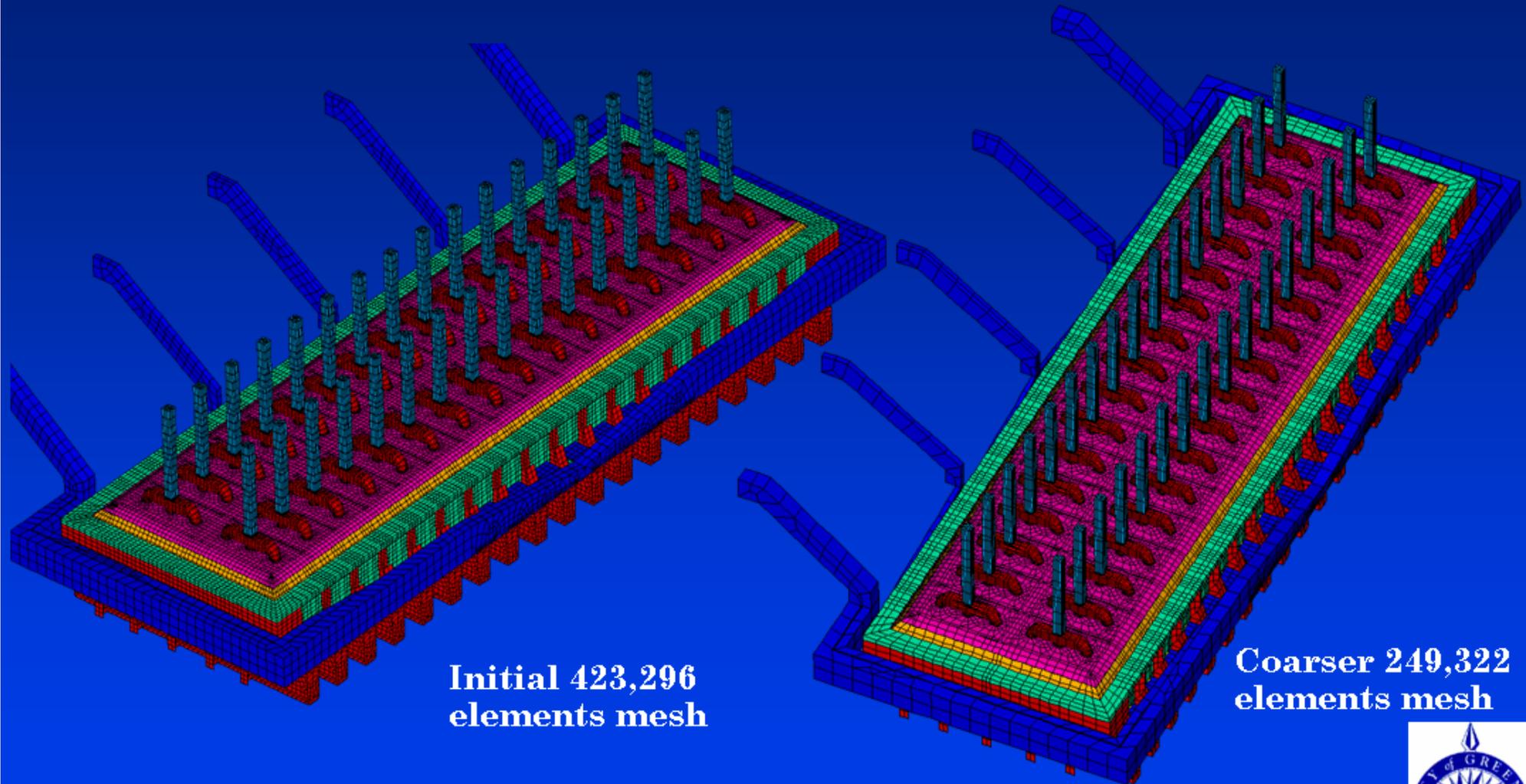


MHD model:
centered around the liquid zone



Thermo-electric model:
no need to include the liquid zone

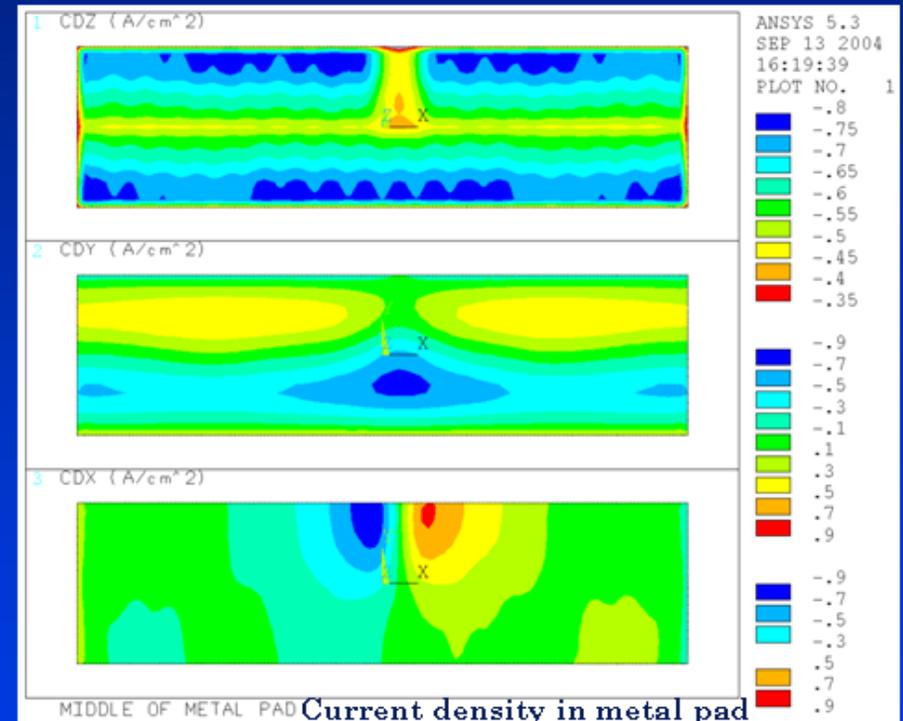
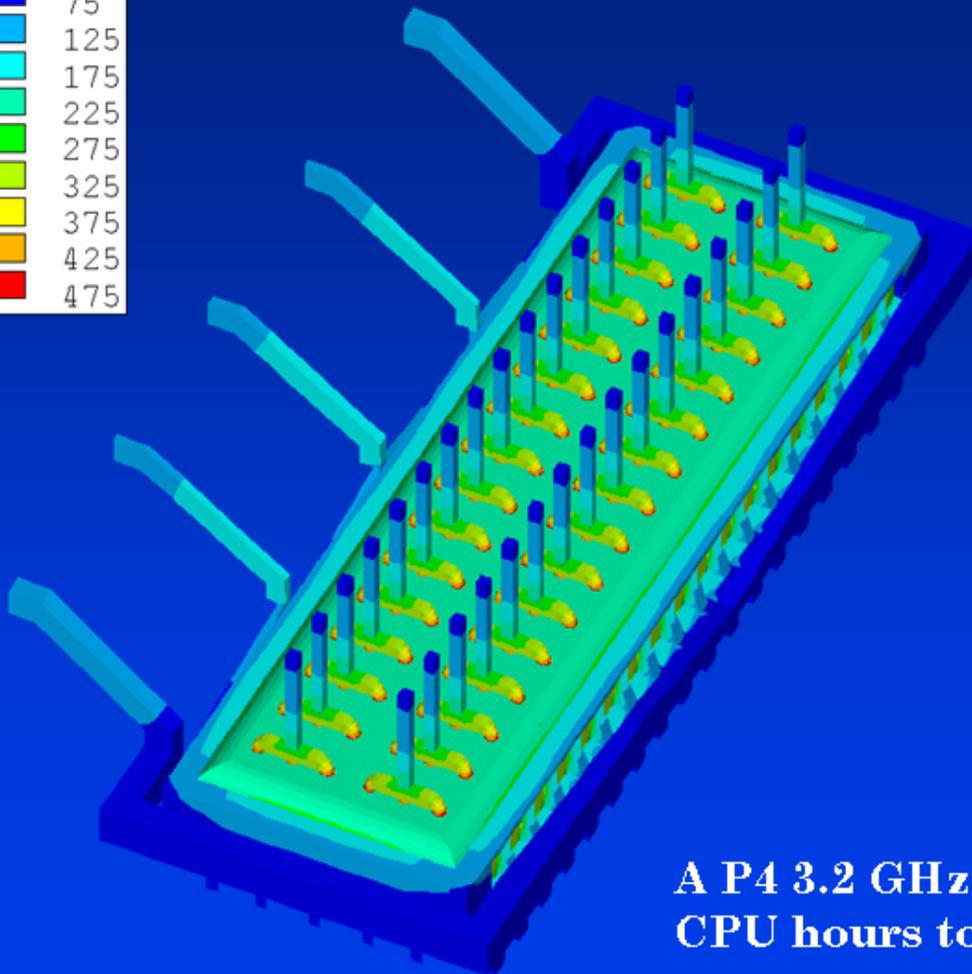
Thermo-Electric Design of a 300 kA Cell Using a Complete Full Cell Quarter Thermo-Electric Model



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Thermo-Electric Design of a 300 kA Cell Using a Complete Full Cell Quarter Thermo-Electric Model

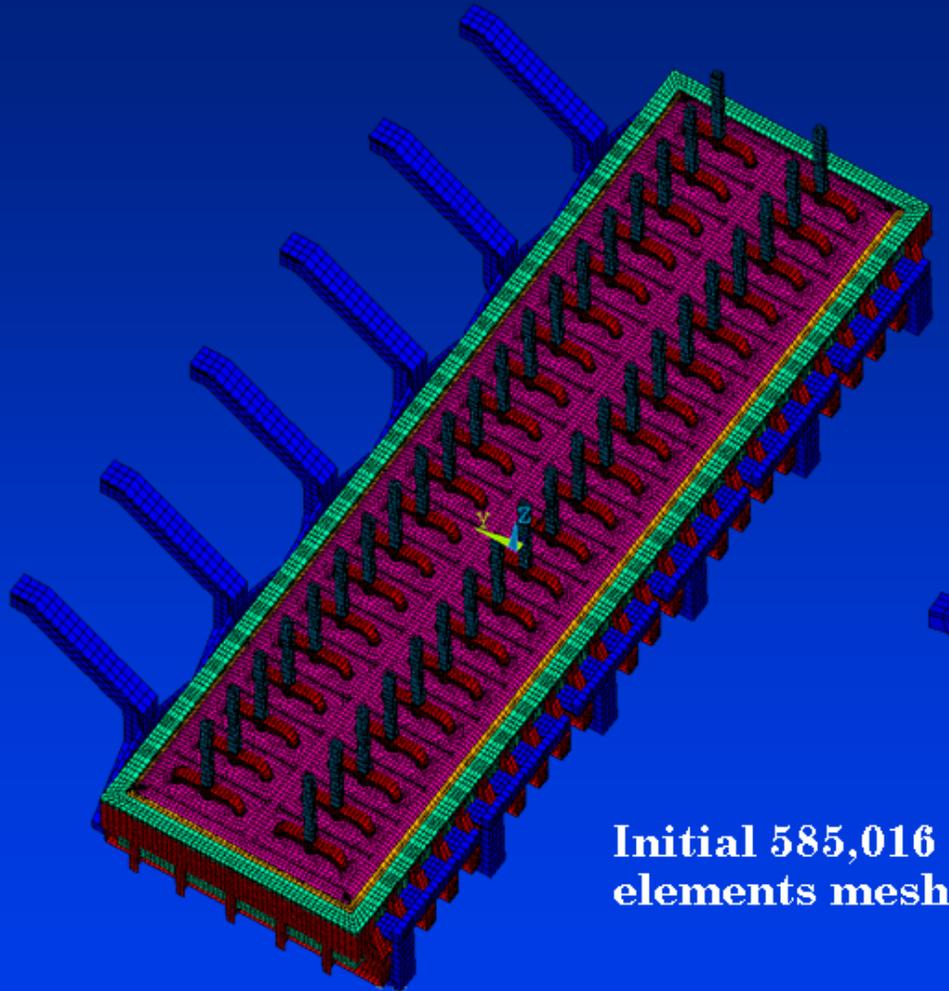


A P4 3.2 GHz computer took 63.7 CPU hours to solve the model once

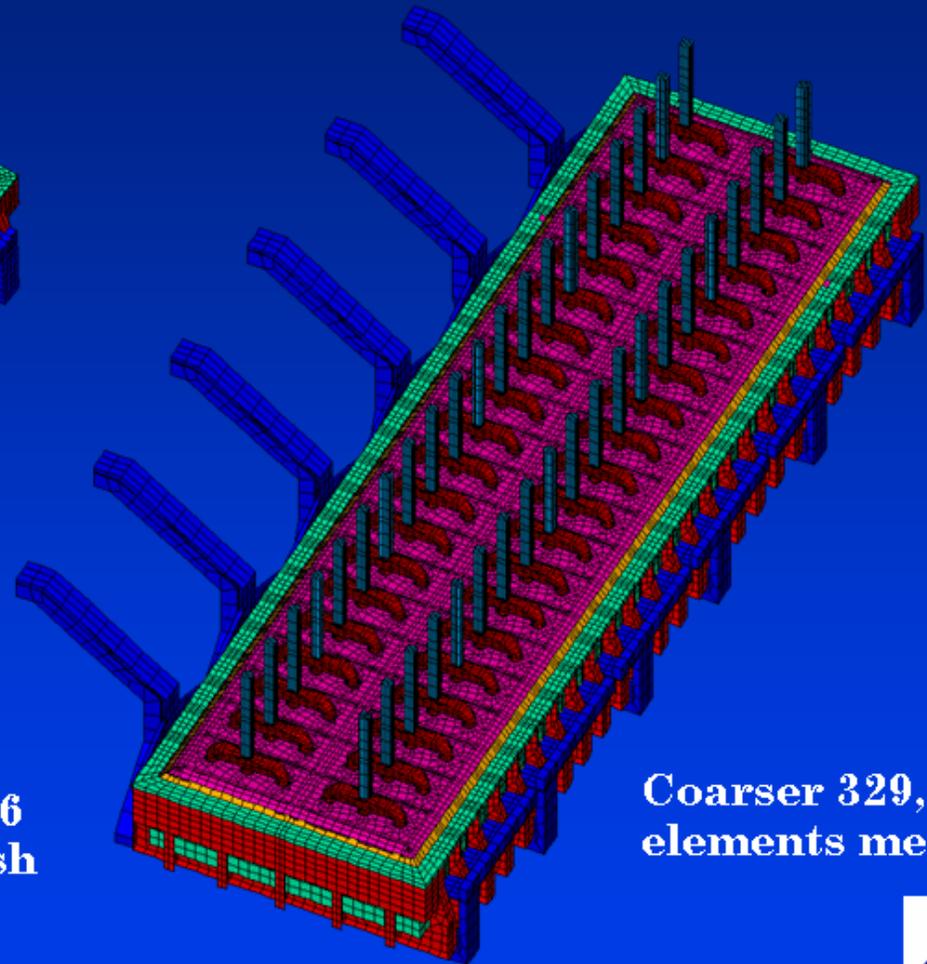
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Thermo-Electric Design of a 500 kA Cell Using a Complete Full Cell Quarter Thermo-Electric Model



Initial 585,016
elements mesh

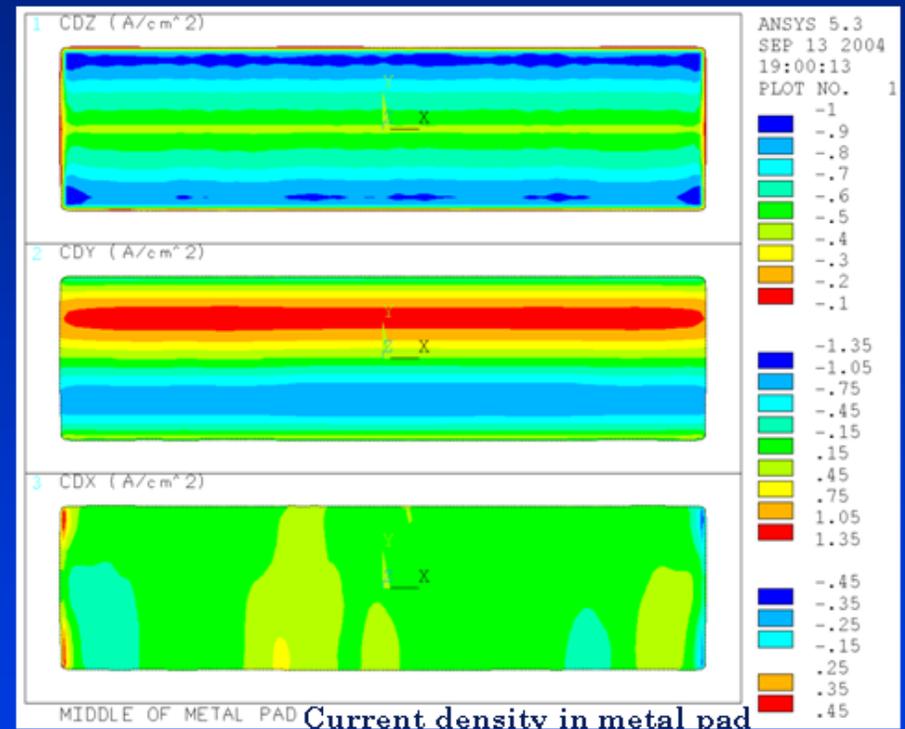
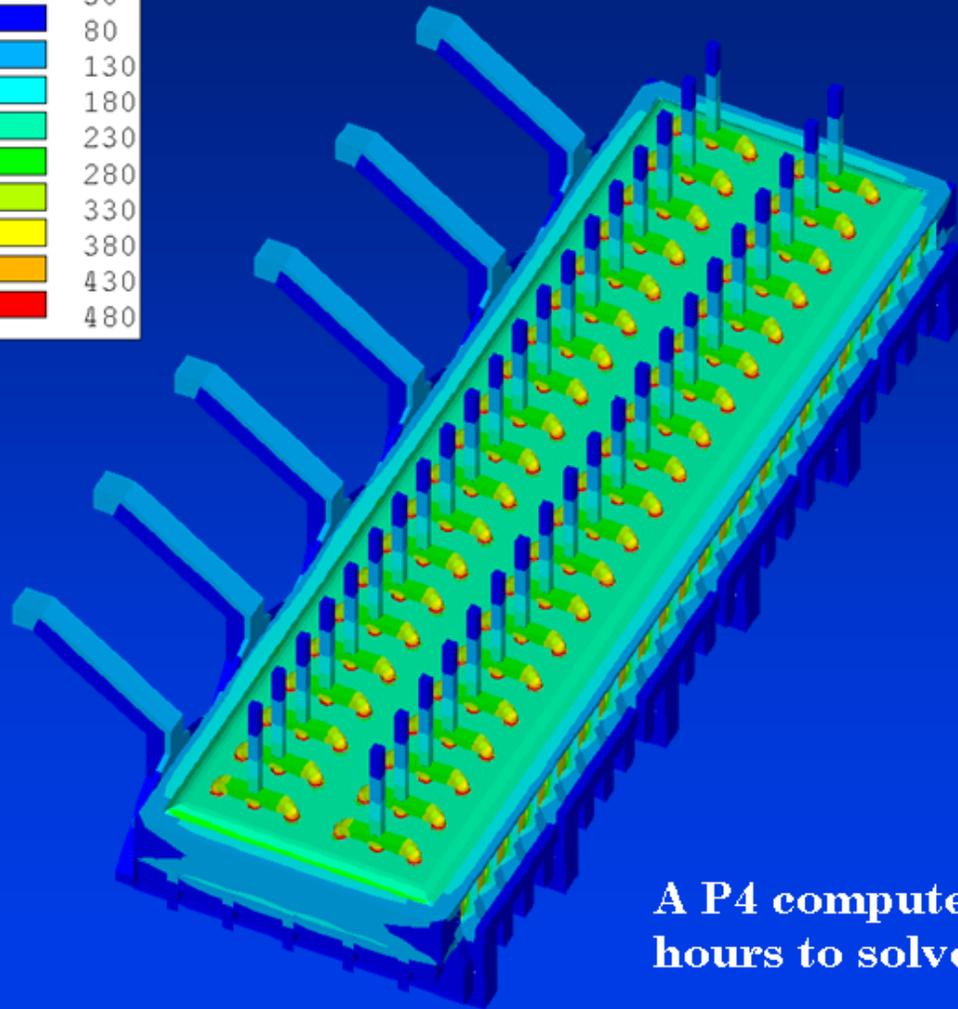
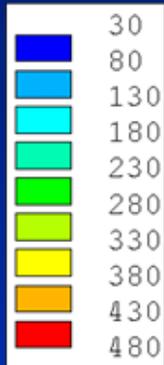


Coarser 329,288
elements mesh

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Thermo-Electric Design of a 500 kA Cell Using a Complete Full Cell Quarter Thermo-Electric Model

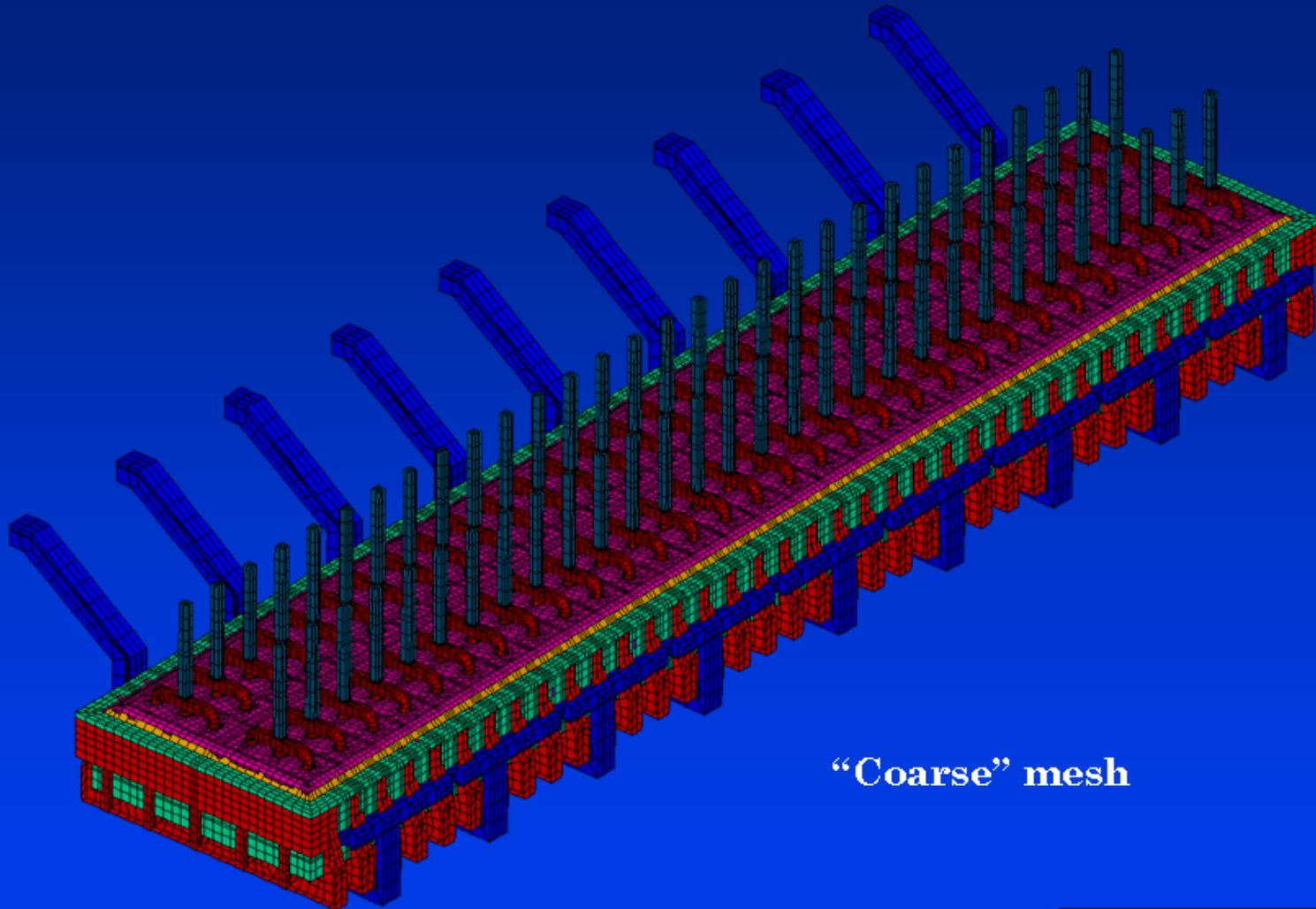


A P4 computer took “only” 40.6 CPU hours to solve the model 6 times

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Thermo-Electric Design of a 740 kA Cell Using a Complete Full Cell Quarter Thermo-Electric Model

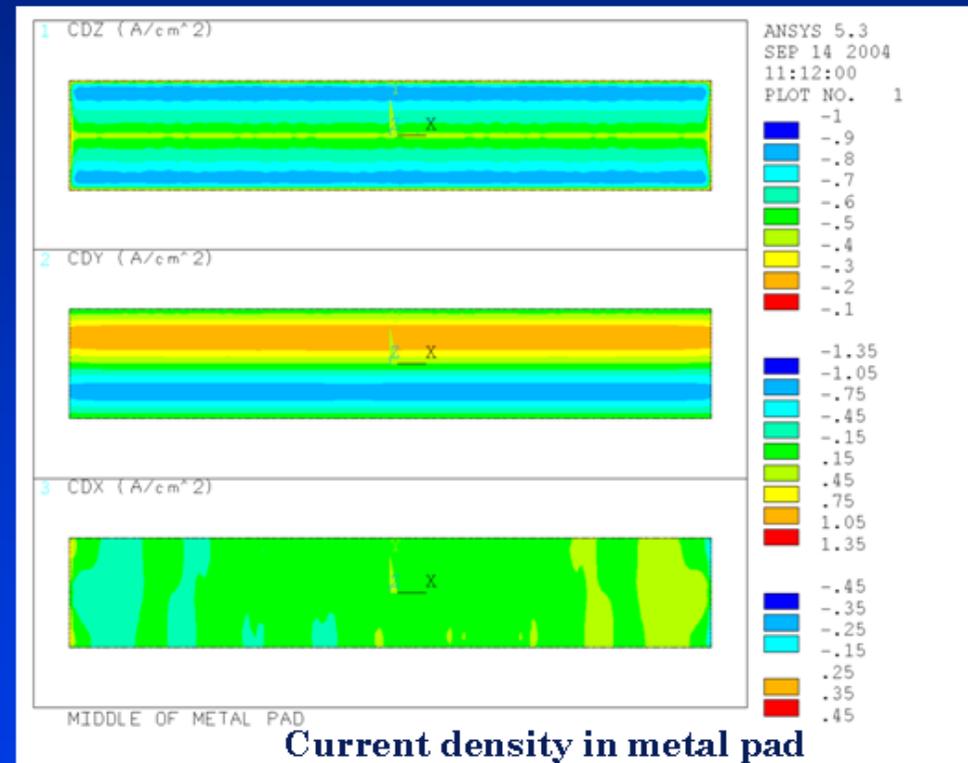
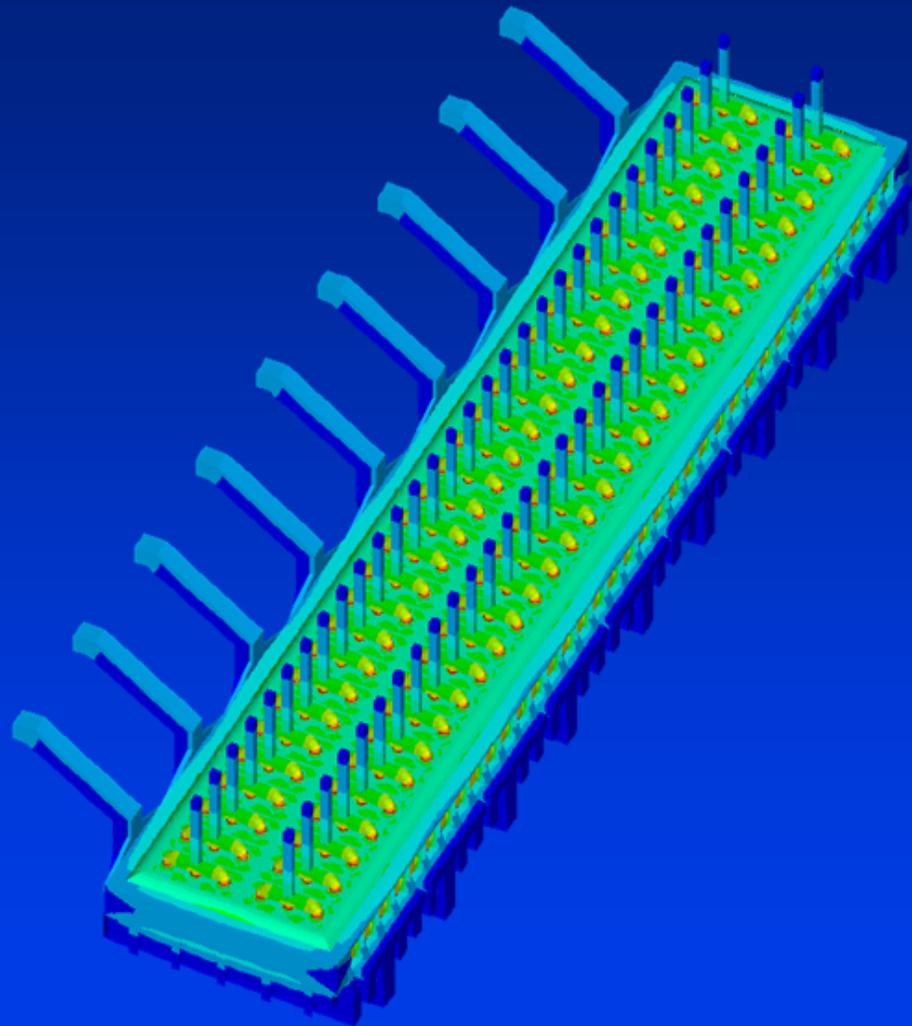


“Coarse” mesh

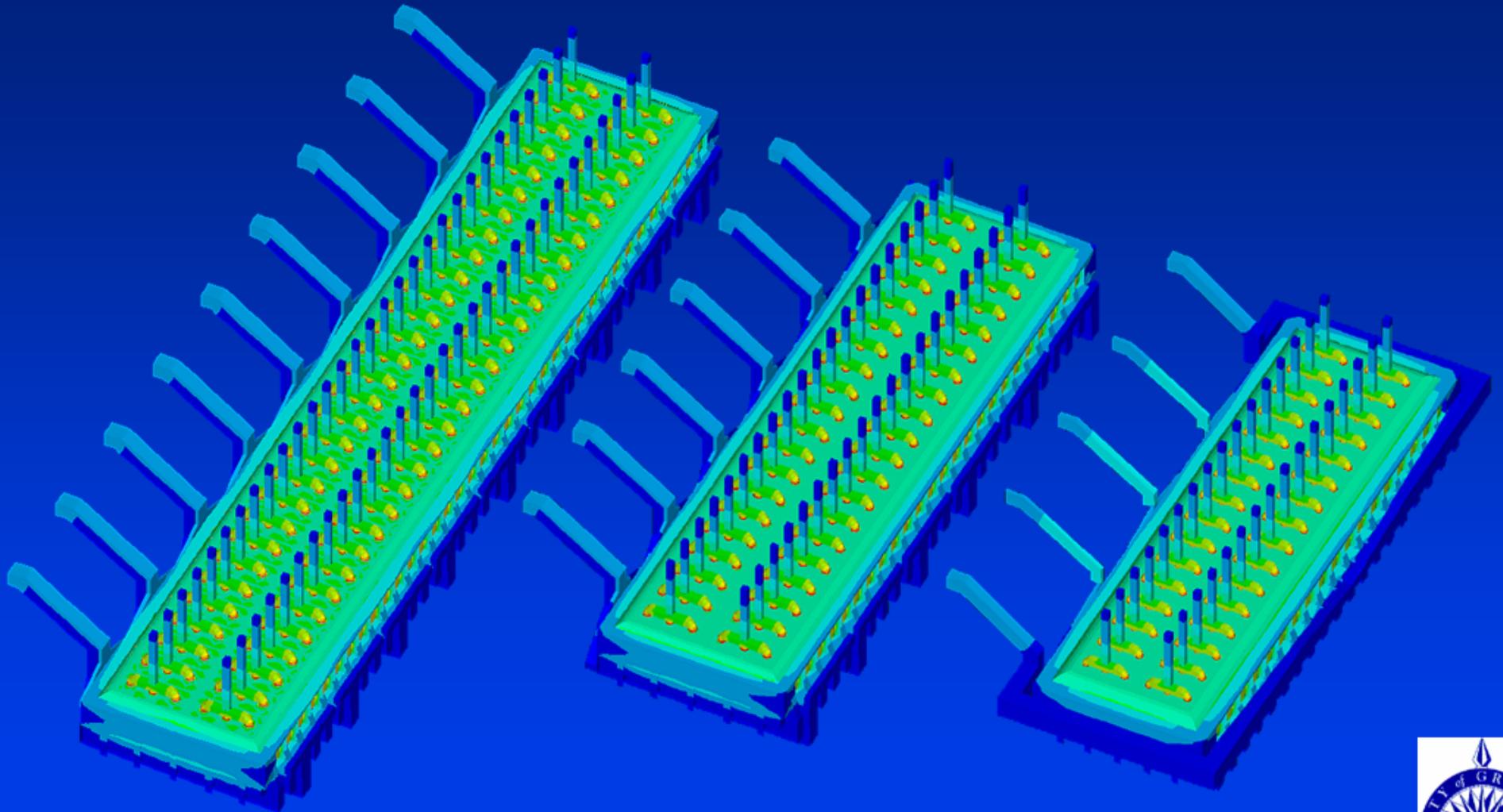
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Thermo-Electric Design of a 740 kA Cell Using a Complete Full Cell Quarter Thermo-Electric Model



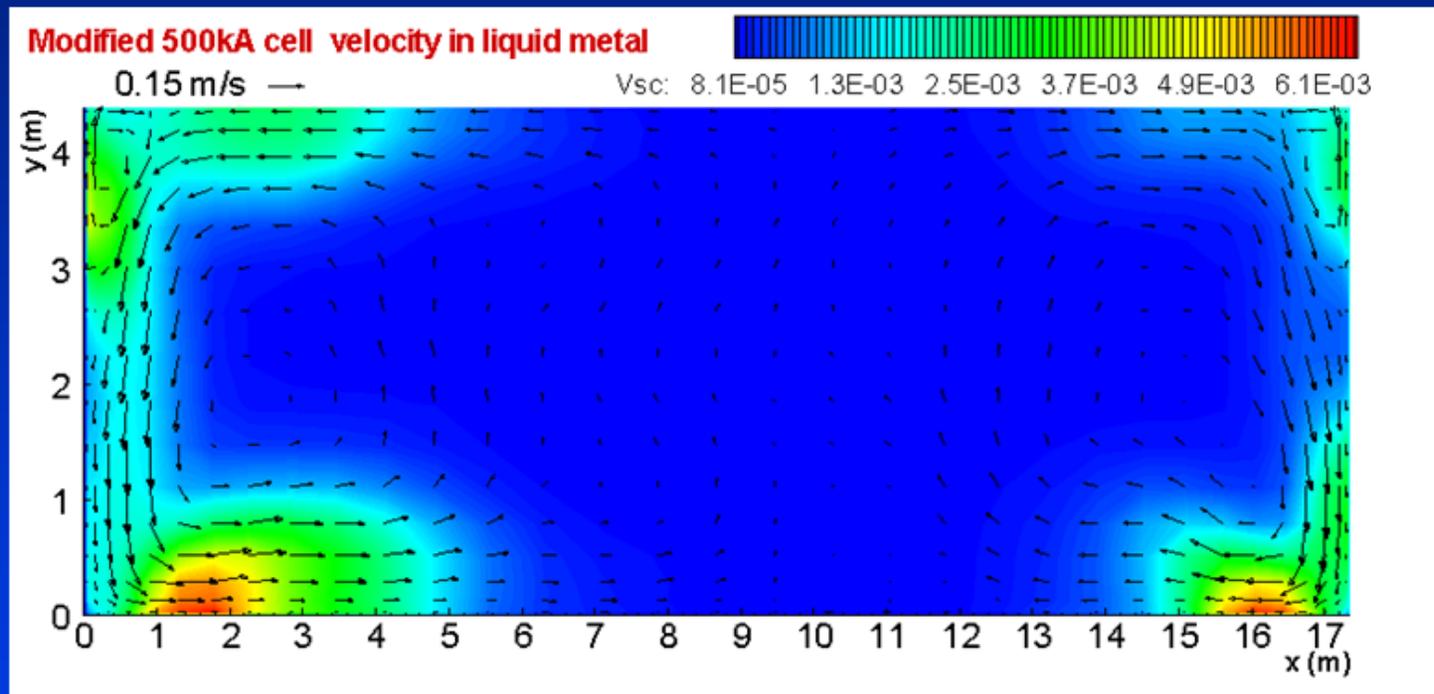
Thermo-Electric Design of 300, 500 and 740 kA Cells Using a Complete Full Cell Quarter Thermo-Electric Model



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First Weakly Coupled Solution Between Thermo-Electric and MHD Models: 500 kA Cell Design

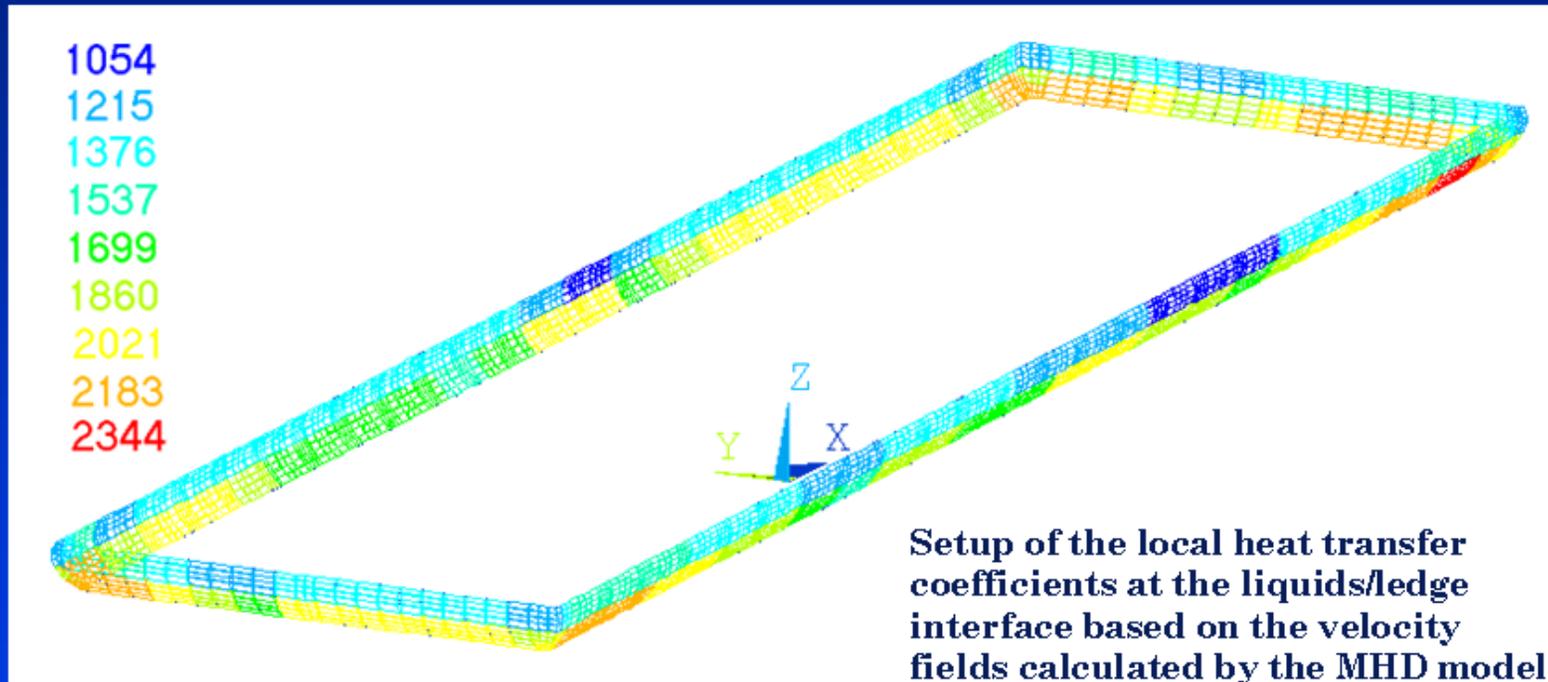


Velocity fields and turbulent effective viscosity distribution in liquid aluminium for the 500 kA cell as predicted by the MHD model

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First Weakly Coupled Solution Between Thermo-Electric and MHD Models: 500 kA Cell Design

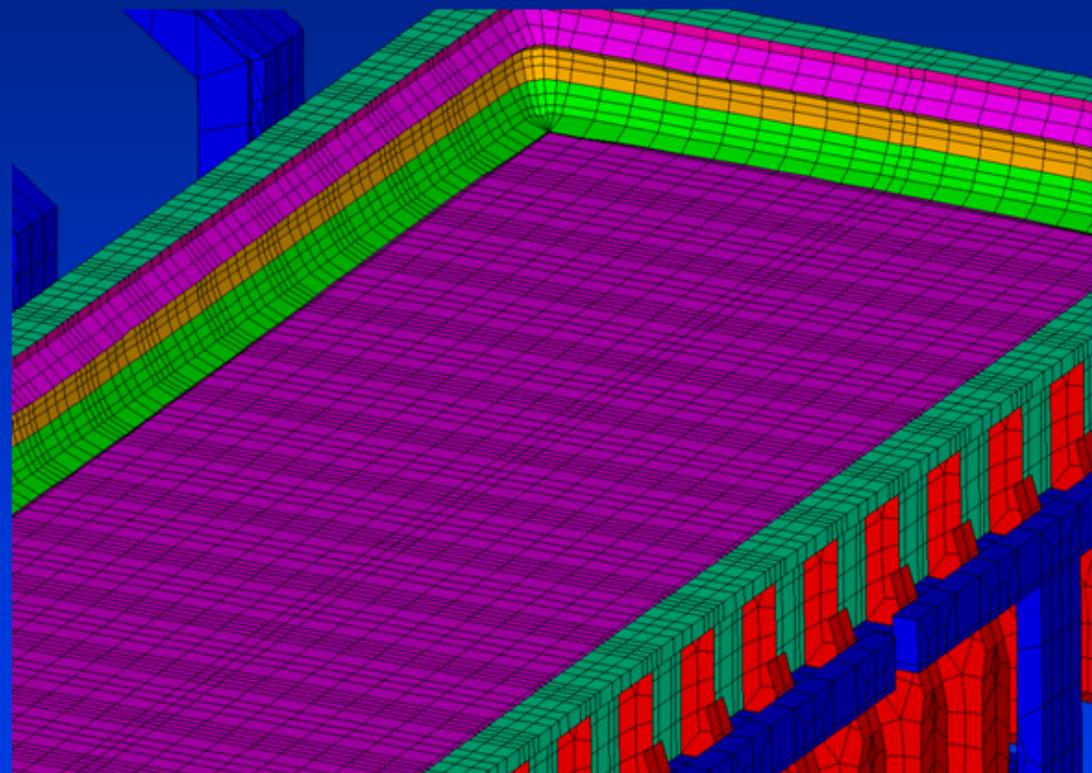


$$h_{\text{metal/ledge}} \text{ (W/m}^2\text{K)} = 1684 + 2000 V^{1/2}_{\text{ (m/s)}}$$

$$h_{\text{bath/ledge}} \text{ (W/m}^2\text{K)} = 1121 + 2000 V^{1/2}_{\text{ (m/s)}}$$

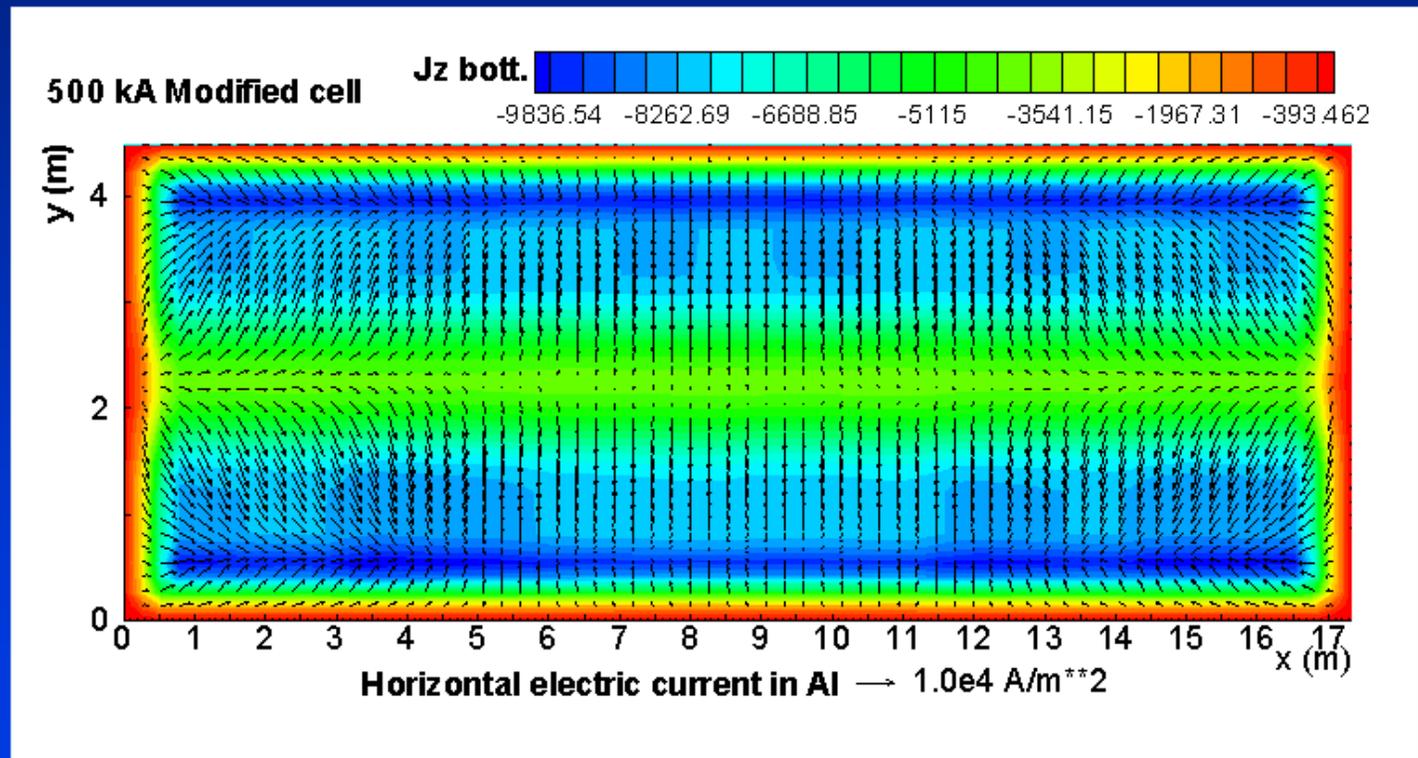
First Weakly Coupled Solution Between Thermo-Electric and MHD Models: 500 kA Cell Design

The obtained ledge profile geometry is transferred to the MHD model and the MHD cell stability analysis is computed again



First Weakly Coupled Solution Between Thermo-Electric and MHD Models: 500 kA Cell Design

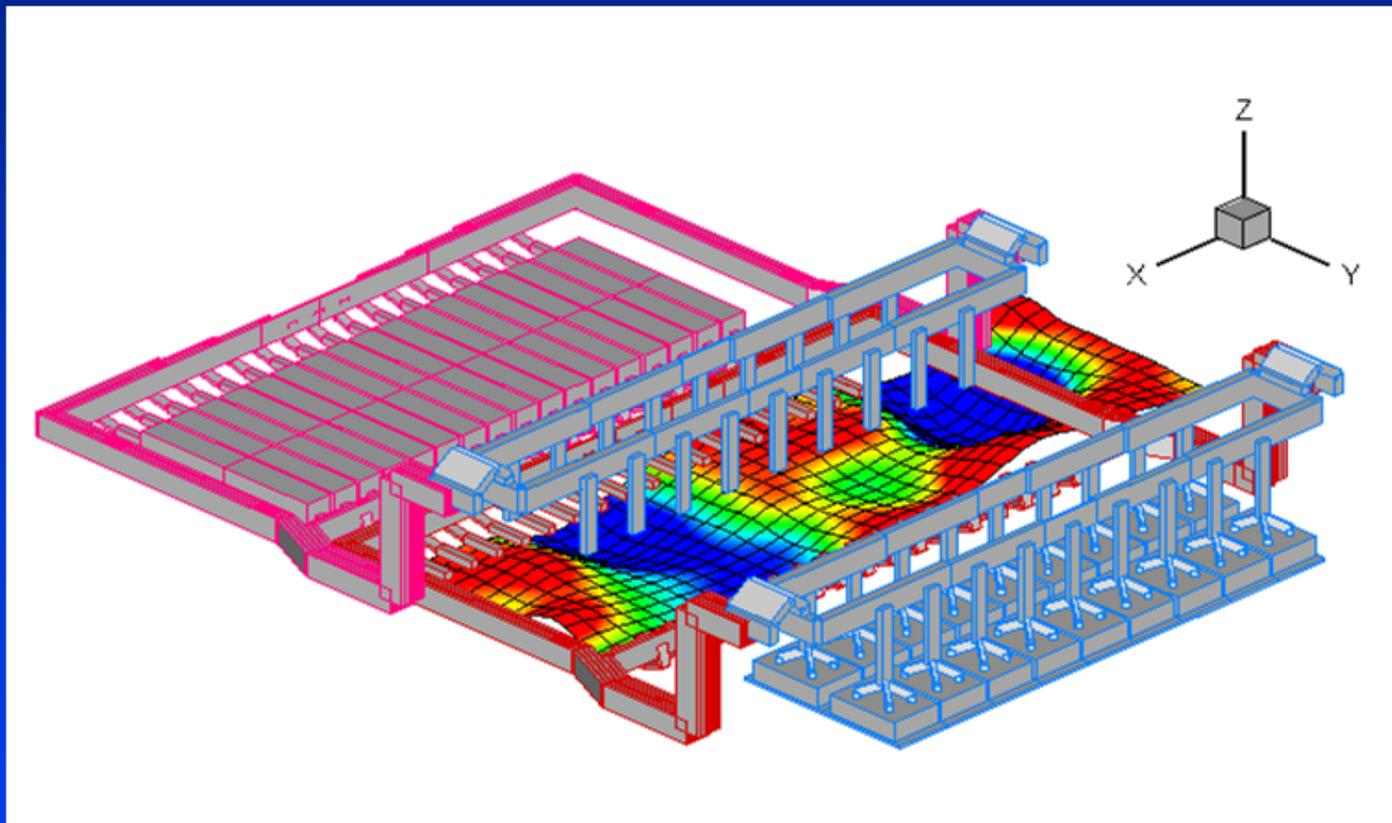
Electric current distribution in the liquid metal computed with the MHD model and the ledge position input from the thermo-electric model



Conclusions

- Three 3D full cell and external bus-bar thermo-electric model have been successfully used to produce demonstration design of 300, 500 and 740 kA Al electrolysis cells.
- A first weakly coupled thermo-electric and MHD run has been successfully carried out.
- Only two iterations of the weakly coupled convergence loop were required because the non-linear coupling effects turned out to be not very significant in the present case.
- Nevertheless, those two iterations required 98 CPU hours on a P4 3.2 GHz computer.

MHD Modelling Package for Aluminium Reduction Cells



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Development Background

- Mercury models for Russian smelter cells (1980-1990):
direct measurements for currents, magnetic field and velocity field used to validate numerical models
- Bojarevics & Romerio 1994: Sele's rotating wave instability via gravity wave frequency shift mechanism
- Nonlinear waves in aluminium cells (1995)
(Progr. Fluid Flow Res., AIAA, 1998)
- Commercial cell models for Reynolds Metals:
coupled waves and large scale circulation velocity, full busbar effects
- Turbulence models validated with direct measurements (In-Ga cold metal, Ti-Al dynamic Induction Skull Melting)

Basic Equations Used in Models

Hydrodynamic

$$\partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\rho^{-1} \nabla p + \nabla \cdot (\nu_e (\nabla \mathbf{v} + \nabla \mathbf{v}^T)) + \rho^{-1} \mathbf{j} \times \mathbf{B} + \mathbf{g},$$

$$\mathbf{e}_n \cdot \mathbf{v} = \mathbf{e}_n \cdot \partial_t \mathbf{R}$$

Electromagnetic interaction:

$\mathbf{j} = \sigma \nabla \varphi$; $\nabla^2 \varphi = 0$ in busbars, electrodes, liquid, etc.

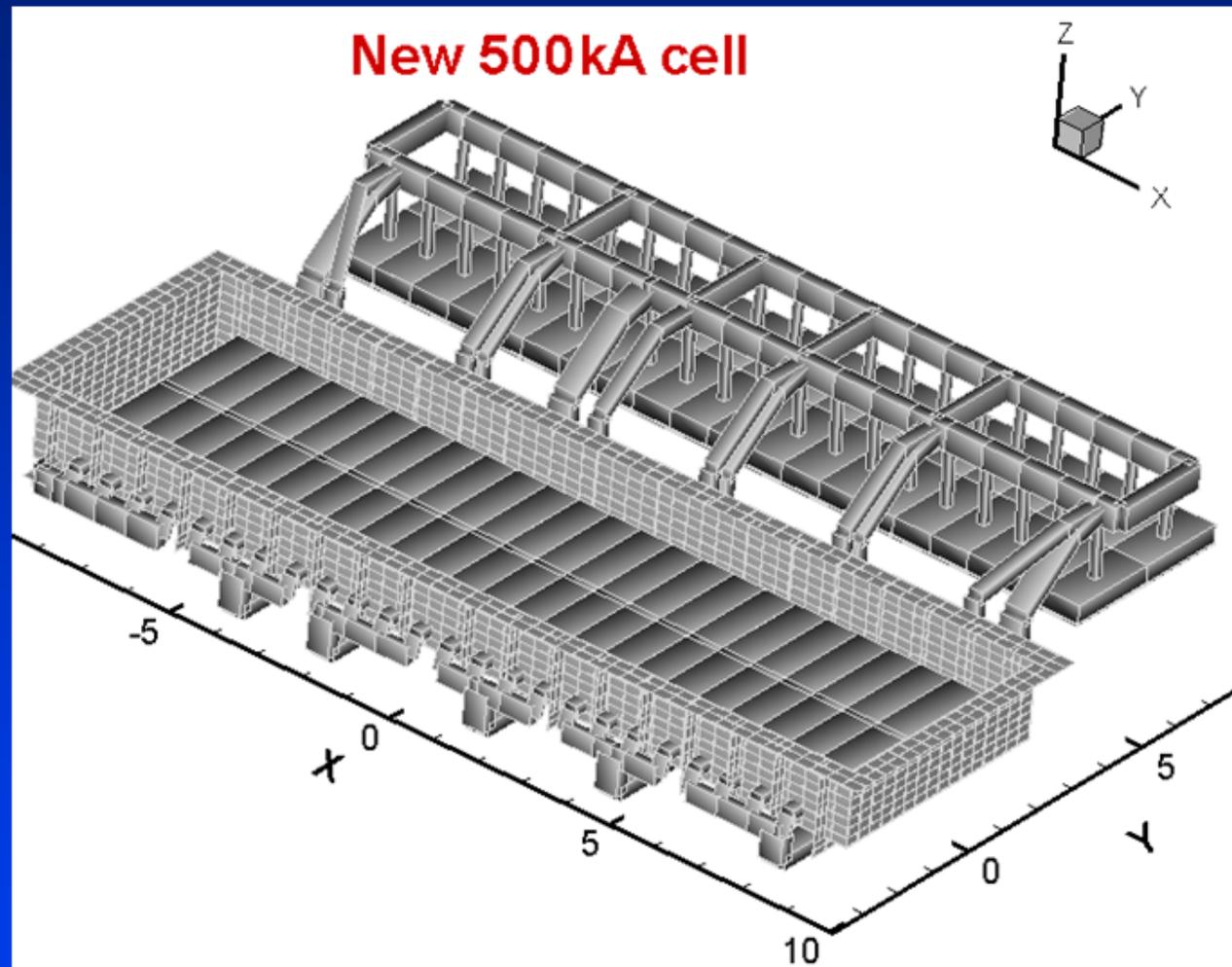
$$\mathbf{B}(\mathbf{r}) = \frac{1}{4\pi} \text{rot} \iiint_{V(j \neq 0)} \frac{\mathbf{j}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}'$$

Magnetic materials

$$\mathbf{H}(\mathbf{r}) = \frac{1}{4\pi} \text{grad div} \iiint_{V(M \neq 0)} \frac{\mathbf{M}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} d\mathbf{r}' + \mathbf{H}^{\text{ext}}(\mathbf{r}),$$

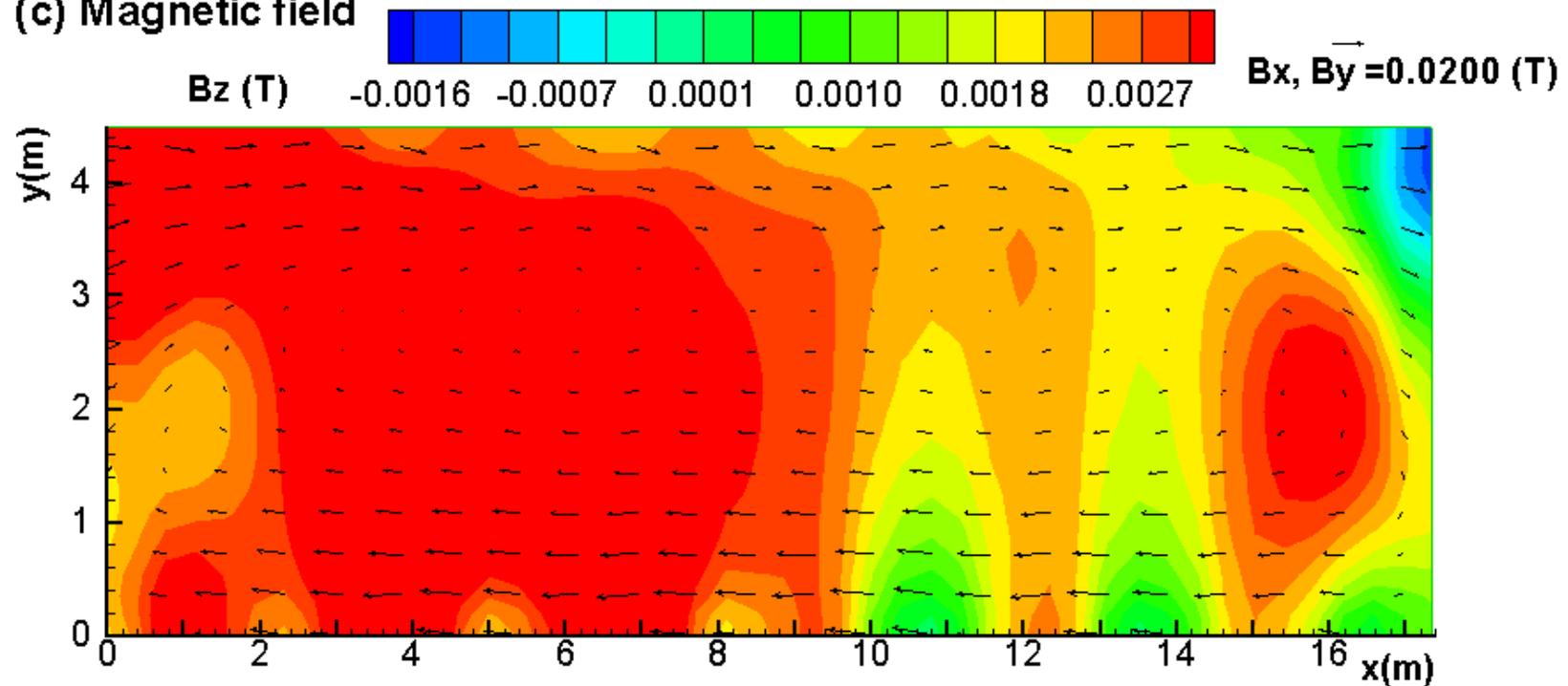
$$\mathbf{B} = \mu(\mathbf{H}) \cdot \mathbf{H} \quad \text{or} \quad \mathbf{M} = \kappa(\mathbf{H}) \cdot \mathbf{H}$$

Initial 500 kA Busbars Design

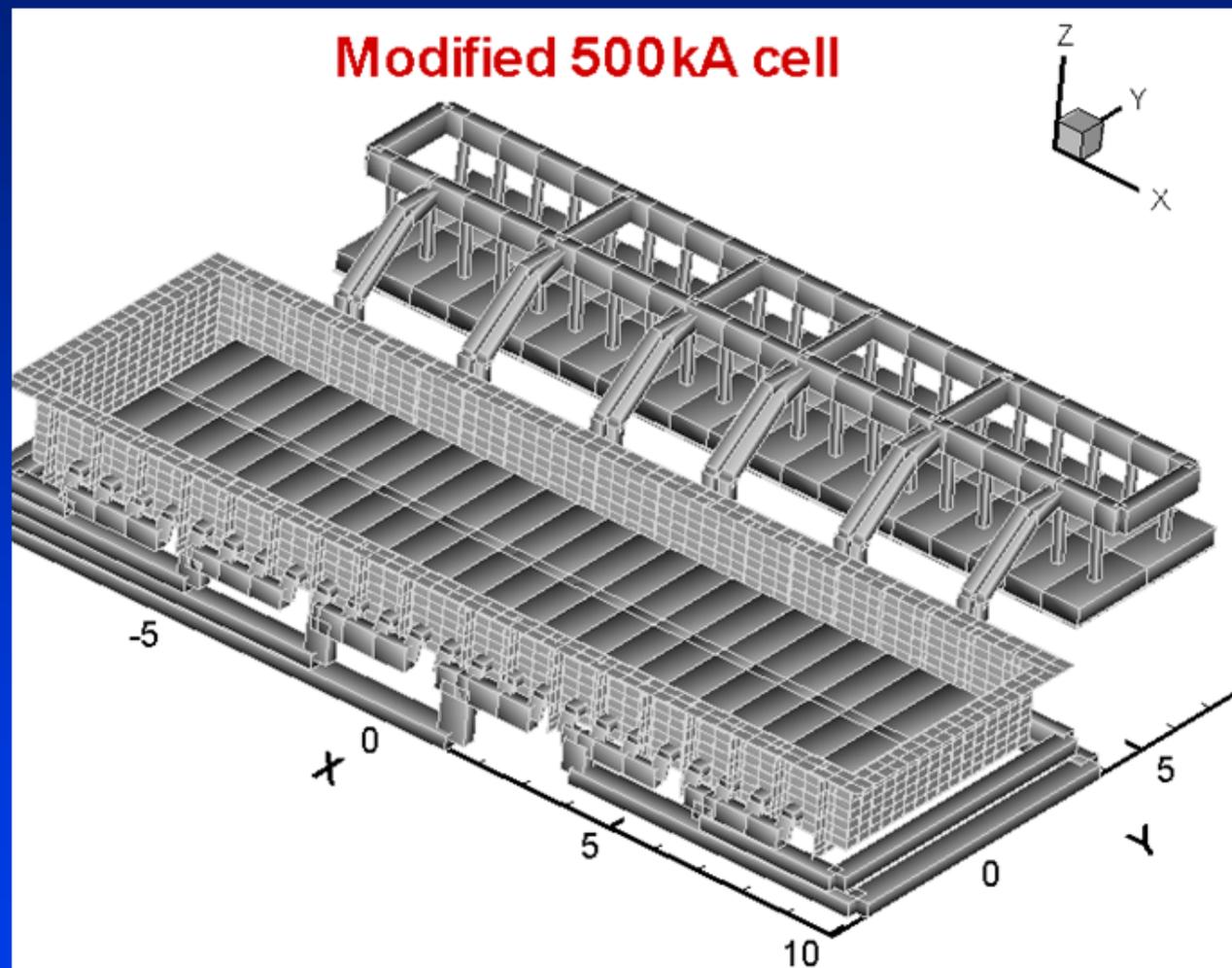


Initial 500 kA Busbars Design

(c) Magnetic field

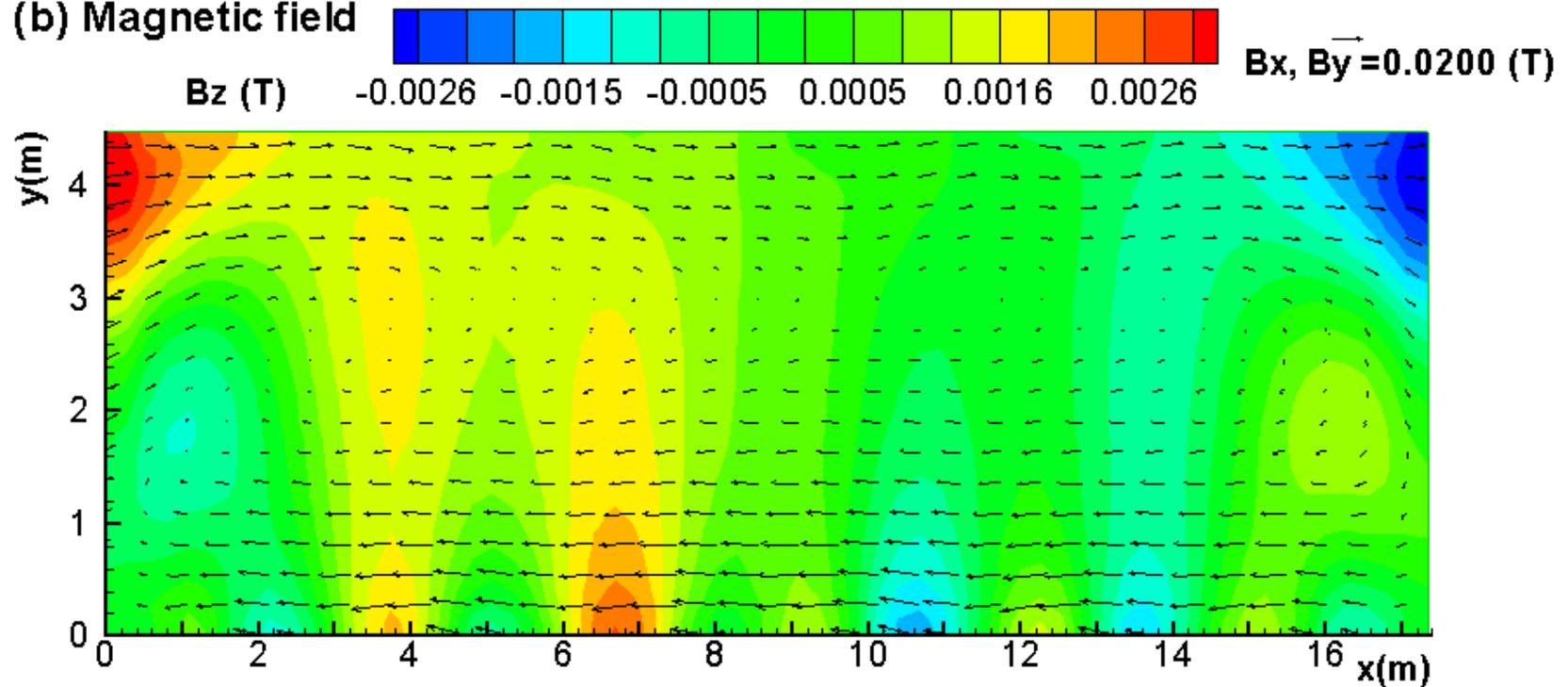


Modified 500 kA Busbars Design



Modified 500 kA Busbars Design

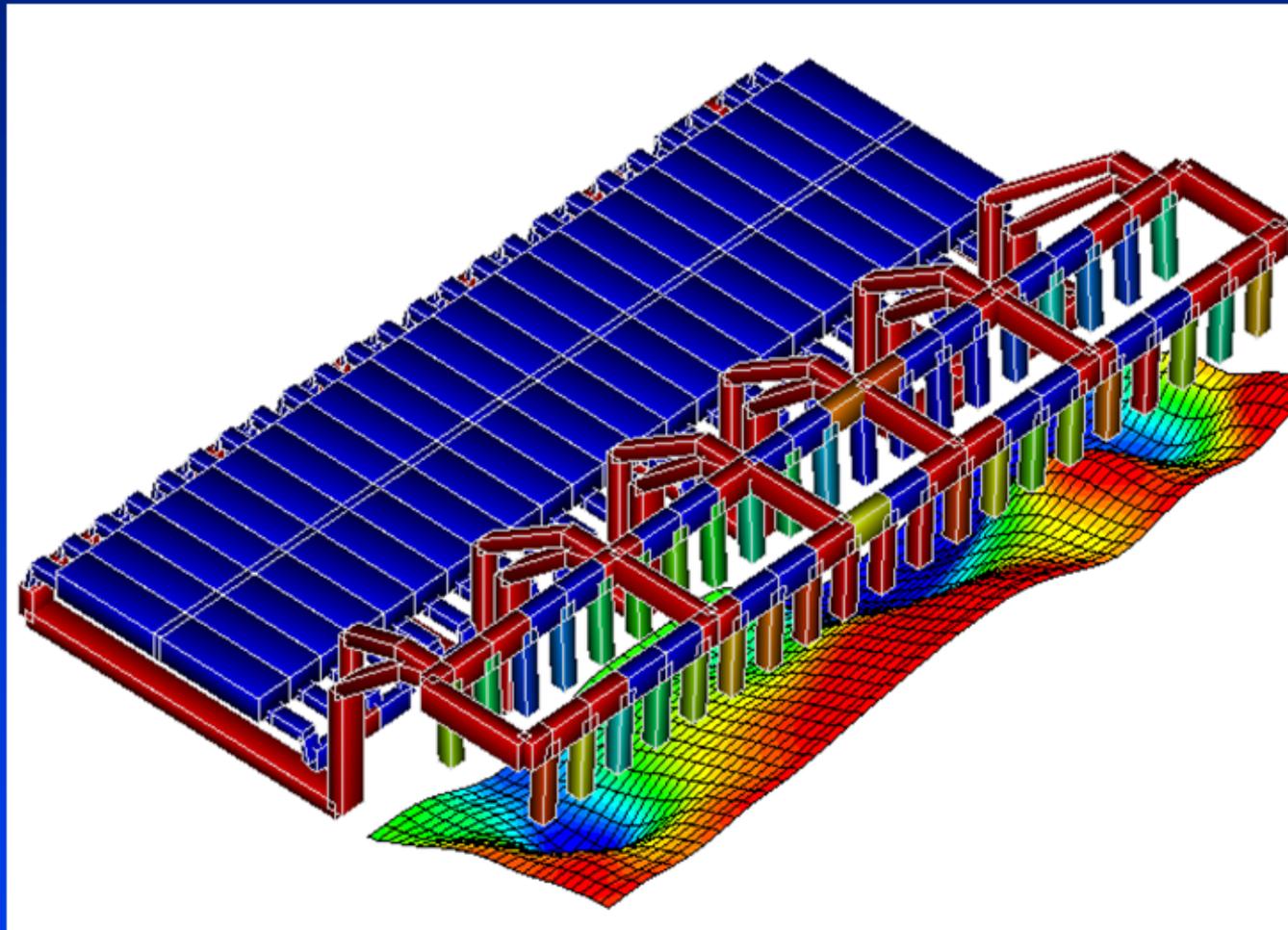
(b) Magnetic field



Waves Coupled to Currents in Busbar Network

- The electric current distribution in the whole bus-bar circuit between the cells, individual anodes and cathode collector bars is coupled to the electric current in the fluid zone
- The electric and magnetic fields are recalculated continuously as the wave shape changes

Waves Coupled to Currents in Busbar Network

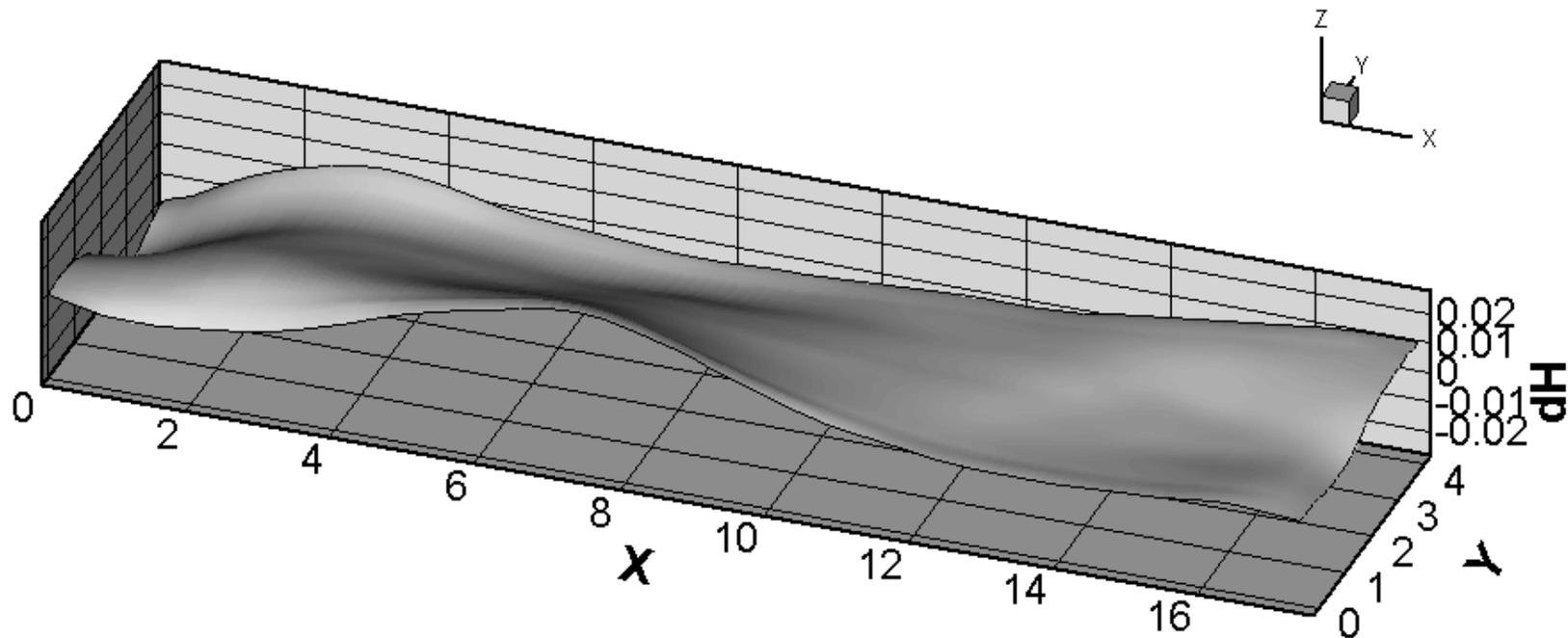


Waves Coupled to Currents in Busbar Network

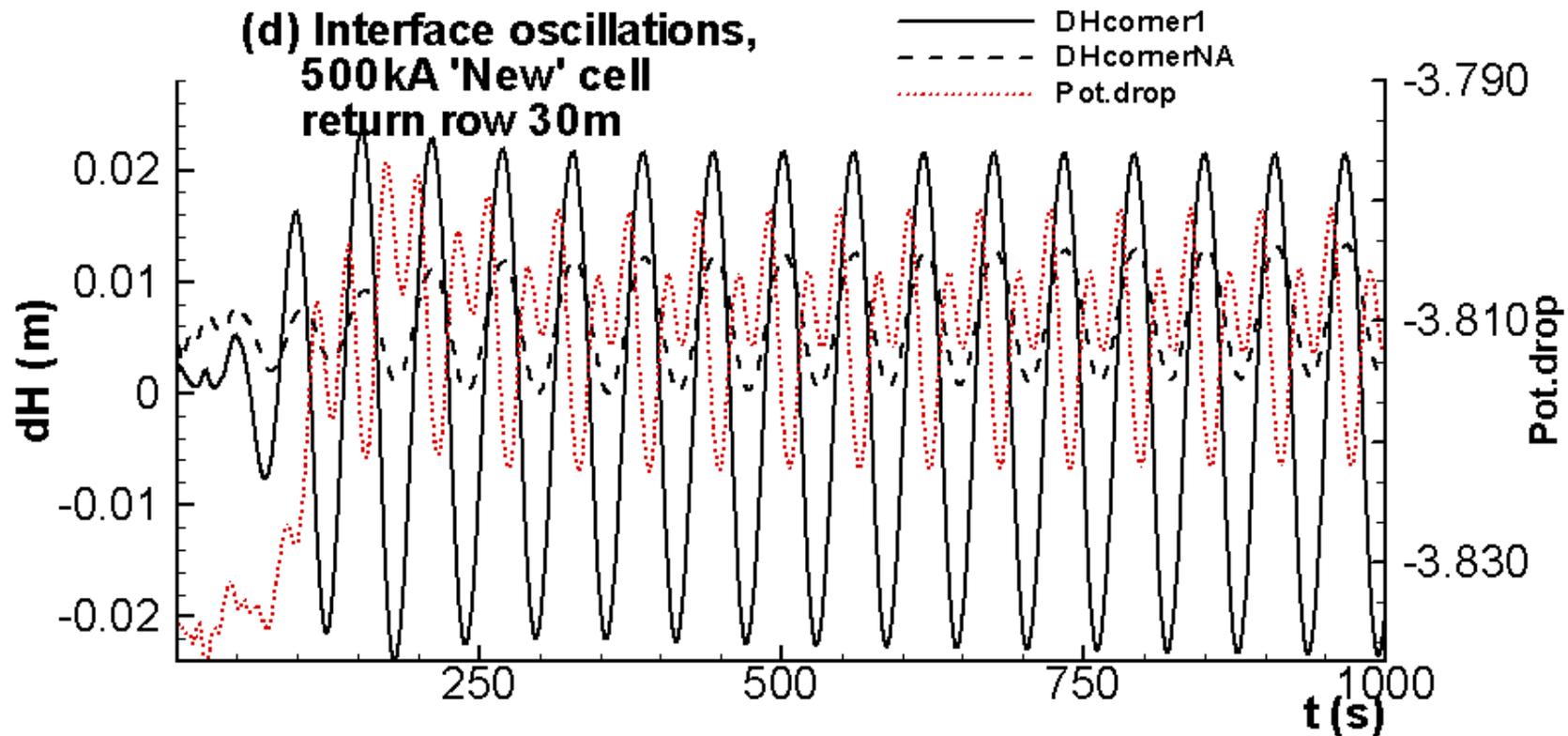
- The fluid flow and wave model are transient and effectively three-dimensional, using for the metal and bath flow the shallow-layer approximation
- The model calculates turbulent flows in the two liquid layers and their effects on the non-linear waves
- The flow turbulent energy distribution identifies mixing rates and the ledge/lining risk zones

Initial 500 kA Cell Busbar Interface of Aluminium Metal Pad

Liquid aluminium surface, dH (m)
500 kA New cell, return row 30 m

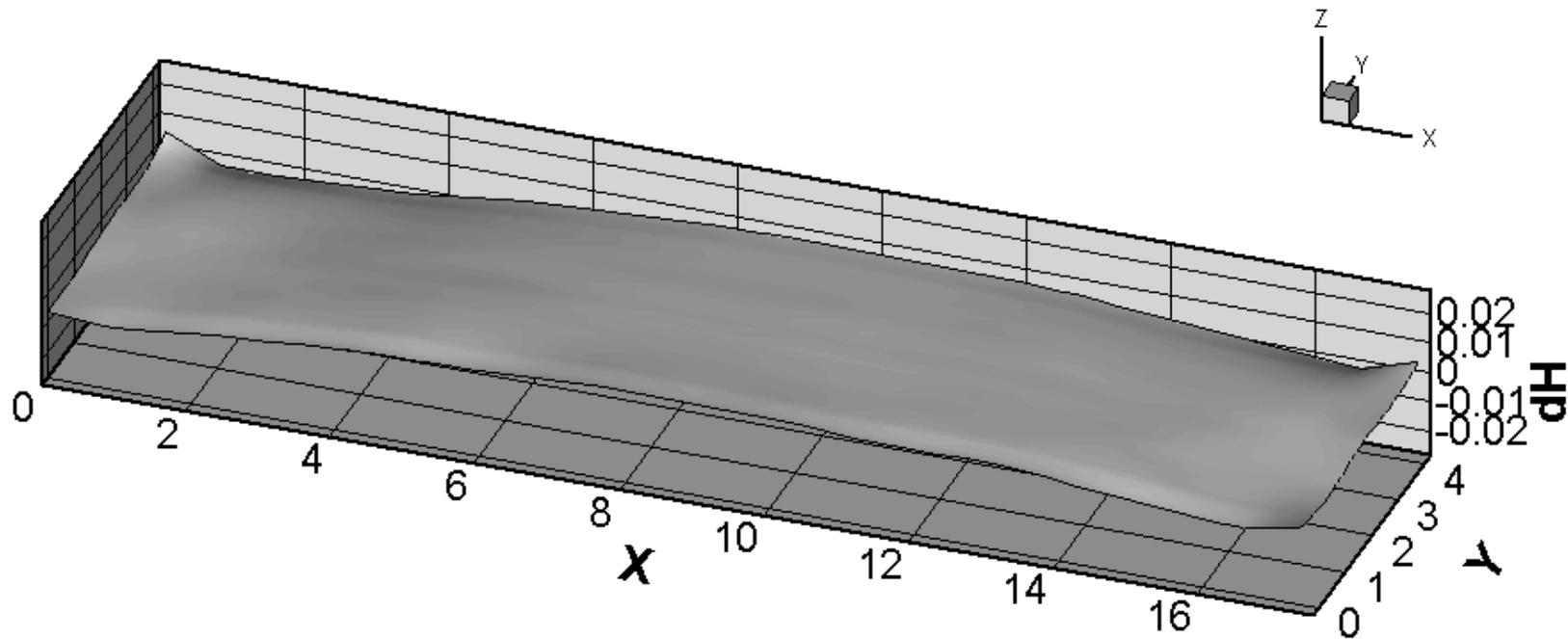


Initial 500 kA Cell Busbar Interface of Aluminium Metal Pad

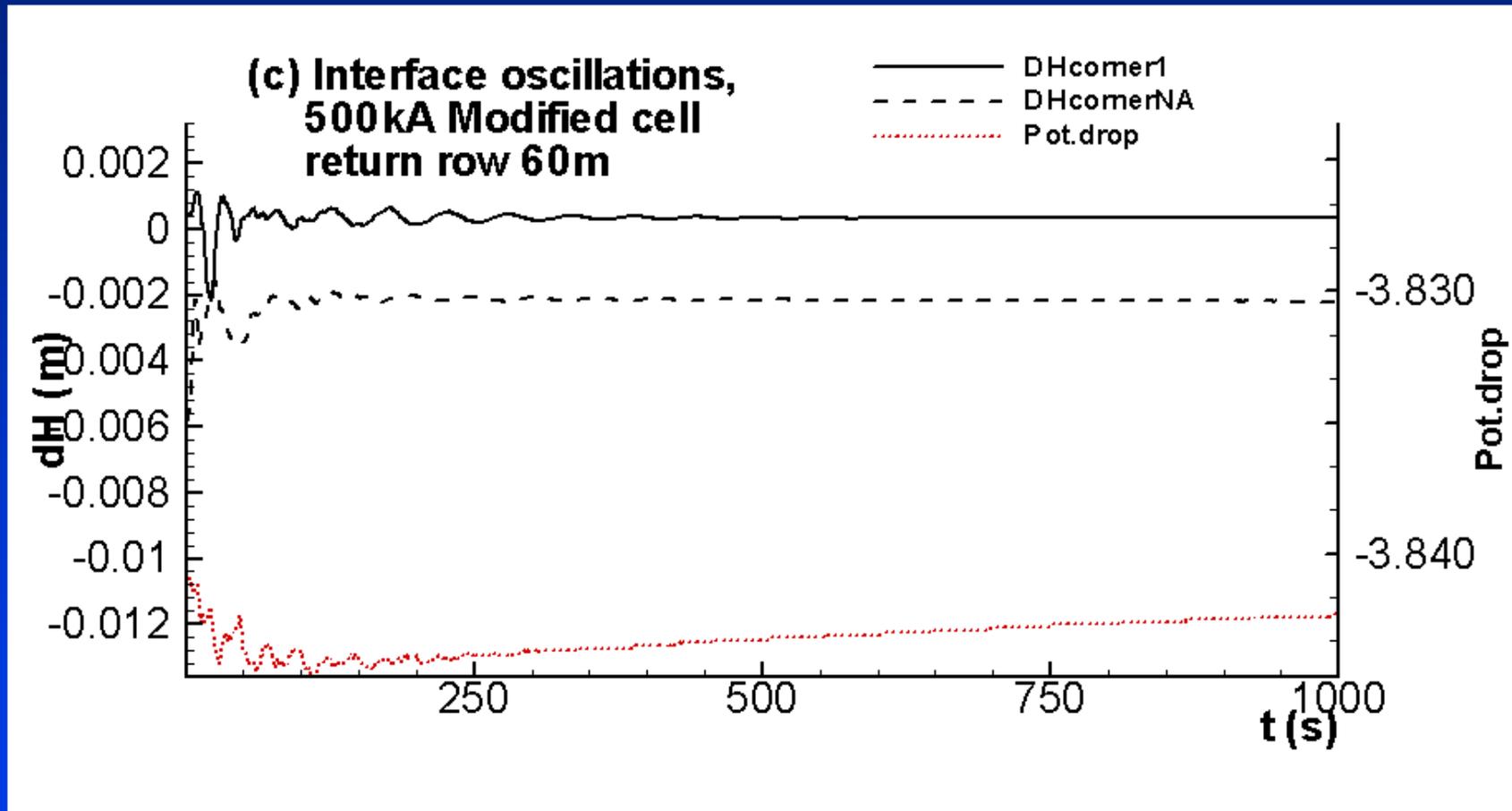


Modified 500 kA Cell Busbar Interface of Aluminium Metal Pad

Liquid aluminium surface, dH (m)
500 kA Modified cell, return row 60 m



Modified 500 kA Cell Busbar Interface of Aluminium Metal Pad



Conclusions

- User oriented package to design MHD stable aluminium reduction cells
- 'Flexible' busbar interactive changes, magnetic field and electric current adjusted – effective busbar design tool
- Time dependent, coupled evolution for background flow, wave stability evaluation, turbulence energy distribution
- Able to couple with the thermo-electric model for evaluation of ledge profile position on the cell stability