Review and Advances of Coupling Methods for the ICFD solver in LS-Dyna

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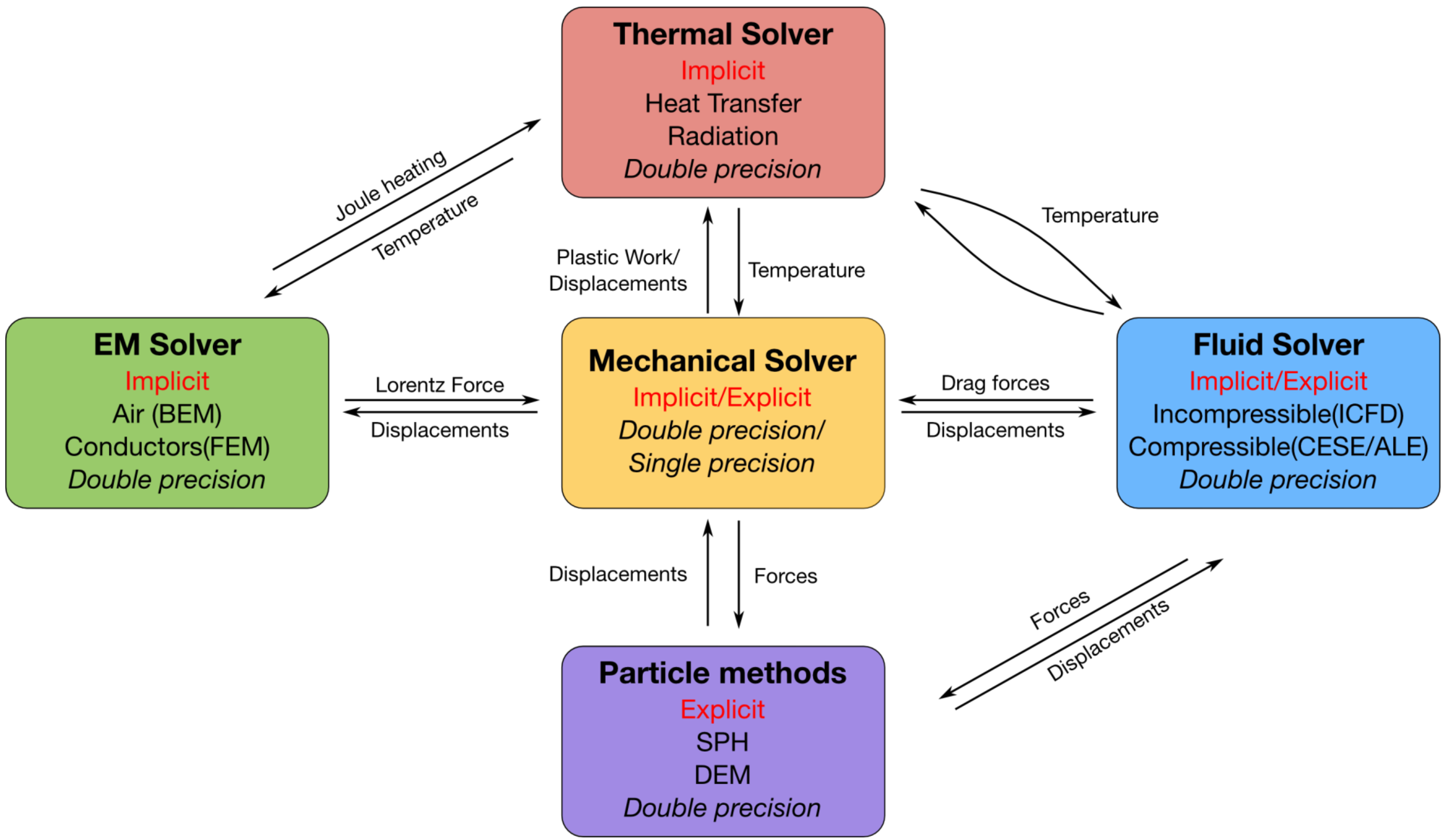
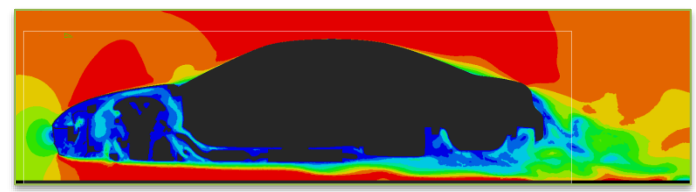
Coupled problems require the simultaneous solution of more than one physics module of LS-DYNA to obtain an accurate result.



Accurate CFD analysis will require structural coupling

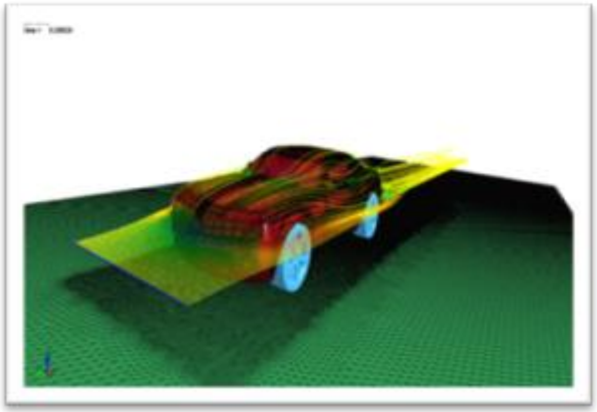
The mechanical behavior of structural parts subject to heat and fluid pressure loads have been neglected.



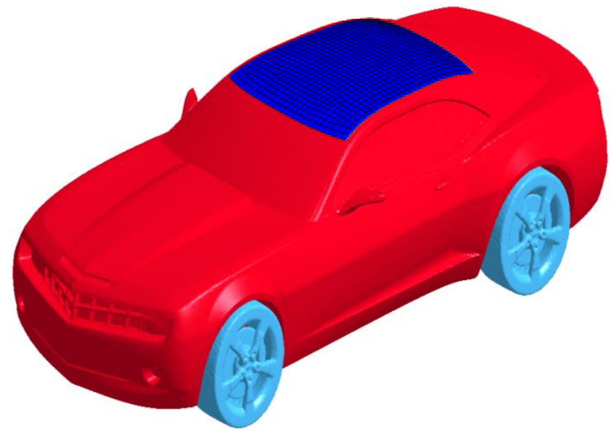
Heat + Underbody panels + Fluid Pressure

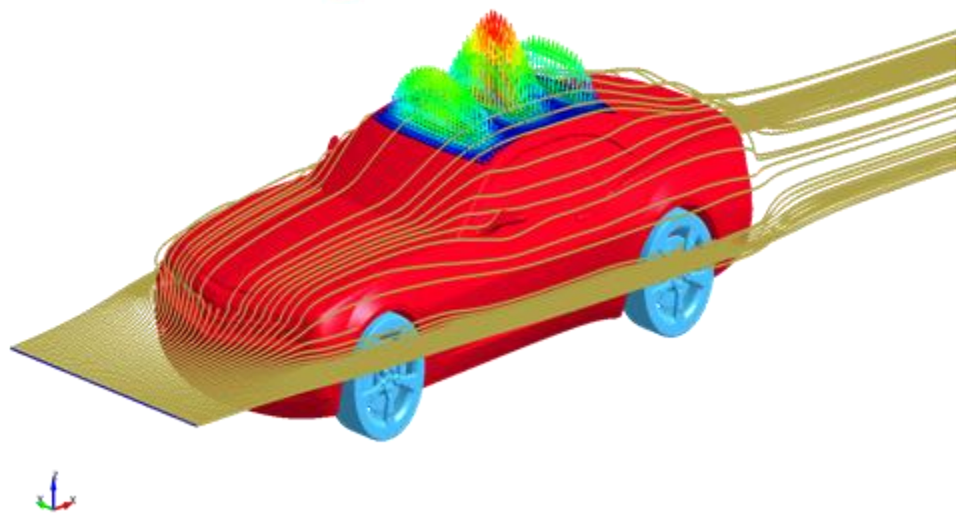
= ? Until the road test

Fluid Structure Interaction
Roof vibration analysis



- CFD analysis of full vehicle.
- Couple parts of the structure to analysis the response in a realistic environment.





Fluid Structure Interaction

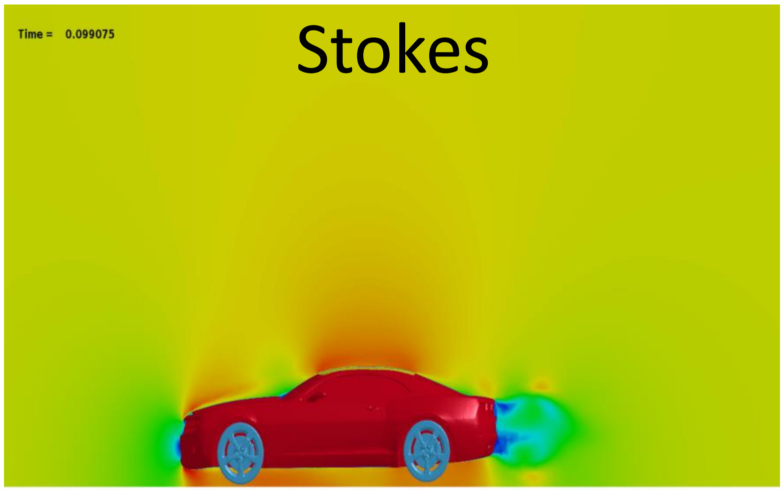
Three different options to solve the same problem:

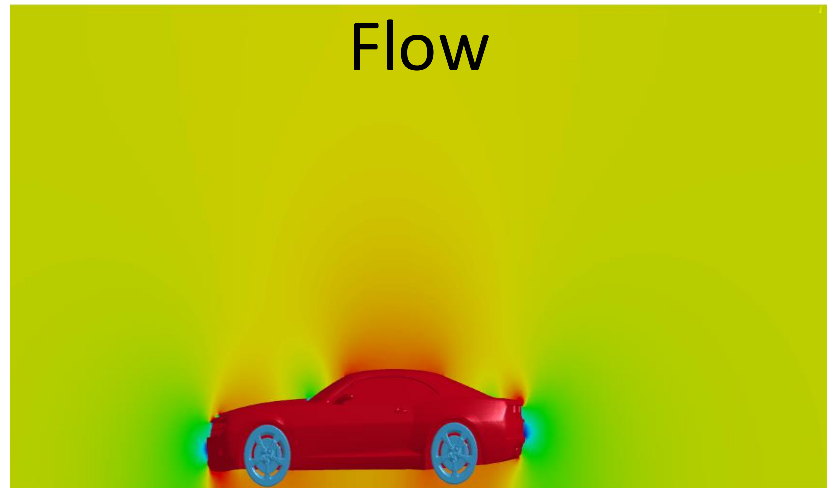
- Solve Full Navier –Stokes with FSI non linear coupling (using weak or strong coupling).
- Solve Potential flow with a non-linear step at the end.
- Solve the structural analysis alone using the output from Navier-Stokes (transient or steady state solver) and the *LOAD_SEGMENT automatically generated input deck. Use **`*ICFD_DATABASE_DRAG`** to write the files.

Fluid Structure Interaction. Results.

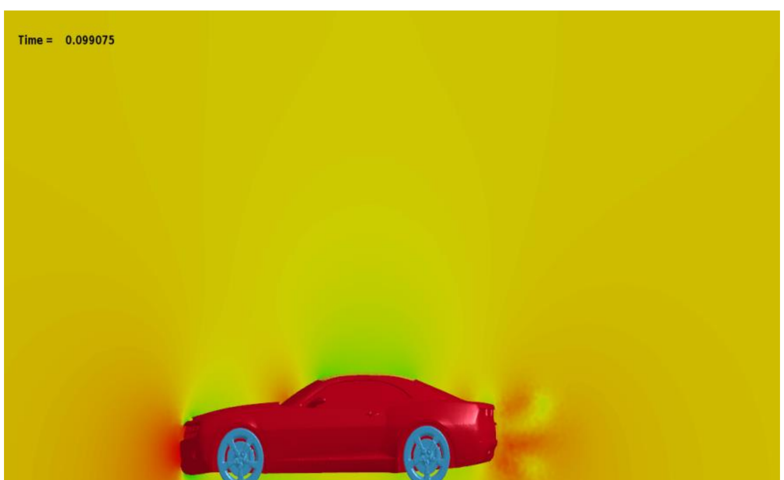
Navier Stokes

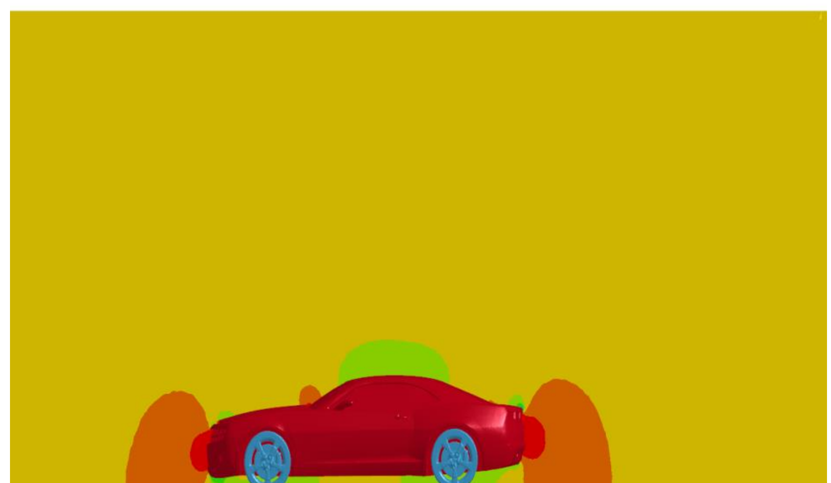
Potential Flow





Velocity

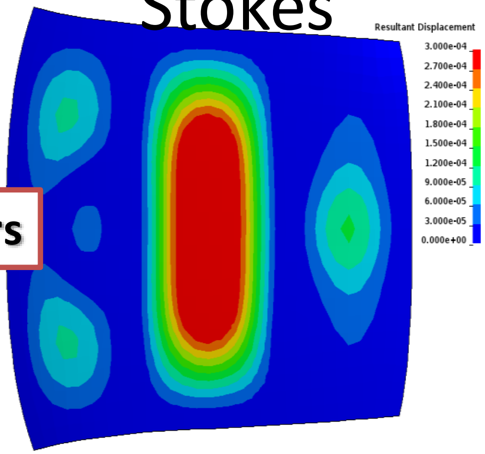




Pressure

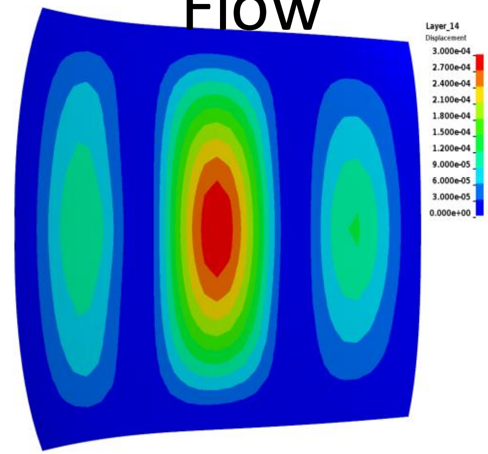
Fluid Structure Interaction. Results.

Navier Stokes



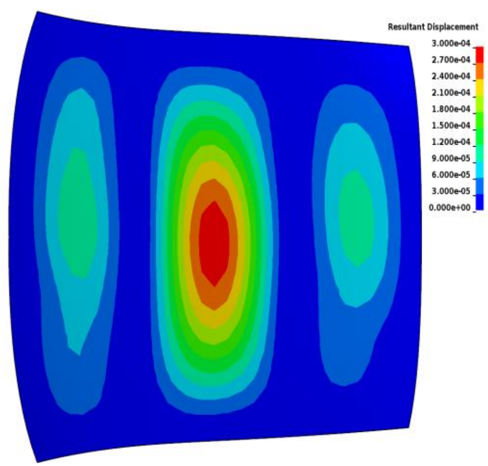
24 hours

Potential Flow



20 minutes
46 times faster

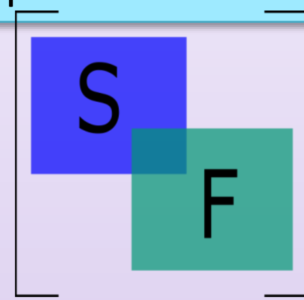
2 seconds



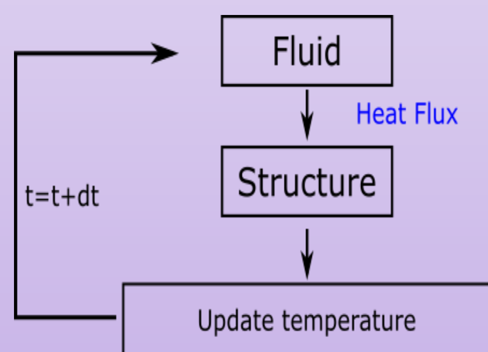
Using **`*LOAD_SEGMENT`**
from Navier-Stockes solution

Thermal Coupling

Monolithic coupling: big jumps of physical properties.



Weak coupling: small jumps or very fine mesh at the interface.



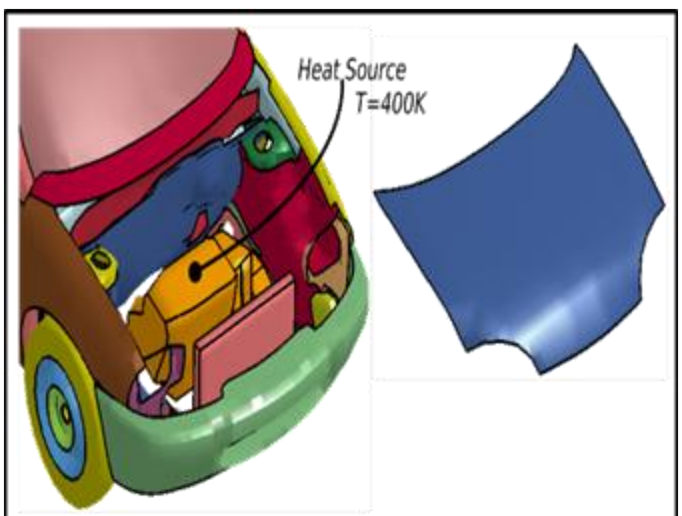
Thermal coupling

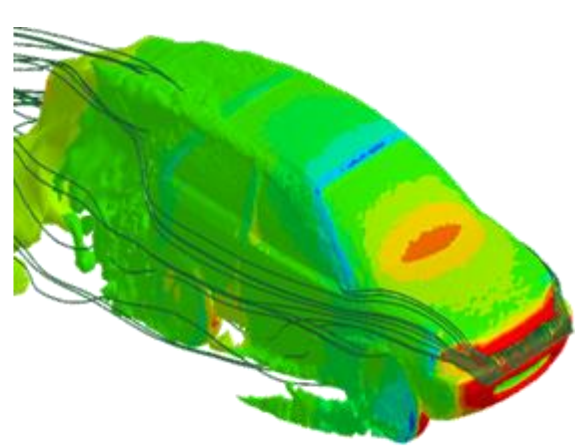
Options to solve the same problem:

- Solve Full Navier –Stokes with thermal non linear coupling (using monolithic or weak coupling). Shut off N.S after a certain steady state has been reached and continue with a pure thermal coupling analysis.
- Solve Navier Stokes using the steady state or potential flow solver and continue with conjugate heat transfer analysis once steady state has been reached.
- Solve the thermal analysis alone using the output from Navier-Stokes (transient or steady state solver) and the *BOUNDARY_CONVECTION_SET automatically generated input deck. Use **`*ICFD_DATABASE_HTC`** to write the files.

Conjugate Heat: Radiation

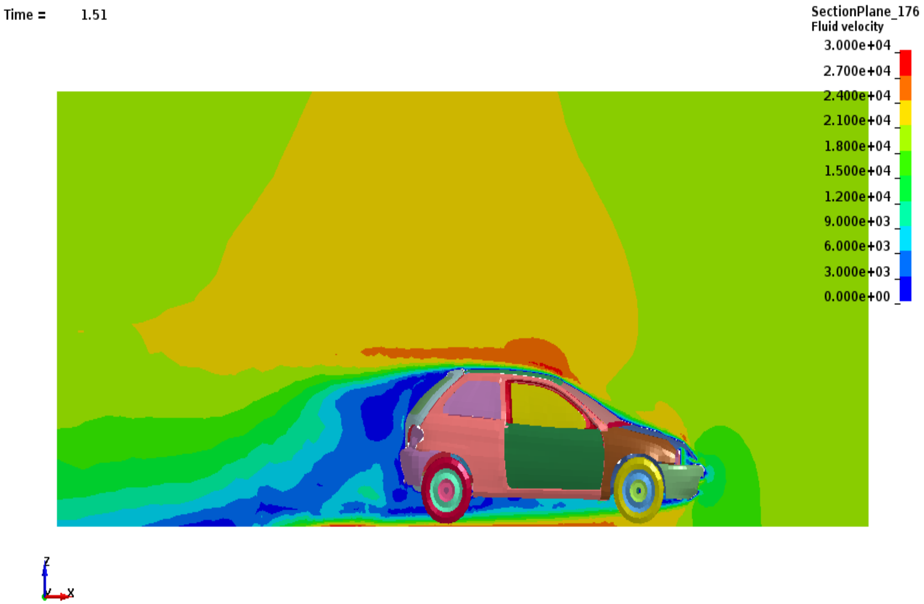
- Run steady state Navier-Stokes or Potential flow. Use **`*ICFD_CONTROL_GENERAL`** to set it up.
- Once steady state reached or Potential flow finishes the conjugate heat solver will use the steady velocity for the thermal analysis.





Conjugate Heat: Radiation. Results.

Navier Stokes
Velocity



Potential Flow
Velocity

Conjugate Heat: Radiation. Results.

Navier Stokes
Temperature

Time: 48 hours

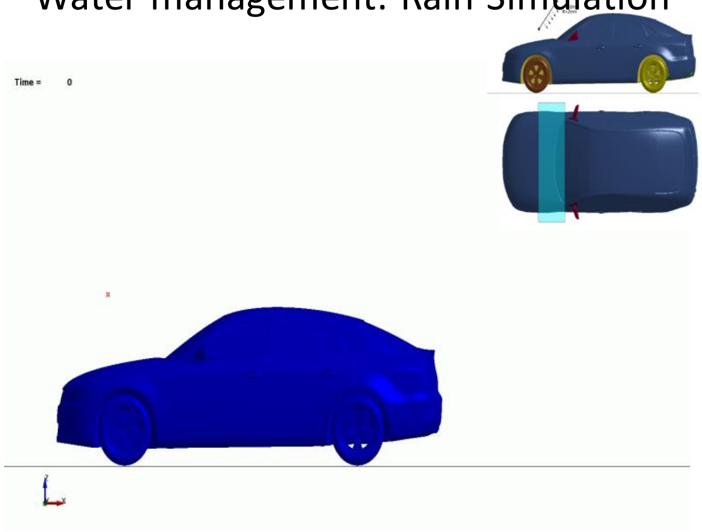
Potential Flow
Temperature

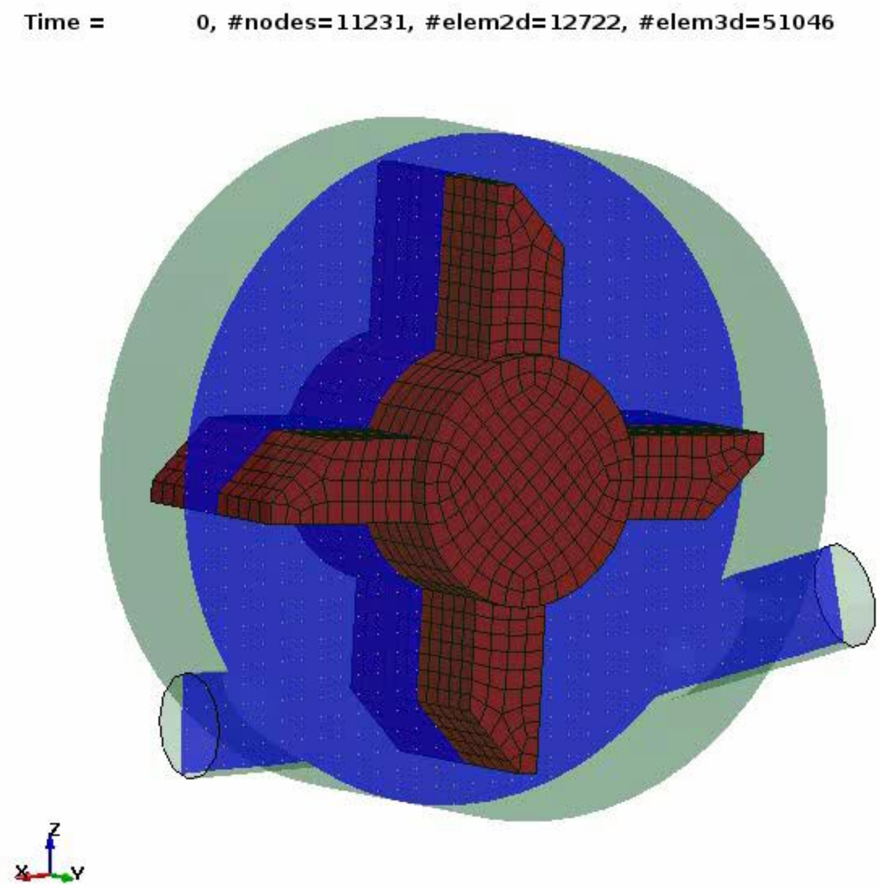
Time: 1 hour 52 min
26 times faster

DEM Coupling

- Two-way coupling
- Particles affect fluid volume

Water management: Rain Simulation





Recent developments introduced in R10 :

- Added Steady state solver. See ICFD_CONTROL_GENERAL and ICFD_CONTROL_STEADY.
- Added wave damping capabilities. See ICFD_DEFINE_WAVE_DAMPING
- Added Windkessel boundary conditions for blood flow. See ICFD_BOUNDARY_WINDKESSEL
- Option to output loads coming from the fluid and applied on the structure by using ICFD_DATABASE_DRAG keyword option. Similar feature for thermal and HTC and using ICFD_DATABASE_HTC
- Two way coupling with DEM particles
- Option to shut off Navier Stokes solve after a certain time for conjugate heat transfer analysis. See ICFD_CONTROL_TIME.

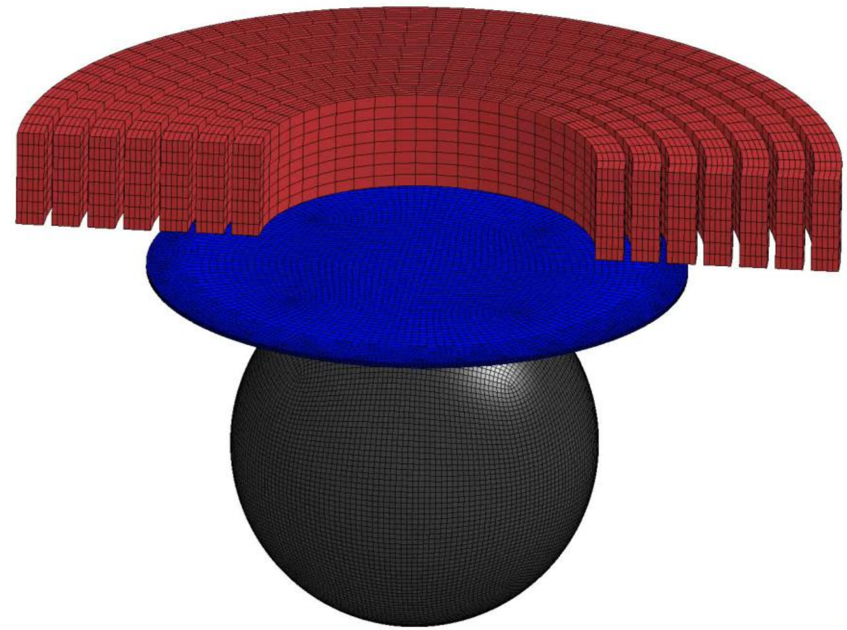
Currently working on :

- Periodic boundary conditions
- Sliding mesh capabilities
- Immersed FSI capabilities
- Monolithic FSI
- 1D parachute model.
- Boundary layer mesh improvements in complex geometry cases.

The EM solver. An overview of its uses and applications

Current main usage:

- The EM solver solves Eddy currents
Using a coupled FEM-BEM method
- This implies that no air mesh
is needed which allows complex shapes
And strong deformations to occur
- The EM solver is therefore the perfect
candidate to solve coupled mechanical
thermal problems where strong
deformations occur such as in
Electromagnetic forming bending welding
and so forth



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Current main usage:

- More features have recently been introduced for such applications :
  - Axisymmetric solver (R10)
  - Conductivity function of material properties defined by the user with a DEFINE_FUNCTION
  - Option to define a circuit using a circuit equation and a DEFINE_FUNCTION to allow more complex types of circuits.
- Investigation is under way to add magnetic material capabilities through the introduction of an alternative monolithic solver.

Three new applications :

- Resistive Spot Welding (RSW) capabilities
  - Extension of the resistive heating solver.
  - Introduction of EM_ISOPOTENTIAL to define a potential difference between electrodes and EM_CONTACT_RESISTANCE to define a contact resistance
  - Current capabilities are 3D, currently working on 2D solver.
- Battery short cut modelling
  - Extension of the resistive heating solver.
  - Introduction of circuit models to model ion transfers in batteries (See EM_RANDLES)
  - Extension of EM capabilities to Thick shells
- Cardiac solver for heart modelling
  - Extension of the resistive heating solver
  - Ten Tusscher & Panfilov cell models

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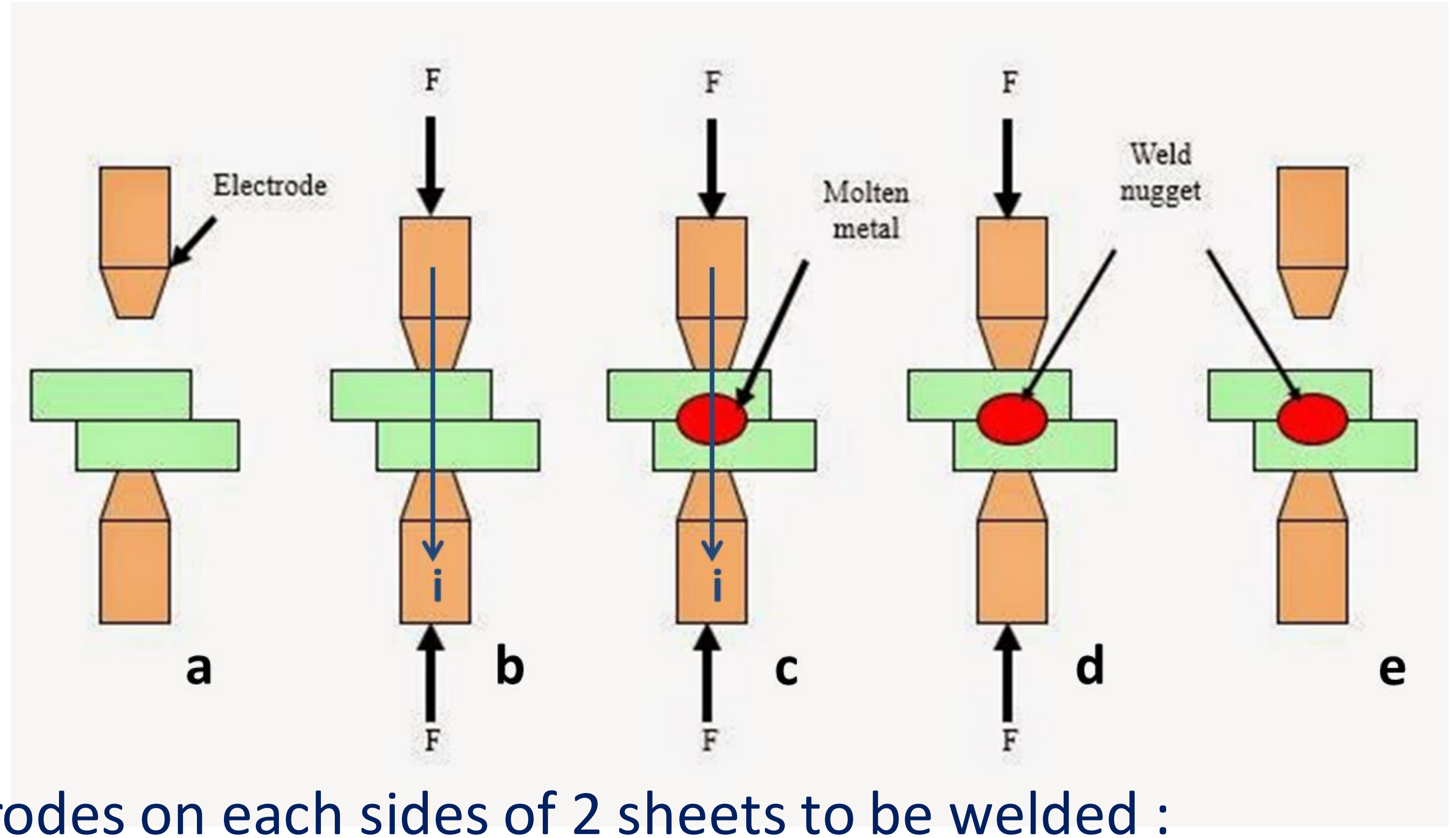
Introduction - RSW



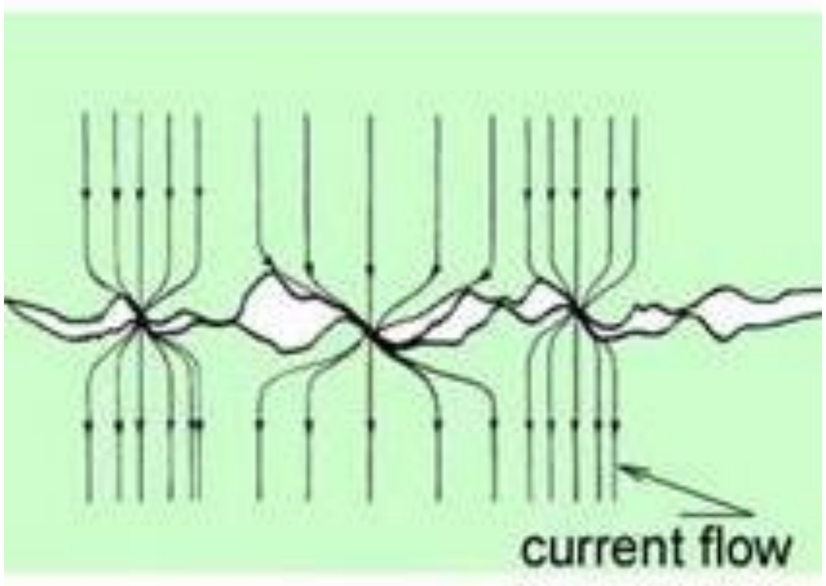
Electrodes on each sides of 2 sheets to be welded :

- Pressure
- Current flow => Joule heating => formation of a molten weld nugget

Coupled mechanical/EM/thermal simulations

RSW and contact resistance

In RSW, contact resistance plays a very important role in the heating of the nugget



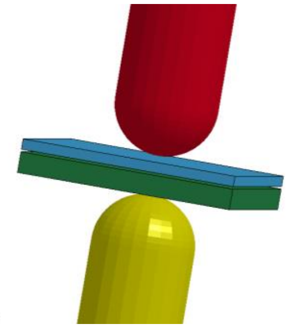
New model in LS-DYNA for local contact resistance (in 3D) depending on local parameters, using *DEFINE_FUNCTION, e.g. Jonny-Kaars model :

$$r(T,P) = r_0 \left(\frac{p - p_k}{p_0 - p_k} \right)^{\varepsilon_p} \cdot \left(\frac{T - T_{\lim} + (293{,}15\ K - T) \cdot 2^{-\frac{1}{\varepsilon_T}}}{293{,}15\,K - T_{\lim}} \right)^{\varepsilon_T}$$

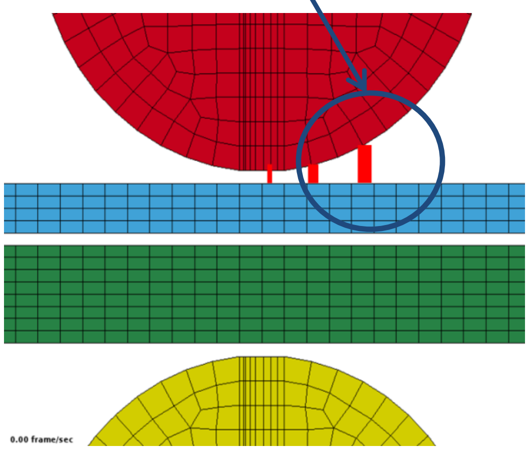
EM model for contact resistance (1)

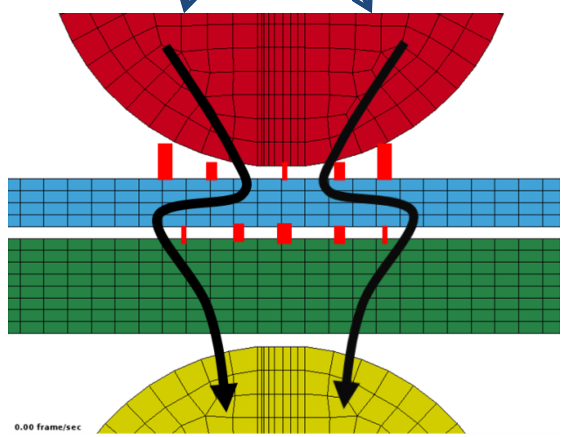
Local contact resistance =
FUNCTION(
pressure,
temperature,
Electrical conductivity,
Contact distance, ….
Using *DEFINE_FUNCTION

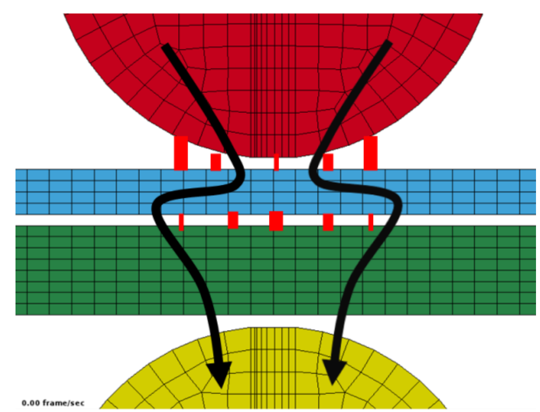
Current flow
depends on
Bulk and
contact resistance



Joule heating
Is locally added
To thermal solver

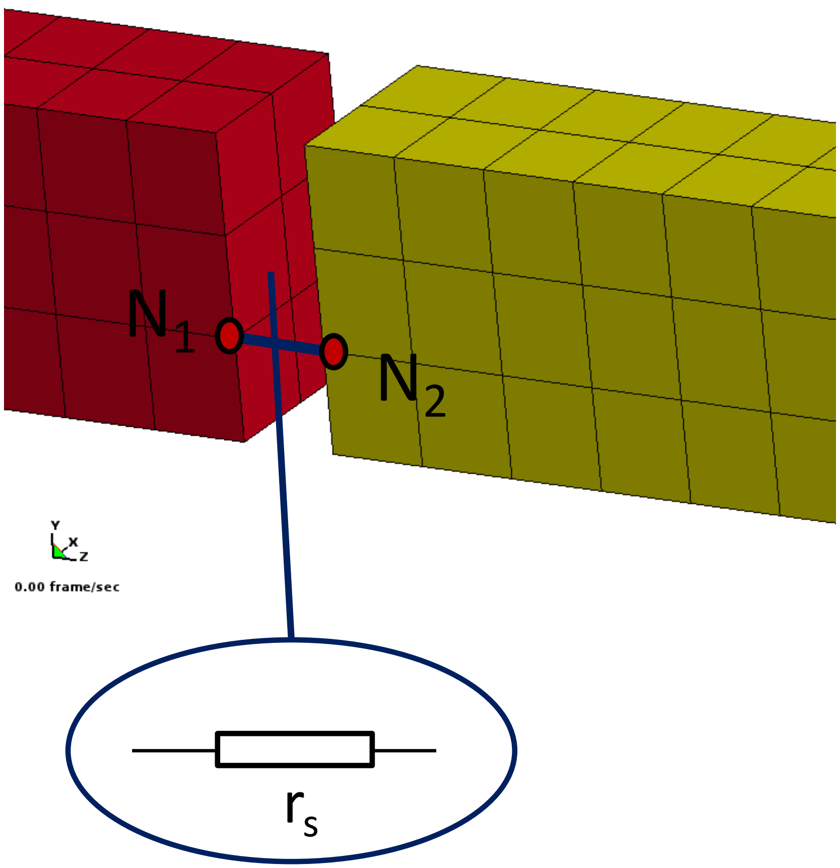






EM model for contact resistance (2)

Contact resistance added in stiffness matrix



FEM solve:

$(S_0 + D) * \varphi = 0$

Where

- S_0 is the Laplacian operator (nodes x nodes)
- D has
  - $1/r_s$ at (N_1,N_1) and (N_2,N_2)
  - $-1/r_s$ at (N_1,N_2) and (N_2,N_1)
  - 0 elsewhere

Row N_1 gives:

$(S_0 * \varphi)_{N1} + (D * \varphi)_{N1} = 0$

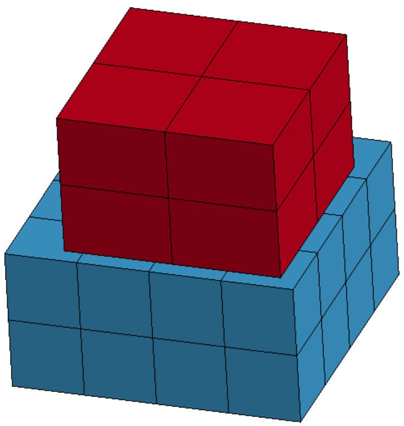
$i_1 + 1/r_s\ (\varphi_1 - \varphi_2) = 0$

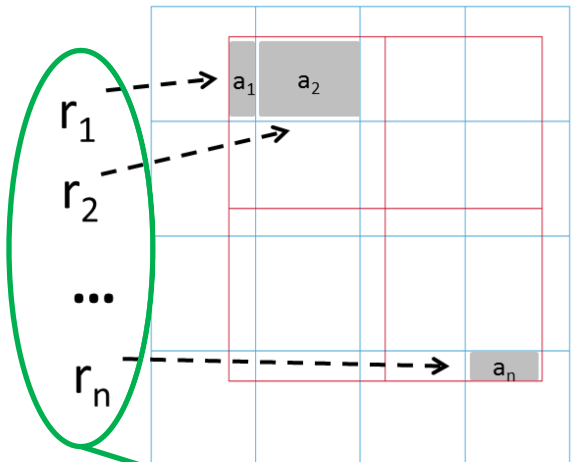
$(\varphi_2 - \varphi_1) = r_s\ i_1$

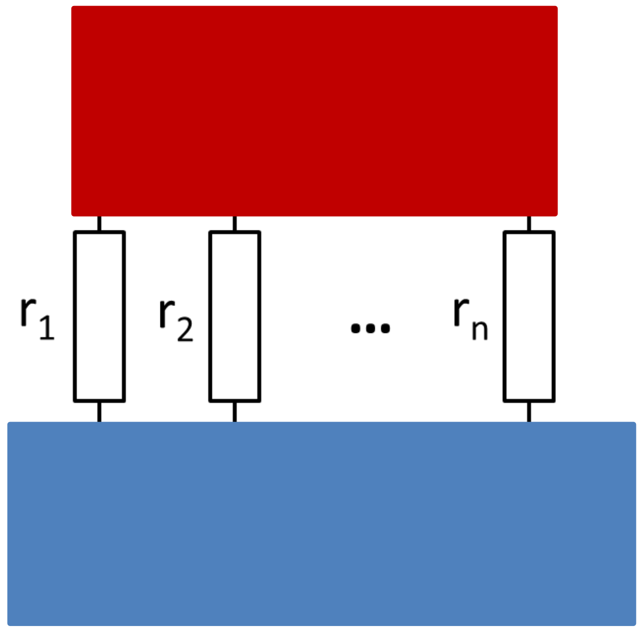
And similar at row N_2

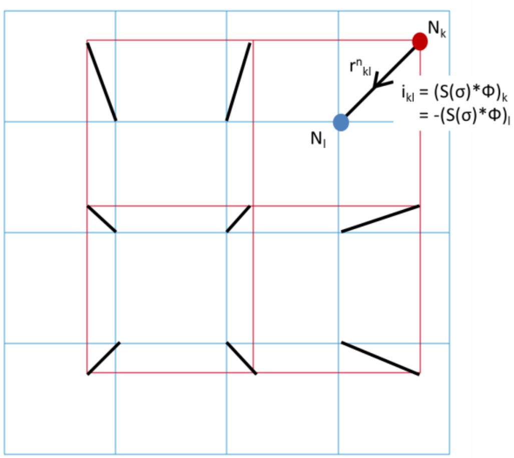
On rows not connected to contact $S_0 * \varphi = 0$ ensures the free divergence of the current in the plates (no charge accumulation)

Contact resistance depends on local parameters









Local contact resistance =
FUNCTION(
a_k, Total contact area,
pressure,
temperature,
Electrical conductivity,
Contact distance, ….
Using *DEFINE_FUNCTION

EM cards to setup contact resistance

*EM_CONTROL_CONTACT

EMCT	CCONLY		COTYPE	EPS1	EPS2	EPS3	D0
1	1						

*EM_CONTACT

CONTID	COTYPE	PSIDM	PSIDS	EPS1	EPS2	EPS3	D0
18	1	1	2	0.3	0.3	0.3	

*EM_CONTACT_RESISTANCE

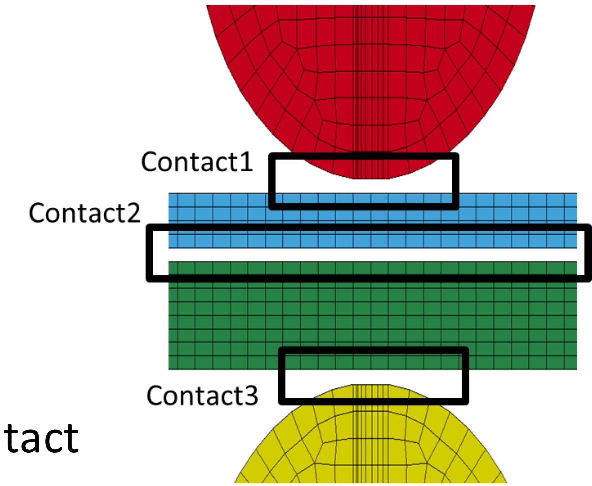
CRID	CONTID	CTYPE	CIRCID	JHRTYPE			D0
12	18	1		1			

LCID	D0
14	

*DEFINE_FUNCTION

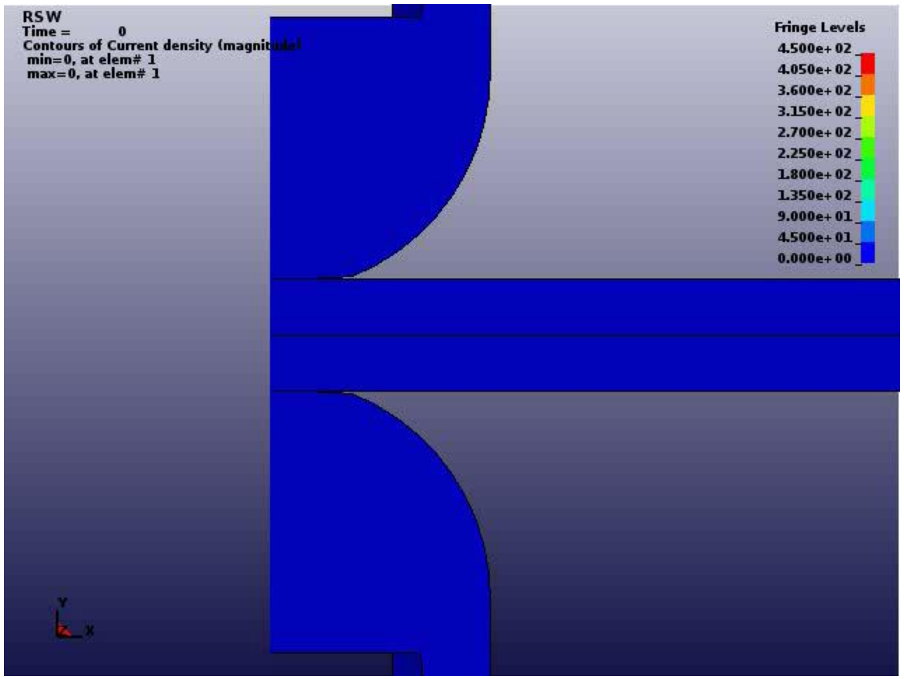
FID
14

Per contact

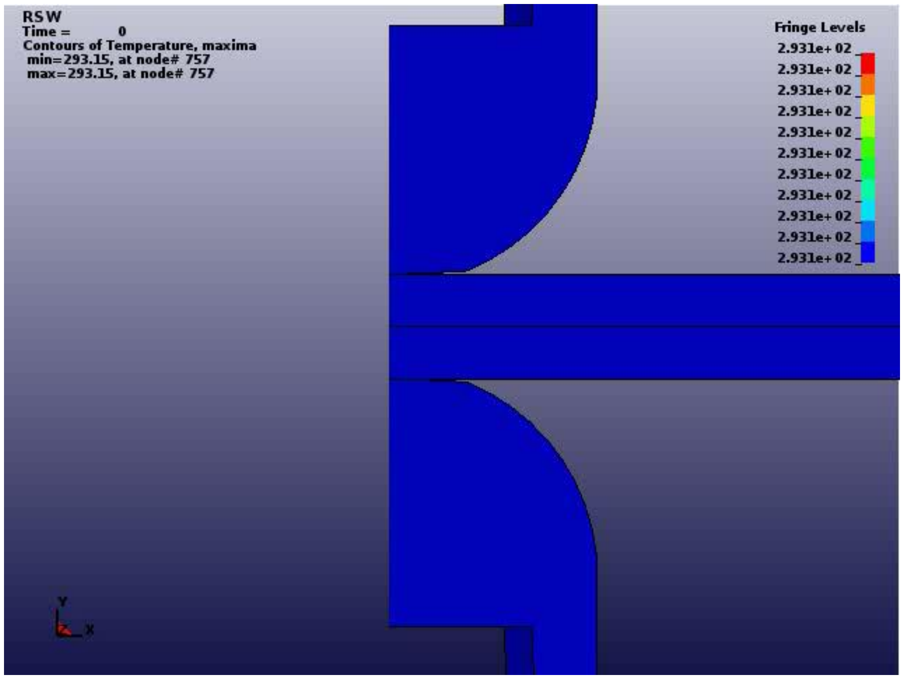


time	Simulation time
area_glo	Global contact area A (see equation (8))
area_loc	Local contact area A (see equation (8))
dist_ct	Distance between the 2 faces in contact
ctpress_mst	Contact pressure on master side
ctpress_slv	Contact pressure on slave side
temp_mst	Contact temperature on master side
temp_slv	Contact temperature on slave side
cond_mst	Electrical conductivity on master side
cond_slv	Electrical conductivity on slave side
vmstress_mst	Von mises stress on master side
vmstress_slv	Von mises stress on slave side

Typical RSW simulation



Current density



Temperature

Application

- The new LS-DYNA EM-Contact enables many approaches to cover the contact resistance for RSW
- The Jonny-Kaars-Model is an approach based on a resistance function of temperature and pressure where its parameter are fitted according experiments.

$$r(T,P) = r_0 \left(\frac{p - p_k}{p_0 - p_k} \right)^{\varepsilon_p} \cdot \left(\frac{T - T_{\lim} + (293{,}15\ K - T) \cdot 2^{-\frac{1}{\varepsilon_T}}}{293{,}15\,K - T_{\lim}} \right)^{\varepsilon_T}$$

pressure temperature

Battery Abuse Simulations in LS-DYNA

LSTC
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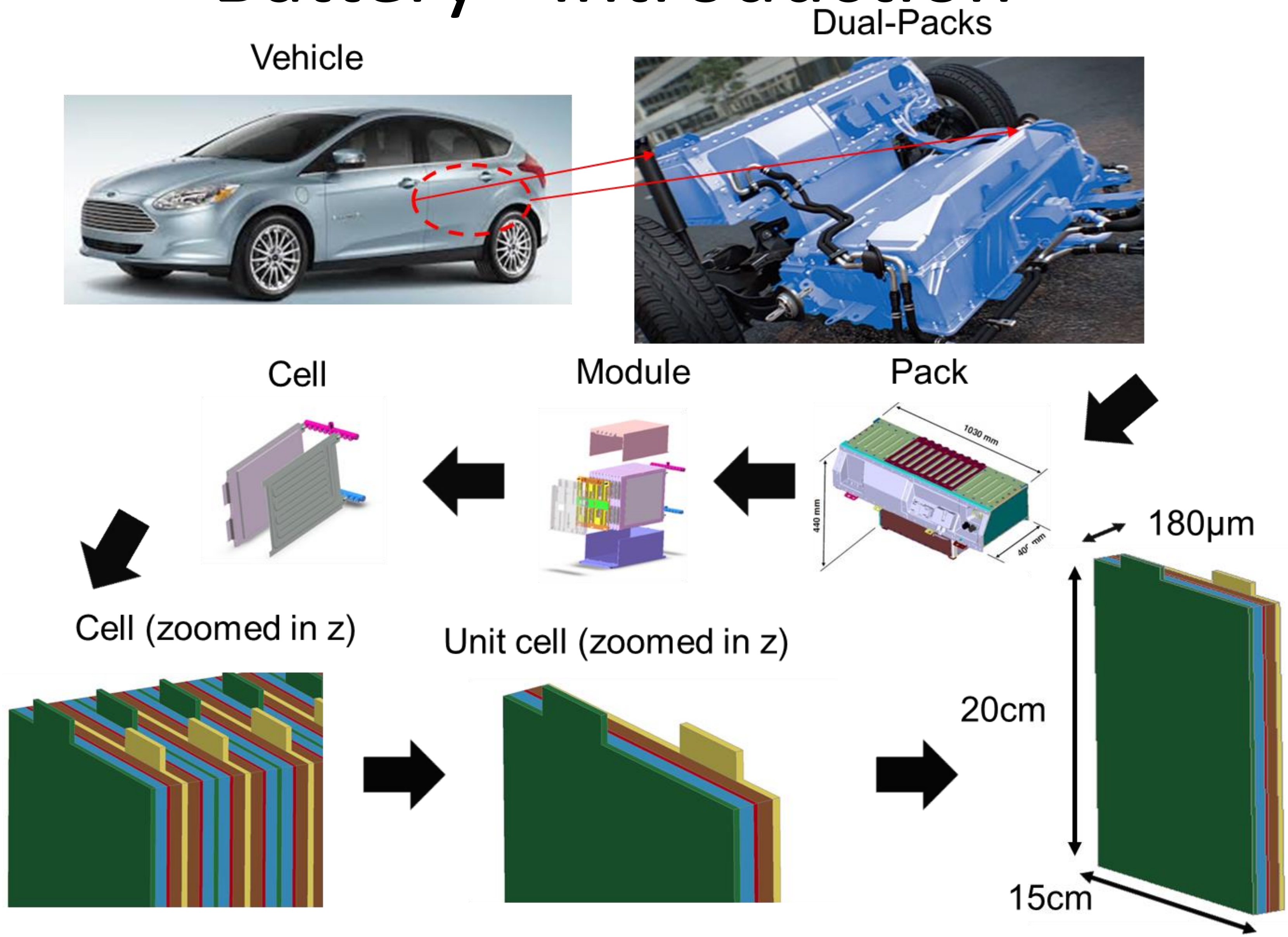
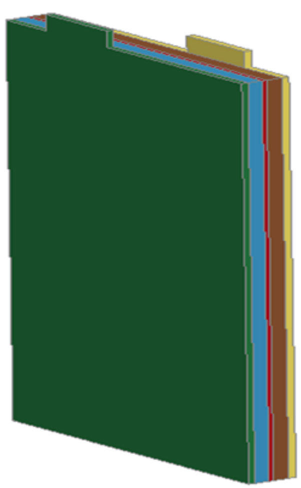
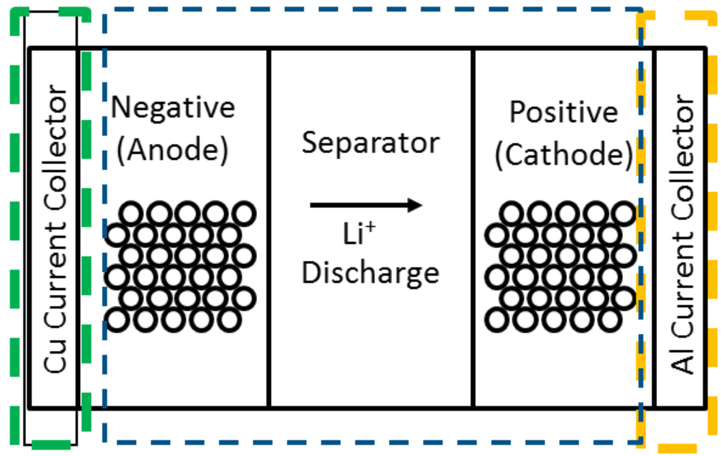
Pierre L'Eplattenier, Sarah Bateau-Meyer, Iñaki Çaldichoury,

Battery - Introduction

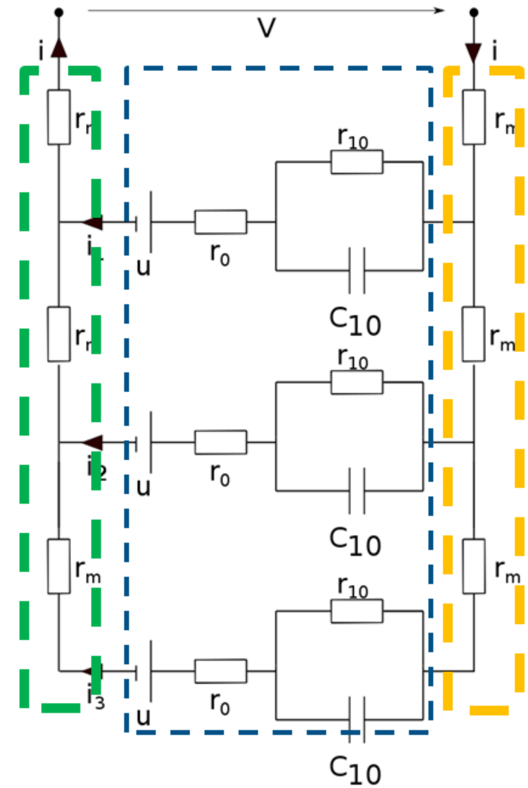


Battery – Distributed Randles circuit model





- Current collectors transport electrons to/from tabs; modeled by resistive elements
- Jelly roll (anode – separator – cathode) transports Li+ ions; modeled with Randle circuit



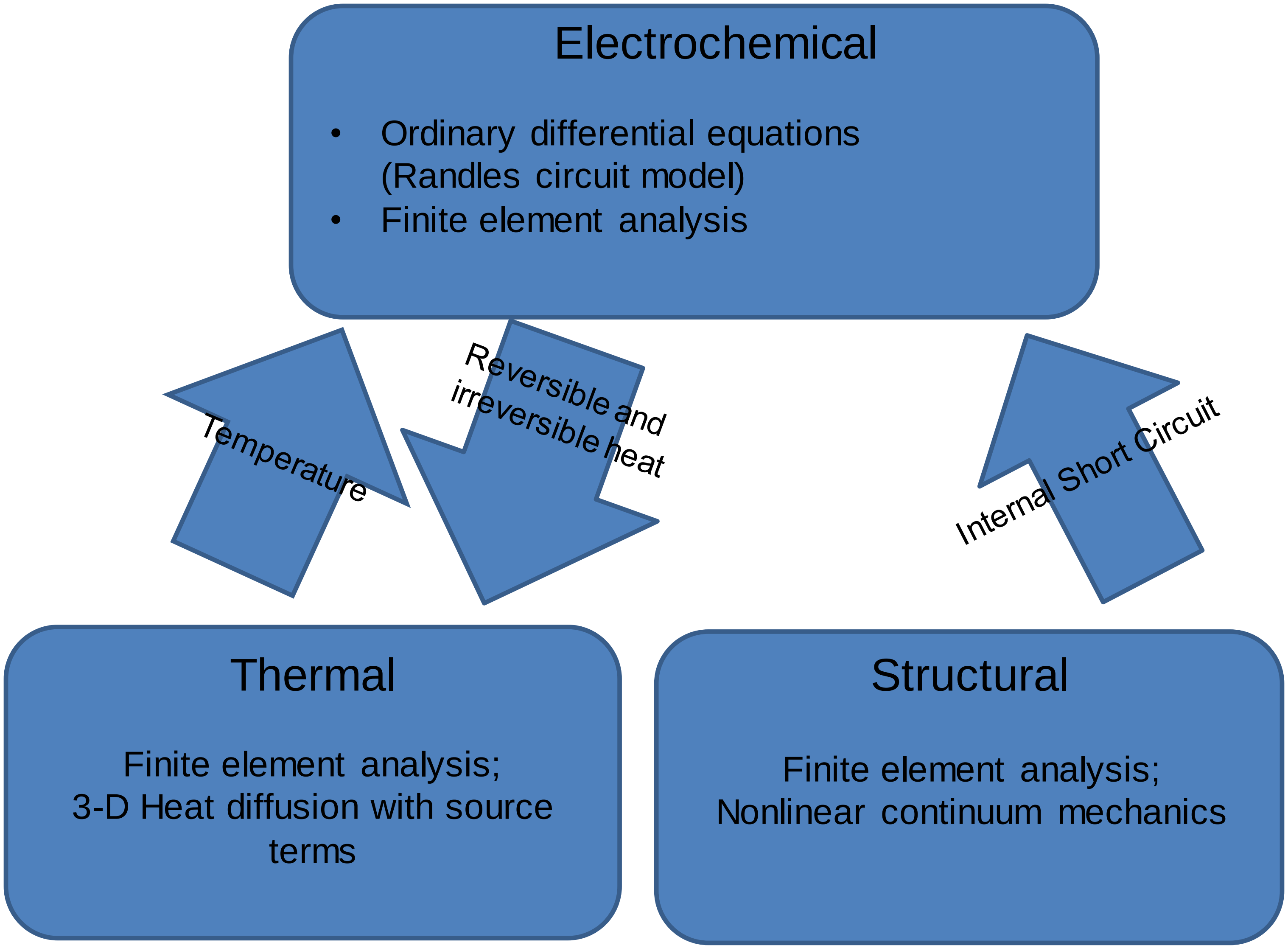
r_0: Ohmic & kinetic

r_{10} & c_{10}: Diffusion

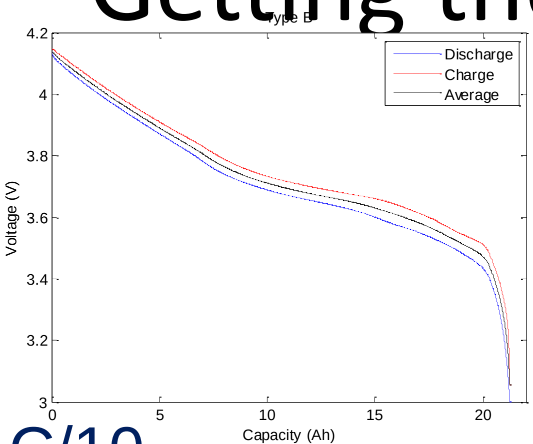
u: Equilibrium voltage (OCV)

r_m: Current collectors

Coupling between the solvers

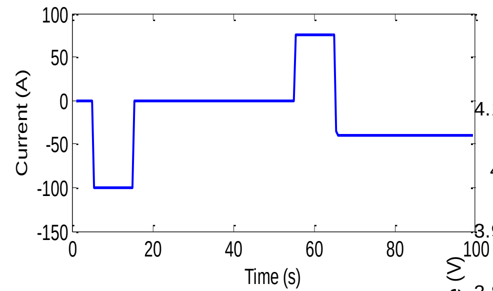


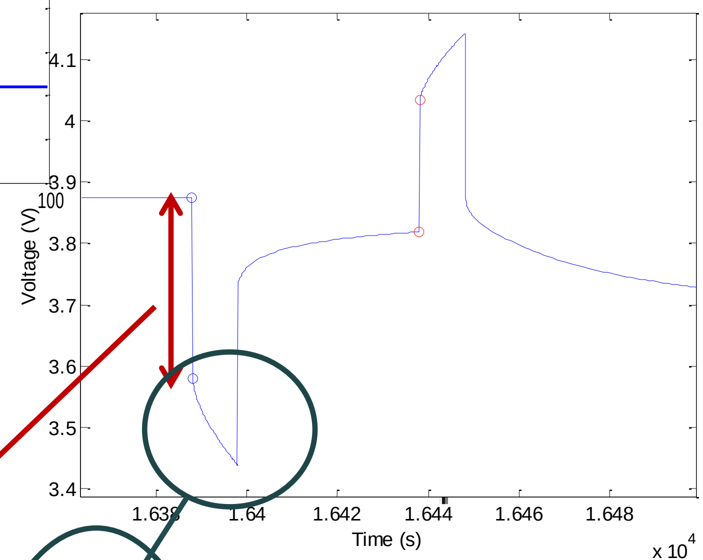
Getting the Randles circuit parameters

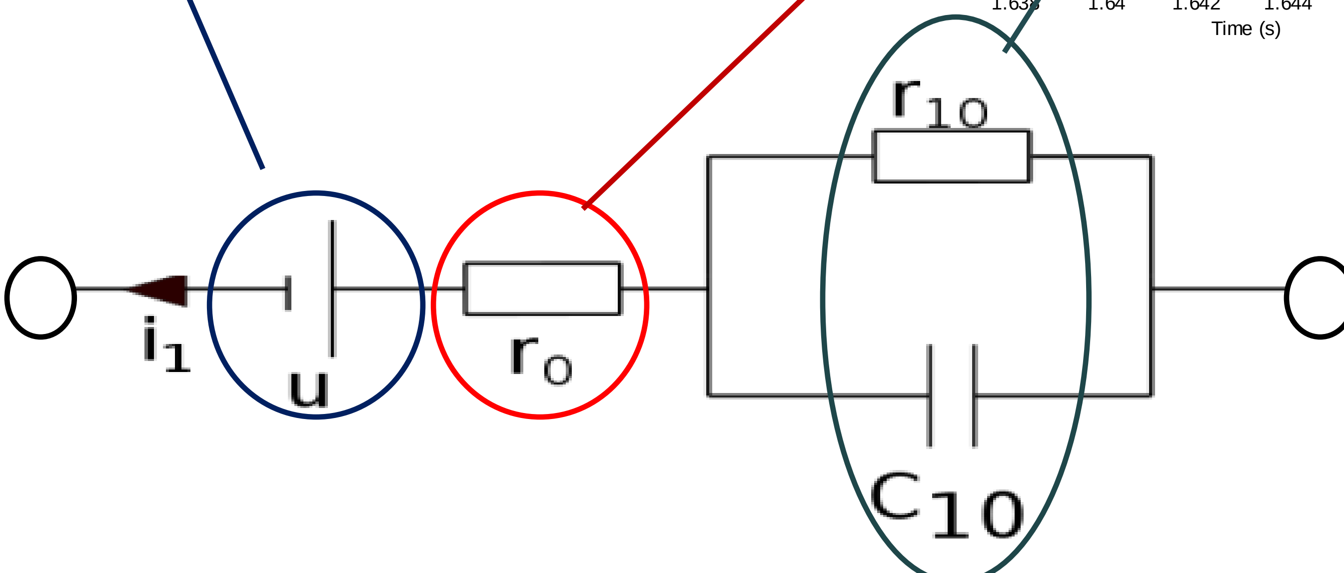


C/10
capacity tests

HPPC tests

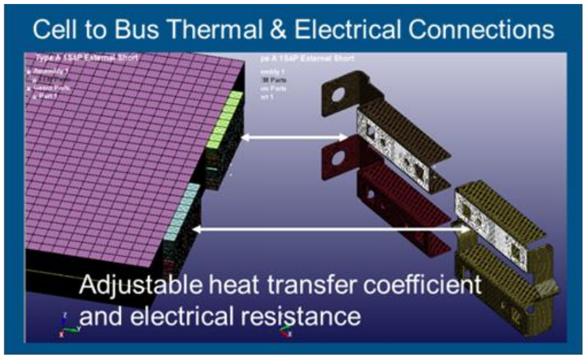


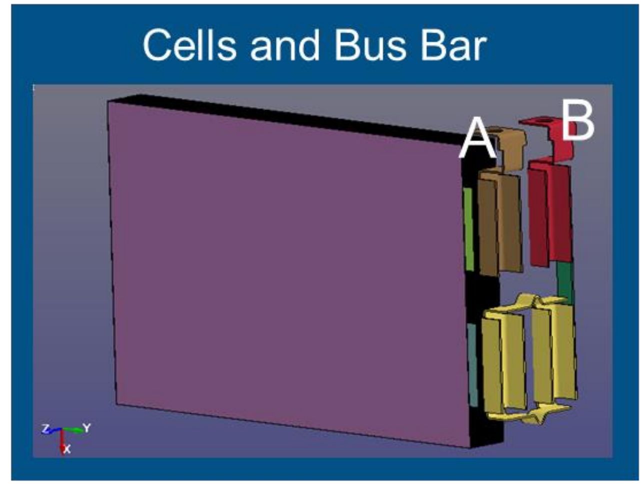




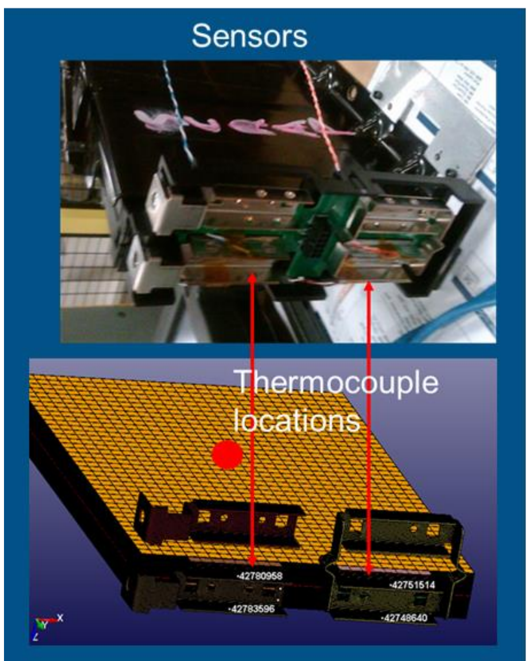
External short (1)

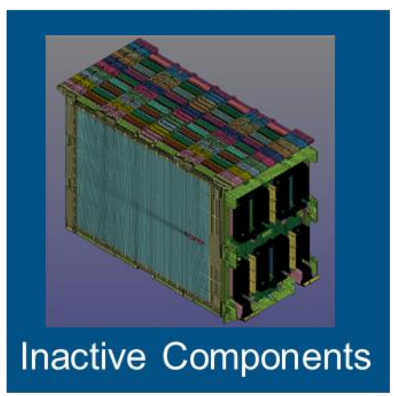
External short on a cell module





Short circuit resistance applied between A and B creates current pathway





In collaboration with J. Marcicki et al
Ford Research and Innovation Center, Dearborn, MI, USA

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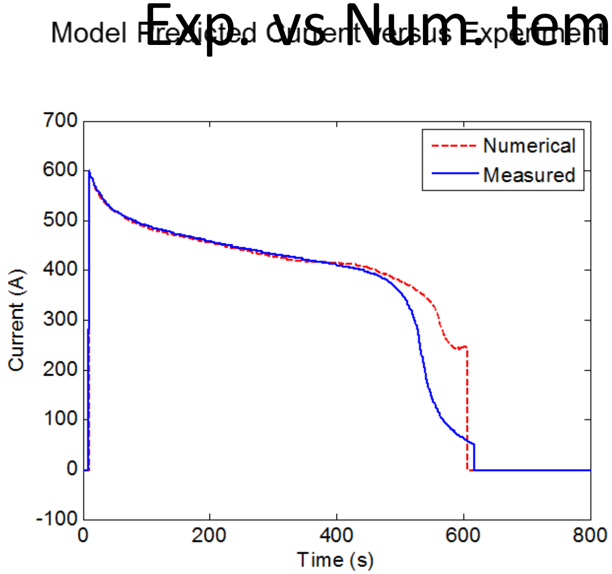
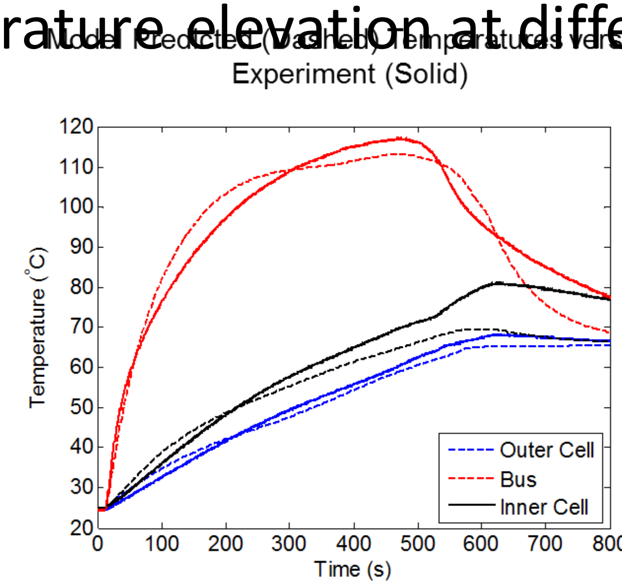
ONE TEAM • ONE PLAN • ONE GOAL

external short (1):
Exp. vs Num. temperature elevation at different locations





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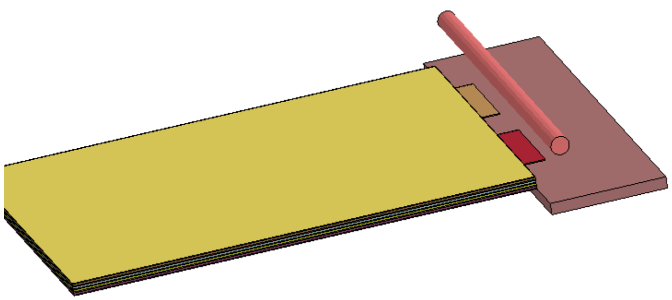
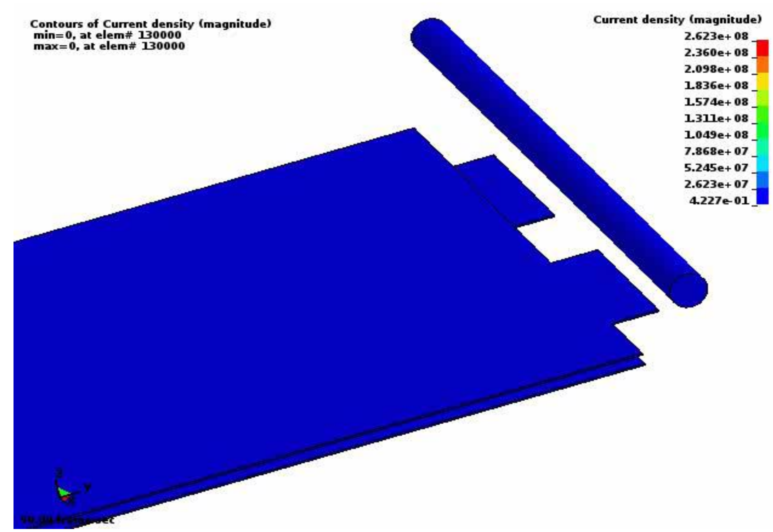
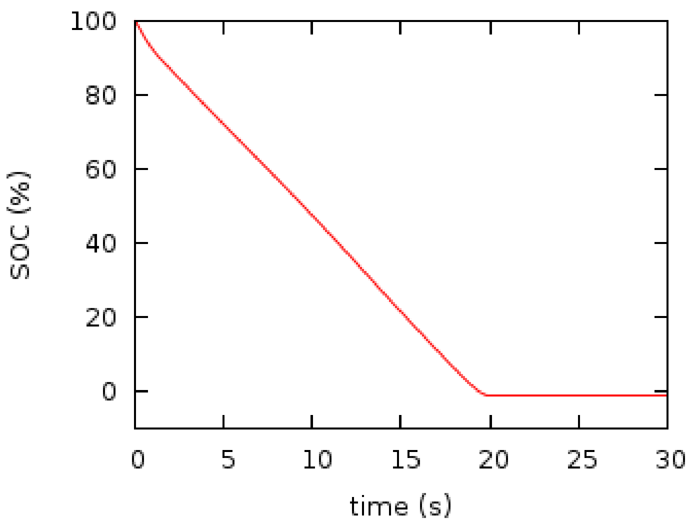
External short (2)

Conducting cylinder falling on the tabs of a cell creates an external short

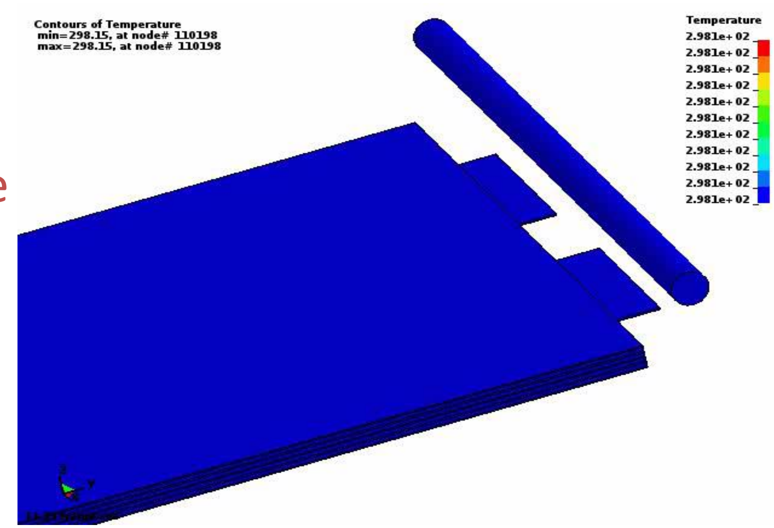




Current density

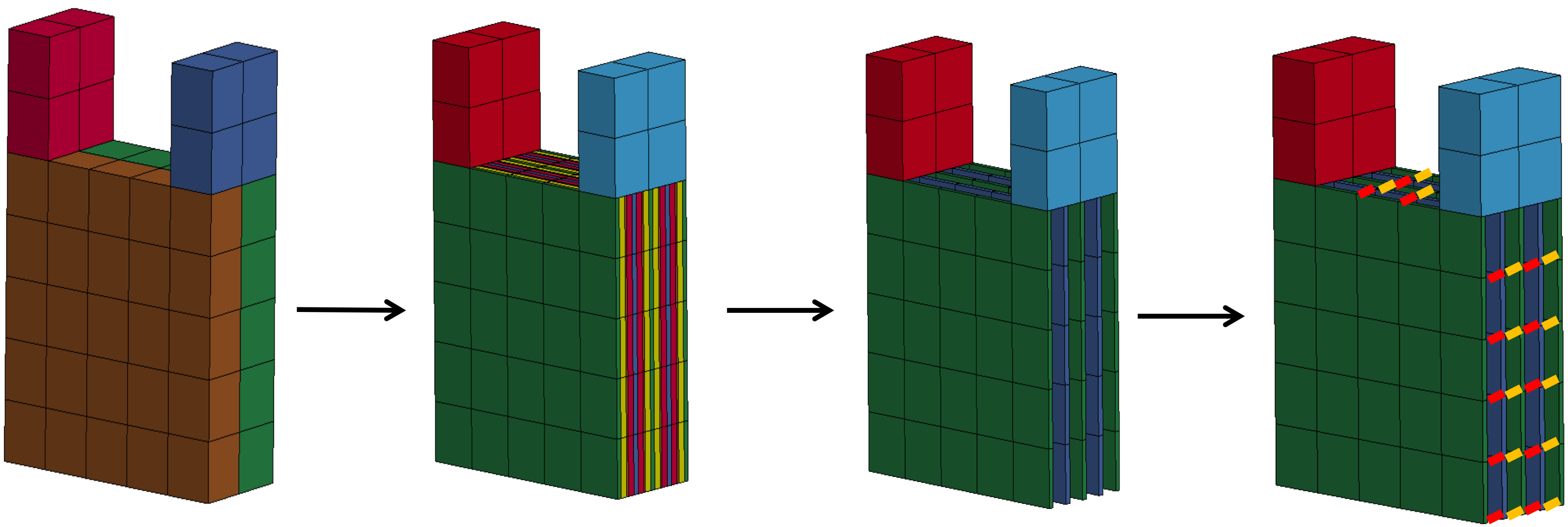


SOC vs time



Temperature

Randles circuits using Composite Tshells



User mesh

a

Layered mesh

b

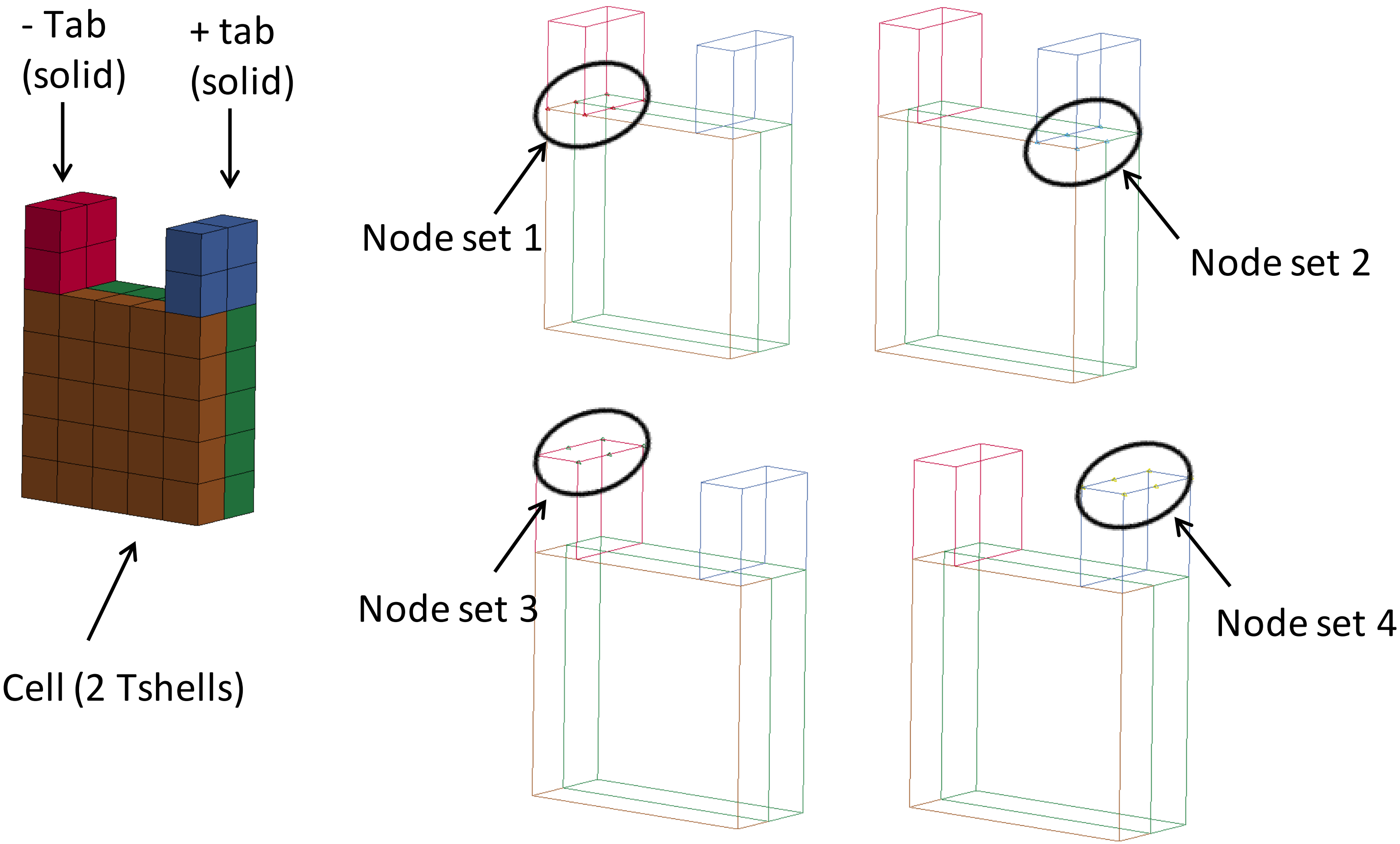
Layered mesh
Conductors only

c

Randles circuits

d

Composite Tshells: Definition of the node sets



Electrical connections using *EM_ISOPOTENTIAL and *EM_ISOPOTENTIAL_CONNECT

Composite Tshells: Keyword setup

```
*PART_COMPOSITE_TSHELL
$#                                                                  title
Layered_Solid
$#     pid    elform      shrf    unused    unused      hgid    unused    tshear
         3         5     0.833
$#    mid1    thick1        b1    ithid1      mid2    thick2        b2    ithid2
        21     0.225     0.000         0        12     0.325     0.000         0
         9     0.100     0.000         0        16     0.325     0.000         0
         5     0.250     0.000         0        16     0.325     0.000         0
         9     0.100     0.000         0        12     0.325     0.000         0
        21     0.225     0.000         0         0     0.000     0.000         0
*PART_COMPOSITE_TSHELL
$#                                                                  title
Layered_Solid
$#     pid    elform      shrf    unused    unused      hgid    unused    tshear
         5         5     0.833
$#    mid1    thick1        b1    ithid1      mid2    thick2        b2    ithid2
        12     0.325     0.000         0         9     0.100     0.000         0
        16     0.325     0.000         0         5     0.250     0.000         0
        16     0.325     0.000         0         9     0.100     0.000         0
        12     0.325     0.000         0        21     0.225     0.000         0
         0     0.000     0.000         0         0     0.000     0.000         0
```

```
*EM_MAT
$--------1---------2---------3---------4---------5---------6---------7---------8
$   em_mid     mtype     sigma     eosId                       randletype
        21         2      5.e6                                          1
        12         1                                                    2
         9         1                                                    3
        16         1                                                    4
         5         2      6.e6                                          5
         2         2      1.e6
         4         2      2.e6
```

Layer1:positive current collector

Layer2:positive electrode

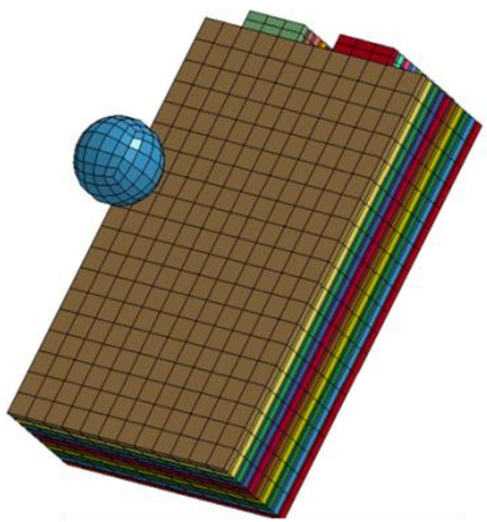
Positive tab

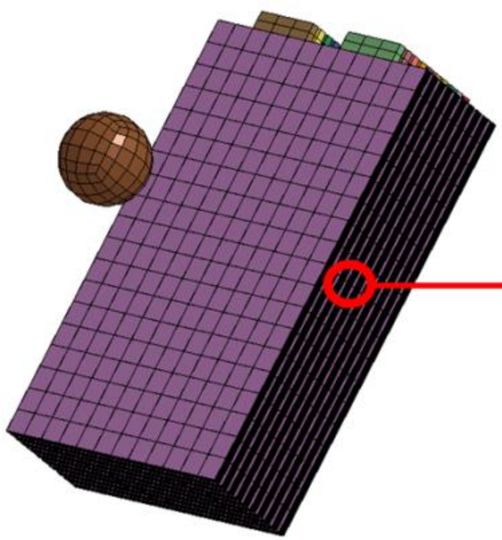
```
*PART
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         6         1         2
*PART
$#     pid     secid       mid     eosid      hgid      grav    adpopt      tmid
         7         1         4
```

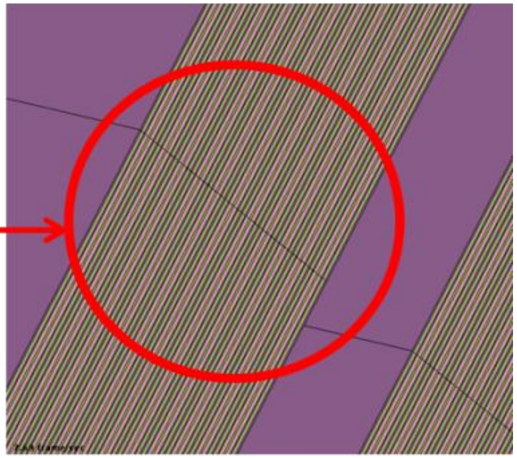
Composite Tshells: Internal short (1)

Module of 10 adjacent cells crushed by a sphere

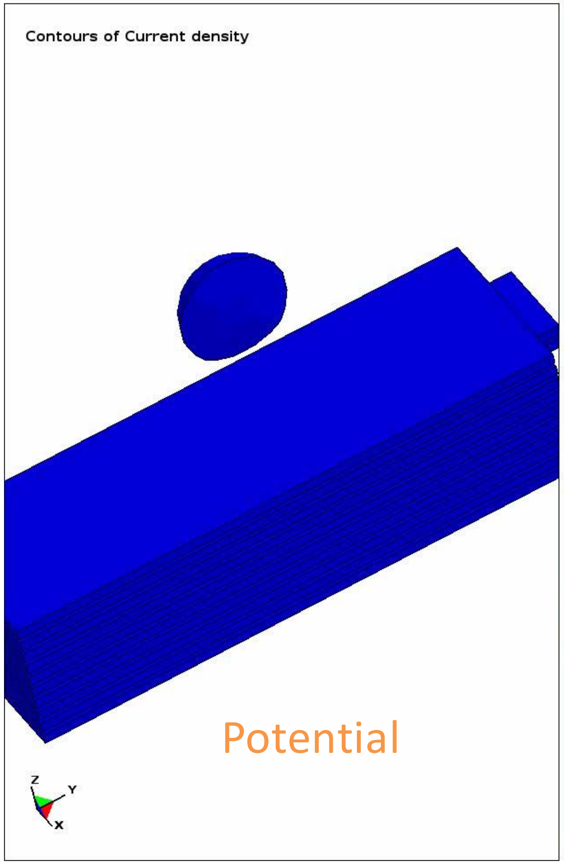
- Each cell is composed of
  - 228 *ELEMENT_TSHELL
  - 22 unit cells (89 layers)
  - 252 Randles circuit in each *unit* cell
- 55,440 Randles circuit total



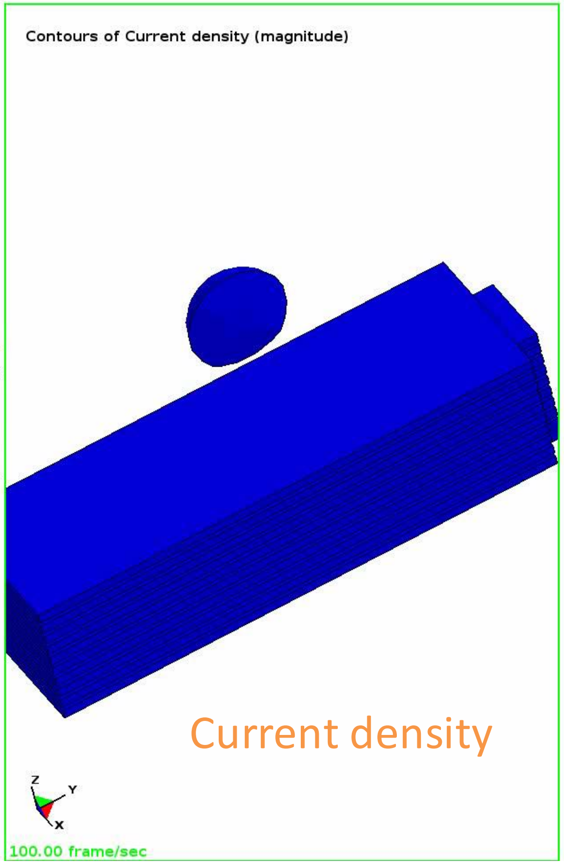




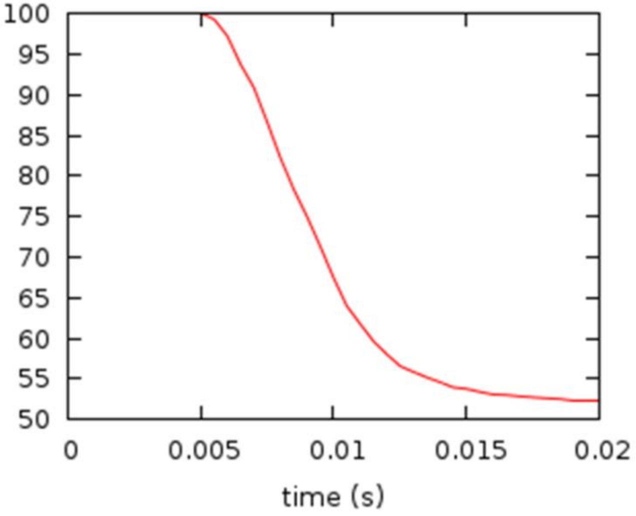
Composite Tshells: Internal short (1)



Potential



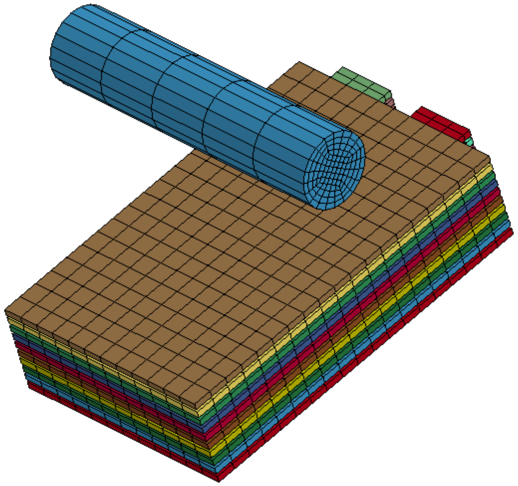
Current density



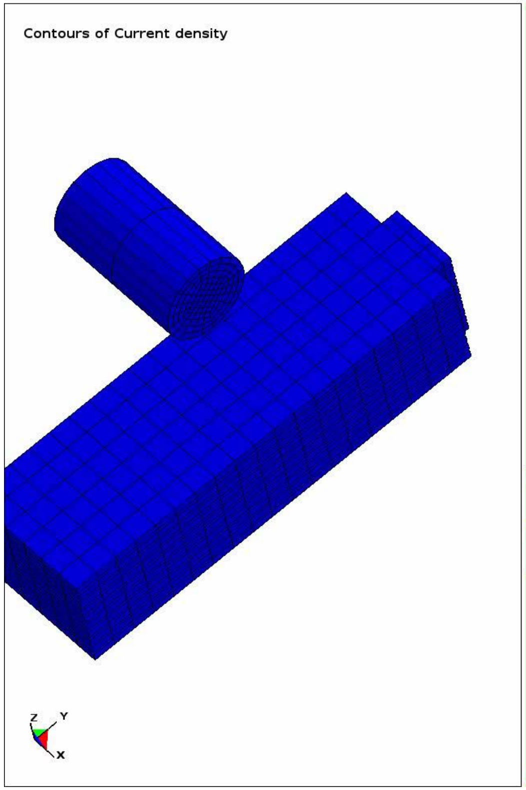
State Of Charge vs time

Composite Tshells: Internal short (2)

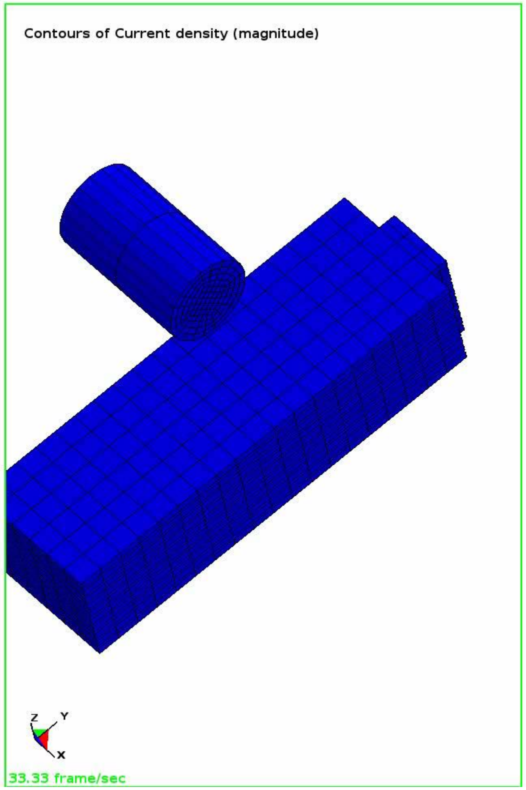
Same 10 cells module crushed
by a cylinder

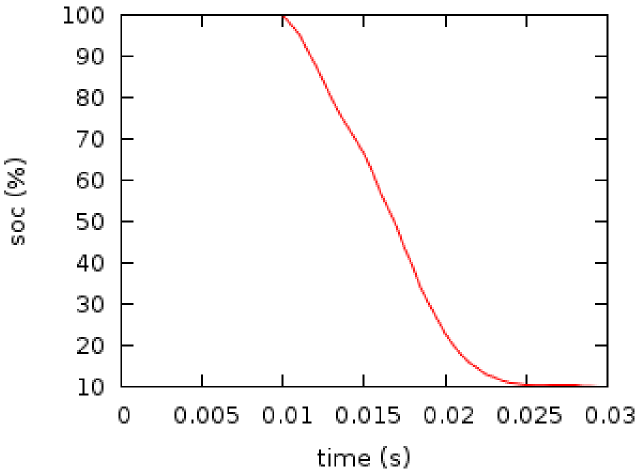


Potential



Current density

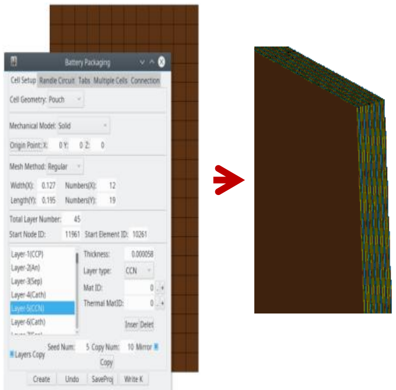




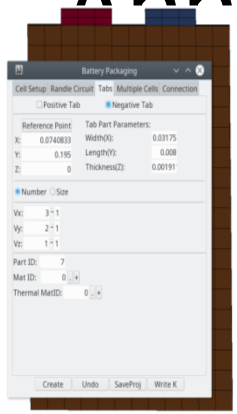
State Of Charge vs time

LS-PREPOST Battery Packaging Application

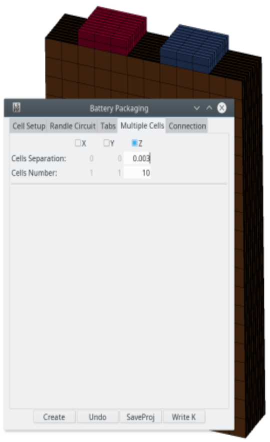
- Easy design of the layers of a single cell
- Addition of connecting tabs
- Multiplication of cells to create modules
- Electrical connections



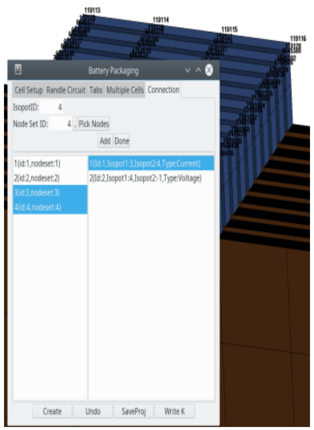
a



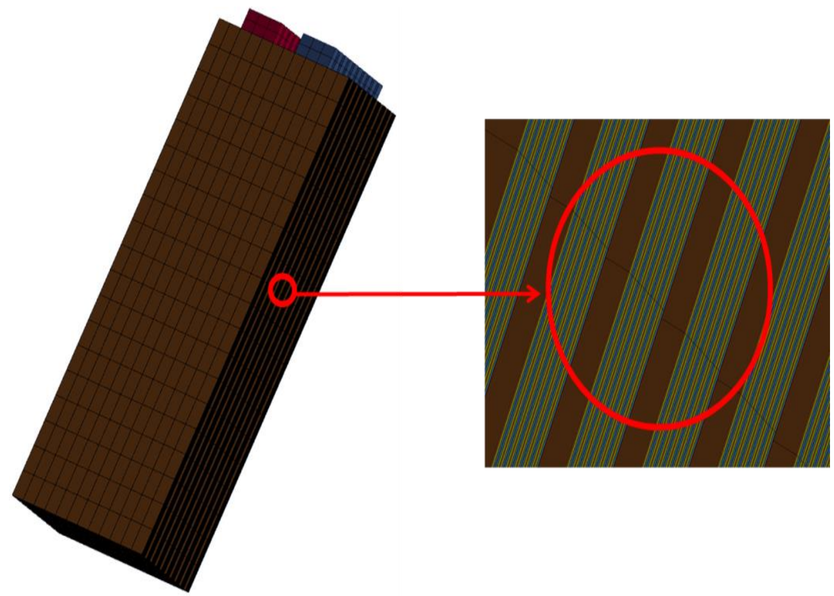
b



c



d



Battery – Plans for the future

- Collaborations with Ford Research and Innovation Center and Oak Ridge National Labs to improve:
  - Mechanical simulations of layered cells
  - Criteria for onset of internal short circuits
  - Setting of internal short resistance

- Development of more macroscopic models for modules and packs

- Addition of new features in LS-PREPOST battery packaging application

Electrophysiology modeling

LSTC
Livermore Software Technology Corp.

Motivation

- Experimental studies involving the *in-vivo* human heart are possible and often available, but they are expensive and very limited.
- Well defined numerical modeling is emerging as a powerful tool that can help to interpret experimental data.
- Cardiac modeling is a complex problem. The maturity of the models of electrical propagation in the heart is still not comparable with the one achieved in other engineering fields mainly due to :
    - Non linear anisotropic inhomogenous material properties
    - Direct observation of electromechanical potential distribution is not trivial. Validation experimental results are difficult to obtain.
    - The problem not only involves multiphysics but is extremely multi-disciplinary.

Electrophysiological models

The bidomain model : well-established description of the electrical activity of the myocardium on a macroscopic scale, taking into account the ionic current, the membrane potential and the extracellular potential.

The monodomain model : The monodomain model is a simplification of the bidomain equations. It assumes that conductivities are proportional in the intracellular and extracellular spaces

I. Verification of cardiac tissue electrophysiology simulator using LS-DYNA

- **GOAL**
  test the **ability** of LS-DYNA for cardiac tissue simulations

Benchmark:

Verification of cardiac tissue electrophysiology simulator using a N-version benchmark, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, vol 369, issue 1954, pp 4331-4351, November 2011

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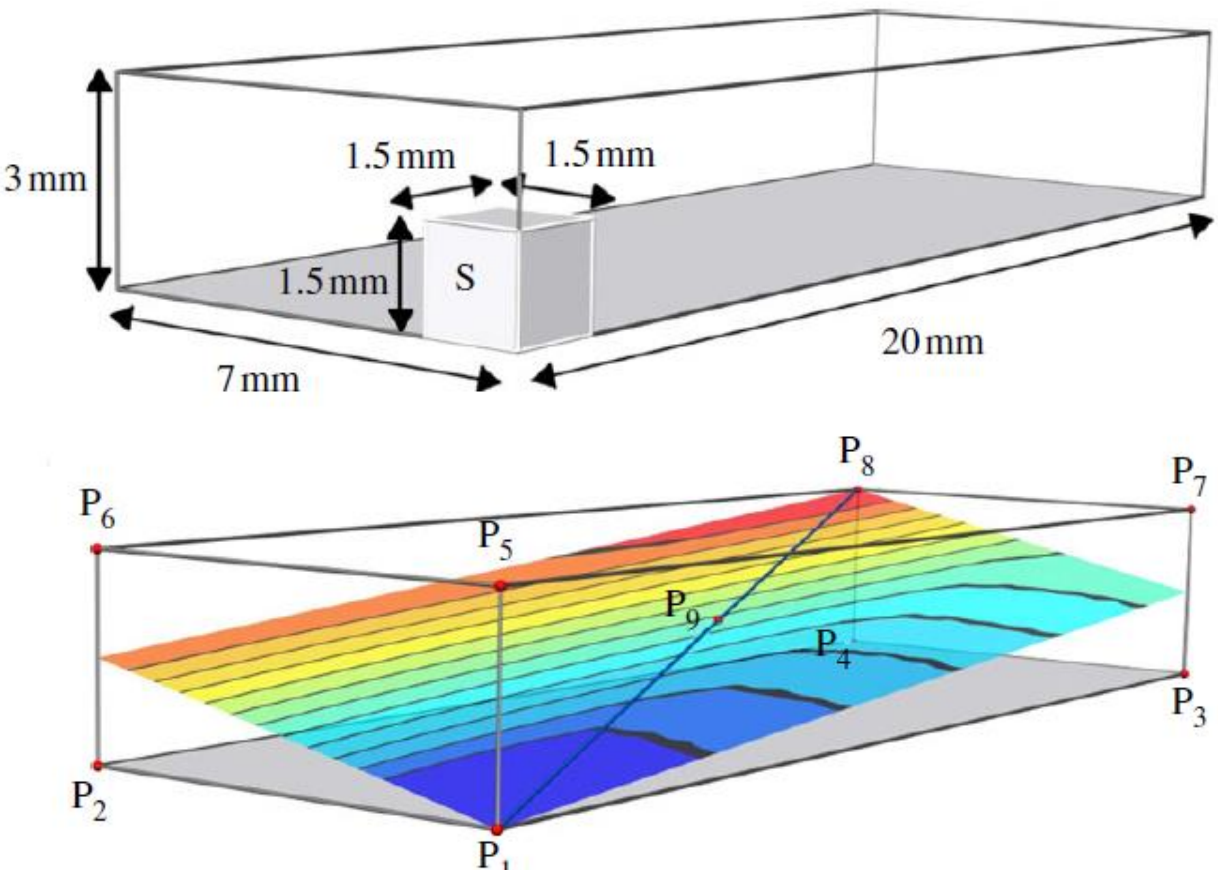
I. Verification of cardiac tissue electrophysiology simulator using LS-DYNA

- **BENCHMARK GOAL**
  Cuboid heart sample with stimulus on one corner. We observe the propagation of the potential inside the cell by determining the nodes' activation time.



Activation time
instant where the potential becomes positive

I. Verification of cardiac tissue electrophysiology simulator using LS-DYNA

- **MODEL DEFINITION**

Variable	Description
equations	monodomain
material	transversely isotropic
PDE solver	explicit
cell model	Ten Tusscher & Panfilov
variant	epicardium cell model
numerical integration scheme	Qu-Garfindel Operator Split
mesh type	hexahedral
solution method	finite element
basis function	linear Nedelec elements (FEMSTER)
pre-conditioners	none
matrix solver	hybrid-parallel, multifrontal, sparse direct solver (MF2)
system architecture	Serial or MPP

I. Verification of cardiac tissue electrophysiology simulator using LS-DYNA

- **MODEL DEFINITION**

1

$$\begin{cases} \beta C_m \dfrac{\partial V}{\partial t} + \beta I_{ion}(u,V,t) - \nabla.(\sigma \nabla V) = I_{stim}(\vec{x},t) \\ \dfrac{\partial u}{\partial t} = f(u,V) \end{cases}$$

monodomain equation

cell model : ten Tusscher & Panfilov ionic equations

V : membrane potential
t : time
σ : conductivity tensor
C_m: membrane capacitance
β : surface area to volume ration
I_{stim} : stimulus current, applied at the position $\vec{x}$
I_{ion} : single cell ionic current
u : set of cell-level variables ⟶ 19 for ten Tusscher model

2

Projection onto the FEM basis functions

$$\beta C_m M.\frac{dV}{dt} + \beta I_{ion} - S.V = I_{stim}$$

V , I_{stim} , I_{ion} ⟶ nodal vectors
M : mass matrix $\quad M(i,j) = \int_\Omega \Phi_i \Phi_j \, d\Omega$
S : stiffness matrix $\quad S(i,j) = \int_\Omega \sigma \overrightarrow{\nabla \Phi_i}.\overrightarrow{\nabla \Phi_j} \, d\Omega$

3

explicit Qu-Garfindel Operator Split

$V = V_t \qquad M.V_{t+1/2} = M.V_t - \dfrac{dt}{2\beta C_m} S.V_t$ Integrate diffusion operator for half timestep

$V = V_{t+1/2} \qquad V^*_{t+1/2} \begin{cases} C_m \dot{V} = I(u,V) \\ \dfrac{du}{dt} = f(u,V) \end{cases}$ Integrate ionic operator for full timestep

$V = V^*_{t+1/2} \qquad M.V_{t+1} = M.V^*_{t+1/2} - \dfrac{dt}{2\beta C_m} S.V^*_{t+1/2}$ Integrate diffusion PDE for half timestep

I. Verification of cardiac tissue electrophysiology simulator using LS-DYNA

- **9 SIMULATIONS**

dx (mm)	number of elements
0.5	3,360
0.2	52,500
0.1	420,000

dt (ms)	number of time steps
0.05	1,600
0.01	8,000
0.005	16,000

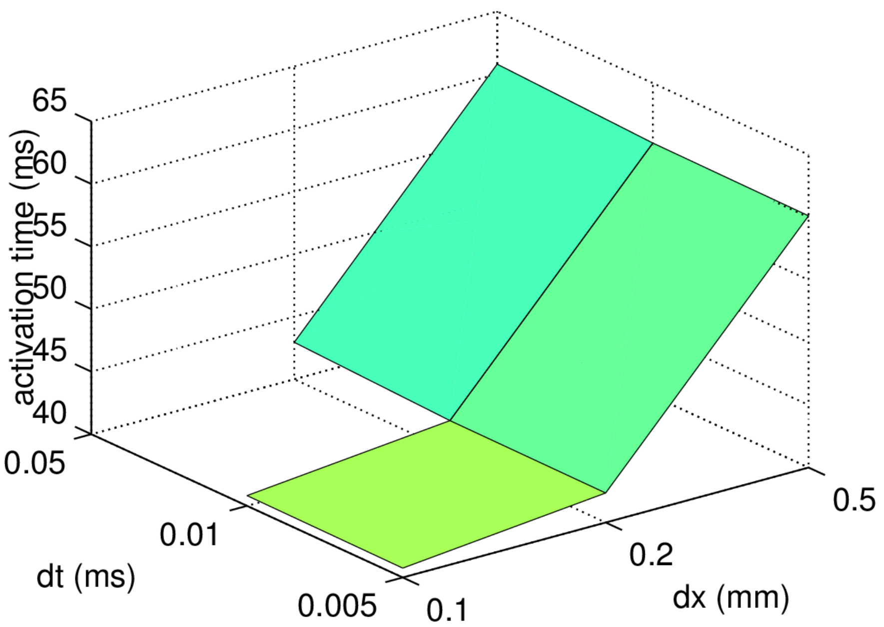
- **RESULTS**

- 8 successful simulations
- 1 failed simulation : dx = 0.1 mm with dt = 0.05 ms

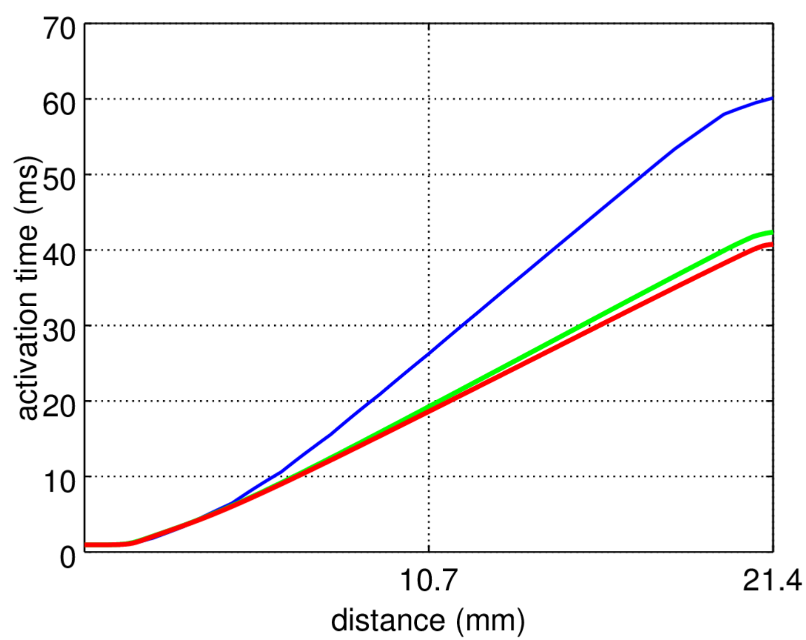
✖ CFL condition $dt \leq \frac{\beta C_m dx^2}{2\sigma_l \sigma_t}$ = 0.046 ms

The results are very similar to the benchmark paper ones

Activation time at P8

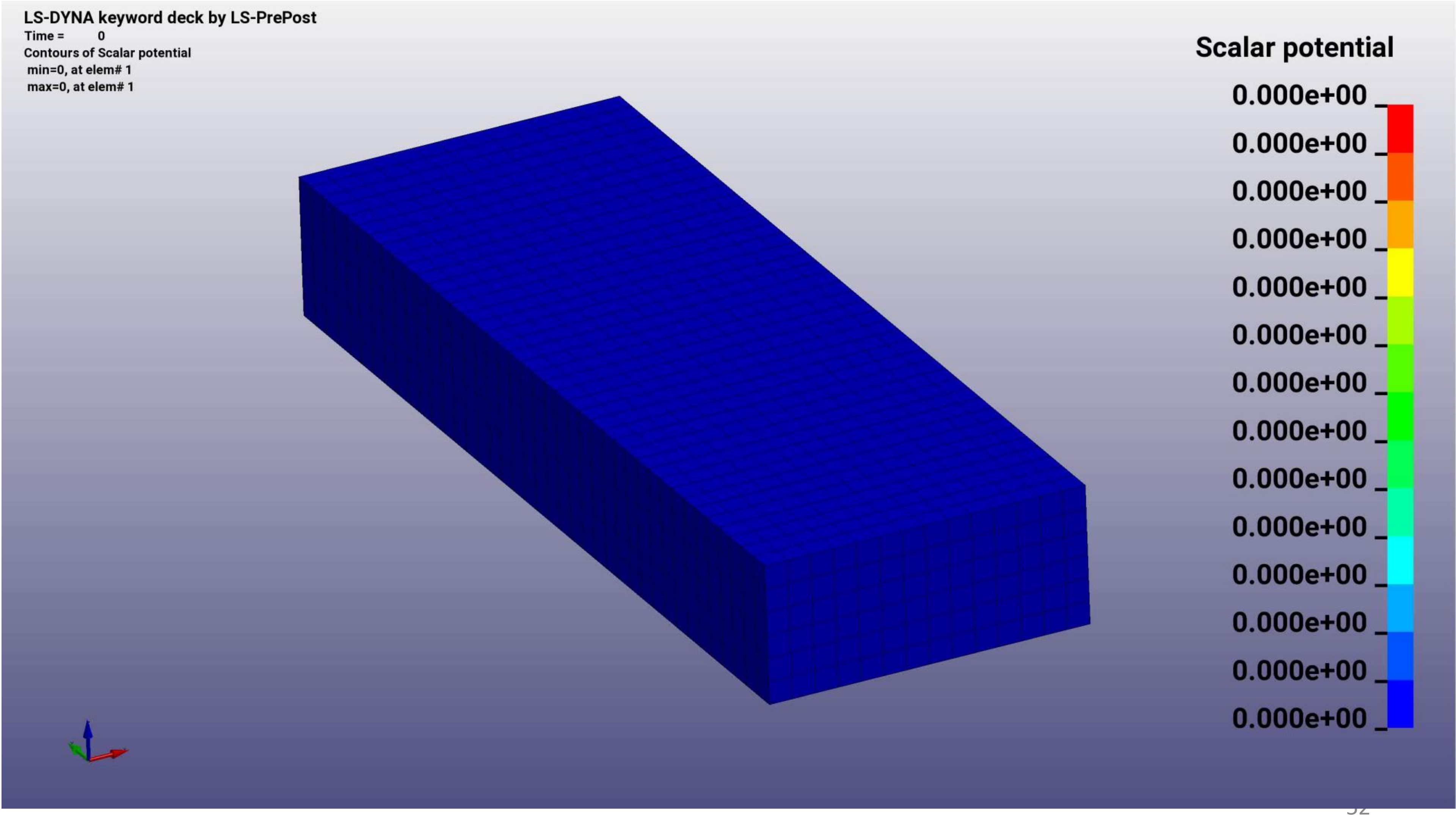


Activation time along P1-P8 for dt = 0.05 ms and **dx = 0.5 mm**, **dx = 0.2 mm** and **dx = 0.1mm**



I. Verification of cardiac tissue electrophysiology simulator using LS-DYNA

- **ELECTRICAL POTENTIAL PROPAGATION**



II. Developments

- Introduction of different solvers for the monodomain equations
- Introduction of bidomain model
- Presentation of the cards in LS-DYNA

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II. Developments

- **TO FACE THE CFL CONDITION**

PDE solver	implicit

implicit Qu-Garfindel Operator Split

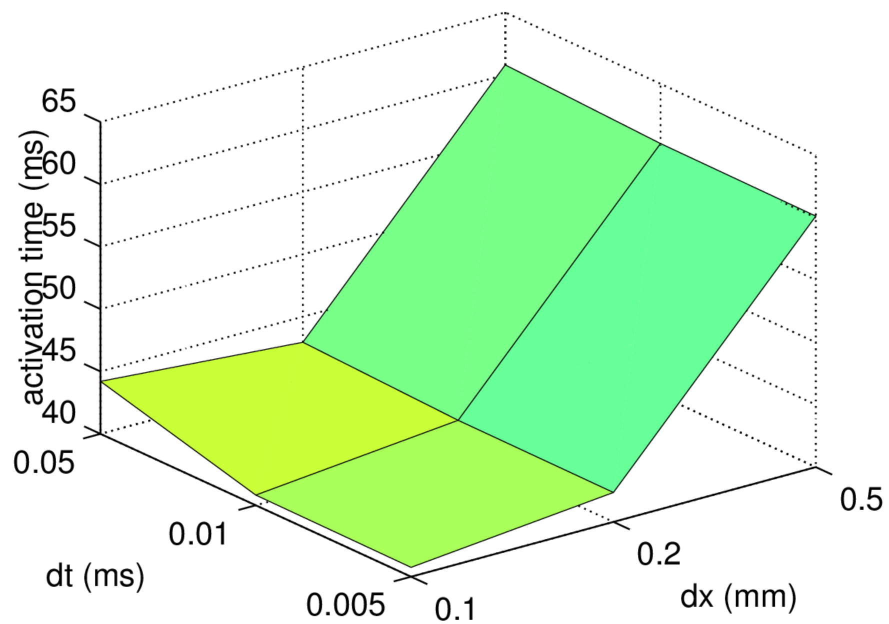
This term now in the lhs

$V = V_t$ $\quad (M + \frac{dt}{2\beta C_m} S).V_{t+1/2} = M.V_t$ — Integrate diffusion operator for half timestep

$V = V_{t+1/2}$ $\quad {V^*}_{t+1/2} \begin{cases} C_m \dot{V} = I(u,V) \\ \frac{du}{dt} = f(u,V) \end{cases}$ — Integrate ionic operator for full timestep

$V = {V^*}_{t+\frac{1}{2}}$ $\quad (M + \frac{dt}{2\beta C_m} S).V_{t+1} = M.{V^*}_{t+1/2}$ — Integrate diffusion PDE for half timestep

Activation time at P8



II. Developments

- **TO GAIN TIME**

numerical integration scheme	Dave's Operator Split

explicit Dave's Operator Split

At even time step

Integrate diffusion operator for one timestep

$$V = V_t \qquad M.V_{t+1} = M.V_t - \frac{dt}{2\beta C_m} S.V_t$$

Integrate ionic operator for full timestep

$$V = V_{t+1} \qquad {V^*}_{t+1} \begin{cases} C_m \dot{V} = I(u,V) \\ \dfrac{du}{dt} = f(u,V) \end{cases}$$

Set $V_{t+1} = {V^*}_{t+1}$

At odd time step

Integrate ionic operator for full timestep

$$V = V_{t+1} \qquad {V^*}_{t+1} \begin{cases} C_m \dot{V} = I(u,V) \\ \dfrac{du}{dt} = f(u,V) \end{cases}$$

Set $V_{t+1} = {V^*}_{t+1}$

Integrate diffusion operator for one timestep

$$V = V_t \qquad M.V_{t+1} = M.V_t - \frac{dt}{2\beta C_m} S.V_t$$

Machine time – simulation time = 80 ms (all the runs were done in serial)

Numerical integration scheme	dt1=0.05ms - dx1=0.5mm	dt1=0.05ms - dx3=0.1mm	dt3=0.005ms - dx3=0.1mm
explicit Qu-Garfindel Operator Split	1min14s	X	33h15min30s
explicit Dave's Operator Split	59s	X	24h49min3s
implicit Qu-Garfindel Operator Split	1min12s	3h23min58s	34h40min16s
implicit Dave's Operator Split	58s	2h32min30s	24h53min12s

II. Developments

- **TO INCREASE THE ACCURACY**

equations	**bidomain**
PDE solver	implicit
numerical integration scheme	Spiteri-Ziaratgahi Operator Split

1

$$\begin{cases} \beta C_m \dfrac{\partial V}{\partial t} + \beta I_{ion}(u,V,t) - \nabla.(\sigma_i \nabla V) - \nabla.(\sigma_i \nabla u_e) = I_{stim}(\vec{x},t) \\ \nabla.(\sigma_i \nabla V) + \nabla.\left((\sigma_i + \sigma_e)\nabla u_e\right) = 0 \\ \dfrac{\partial u}{\partial t} = f(u,V) \end{cases}$$

bidomain equations

u_e: extracellular potential
σ_i: intracellular conductivity tensor
σ_i: extracellular conductivity tensor

2

Projection onto the FEM basis functions

$$\beta C_m M.\frac{dV}{dt} + \beta I_{ion} - S_i.V - S_i.U_e = I_{stim}$$
$$S_i.V + S_{ie}.U_e = 0$$

V, U_e, I_{stim}, I_{ion} $\longrightarrow$ nodal vectors

2 stiffness matrices $S_i(i,j) = \int_\Omega \sigma_i \overrightarrow{\nabla\Phi_i}.\overrightarrow{\nabla\Phi_j}\,d\Omega$

$S_{ie}(i,j) = \int_\Omega (\sigma_i + \sigma_{ie})\overrightarrow{\nabla\Phi_i}.\overrightarrow{\nabla\Phi_j}\,d\Omega$

3

implicit Spiteri-Ziaratgahi Operator Split

$$u_{t+1} = u_t + dt\, f(u_t, V_t, t)$$
$$\begin{bmatrix} \dfrac{\beta C_m}{dt} M + S_i & S_i \\ S_i & S_{ie} \end{bmatrix} . \begin{bmatrix} V_{t+1} \\ U_{e\ t+1} \end{bmatrix} = \begin{bmatrix} \dfrac{\beta C_m}{dt} M.V_t - \beta M.I_{ion}(u_{t+1}, V_t, t) \\ 0 \end{bmatrix}$$

solved using a PCG method, where the preconditioner is the diagonal line of the matrix, or with the hybrid-parallel, multifrontal, sparse direct solver, MF2

cell model	**Purkinje**

III. Creation of a model

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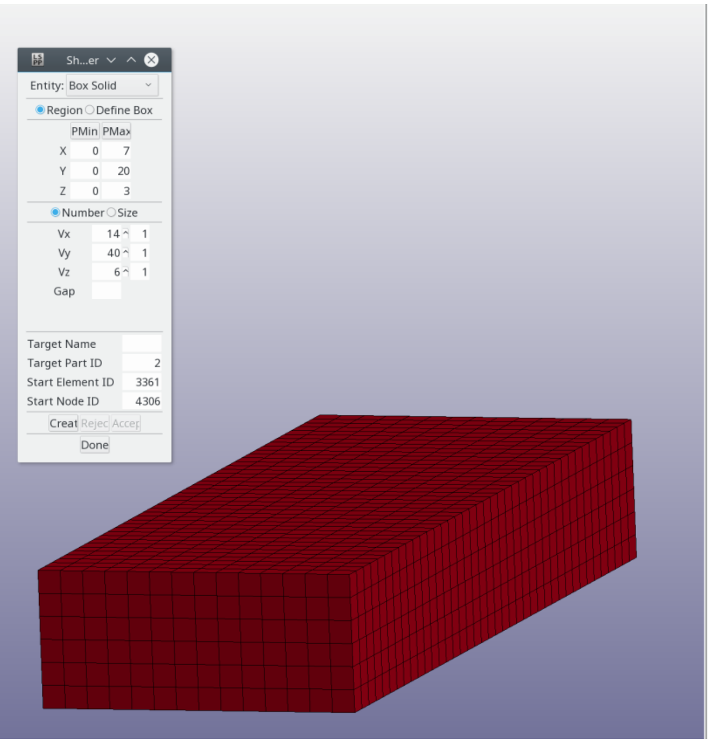
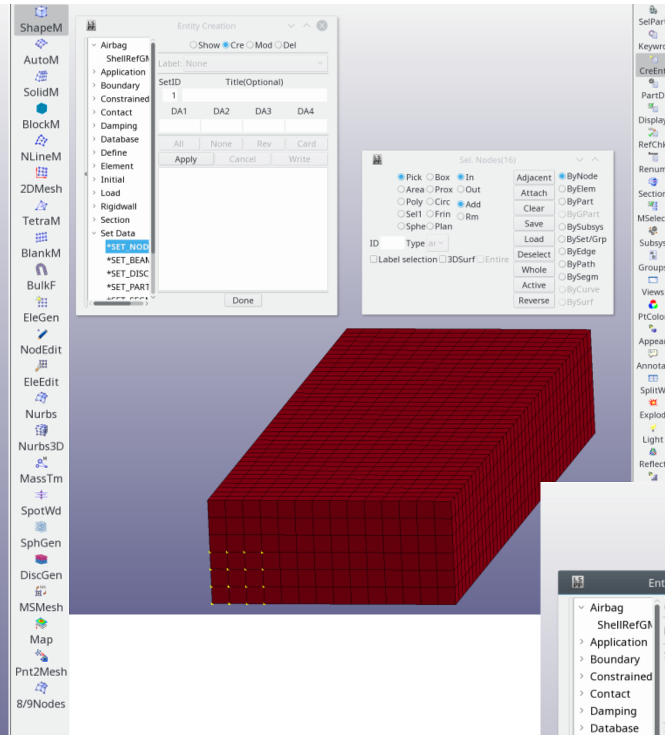
III. Creation of a model

- **LS-PREPOST**

1 Build a mesh

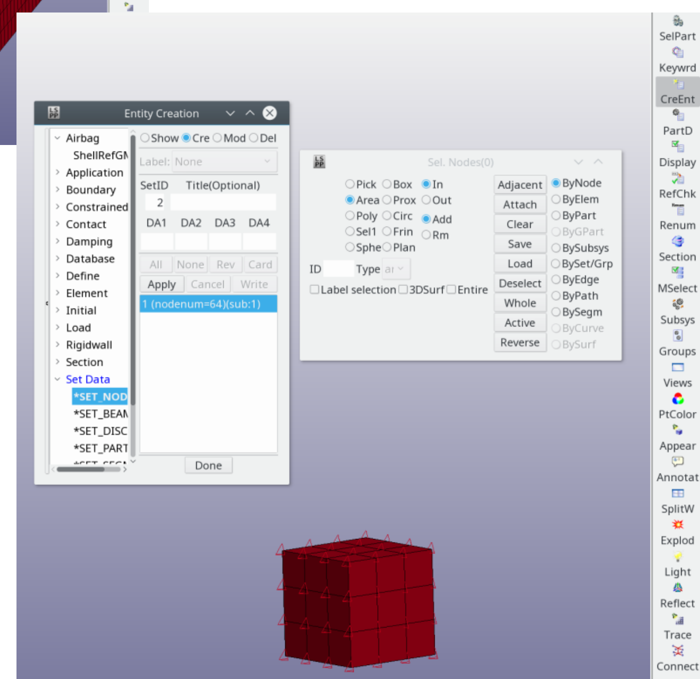
2 Select the nodes where the stimulus is applied





Mode ⟶ CreEntity ⟶ Set Data
⟶ Set Nodes ⟶ Create

Sel. Nodes window : Pick ByNode
Apply



To select nodes inside the solid

- Blank the unwished elements with EleTools ⟶ Blank ⟶ Element
  Sel. Elem. window : Pick or Area ByElem
  Apply
- Create the nodes set using Sel. Nodes window : Area ByNode

III. Creation of a model

- **INPUT DECK – MECHANIC (for now, i.e. for pure EP model without mechanical coupling)**

```
*KEYWORD
*INCLUDE
mesh.k
$ ****************************************************************************
$ MECHANIC
$ ****************************************************************************
*CONTROL_TERMINATION
$--------1---------2---------3---------4---------5---------6---------7---------8
$   endtim
       80.
*CONTROL_TIMESTEP
$--------1---------2---------3---------4---------5---------6---------7---------8
$   dtinit                                                     lctm
      0.05                                                        3
*DEFINE_CURVE
3
0.,0.05
10.,0.05
*DATABASE_BINARY_D3PLOT
$--------1---------2---------3---------4---------5---------6---------7---------8
$       dt
       0.2
*PART
$--------1---------2---------3---------4---------5---------6---------7---------8
cellule
$      pid     secid     matid     eosid      hgid      grav    adpopt      tmid
         1         1         1
*SECTION_SOLID
$--------1---------2---------3---------4---------5---------6---------7---------8
$      sid    elform
         1         1
*MAT_ELASTIC
$--------1---------2---------3---------4---------5---------6---------7---------8
$    matid        ro         E        pr
         1   8928.57   200.e+09        .3
```

III. Creation of a model

- **INPUT DECK – ELECTROMAGNETISM for MONODOMAIN**

```
$ ***************************************************************************
$ ELECTROMAGNETIC
$ ***************************************************************************
*EM_CONTROL
$--------1---------2---------3---------4---------5---------6---------7---------8
$    emsol     numls  emdtinit   emdtmax   emtinit    emtend  ncyclFem  ncyclBem
        11         1      0.05
*EM_SOLVER_FEM
$--------1---------2---------3---------4---------5---------6---------7---------8
$   relTol   maxIter solveType   precond   uselast
     1.e-6     10000         1         2         1
*EM_MAT_003
$--------1---------2---------3---------4---------5---------6---------7---------8
$    matid     mtype   sigmaXX   sigmaYY   sigmaZZ      beta        Cm
         1         2 1.7606e-51.33418e-4 1.7606e-5      0.14      0.01
$--------1---------2---------3---------4---------5---------6---------7---------8
$  sigmaXY   sigmaXZ   sigmaYX   sigmaYZ   sigmaZX   sigmaZY      AOPT
                                                                    2.
$--------1---------2---------3---------4---------5---------6---------7---------8
$       XP        YP        ZP        A1        A2        A3      MACF
                                       0         0         1
$--------1---------2---------3---------4---------5---------6---------7---------8
$       V1        V2        V3        D1        D2        D3
                                       0        -1         0
```

emsol 11 ⟶ **monodomain** equations
numerical integration scheme:
numls 1 ⟶ explicit Qu-Garfindel
2 ⟶ implicit Qu-Garfindel
3 ⟶ explicit Dave
4 ⟶ implicit Dave

emsol = 11 ⟶ ***EM_MAT_003** Definition of 1 conductivity tensor e.g. $\sigma = \begin{bmatrix} 0.017606 & 0 & 0 \\ 0 & 0.133418 & 0 \\ 0 & 0 & 0.017606 \end{bmatrix}$ in $S.m^{-1}$

The conductivity is more important along the direction Y, which represents the fiber length.

III. Creation of a model

- **INPUT DECK – ELECTROMAGNETISM for BIDOMAIN**

```
$ ************************************************************************
$ ELECTROMAGNETIC
$ ************************************************************************
*EM_CONTROL
$--------1---------2---------3---------4---------5---------6---------7---------8
$    emsol     numls  emdtinit   emdtmax   emtinit    emtend  ncyclFem  ncyclBem
        12         2       &dt                                    50000
*EM_SOLVER_FEM
$--------1---------2---------3---------4---------5---------6---------7---------8
$   relTol   maxIter solveType   precond   uselast
      1.e-6    10000         1         2         1
*EM_MAT_005
$--------1---------2---------3---------4---------5---------6---------7---------8
$ intramid     mtype   sigmaXX   sigmaYY   sigmaZZ      beta        Cm
         1         2 0.019e-3   0.17e-3  0.019e-3      0.14      0.01
$--------1---------2---------3---------4---------5---------6---------7---------8
$  sigmaXY   sigmaXZ   sigmaYX   sigmaYZ   sigmaZX   sigmaZY

$--------1---------2---------3---------4---------5---------6---------7---------8
$ extramid            sigmaXXb  sigmaYYb  sigmaZZb
         1             0.24e-3   0.62e-3   0.24e-3
$--------1---------2---------3---------4---------5---------6---------7---------8
$ sigmaXYb  sigmaXZb  sigmaYXb  sigmaYZb  sigmaZXb  sigmaZYb

$--------1---------2---------3---------4---------5---------6---------7---------8
$#    AOPT        XP        YP        ZP        A1        A2        A3      MACF
                                       0         0         1
$--------1---------2---------3---------4---------5---------6---------7---------8
$#      V1        V2        V3        D1        D2        D3
                                       0        -1         0
```

emsol 12 ⟶ **bidomain** equations

numerical integration scheme:

numls 1 ⟶ implicit Spiteri-Ziaratgahi
where the preconditioner is the diagonal line of the matrix

numls 2 ⟶ implicit Spiteri-Ziaratgahi
with the hybrid-parallel, multifrontal, sparse direct solver, MF2 (**faster**)

emsol = 12 ⟶ *EM_MAT_005

Definition of 2 conductivity tensors σ_i and σ_e

III. Creation of a model

- **INPUT DECK –**

CELL MODEL VARIABLES

*EM_EP_TENTUSSCHER

Variables linked to a material id

```
*EM_EP_TENTUSSCHER
$--------1---------2---------3---------4---------5---------6---------7---------8
$    matid
         1
$ CONSTS
$--------1---------2---------3---------4---------5---------6---------7---------8
$  consts1   consts2   consts3   consts4   consts5  consts52  consts53  consts10
$        R         T         F        Cm        Vc       Vsr       Vss     p_KNa
 8314.472     31096485.3415     0.185  0.016404 0.0010940.00005468      0.03
$--------1---------2---------3---------4---------5---------6---------7---------8
$ consts11  consts12  consts13
$      K_o      Na_o      Ca_o
       5.4      140.        2.
$--------1---------2---------3---------4---------5---------6---------7---------8
$ consts14  consts15  consts16  consts17  consts18  consts19  consts20  consts21
$     g_K1      g_Kr      g_Ks      g_Na     g_bNa     g_CaL     g_bCa      g_to
     5.405     0.153     0.392    14.838    0.0002 0.0000398  0.000592     0.294
$ consts31  consts33
$    g_pCa      g_pK
    0.1238    0.0146
$--------1---------2---------3---------4---------5---------6---------7---------8
$ consts22  consts23  consts24  consts25  consts26  consts27  consts28  consts29
$    P_NaK      K_mK     K_mNa    k_NaCa      ksat     alpha     gamma     Km_Ca
     2.724        1.       40.     1000.       0.1       2.5      0.35      1.38
$ consts30  consts32
$   Km_Nai     K_pCa
      87.5    0.0005
$--------1---------2---------3---------4---------5---------6---------7---------8
$ consts34  consts35  consts36  consts37  consts38  consts39  consts40
$      k1'       k2'        k3        k4        EC    max_sr    min_sr
      0.15     0.045      0.06     0.005       1.5       2.5        1.
$ consts41  consts44  consts42  consts45  consts43
$    V_rel    V_leak    V_xfer   Vmax_up      K_up
     0.102   0.00036    0.0038  0.006375   0.00025
$ consts46  consts47  consts48  consts49  consts50  consts51
$    Buf_c   K_buf_c    Buf_sr  K_buf_sr    Buf_ss  K_buf_ss
       0.2     0.001       10.       0.3       0.4   0.00025
$ INIT STATES
$--------1---------2---------3---------4---------5---------6---------7---------8
$  states1   states2   states3   states4  states11  states18  states19
$        V       K_i      Na_i      Ca_i     Ca_ss     Ca_sr        R'
    -85.23    136.89     8.604  0.000126   0.00036      3.64    0.9073
$--------1---------2---------3---------4---------5---------6---------7---------8
$  states5   states6   states7   states8   states9  states10  states12  states13
$      xr1       xr2        xs         m         h         j         d         f
   0.00621    0.4712    0.0095   0.00172    0.7444    0.7045  3.373e-5    0.7888
$ states14  states15  states16  states17
$       f2     fCass         s         r
    0.9755    0.9953  0.999998   2.42e-8
```

III. Creation of a model

- **INPUT DECK - STIMULUS**

```
*EM_EP_TENTUSSCHER_STIMULUS
$--------1---------2---------3---------4---------5---------6---------7---------8
$   stimid      nsid
         1         1
$ constants for stimulus
$--------1---------2---------3---------4---------5---------6---------7---------8
$  consts6   consts7   consts8   consts9
$stimStart     stimT    stimDur   stimAmp
        0.     1000.         2.       50.
*EM_EP_TENTUSSCHER_STIMULUS2
$--------1---------2---------3---------4---------5---------6---------7---------8
$   stimid      nsid      lcid
         2         2        33
*DEFINE_CURVE
33
0.,50.
2.,50.
2.1,0.
10.,0.
10.1,50.
12.,50.
12.1,0.
20.,0.
```

Node set id where stimulus is applied

***EM_EP_TENTUSSCHER_STIMULUS**

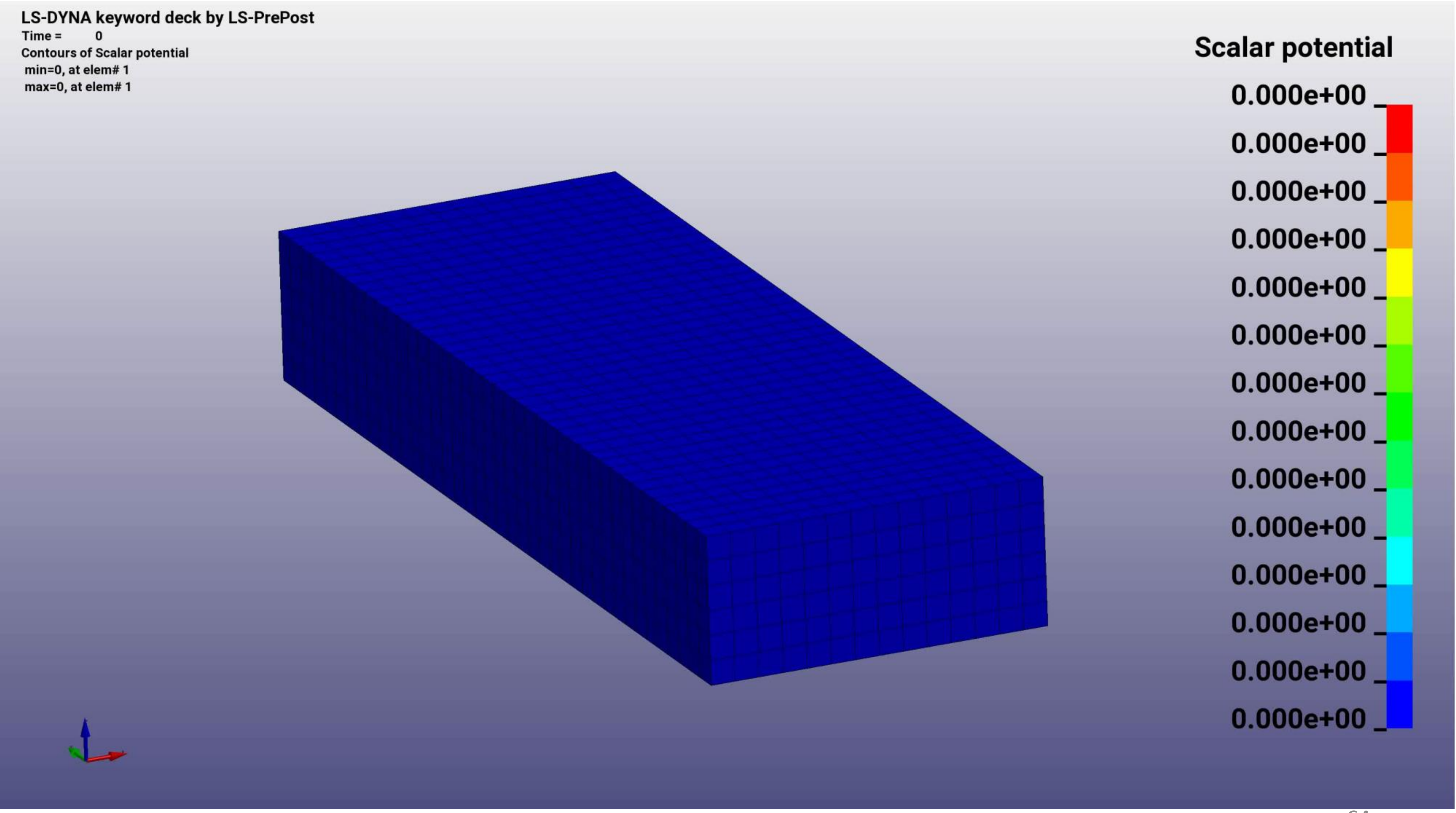
Definition of :
- the starting time
- the period
- the duration
- the amplitude

***EM_EP_TENTUSSCHER_STIMULUS2**

Stimulus loaded by a load curve representing stimulus amplitude vs time

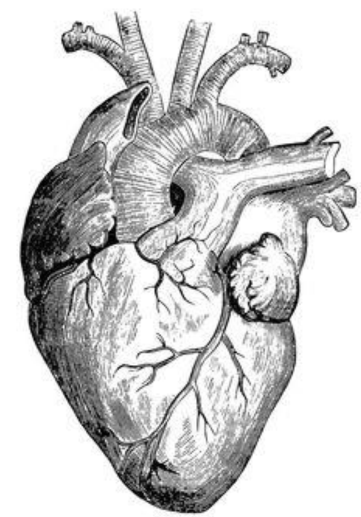
III. Creation of a model

- **ELECTRICAL POTENTIAL PROPAGATION - 2 STIMULUS**



CONCLUSION

- Different EP models in LS-DYNA, for both monodomain and bidomain equations
- The ten-Tusscher cell model has been introduced
- They give good results on the first benchmark tests
- These models are available to the users through new cards
- More cell models will be added in the future



- What should be the priorities on pure EP?
  - Other cell models (Purkinje, …) ?
  - Introduce fractal Purkinje network ?
  - Try runs with many elements ?
  - Try runs with models closer to full heart with different cell models ?
- We are interested in the APD restitution results and whether more developments are needed to simulate tachycardia and fribrillation