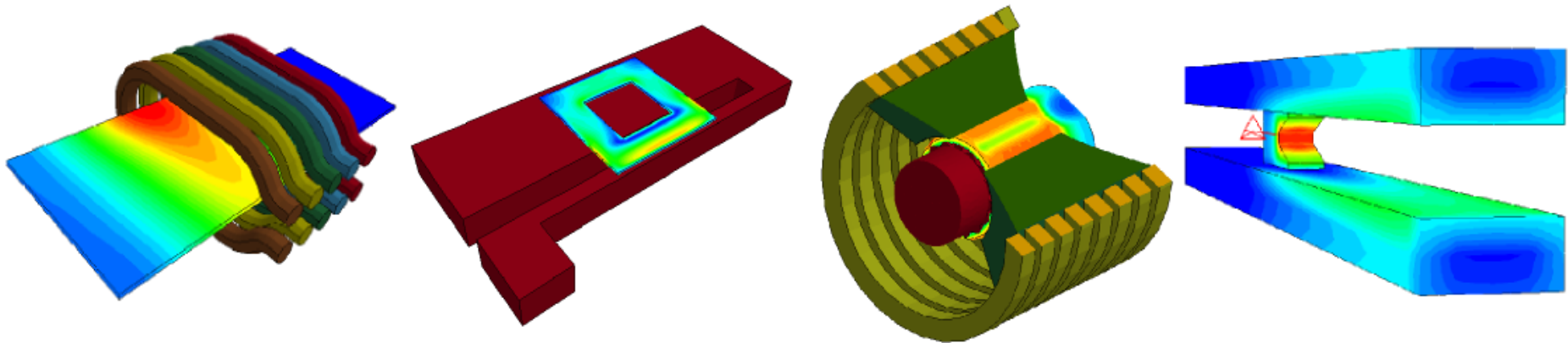


Electromagnetism Module Presentation

Pierre L'Eplattenier, Iñaki Çaldichoury



Introduction

1.1 Background

1.2 Main characteristics and features

1.3 Examples of applications

LS-DYNA® is a **general-purpose** finite element program capable of simulating complex real world problems. It is used by the **automobile, aerospace, construction, military**, manufacturing, and bioengineering industries. LS-DYNA® is optimized for shared and distributed memory Unix, Linux, and Windows based, platforms, and it is fully QA'd by LSTC. The code's origins lie in **highly nonlinear, transient dynamic finite element analysis** using **explicit time integration**.

Some of LS-DYNA® main functionalities include :

- Full **2D** and **3D** capacities
- **Explicit/Implicit** mechanical solver,
- Coupled **thermal** solver,
- Specific methods : **SPH, ALE, EFG**.....,
- **SMP** and **MPP** versions.

- The new release version pursues the objective of LS-DYNA® to become a strongly coupled **multi-physics solver** capable of solving complex real world problems that include several domains of physics.
- Three main new solvers will be introduced. Two fluid solvers for both compressible flows (CESE solver) and incompressible flows (ICFD solver) and the **Electromagnetism solver (EM)**.
- This presentation will focus on the EM solver.
- The **scope** of these solvers is not only to solve their particular equations linked to their respective domains but to fully make use of LS-DYNA® capabilities by **coupling** them with the existing **structural** and/or **thermal** solvers.

Introduction

1.1 Background

1.2 Main characteristics and features

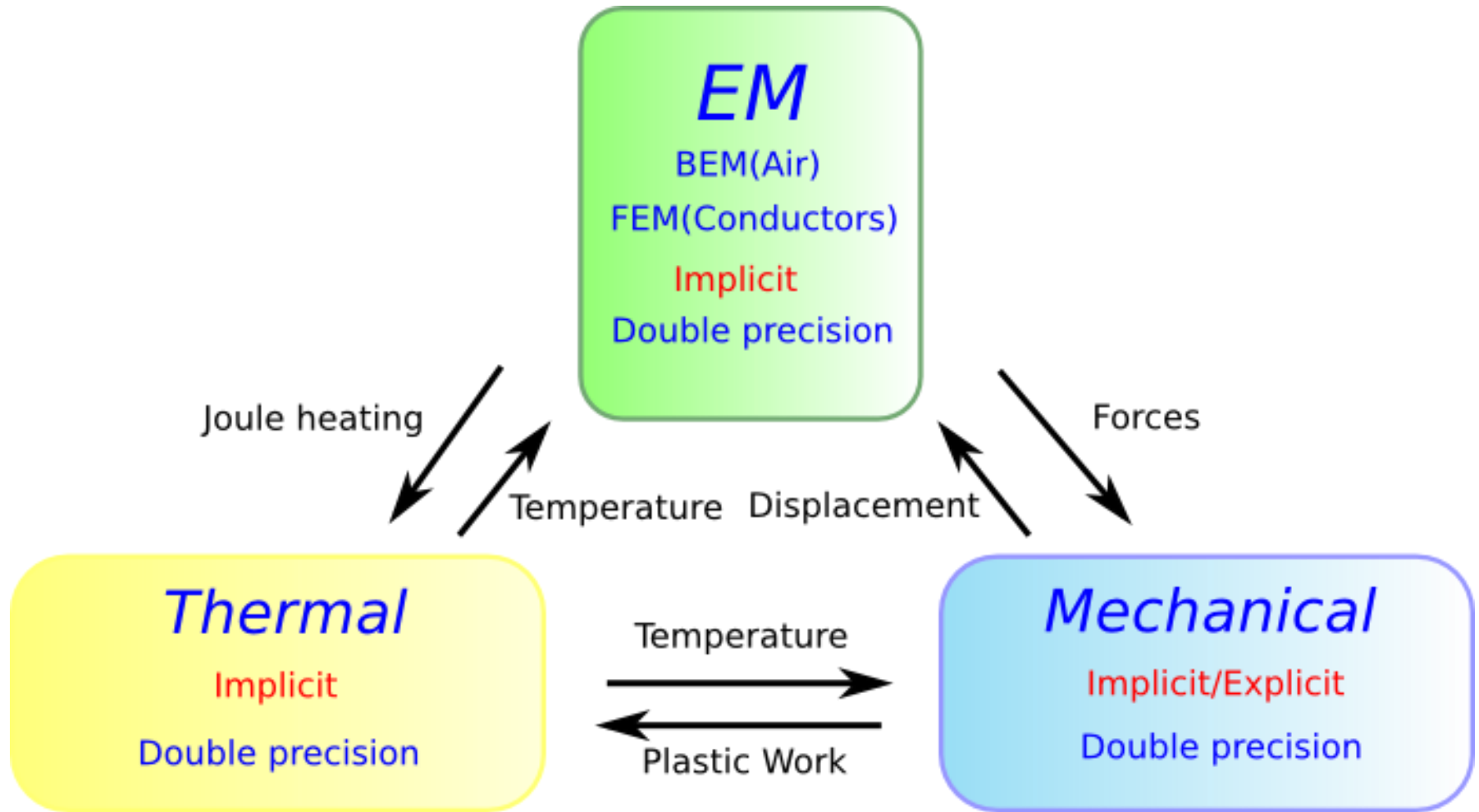
1.3 Examples of applications

Characteristics

- Double precision
- Fully **implicit**
- **2D axisymmetric** solver / **3D** solver
- Solid elements for conductors. Shells can be isolators.
- **SMP** and **MPP** versions available
- Dynamic memory handling
- **Automatically coupled** with LS-DYNA solid and thermal solvers.
- New set of keywords starting with ***EM** for the solver
- FEM for conducting pieces only, no air mesh needed (**FEM-BEM method**)

Features

- **Eddy current** solver
- **Induced heating** solver
- **Resistive heating** solver
- Uniform current in conductors
- Imposed **tension** or **current circuits** can be defined
- **External fields** can be applied
- **Axi-symmetric capabilities**
- EM Equation of states are available
- EM contact between conductors is possible
- **Magnetic materials** capabilities

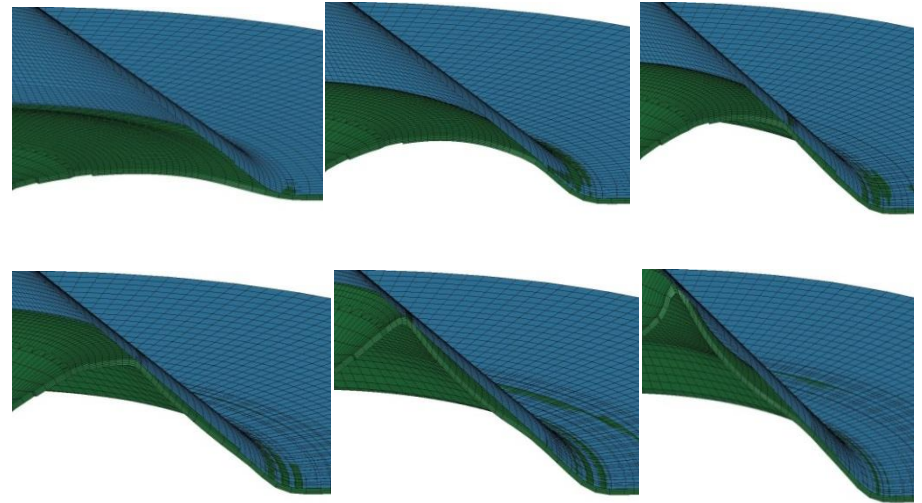
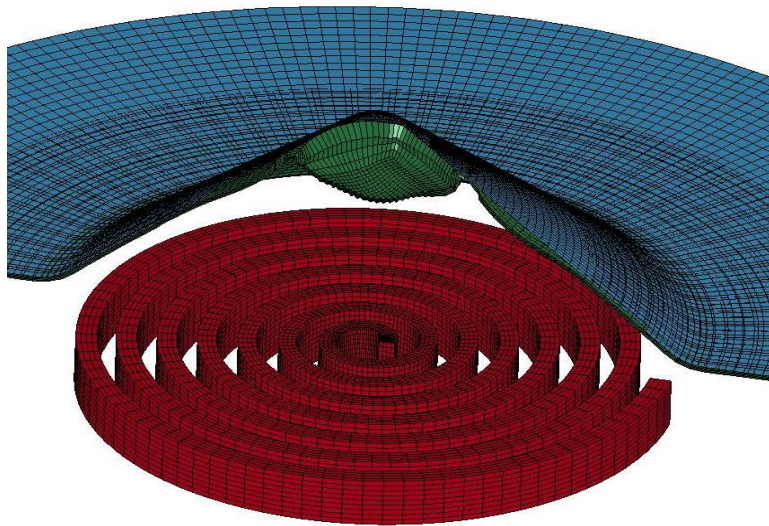


Introduction

1.1 Background

1.2 Main characteristics and features

1.3 Examples of applications

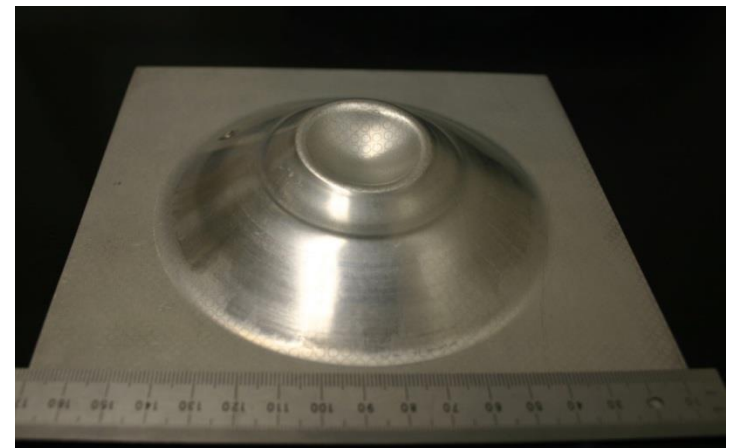


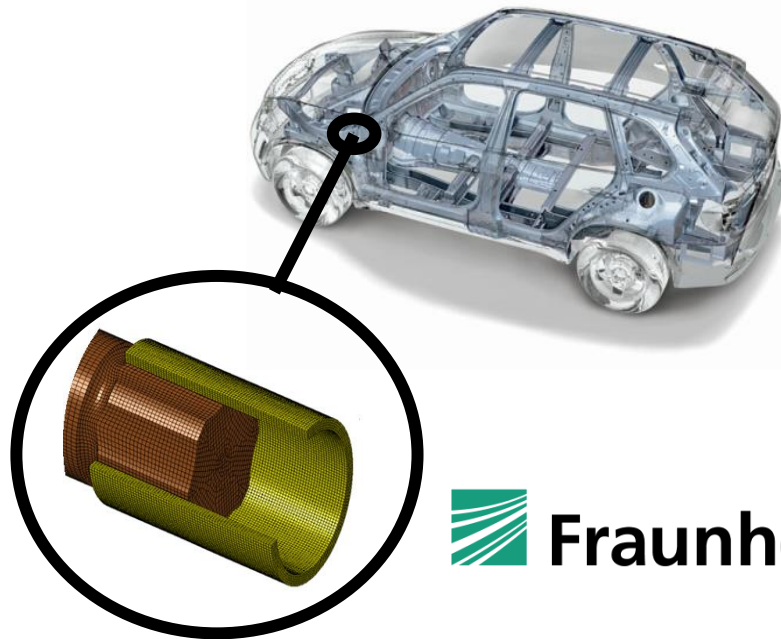
Sheet forming on conical die

In collaboration with:

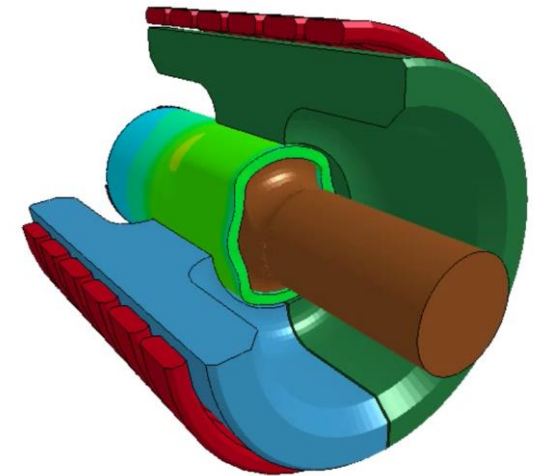
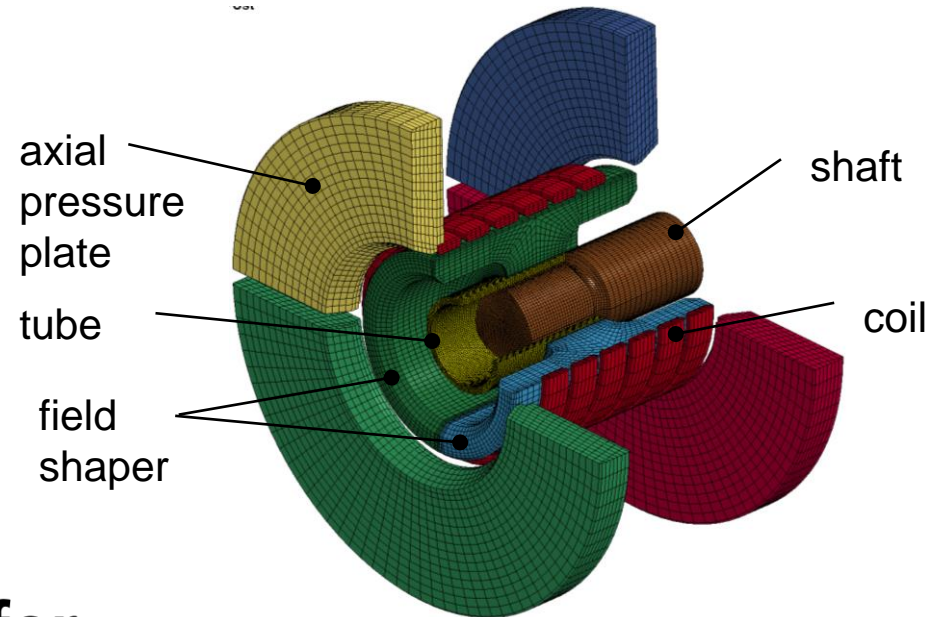
M. Worswick and **J. Imbert**

University of Waterloo, Ontario,
Canada





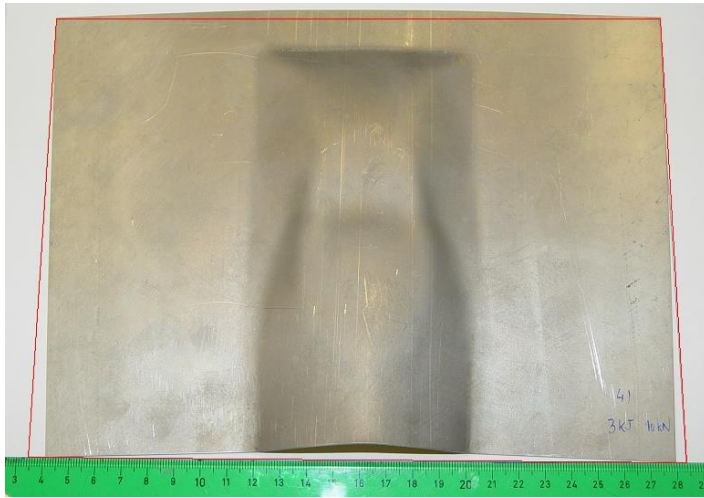
 **Fraunhofer**
IWU



Simulation of a tube-shaft joint:

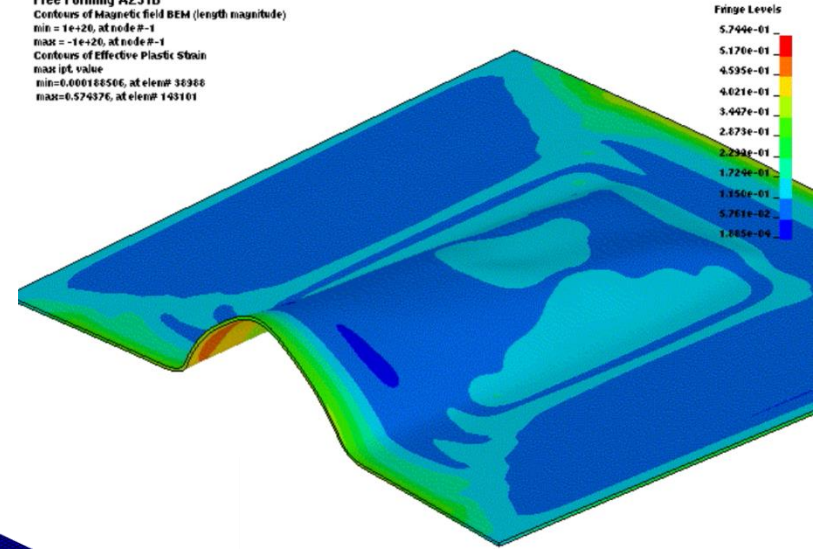
In collaboration with:

Fraunhofer Institute for Machine Tools and Forming
Technology IWU, Chemnitz, Dipl.-Ing. [Christian Scheffler](#)
Poynting GmbH, Dortmund, Dr.-Ing. [Charlotte Beerwald](#)



Experimental result

Free Forming AZ31B
Contours of Magnetic field BEM (length magnitude)
min = 1e+26, at node 9-1
max = -1e+26, at node 8-1
Contours of Effective Plastic Strain
max ipt. value
min=0.000188506, at elem# 30380
max=0.574876, at elem# 148101

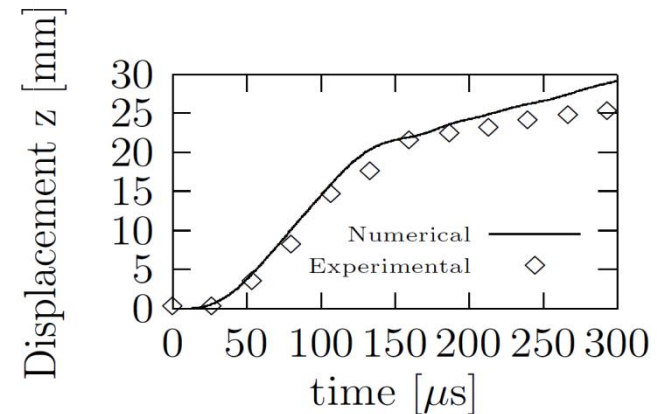


Numerical result

Magnetic metal forming:

In collaboration with:

Ibai Ulacia, University of Mondragon,
Gipuzkoa, Basque country

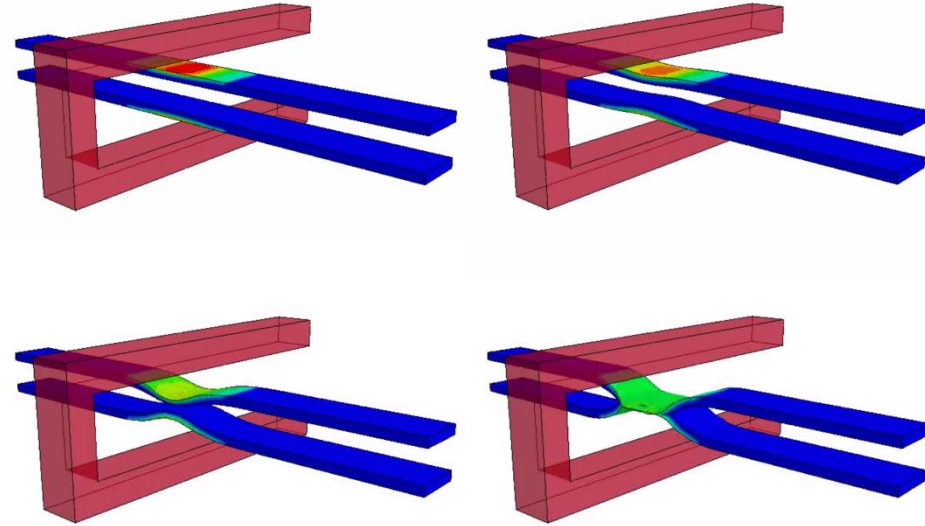
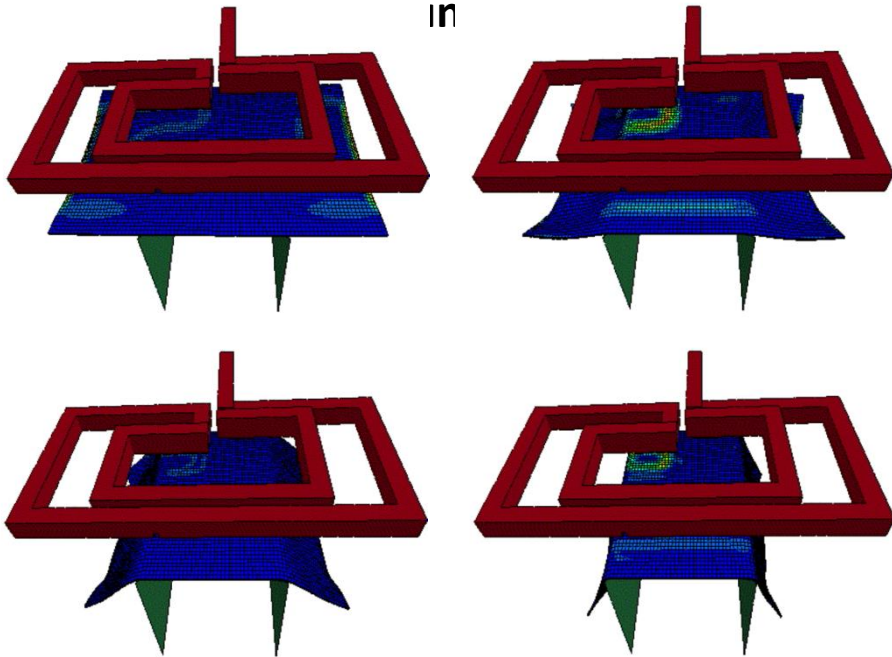


Magnetic metal welding and bending:

In collaboration with:

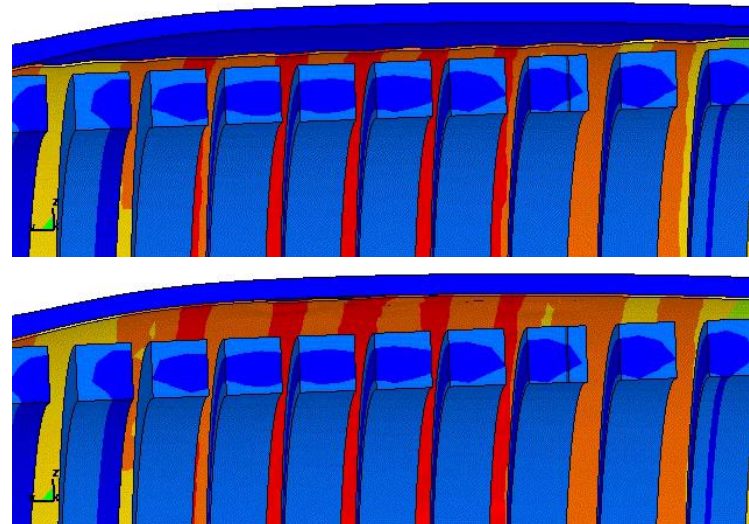
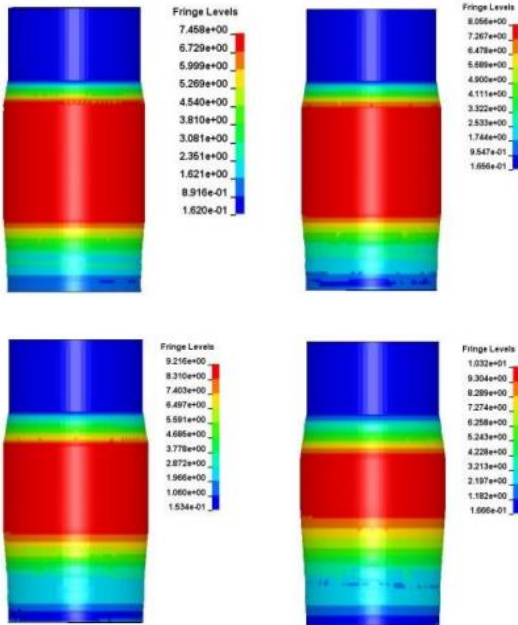
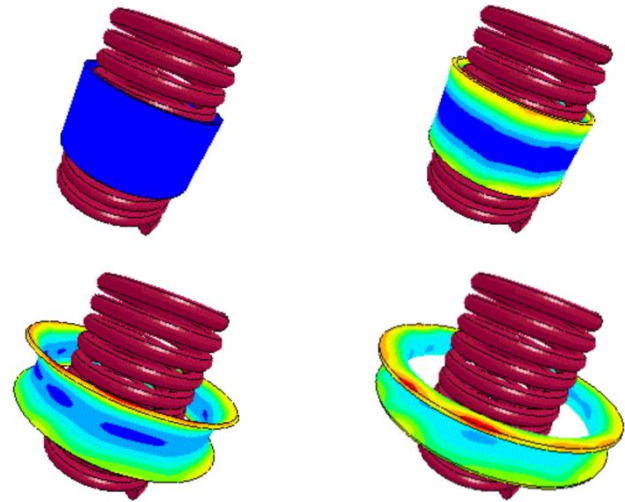
Ibai Ulacia , University of Mondragon,

in



Ring expansions:

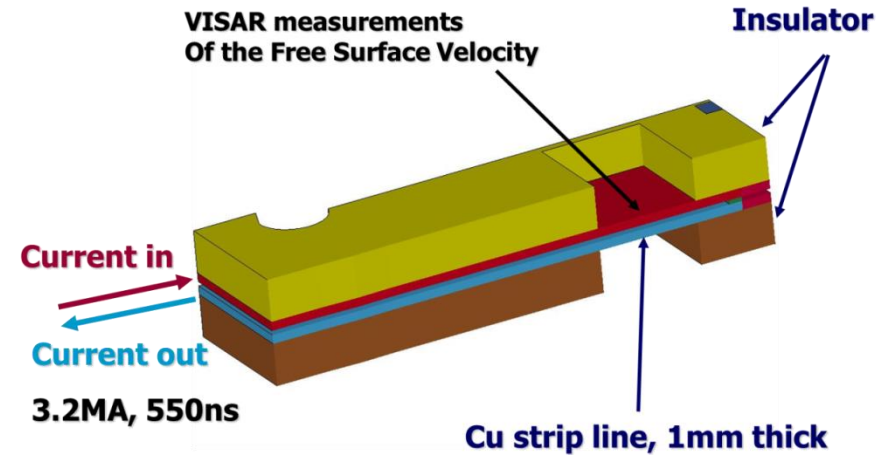
Numerous collaborations :



High Pressure Generation

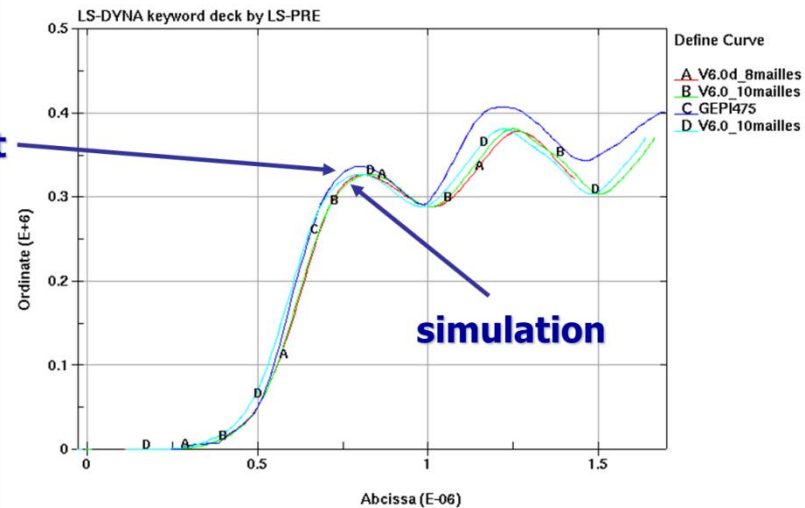
In collaboration with :

G. Le Blanc, G. Avriilaud,
P.L.Hereil, P.Y. Chanal, Centre
D'Etudes de Gramat (CEA),
Gramat, France

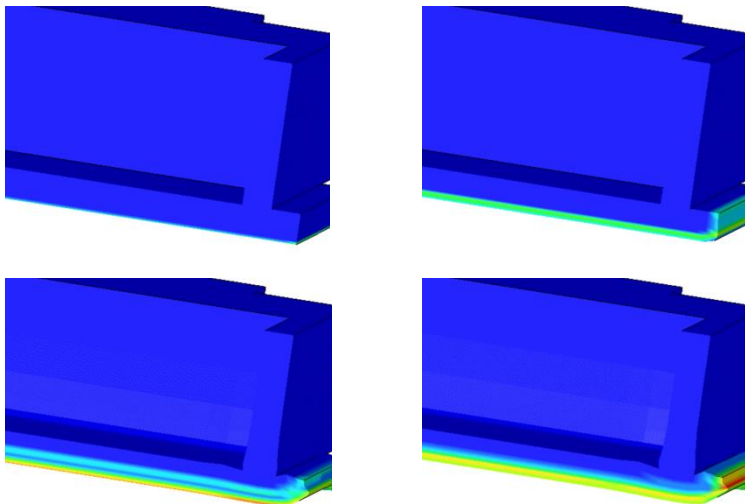


111,000 elements, 10 elements through line thickness

experiment



Free surface velocity vs time

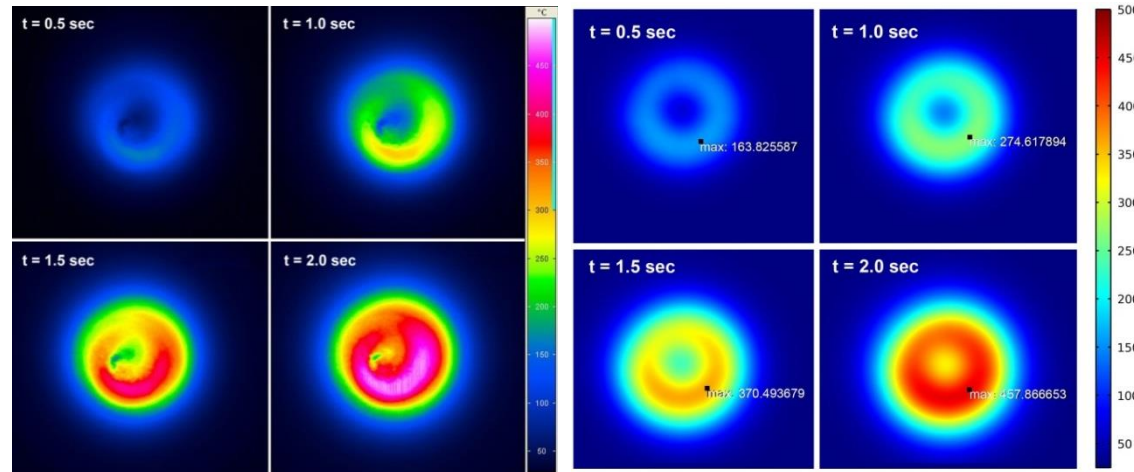
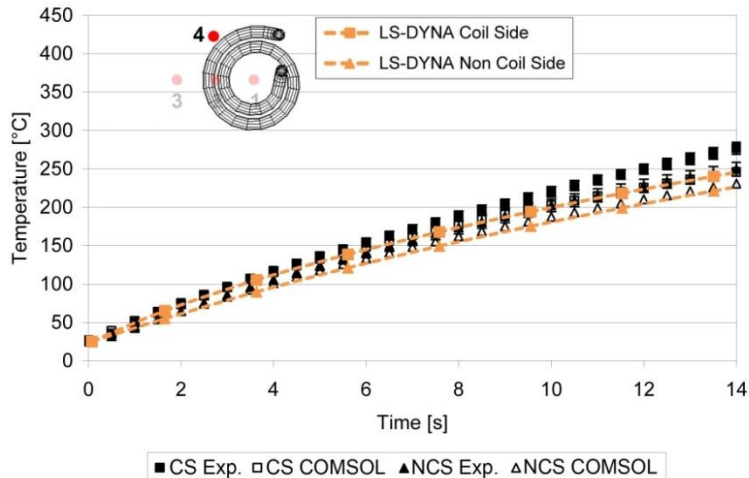
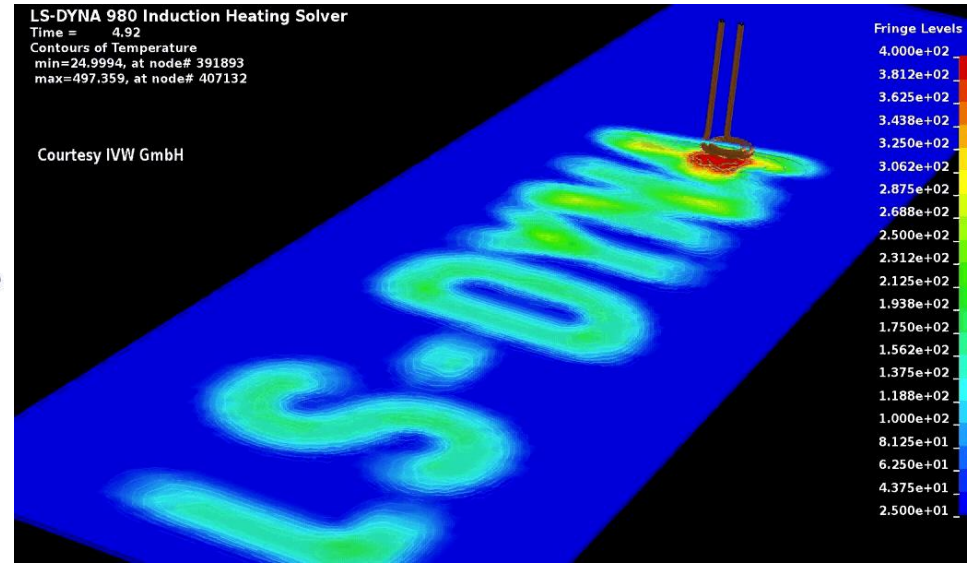


Heating of a steel plate by induction

In collaboration with:

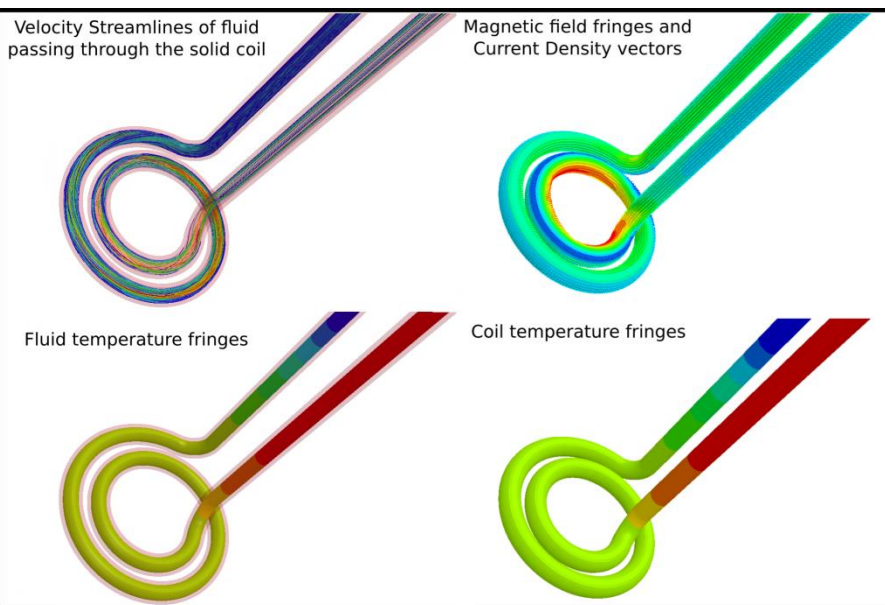
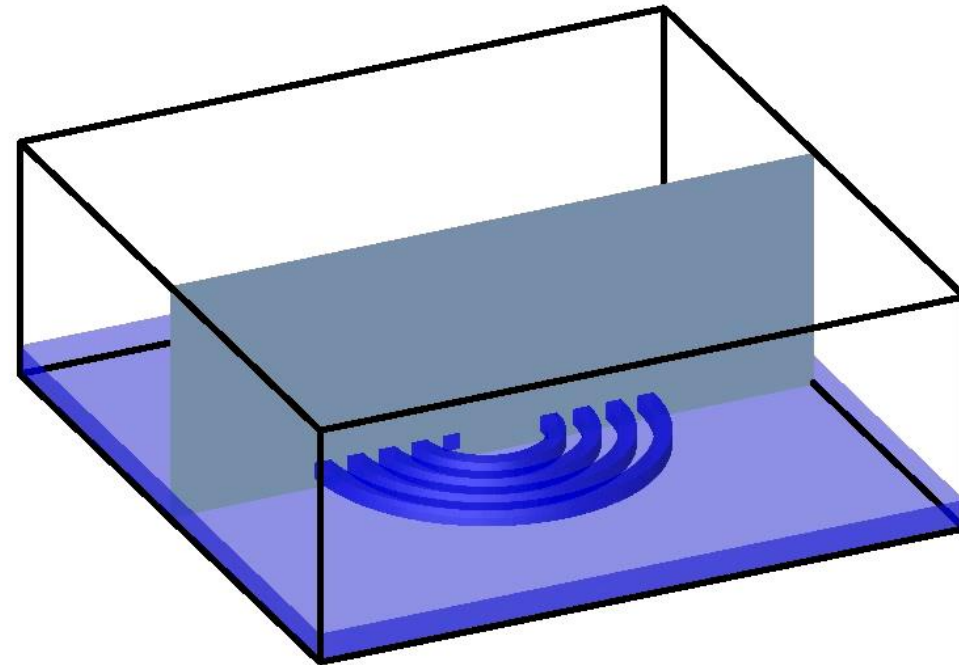


**M. Duhovic, Institut für
Verbundwerkstoffe, Kaiserslautern,
Germany**



Coupled Thermal Fluid and EM problems:

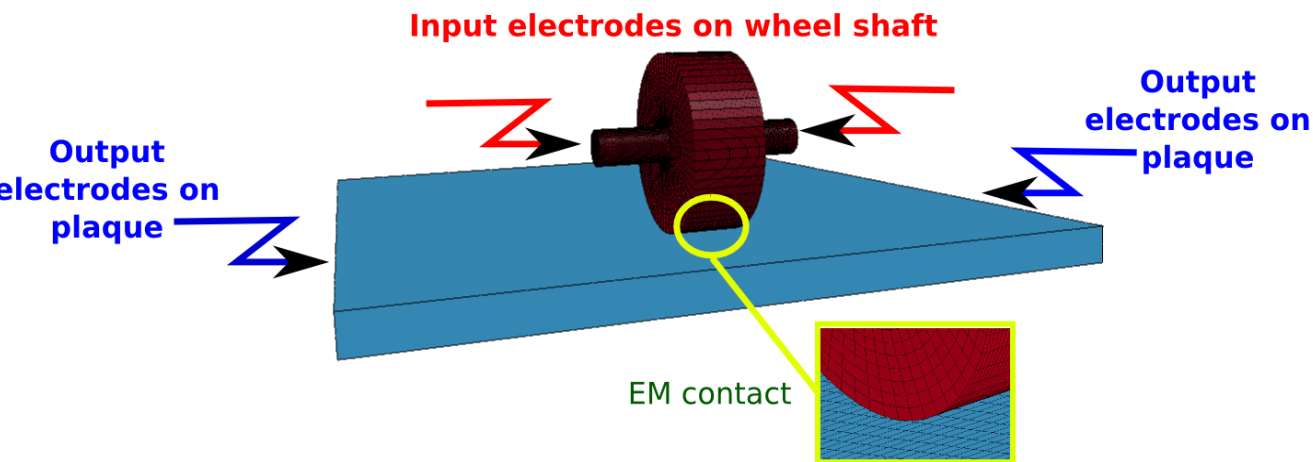
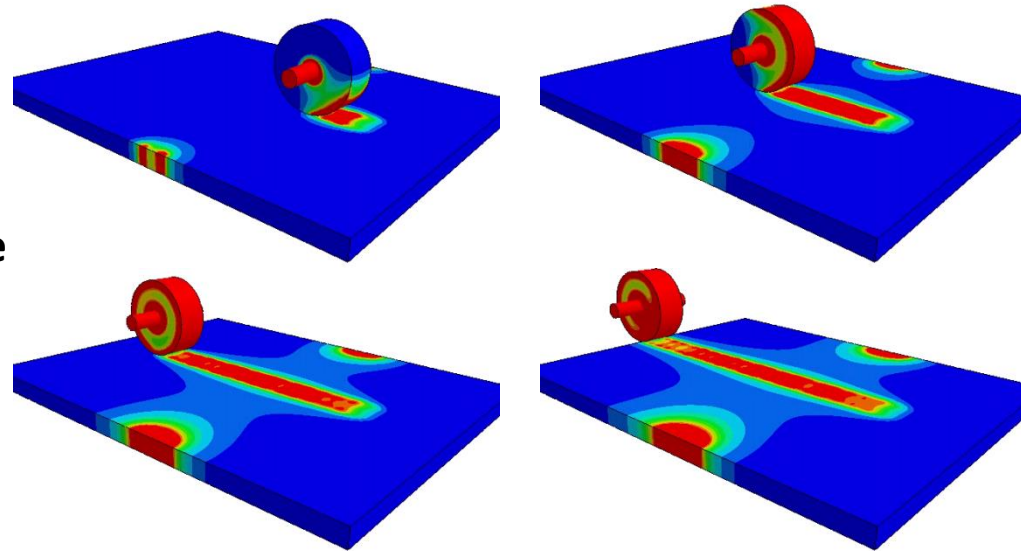
- Coils being heated up due to Joule effect
- The heated coil can be used to warm up a liquid or a coolant can be used to cool them off
- Multiphysics problem involving the EM-ICFD and Solid thermal solvers.



- Courtesy of Miro Duhovic from the Institute for composite materials in Kaiserslautern

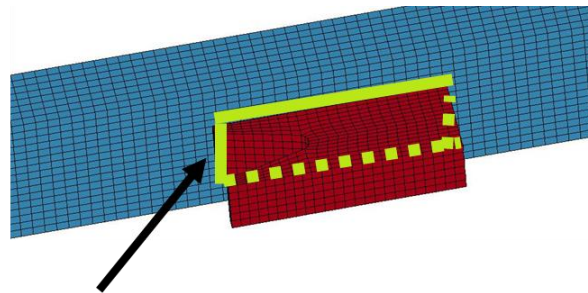
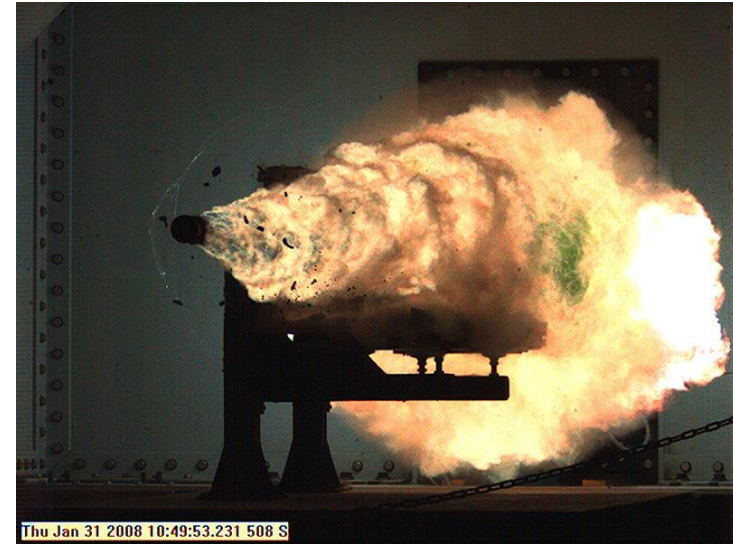
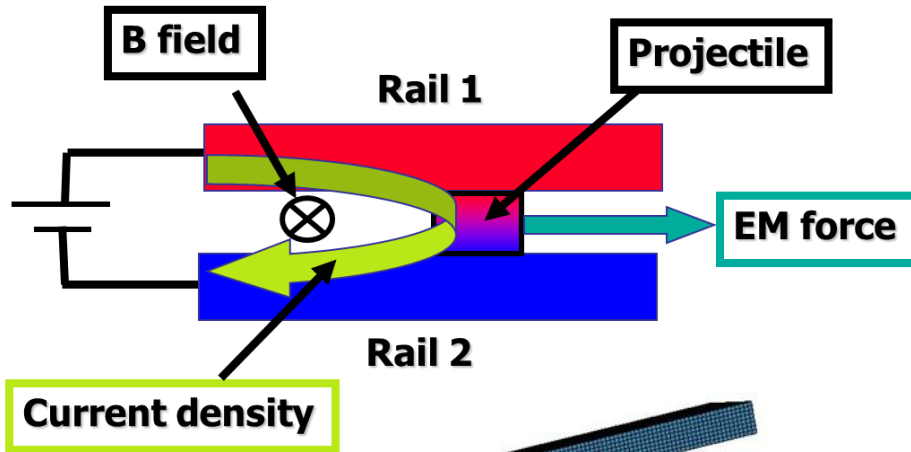
Rotating Wheel moving on a plaque:

- EM resistive heating problem,
- EM contact between wheel and plaque allowing current flow,

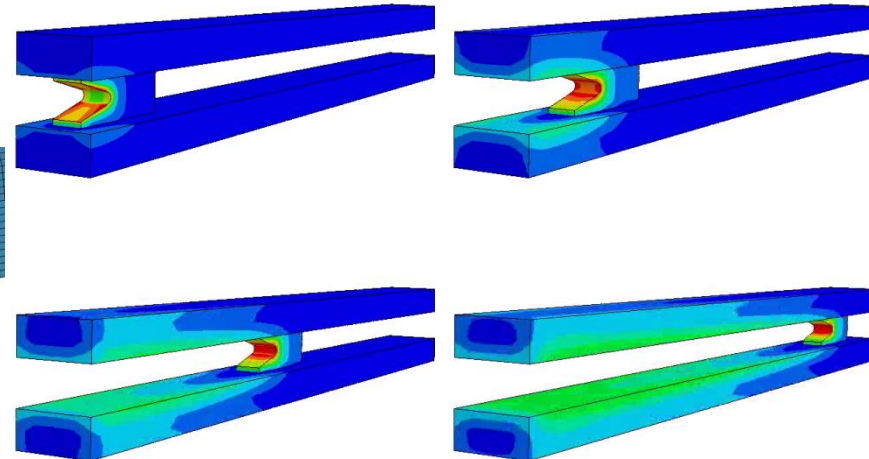


- Current density flow remains constrained to the bottom of the wheel until the wheel leaves the plaque

Rail Gun type simulations



Sliding contact between the rails and the projectile



Solver features

2.1 What are Eddy currents ?

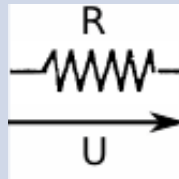
2.2 Inductive heating solver, Resistive heating solver, EM EOS

2.3 The FEMSTER library

2.4 What's new ?

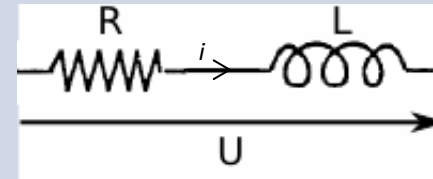
- The Electromagnetic solver focuses on the calculation and resolution of the so-called **Eddy currents** and their effects on conducting pieces.
- Eddy current solvers are also sometimes called **induction-diffusion solvers** in reference to the two combined phenomena that are being solved.
- In Electromechanics, induction is the property of an **alternating of fast rising current** in a conductor to generate or “**induce**” a voltage and a current in both the conductor itself (**self-induction**) and any nearby conductors (**mutual or coupled induction**).
- The self induction in conductors is then responsible for a second phenomenon called **diffusion or skin effect**. The skin effect is the tendency of the fast-changing **current** to gradually **diffuse through the conductor’s thickness** such that the current density is largest near the surface of the conductor (at least during the current’s rise time).
- Solving those two coupled phenomena allows to calculate the electromechanic force called the **Lorentz force** and the **Joule heating energy** which are then used in forming, welding, bending and heating applications among many others.

Basic circuit considerations



$$U = Ri$$

- **Does not consider inductive effects.**
- **No Lorentz force** can be generated but Joule heating can still be calculated.
- This circuit model is only **for very slow rising currents** where inductive effects can be considered infinitely brief.

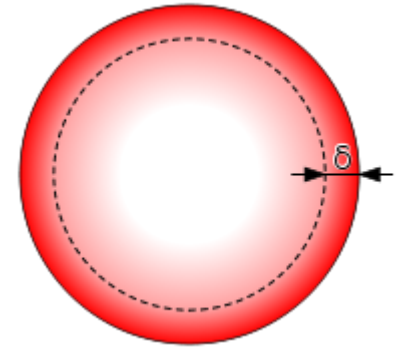


$$U = Ri + L \frac{di}{dt}$$

- **Considers inductive effects** (self inductance term added).
- When approaching other conductors, induced currents and a **Lorentz force** can be generated.
- **Still a crude circuit approximation** that does not take into account the diffusion of the currents (skin effect) and the geometry of the conductors.

- The importance of the skin effect or diffusion of the currents is usually determined by the **skin depth**.
- The skin depth is defined as the depth below the surface of the conductor at which the current density has fallen to $1/e$
- In usual cases, it is well approximated as :

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$



Where f is the frequency of the rising current, μ is the permeability of the conductor ($= \mu_0$, , vacuum permeability for non magnetic materials) and σ its electrical conductivity, all in I.S.U units where $\mu_0 = 4\pi \cdot 10^{-7}$.

- This skin effect is therefore all the more important in cases where the material's **conductivity is high**, or when the **current rising time is very fast** or similarly, in cases where the current's **oscillation frequency is very high**.
- This diffusion can only be modeled in elements with thickness which explains why only solids are solved with the EM solver.

Maxwell equations with Eddy Current approximation

$$\vec{\nabla} \wedge \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

Faraday

$$\vec{\nabla} \wedge \vec{H} = \vec{j} + \epsilon_0 \frac{\partial \vec{E}}{\partial t}$$

Ampere

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \cdot \vec{E} = 0$$

$$\nabla \cdot \vec{j} = 0$$

$$\vec{j} = \sigma \vec{E} + \vec{j}_s$$

Ohm

$$\vec{B} = \mu_0 \vec{H}$$

} Gauss

Mechanics: Extra Lorentz force

$$\rho \frac{D\vec{u}}{Dt} = \nabla \cdot \vec{\sigma} + \vec{f} + \boxed{\vec{j} \wedge \vec{B}}$$

Thermal: Extra Joule heating

$$\frac{D\varepsilon}{Dt} = \vec{\sigma} : \dot{\varepsilon}^{pl} + \frac{Dq}{Dt} + \boxed{\frac{j^2}{\sigma\rho}}$$

EOS: Conductivity vs temperature (and possibly density)

$$\sigma = \sigma(T, \rho)$$

Solver features

2.1 What are Eddy currents ?

2.2 Inductive heating solver, Resistive heating solver, EM EOS

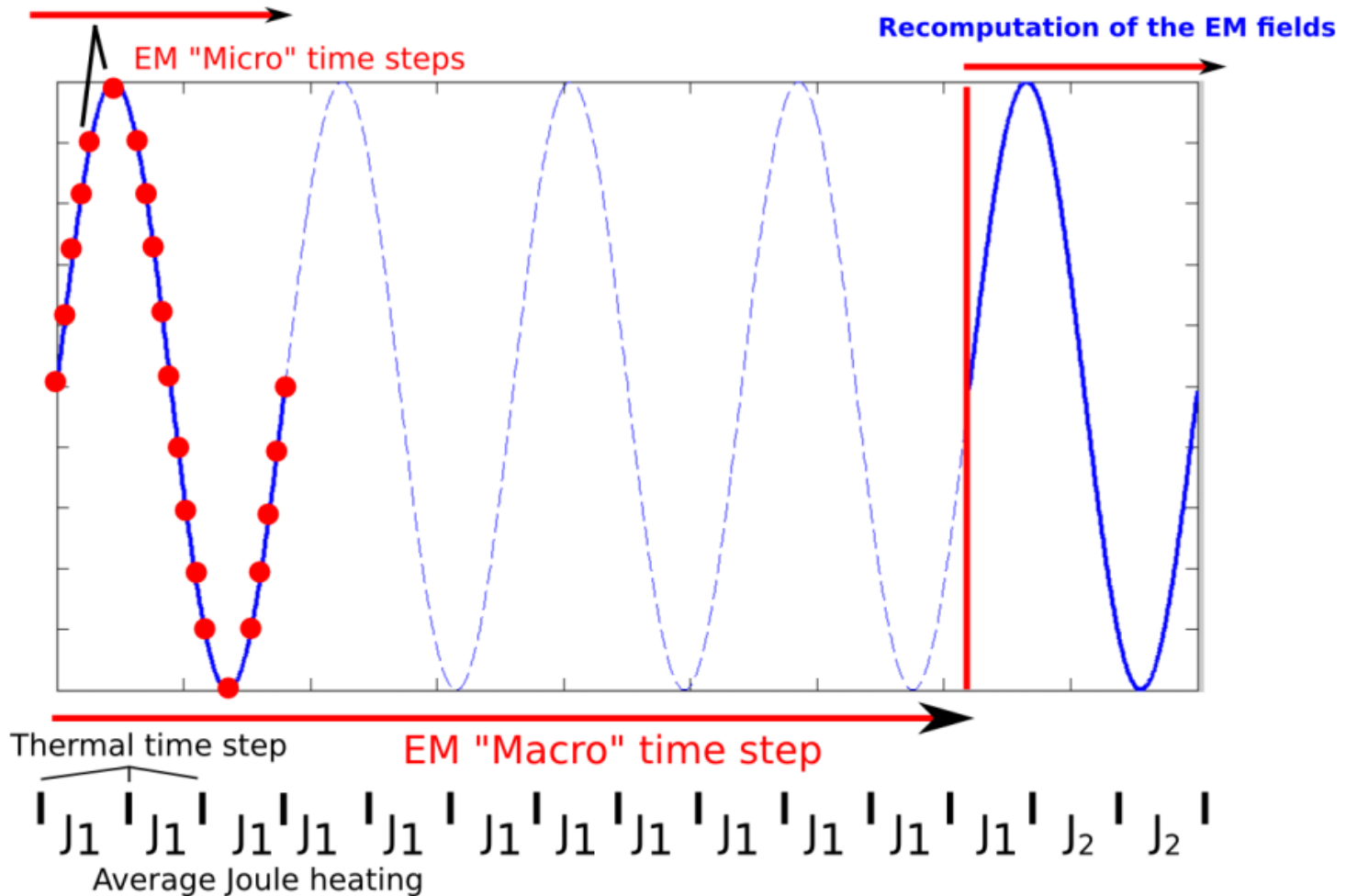
2.3 The FEMSTER library

2.4 What's new ?

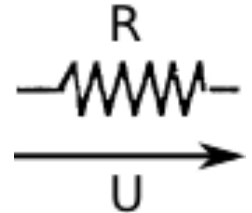
- The default EM solver is the Eddy current solver and allows to solve the induction-diffusion effects over time with any current/tension input shape including periodic oscillatory behavior (sinusoidal current).
- However, it can be guessed that the **calculation costs would rise dramatically** if **more than a few periods were to be calculated** during the whole EM run.
- Unfortunately, in most electromagnetic heating applications, the **coil's current oscillation period is usually very small compared to the total time of the problem** (typically an AC current with a frequency ranging from kHz to MHz and a total time for the process in the order of a few seconds).
- Therefore, using the classic Eddy-Current solver would take too long for such applications.
- It is for these reasons that a new solver called “**Induced heating solver**” was developed.

- The inductive heating solver works the following way :
 - A **full Eddy Current problem** is first solved on **one full period** using a **“micro” EM time step**.
 - An **average of the EM fields and Joule heating energy** during this period is computed.
 - It is then assumed that the **properties of the material** (heat capacity, thermal conductivity as well as electrical conductivity) **do not significantly change** over a certain number of oscillation periods delimited by a **“macro” time step**. In cases where those properties are not temperature dependent (e.g : no EM EOS defined and thus no electrical conductivity depending on temperature) and there is no conductor motion, then the macro time step can be as long as the total time of the run.
 - **No further EM calculation is done over the macro time step** and the Joule heating is simply added to the thermal solver at each thermal time step.
 - **After reaching a “macro” timestep, a new cycle is initiated** with a full Eddy Current resolution.
 - This way, **the solver can efficiently solve inductive heating problems** involving a big amount of current oscillation periods.

- The inductive heating solver works the following way :



- So far, full Eddy current problems have been considered i.e both inductive and diffusive effects were present.
- There also exists a certain kind of **configuration where no induction or diffusion effects occur** (in cases of **very slow rising currents**).
- In such cases, the user is generally mostly interested in calculating the conductors' resistance and **Joule heating**.
- For such applications, it isn't needed to solve the full and costly Eddy Current problem.
- Therefore a so-called "**resistive heating solver**" has been implemented for this special kind of applications.
- Since no BEM is computed, very large time steps can be used which makes this solver very fast.



$$U = Ri$$

- In some cases, for more accuracy, it may be useful to take into account the **influence of the temperature on the material's conductivity**. This is all the more important in cases involving **substantial heating** due to the Joule effect.
- In the EM solver, **several EM equation of state models** exist that allow the user to define the behavior of a **material's conductivity as a function of the temperature** :
 - A Burgess model giving the electrical conductivity as a function of temperature and density. The Burgess model gives the electrical resistivity vs temperature and density for the solid phase, liquid phase and vapor phase. For the moment, only the solid and liquid phases are implemented
 - A Meadon model giving the electrical conductivity as a function of temperature and density. The Meadon model is a simplified Burgess model with the solid phase equations only.
 - A tabulated model allowing the user to enter his own load curve defining the conductivity function of the temperature.
- **Warning** : These EOSs have nothing to do with the EOSs that have to be defined for fluids in compressible CFD solvers (LS-DYNA ALE module, CESE, ...)

Solver features

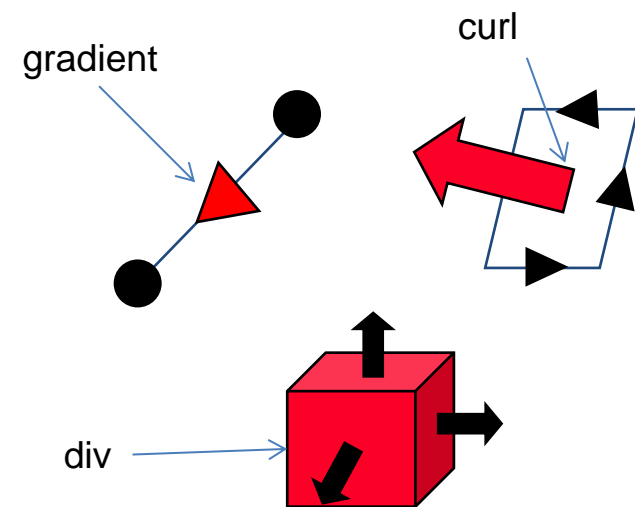
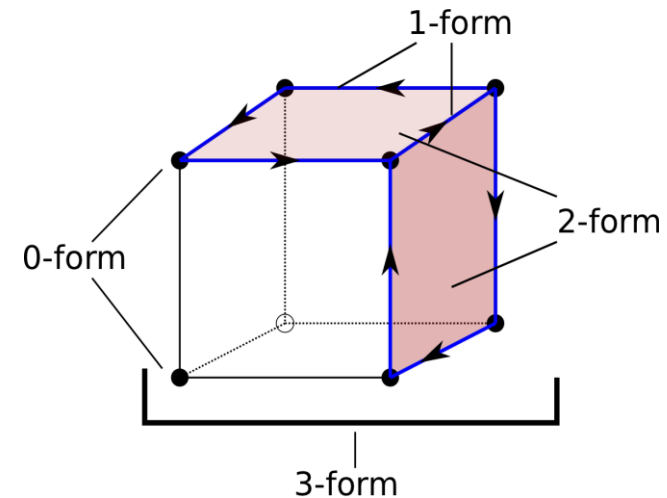
2.1 What are Eddy currents ?

2.2 Inductive heating solver, Resistive heating solver, EM EOS

2.3 The FEMSTER library

2.4 What's new ?

- LS-DYNA uses “**FEMSTER**”, a finite element library based on differential form from LLNL.
- FEMSTER provides:
 - **Higher order basis function** for 0-,1-,2-,and 3-forms (Nedelec Elements).
 - Elemental computation of derivative operator (grad, curl, and div) matrices.
 - Vector calculus identities such as **$\text{curl}(\text{grad}())=0$** or **$\text{div}(\text{curl}())=0$** are **satisfied exactly** (Divergence free conditions, see Gauss equations).
- In short, FEMSTER ensures a very good elemental conservation of the solution.
- Tets and wedges are compatible with the FEMSTER library but hexes are preferred whenever possible (better resolution of the derivative operators).
- The whole electromagnetism analysis in solid conductors (the FEM part) is done using FEMSTER.



	Form type	Associated with	DOFs
0-form φ	Nodes	Nodal value	
1-form \vec{E}	Edges	Line integral	
2-form \vec{B}	Faces	Flux	
3-form $\vec{\nabla} B = 0$	Cells	Volume integral	

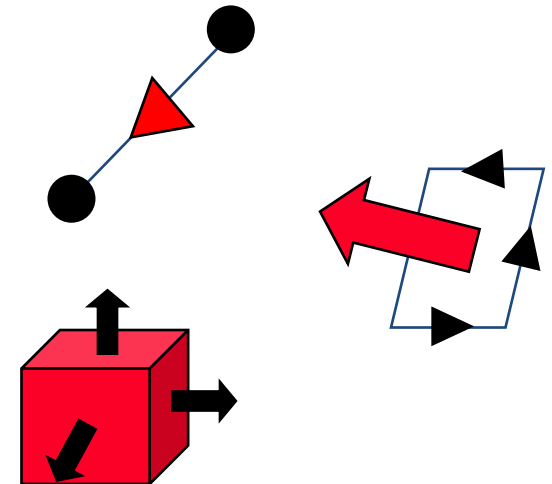
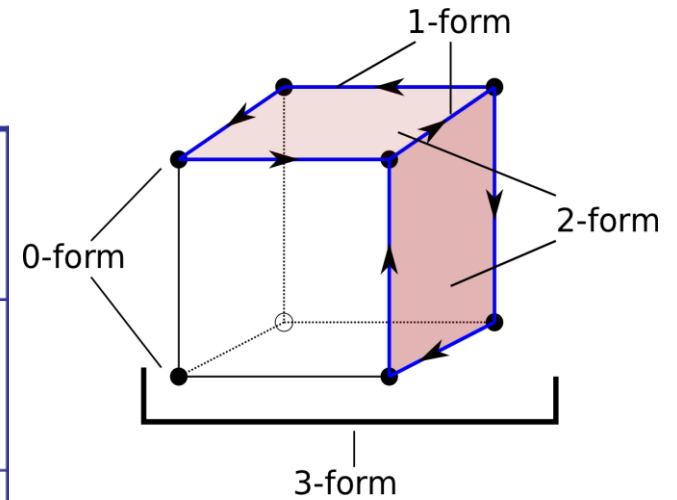
gradient



curl



divergence



Solver features

2.1 What are Eddy currents ?

2.2 Inductive heating solver, Resistive heating solver, EM EOS

2.3 The FEMSTER library

2.4 What's new ?

Application : Composite materials

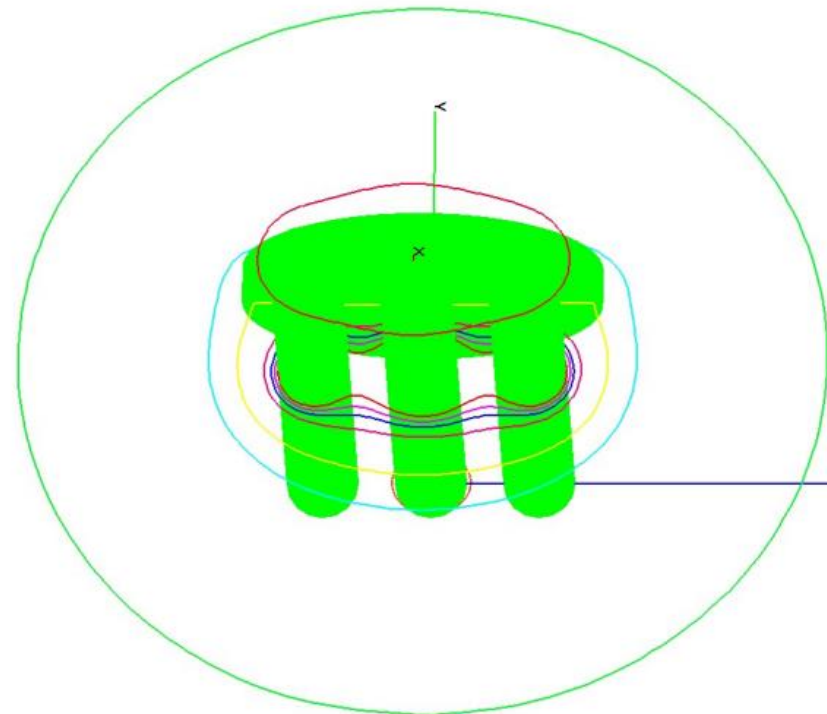
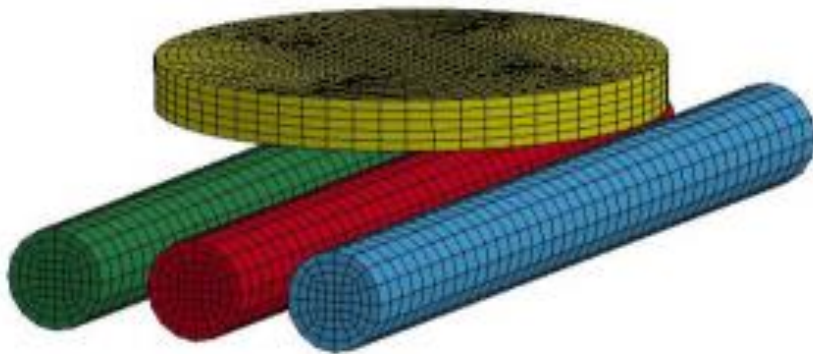
Current development : It is now possible to use orthotropic materials for the EM conductivity.

KEYWORD: *EM_MAT_003

$$\sigma = \begin{matrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{matrix}$$

Application : Magnetic field lines in the air

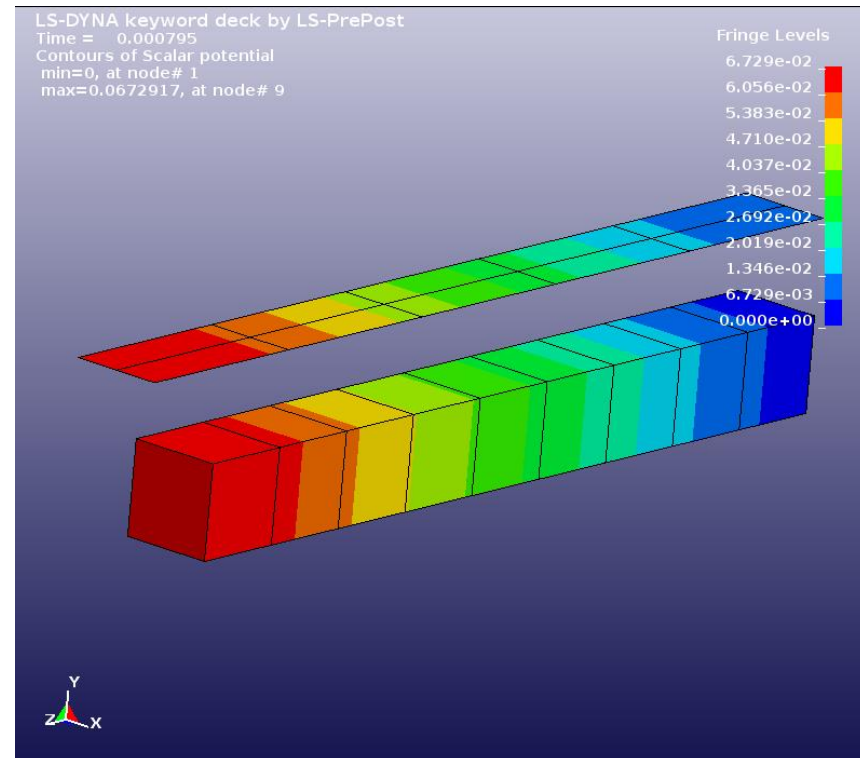
Current development : It is now possible to output magnetic field lines propagating in the air (LSPP post treatment pending).



Application : Conducting Shells in 3D cases.

Current development : Working on adding the option to define shells as conductors in 3D cases.

KEYWORD: *EM_MAT_004



Application : EM contact.

Current development : Added the option to add some resistive heating due to EM contact.

KEYWORD: *EM_CONTACT_RESISTANCE
*EM_CONTACT

Future developments :

- **Piezo-electric materials**
- **Symmetry boundary conditions**
- **Magnetic materials**

Thank you for your attention

Questions ?