LS-DYNA® - Class Notes

LSTC
Livermore Software Technology Corp.

Electromagnetism (EM) Module Presentation

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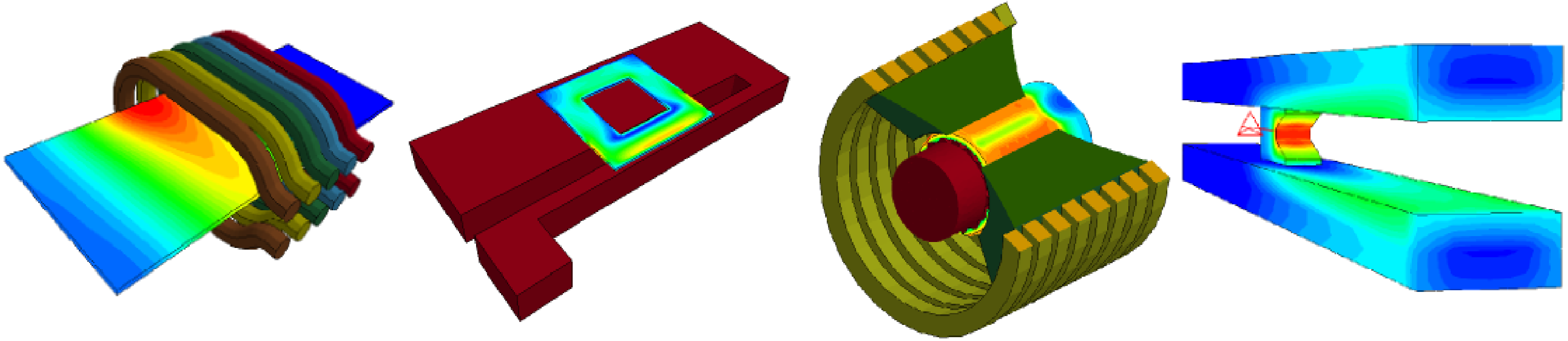

Introduction

1.1 Background

1.2 Main characteristics and features

1.3 Examples of applications

Background

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

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1.2 Main characteristics and features

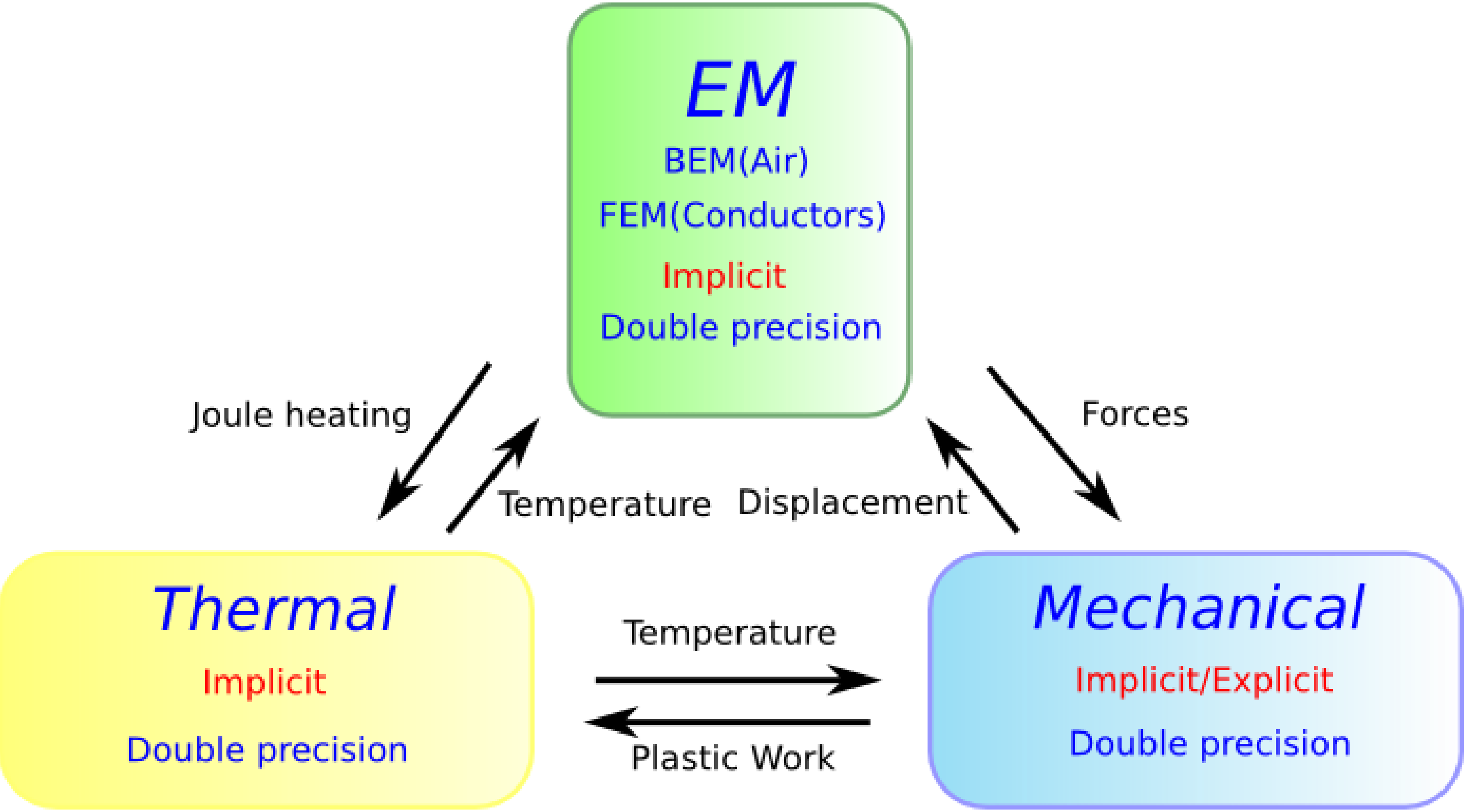
1.3 Examples of applications

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



EM

BEM(Air)

FEM(Conductors)

Implicit

Double precision

Joule heating

Temperature

Displacement

Forces

Thermal

Implicit

Double precision

Temperature

Plastic Work

Mechanical

Implicit/Explicit

Double precision

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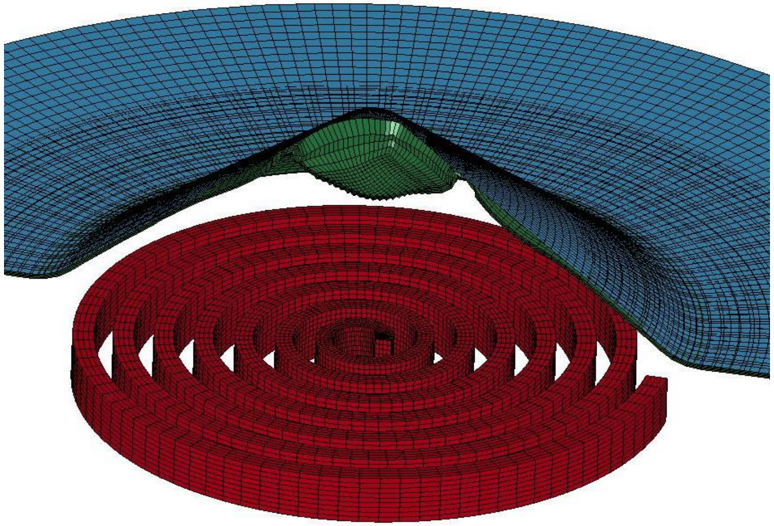
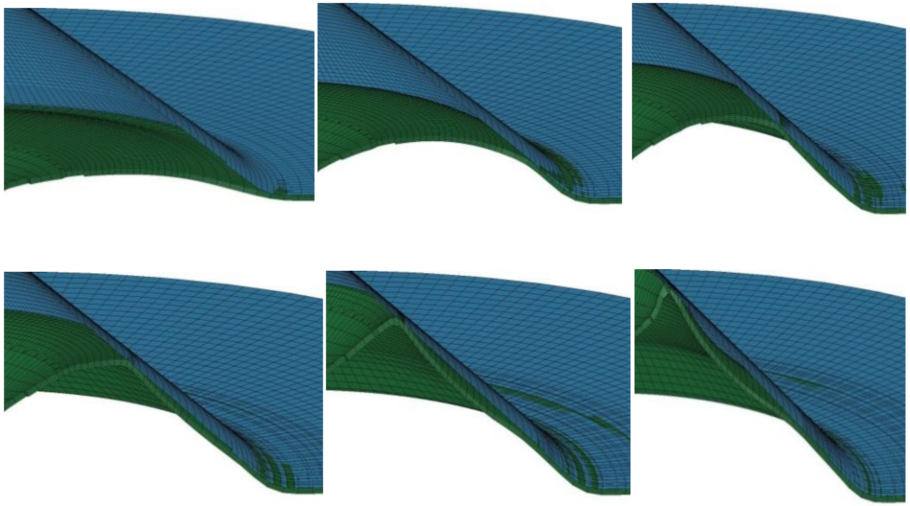
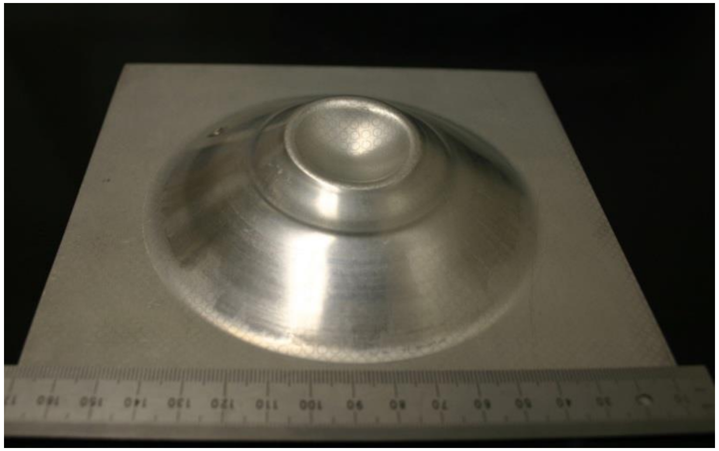
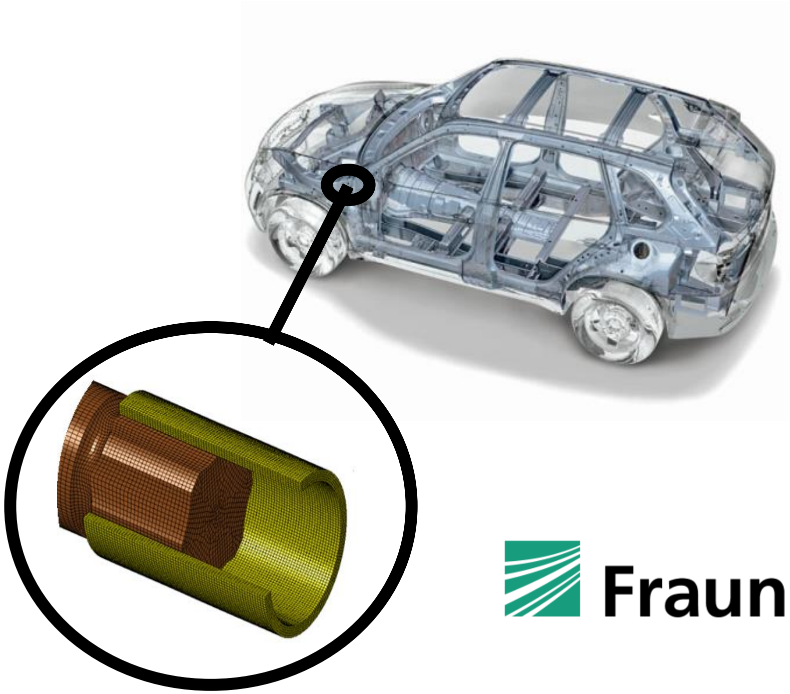


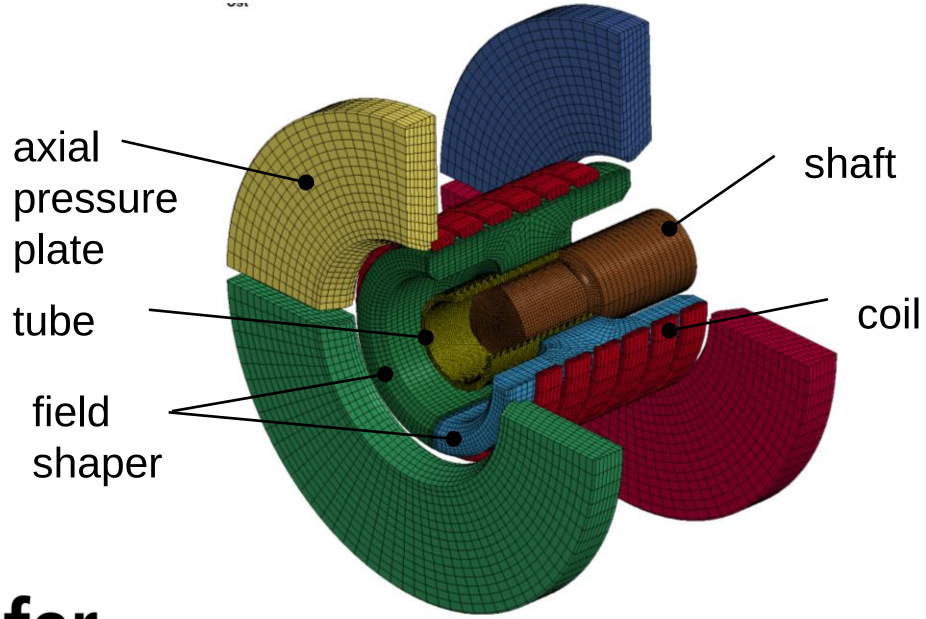


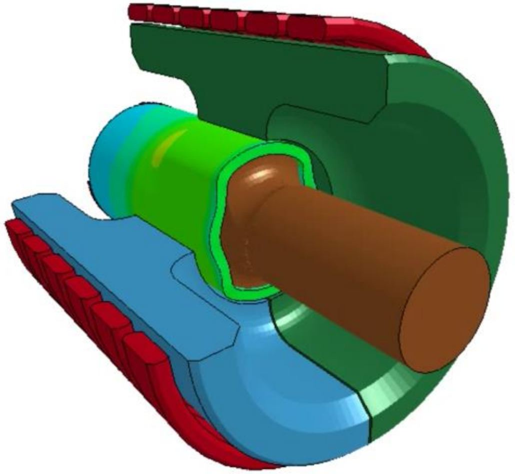
Sheet forming on conical die

In collaboration with:
M. Worswick and J. Imbert
University of Waterloo,
Ontario, Canada



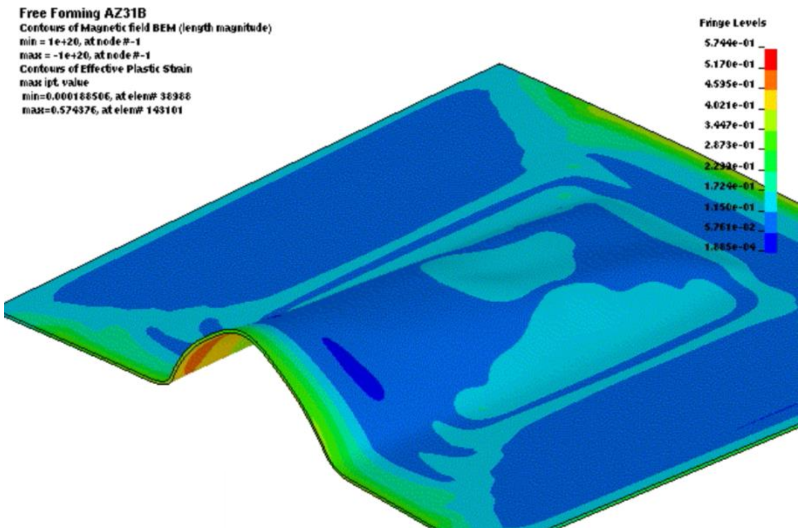


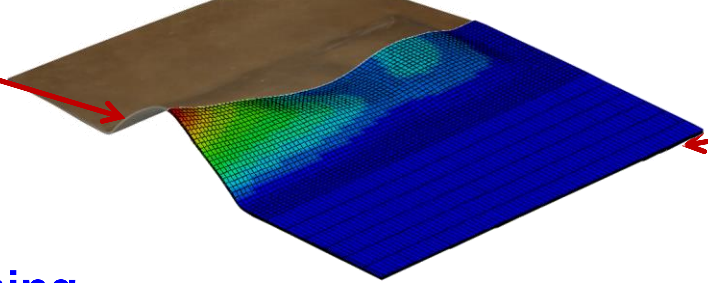




Forming of a tube-shaft joint

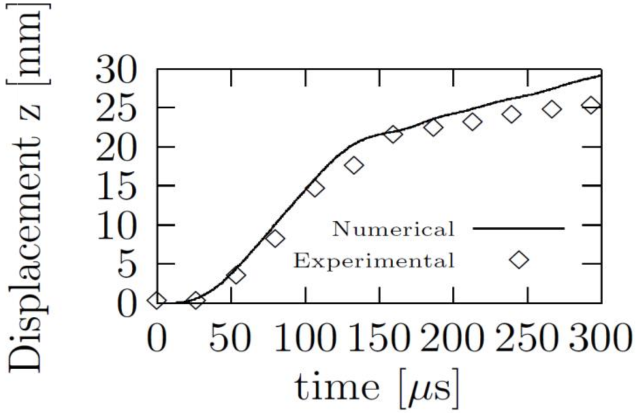
In collaboration with:
Fraunhofer Institute for Machine Tools and Forming Technology IWU, Chemnitz, Dipl.-Ing. Christian Scheffler
Poynting GmbH, Dortmund, Dr.-Ing. Charlotte Beerwald





Experimental result

Numerical result



Magnetic metal forming

In collaboration with:
Ibai Ulacia , University of Mondragon,
Gipuzkoa, Basque country

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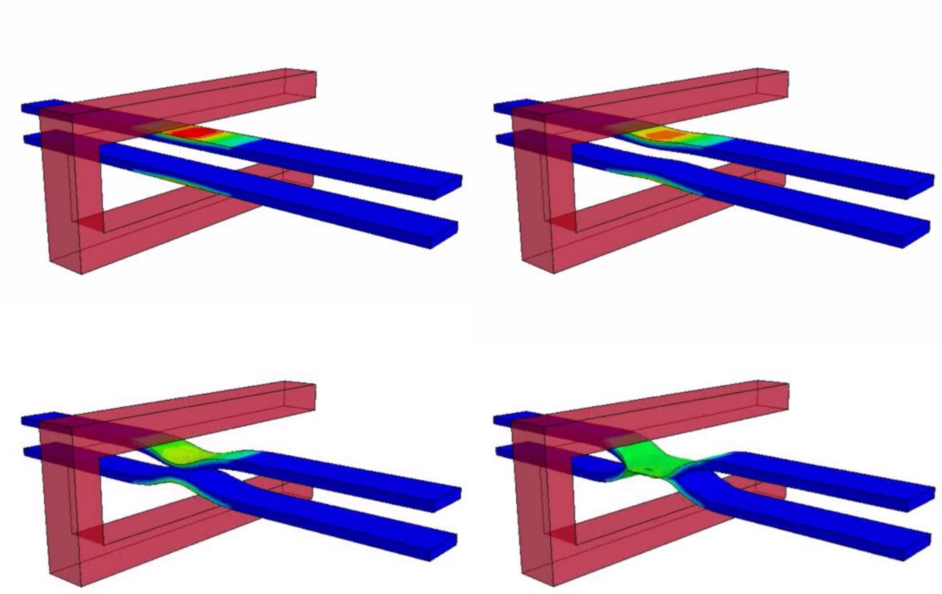
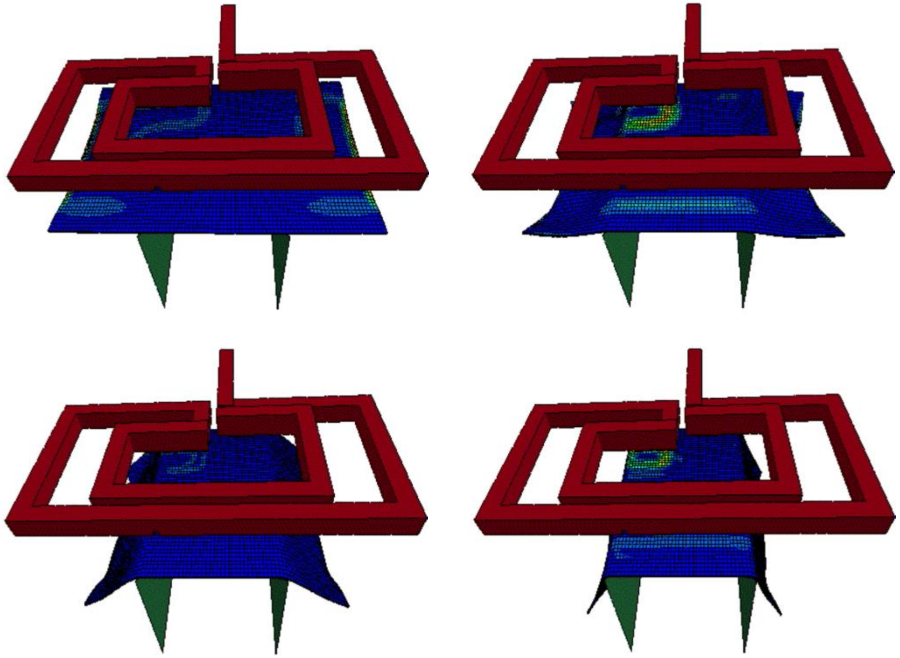
Magnetic metal welding and bending

In collaboration with:
Ibai Ulacia , University of Mondragon,
Gipuzkoa, Basque country , Spain





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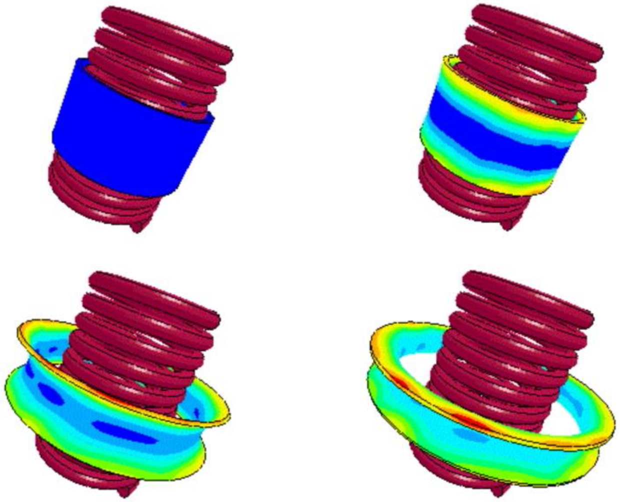
WATERLOO

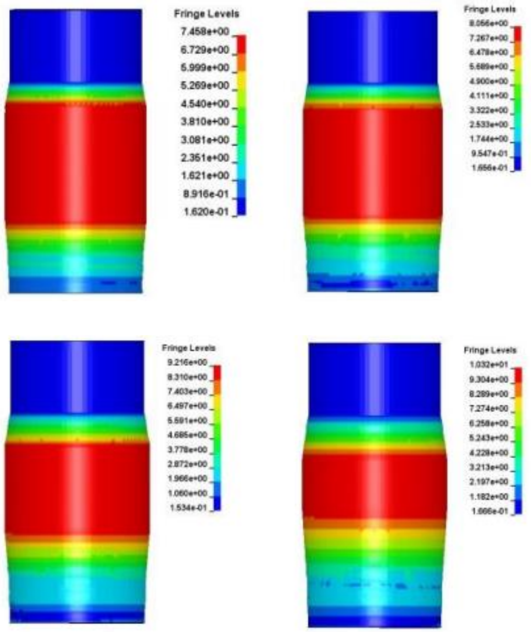
Ring expansions

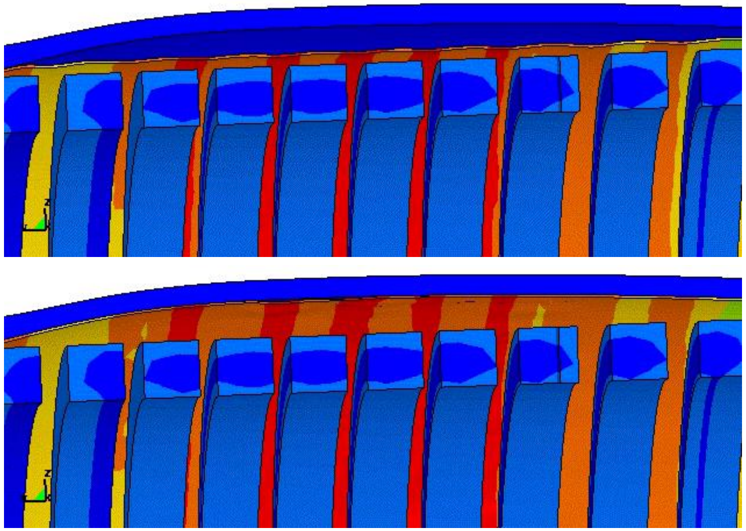
Numerous collaborations with

THE OHIO STATE UNIVERSITY

EWI® We Manufacture Innovation

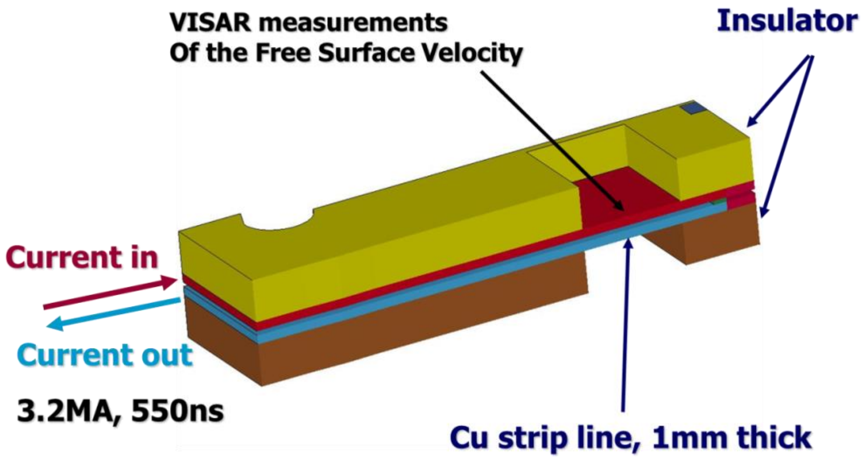




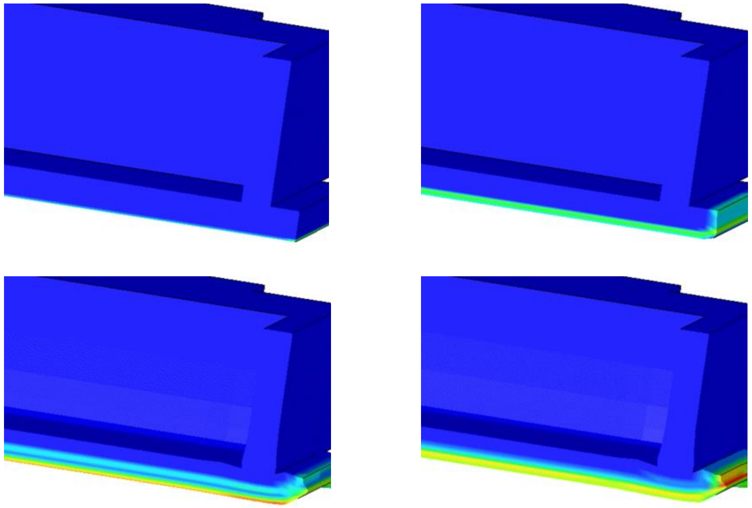


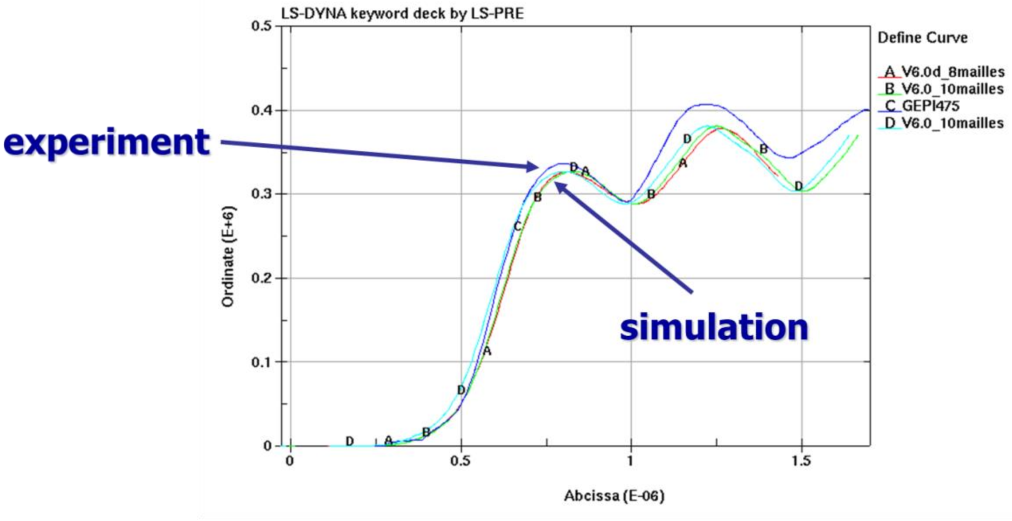
High Pressure Generation

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



111,000 elements, 10 elements through line thickness



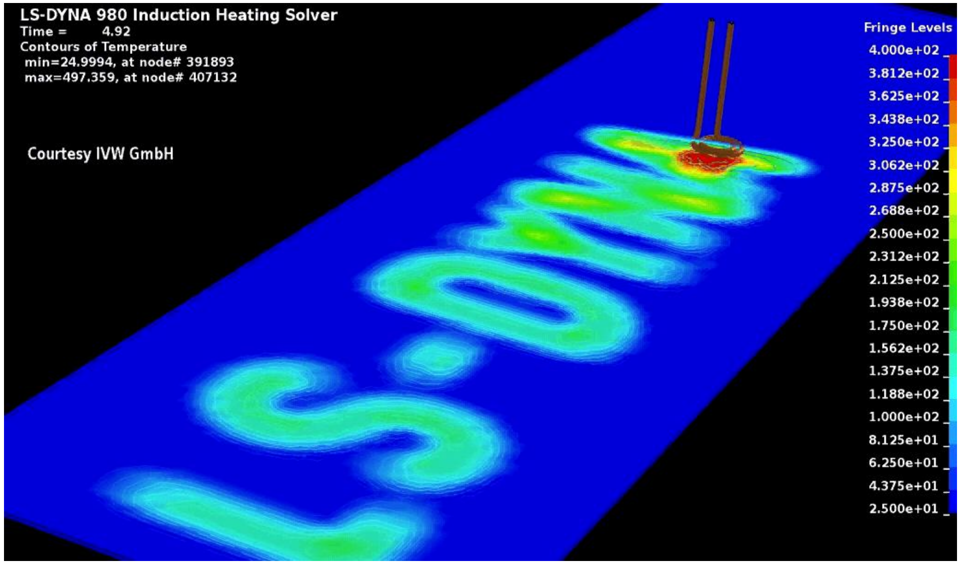


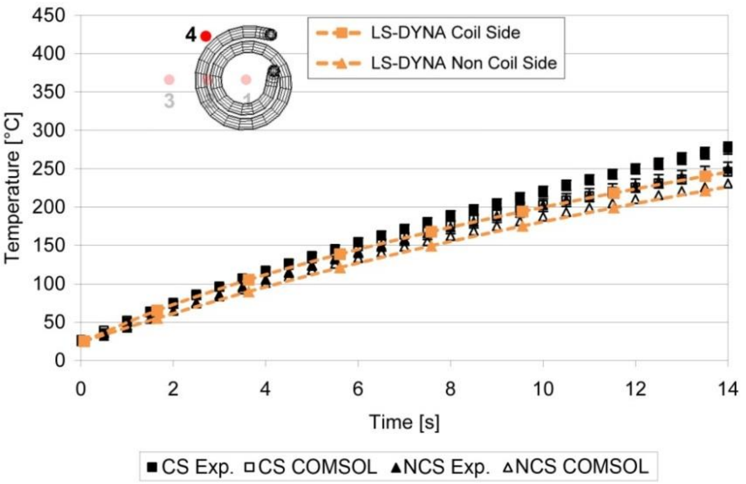
Free surface velocity vs time

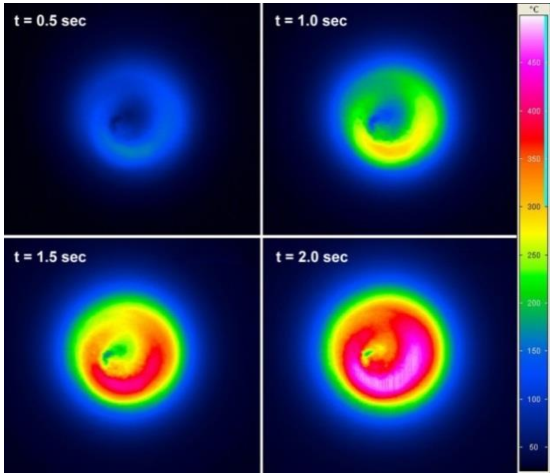
Heading of a steel plate by induction

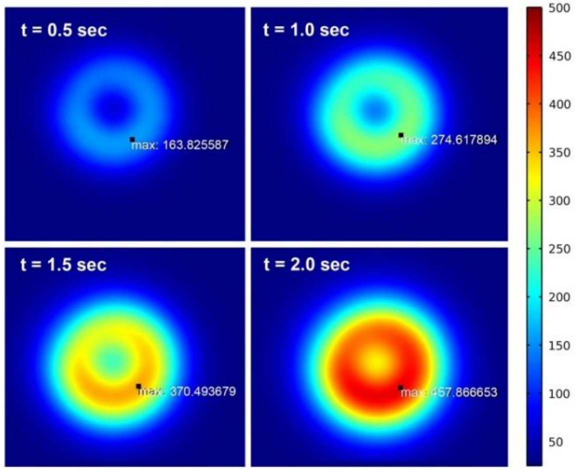
In collaboration with
M. Duhovic,
Institut für Verbundwerkstoffe,
Kaiserslautern, Germany

Institut für Verbundwerkstoffe



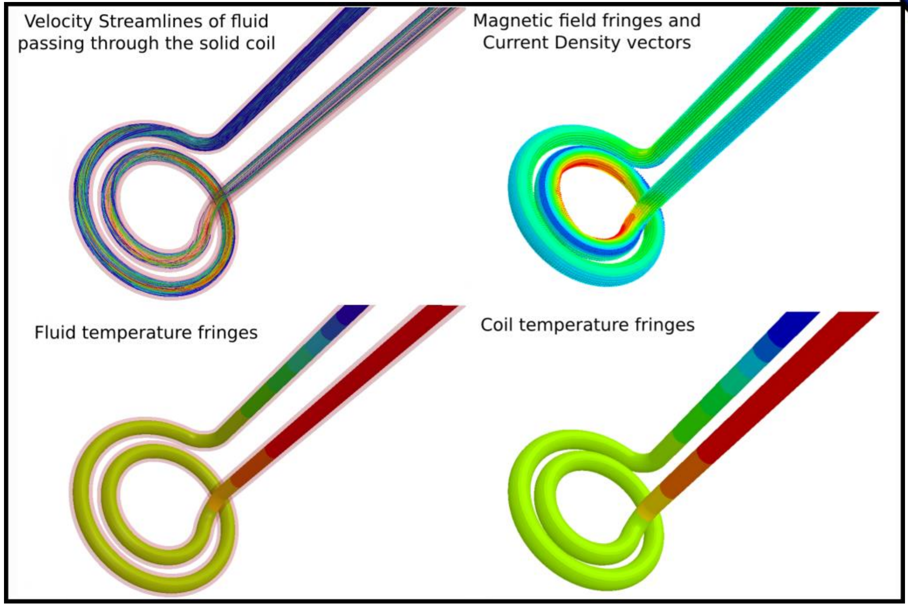


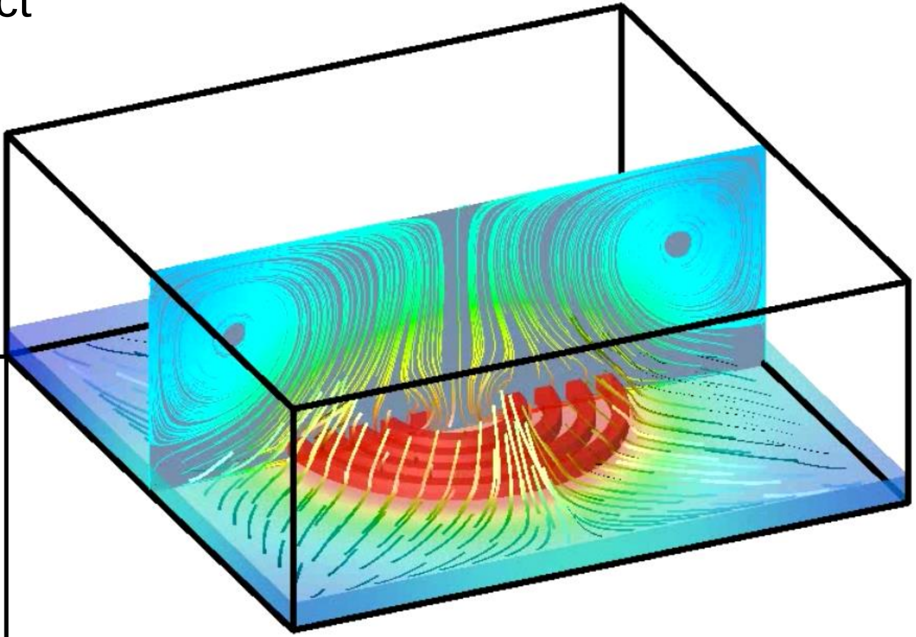




Coupled Thermal Fluid and EM problems

- Coils being heated up due to Joule effect
- Coil can be used heat liquids
- Coolant can be used to cool the coil
- Multiphysics problem involving the EM-ICFD and Solid thermal solvers

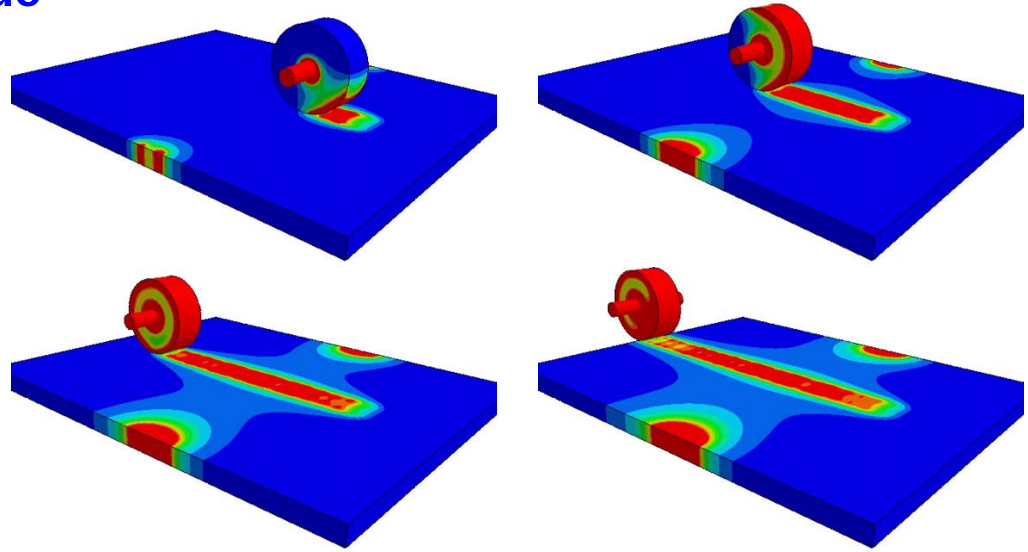


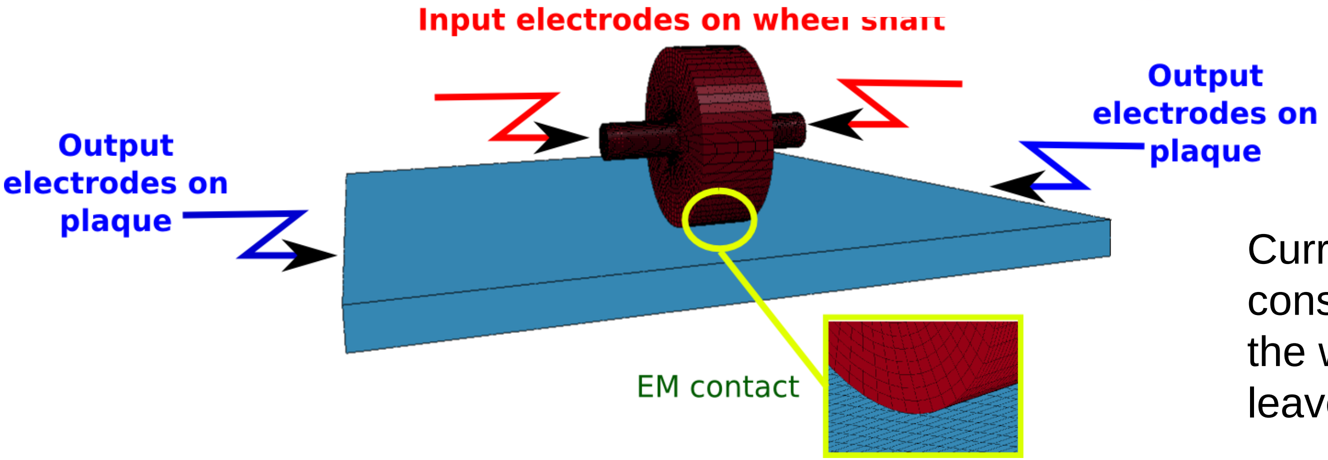


Courtesy of Miro Duhovic,
Institut für Verbundwerkstoffe,
Kaiserslautern, Germany

Rotating Wheel moving on a plaque

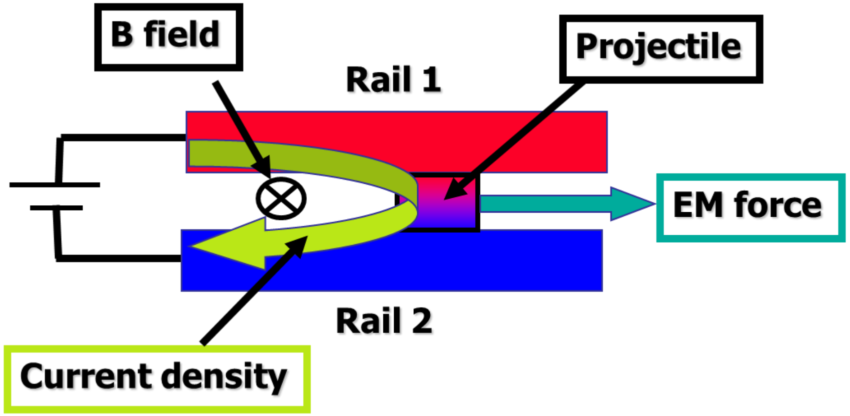
- EM resistive heating problem
- EM contact between wheel and plaque allowing current flow

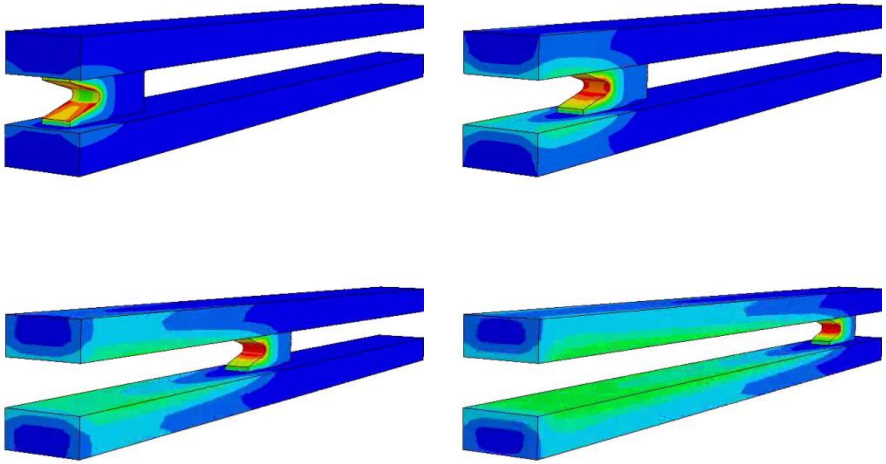


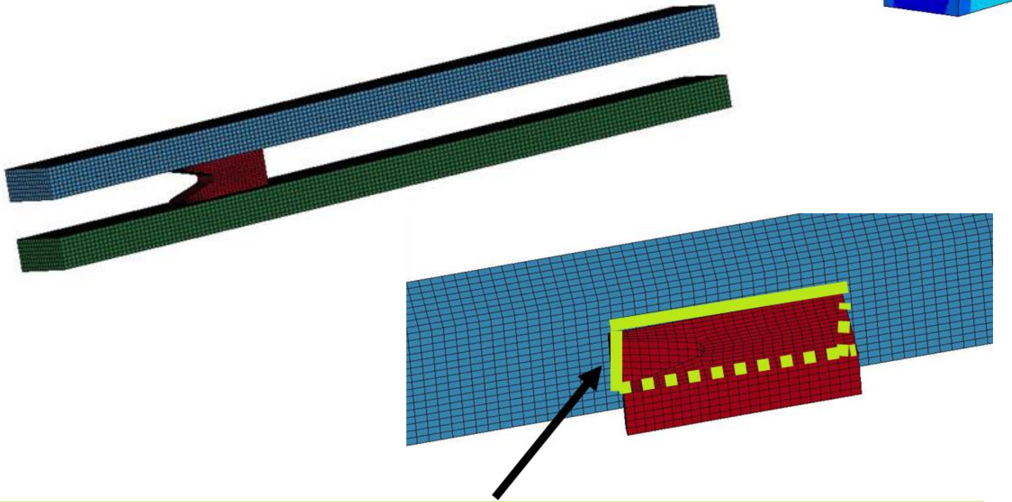


Current density flow remains constrained to the bottom of the wheel until the wheel leaves the plaque

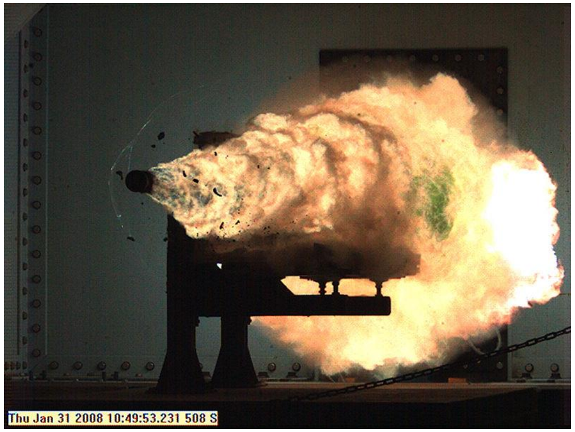
Rail Gun type simulations







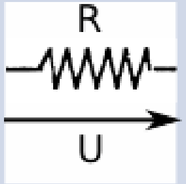
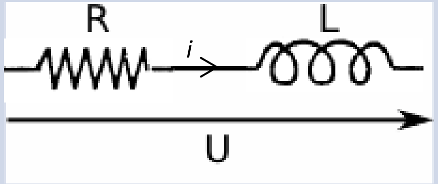
Sliding contact between the rails and the projectile



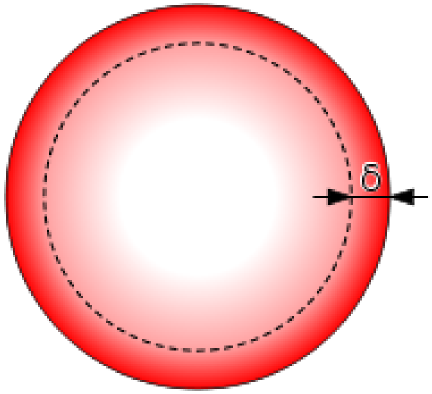
Solver features

- 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

	
$U = Ri$	$U = Ri + L\frac{di}{dt}$
• **Does not consider inductive effects** • **No Lorentz force** can be generated but Joule heating can still be calculated	• **Considers inductive effects** (self inductance term added) • When approaching other conductors, induced currents and a **Lorentz force** can be generated
• This circuit model is only **for very slow rising currents** where inductive effects can be considered infinitely brief	• **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:



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

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

- 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

$$\vec{\nabla} \wedge \vec{H} = \vec{j} + \varepsilon_0 \xcancel{\frac{\partial \vec{E}}{\partial t}}$$

Ampere

$$\left.\begin{array}{l} \nabla \bullet \vec{B} = 0 \\ \nabla \bullet \vec{E} = 0 \\ \nabla \bullet \vec{j} = 0 \end{array}\right\}$$

Gauss

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

Ohm

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

Mechanics: Extra Lorentz force

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

Thermal: Extra Joule heating

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

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 and magnetic material capabilities

2.3 The FEMSTER library

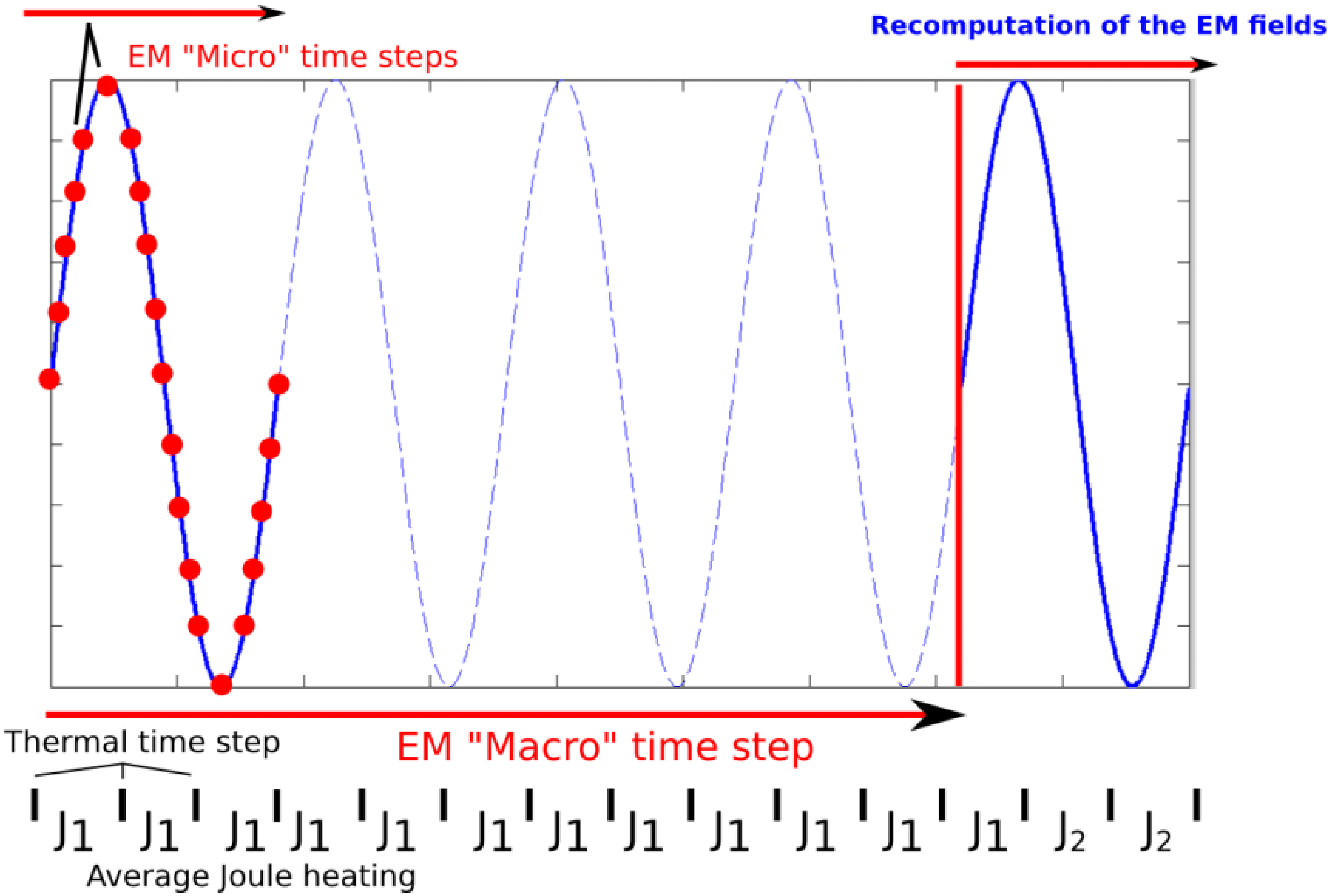
2.4 Future developments

- 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

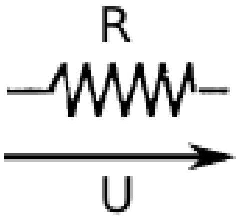
The inductive heating solver works the following way:

- 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** is computed during this period
- 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



$$U = Ri$$

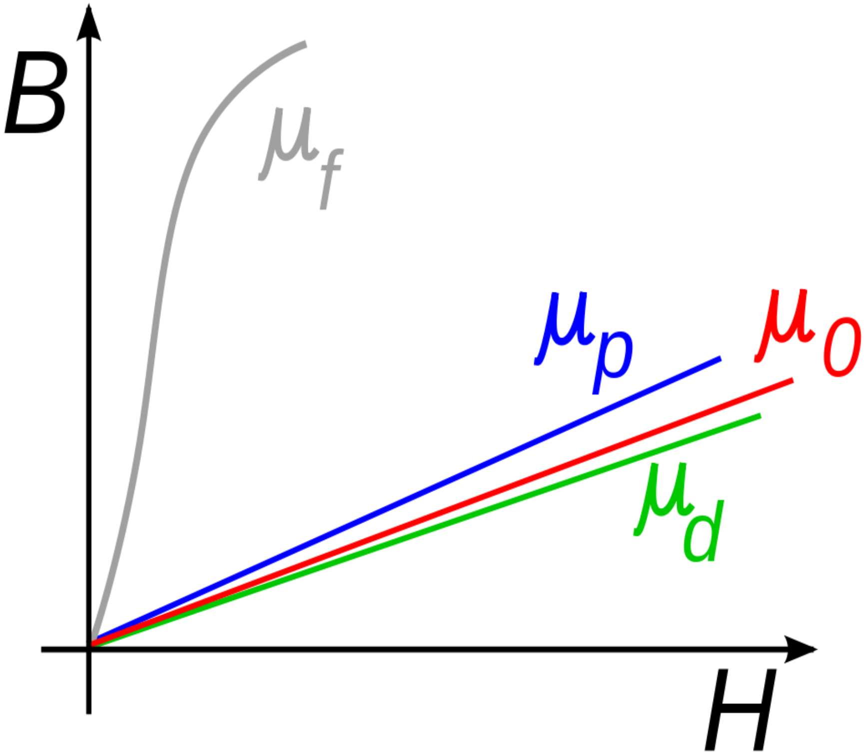
- In some cases, for more accuracy, it may be useful to take into account the **influence of the temperature on the material's conductivity**
- This is all the more important in cases involving **substantial heating** due to the Joule effect
- In the EM solver, **several EM equation of state models** 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 EOS have nothing to do with the EOS that have to be defined for fluids in compressible CFD solvers (LS-DYNA ALE module, CESE, …)

- By default and for the majority of current EM solver applications, conductors were considered non magnetic materials
- This means that their permeability is considered equal to the vacuum permeability ($\mu_0 = \mu_{material}$)
- Certain type of conductors exhibit **magnetization behavior** in response to an applied magnetic field, i.e. **magnetic materials**
- It is **not to be confused with magnets** that are capable of generating their own magnetic field and are a special kind of magnetic materials
- The permeability is expressed as $B = \mu\, H$ where B is the magnetic flux density and H the magnetic field intensity
- For magnetic materials, **$\boldsymbol{\mu}$ is different from the vacuum permeability $\boldsymbol{\mu_0}$**
- It is further possible of dividing magnetic materials into **linear magnetic materials** (μ remains a fixed and constant value over each element) and **nonlinear magnetic** materials (the value of μ depends on B)

It is possible with the EM solver to reproduce the following magnetic materials behavior

- μ_0 for non magnetic materials
- μ_p for **paramagnet** materials (linear, μ remains constant over the elements)
- μ_d for **diamagnet** materials (linear, μ remains constant over the elements)
- μ_f for **ferromagnet** materials (non-linear, μ varies with B over the elements)

μ definition: $B = \mu H$ at each point



Solver features

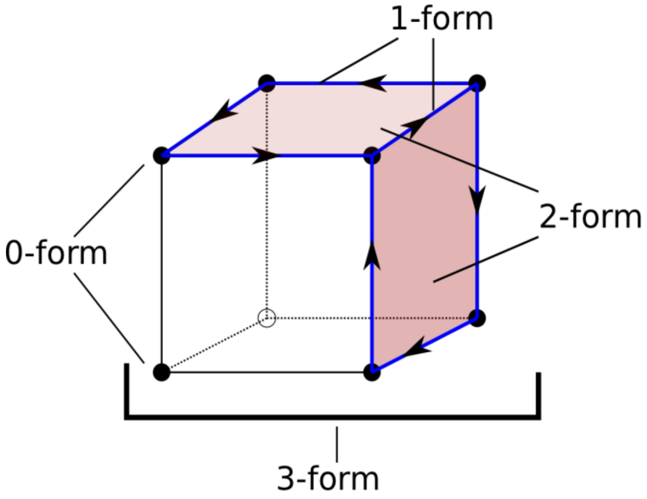
2.1 What are Eddy currents ?

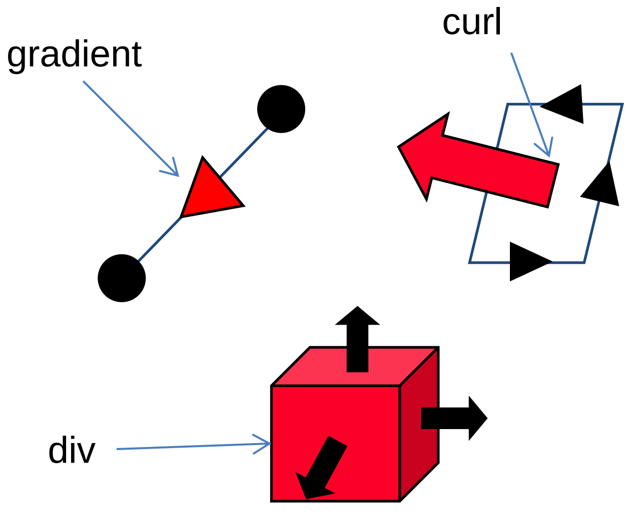
2.2 Inductive heating solver, Resistive heating solver, EM EOS and magnetic material capabilities

2.3 The FEMSTER library

2.4 Future developments

- 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 $\mathbf{curl[grad(\cdot)] = 0}$ or $\mathbf{div[curl(\cdot)] = 0}$ are **satisfied exactly** (Divergence free conditions, see Gauss equations)
- In short, FEMSTER ensures a very good elemental conservation of the solution
- Tetrahedrons 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



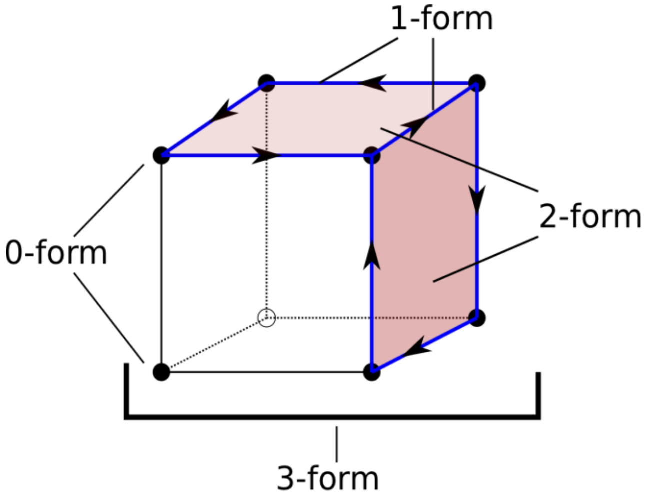


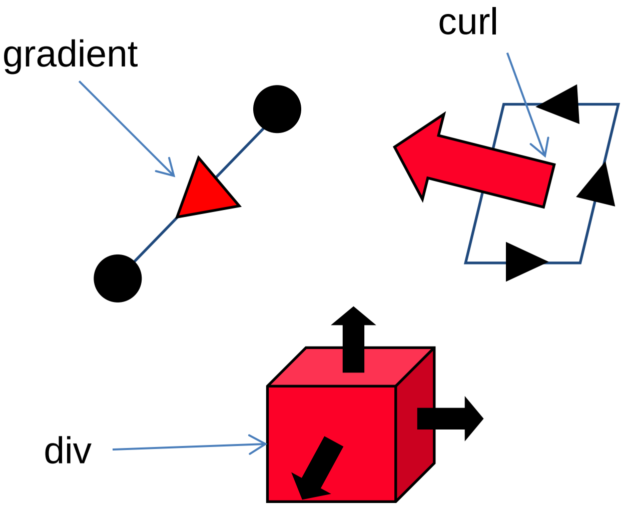
gradient

curl

divergence

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 $\overrightarrow{\nabla B} = 0$	Cells	Volume integral





Solver features

2.1 What are Eddy currents ?

2.2 Inductive heating solver, Resistive heating solver, EM EOS and magnetic material capabilities

2.3 The FEMSTER library

2.4 Future developments

- A new solving method is currently being investigated to solve magnetic material problems faster (This may also apply to Eddy current problems)
- In some cases, this **magnetization process is very fast** compared to the total time of the analysis
- One does therefore not necessary wish to solve the whole transient state but rather directly consider the material as having reached its steady magnetized state
- We are therefore focusing on developing a method which would be capable of applying a magnetostatic state on certain conductors (**magnetostatic solver**)

Thank you for your attention!