

Eddy Current Solver in LS-DYNA

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Introduction : What is the LS-DYNA EM solver ?



/ EM solver terminology

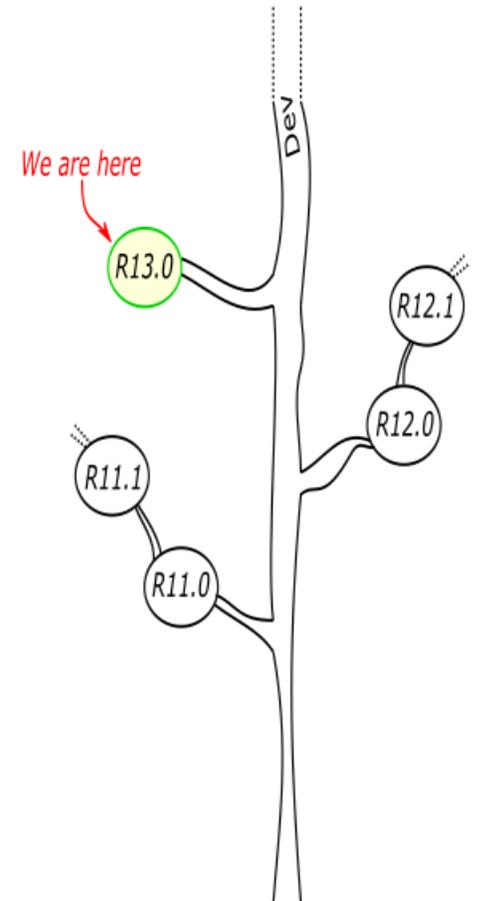
- Electromagnetics capabilities in LS-DYNA are all solvers contained within the 'EM solver' (keywords starting with *EM).
- Several EM solvers are available. They can be broadly divided in two categories : - **Eddy current solvers** and **Resistive solvers**.
- Main feature of Eddy current solvers :
 - FEM-BEM system i.e no air mesh is necessary to model the interaction between conductors.
 - Coupling with structural and thermal solvers is straightforward and data transfer is seamless.
- This makes it a powerful proposition for all applications involving moving or deforming structures including :
 - Magnetic Metal forming, bending and welding
 - Electromagnetic Launchers (Railgun, coilguns)
 - Magnets snapping and magnet interactions
 - Actuators and D.C motors
 - Inductive heating

Executable info and recommendations

- EM solver is available on double precision executables only.
- Available with SMP and MPP executables. Does not scale using the SMP executable => Recommend switching to MPP.
- Dynamic memory handling i.e 'memory=..M' command has not effect on the EM part.
- Examples available on dynaexamples.com. LS-DYNA Multiphysics youtube channel has tutorial videos.
- Avoid R11.0/ R12.0 etc executables. Prefer R11.1, R11.2, R12.1 versions that are often more stable. Look for revision number (d3hsp, messag) to determine correct executable to use.

Warning : the revision number is not enough, and the branch name must be associated to it for e.g R12 revision 120001 and R11 revision 120002 may appear close but be completely different.

- Description of EM keywords available in Vol III of Keyword manual.

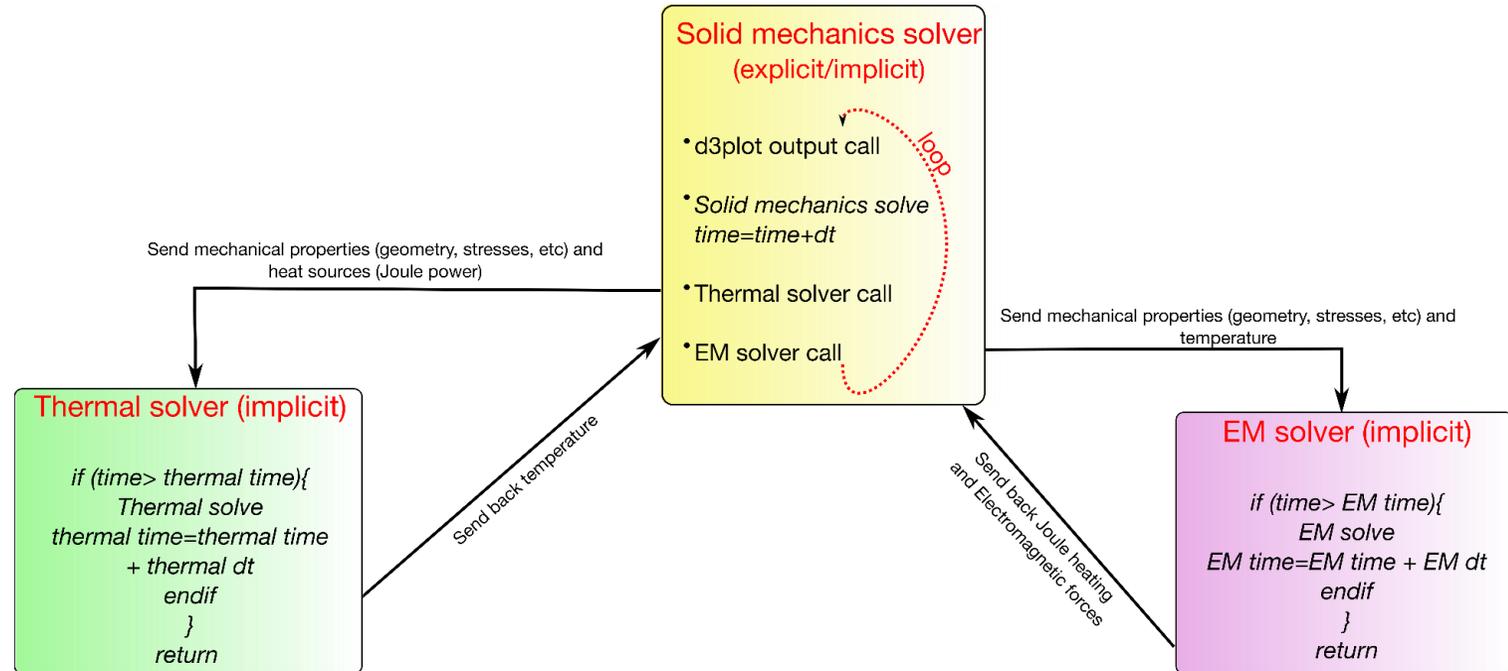


EM solvers evolution (non exhaustive)

Eddy Current solvers		Resistive Solvers	
Transient	Inductive heating	Resistive	Battery module
R11 : Available. Main use in Magnetic metal forming	R11 : Basics	R11 : Available	R11 : N/A
R12 : Improvements on EM contact for Electromagnetic launchers	R12 : Basics	R12 : Addition of 2D-axi solver. Shell/beams/solids can be conductors	R12 : First release
R13 : Addition of magnet simulation capabilities	R13 : Addition of ferromagnets with linear permeabilities (for flux concentrators)	R13 : WIP on coupling with ICFD solver.	R13 : Addition of capabilities based on user feedback
R14 : Magnetostatics enhanced capabilities for actuators and magnet simulations	R14 : Support of non linear B-H curves	R14 : Introduction of Electrophysiology capabilities	R14 : Thermal exothermal reaction model
R15 : Introduction of a frequency based Eddy current solver for inductive heating and other app.	R15 : Support of non linear B-H curves that are temperature dependent	R15 : Introduction of a complex solver for Radiofrequency heating	R15 : Better erosion criteria in solid model

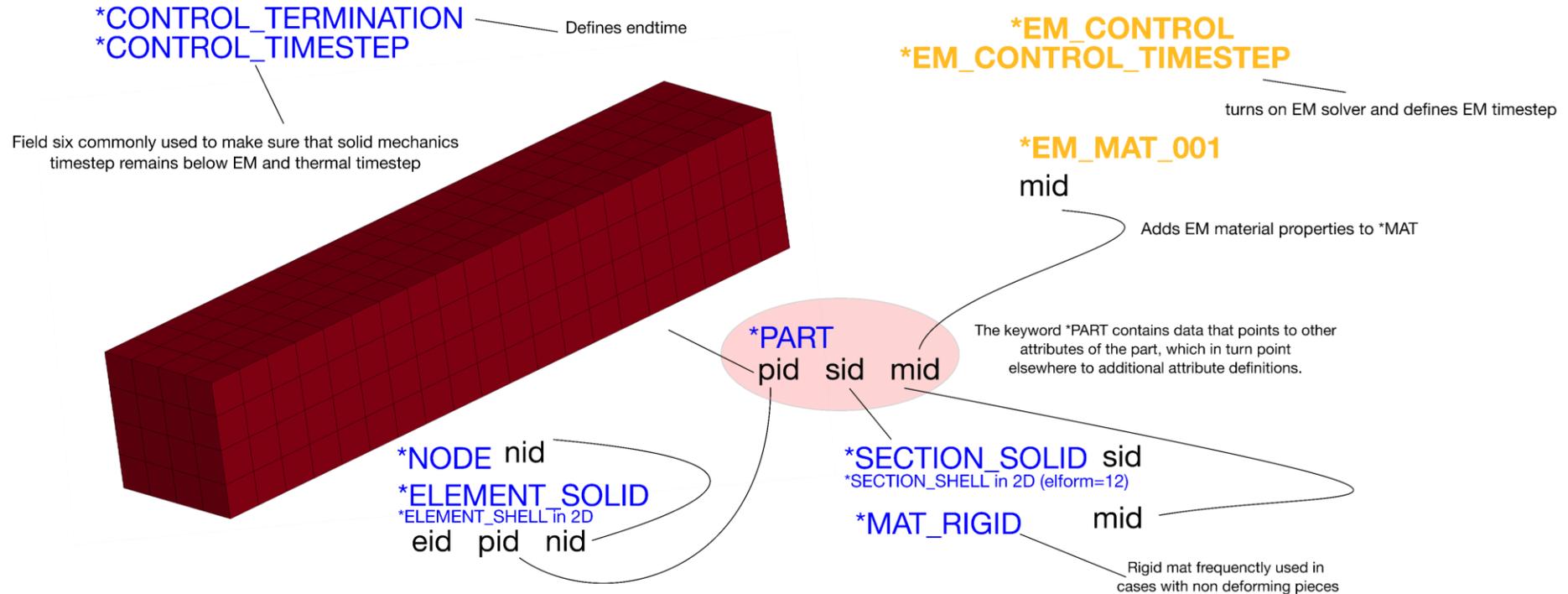
LS-DYNA internal structure

- Solvers such as the EM solver and the thermal solver are integrated in the main LS-DYNA trunk and are called in sequence during the solid mechanics solve.
- Each solver retains its own timestep which must be equal or higher than the solid mechanics timestep.
- The Solid mechanics solver can pass information such as element positions, velocities, deformations and the Electromagnetic solver can feed back forces and/or powers.
- A solid mechanics problem must always be defined before calling the EM solver, even if all parts are rigid.



Basic keyword structure

- Before running any EM problem, it is important to properly define the solid mechanics keywords
- LS-DYNA keyword structure is centered around the concept of “PART”s and “CONTROL” tools that control the various modelling options.
- For an EM problem, the keywords *EM_CONTROL, *EM_CONTROL_TIMESTEP and *EM_MAT will always be present.



The Unit System

- The keyword structure relies on the user to keep unit consistency (certain GUIs that support LS-DYNA's input format can assist the user).
- For the Electromagnetic solver, vacuum permeability is a constant $\mu_0 = 4. \pi e - 7$ that cannot be changed by the user.
- This results in a “shifted” EM unit system where the fundamental S.I unit for electromagnetics, the Ampere, has been replaced by the “Henry/meter”. All EM quantities must therefore be adjusted accordingly.

Example : if meters represent the fundamental distance unit [L], seconds represent the fundamental time unit [T] and kilograms represent the fundamental mass unit [M], then if we define Henry/m as [U], current can be expressed as :

$$\text{Ampere} = [M]^{0.5} [L]^{0.5} [T]^{-1} [U]^{-0.5}$$

and voltage as :

$$\text{Voltage} = [M]^{0.5} [L]^{1.5} [T]^{-2} [U]^{0.5}$$

- In practice, this shifted unit system simplifies the input. With a constant permeability (and therefore constant [U]) , all EM quantities can be expressed as combinations of mass, distance and time without having a “fourth” unit to adjust.

The Unit System

- The table below can be used as guidance. It works the following way. Once a unit system has been chosen, multiply the input quantities by the inverse of the table values, and then multiply the solver outputs by the table values to recover S.I (kg/m/s) results.

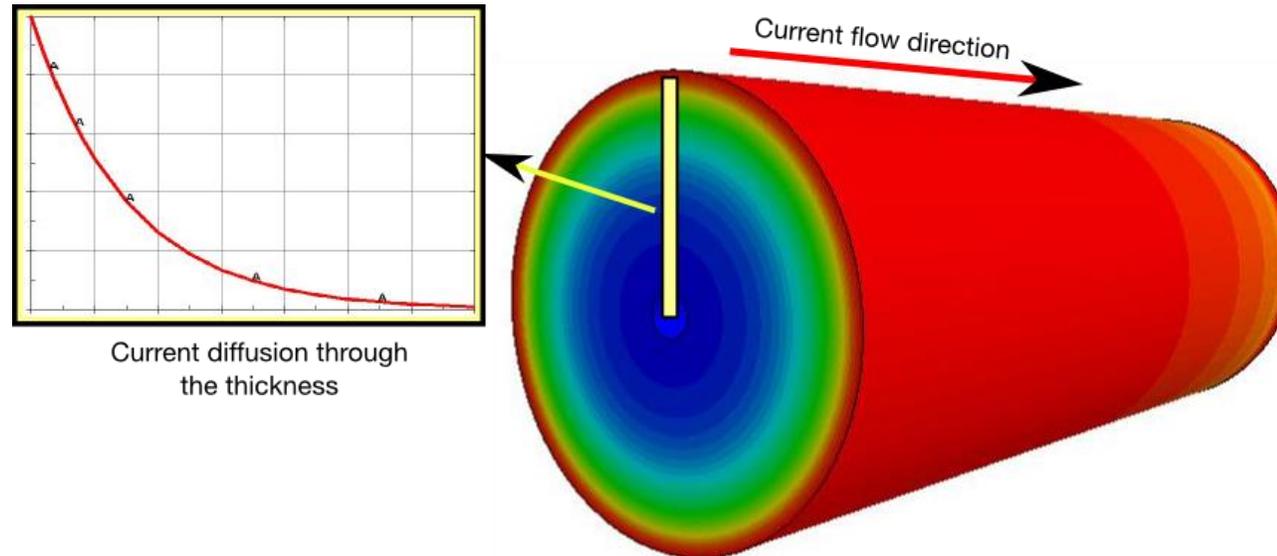
Quantities	Units	g/mm/s	g/mm/ms	Tons/mm/s
Energy	Joule (J)	1.e-9	1.e-3	1.e-3
Force	Newton (N)	1.e-6	1.	1.
Pressure/Stress	Pascal (Pa)	1.	1.e6	1.e6
Conductivity	Siemens (S)	1.e6	1.e3	1.e6
Current	Ampere (A)	1.e-3	1.	1.
Voltage	Volts (V)	1.e-6	1.	1.e-3
Inductance	Henry (H)	1.e-3	1.e-3	1.e-3
Resistance	Ohm (Ω)	1.e-3	1.	1.e-3
Magnetic flux (B)	Tesla (T)	1.	1.e3	1.e3
Capacity	Faraday (F)	1.e3	1.e-3	1.e3
Charge	Coulomb (C)	1.e-3	1.e-3	1.

Introduction : Principles of Eddy Currents and EM solver



Eddy currents

- Eddy currents is a term used to characterize electromagnetic phenomena occurring under certain conditions.
- An alternating or fast rising current source will generate a magnetic field in its surrounding environment that can induce currents in nearby conductors and also cause the diffusion of this current in the surrounding conductors as well as in itself. This combination is referred as “inductive diffusive effects”.
- When current diffuses through the thickness of a conductor, it follows an exponential law : $\frac{J}{J_{surf}} = e^{-\frac{y}{\delta}}$.



Eddy currents

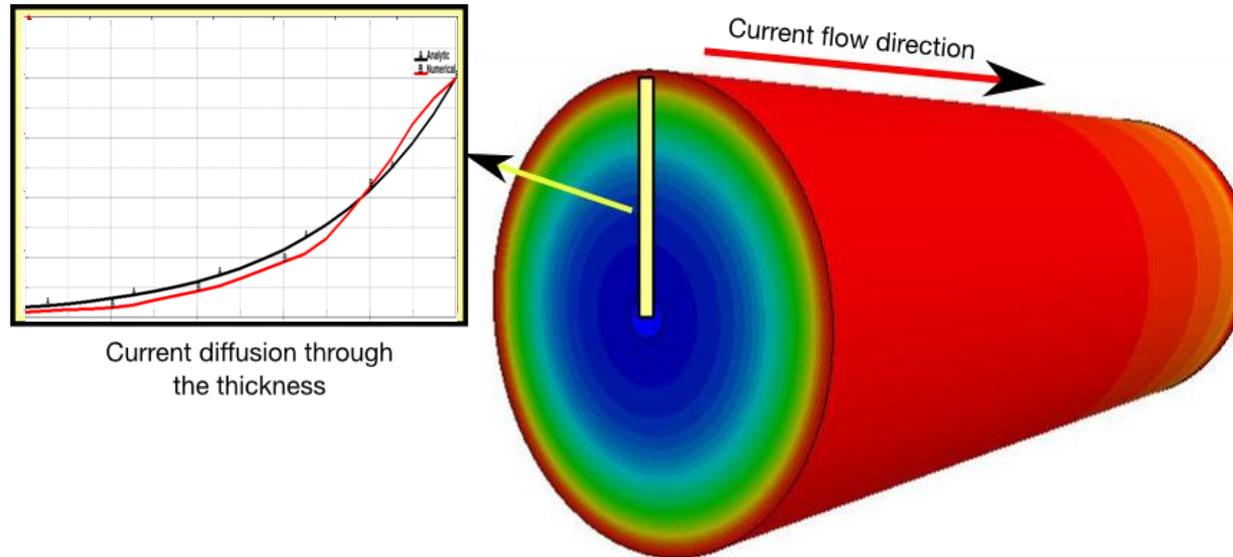
- For diffusive effects to be noticeable, the total thickness of the conductor must be bigger than the decay rate δ called skin depth => Fundamental rule of Eddy currents.

- The value of the decay rate a.k.a skin depth is usually well approximated by :
$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

f : current frequency (or rising time)
 μ : permeability
 σ : conductivity

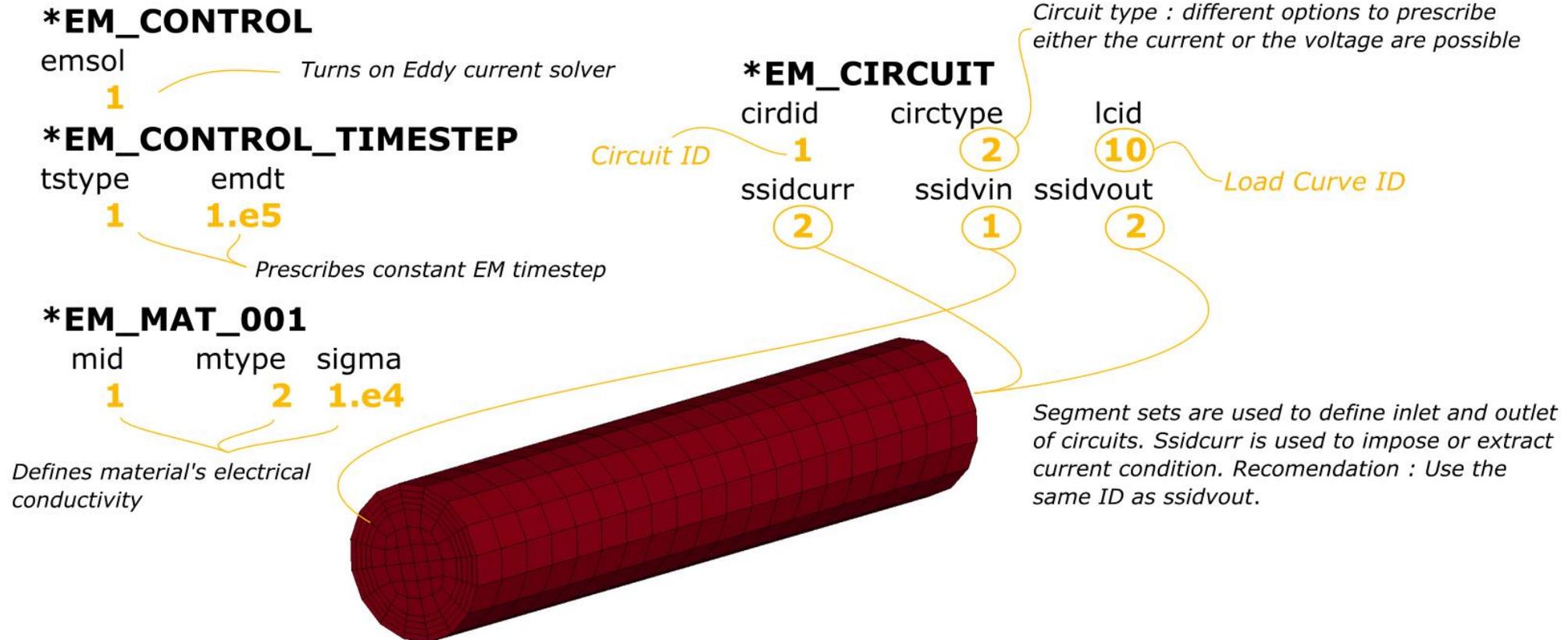


In order to capture this current diffusion, it is mandatory to have a mesh which is fine enough. Generally, it is recommended to have at least three elements in the first layer δ closest to the conductors' surface.



Case Study – Basic Input deck

Conducting Rod with source current

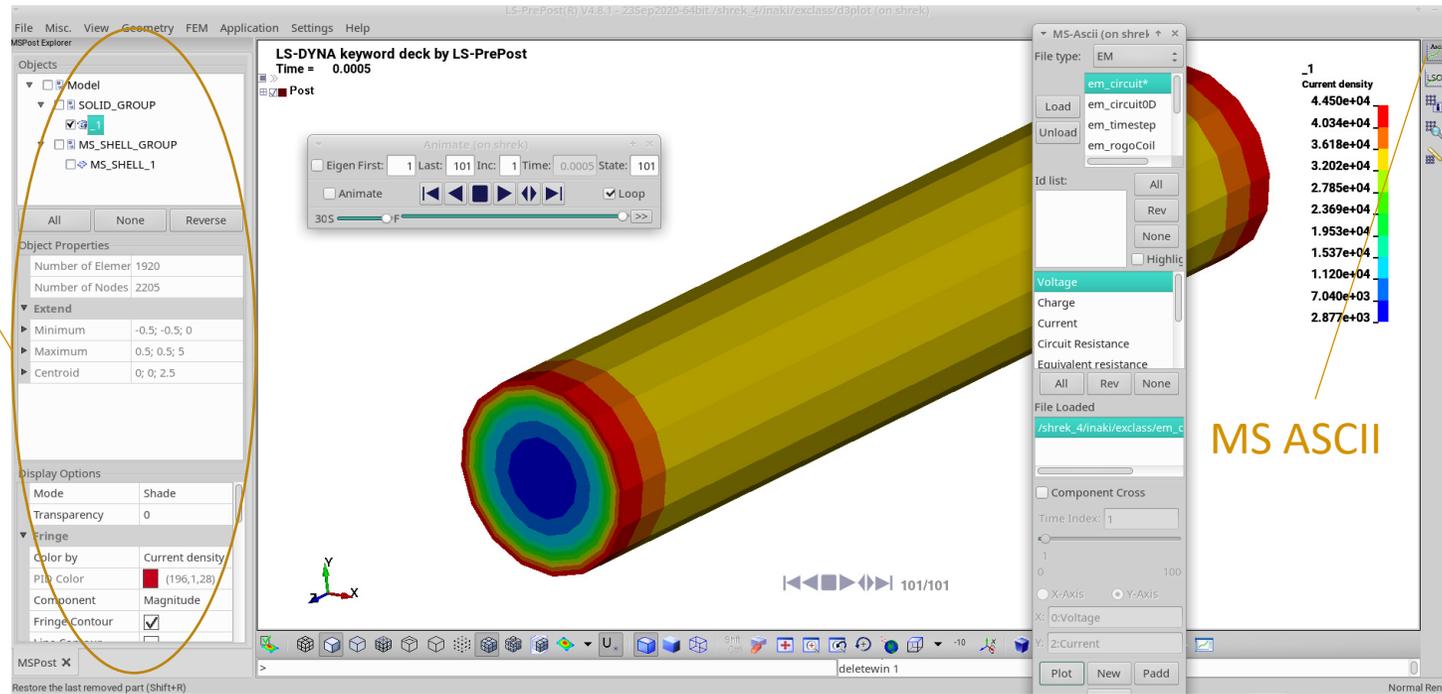


Case Study - post

Conducting Rod with source current

- Use the MS GUI and MS ASCII Icon to extract EM quantities and plot results associated to circuits
- Take a look at the circuit resistance and compare it to Ohm's law. In your opinion, why is the result not the same (answer : because Eddy currents are present i.e current density is not a constant) ?
- Notice the MS_Shell part ? This is the internal Boundary Element Mesh the solver has automatically built.
- Use the right click on Part 1 to create section planes, vectors, streamlines and extract data on nodes/points.

MS Post GUI



MS ASCII

/ Imposing voltage/current

- The imposition of a source voltage or source current is done via the introduction of the EM_CIRCUIT keyword.
- Imposing a voltage requires to solve an additional equation on the scalar potential (With Dirichlet conditions applied at the boundaries, SIDIN and SIDOUT).
- Imposing a current implies defining a segment set (See SIDCURR in EM_CIRCUIT) where a global current condition will be applied by adding a Dirichlet constraint to the BEM system (SIDIN and SIDOUT are simply removed from the BEM mesh).
- When defining a EM_CIRCUIT, the definition of SIDCURR also allows to retrieve additional output quantities in *em_circuit.dat*.
- SIDCURR can be defined as any segment set through which the entirety of the current will flow. For convenience reasons, SIDCURR is often defined as equal to SIDOUT but consequently, boundary effects can be present in the output quantities provided by *em_circuit.dat*.

/ Imposing voltage/current

EM Circuit data time,	Voltage,	Charge,	Current,	ResistD,	ResistJ,	Induct,	Mutual1,	Muti
0.10000000E-04	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.29587592E-02	0.00000000E+00	
0.20000000E-04	0.38455211E+00	0.00000000E+00	0.62831750E+00	0.00000000E+00	0.61203469E+00	0.29587592E-02	0.00000000E+00	
0.30000000E-04	0.16452816E+01	0.00000000E+00	0.12566288E+01	0.00000000E+00	0.13092821E+01	0.29587592E-02	0.00000000E+00	

ResistD : Computed by solving a Laplace equation $S(\sigma) = 0$ with Dirichlet conditions $\varphi = 1$ and $\varphi = 0$ on SIDIN and SIDOUT. Current is retrieved by integrating $\vec{j} = -\sigma \nabla \varphi$ over SIDCURR. Ohm's law is applied to retrieve ResistD.

The output of ResistD corresponds to Pouillet's law for the Resistance : $R = \frac{L}{\sigma A}$. It does not consider Eddy current/skin depth effects.

This output is only calculated when the stiffness matrix S is assembled i.e in imposed voltage cases. Otherwise, a 0 value will be returned.

/ Imposing voltage/current

EM Circuit data time,	Voltage,	Charge,	Current,	ResistD,	ResistJ,	Induct,	Mutual1,	Muti
0.10000000E-04	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.29587592E-02	0.00000000E+00	
0.20000000E-04	0.38455211E+00	0.00000000E+00	0.62831750E+00	0.00000000E+00	0.61203469E+00	0.29587592E-02	0.00000000E+00	
0.30000000E-04	0.16452816E+01	0.00000000E+00	0.12566288E+01	0.00000000E+00	0.13092821E+01	0.29587592E-02	0.00000000E+00	

ResistJ : After the full Eddy current problem is solved the current density \vec{j} is retrieved. The total Joule heat rate can be extracted by $P_{JHR} = \int_{Volume} \frac{\vec{j}^2}{\sigma} dV$. The flux through SSIDCURR allows to retrieve a current I and ResistJ can be retrieved with $R_j = \frac{P_{JHR}}{I^2}$

Since it takes into account the skin effects, this output is a more realistic measure of the resistance the conductor is experiencing with those particular settings.

Provided the current is fully diffused through the conductors and SIDCURR is defined far enough from SIDIN/SIDOUT, ResistJ and ResisD should become very close.

Imposing voltage/current

```
EM Circuit data
time, Voltage, Charge, Current, ResistD, ResistJ, Induct, Mutual1, Mutu
0.10000000E-04 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.00000000E+00 0.29587592E-02 0.00000000E+00
0.20000000E-04 0.38452111E+00 0.00000000E+00 0.62831750E+00 0.00000000E+00 0.61203469E+00 0.29587592E-02 0.00000000E+00
0.30000000E-04 0.16452816E+01 0.00000000E+00 0.12566288E+01 0.00000000E+00 0.13092821E+01 0.29587592E-02 0.00000000E+00
```

Induct : Defined as the flux of the magnetic field over the surface divided by the current :

$$L = \frac{\iint B \cdot dS}{I} = \frac{\int A \cdot dl}{I}$$

Stoke's theorem : transform magnetic flux integration into vector potential integration.

A special solve on the BEM system $P k = D a$ allows to recover $L I$ and therefore L .

A similar solve is done to estimate the mutual inductances between the different circuits (up to three are written in the ascii file).

Imposing voltage/current

EM Circuit data time,	Voltage,	Charge,	Current,	ResistD,	ResistJ,	Induct,	Mutual1,	Muti
0.10000000E-04	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.00000000E+00	0.29587592E-02	0.00000000E+00	
0.20000000E-04	0.38455211E+00	0.00000000E+00	0.62831750E+00	0.00000000E+00	0.61203469E+00	0.29587592E-02	0.00000000E+00	
0.30000000E-04	0.16452816E+01	0.00000000E+00	0.12566288E+01	0.00000000E+00	0.13092821E+01	0.29587592E-02	0.00000000E+00	

Current : Is calculated by integrating the current density over SIDCURR.

Charge : Only calculated in R,L,C circuit configuration and is solved by the R,L,C circuit equations.

Voltage : $V = R_D I + L \frac{dI}{dt}$. Note that in imposed current cases, only the $L \frac{dI}{dt}$ component will be calculated since the equation for R_D is not solved.

Outputting global energies

Warning : Versions prior to R14 output the Joule Heat Rate instead of the Energy.

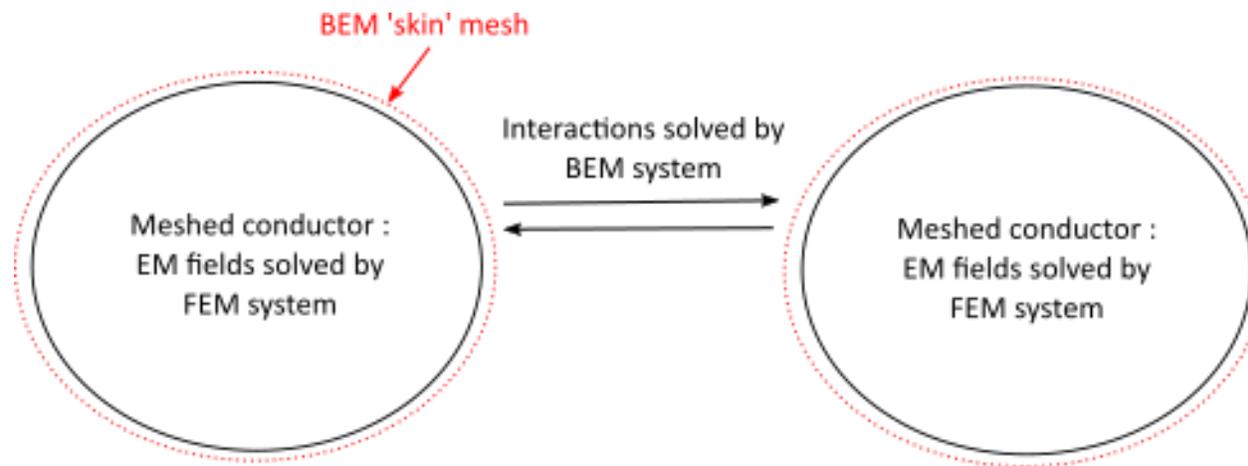
- In addition to the circuit output, it is possible to output EM global energy values using the keyword `EM_DATABASE_GLOBALENERGY`.
- The electromagnetic energy contributions can be divided into three components (respectfully *Mesh.JH*, *Mesh.Mag* and *Air.Mag*) :
 - Joule heat : $E_{JHR} = \int \int_{Volume} \frac{\vec{j}^2}{\sigma} dV dt$ with \vec{j} the current density and σ the conductivity.
 - Magnetic Energy : $E_{Mag} = \int_{Volume} \frac{\vec{B}^2}{2\mu} dV$ with \vec{B} the magnetic flux and μ the permeability.
 - Air Magnetic Energy : $E_{air} = \frac{1}{2} \sum_i^{Ncircuit} \sum_j^{Ncircuit} M_{ij} I_i I_j$ with M_{ij} the Mutual inductance between circuit i and circuit j .
- If a R,L,C circuit is defined, additional energies (capacitor energy, external joule heat and external magnetic energy) coming from the circuit equations are calculated and output.
- The ASCII file also outputs the mechanical Internal Energy as well as the Kinetic Energy.

Interaction between conductors

The EM solver uses finite elements to solve the EM fields within conductors (FEM) but the interaction between conductors is handled by a boundary elements method (BEM) (double integral of Biot-Savart type). This results in a coupled FEM-BEM system.

In order to solve this BEM system, the EM solver will automatically create those boundary elements based on the surface mesh size of the conductors resulting in BEM surface parts, accessible in the d3plots.

This means that no air mesh is necessary.

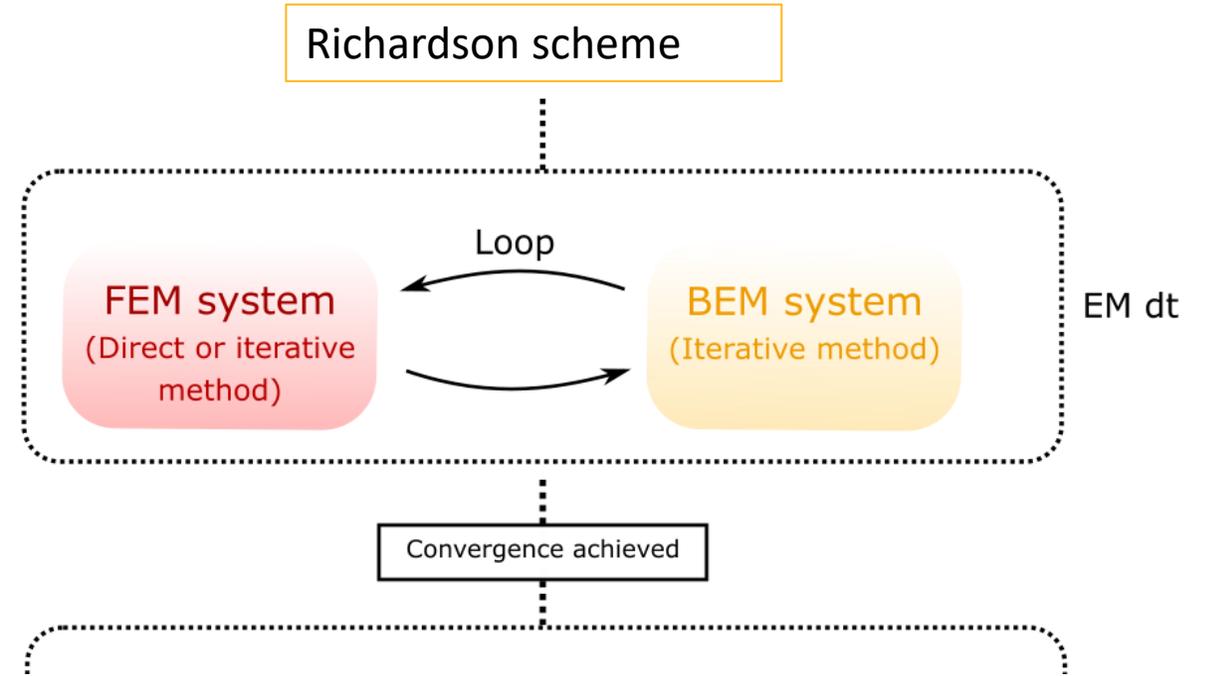


External source field and B field measurement in the air

- It is also possible to directly impose an external magnetic field on conductors via the keyword `EM_EXTERNAL_FIELD`. This field is uniform in space but can vary through time.
- It is commonly encountered in verification cases (T.E.A.M 4 problem, T.E.A.M 11 problem).
- The `EM_DATABASE_POINTOUT` keyword is used to measure the magnetic flux in the air (equivalent to a Hall probe) . Since the solver uses a BEM approach with no air mesh, a Biot-Savard calculation is done by the solver to retrieve the values of the magnetic field in the air. Vacuum permeability is assumed.
- This output calculation will add a small extra cost to the total calculation times.
- If the point falls in the mesh, an automatic search will be done by the solver to find in which element the point belongs to and assign the elemental values to it.

Available solvers

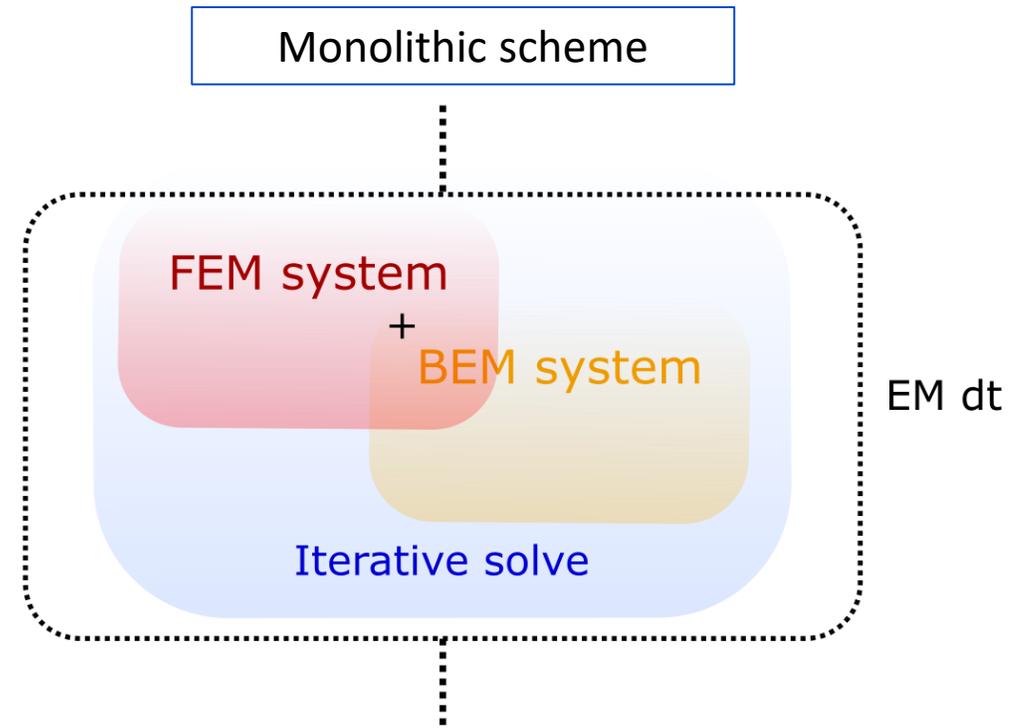
- Two approaches are available to solve Eddy-current problems : The Richardson scheme and the Monolithic scheme.
- The Richardson method is an iterative solve, where the FEM and BEM systems are assembled separately and solved via an iterative loop.
- The solving time per timestep is low when using this approach. However, the timestep is bounded by the CFL condition on Eddy current diffusion ($\Delta t \leq \frac{l^2}{2D}$, $D = \frac{1}{\mu\sigma}$) and it cannot handle ferromagnetic materials or permanent magnets ($\mu = \mu_0$).
- For this reason, this approach is mainly used in applications that involve a rapid electric pulse or fast rising current such as metal forming, bending or welding.



EM_SOLVER_FEMBEM : Controls the tolerance and number of iterations during the iterative loop. (Default values are usually enough)

Available solvers

- For the monolithic solve, the FEM and BEM matrix assemblies are used to populate a global matrix that is solved in a single step (using either MINRES or GMRES iterative methods).
- Its cost per timestep is higher but it allows higher timesteps and, more importantly it allows to solve ferromagnetic materials.
- Since its first introduction in R12, its capabilities have been further extended in each new version and it is now used in various problems such as magnet snapping, magnetic gears, magnetostatic analysis, actuators, crack detection etc.

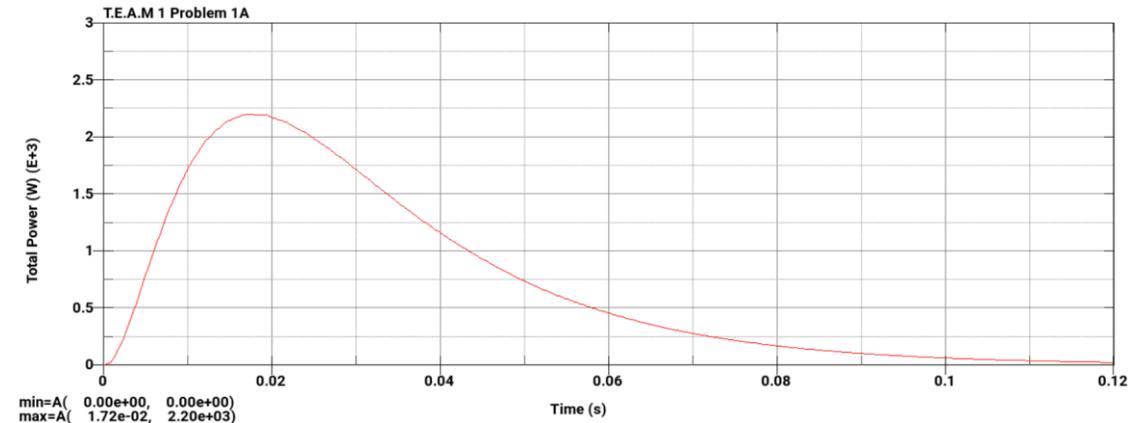
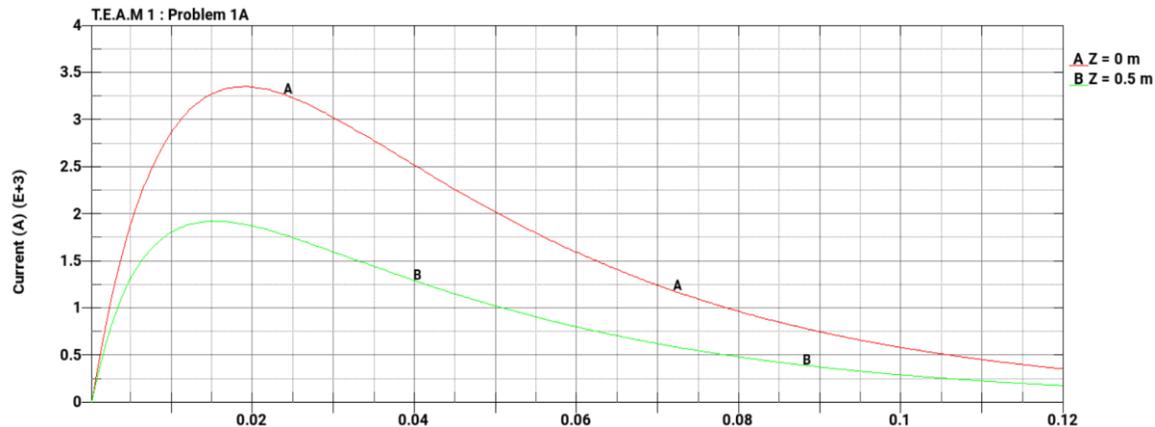
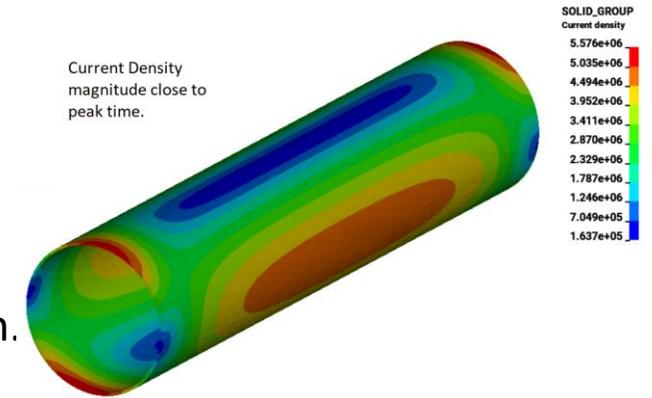


EM_SOLVER_FEMBEM_MONOLITHIC : Turns on the Monolithic solve (default solver is Richardson solve) and controls the tolerance and number of iterations during the monolithic solve.

Case Study – T.E.A.M 1

The Felix Cylinder problem

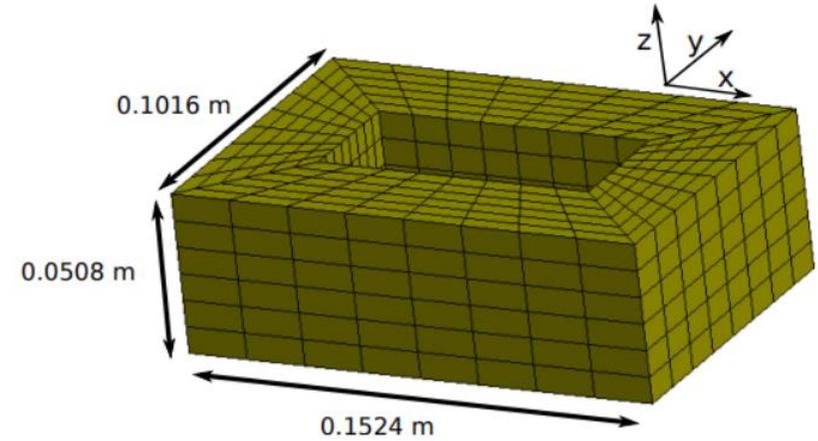
- A conducting cylinder is placed in a uniform magnetic field.
- The applied field varies with time as a step function, requiring a fully transient solution.
- The objective is to measure the current and Power Loss function of time.
- This example is an application example of EM_CIRCUIT_ROGO and EM_DATABASE_PARTDATA.
- The Richardson solve or the Monolithic solve can be used and different timesteps can be selected to study the impact of stability and solution time.



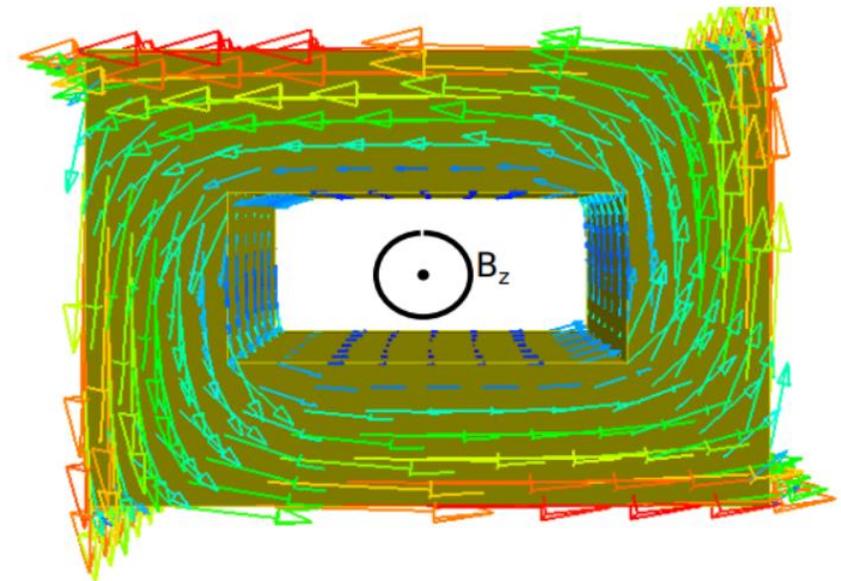
Case Study – T.E.A.M 4

The Felix Brick problem

- An aluminium is in placed in a uniform magnetic field.
- The applied field varies with time as a step function, requiring a fully transient solution.
- The objective is to measure the current and Power Loss function of time.
- This example is an application example of EM_CIRCUIT_ROGO.
- Similarly to the T.E.A.M 1 problem the Richardson solve or the Monolithic solve can be used and different timesteps can be selected to study the impact of stability and solution time.



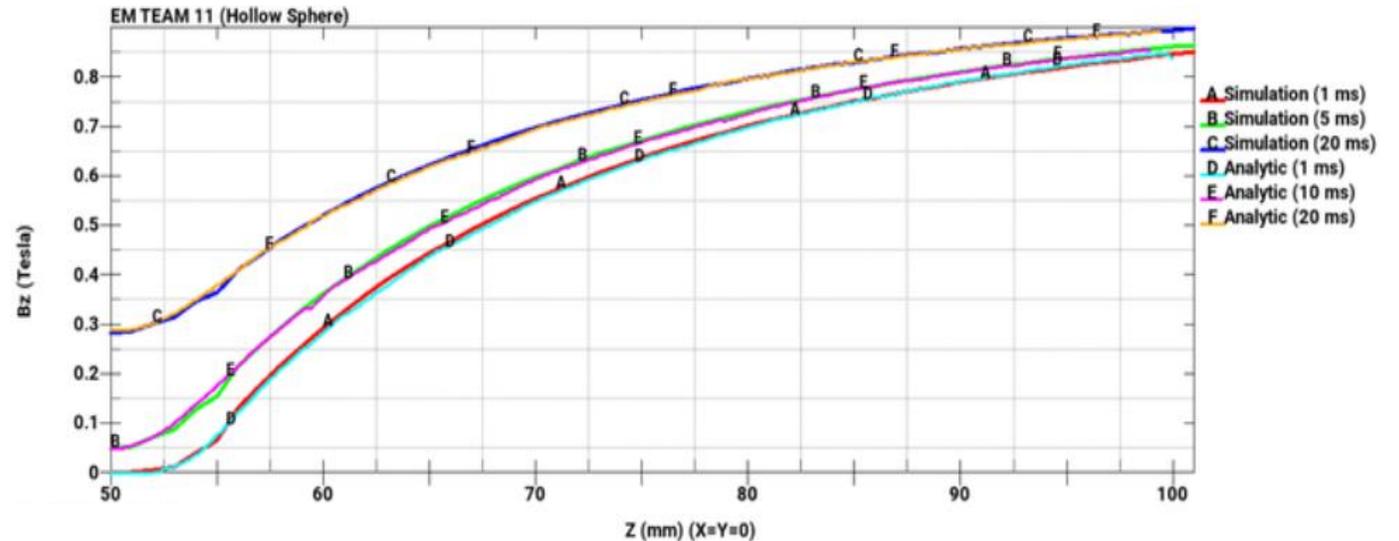
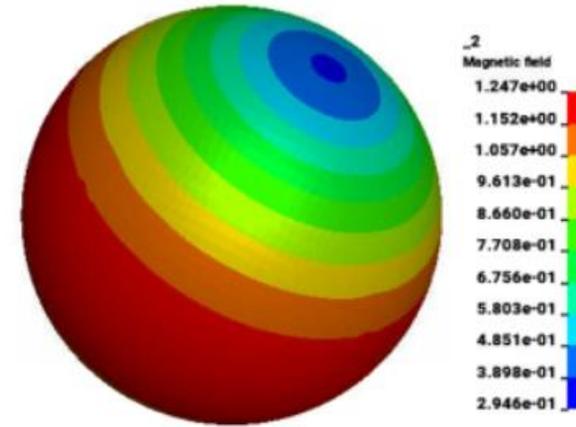
Current Density Vectors :



Case Study – T.E.A.M 11

Hollow Sphere

- A hollow conducting sphere is placed in a uniform magnetic field.
- The applied field varies with time as a step function, requiring a fully transient solution.
- The objective is to measure the magnetic flux in and outside the sphere at different instants and compare to the analytical solution.
- This example is an application example of EM_EXTERNAL_FIELD and EM_DATABASE_POINTOUT.

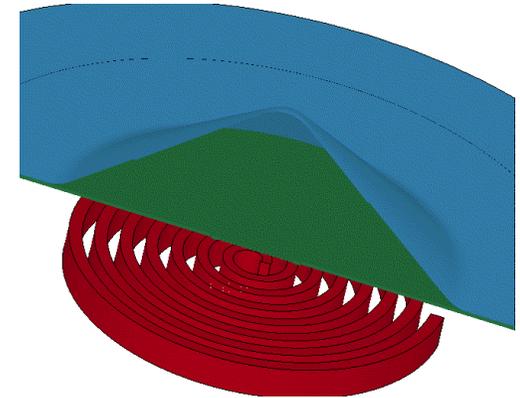
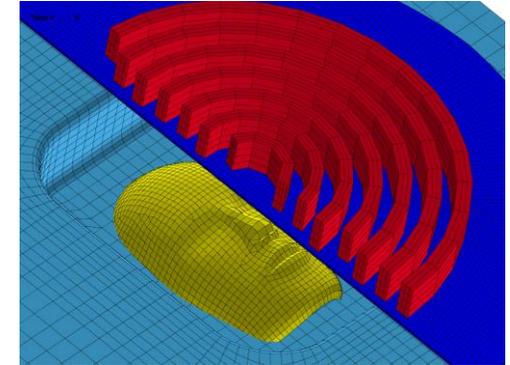
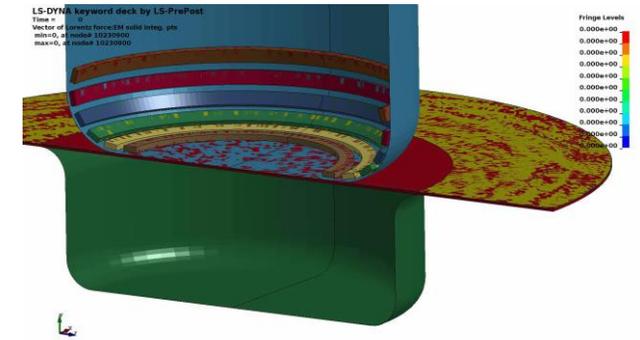


Focus on Magnetic Metal Forming



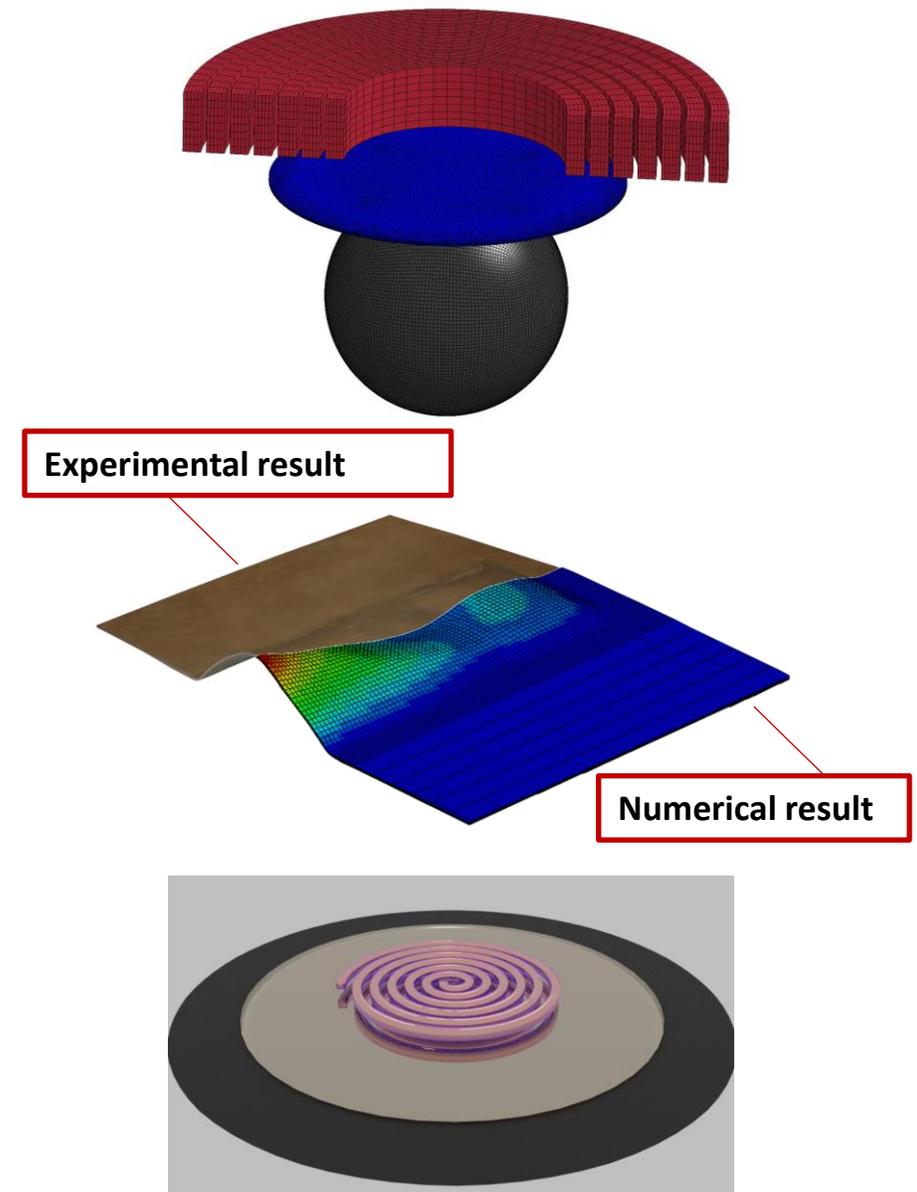
MMF principles

- A conducting coil induces electrical currents (Eddy currents) in the workpiece.
- This creates a strong electromagnetic force pushing the workpiece against the die.
- It is a high velocity forming process where:
 - The forming limits can be significantly increased (80%).
 - The springback is reduced.
 - The wrinkling is reduced.
 - Shock hardening of the material.
 - The amount of energy can be tightly controlled.
 - High reproducibility.
 - No contact between the coil and the workpiece (one sided die+no friction)



MMF principles

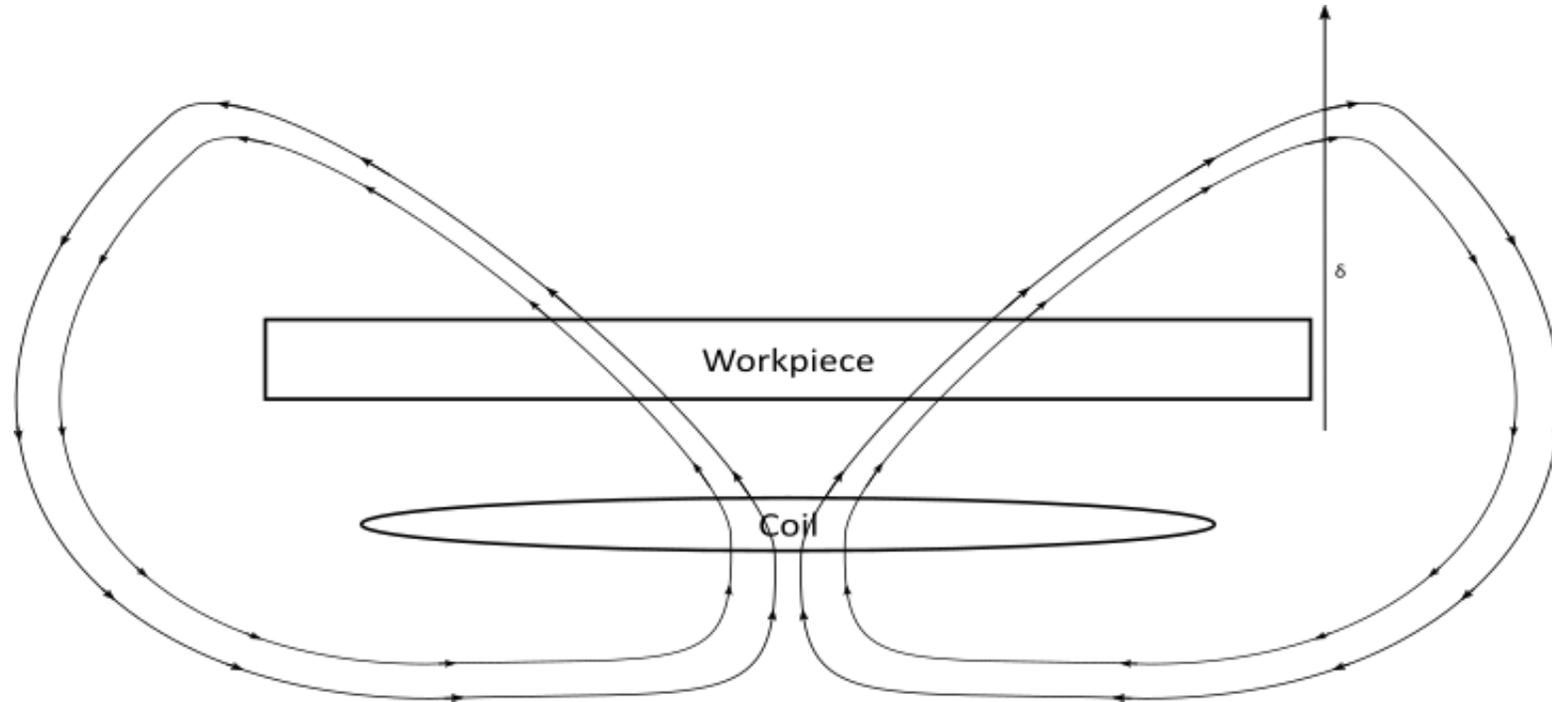
- The Lorentz forces generated by the coil result in intense and fast deformations in the workpiece => strong non linear Multiphysics required.
- Contrary to solid mechanics, EM fields are in the surrounding air too ! However, due to the strong deformations, meshing this air domain would prove to be inadequate especially for handling small gaps, contact between conductors and complex geometries => FEM/BEM method is the answer.
- In a FEM/BEM method, the Eddy currents are solved in the conductors and the interaction between conductors (coil/workpiece) is done using boundary integrals (BEM) => huge simplification of the input for the user.



/ Interaction between conductors

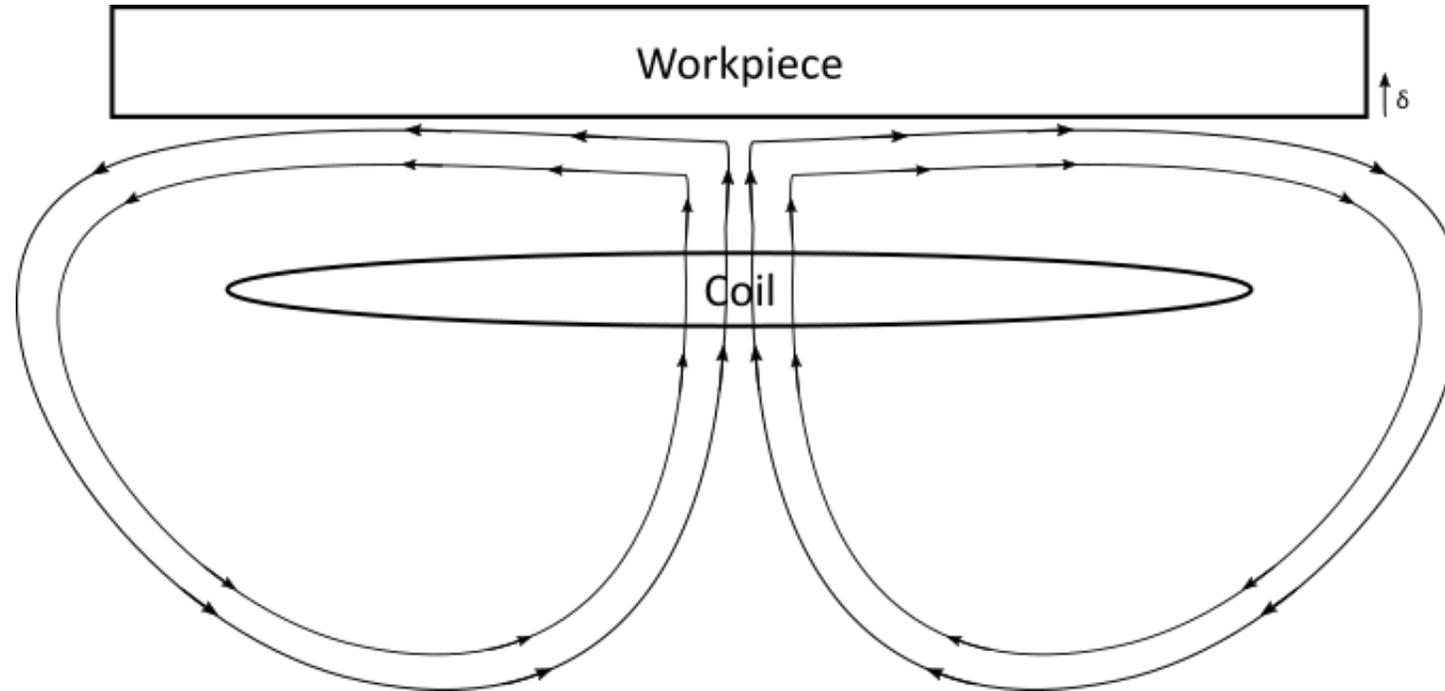
Let us consider a conductor carrying a source circuit i.e a coil which generates a magnetic field.

If the nearby workpiece is made of an insulator material or if the skin depth is a lot higher than its thickness, then the magnetic field will 'ignore' that workpiece and the magnetic field lines will flow through.



/ Interaction between conductors

However, if the skin depth of the workpiece is lower than its thickness, then the magnetic field line's path is deviated, and an induced current appears that will generate its own magnetic field. The Eddy currents are the combination of those inductive-diffusive effects.

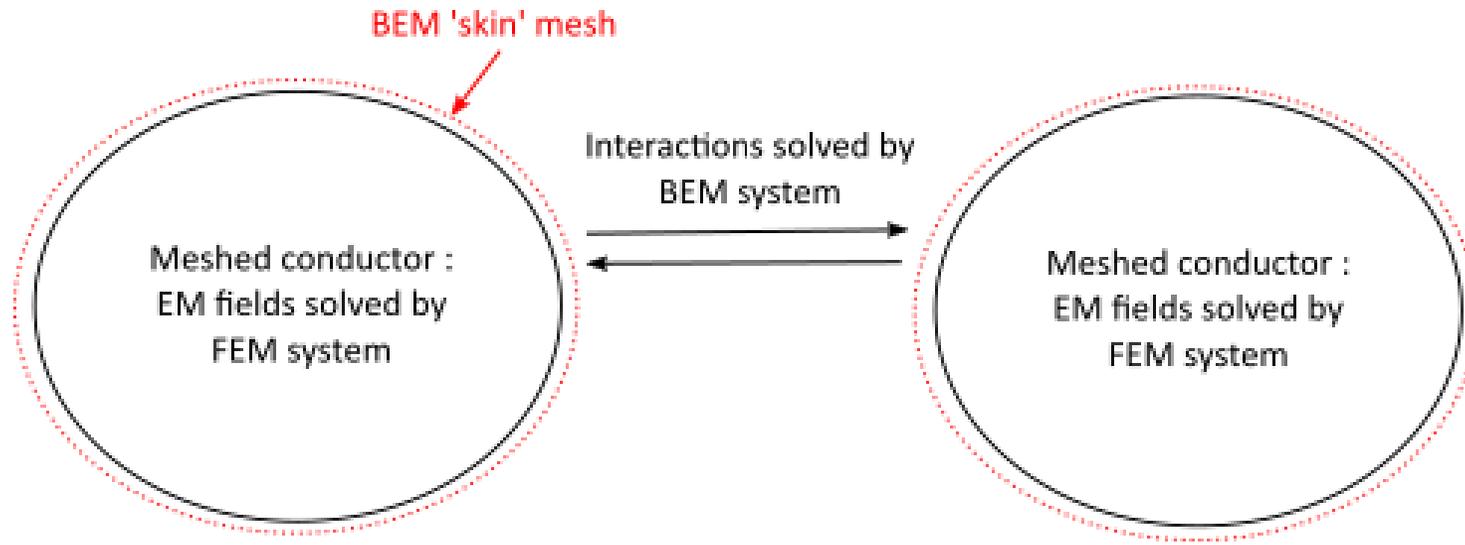


Interaction between conductors

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In order to solve this BEM system, the EM solver will automatically create those boundary elements based on the surface mesh size of the conductors resulting in BEM surface parts, accessible in the d3plots.

This means that no air mesh is necessary.



Coupling between conductors

- The Electromagnetic force generated by the Eddy currents is called the Lorentz force. It is equal to the cross product of the current density vector and the magnetic flux vector. It acts as an external force applied to the solid elements.
- The Electromagnetic heating is called the Joule heating. It is proportional to the current density squared divided by the electric conductivity. It acts as an external heat source term in the heat equation solve.

Maxwell equations

<i>Faraday</i>	$\vec{\nabla} \times \vec{E} = - \frac{\partial \vec{B}}{\partial t}$	$\left. \begin{array}{l} \text{Extra Lorentz force : } \vec{F}_{em} = \vec{j} \times \vec{B} \\ \text{Extra Joule heating: } q = f \left(\frac{j^2}{\sigma} \right) \end{array} \right\}$
<i>Ampere</i>	$\vec{\nabla} \times \vec{B} = \mu_0 \vec{j} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t}$	
<i>Gauss</i>	$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\epsilon_0} = 0$	
	$\vec{\nabla} \cdot \vec{B} = 0$	

No free charge accumulation (see electrostatics)

Eddy current approximation : radiation term neglected
(no radar, sonar or EM wave propagation)

/ Coupling between conductors

- The Lorentz force is automatically transferred to the solid mechanics solver. No extra keyword is necessary. This is true whether the solid mechanics explicit or implicit solvers are used.
- In a similar way, if the thermal problem is defined and the thermal solver is turned on, the joule heating term will automatically be applied as a heat source.
- R12 and more recent versions allow to turn off this coupling by using `*EM_CONTROL_COUPLING`.

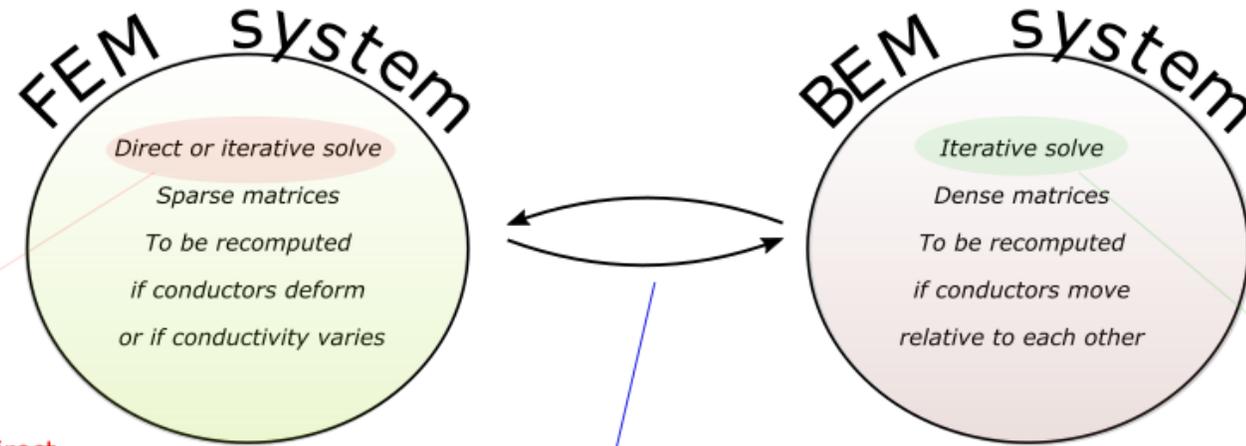
FEM/BEM system considerations

- One important point to consider is the periodic recomputation of the FEM and BEM systems which, by default, are only set up once during the initialization phase.
- For example, if the conductors deform and their meshes become distorted, then it becomes important to recompute the FEM system regularly to avoid inaccuracies.
- If the conductors deform or move in respect to one another, then it becomes important to recompute the BEM system.
- In an ideal scenario, the FEM/BEM systems would be recomputed at every timestep. However, this would prove to be too costly (especially the BEM system which consists of dense matrices). So, it is up to the user to set reasonable values, compromising between accuracy and speed.
- The classic way of defining those recomputation frequencies is by using field 7 and 8 of *EM_CONTROL. Alternatively, and, starting with R12, an automatic criteria can be defined using *EM_CONTROL_SOLUTION.

/ EM equation of state

- It is also possible to consider the changes of the electric conductivity due to a temperature increase via the introduction of an EM EOS. The keyword `*EM_EOS_...` is associated to the keyword `*EM_MAT_001`.
- The simplest type of EOS simply requires the user to specify a load curve which gives how the conductivity should vary function of temperature (See `EM_EOS_TABULATED1`). However, more complex EOS types exist (See `EM_EOS_MEADON`). It is also possible to use a user defined EOS via the introduction of a `DEFINE_FUNCTION` (See `EM_EOS_TABULATED2`).
- In order for the EM solver to take into account the conductivity changes, it becomes necessary to periodically recompute the FEM system.

FEM-BEM system

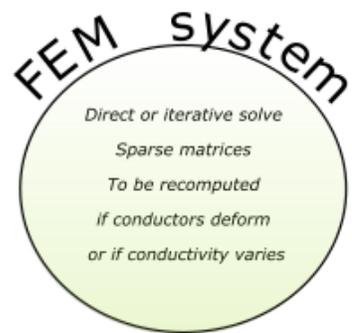


Choice available in *EM_SOLVER_FEM. Direct solve is usually preferred for small problems, the switch to an iterative solve is warranted in large problems to reduce memory

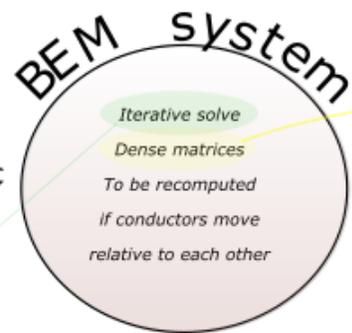
Iterative FEM-BEM solve (Richardson method).
Tolerances can be controlled in *EM_SOLVER_FEMBEM. Recommendation is to leave default values and to favor other criteria (mesh quality, matrice tolerances, timestep) to improve analysis.

Choice available in *EM_SOLVER_BEM. Default solve options are recommended. Tolerances can be lowered for more accuracy.

The BEM matrix assemblies



Small terms of BEM matrices can be removed to reduce memory cost and matrix assembly times. This will however impact accuracy and robustness. See *EM_SOLVER_BEMMAT

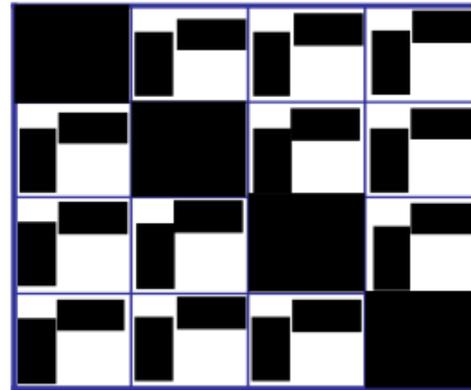


Choice available in *EM_SOLVER_BEM.
Default solve options are recommended.
Tolerances can be lowered for more accuracy.

Low rank approximations on the non-diagonal sub blocks of the BEM

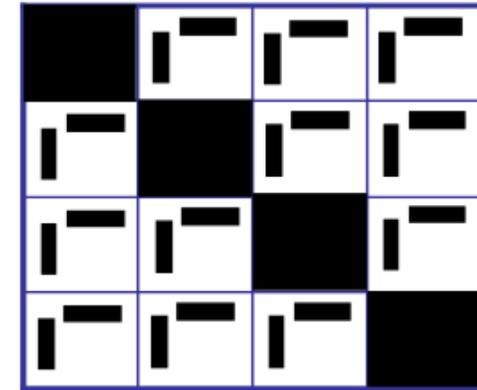
Small blocks

: low tolerance value in *EM_SOLVER_BEMMAT



Larger blocks

: higher tolerance value in *EM_SOLVER_BEMMAT



Two BEM matrices make up the BEM system in the classic Richardson approach, the P and the Q matrices. See Theory manual

/ Interaction between conductors - Summary

- No air mesh means that it is easier to have motion of conductors where no potential air mesh deformations and remeshing can occur or are needed. This is very useful in cases with very fast movements and deformations of conductors (forming, welding, bending..)
- Easier to handle small gaps between conductors or complex conductor shapes.
- No artificial approximations at the simulation zone boundary.
- Optimization techniques such as low rank approximation during the iterative solve are implemented to deal with the BEM dense matrices. Their size can be further reduced by user-controlled keywords.
- Any quantity extracted in the air (magnetic field value or field line plotting) becomes a post treatment feature.
- Seamless coupling with the structure. Lorentz force is passed to the structure and mechanical properties and displacements are retrieved
- Joule heating is passed to the thermal solver and Temperatures are retrieved.
- Periodic recomputing of FEM and BEM matrices are controlled by the user.

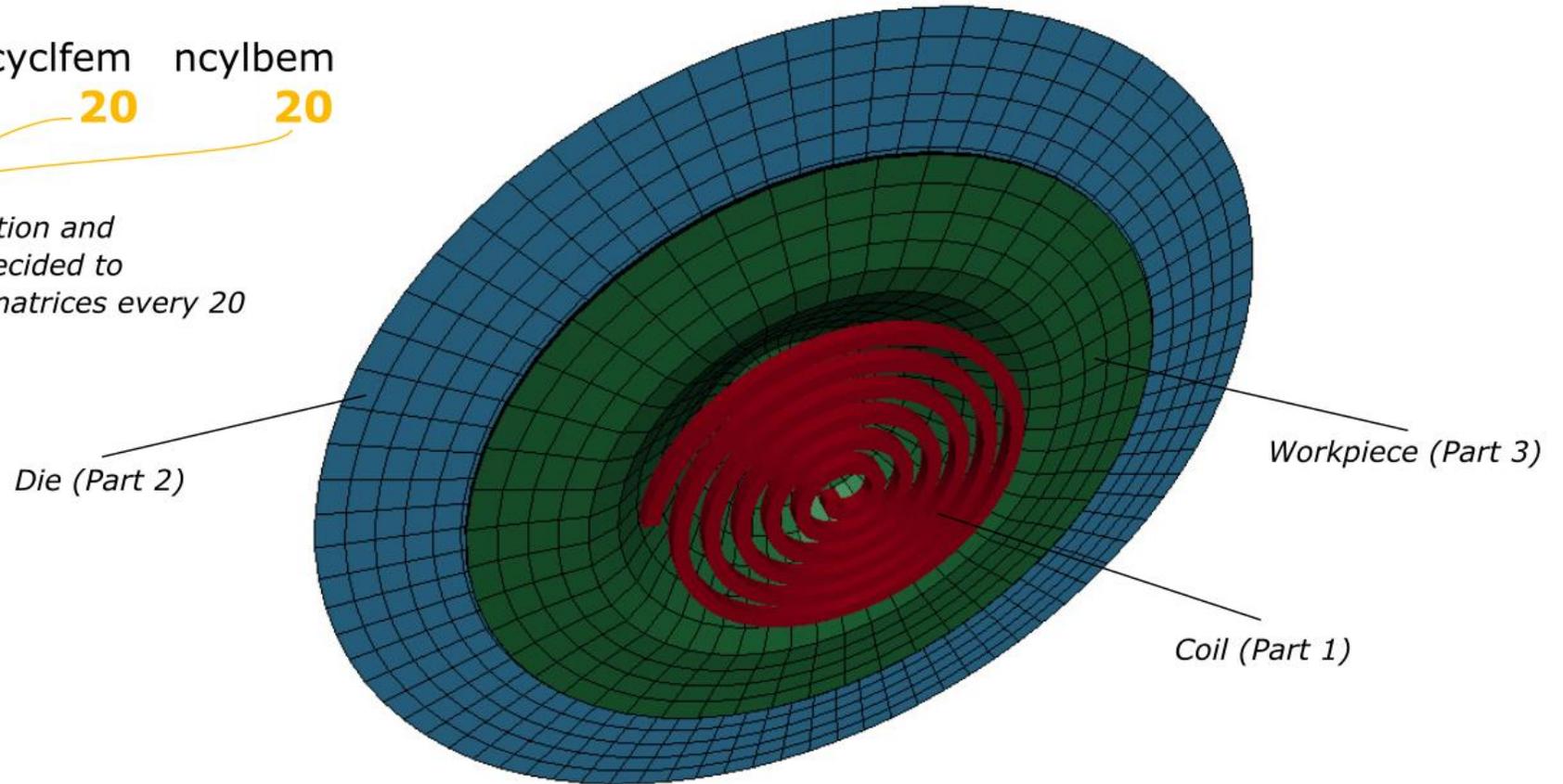
Case Study – EM forming

Electromagnetic forming application – control keyword

*EM_CONTROL

```
emsol          ncyclfem  ncylbem  
  1             20         20
```

Due to the workpiece deformation and displacements, the user has decided to recompute the FEM and BEM matrices every 20 EM timesteps.



Case Study – EM forming

Electromagnetic forming application – timestep keyword

*EM_CONTROL_TIMESTEP

tstype

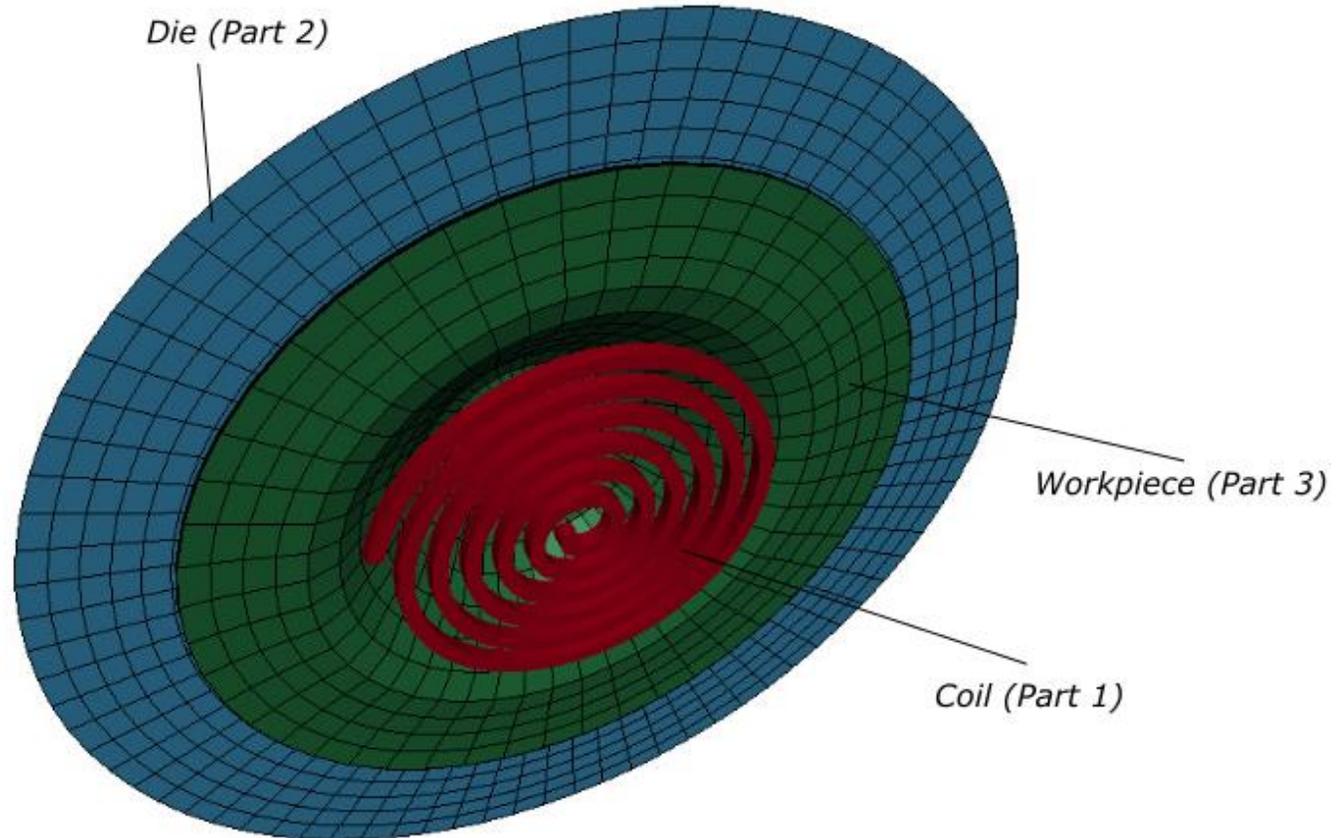
3

The user has selected an automatic EM timestep. The EM solver will use the Eddy current CFL number to estimate a stable timestep value :

$$\Delta t \leq \frac{l^2}{2D}$$

l is the characteristic mesh size and D is the diffusion coefficient function of permeability and conductivity :

$$D = \frac{1}{\mu\sigma}$$



Case Study – EM forming

Electromagnetic forming application – material definition

*EM_MAT_001

mid	mtype	sigma
2	1	

The Die is an insulator and is excluded from the EM analysis

*EM_MAT_001

mid	mtype	sigma
1	2	25.

The Coil has a constant conductivity defined by sigma

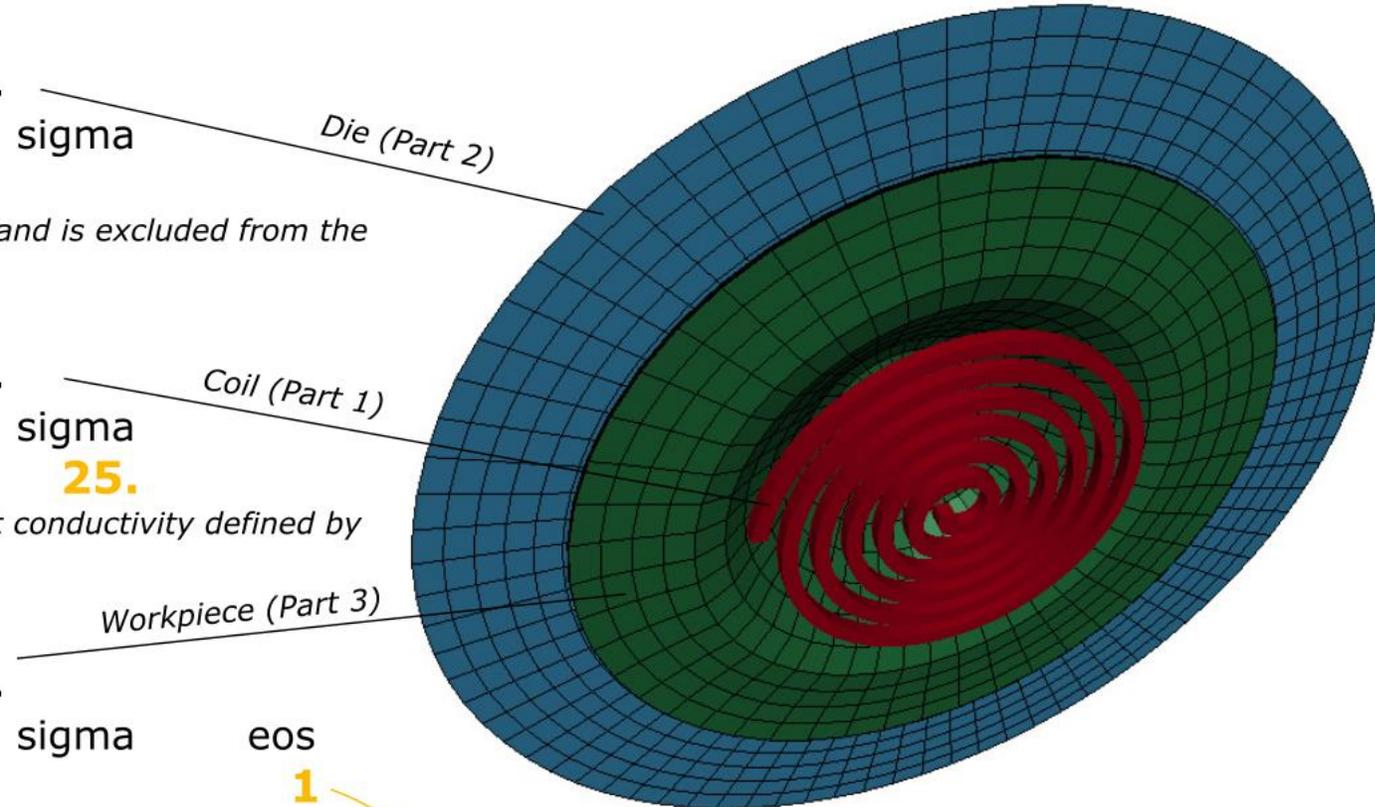
*EM_MAT_001

mid	mtype	sigma	eos
3	2		1

*EM_EOS_TABULATED1

eosid	lcid
1	43

The workpiece has got a conductivity defined by an EOS. It is made function of temperature (See load curve 43).

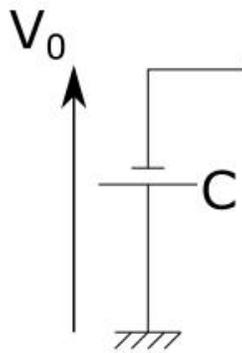


Case Study – EM forming

Electromagnetic forming application – source current

*EM_CIRCUIT

circid	circype	R	L	C	V0
1	3	5.96	2.3e-4	2.0e-7	7.0e9
ssidcurr	ssidvin	ssidvout			
2	1	2			



*EM_CIRCUIT_ROGO

rogid	setid	setype	curtype
1	4	1	1

This keyword outputs an ASCII file which allows the user to look at the average current or magnetic field flowing through a segment set.

*EM_DATABASE_CIRCUIT0D

outlvl
1

This keyword triggers a 0D preliminary calculation giving the R,L,C circuit current without considering the inductive/diffusive effects

Case Study – EM forming

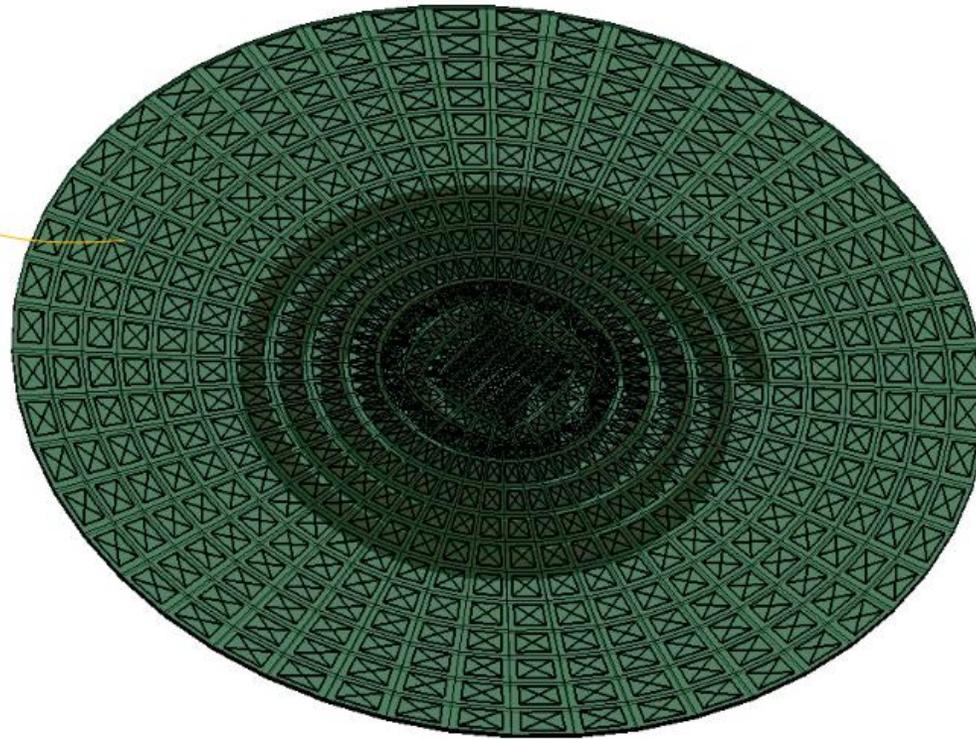
Electromagnetic forming application – optimization

```
*EM_BOUNDARY
```

```
ssid      btype
```

```
6         9
```

The user has decided to apply this keyword to the upper surface of the workpiece. This removes those faces of the BEM mesh and therefore saves some calculation time. This can be done in regions where the effects of the magnetic field are small (typically on faces facing away from coils or other magnetic field sources)



Case Study – EM forming

Electromagnetic forming application – monitoring

A very useful keyword to use in order to monitor the analysis is EM_OUTPUT. Setting up the first four flags to 2 will output information about the EM solve and matrix assembly in both the message file and the terminal output

Matrix assembly stage

```
building Q mat
*****
starting building BEM matrix
6536 dofs in 32 domains
building near interactions part
10 percent completed
20 percent completed
addingSingToReg1 72 270 5 1 -0.4280E-09 -0.1095E-08 -0.1523E-08
30 percent completed
40 percent completed
50 percent completed
60 percent completed
70 percent completed
80 percent completed
90 percent completed
100 percent completed
```

Number of iterations of the FEM BEM system

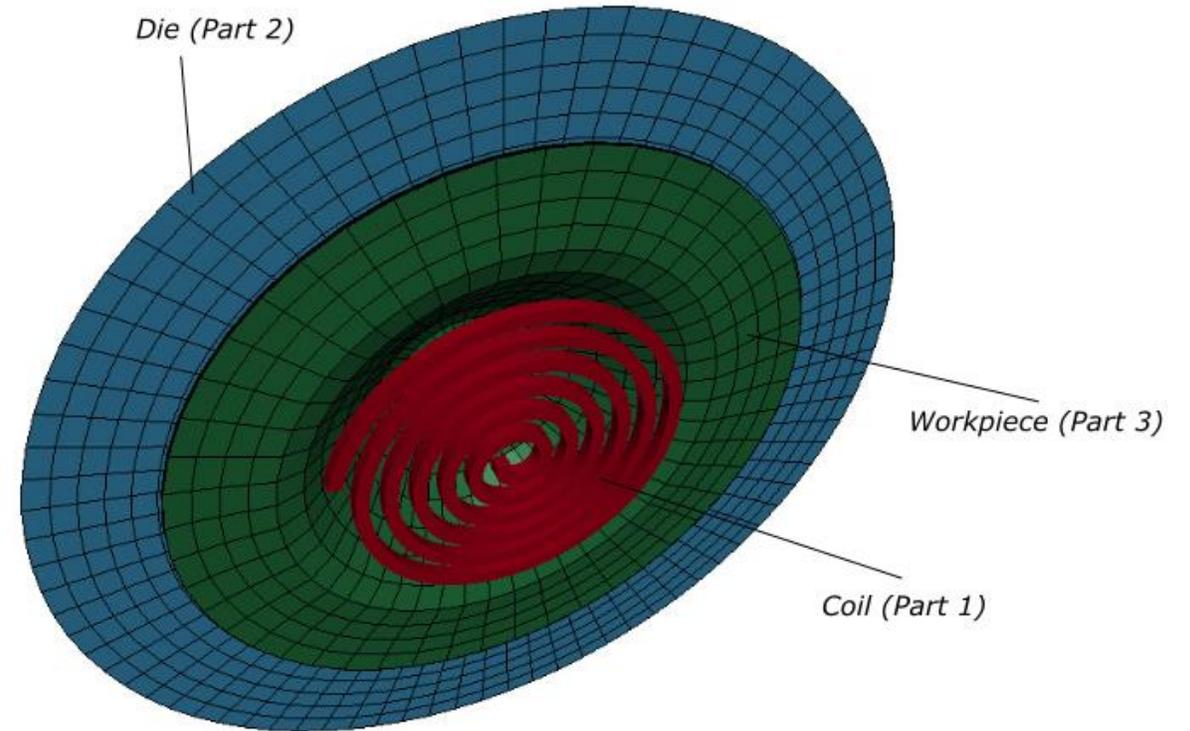
- 41 t 8.2000E-05 dt 2.00E-06 electromagnetism step
- EM-BEM iter # 1, ah= 0.1295009E+04, %v= 0.1000E+01, ks= 0.1698667E+09, %v= 0.3681E+00, pcglt 125, tot 5906, EMTime 8.20E-05, mechTime 8.20E-05
- EM-BEM iter # 2, ah= 0.1301137E+04, %v= 0.1454E-01, ks= 0.1645545E+09, %v= 0.4218E-01, pcglt 32, tot 5938, EMTime 8.20E-05, mechTime 8.20E-05
- EM-BEM iter # 3, ah= 0.1301134E+04, %v= 0.9004E-03, ks= 0.1650322E+09, %v= 0.5921E-02, pcglt 10, tot 5948, EMTime 8.20E-05, mechTime 8.20E-05
- 2691 t 8.3978E-05 dt 2.88E-08 write d3plot file 01/05/18 10:19:38

Residuals of the FEM BEM system, needs to decrease and reach tolerance criteria

Case Study – EM forming

Electromagnetic forming application – shells

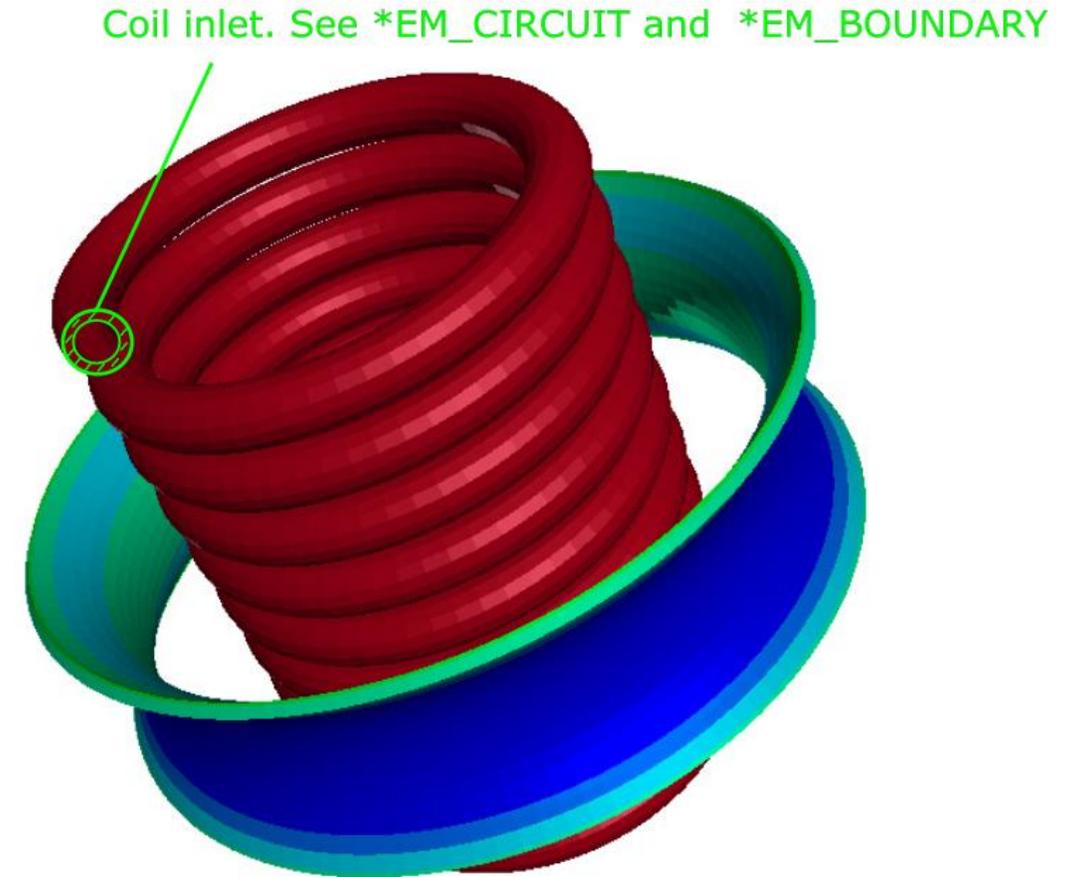
- The workpiece on other conductors can also be modelled using shell elements.
- The EM solver will reconstruct an internal mesh with a user specified number of elements and based on the shell thickness defined in *SECTION_SHELL. The *EM_MAT_001 must be replaced by *EM_MAT_004.
- A single value of the force (integrated over the thickness) and joule heating will be passed to the structure and thermal. Results can be less accurate in cases involving a strong diffusion gradient.
- The choice of using shells must be driven by solid mechanics or thermal solver considerations. No gain (accuracy, solve times) is expected on the EM solve.



Case Study – Tube expansion

Using `*EM_BOUNDARY` to provide consistent circuit boundary conditions

- The coil in this application is hollow. Two closed loops can be formed (one inner, one outer) at the intersection of the inlet segment set faces and the rest of the BEM surface mesh.
- The boundary condition imposed by `*EM_CIRCUIT` relies on providing one and only one intersection between the boundary faces and the BEM mesh.
- Consequently, in such configurations, the user must remove faces from the BEM system.
- Typically, this is applied to the internal surface faces of the coil due to the weak contribution of the magnetic field on the external coil-workpiece interactions. See `*EM_BOUNDARY`.



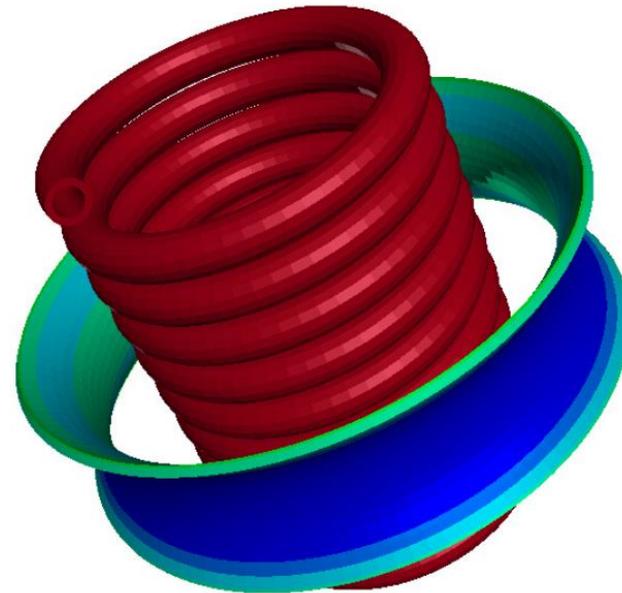
Case Study – Tube expansion

Using ***EM_CONTROL_SOLUTION** to recompute FEM/BEM matrices

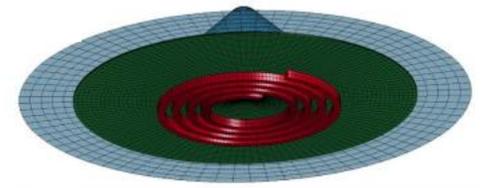
***EM_CONTROL_SOLUTION**

ncylfem	ncylbem	autofem	autobem	tol1fem	tol2fem	tol1bem	tol2bem
		1	1	0.5	0.2	0.5	0.2

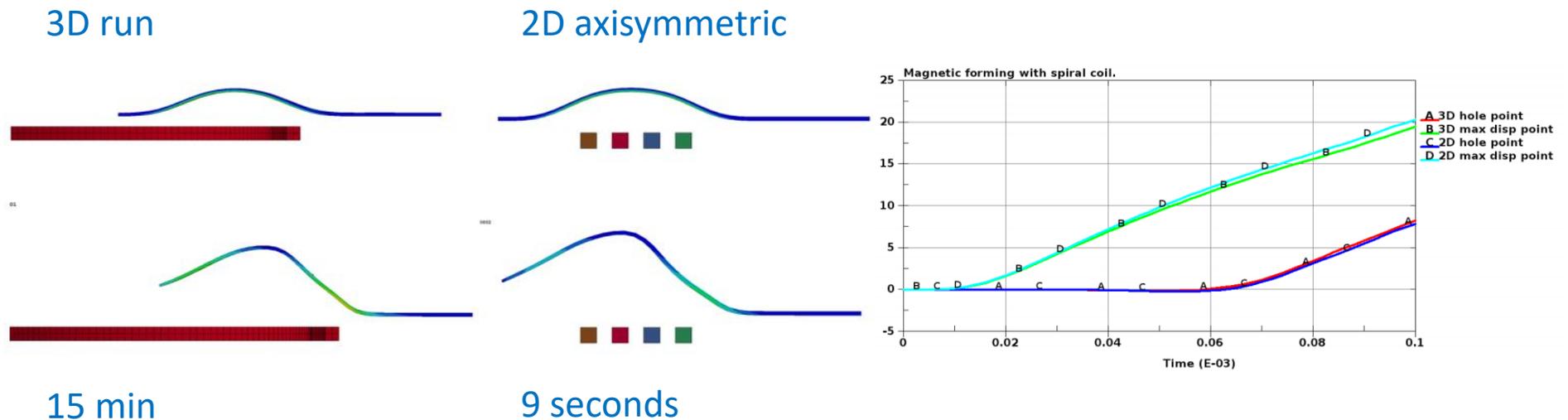
- The user has selected an automatic criteria for the FEM BEM recomputations.
- Check in the output message file when the P and Q matrices are being recomputed.



2D Axisymmetric solver



- In the previous parts, we saw a typical metal forming application involving a workpiece and a coil. The main part of the EM solve was spent in the BEM matrix assembly and we saw some techniques to reduce the size of the problem or improve the speed.
- However, this case also exhibits a particular feature which is encountered in metal forming application from time to time but more frequently in tube expansion problems : a near perfect axisymmetry.
- For such problems, it might be interesting to switch to the EM axisymmetric solver.



/ 2D Axisymmetric solver

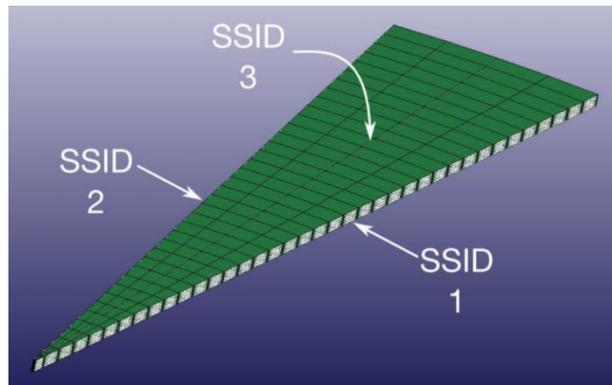
- The axisymmetric feature has been developed in order to simplify certain types of cases and save some calculation time .
- Since LS-DYNA is primarily a 3D code, where most of the features are available only in 3D, it was decided to couple the EM-2D with the LS-DYNA's 3D solver.
- The user needs to provide a slice of the full 3D mesh (with symmetry mechanical boundary conditions) and a segment set to define the plane where the EM-2D is done for each conducting part.
- Once the EM fields are computed in 2D on this plane, results are reported over the full 3D mesh by rotations around the axis.
- Coupling with the thermal and solid mechanics solvers again happens automatically.
- The axi-symmetric solver is usually very fast and can in some cases give a quick and good approximation of the final solution.

2D Axisymmetric solver

- The user can define any rotation axis. See EM_ROTATION_AXIS keyword.
- For every EM axi-symmetric part, a user defined ratio of the full circle mesh has to be built. The ratio has to be a power of 2 (NUMSEC=4 means that the mesh represents one fourth of the full 360 circle). ($Ratio = 360 / (Angular\ extension) = 2^n$).
- A segment set has to go through the center plane for each EM axisymmetric part. This defines the plane where the 2D EM system is computed.

*EM_2DAXI

PID	SSID			STARTSSID	ENDSSID	NUMSEC	
3	3			1	2	32	



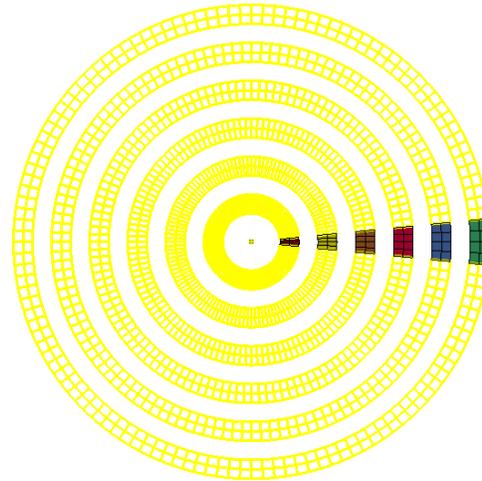
2D Axisymmetric solver

- It is also possible in the EM solver to impose a linear constraint on the global current between two circuits ($c_1 i_1 + c_2 i_2 = 0$). This allows the modelling of quasi-axisymmetric geometries such as pancake type or helix type coils combined with a R,L,C circuit by connecting the different turns together. Of course, the 3D effect of the winding coil can not be taken into account.
- In order to get the best results with a R,L,C circuit, the R,L and C of the coil are evenly spread between the different 2D circuits ($R_i = R/N, L_i = L/N, V0_i = V0/N, C_i = N C$).

3D Coil model



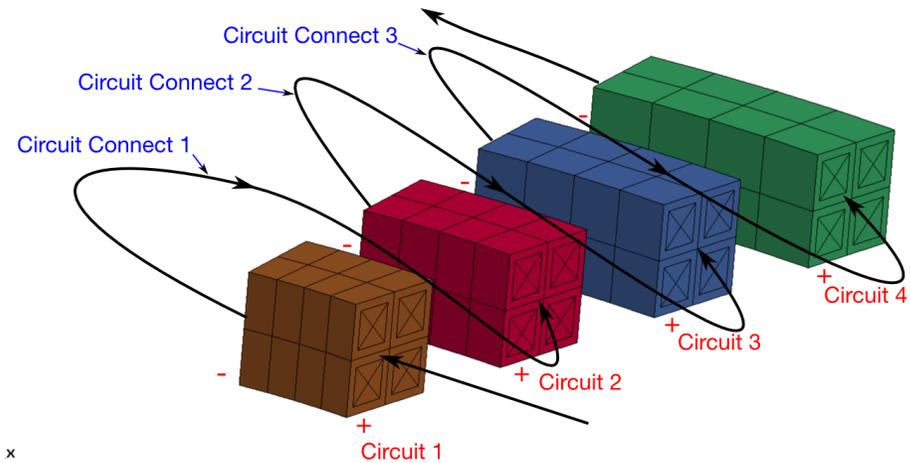
Equivalent coil model with axisymmetric solver



2D Axisymmetric solver

***EM_CIRCUIT_CONNECT** (defined three times to connect four circuits)

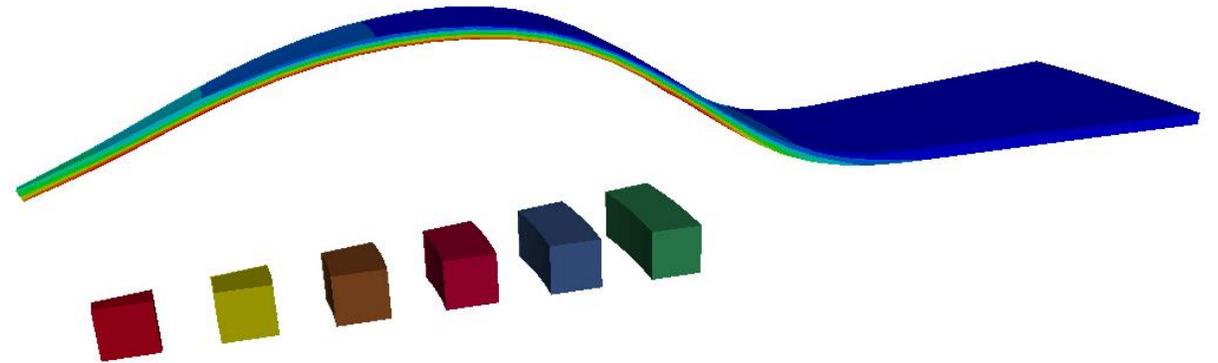
CONID	CONTYPE	CIRCID1	CIRCID2	C1	C2		
1	1	1	2	1	-1		
CONID	CONTYPE	CIRCID1	CIRCID2	C1	C2		
2	1	2	3	1	-1		
CONID	CONTYPE	CIRCID1	CIRCID2	C1	C2		
3	1	3	4	1	-1		



Case-Study Axisymmetric problem

A 2D axisymmetric forming problem

- Check the symmetry conditions on the solid mechanics side (SPCs).
- Check the choice of the R,L,C parameters and compare to the 3D case.
- Check the *EM_2DAXI keywords and *EM_ROTATION_AXIS
- See the *EM_CIRCUIT_CONNECT keywords

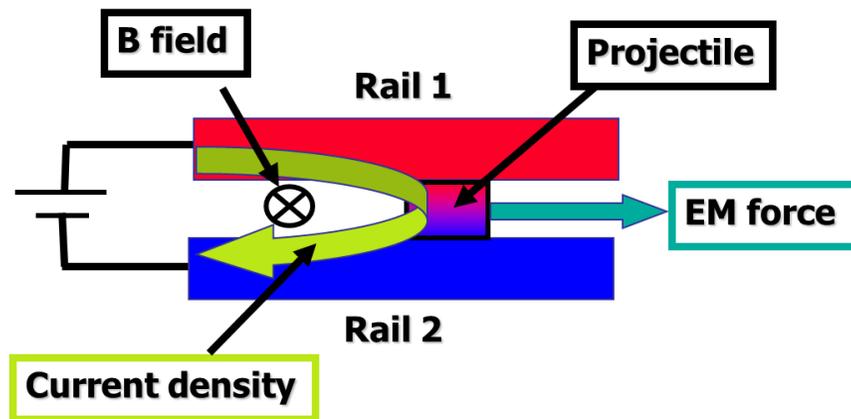


**Focus on Electromagnetic
launchers : railguns and coilguns**



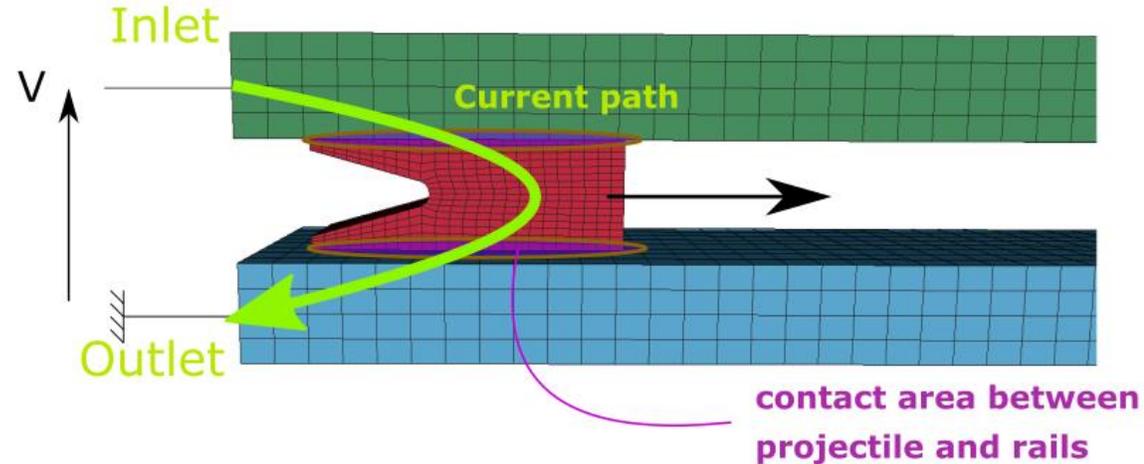
/ Railgun

- A railgun is an electric gun using Eddy currents and electromagnetic forces in order to accelerate and launch projectiles at several times the speed of sound.
- In its most basic form, a railgun consists of two parallel metal rails connected to an electric power supply. When a projectile is inserted between the two bars, it provides a conductive path between the rails thus completing the circuit. The current flowing through the circuit generates a powerful magnetic field between the bars which in turn creates a Lorentz force applied on the projectile.
- For such problems, the EM solver needs to be capable of handling the current flow between the rails and the projectile.



/ EM contact

- Once contact has been detected, the two systems (FEM and BEM) have to handle two conductor faces approaching each other.
- Boundary methods rely on the distance between faces to calculate electromagnetic interactions. If conductors come into contact, that distance becomes zero => special treatment for the BEM system.
- For the FEM system, boundary conditions are typically applied on the scalar potential. Those can be either constraint based or penalty based.



Contact between faces

- In order to turn on the EM contact detection the keyword `*EM_CONTROL_CONTACT` must be turned on.

`*EM_CONTROL_CONTACT`

EMCT	CCONLY	CTYPE	DTYPE	EPS1	EPS2	EPS3	D0
0	0	0	0	0.3	0.3	0.3	

Controls FEM system contact method

Controls detection parameters

EMCT=1 to turn on EM contact detection (search triggers extra calculation time)

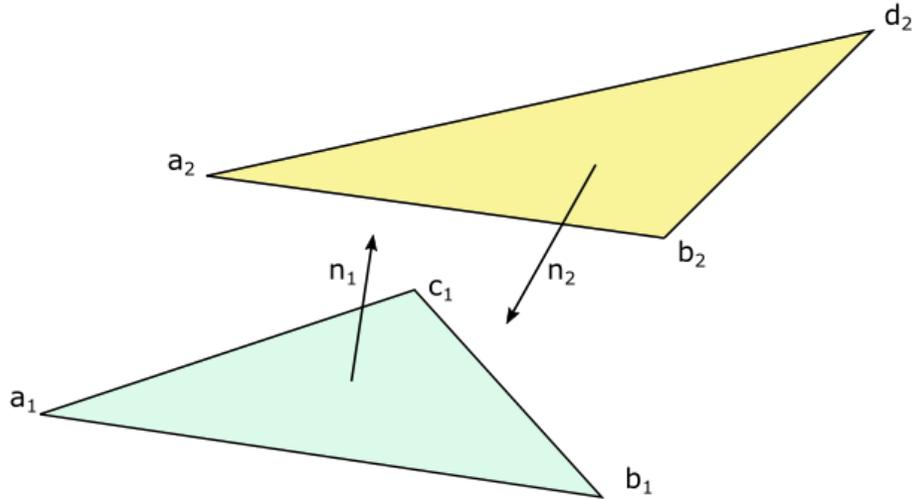
CCONLY = 0 : Look for EM contact on all faces.

= 1 : Restrict search on local contacts defined by `*EM_CONTACT` keyword.

Contact between faces conditions

*EM_CONTROL_CONTACT

EMCT	CCONLY	CTYPE	DTYPE	EPS1	EPS2	EPS3	D0
0	0	0	0	0.3	0.3	0.3	



Controls detection parameters

Condition 1 :
 $\vec{n}_1 \cdot \vec{n}_2 \leq -1 + \epsilon_1$ ← Face normals must be aligned

Condition 2 :
 $-\epsilon_2 \leq \alpha_1 \leq 1 + \epsilon_2$
 $-\epsilon_2 \leq \alpha_2 \leq 1 + \epsilon_2$
 $-\epsilon_2 \leq \alpha_3 \leq 1 + \epsilon_2$ ← Points must fall on face

Distance between faces must be low enough

$DTYPE = 0$
 Condition 3 :
 $d \leq \epsilon_3 S_1$
 $S_1 = \min$
 $[d(a_1, b_1), d(b_1, c_1), d(c_1, a_1)]$

$DTYPE = 1$
 Condition 3 :
 $d \leq D0$

Contact - FEM system

- In order to turn on the EM contact detection the keyword `*EM_CONTROL_CONTACT` must be turned on.

`*EM_CONTROL_CONTACT`

EMCT	CCONLY	CTYPE	DTYPE	EPS1	EPS2	EPS3	D0
0	0	0	0	0.3	0.3	0.3	

CTYPE = -1 : Node to node contact based on constraints on the scalar potential (Basic recommended).

= 0 : Node to node penalty based contact on the scalar potential (Not recommended).

= 1 : Discrete mortar penalty contact on the scalar potential and vector potential (High accuracy but higher calculation times).

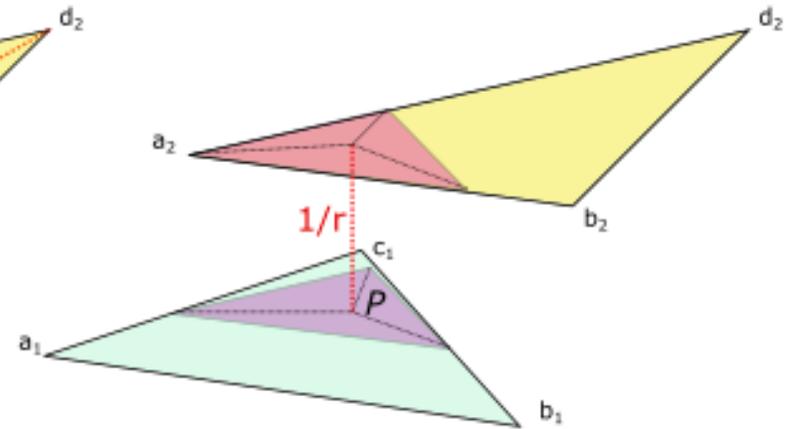
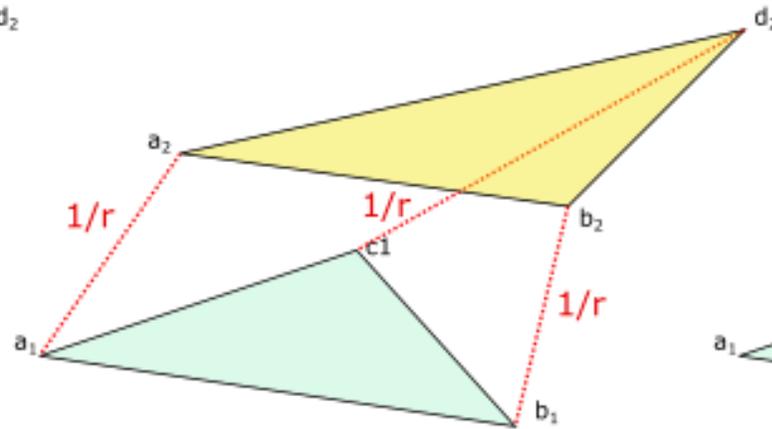
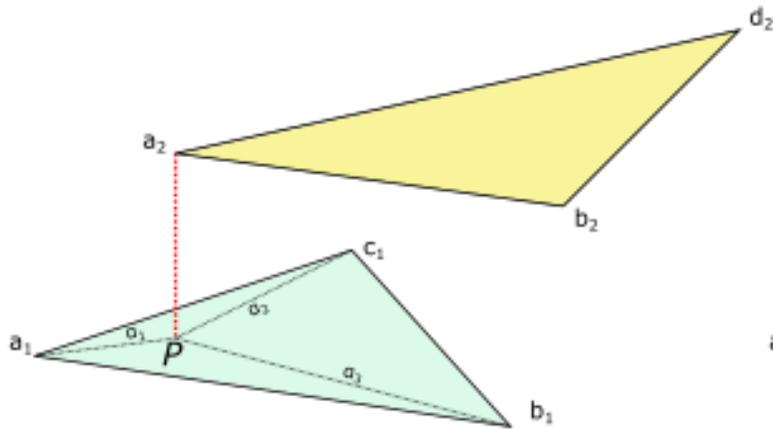
= 2 : Continuous mortar penalty contact on the scalar potential and vector potential (Similar to 1).

Contact - FEM system

CTYPE = -1. Constraints method when the projected node of master face on slave face generates a new constraint added to the constraint matrix : $P_1 = a_1A_1 + a_2B_1 + a_3C_1$

CTYPE = 0. Node to node penalty method where a high contact resistance inverse is added to the nodes detected in contact

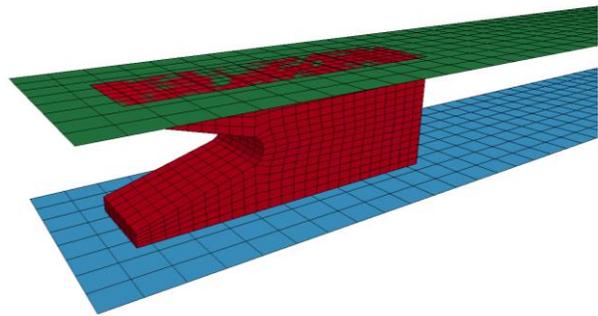
CTYPE = 1-2. Mortar contacts. The intersection polynomial between faces is reconstructed and accurate coefficients are distributed to the local face to face stiffness matrix before addition to the global stiffness matrix.



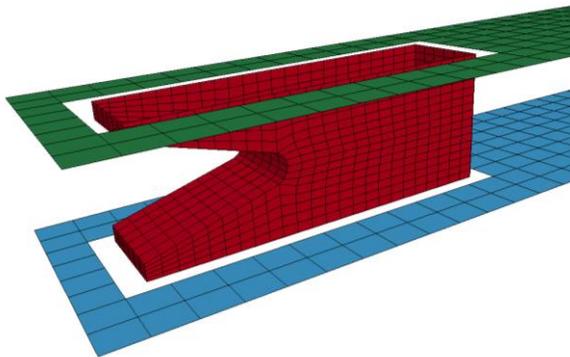
Contact – BEM system

- The EM solver uses a BEM method based on the Biot-Savart law in order to calculate the interaction between conductors. If two BEM mesh elements come into contact, this will lead to a divergence.
- Instead, when the electromagnetic contact detection is turned on, the EM solver will remove the faces that are on the contact surface from the BEM and internally stitch the two BEM surfaces together in order to achieve a continuous closed BEM mesh.
- A decent quality for the surface mesh around the contact area is recommended.

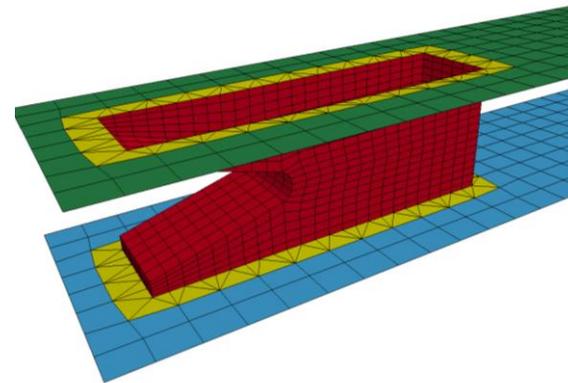
1 : Initial BEM mesh



2 : Removing BEM faces

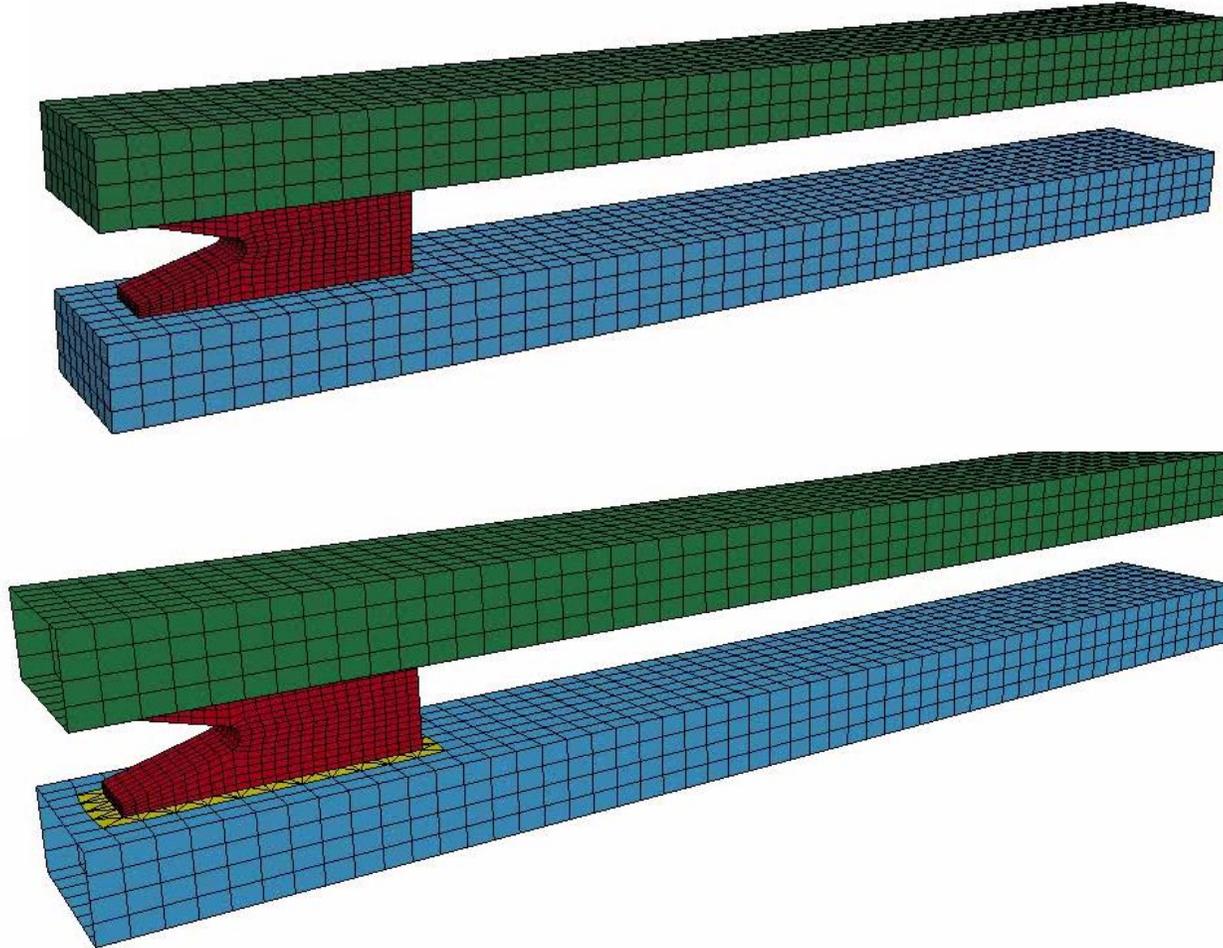


3 : 'Stitching' BEM meshes together



Contact – BEM system

The 'contact skirt' is rebuilt every time the BEM system is recomputed. Depending on the problem, a high recomputation frequency might be needed to ensure the stability of the calculation (See for example ncyclbem in *EM_CONTROL).



Case-Study Railgun example

A simple railgun input deck

```

*EM_CIRCUIT
  circid  circitype  lcid
    1      1         4
  ssidcurr  ssidvin  ssidvout
    4      1         2

```

User has decided to apply global current condition on projectile mid section (See Segment Set 4)

```

*EM_CONTROL_SOLUTION
  ncylfem  ncylbem  autofem  autobem  tol1fem  tol2fem  tol1bem  tol2bem
    1      1      0.3      0.1      4.0      1.5

```

User has decided to use an automatic criteria for the FEM-BEM matrix recomputation frequency. High tolerance values have been selected for the BEM solve to avoid too frequent recomputations

Recomputing the BEM system also updates the contact detection

```

*EM_CONTROL_CONTACT
  emct  cconly  ctype
    1    1      2

```

Turning on EM contact search. Will detect BEM faces in proximity between the projectile and the rails

Penalty based contact on FEM system

```

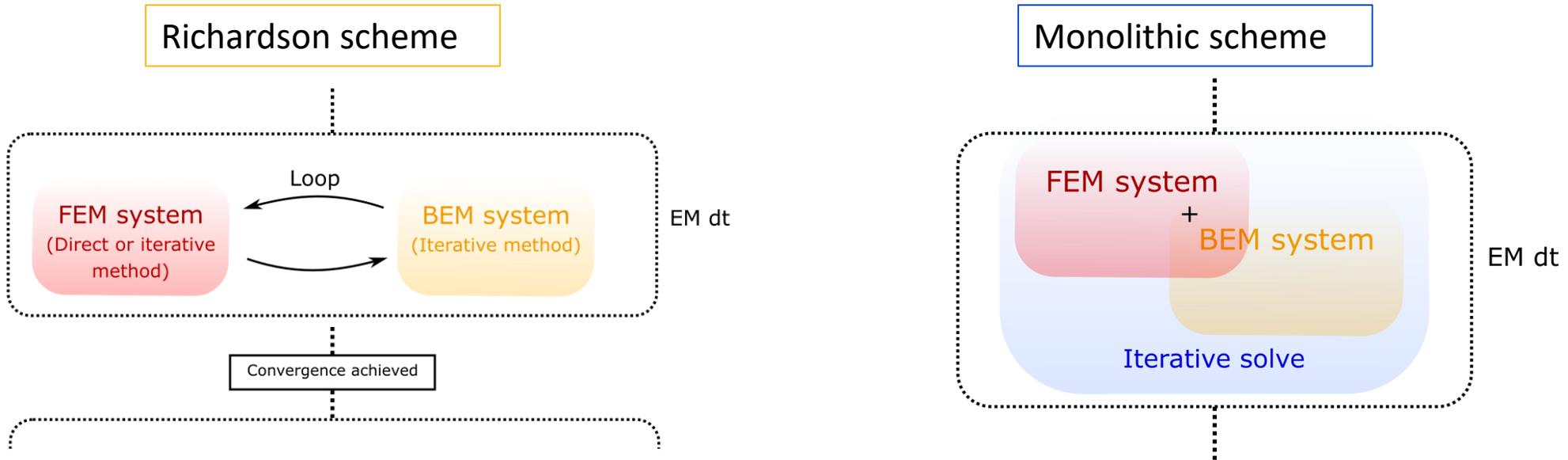
*EM_DATABASE_PARTDATA/GLOBALENERGY

```

Those keywords output ascii files and allow the user to have access to part specific quantities (such as total force on projectile) or total quantities (such as amount of generated magnetic energy).

Coilgun

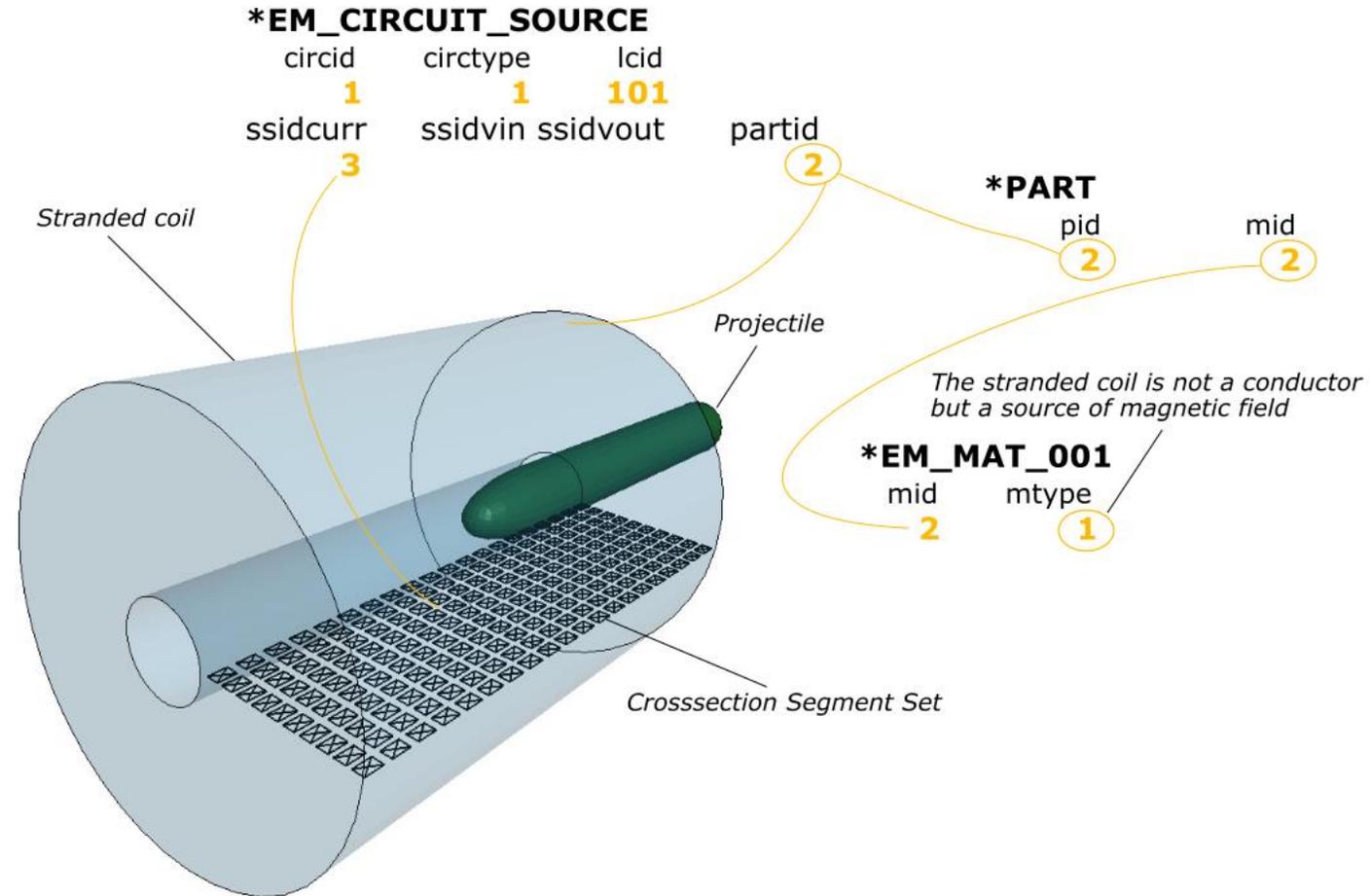
- In order to handle high permeability values, a more robust approach than the classic iterative coupling between the FEM and BEM systems is required. A switch needs to be made to a monolithic scheme which solves the two FEM and BEM system in a single unified approach. This approach is more robust and is capable of handling strong nonlinear permeabilities (BH curve). *EM_SOLVER_FEMBEM_MONOLITHIC replaces *EM_SOLVER_FEMBEM.



Case Study – Coilgun

The coil– modelled stranded conductors a.k.a Source circuit

- Stranded Conductors are usually modelled as continuous cylinders with one segment set through its section.
- A uniform current can be imposed and will generate a magnetic field source on other conductors.
- The keyword is `*EM_CIRCUIT_SOURCE` and needs to be associated to a Part ID. The imposed current value is the Ampere-Turns value (for eg 1A and 203 turns means the value 203 needs to be imposed).

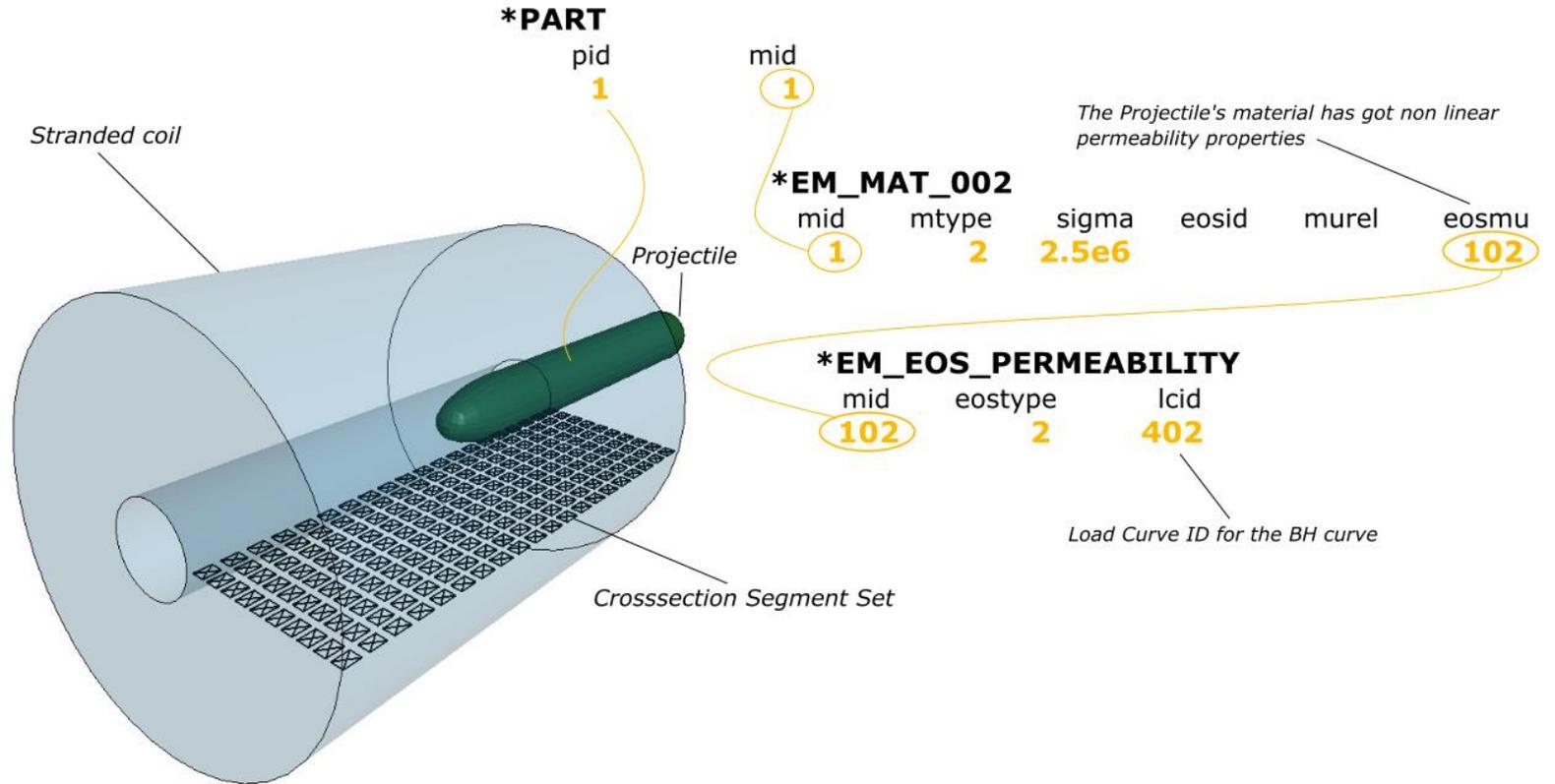


Case Study – Coilgun

The Projectile – Non linear permeability material => switch to magnetic surface force

*EM_CONTROL_COUPLING

THCPL	SMCPL
	2



SMCPL = 2 replaces the traditional Volumetric Lorentz Force by the Magnetic surface force, to be used in conjunction of the monolithic solver and to be preferred in cases involving non linear permeabilities.

SMCPL = 3 allows the solver to automatically trigger the most robust force calculation on the different conductors depending on their material properties.

Case Study – Coilgun

Turning on Monolithic solver

***EM_SOLVER_FEMBEM_MONOLITHIC** (replaces **EM_SOLVER_FEMBEM**)

MTYPE	STYPE	ABSTOL	RELTOL	MAXIT
		1.e-6	1.e-4	500

First line defines tolerances of monolithic solve

	NEW_STOL	NEW_ATOL	NEW_RTOL	NEW_MAX
	1.e-4	1.e-8	1.e-4	

Second line defines tolerances for non linear convergence when BH curve is present

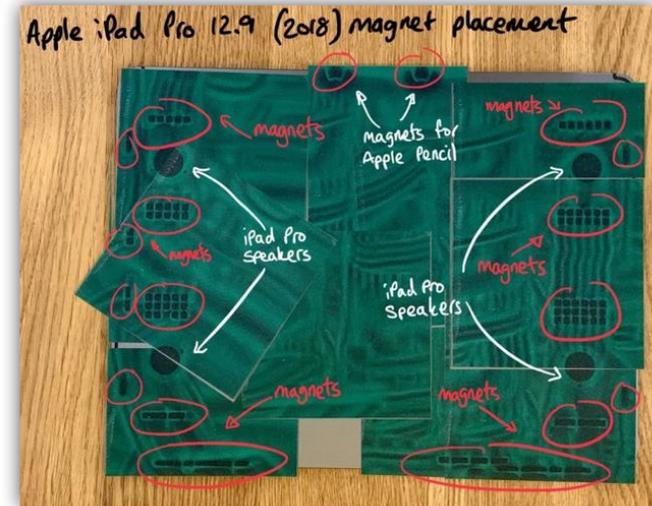
In addition to the traditional P and Q matrices, a third matrix W is being assembled in the case of the monolithic solver and its tolerances can again be adjusted in the keywords ***EM_SOLVER_BEMMAT**.

Focus on magnet simulations

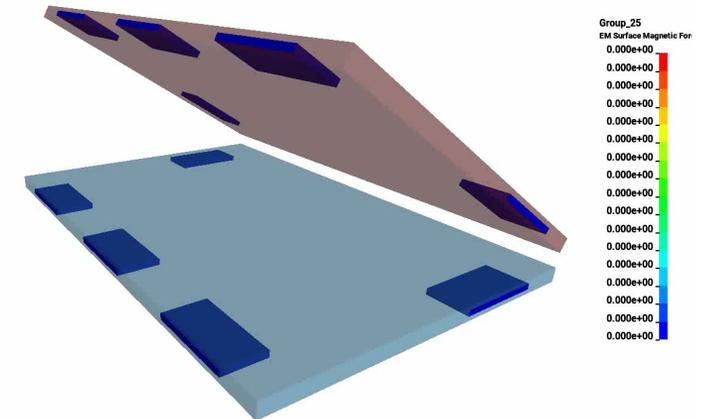


Background

- Magnets used in modern electronics devices have seen a **multi-fold increase** in the recent past.
- **Simulation Engineer Pain-Point:** How to simulate the impact of two bodies resulting from magnetic force?
- The use of **simulation** in this context will reduce the cost and development time for such mechanisms while increasing the confidence in the design.
- No air mesh between conductors is crucial as it will allow magnets to interact with other magnets and conductors as well as freely translate and rotate in all directions.

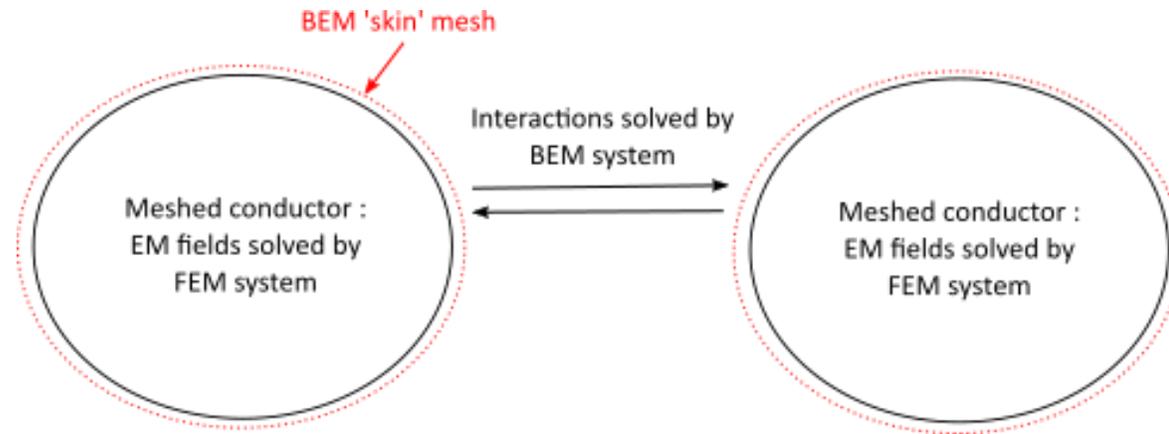


LS-DYNA keyword deck by LS-PrePost
Time = 0



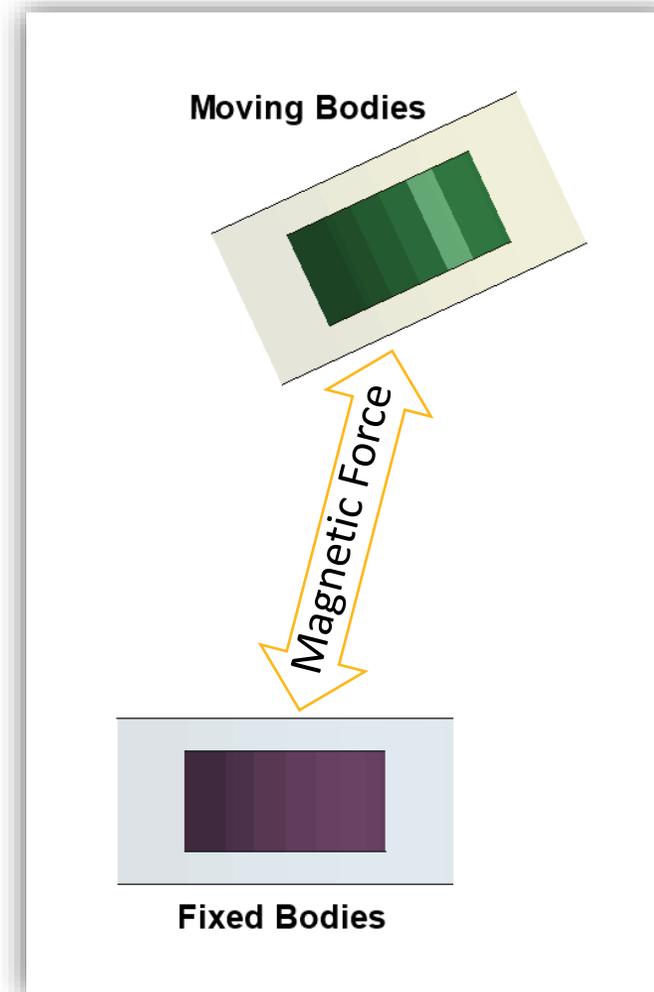
Interaction between conductors

- The EM solver uses finite elements to solve the EM fields within conductors (FEM) but the interaction between conductors is handled by a boundary elements method (BEM) (double integral of Biot-Savart type). This results in a coupled FEM-BEM system.
- In order to solve this BEM system, the EM solver will automatically create those boundary elements based on the surface mesh size of the conductors resulting in BEM surface parts, accessible in the d3plots.
- This means that no air mesh is necessary.



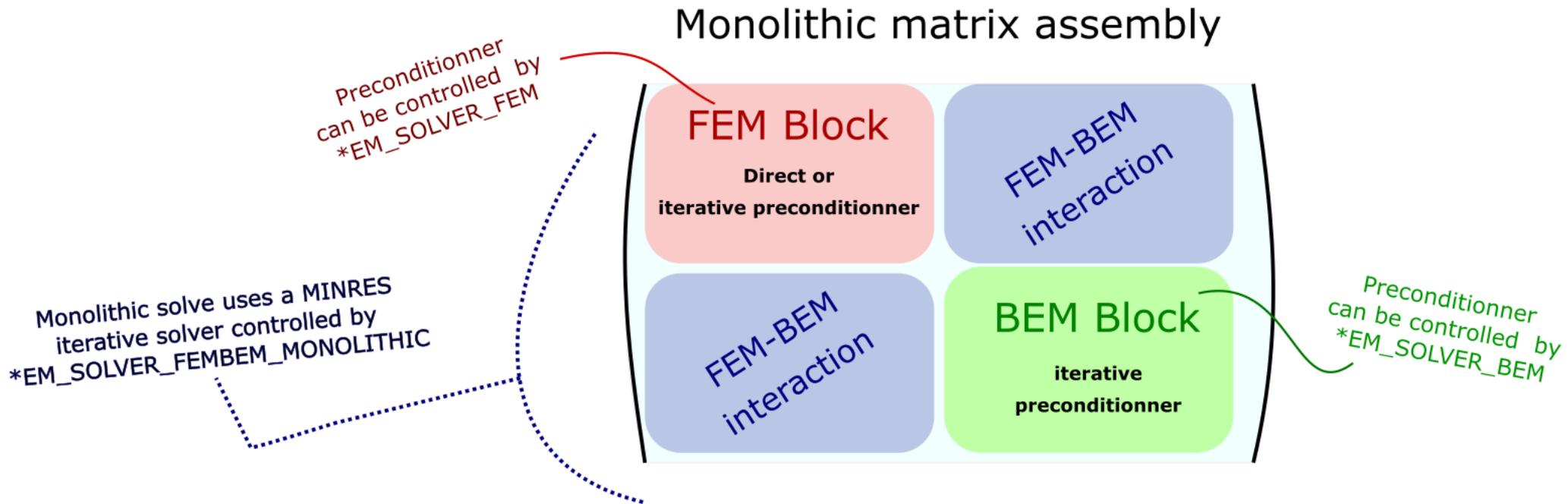
Interaction between magnets/ferromagnets

- In order to solve the magnetic field generated by magnets, the FEM-BEM system must be solved using a monolithic approach rather than the classic iterative Richardson approach. See `*EM_SOLVER_FEMBEM_MONOLITHIC`.
- Magnets can be assigned a conductivity or can be defined with a “zero conductivity” in which case no Eddy current effects will be present. This is equivalent to a magnetostatic problem being solved at each timestep.
- In any case, the calculation of the magnetic force will not rely on Lorentz force but be driven by a magnetization force applied on the surface of the magnets or ferromagnets. Set `*EM_CONTROL_COUPLING, SMCPL` field to 2.



Monolithic EM solve

- FEM and BEM system are assembled and solved in a single matrix. This approach needs to be triggered by `*EM_SOLVER_FEMBEM_MONOLITHIC`.
- The advantage of such an approach is robustness, higher timesteps can be used, varying permeability problems can be solved as well as magnet interactions.



Magnet definition

- A magnet needs to be defined by its relative permeability (often linear and close to 1.) as well as its coercive force a.k.a magnetization.

*EM_PERMANENT_MAGNET

MID	PID	MTYPE	NORTH	SOUTH	HC
					9.e5
X/NID1	Y/NID2	Z			

*EM_MAT_002

MID	MTYPE	SIGMA	EOSID	MUREL	EOSMU
1	2	0.		1.05	

MID is a magnet ID associated to a part ID PID.

MTYPE says whether the magnet is defined by North/South segment/node sets or by a global vector orientation.

North/South are the two segment/node set IDs defining the two poles of the magnet

X/NID1, Y/NID2, Z are used for the global vector orientation when the corresponding MTYPE is selected.

HC is the coercive force of the magnet ($H_c = B_r/\mu$). Careful about units !

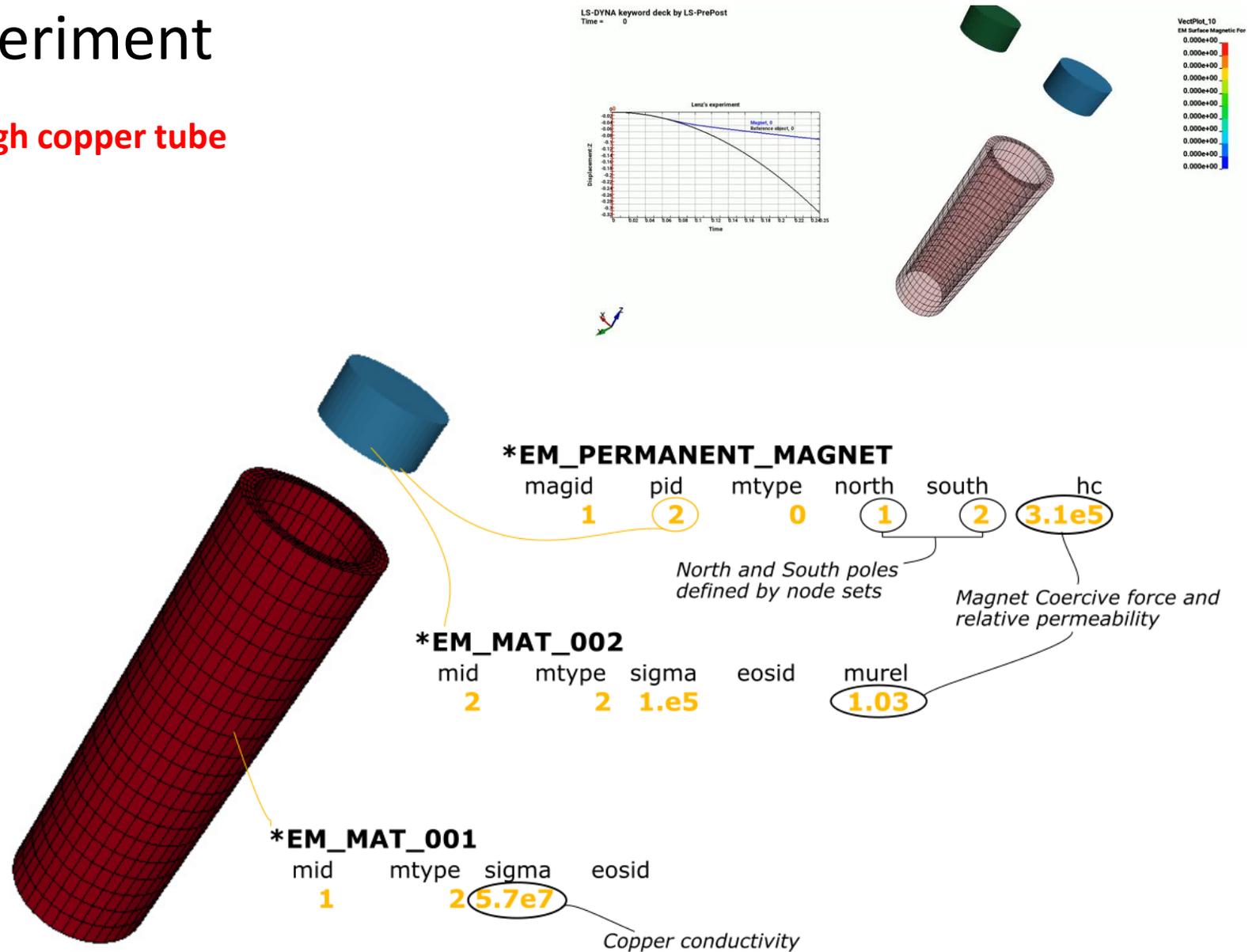
FEM/BEM system considerations

- As in classic Eddy current applications, one important point to consider is the periodic recomputation of the FEM and BEM systems which, by default, are only set up once during the initialization phase.
- For example, if the conductors deform and their meshes become distorted, then it becomes important to recompute the FEM system regularly to avoid inaccuracies.
- If the conductors move in respect to one another, then it becomes important to recompute the BEM system.
- In an ideal scenario, the FEM/BEM systems would be recomputed at every timestep. However, this would prove to be too costly (especially the BEM system which consists of dense matrices). So, it is up to the user to set reasonable values, compromising between accuracy and speed.
- The classic way of defining those recomputation frequencies is by using field 7 and 8 of *EM_CONTROL. Alternatively, and, starting with R12, an automatic criteria can be defined using *EM_CONTROL_SOLUTION.

Case Study – Lenz Experiment

Lenz experiment – magnet falling through copper tube

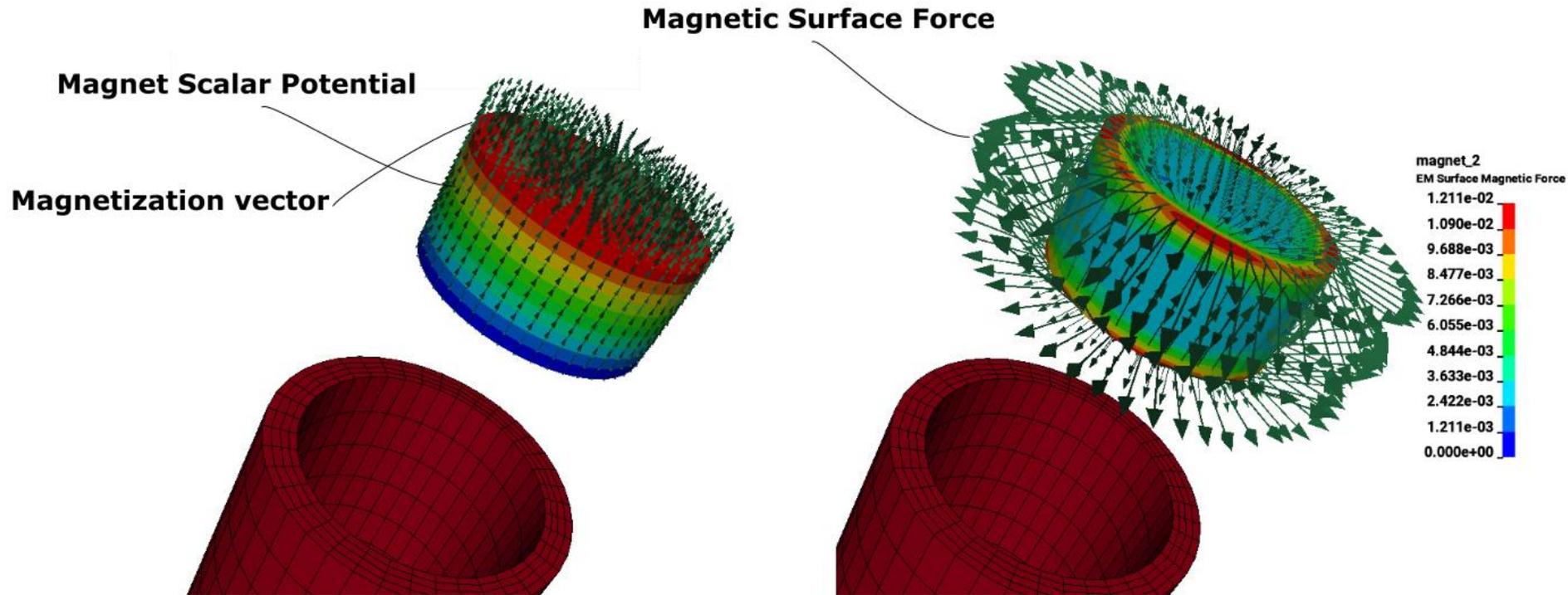
- This famous problem consist of a permanent magnet falling through a copper pipe. The temporal change of the magnetic field in the copper induces currents which themselves create an opposing magnetic field that slows the fall.
- Check magnet and solver properties. Notice the presence of `*EM_SOLVER_FEMBEM_MONOLITHIC` and `*EM_CONTROL_COUPLING`.
- The FEM matrix recomputation frequency (`ncyclFEM`) is set to a high value since no conductors deform while the BEM matrix recomputations (`ncyclBEM`) happen frequent since the magnet is moving.



Case Study – Lenz Experiment

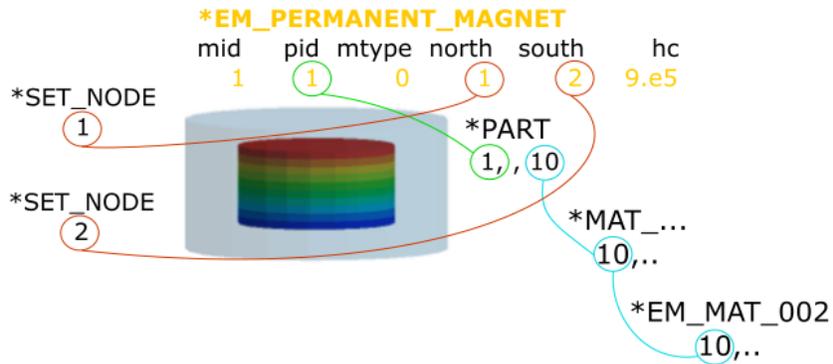
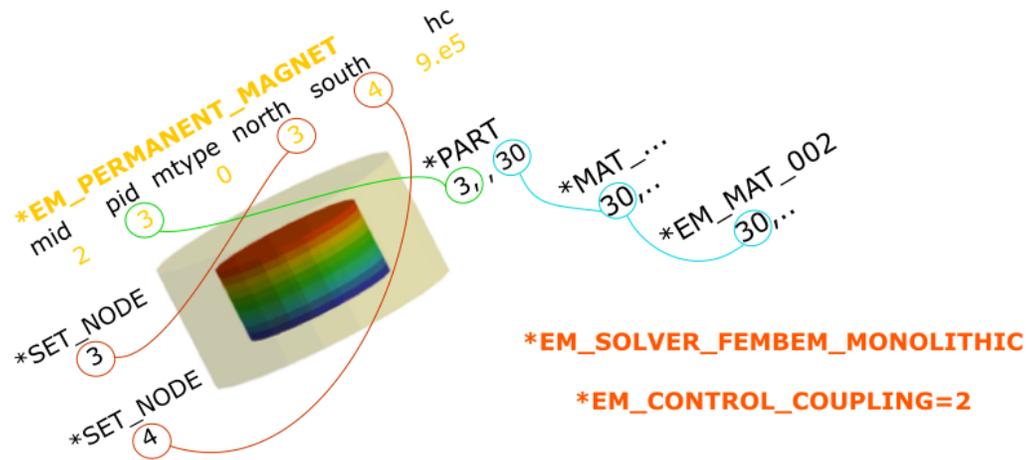
Post-treatment :

- The North/south Poles will allow the solver to calculate a magnetization vector. Its orientation can be checked.
- The magnetic surface force that magnets apply on themselves and on other conductors can also be accessed
- For each magnet, an ASCII file is output “em_magnet_magid.dat” which gives various info on each magnet for e.g total magnetic force applied on the magnet.



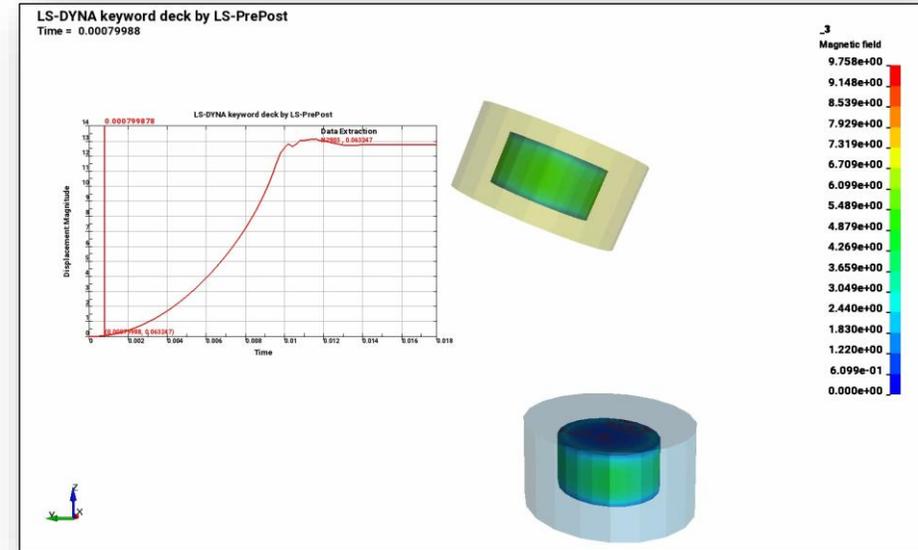
Case Study – Magnet snapping

Magnet snapping



The solid mechanics contact must be precisely defined :

```
*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_MPP
$# cid title
$ 1
,1
$# ssid msid sstyp mstyp sboxid mboxid spr mpr
$# fs fd dc vc vdc penchk bt dt
$# 0.1 0.05 0.0 0.0 100.0 0 0.01.00000E20
$# sfs sfm sst mst sfst sfmt fsf vsf
$# 1.0 1.0 0.0 0.0 1.0 1.0 1.0 1.0
$# soft sofscl lcidab maxpar sbopt depth bsort frcfrq
$# 0 0.1 0 1.025 2.0 2 5 1
$# penmax thkopt shlthk snlog isym i2d3d sldthk sldstf
$# 0.0 1 2 0 0 0 0.0 0.0
```

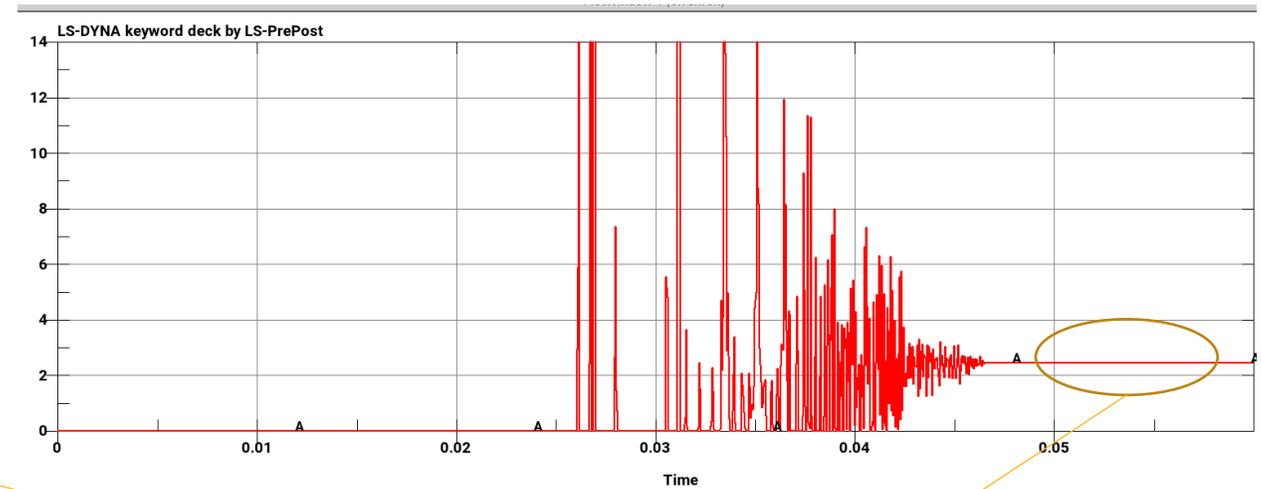
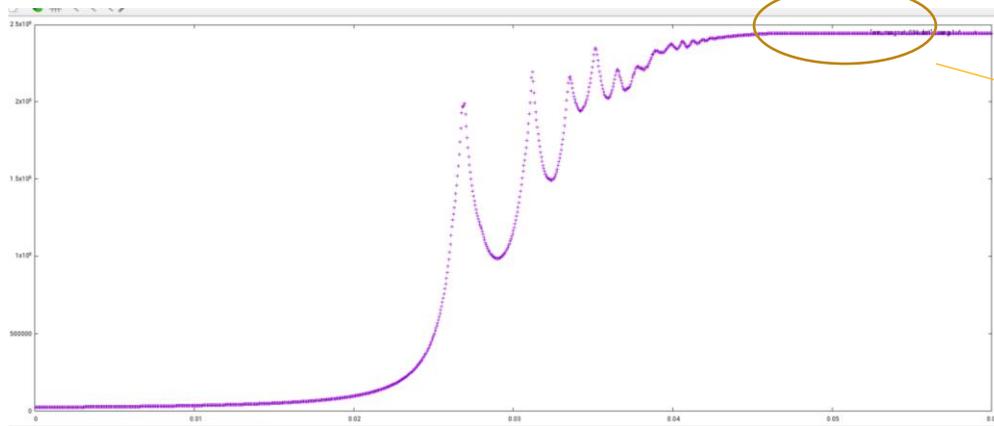


Case Study – Magnet snapping

Post :

Rcforc gives the contact force :

Use the “em_magnet_magid.dat” to estimate the total magnet force function of time :

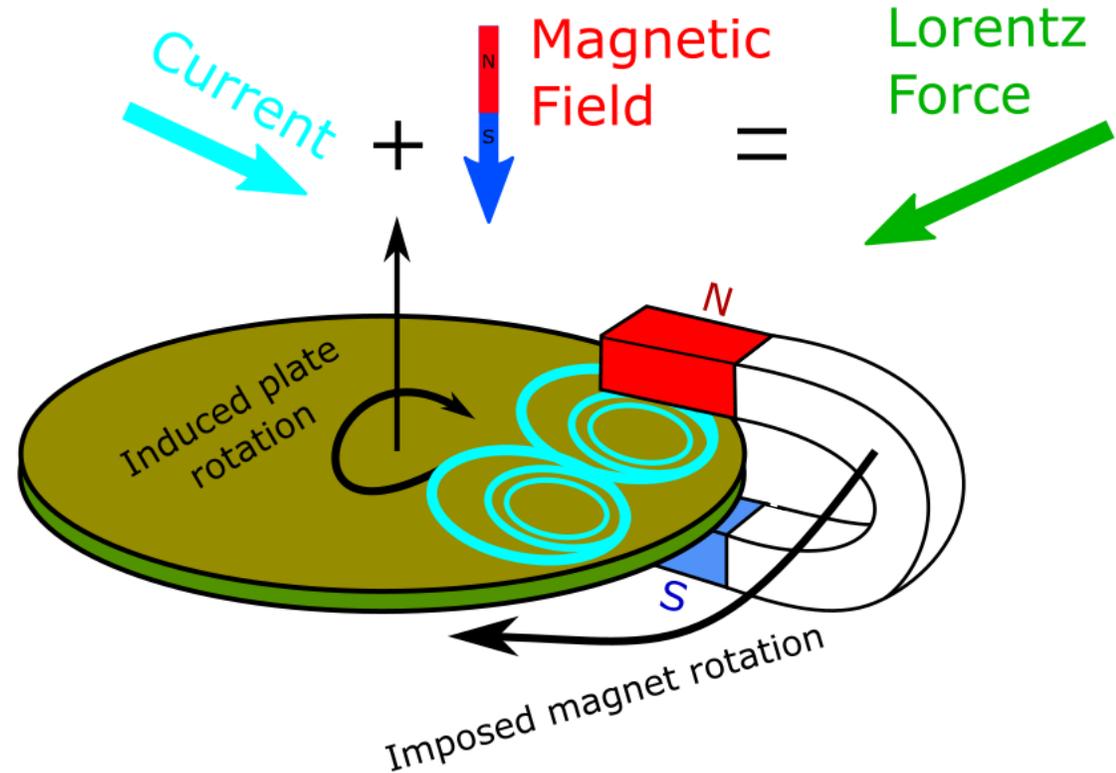


Matching results at equilibrium

Case Study – Arago's disk

Principle :

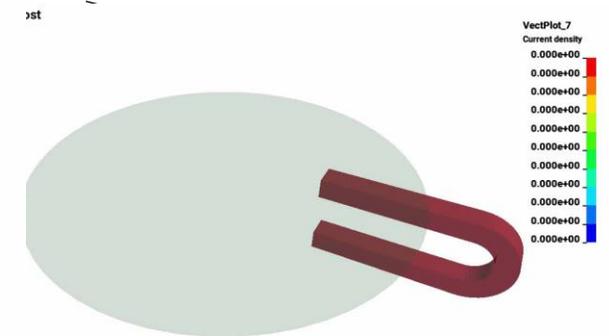
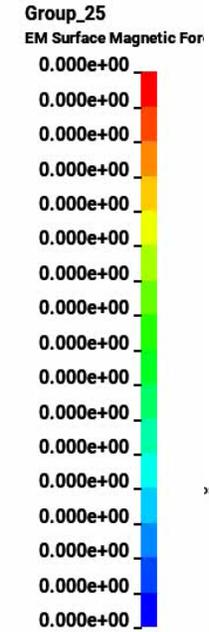
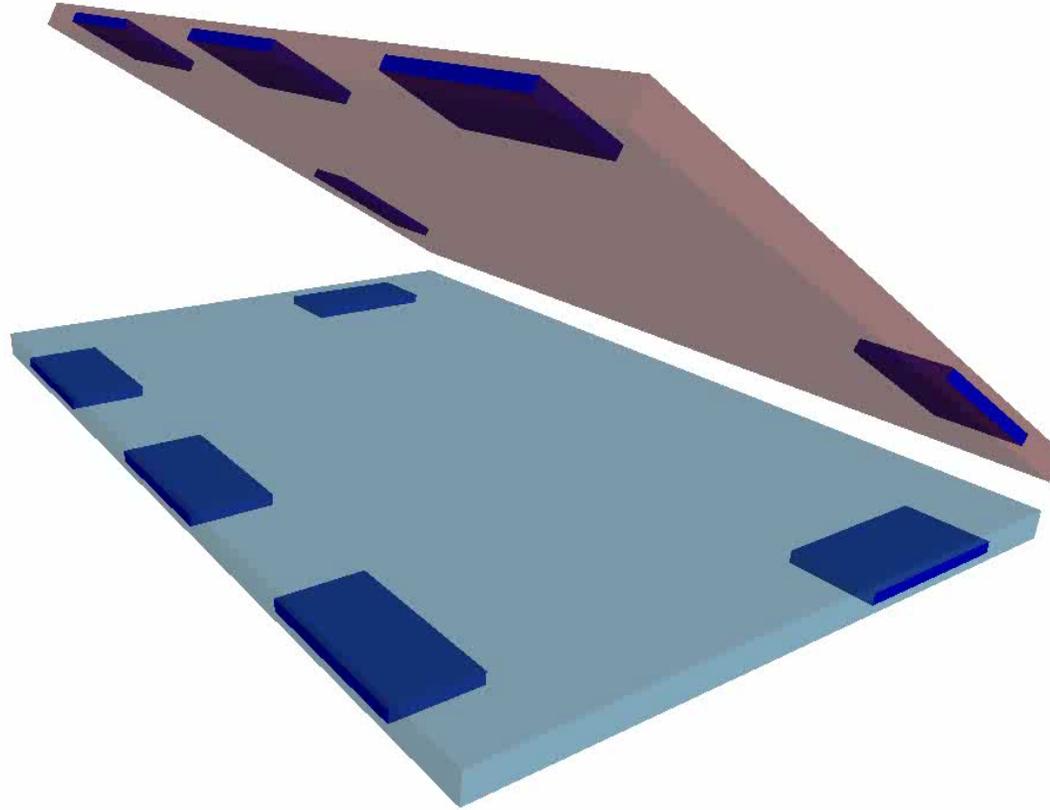
- First established by François Arago in 1824, this experiment reflects the base concepts behind eddy current brake or motor applications.
- A horseshoe magnet spins around a conductor plate generating fast moving magnetic field lines in the plate's vertical direction. This, combined with the electrical conductivity properties of the plate will generate Eddy currents in the plate.
- This will generate an electromagnetic force (Lorentz force) which is orthogonal to both the magnetic field and the induced current (eddy current right-hand-side rule). This will induce a rotation in the plate albeit at a slower pace than the magnet rotation.



Case Study – Arago's disk

Input deck study :

LS-DYNA keyword deck by LS-PrePost
Time = 0

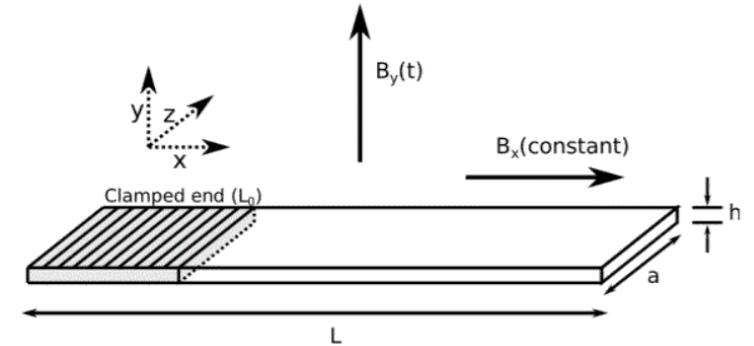


Case Study – Cantilever beam

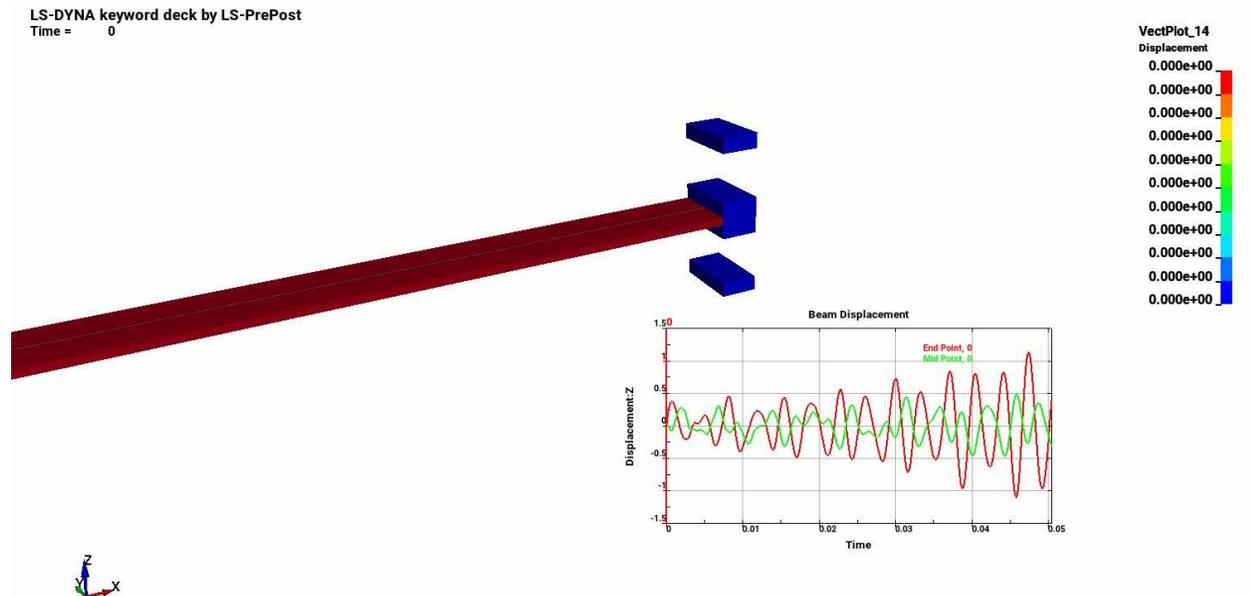
Modified T.E.A.M 12 example :

- In the original configuration the beam's oscillations are triggered by an external field. See *EM_EXTERNAL_FIELD.
- In this modified version, two magnets are placed at the end of the beam and a third magnet is attached to the beam.
- An initial displacement is applied on the beam's tip. The magnets will interact with each other as well as with the beam to provide attraction/repulsive forces.
- This will generate deformations and oscillations in the elastic beam.
- Reminder : the EM solver can be coupled with either the implicit solid mechanics solver or the explicit solid mechanics solver, based on needs.

Original configuration :



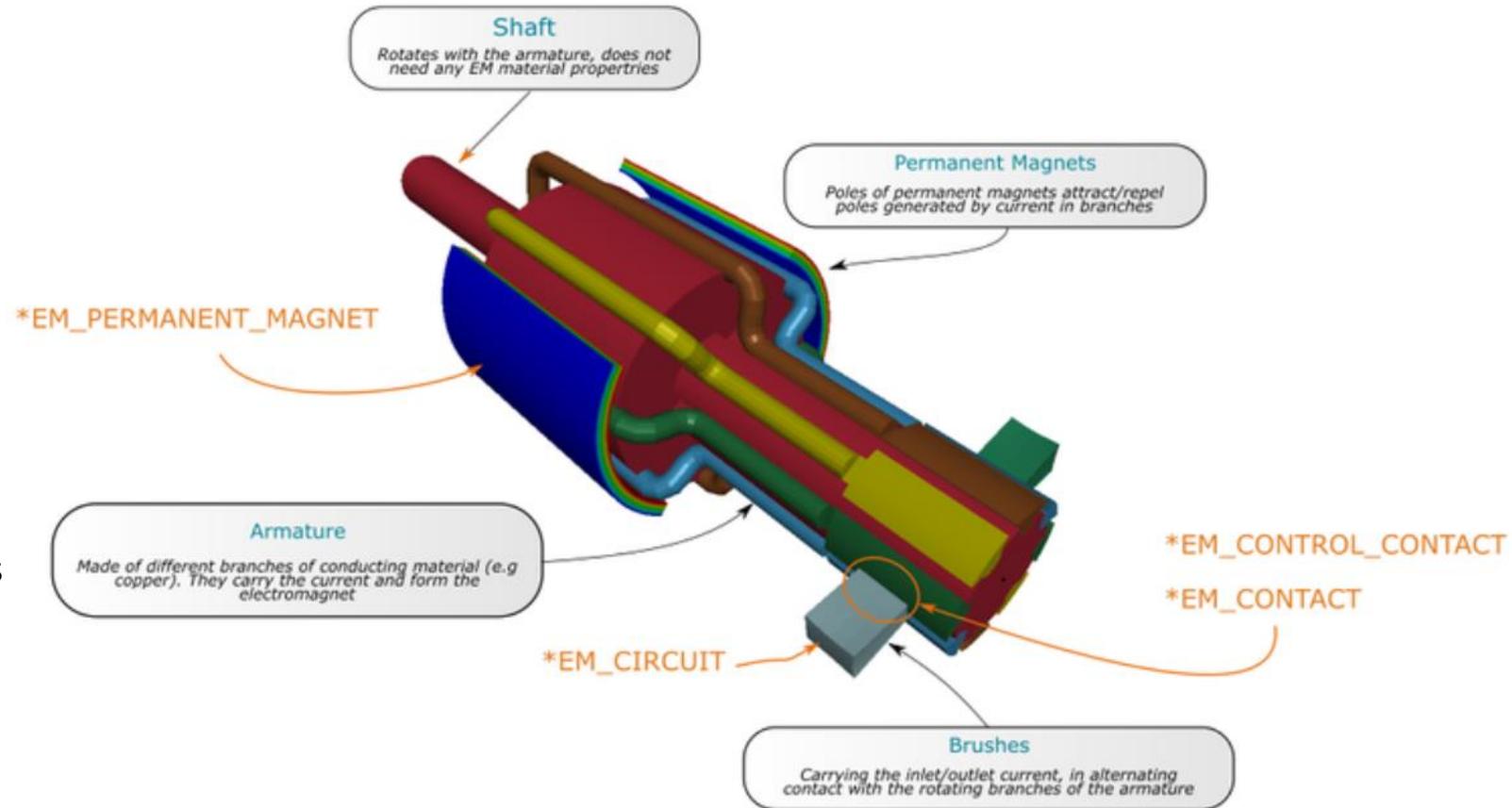
Modified version :



Case Study – DC motor

Principle :

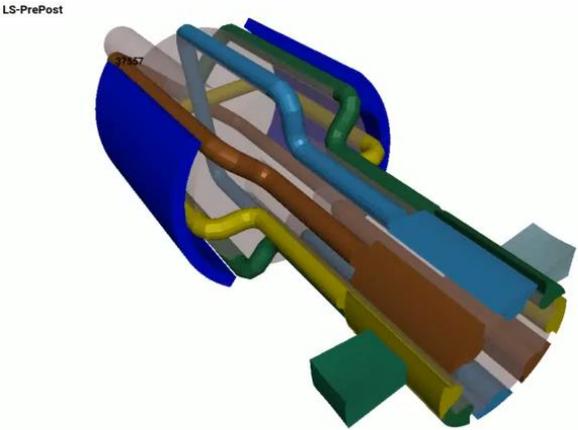
- A standard voltage of 12 V is applied between the two brushes of the motor.
- Permanent magnets located on each side of the armature cause the branches to start moving.
- The EM contact algorithm allows the current path to "switch" between the different branches and maintain the movement.
- The use of LS-DYNA FEM/BEM method to handle the electromagnetic fields as well as its integrated and automatic coupling with the structure makes it a powerful tool for such simulations



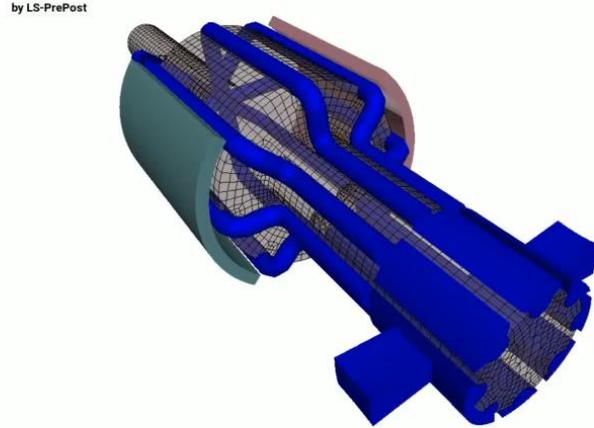
Case Study – DC motor

Post :

Magnetic potential in stator (permanent magnets)

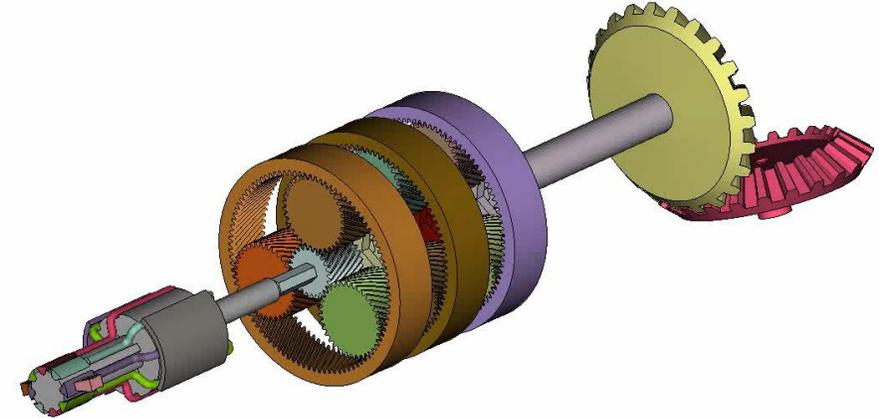


Scalar potential in armature branches and brushes



Increasing the complexity :

0:d3plot : LS-DYNA keyword deck by LS-PrePost : STATE 2 ,TIME 1.00000000E-04

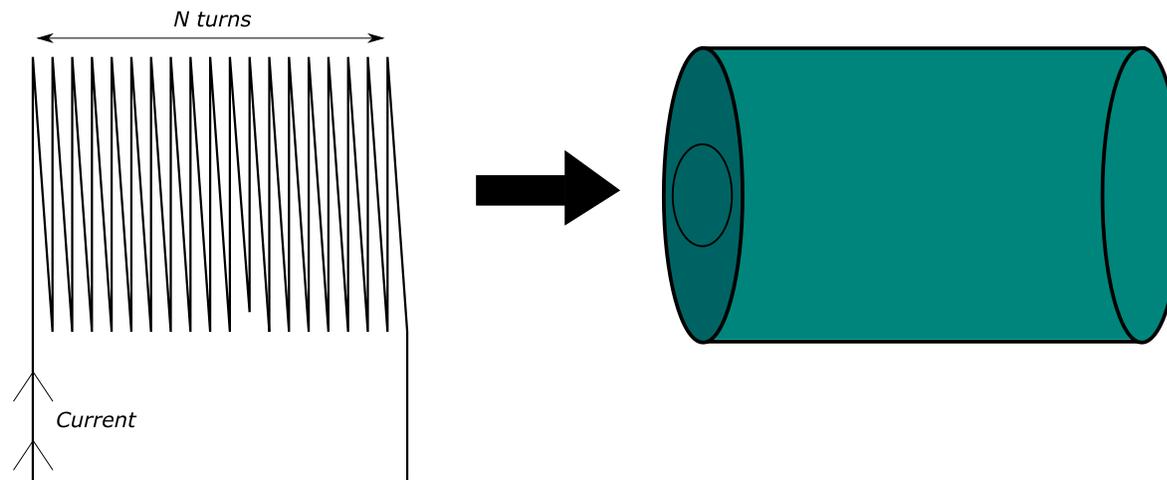


**Focus on stranded conductors,
magnetostatics and actuators**



Source circuit

- Stranded Coils refers to coils consisting of many fine turns of conducting wires.
- Since the cross-section of the wires is small compared to the skin depth, the eddy currents can be neglected and the magnitude of the current density within the wires can be considered constant.
- Numerically, the wires are modelled by a continuous cylinder and a uniform current or voltage can be imposed on its cross-section. This will generate a magnetic field source on other conductors.
- The keyword is `*EM_CIRCUIT_SOURCE` and needs to be associated to a Part ID. The imposed current value is the Ampere-Turns value (for eg 1A and 203 turns means the value 203 needs to be imposed).



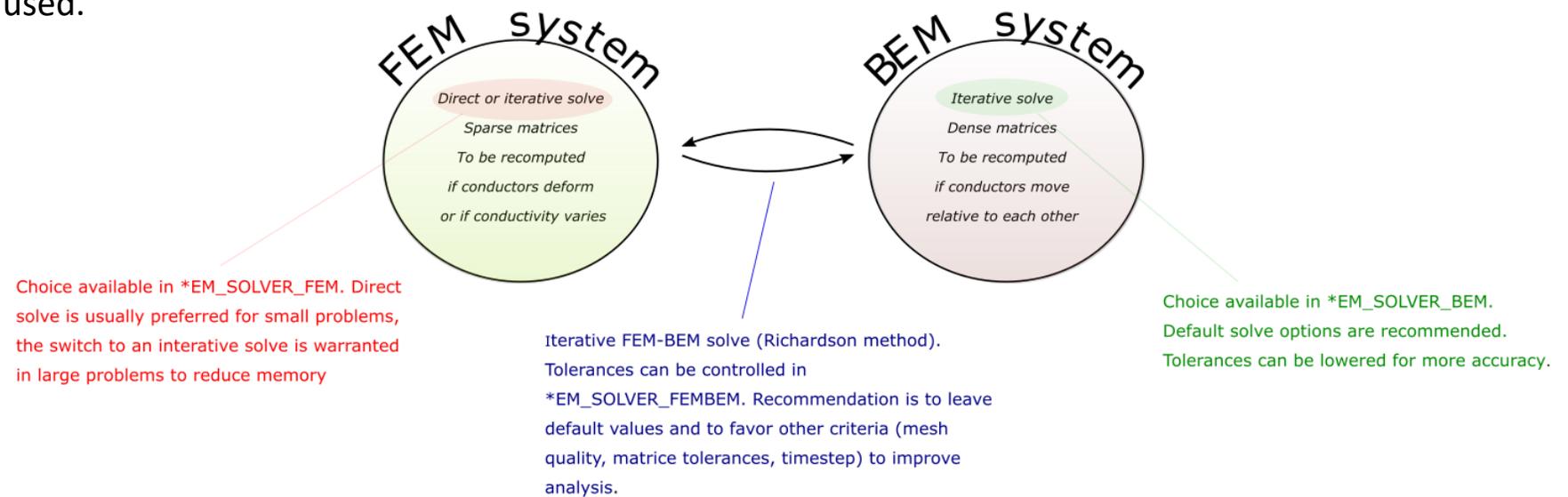
EM timestep considerations

- Based on the Vector Potential equation, the CFL timestep for Eddy currents is :

$$\Delta t \leq \frac{l^2}{2D} \quad D = \frac{1}{\mu\sigma}$$

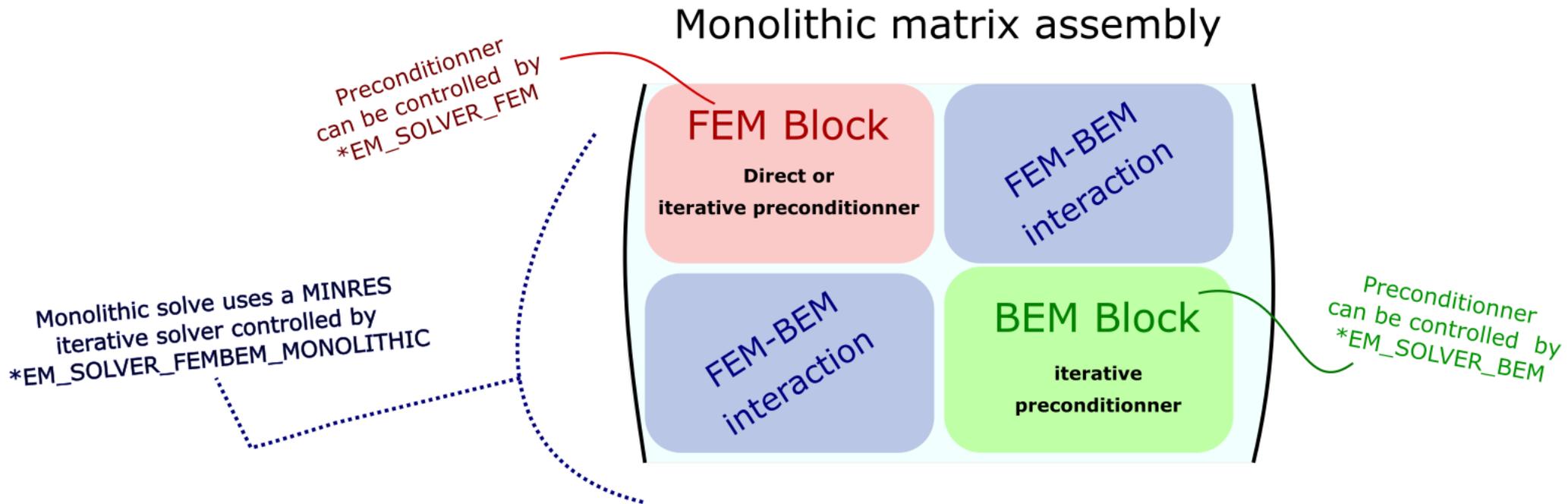
Mesh size

- The EM solver is implicit so higher values can be allowed. However, by default, the coupled FEM-BEM system is solved in a partitioned way (Richardson approach) which puts a limit on how high the EM timestep can be.
- Contrary to magnetic metal forming which is a fast forming process (μs to ms), applications involving stranded coils often operate at lower frequency, and over longer periods of time.
- The EM solver provides the option to switch to a monolithic FEM/BEM solver. The cost per timestep is higher but the higher timesteps can be used.



Monolithic EM solve

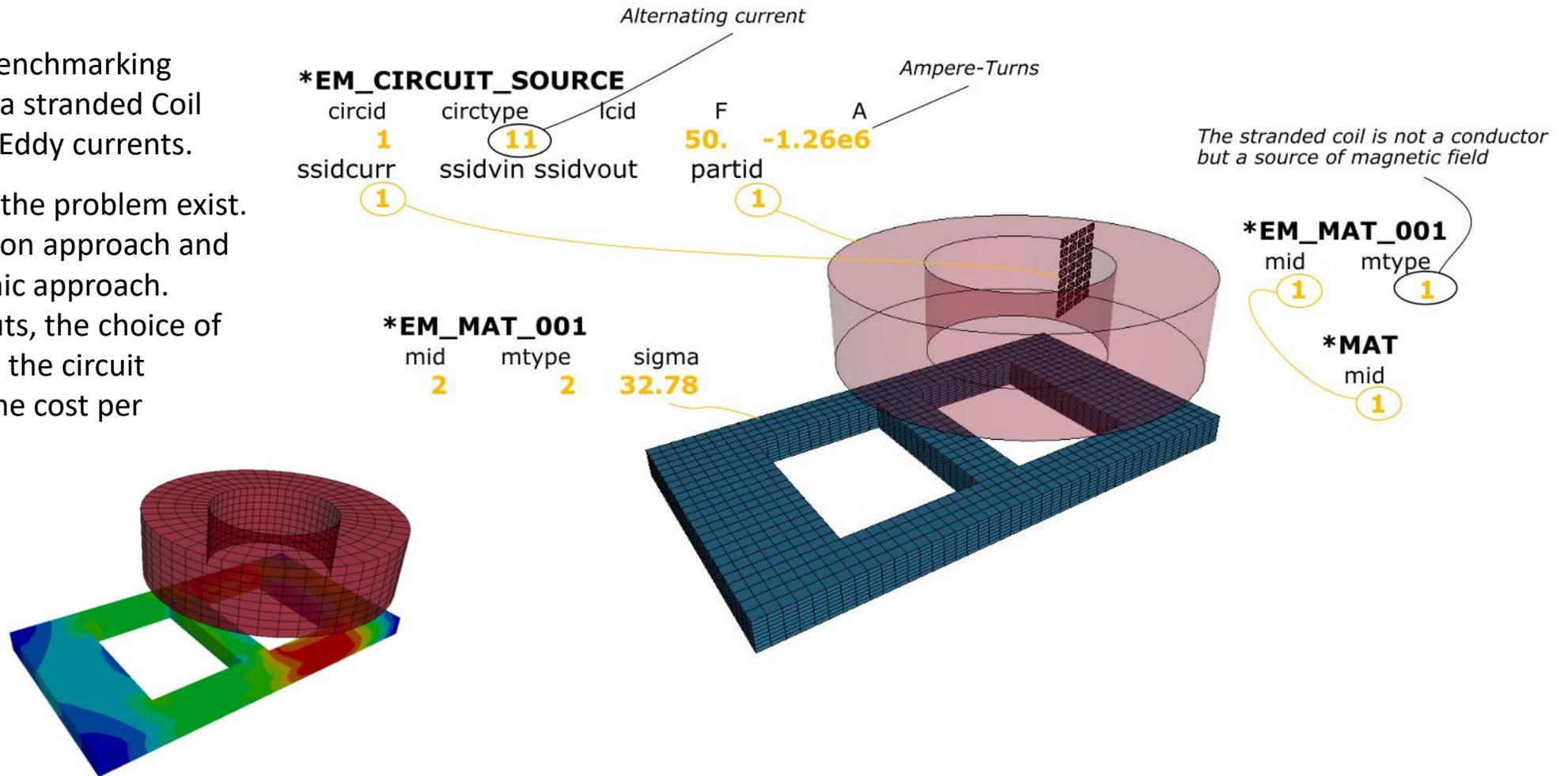
- FEM and BEM system are assembled and solved in a single matrix. This approach needs to be triggered by `*EM_SOLVER_FEMBEM_MONOLITHIC`.
- The advantage of such an approach is robustness, higher timesteps can be used, varying permeability problems can be solved as well as magnet interactions.



Case Study – TEAM 3 problem

Stranded Coil + workpiece

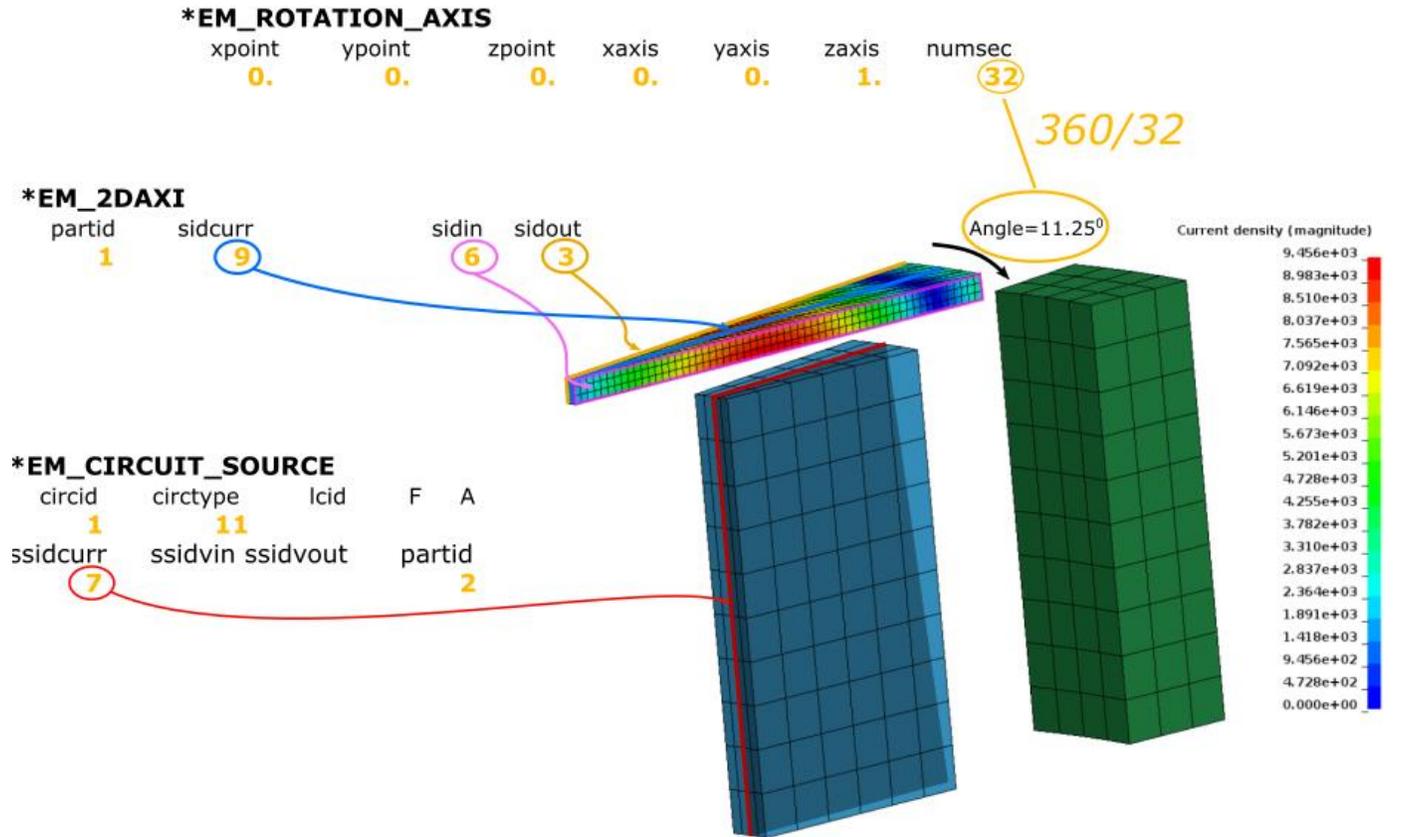
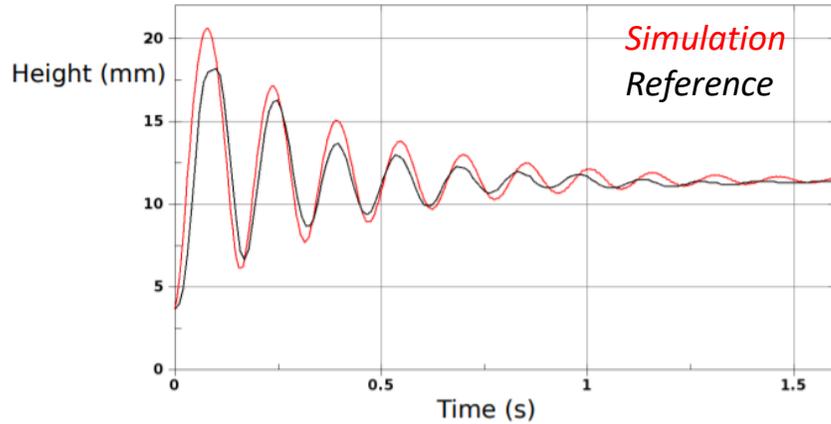
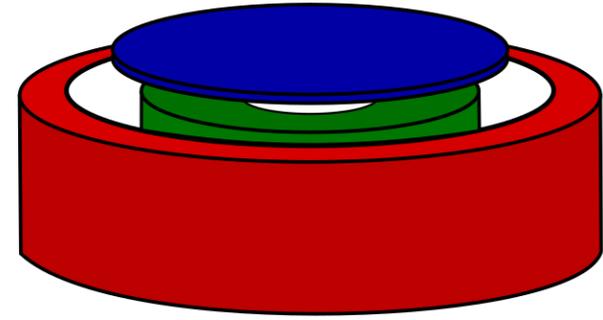
- Classic Eddy current benchmarking problem consisting of a stranded Coil and a workpiece with Eddy currents.
- Two configurations of the problem exist. One with the Richardson approach and one with the monolithic approach. Compare the two inputs, the choice of timestep compared to the circuit frequency as well as the cost per timestep.



Case Study – TEAM 28 problem

2D axisymmetric levitation device

- Classic Eddy current benchmarking problem consisting of two stranded coils that generate Lorentz forces on a plate which counters gravity and brings the plate to an equilibrium position.
- Stranded coils can be modelled as well by applying the *EM_CIRCUIT_SOURCE to the mid-segment set



Magnetostatics

- Stranded Coils are also frequently encountered in magnetostatic applications where they act as the main current source.
- Magnetostatics is the study of magnetic fields in systems where the currents are not considered or considered steady. Typically, such applications have a dominant magnetic material where the permeability is high ($\mu_r = \frac{\mu}{\mu_0} \gg 1$.) or non linear (B-H curve).
- In order to define such a material, the user has to assign a “0.” conductivity to the conductor and a relative permeability :

*EM_MAT_002

MID	MTYPE	SIGMA	EOSID	MUREL	EOSMU
1	2	0.		1000.	100

*EM_EOS_PERMEABILITY

EOSID	EOSTYPE	LCID
100	1	101

Option A : Defines a linear (constant) permeability

Option B : Defines a non-linear (B-H curve) permeability

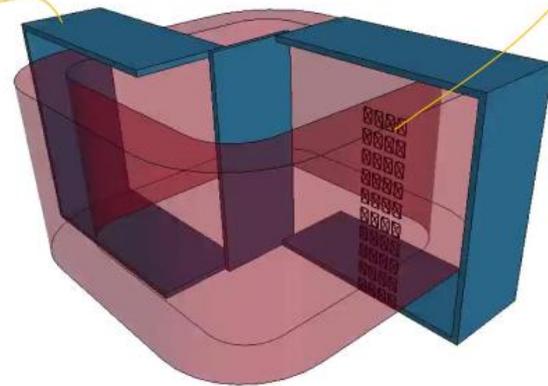
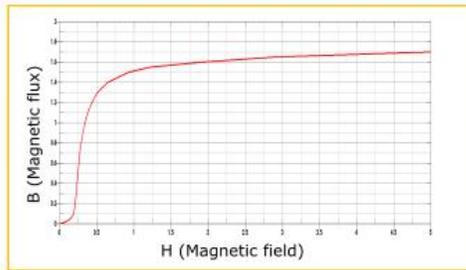
/ Magnetostatics

- The monolithic solver is the only solver capable of solving magnetostatic materials. It will automatically switch to a robust and state of the art AMS solver to handle the zero-conductivity regions.
- In cases involving non-linear materials, the cost for the initial convergence can be heavy. If the conductors do not change or move over time, all subsequent timesteps will then be fast since nothing will change.
- For a magnetostatic solve involving non-linear materials, it is recommended to activate the line search feature. This will allow the solver to better position itself along the BH curve during the iterations and reach a faster and more robust convergence. In non-magnetostatic cases, this line search is often not used since the evolution of the magnetic fields are mostly driven by small timestep increments.
- The BEM preconditioner solve of the monolithic BEM block becomes a key component of robustness and solving times. For non linear cases, it is recommended to switch to a LLT factorization approach. See EM_SOLVER_BEM.

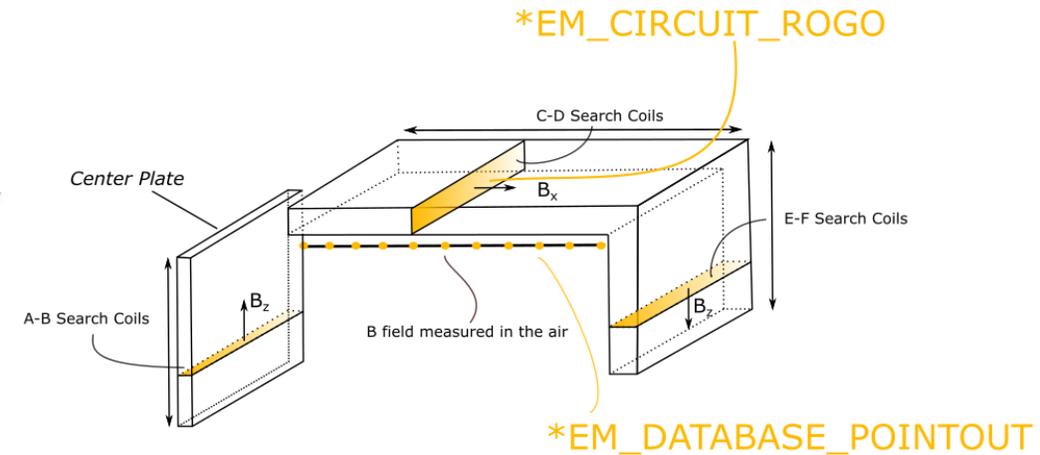
Case Study – T.E.A.M 13

Non-linear steel plates around stranded coils :

- As illustration of the magnetostatic capabilities, the T.E.A.M 13 problem will be considered. It consists of steel plates placed around a stranded coil with a constant current. The steel plates have highly non linear permeabilities making it a challenging computational problem.
- The objective is to study the magnetic flux in the plate sections after saturation has been achieved. This problem can therefore be modelled using a time dependent approach by considering the conductivity of the steel plates (current will diffuse through the thickness until steady state is achieved) or solving it directly using a magnetostatic approach (1 step solve).



*EM_CIRCUIT_SOURCE
Constant current : 1000 AT



Case Study – T.E.A.M 13

Keyword discussion :

***EM_SOLVER_FEMBEM_MONOLITHIC (replaces EM_SOLVER_FEMBEM)**

MTYPE	STYPE	ABSTOL	RELTOL	MAXIT
		1.e-8	1.e-4	500

First line defines tolerances of monolithic solve at each Non linear Newton step.

	NEW_STOL	NEW_ATOL	NEW_RTOL	NEW_MAX
	1.e-2	1.e-6	1.e-2	

Second line defines tolerances for non linear convergence when BH curve is present

LS_ON	LS_FTOL	LS_GTOL	LS_RTOL	
0	0.01	0.5	0.01	

Third line defines line search tolerances (Default recommended). LS_ON=0 (on) for magnetostatic case only

Case Study – T.E.A.M 13

Keyword discussion :

*EM_CONTROL_TIMESTEP

TSTYPE	DTCONST	LCID
2		50

*DEFINE_CURVE

LCID	
50	
0.	1.e-5
2.e-3	1.e-5
2.1e-3	2.e-5
5.e-3	2.e-5
5.1e-3	1.e-4

EM timestep defined by load curve in time dependent case. Small timestep for first steps is used until the magnetic fields have reached the linear portion of BH curve

*EM_CONTROL_TIMESTEP

TSTYPE	DTCONST	LCID
1	1.e-4	

Magnetostatic results are timestep independent. Since the case is static (conductors do not move, the final result will be obtained after the first solve).

Case Study – T.E.A.M 13

Keyword discussion :

*EM_SOLVER_BEM

RELTOL	MAXITE	STYPE	PRECOND
1.e-6		2	4

Relative tolerance for BEM solve. Lower values will augment calculation times but improve robustness

Use STYPE=2, PCG solve.

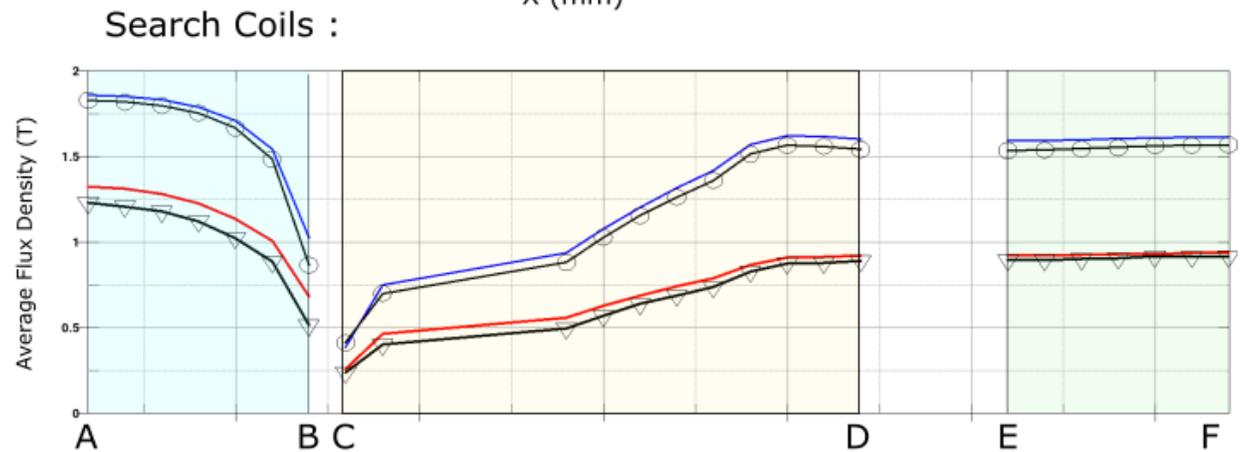
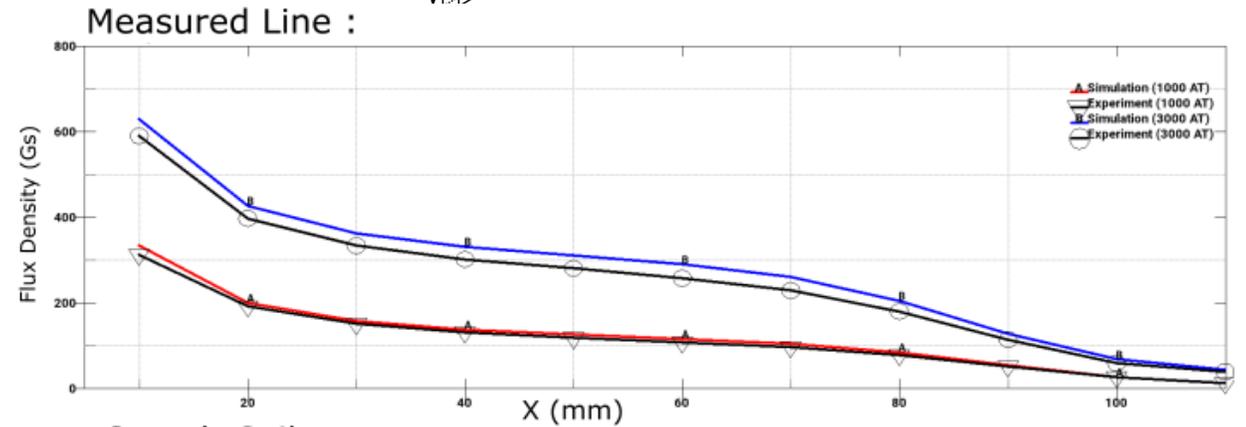
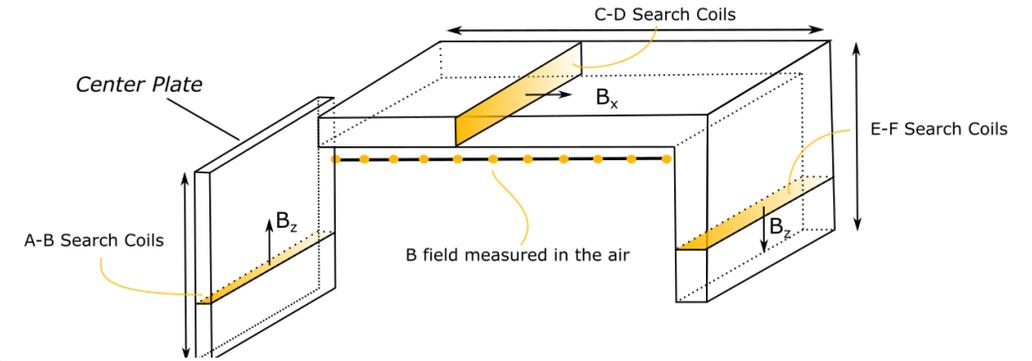
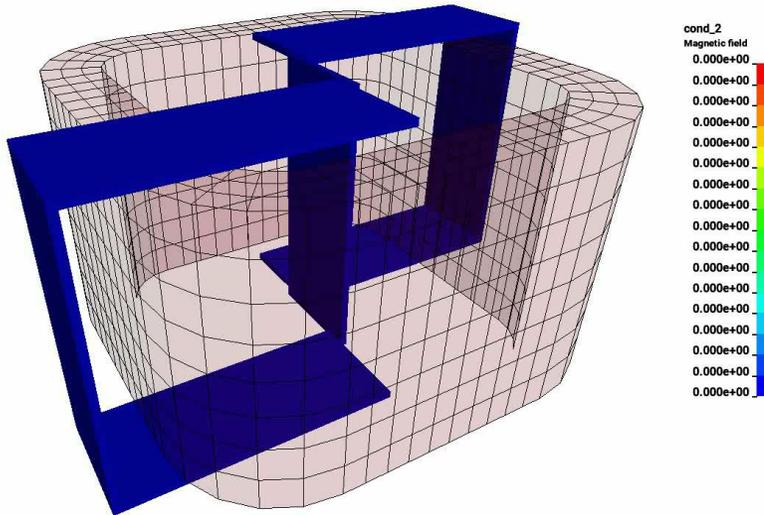
Default is 2 : Diagonal block preconditioner. For non linear material cases, try 4 : LLT factorization for speed up.

Case Study – T.E.A.M 13

Post :

- Results are almost identical between the time dependent and the magnetostatic solve.
- Look for “NL newton” in the message file. Compare results between magnetostatic and time dependent case.

LS-DYNA keyword deck by LS-PrePost
Time = 0



Voltage driven source circuit

- As seen previously, if the stranded coil's current is known, it can be directly imposed in the cross-section of the stranded conductor.
- However, if the terminal voltage is specified in a given problem (e.g actuators) then the current is unknown.
- In this situation the current must be deduced from the specified voltage, the number of windings and the coil's total resistance. In our formulation, it is added as an unknown in the FEM/BEM system.
- Since the source circuit becomes part of the FEM/BEM system, the EM_CIRCUIT_SOURCE must be associated to a *EM_MAT type 2 instead of type 1 in the imposed current case.

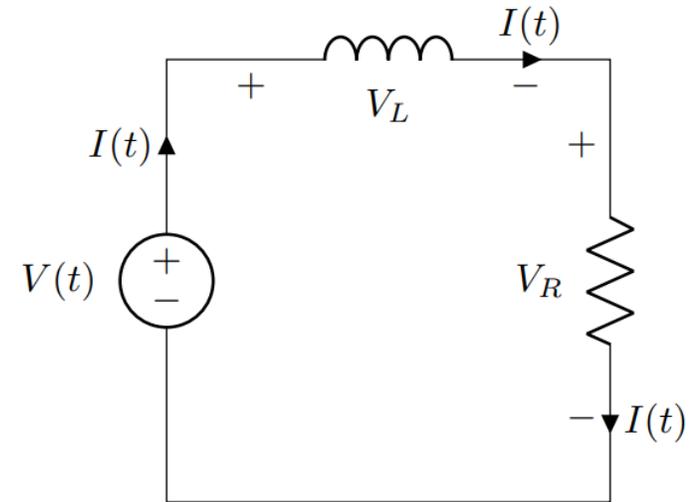
Network equation added to system :

$$\dot{\varphi}(t) + RI(t) = V(t)$$

with R the coil resistance, $V(t)$, the given voltage, $I(t)$ the current (unknown) and $\varphi(t)$ the magnetic flux of the coil :

$$\varphi(t) = \frac{N_c}{S_c} \int \mathbf{A} \cdot \boldsymbol{\tau} dx$$

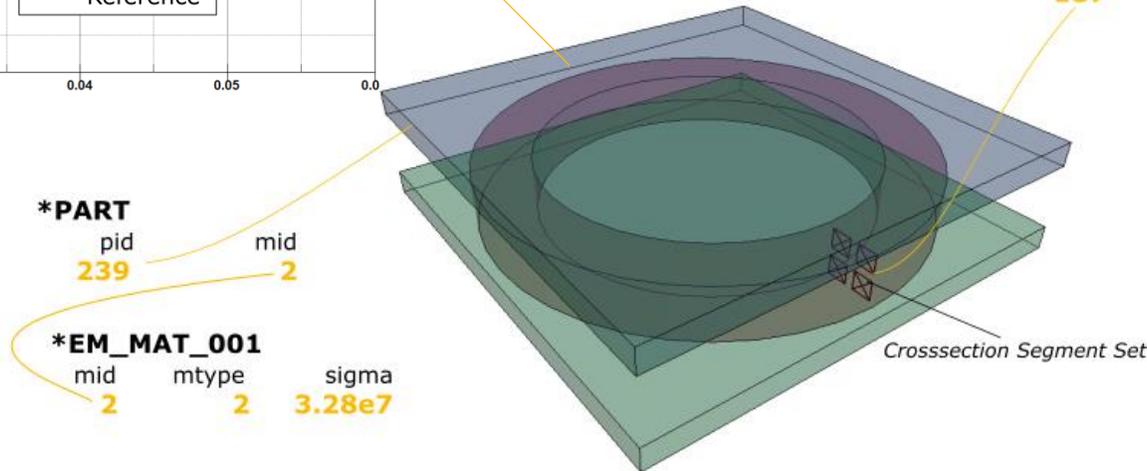
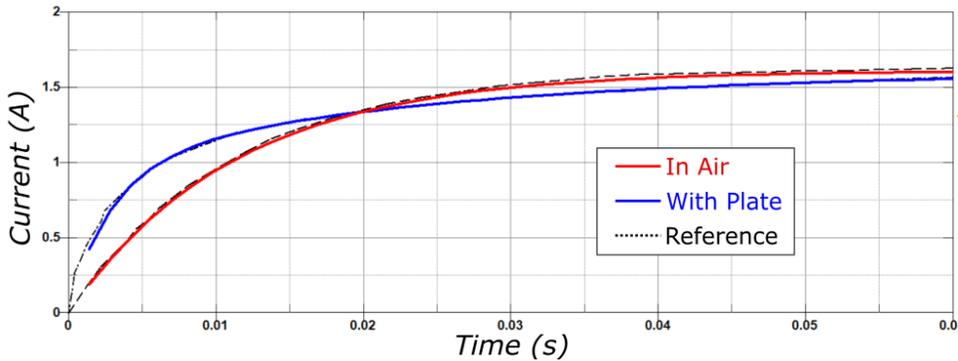
With N_c the number of turns, S_c the section area of the coil, and $\int \mathbf{A} \cdot \boldsymbol{\tau} dx$ the scalar product of the vector potential and the current direction vector of the coil, integrated over the volume.



Case Study – Leonard & Rodgers benchmark

Voltage Driven coil

- Classic validation problem consisting of a voltage driven coil between two conducting plates (sigma=3.28e7 Siemens).
- Constant voltage of 20V, resistance of 12.4 Ohms and 700 turns.
- Objective is to predict the coil's current under the influence of the conducting plates.



```

*PART
pid      mid
239     2

*EM_MAT_001
mid      mtype      sigma
2        2          3.28e7
    
```

```

*EM_CIRCUIT_SOURCE
circid   circtype   lcid      R      NTurns
1        2          333      12.4   700
ssidcurr ssidvin   ssidvout  partid
187     1          1
    
```

```

*PART
pid      mid
1        1
    
```

```

*EM_MAT_002
mid      mtype      sigma
1        2          0.
    
```

Voltage driven coil is defined by a imposed voltage lcid, a resistance and a number of turns

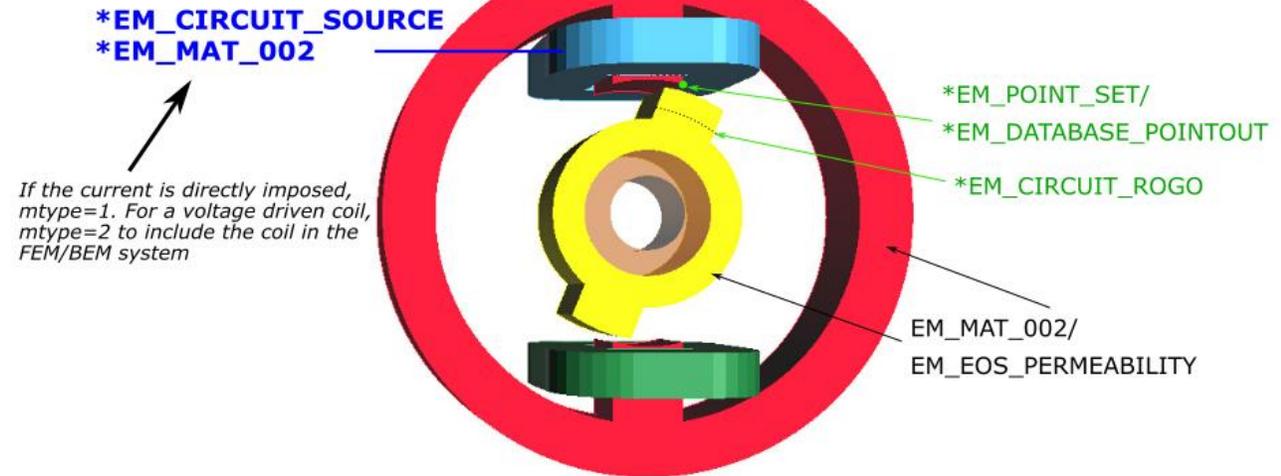
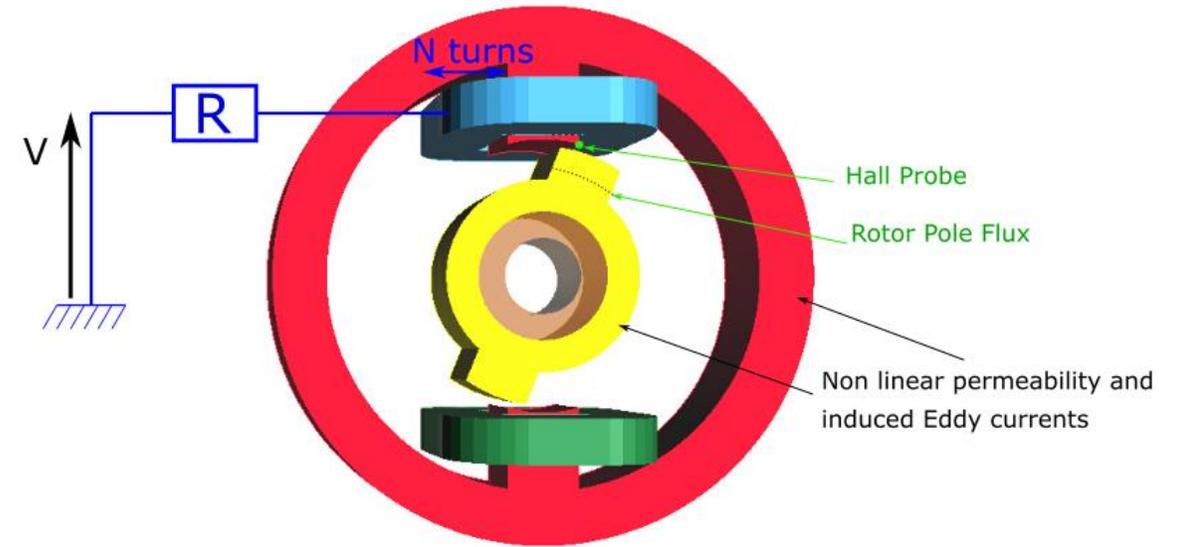
The voltage driven coil is defined as a conductor, part of the FEM/BEM system



Case Study – T.E.A.M 24

Model Setup :

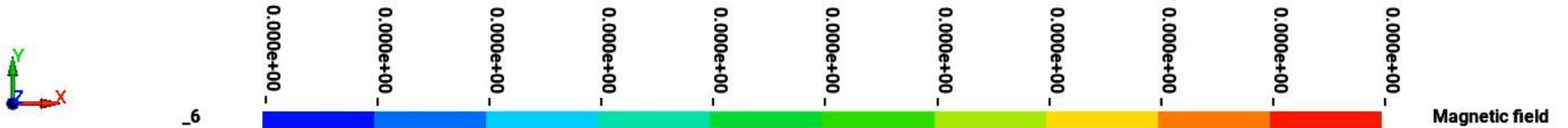
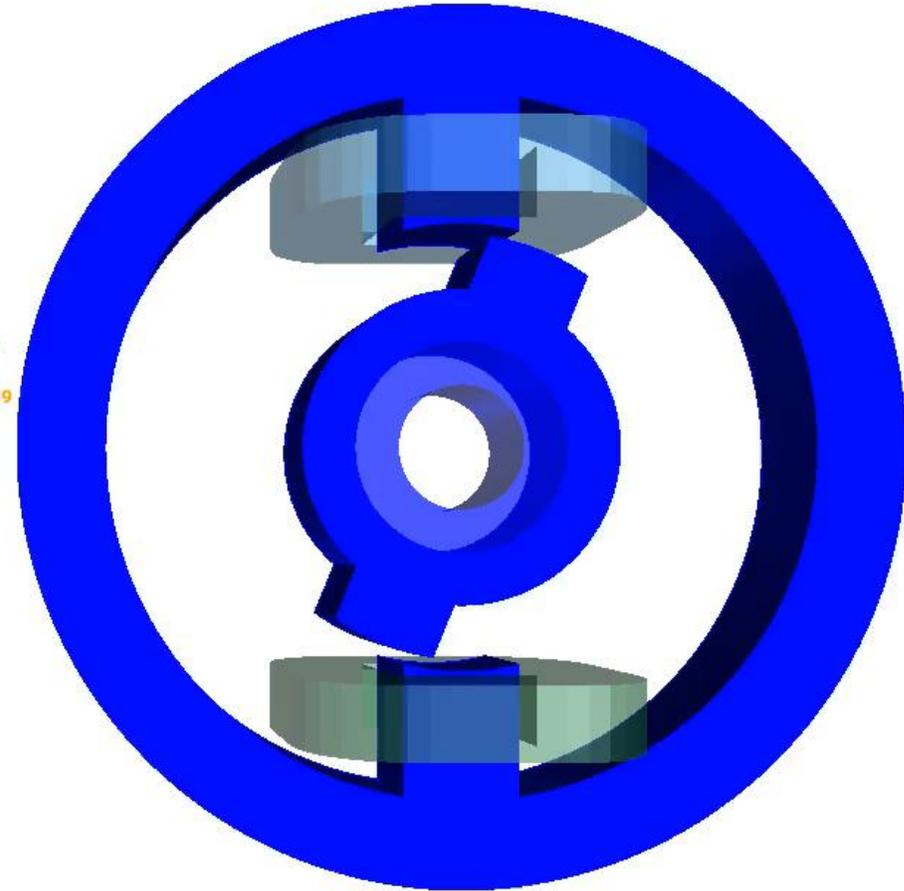
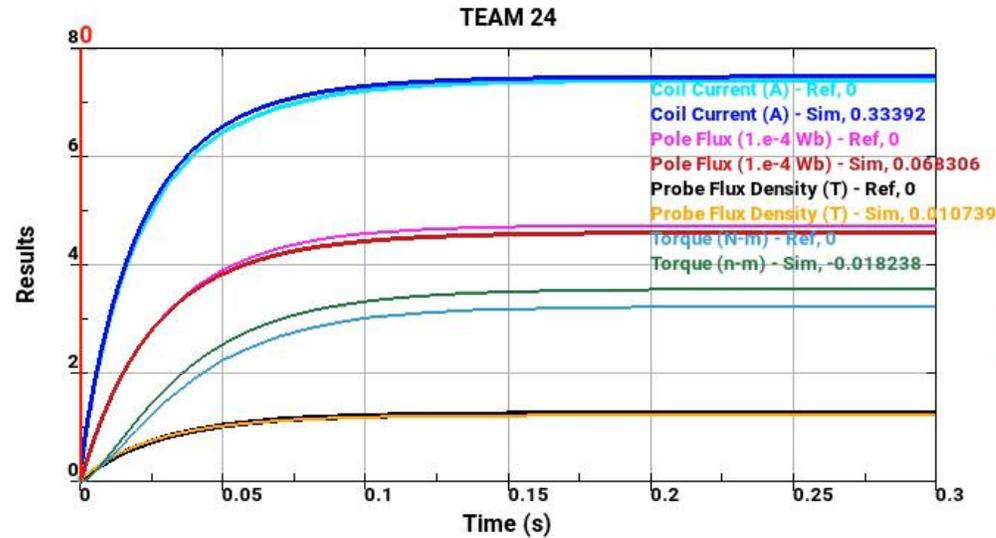
- Classic validation problem consisting of a voltage driven coil between two conducting plates ($\sigma=3.28e7$ Siemens).
- Constant voltage of 20V, resistance of 12.4 Ohms and 700 turns.
- Objective is to predict the coil's current under the influence of the conducting plates.



Case Study – T.E.A.M 24

LS-DYNA keyword deck by LS-PrePost
Time = 0

Post :

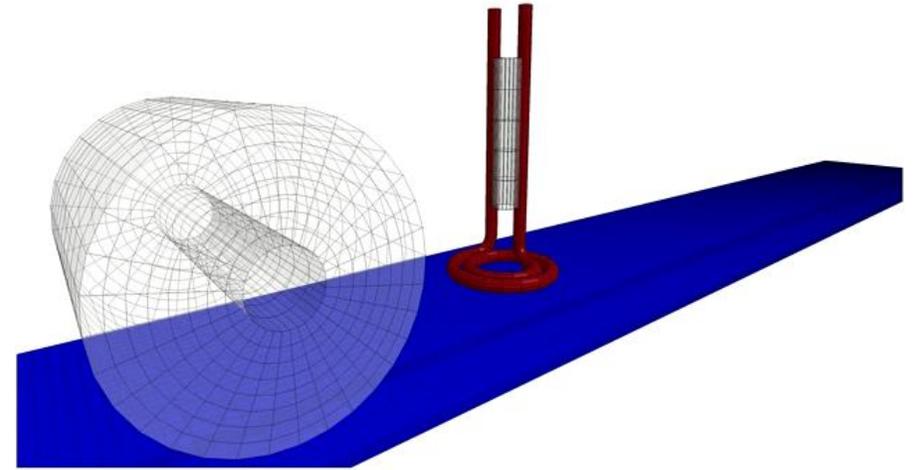


Focus on inductive heating



Introduction

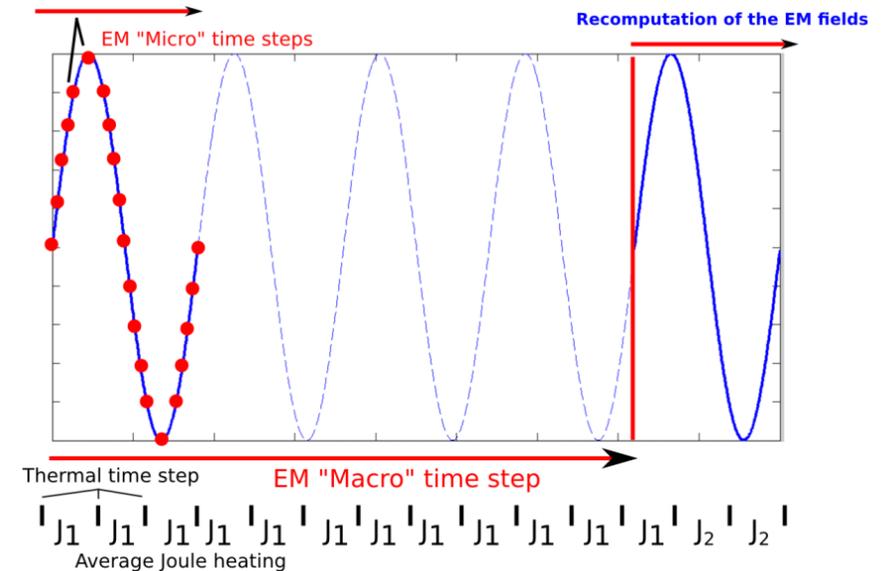
- Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, through heat generated in the object by eddy currents. It has applications in diverse industries such as induction welding, inductive charging or even cancer therapy.
- Compared to MMF, the inductive heating process involves lower amplitude voltages but over a longer period of time => typical application involves AC current with frequency in the kHz~Mhz range and a total application time of several seconds.
- Numerically, special techniques must be developed, as solving each EM step over hundreds or thousands of periods would prove to be impractical.



Introduction

The inductive heating solver works the following way :

- After a sinusoidal current has been defined, 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. **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.



Inductive Solver Keywords

*EM_CIRCUIT

CIRCID	CIRCTYPE	LCID	R/F	L/A	C/T0	V0	T0
1	11		25.e3	200.	0.		
SIDCURR	SIDVIN	SIDVOUT					
2	1	2					

VARIABLE	DESCRIPTION
Circtype	Circuit type: EQ.11: Imposed AC current. EQ.12: Imposed AC voltage.
F/A/T0	Circuit Frequency, Amplitude and phase shift so that : $I = A \sin(2 \pi F (t-T0))$

In order to have F, A or T0 vary in time, a load curve can be used by defining a negative value for each of those quantities (the negative value will refer to the LCID).

Inductive Solver Keywords

*EM_CONTROL

EMSOL	NUMLS						
2	100						

VARIABLE	DESCRIPTION
EMSOL	EM Solver: EQ.1: Eddy current solver. EQ.2: Inductive heating solver.
NUMLS	Number of local Eddy Current steps in a full current oscillation period => 'micro' EM step is defined as $1/(NUMLS * F)$

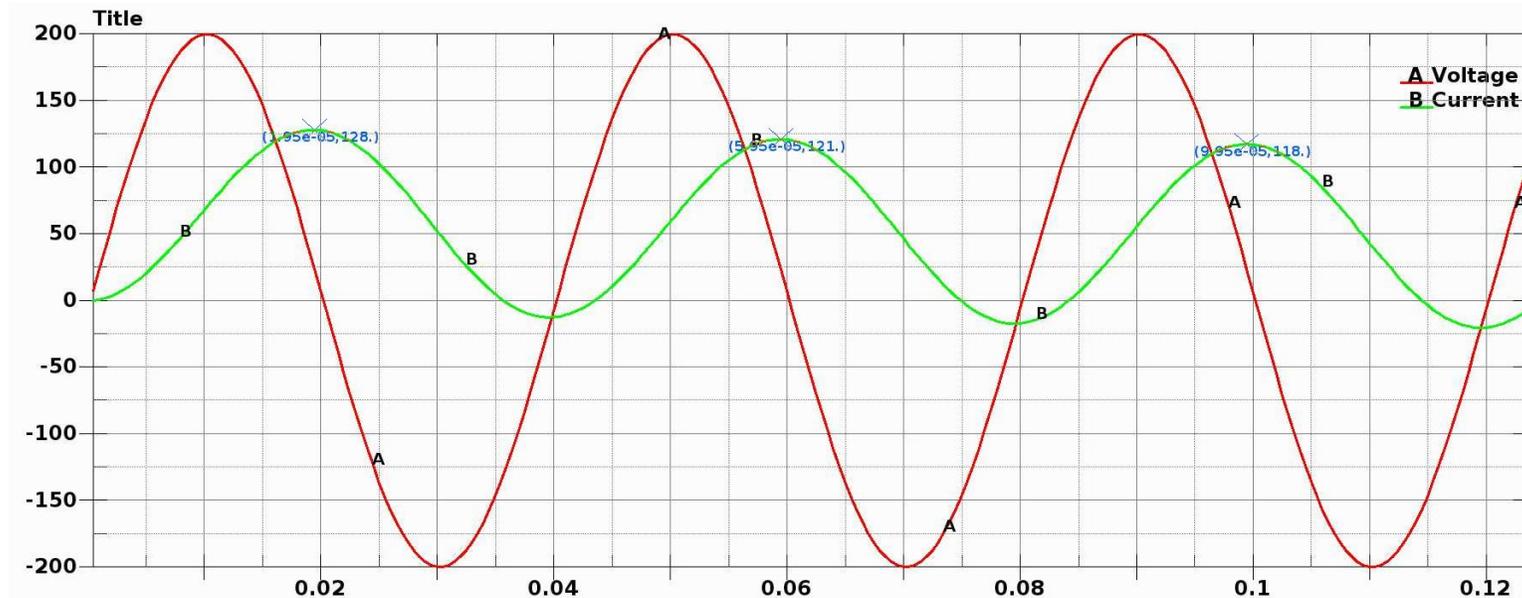
In order to have NUMLS vary in time, a load curve can be used by defining a negative value for each of those quantities (the negative value will refer to the LCID).

/ The Macro Timestep

- After the initial solve over the period, a joule heating term is extracted and the analysis proceeds as pure structural thermal problem.
- The EM timestep in `*EM_CONTROL_TIMESTEP` becomes the EM macro timestep i.e the times where the analysis will stop and a new full Eddy current problem will be solved over one period. It only makes sense to define a macro timestep lower than the total time of the run if :
 - EM properties (conductivity, permeability) have changed function of temperature.
 - Mechanical displacement and/or deformation has occurred.
 - Circuit properties (Frequency, amplitude, etc) have changed in time.

The Average Joule heating

- By default, the solver solves the EM fields over two consecutive periods and only keeps the Joule heating term of the second one. This is because, as all fields are starting at 0., it often takes at least one period for the current amplitude and phase to achieve its correct oscillatory behavior. However, in certain configurations, more periods may be needed to achieve higher accuracy (or conversely, using two periods may be too conservative and good results may be achieved by directly taking the first period, in cases with little time shifts between the voltage and current oscillations for example).
- The number of periods to be solved can be controlled by the fifth flag of *EM_CONTROL.



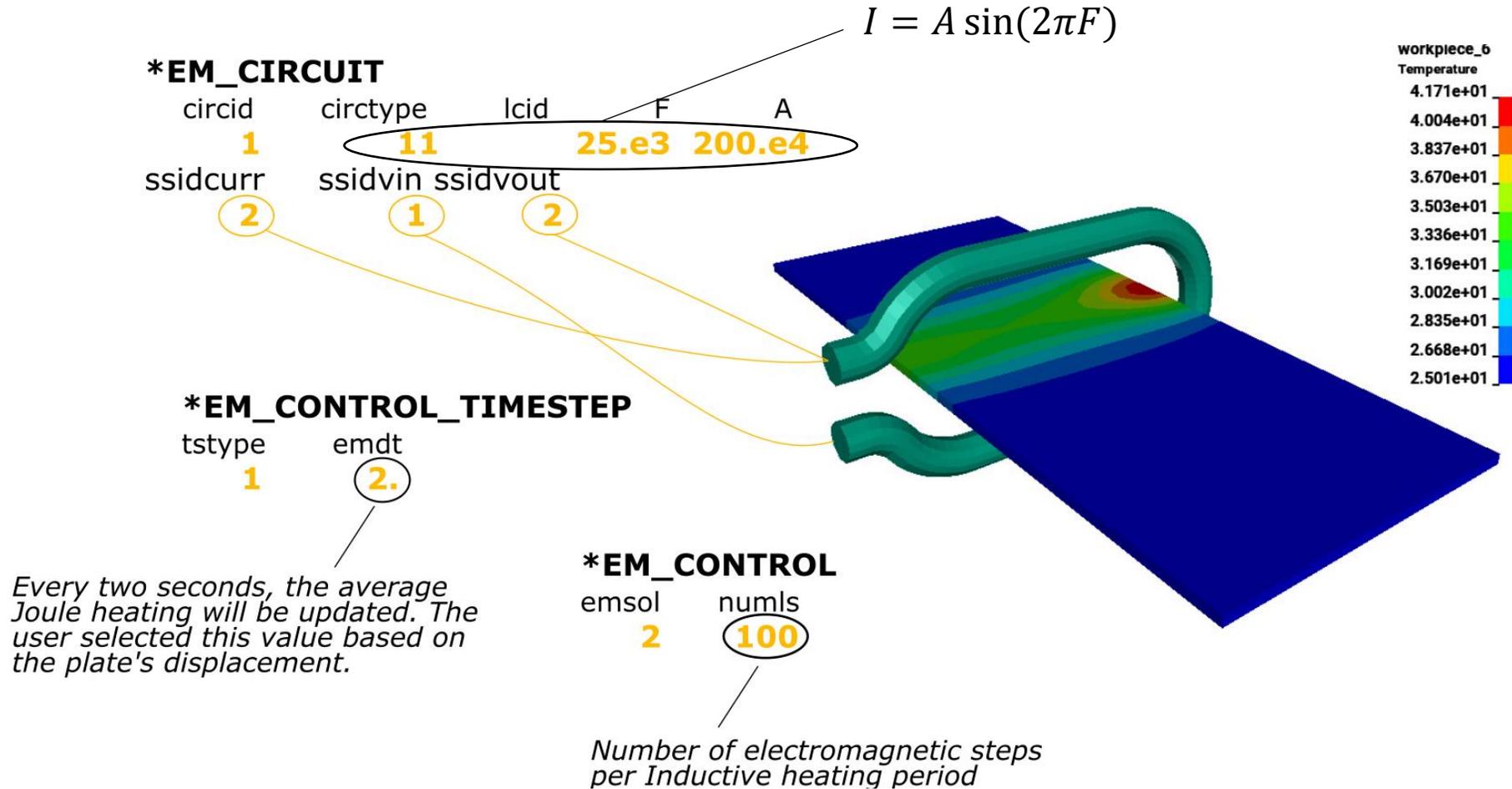
/ The switch option

- The EM solver also features an option to turn on off the EM solve during the run (See *EM_CONTROL_SWITCH). In metal forming applications, it is used to study the mechanical deformation or springback analysis after the coil discharge. In Inductive heating applications, it can be used in combination with *DEFINE_CURVE_FUNCTION to implement simple temperature based sensors.

```
*EM_CONTROL_SWITCH
7
*DEFINE_CURVE_FUNCTION
$#   lcid   sidr   s
      007
$ function value
if(LC400,LC202,LC203,LC204)
*DEFINE_CURVE_FUNCTION
$#   lcid
      400
$ function value
temp(8820)-40
*DEFINE_CURVE_FUNCTION
$#   lcid
      202
0.
*DEFINE_CURVE_FUNCTION
$#   lcid
      203
1.
*DEFINE_CURVE_FUNCTION
$#   lcid
      204
-1.
```

Case Study – Inductive heating

Plate moving through static coil



Case Study – Inductive heating

Post

- In inductive heating solution, the electromagnetic solver outputs average quantities over the period (check if Joule Heating happens in the right location):

Average Joule heating :

$$J_{avg} = \frac{1}{T} \int_0^T J_{ih} dt$$

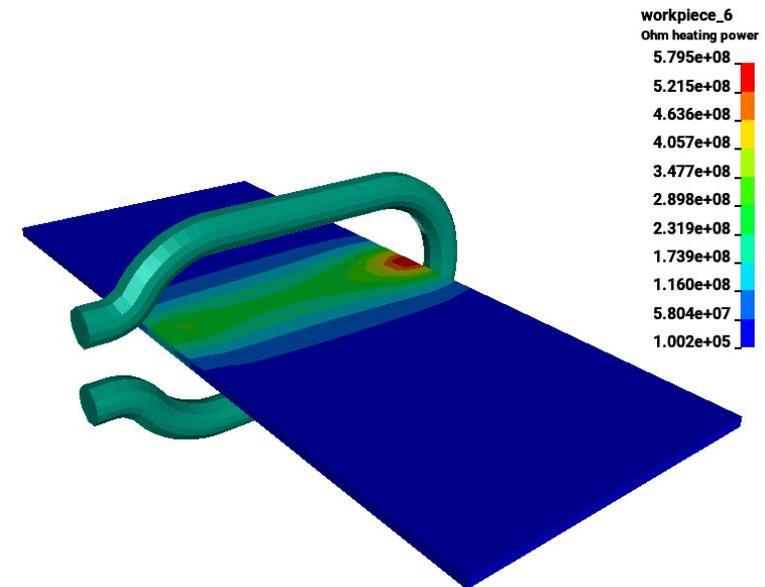
Average Magnetic flux :

$$B_{avg} = \sqrt{\frac{1}{T} \int_0^T B_{ih}^2 dt}$$

- The most important post treatment quantity is the temperature !

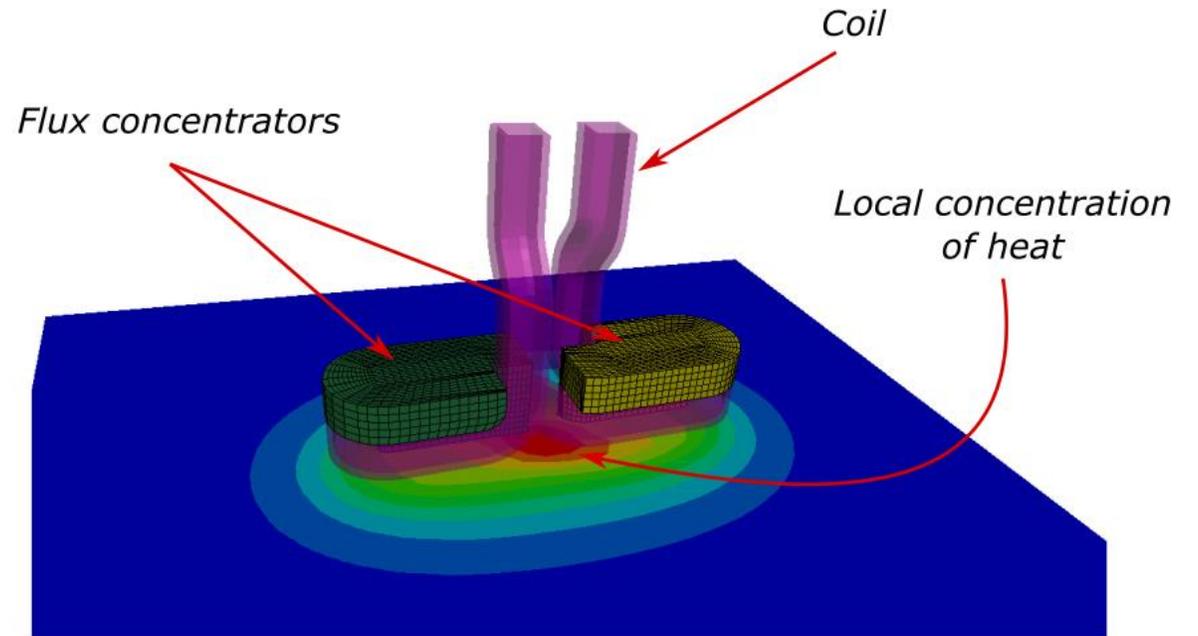
Check the EM-IH step to track the Electromagnetic micro steps :

```
2 t 8.0000E-07 dt 4.00E-07 02-period EM-IH step
3 t 1.2000E-06 dt 4.00E-07 02-period EM-IH step
4 t 1.6000E-06 dt 4.00E-07 02-period EM-IH step
5 t 2.0000E-06 dt 4.00E-07 02-period EM-IH step
6 t 2.4000E-06 dt 4.00E-07 02-period EM-IH step
7 t 2.8000E-06 dt 4.00E-07 02-period EM-IH step
8 t 3.2000E-06 dt 4.00E-07 02-period EM-IH step
9 t 3.6000E-06 dt 4.00E-07 02-period EM-IH step
```



/ The monolithic approach

- In many inductive heating applications, flux concentrators are used in the vicinity of the coil. They allow a better concentration of magnetic field lines and consequently a higher and more focused temperature rise.
- Those flux concentrators are usually made of ferrite which is a non-conductor material with high permeability values that are often non linear (BH curve needs to be defined). See *EM_MAT_002.
- For such applications, the user has to switch to the monolithic solver. See *EM_SOLVER_FEMBEM_MONOLITHIC to turn it on.



Turning on Monolithic solver

***EM_SOLVER_FEMBEM_MONOLITHIC (replaces EM_SOLVER_FEMBEM)**

MTYPE	STYPE	ABSTOL	RELTOL	MAXIT
		1.e-6	1.e-4	500

First line defines tolerances of monolithic solve

	NEW_STOL	NEW_ATOL	NEW_RTOL	NEW_MAX
	1.e-4	1.e-8	1.e-4	

Second line defines tolerances of non linear sub stepping when BH curve is present

In addition to the traditional P and Q matrices, a third matrix W is being assembled in the case of the monolithic solver and its tolerances can again be adjusted in the keywords *EM_SOLVER_BEMMAT.

Flux concentrator material

***EM_MAT_002**

MID	MTYPE	SIGMA	EOSID	MUREL	EOSMU
1	2	0.		1000.	100
LCIDMUSF					

Permeability either defined as constant or via B-H curve (See *EM_EOS_PERMEABILITY keyword associated to EOSMU)

Ferrite has got a zero conductivity but MTYPE=2 to include material in EM solver

Optional second line giving permeability function of temperature.

BEM Preconditioner

For the monolithic approach, the diagonal block of the monolithic system (FEM-FEM plus BEM-BEM) is used as a preconditioner in the iterative solve. The parameters for the preconditioner solve are controlled by *EM_SOLVER_FEM and *EM_SOLVER_BEM respectively.

*EM_SOLVER_BEM

RELTOL	MAXIT	STYPE	PRECOND	USELAST	NCYCLBEM
1.e-6	1000	2	2		

Lower values will increase calculation times but potentially improve accuracy and robustness.

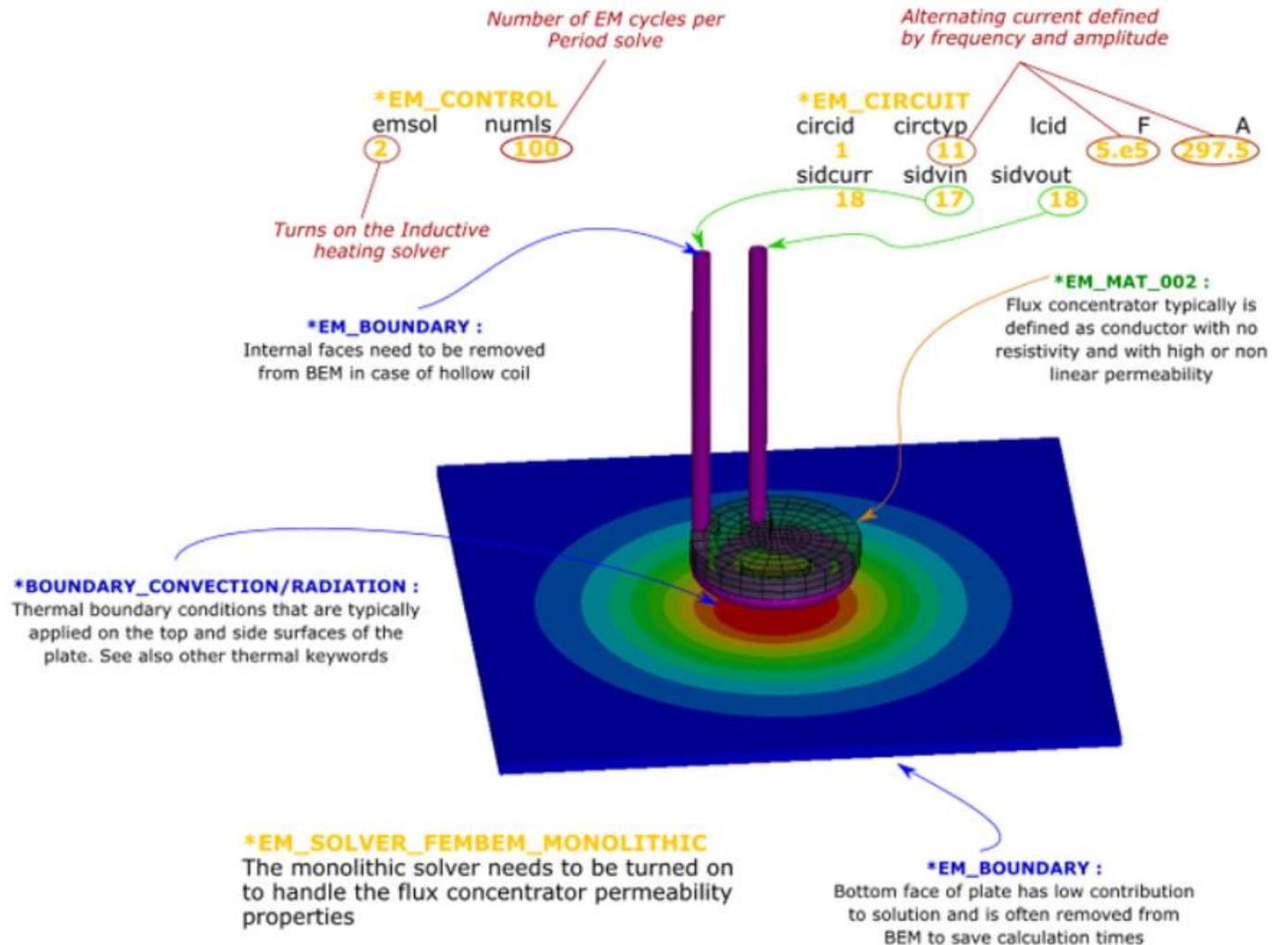
Default uses a diagonal block preconditioner. For cases involving materials with high or non-linear permeability cases, it is recommended to switch to 4 : LLT factorization for improved computation times.



Case Study – Pancake coil with flux concentrator

Hollow coil : Using *EM_BOUNDARY

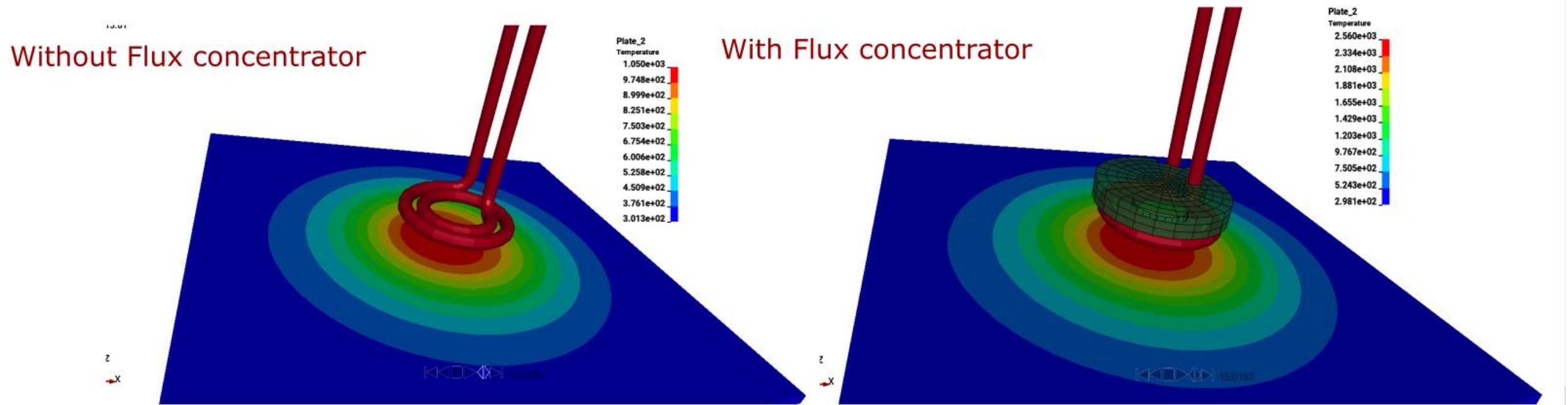
- The coil in this application is hollow. Two closed loops can be formed (one inner, one outer) at the intersection of the inlet segment set faces and the rest of the BEM surface mesh.
- The boundary condition imposed by *EM_CIRCUIT relies on providing one and only one intersection between the boundary faces and the BEM mesh.
- Consequently, in such configurations, the user must remove the internal faces of the coil from the BEM system using *EM_BOUNDARY.
- The *EM_BOUNDARY keyword can also be used to save calculation time by removing faces from the BEM where it will not have a large impact on the magnetic field.



Case Study – Pancake coil with flux concentrator

Post :

- Check input for flux concentrator and check difference in results and calculation times with and without it.
- Check the choice of preconditioner in EM_SOLVER_BEM and the influence in calculation times.



/ 2D Axisymmetric solver

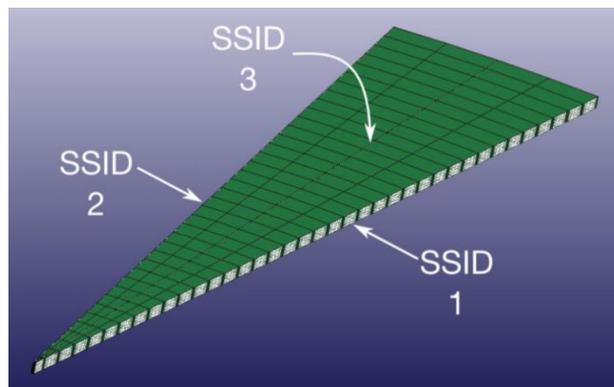
- The axisymmetric feature has been developed in order to simplify certain types of cases and save some calculation time . Inductive heating cases where a helicoidal coil surrounds a cylindrical workpiece a common and could therefore be modelled using the 2D axisymmetric solver.
- Since LS-DYNA is primarily a 3D code, where most of the features are available only in 3D, it was decided to couple the EM-2D with the 3D LS-DYNA solver.
- This means that the user needs to provide a 3D mesh as well as, for each conducting part, a segment set to define the plane where the EM-2D is done. Once the EM fields are computed in 2D on this plane, they are just reported over the full 3D mesh by rotations around the axis.
- Coupling with the thermal solver again happens automatically.
- The axi-symmetric solver is usually very fast compared to its 3D equivalent.

2D Axisymmetric solver

- The user can define any rotation axis. See EM_ROTATION_AXIS keyword.
- For every EM axi-symmetric part, a user defined ratio of the full circle mesh has to be built. The ratio has to be a power of 2 (NUMSEC=4 means that the mesh represents one fourth of the full 360 circle). ($Ratio = 360 / (Angular\ extension) = 2^n$).
- A segment set has to go through the center plane for each EM axisymmetric part. This defines the plane where the 2D EM system is computed.

*EM_2DAXI

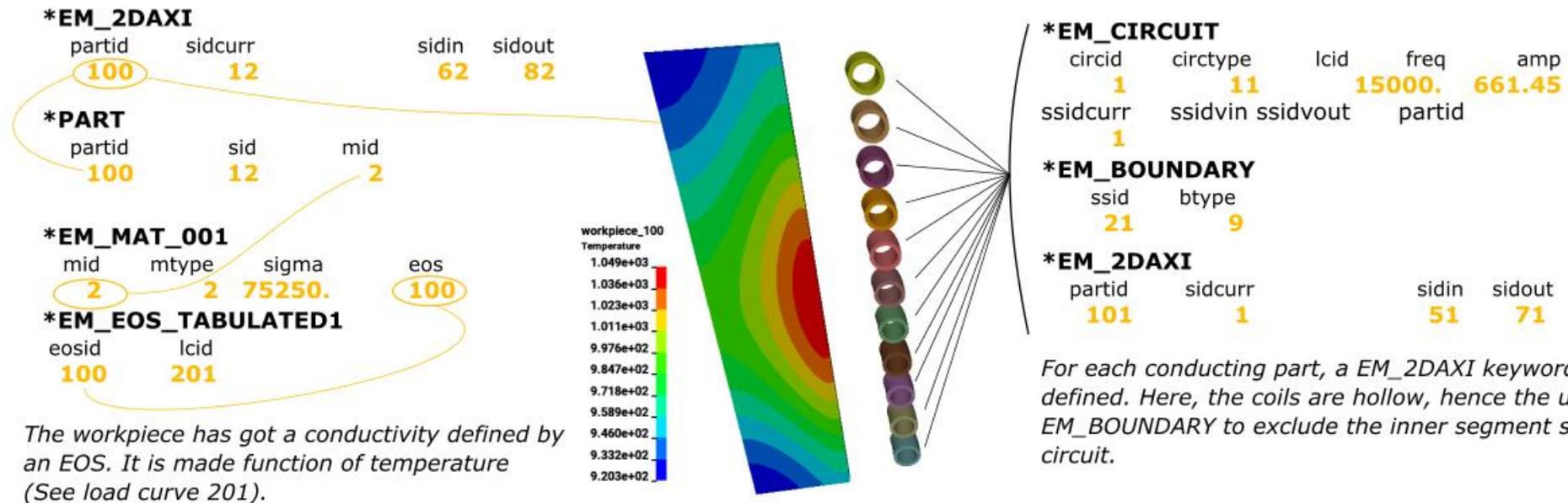
PID	SSID			STARTSSID	ENDSSID	NUMSEC	
3	3			1	2	32	



Case Study – 2D axisymmetric heating

Helicoidal Coil

- 2D axisymmetric cases in inductive heating usually involve a helicoidal coil around the object to be heated.
- 2D axisymmetric Inductive heating example with periodic recomputation of EM fields due to varying conductivity in the workpiece.
- This example uses the monolithic solver to solve the FEM/BEM system which allows to use higher timesteps.



**Focus on Temperature
dependent nonlinear magnetic
material models (BH curves)**



/ Temperature dependent BH curves

- Temperature effects can be taken into account when modelling nonlinear magnetic materials.
- The main application for this feature will be in inductive heating but it is applicable to any Eddy current problem featuring nonlinear magnetic materials.
- There are several approaches available to the user based on the complexity of the model or the amount of data he has available.
- The following feature is not limited to including temperature dependent effects, but in some cases can be used to include other effects such as von mises stress dependent nonlinear magnetic materials (magnetostriction).

/ Analytical approach

- EM_EOS_PERMEABILITY allows the user to define the B field behavior function of H using analytical laws :

EOSTYPE=7 - Atan Law :

$$B(H, T) = \mu_0 H + \frac{2B_s}{\pi} \operatorname{atan}\left(\frac{\pi}{2B_s} H \mu_0 (\mu_{r0} - 1.)\right) F(TEMP) SF$$

EOSTYPE=8 - Froelich Law :

$$B(H, T) = \mu_0 H + H \frac{B_s}{1. + \mu_{r0} H} F(TEMP) SF$$

- $F(TEMP)$ and SF are two optional coefficients that can be added and made function of temperature.

Analytical approach

- The $F(TEMP)$ coefficient follows an exponential decay law and can be directly defined in the EM_EOS_PERMEABILITY keyword :

***EM_EOS_PERMEABILITY**

EOSID	EOSTYPE	LCID	BS	MURO	C	TC

Analytical law parameters

Used for F(TEMP)

$F(TEMP)=1.$ by default. If C defined, then the default scaling coefficient function of temperature becomes:

$$F(TEMP) = \max(0., 1. - \exp\left(\frac{T-T_s}{c}\right))$$

/ Analytical approach

- The SF scaling factor is defined in the second line of EM_MAT_002. It is a more general approach where the user can define his own temperature dependent law or even include different parameters e.g stress/strain (See EM_EOS_TABULATED and DEFINE_FUNCTION).

***EM_MAT_002**

MID	MTYPE	SIGMA	EOSID	MUREL	EOSMU
	LCIDMUSF				

Optional second line. Refers to a EM_EOS_TABULATED ID which can give permeability function of temperature and other variables.

/ Scaled BH curve approach

- The SF scaling factor defined by EM_MAT_002 can also be used when the non linear magnetic material is defined by a BH curve given by the user (See EOSTYPE=1 in EM_EOS_PERMEABILITY).
- When defined, the scale factor will be applied the following way :

$$B(H, T) = \mu_0 H + G(H) SF$$

- In other words, the nonlinear behavior of B(H,T) will be decomposed into a linear part $\mu_0 H$ and a nonlinear part $G(H) SF$ with G(H) determined by the load curve given by the user and SF the scale factor as defined by the user. Thus, the physical behavior of B function of H will be retained when saturation occurs ($B \rightarrow \mu_0 H + M_s$ with M_s saturation magnetization for very high H values).
- In order to avoid stability issues, it is recommended to set a minimum value for SF such that $SF > 0$.

Multiple BH curve inputs approach

- The final approach to define temperature dependent behavior is to directly input several BH curves for different temperature values using EOSTYPE=3 in EM_EOS_PERMEABILITY.
- When this approach is selected, for a given element temperature, the solver will do a linear interpolation between two given BH curves and locally reconstruct the corresponding spline.

*EM_EOS_PERMEABILITY

EOSID	EOSTYPE	LCID	BS	MURO	C	TC
	3	40				

Permeability defined by a load curve where B-H load curves ($B=\mu H$) may be defined function of temperature.

Temperature values

*DEFINE_CURVE

40

0

300

400

500

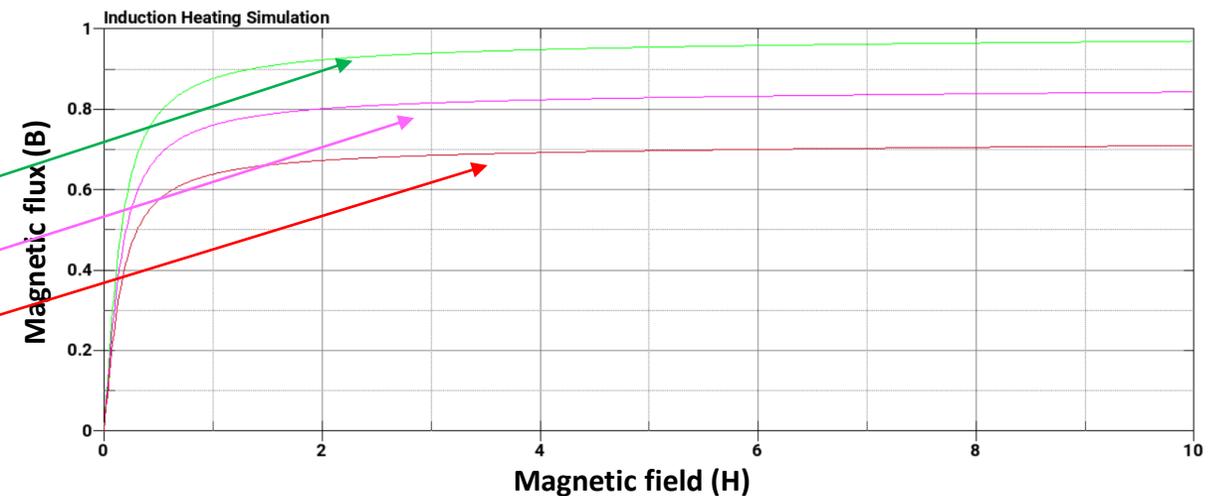
1

1

2

3

LCIDs



/ Input deck setup examples

- Summarizing the four different approaches, those four input deck setups should give very close or identical results :

Approach one : Using an analytical law and directly applying imbedded exponential decay coefficient law :

***EM_EOS_PERMEABILITY**

EOSID	EOSTYPE	LCID	BS	MURO	C	TC
1	7		1.2	3500.	50.	360.

Input deck setup examples

Approach two : Using the same analytical law but reproducing the temperature dependency behavior with the scaling factor available in EM_MAT_002 :

*EM_EOS_PERMEABILITY

EOSID	EOSTYPE	LCID	BS	MURO	C	TC
1	7		1.2	3500.		

*EM_MAT_002

MID	EOSMURID
	1

LCIDMUSF
100

*EM_EOS_TABULATED2

EOSID	LCID
100	200

*DEFINE_FUNCTION

```
200  
float temp_sf(float temp)  
{float coeff;  
coeff=1.-EXP((temp-360.)/50.);  
return coeff;}
```

Input deck setup examples

Approach three : The user inputs the BH curve directly as a discretized load curve and applies the same scaling factor in EM_MAT_002 :

*EM_EOS_PERMEABILITY

EOSID	EOSTYPE	LCID	BS	MURO	C	TC
1	1	10				

*EM_MAT_002

MID	EOSMURID
	1

LCIDMUSF

100

*EM_EOS_TABULATED2

EOSID	LCID
100	200

*DEFINE_FUNCTION

200

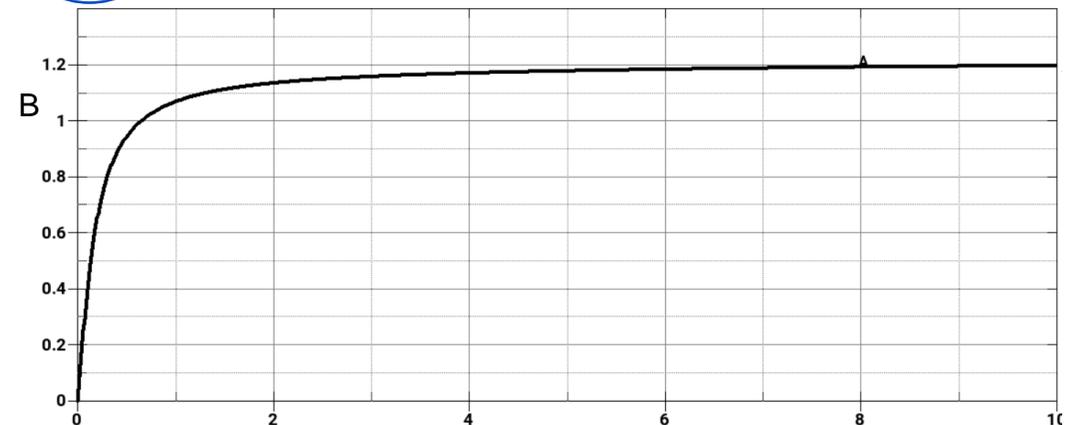
```
float temp_sf(float temp)
{float coeff;
coeff=1.-EXP((temp-360.)/50.);
return coeff;}
```

Obtained in this case by doing :

$$B(H, T) = \mu_0 H + \frac{2.4}{\pi} \operatorname{atan} \left(\frac{\pi}{2.4} H \mu_0 (3500. - 1.) \right)$$

*DEFINE_CURVE

10



Input deck setup examples

Approach four : The user inputs several BH curves for the different temperature values:

```
*EM_EOS_PERMEABILITY
```

EOSID	EOSTYPE	LCID	BS	MURO	C	TC
1	3	40				

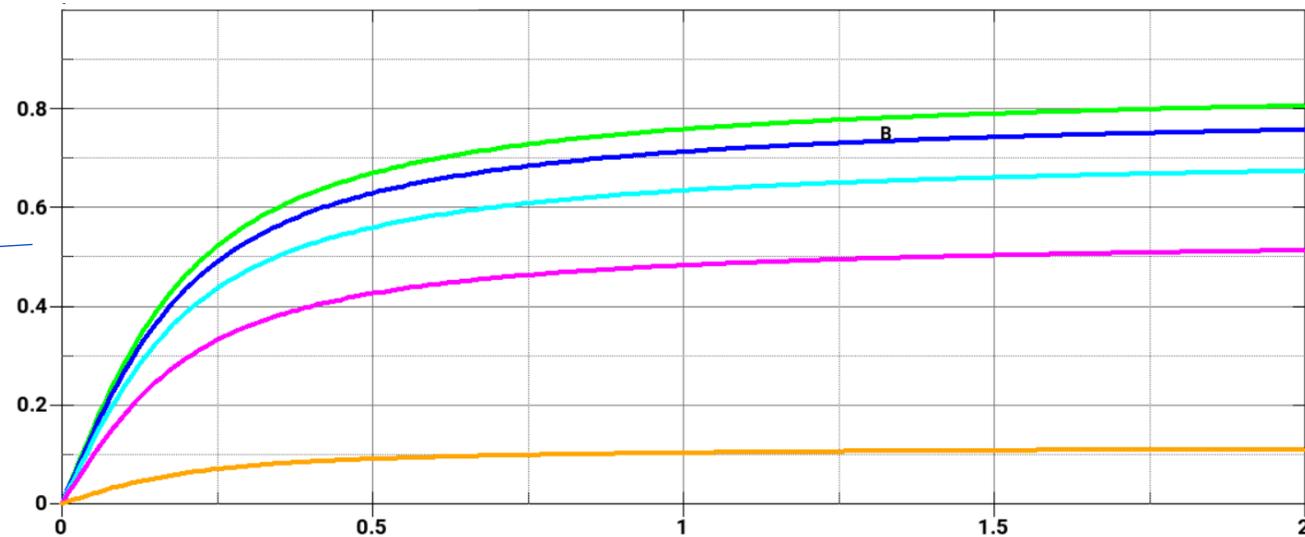
```
*DEFINE_CURVE
```

```
40  
0  
298  
305  
315  
330  
355
```

```
1  
1  
2  
3  
4  
5
```

Temperature values

Load curve IDs pointing to BH curves



**Focus on Frequency based Eddy
current solver**



/ Introduction

- As mentioned in the previous section the inductive heating solver is a time-based solver, where the EM fields are solved per small steps over one or several periods before an average can be calculated (and passed to the thermal solver in the case of Joule heating).
- For nonlinear magnetic materials such as previously described, this remains the unique way of solving.
- However, for materials that adopt a linear permeability, it can be convenient to adopt a frequency-based solver for Eddy currents. In this approach, the entire Eddy current problem is solved in one single step for a whole given period and averaged fields over the period can be directly retrieved for coupling with the mechanical or thermal solvers.
- This can allow users to save important amounts of calculation times, especially in problems with moving coils where the EM fields need to be updated and recomputed several times at different locations or at different material properties.
- Inductive heating is an obvious application, but frequency-based Eddy current solver are also used in other domains such as crack detections in pipes or over surfaces.

/ Inductive Solver Keywords

*EM_CONTROL

EMSOL	NUMLS/F						
4	50						

VARIABLE	DESCRIPTION
EMSOL	EM Solver: EQ.1: Eddy current solver. EQ.2: Inductive heating solver. EQ.4: Frequency based Eddy current solver.
NUMLS/F	Frequency. A negative value will refer to a LCID to give a varying frequency function of the 'macro time'.

Inductive Solver Keywords

***EM_CIRCUIT (or *EM_CIRCUIT_SOURCE)**

CIRCID	CIRCTYPE	LCID			T0		
1	1						
SIDCURR	SIDVIN	SIDVOUT					
2	1	2					

VARIABLE	DESCRIPTION
Circtype	Circuit type: EQ.1: Imposed Current. EQ.2: Imposed Voltage.
LCID	Load curve ID for circuit Amplitude function of 'macro time'.
T0	Optional phase shift (in time value). A negative value will point to a LCID allowing this quantity to vary function of "macro time".

Case Study – T.E.A.M 6

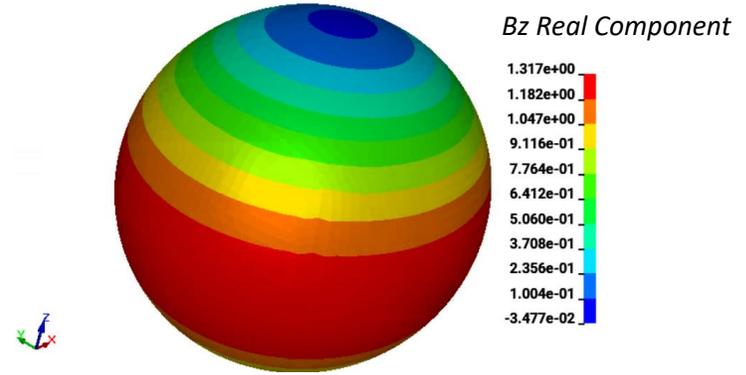
Hollow Sphere in oscillation magnetic field

- A hollow conducting sphere is placed in a magnetic field in the Z direction.
- The field is spatially uniform but varies with a given frequency. The objective is to measure the real and imaginary components of the magnetic flux in and outside the sphere.
- This example is the equivalent of the T.E.A.M 11 problem solved in the frequency domain.

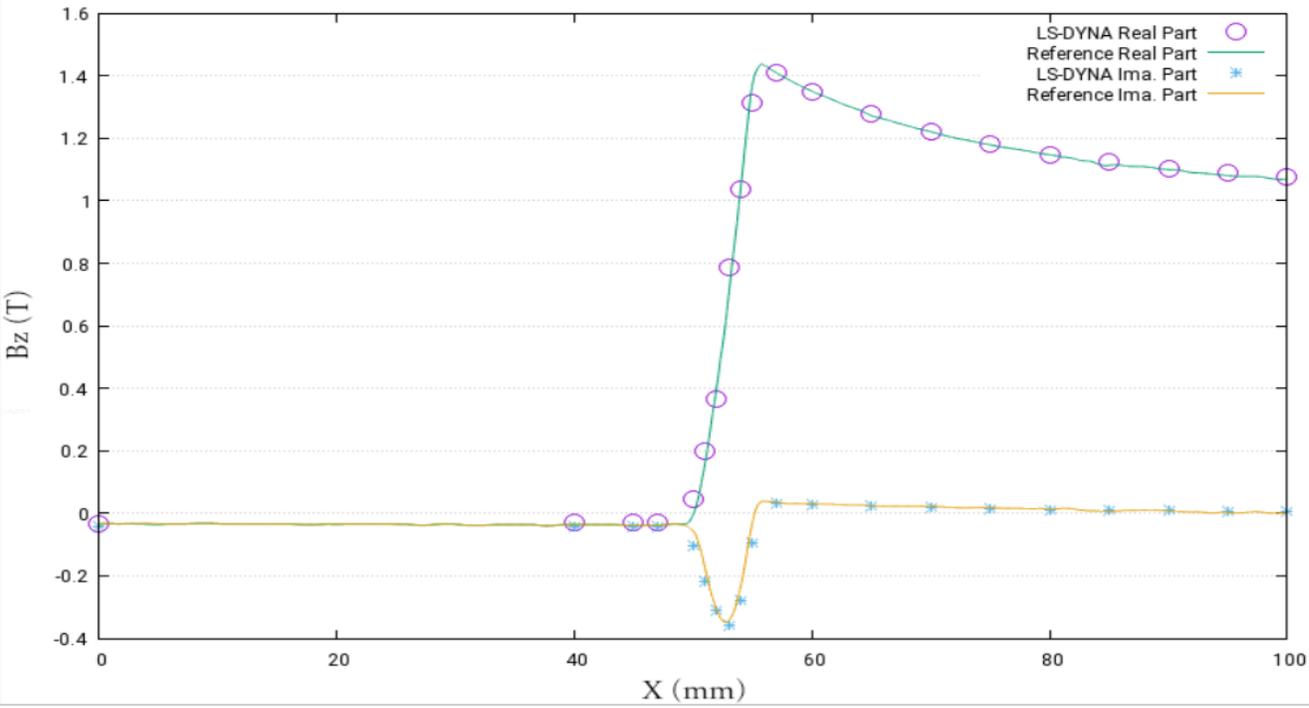
Inner Radius	0.050 m
Outer Radius	0.055 m
B_y Amplitude	1.0 T
Frequency	50 Hz
Conductivity	500. e ⁶

Case Study – T.E.A.M 6

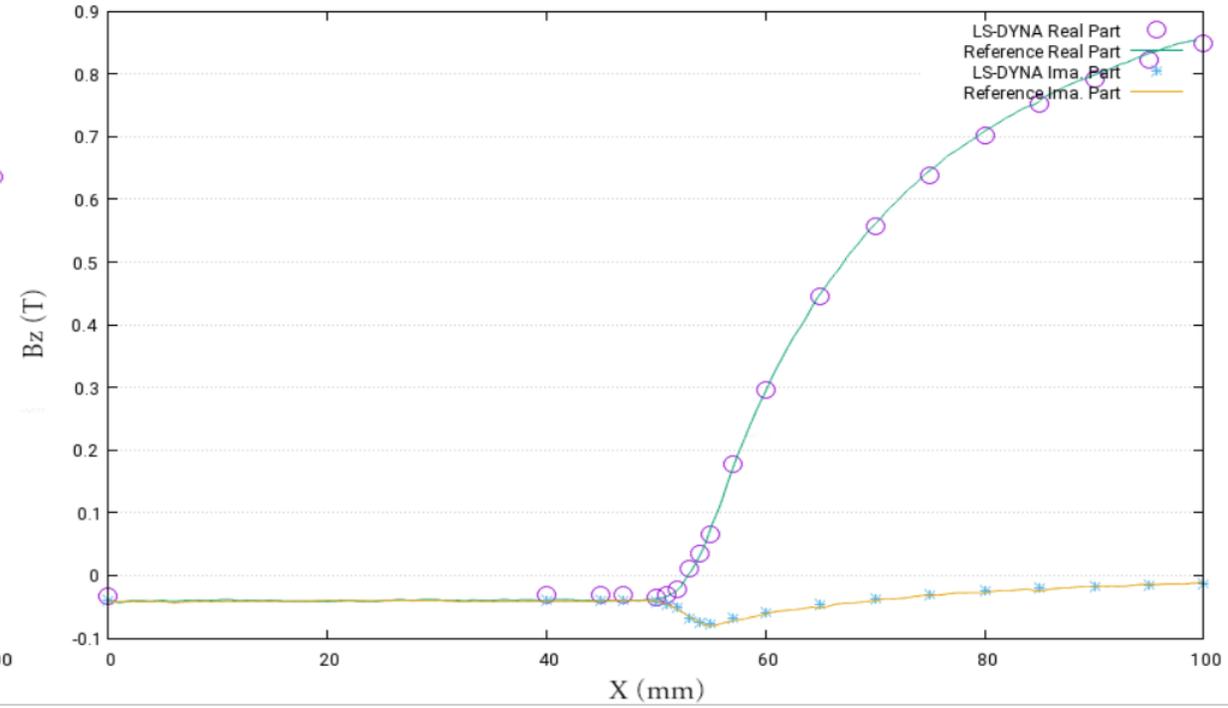
Results



TEAM 6 : Magnetic Flux along x axis



TEAM 6 : Magnetic Flux along z axis



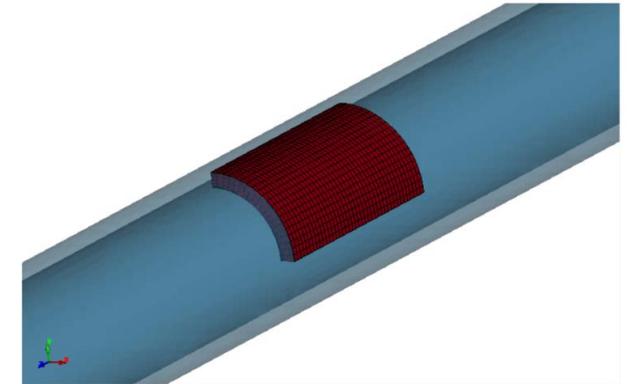
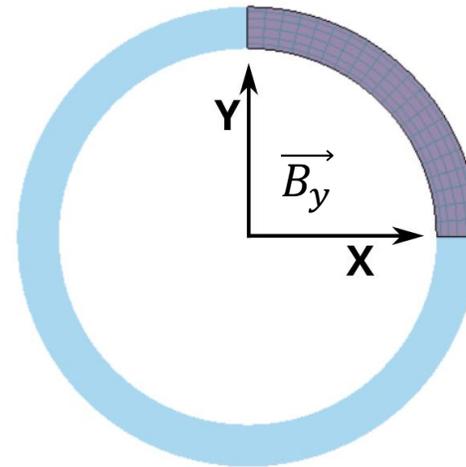
Case Study – T.E.A.M 2

Infinite Cylinder in a Uniform Sinusoidal Field

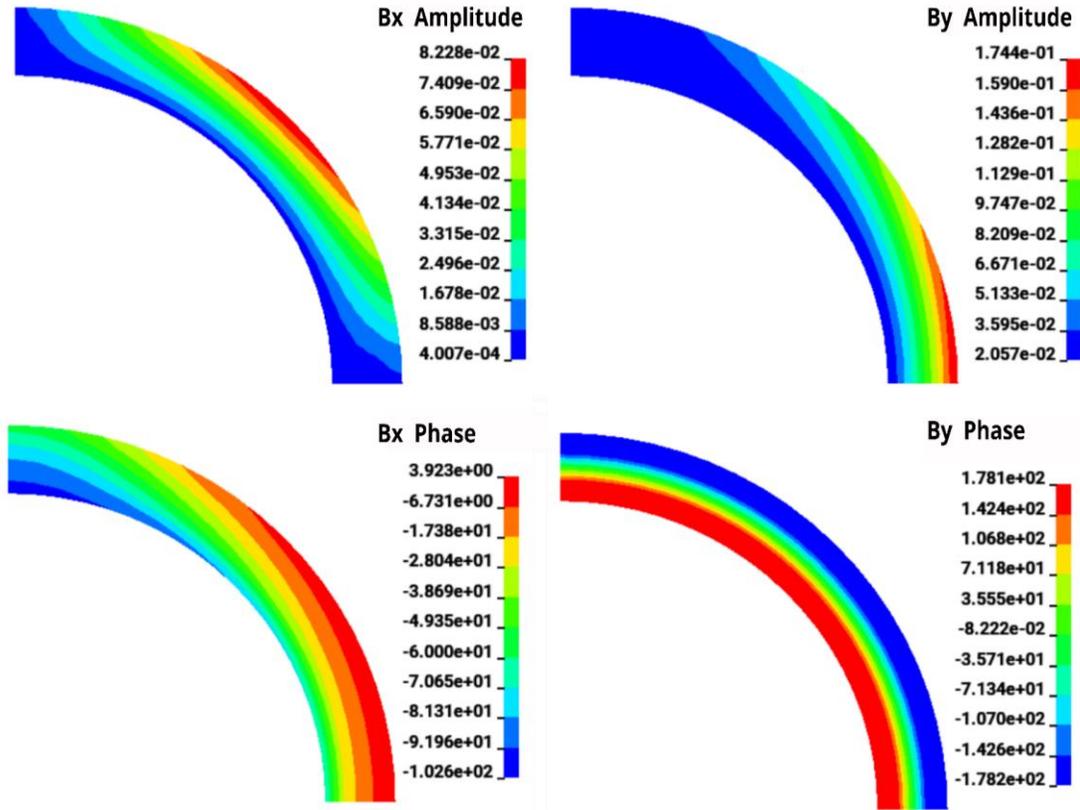
- Frequency Eddy current solver used.
- Cylinder modelled as 3D part (2 m long).
- The objective is to measure the magnetic flux amplitude and phase inside and outside the cylinder at different instants and compare to the analytical solution.

Inner Radius	0.05715 m
Outer Radius	0.06985 m
B_y Amplitude	0.1 T
Frequency	60 Hz
Conductivity	$25.38e^6$

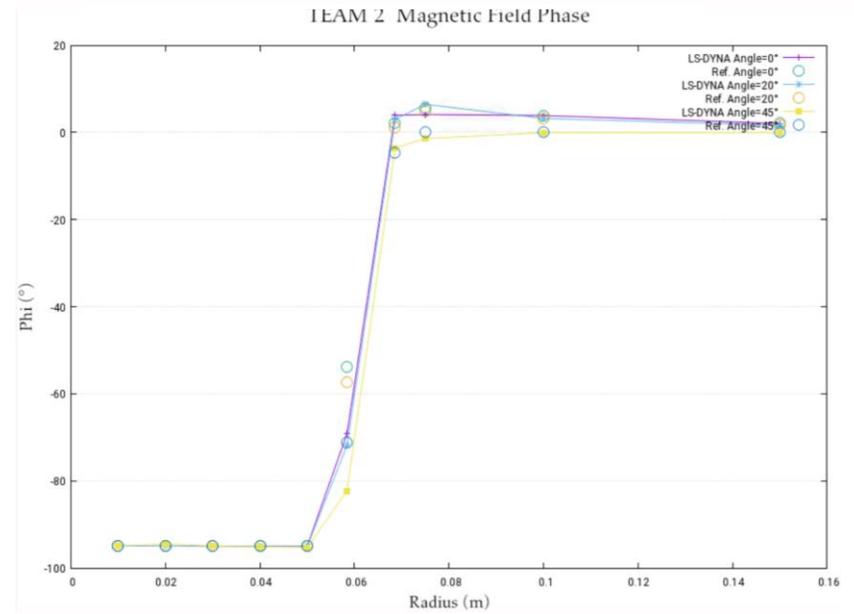
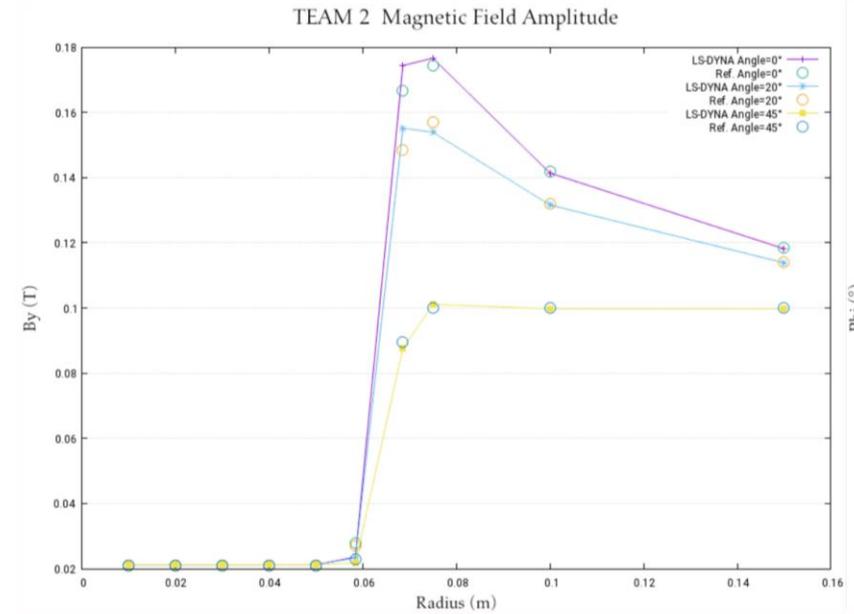
Power Loss and Forces time averaged on $\frac{1}{4}$ model



Case Study – T.E.A.M 2



Total quantities in the quarter region (Time Average)	Power Loss	F_x	F_y
Reference:	2288.2	-333.4	-166.7
LS-DYNA:	2260.3	-370.7	-143.9

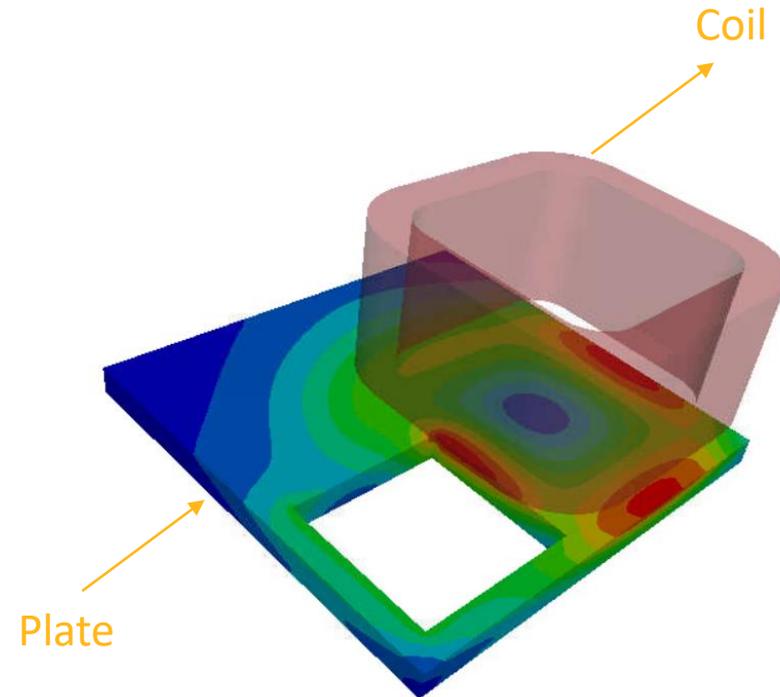


Case Study – T.E.A.M 7

ASYMMETRICAL CONDUCTOR WITH A HOLE

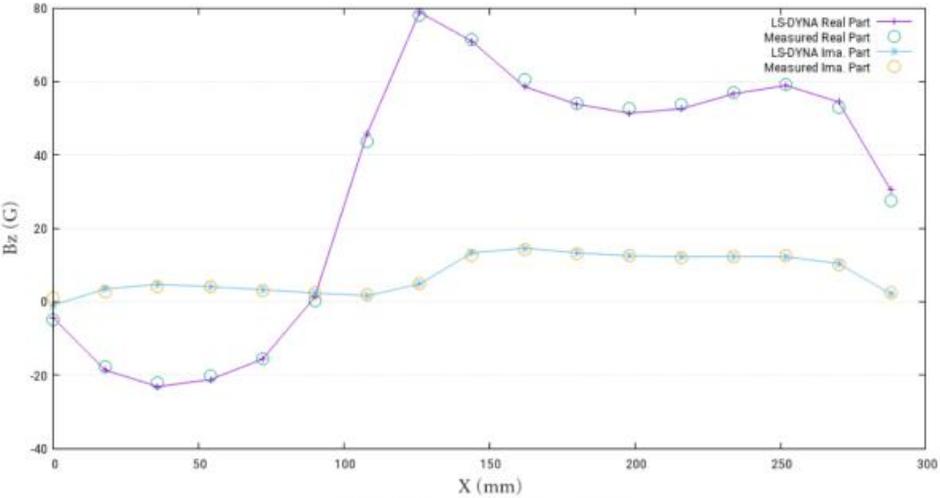
- Frequency Eddy current solver used.
- Coil with imposed current (Amplitude and frequency given) over a conducting plate (conductivity given).
- The objective is to measure the magnetic flux real and imaginary parts along two lines in the air between the coil and the plate.

Amplitude	2742. AT
Frequency	50/200 Hz
Conductivity	$35.26e^6$

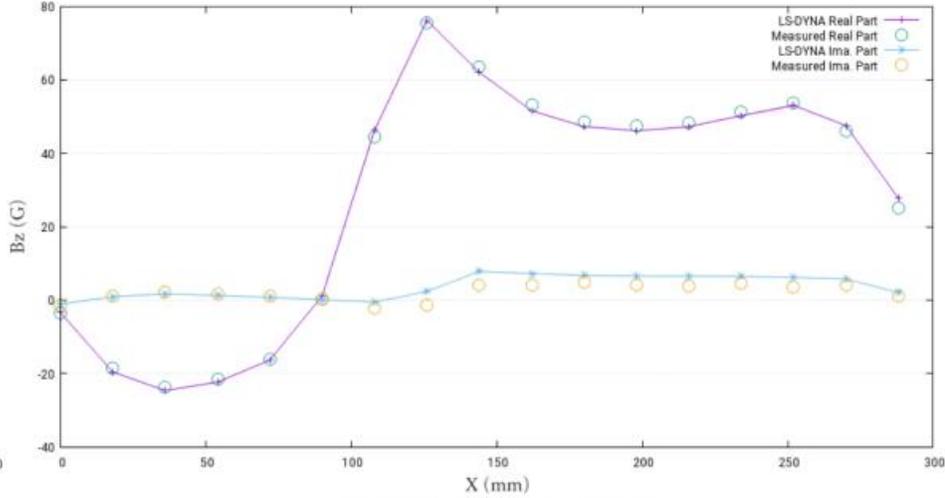


Case Study – T.E.A.M 7

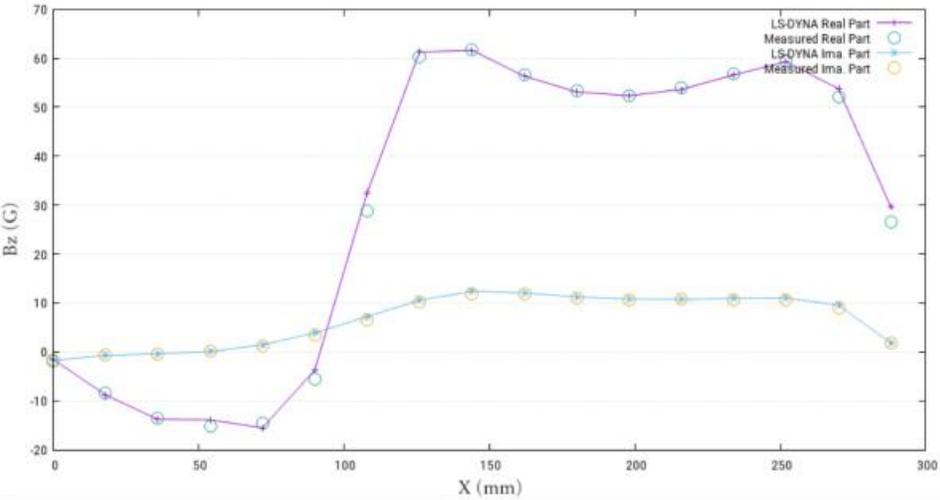
TEAM 7 : 50 Hz Line A1-B1



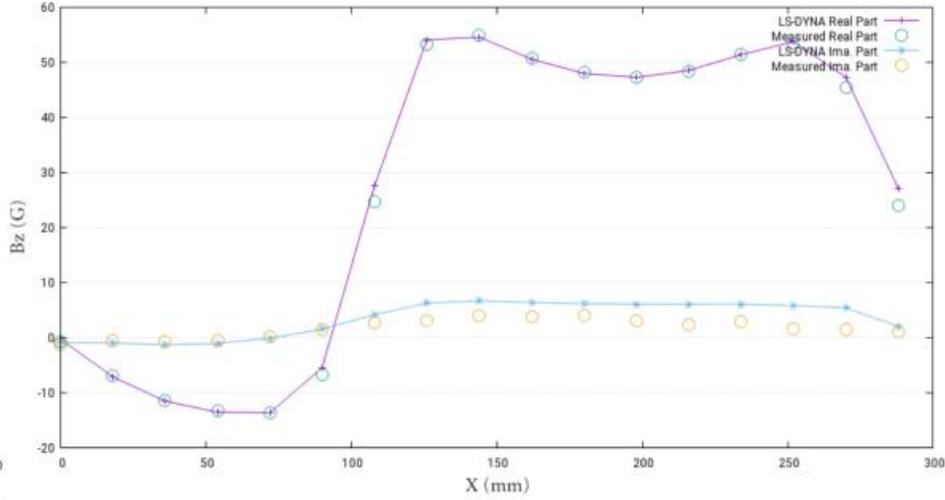
TEAM 7 : 200 Hz Line A1-B1



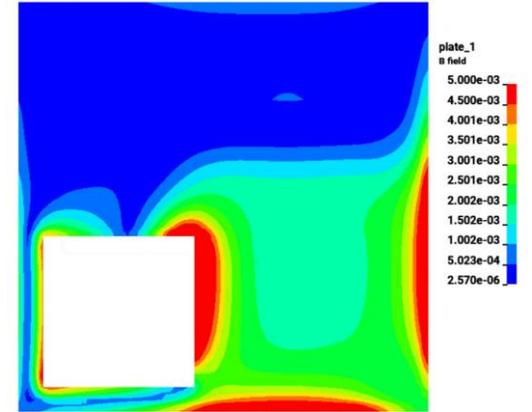
TEAM 7 : 50 Hz Line A2-B2



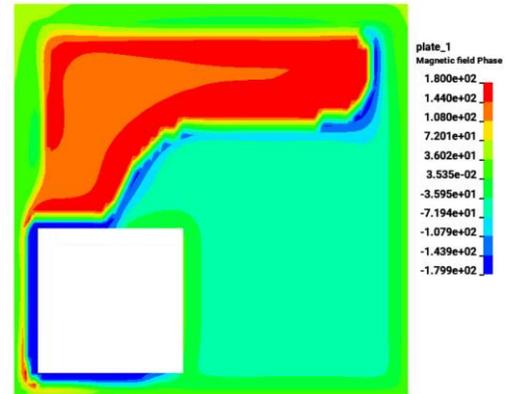
TEAM 7 : 200 Hz Line A2-B2



Bz Amplitude



Bz Phase



Thank you

