

Magnets, Ferromagnets and Actuators simulated with LS-DYNA

Nov 2021



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- Inductive heating

Focus of Webinar



Introduction : What is the LS-DYNA EM solver ?



/ EM solver terminology

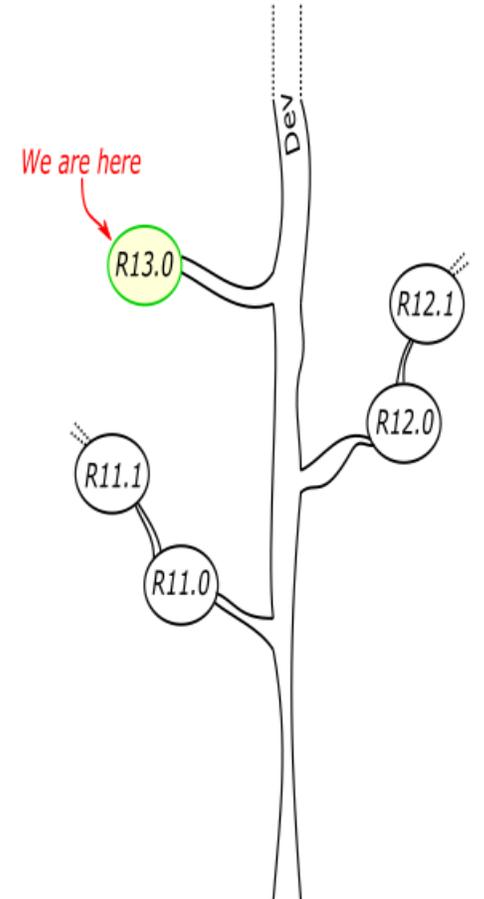
- Electromagnetics capabilities in LS-DYNA are all solvers contained within the 'EM solver' (keywords starting with *EM).
- Several EM solvers are available. They can be broadly divided in two categories : - **Eddy current solvers** and **Resistive solvers**.
- Main feature of Eddy current solvers :
 - 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.

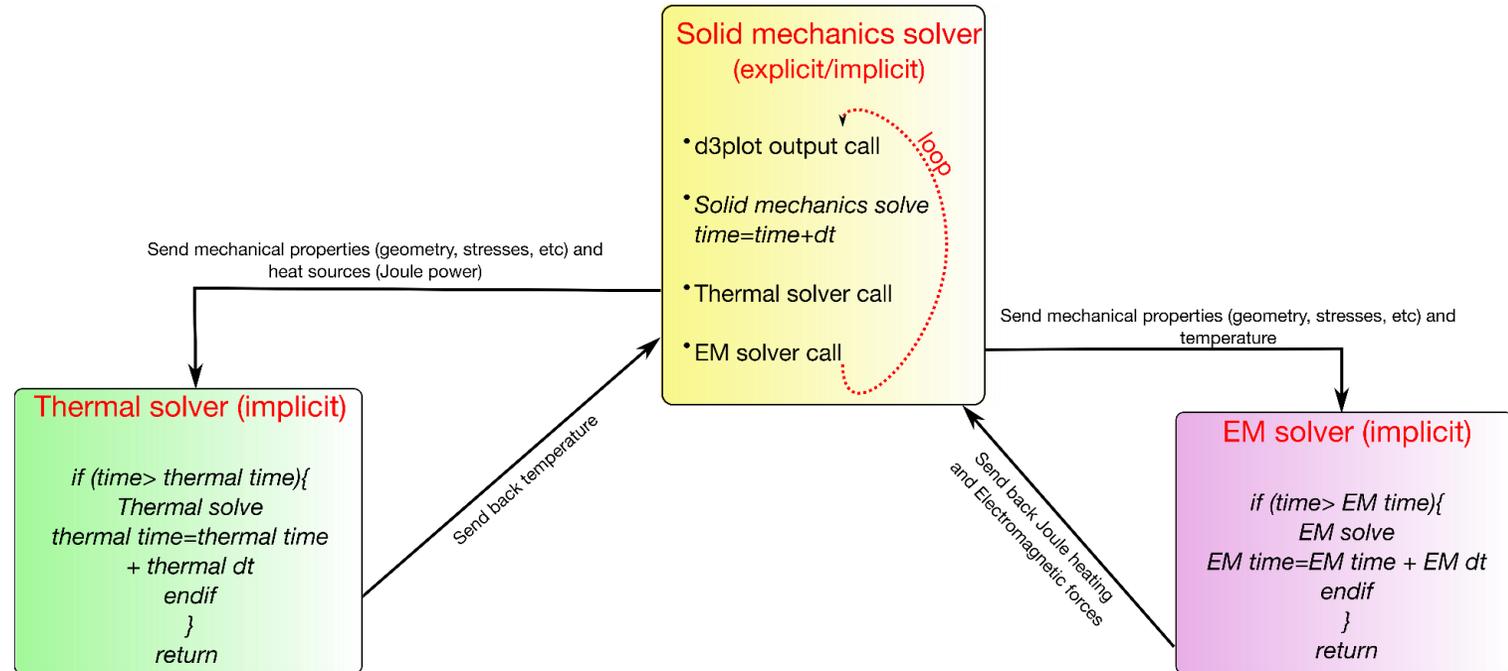
Warning : the revision number is not enough, and the branch name must be associated to it for e.g R12 revision 120001 and R11 revision 120002 may appear close but be completely different.

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



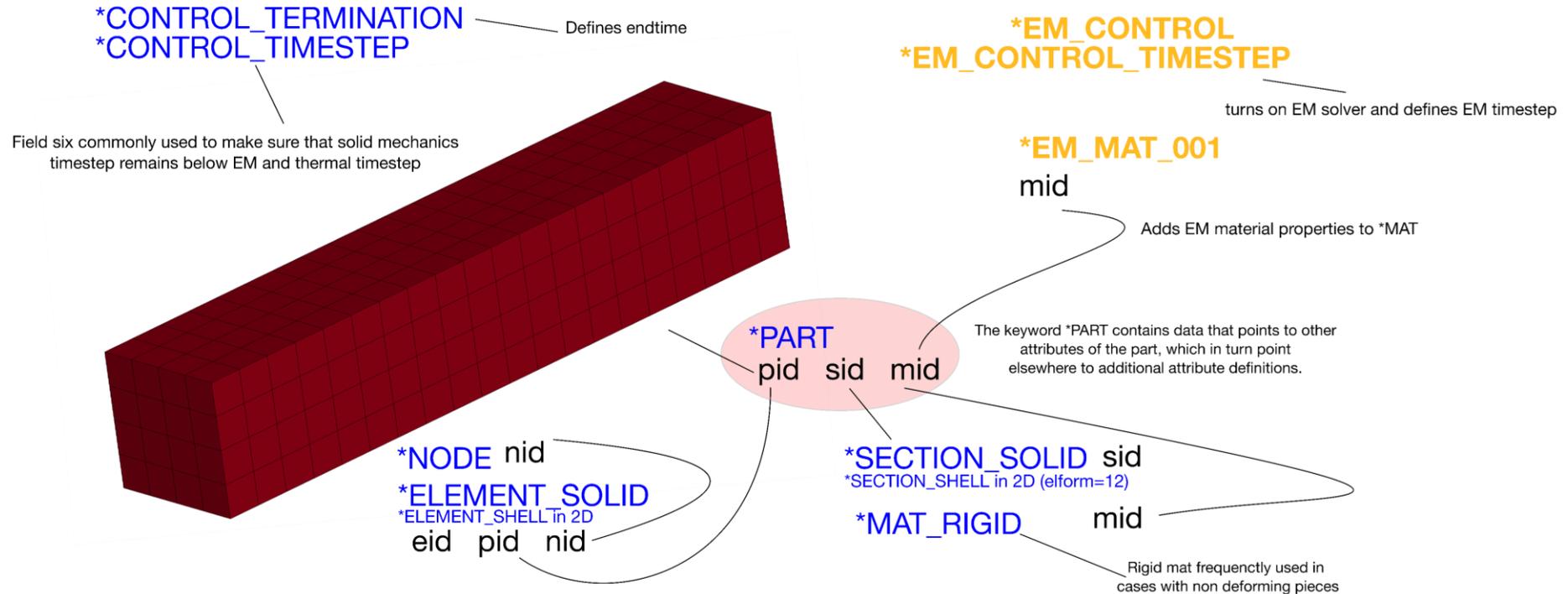
LS-DYNA internal structure

- 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

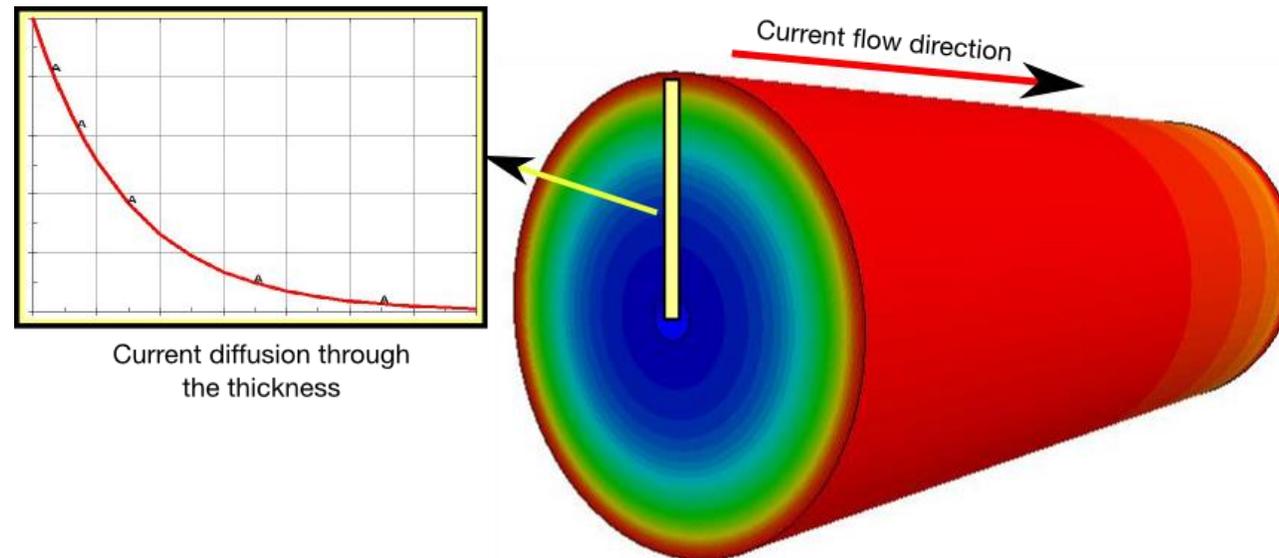
- Before running any EM problem, it is important to properly define the solid mechanics keywords
- LS-DYNA keyword structure is centered around the concept of “PART”s and “CONTROL” tools that control the various modelling options.
- For an EM problem, the keywords *EM_CONTROL, *EM_CONTROL_TIMESTEP and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



Introduction : Principles of Eddy Currents

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

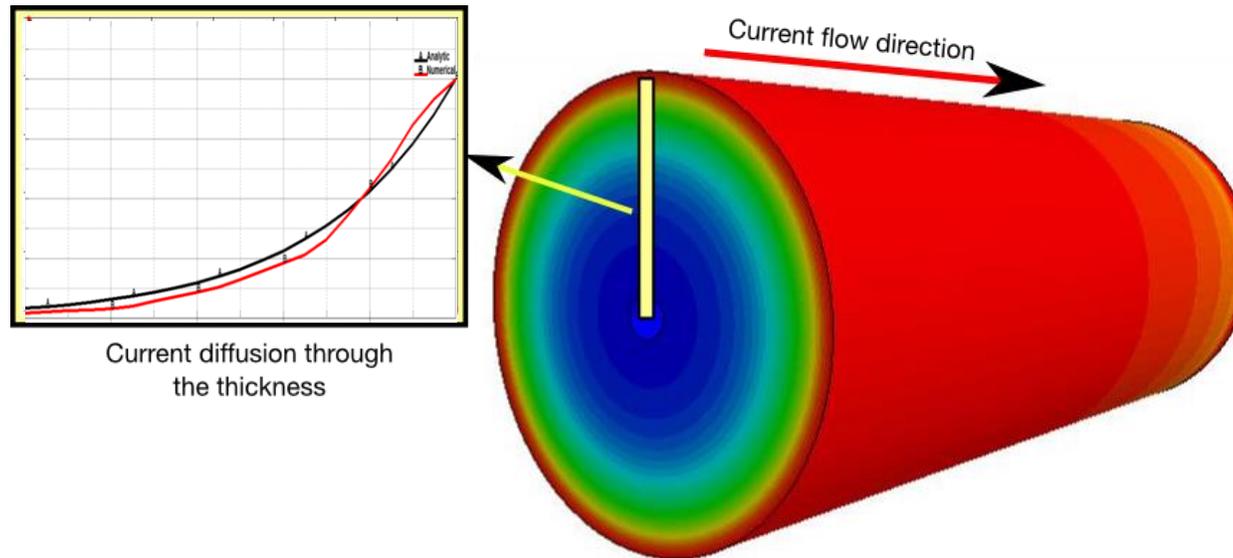
- For diffusive effects to be noticeable, the total thickness of the conductor must be bigger than the decay rate δ called skin depth => Fundamental rule of Eddy currents.

- 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

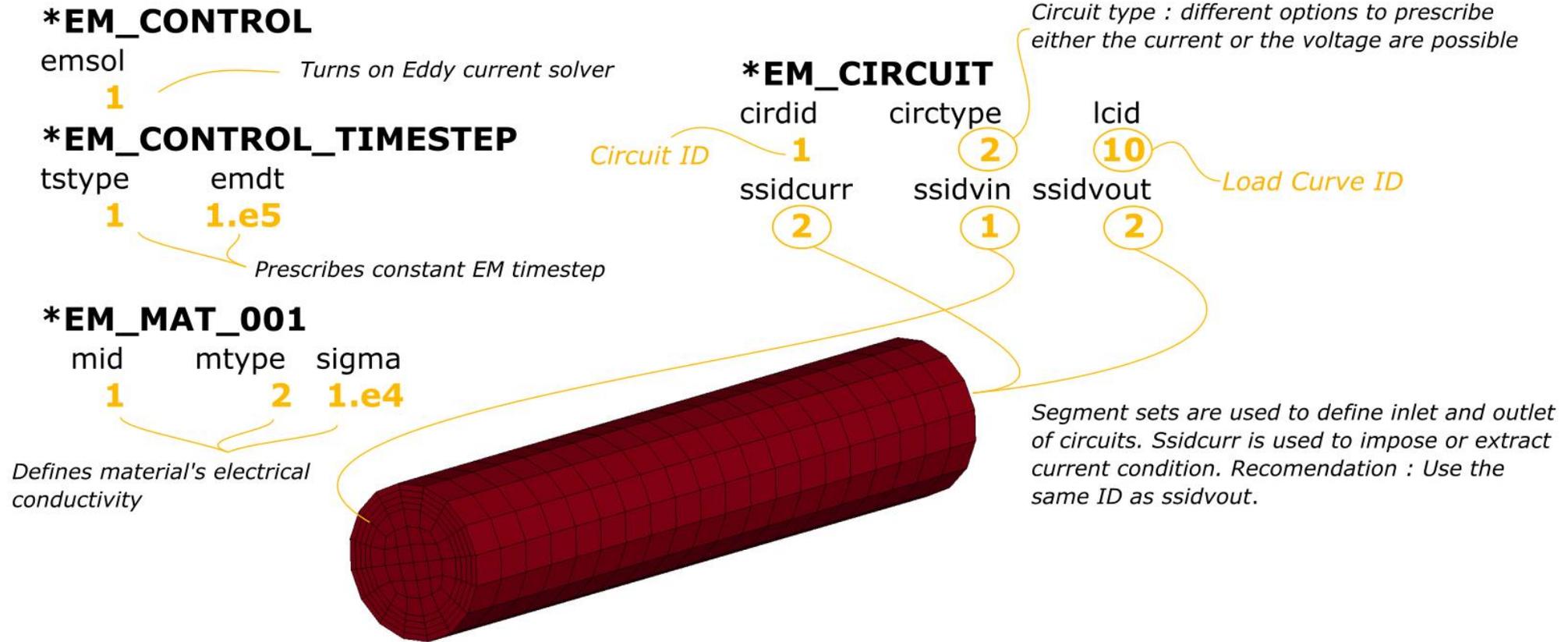


In order to capture this current diffusion, it is mandatory to have a mesh which is fine enough. Generally, it is recommended to have at least three elements in the first layer δ closest to the conductors' surface.



Case Study – Input deck

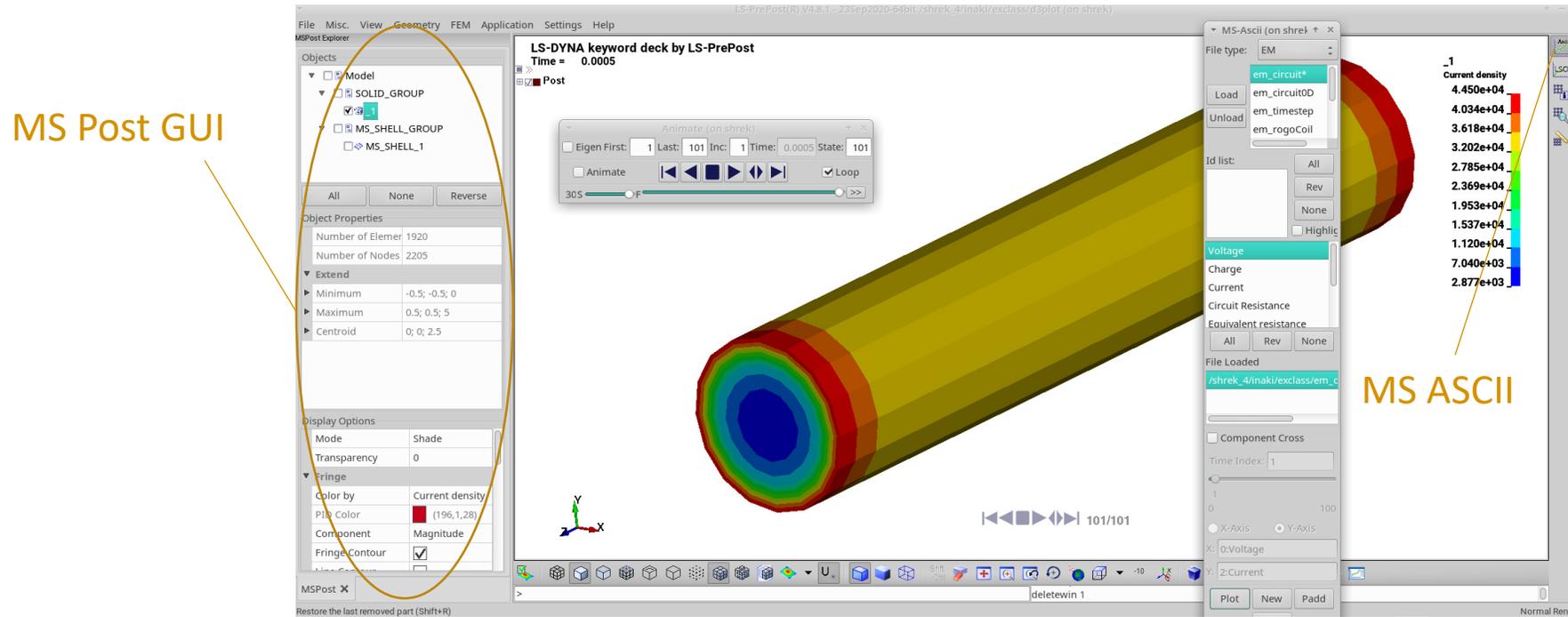
Conducting Rod with source current



Case Study - post

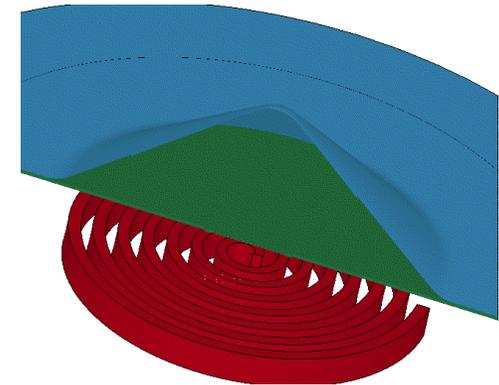
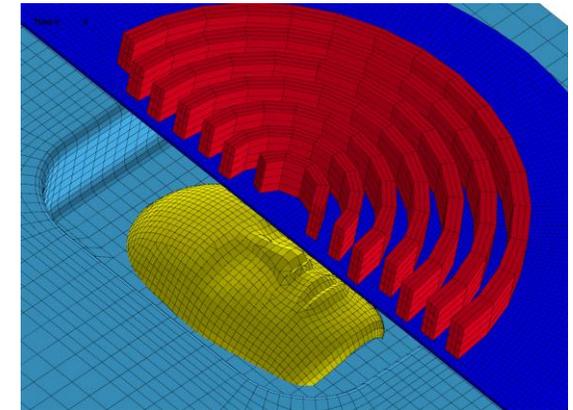
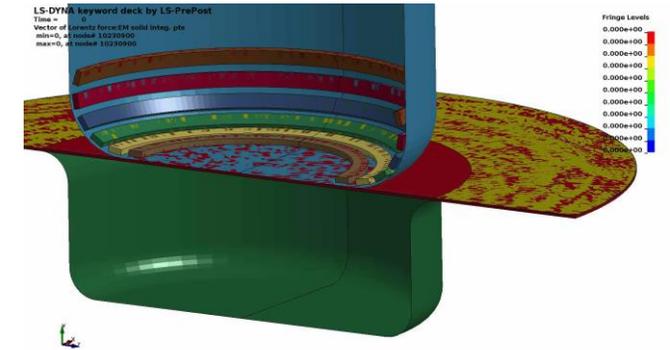
Conducting Rod with source current

- 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.



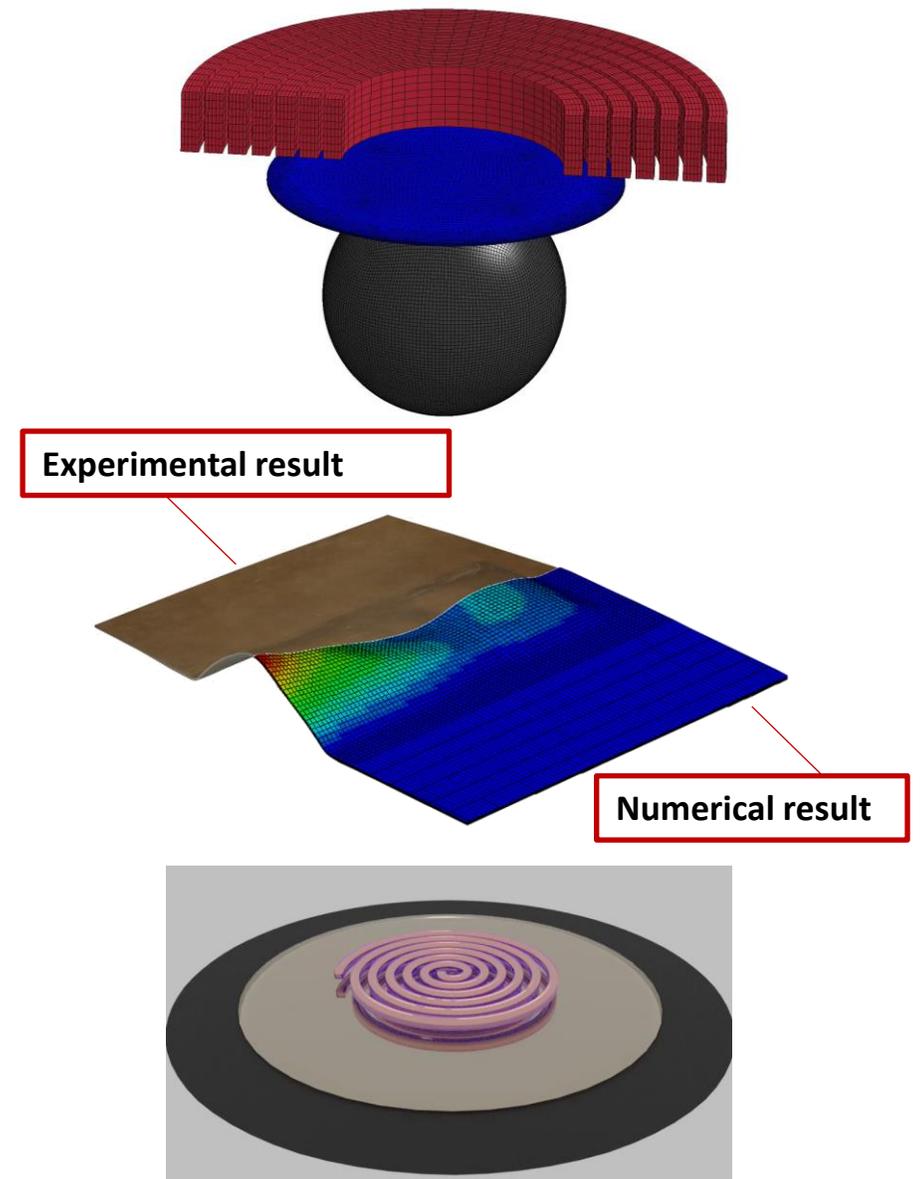
MMF principles

- 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.

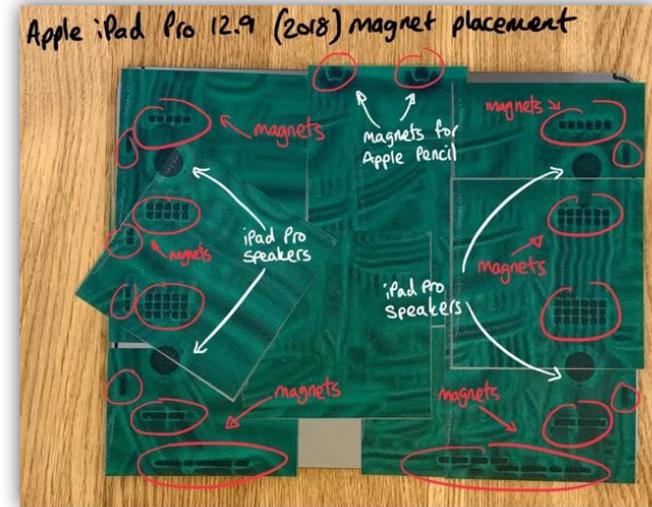


Magnet simulations

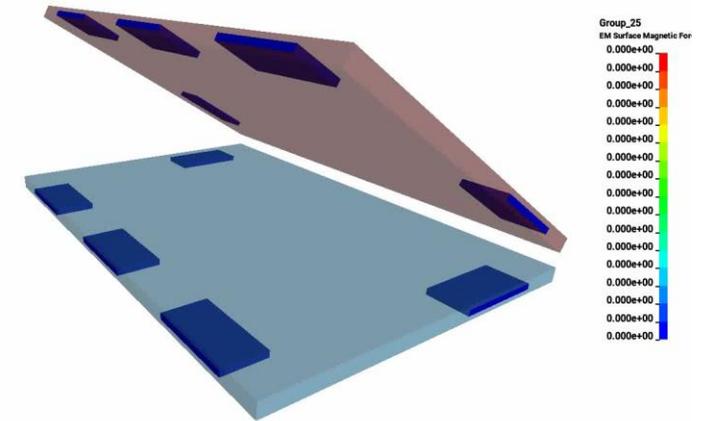


Background

- 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.

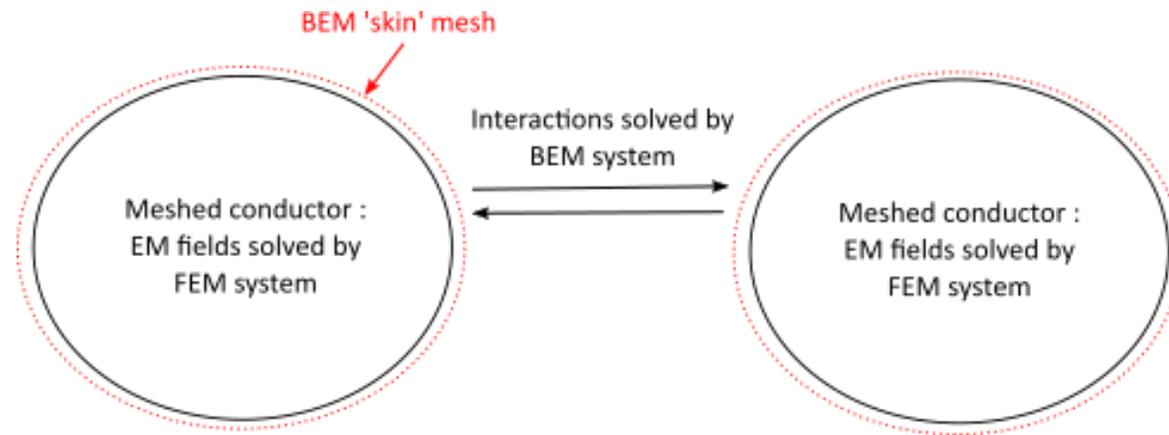


LS-DYNA keyword deck by LS-PrePost
Time = 0



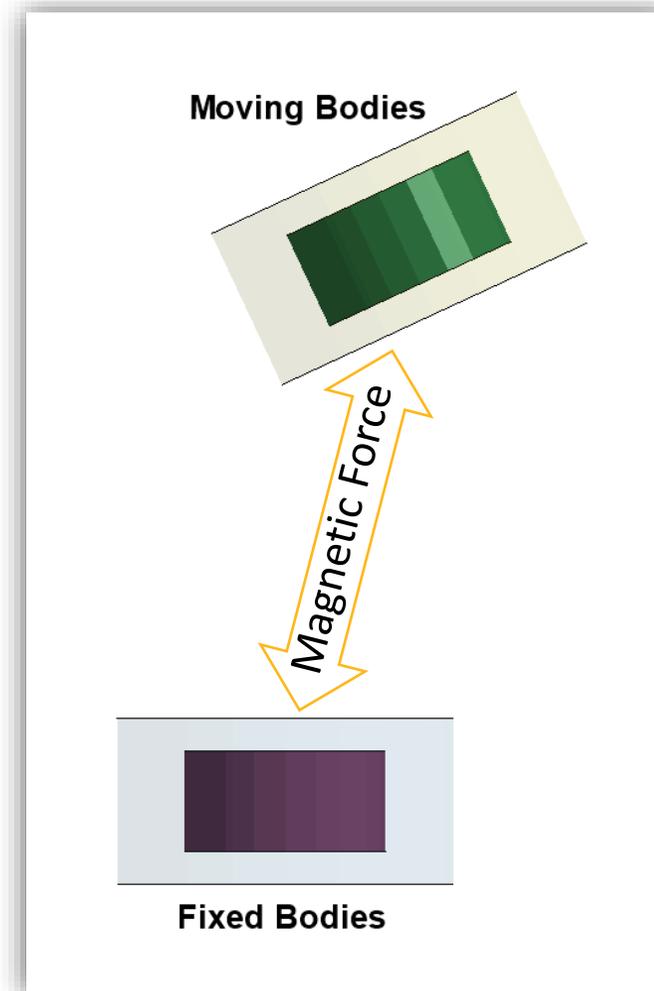
Interaction between conductors

- 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.



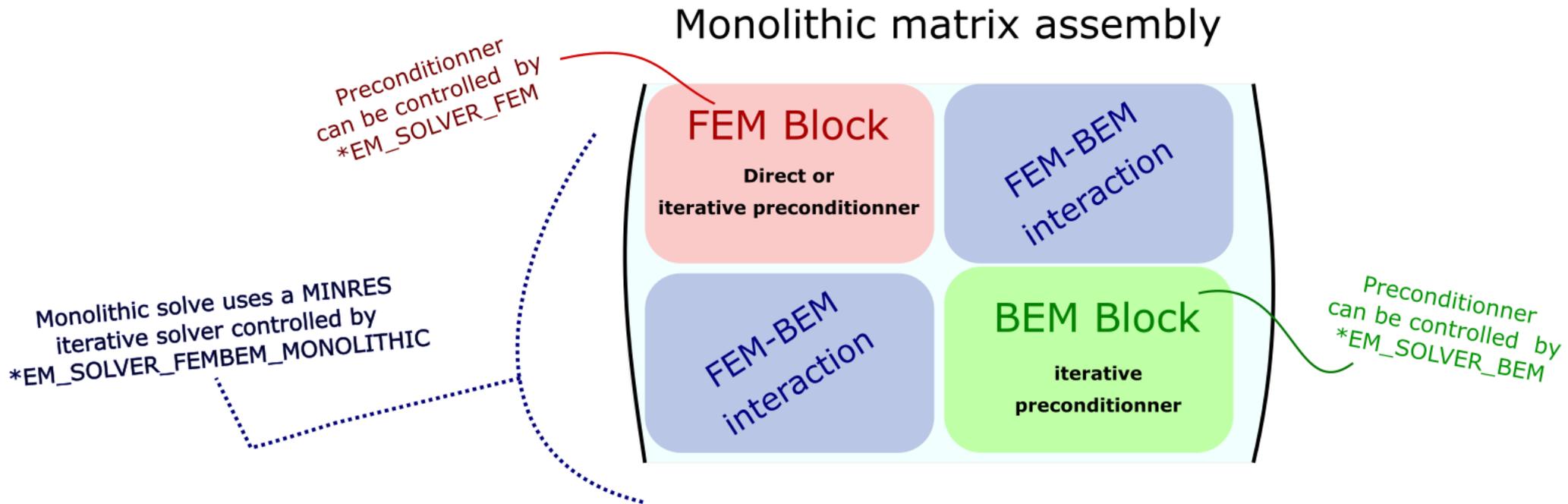
Interaction between magnets/ferromagnets

- 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 ($H_c = B_r/\mu_0$). Careful about units !

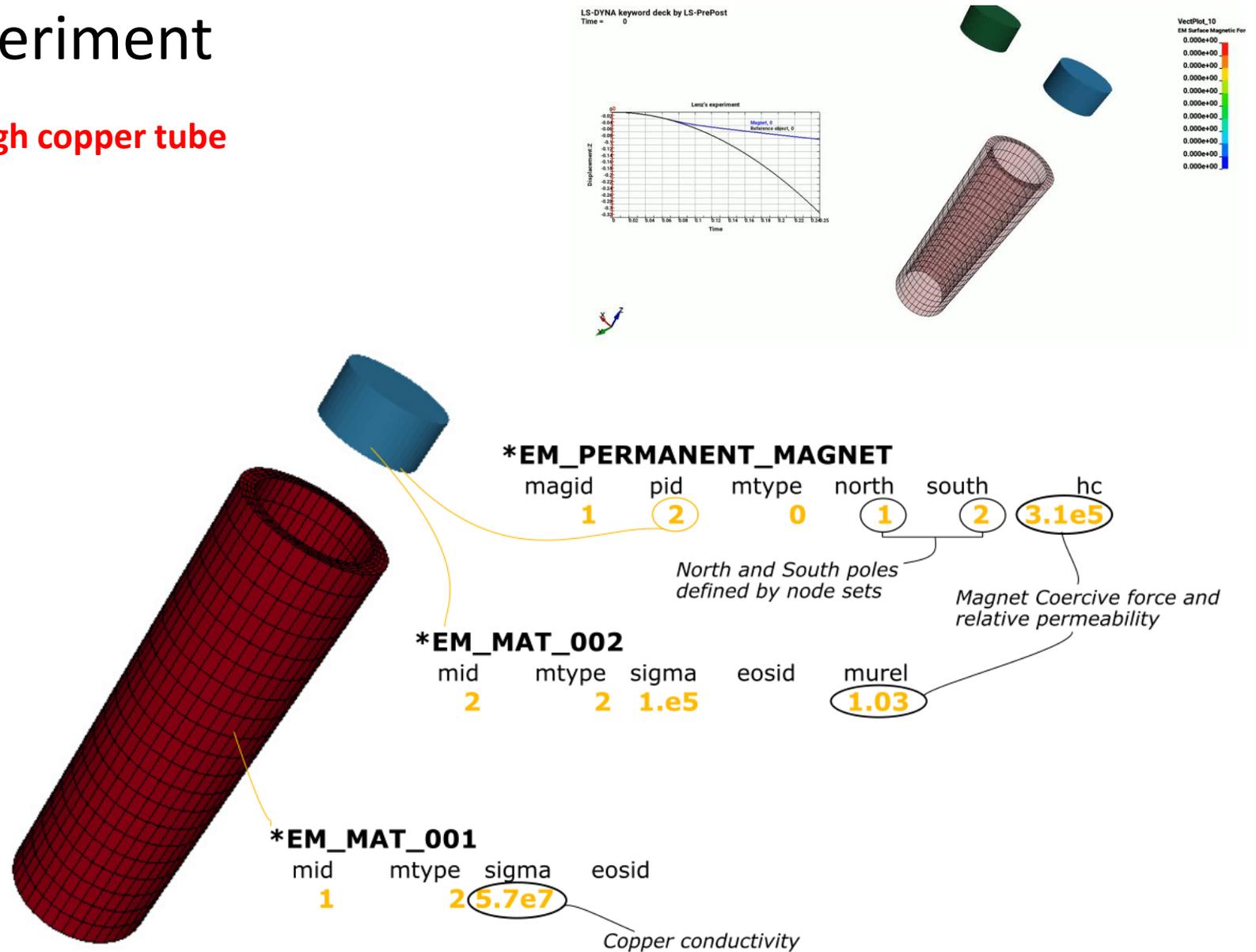
FEM/BEM system considerations

- 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

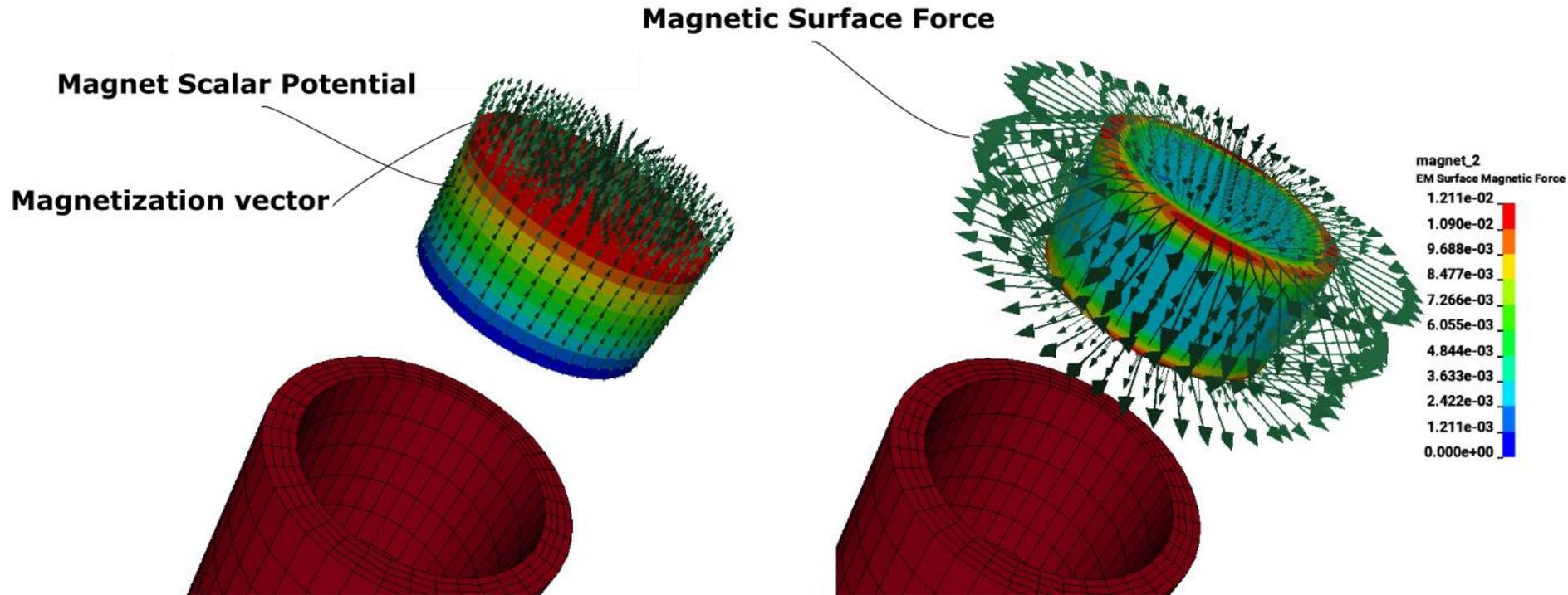
- This famous problem consist of a permanent magnet falling through a copper pipe. The temporal change of the magnetic field in the copper induces currents which themselves create an opposing magnetic field that slows the fall.
- Check magnet and solver properties. Notice the presence of `*EM_SOLVER_FEMBEM_MONOLITHIC` 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

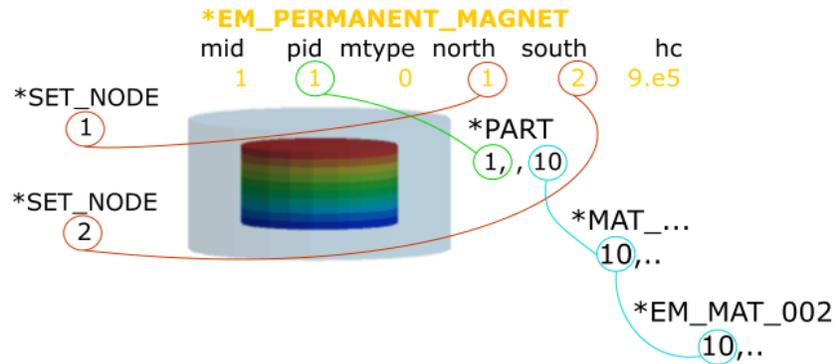
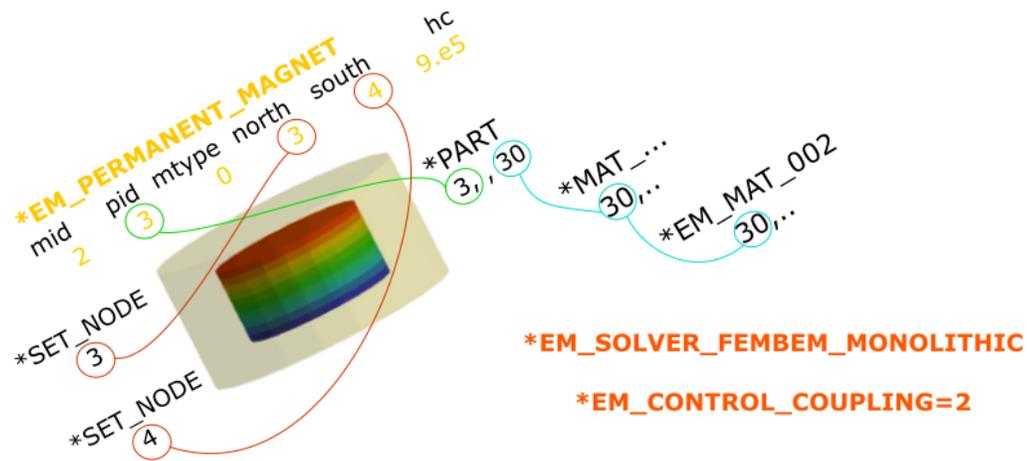
Post-treatment :

- 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.



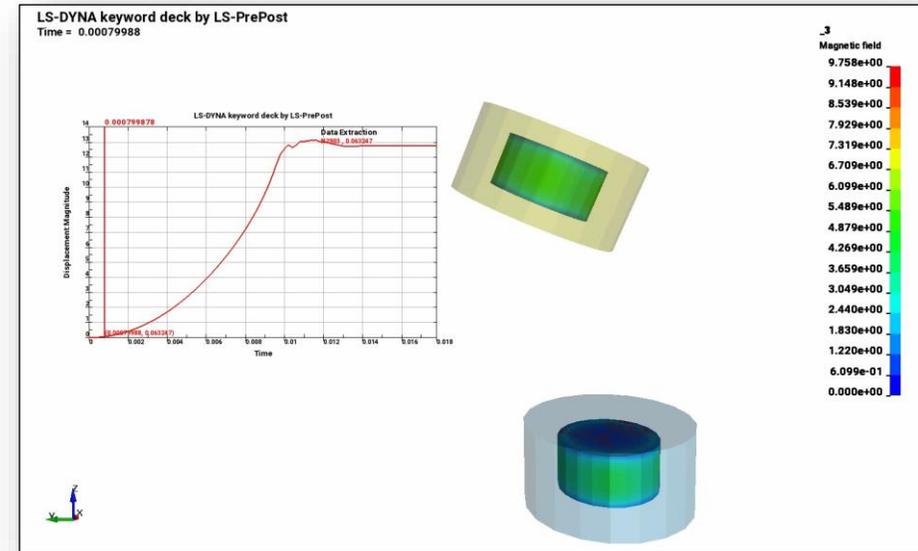
Case Study – Magnet snapping

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 frcfreq
$# 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
```

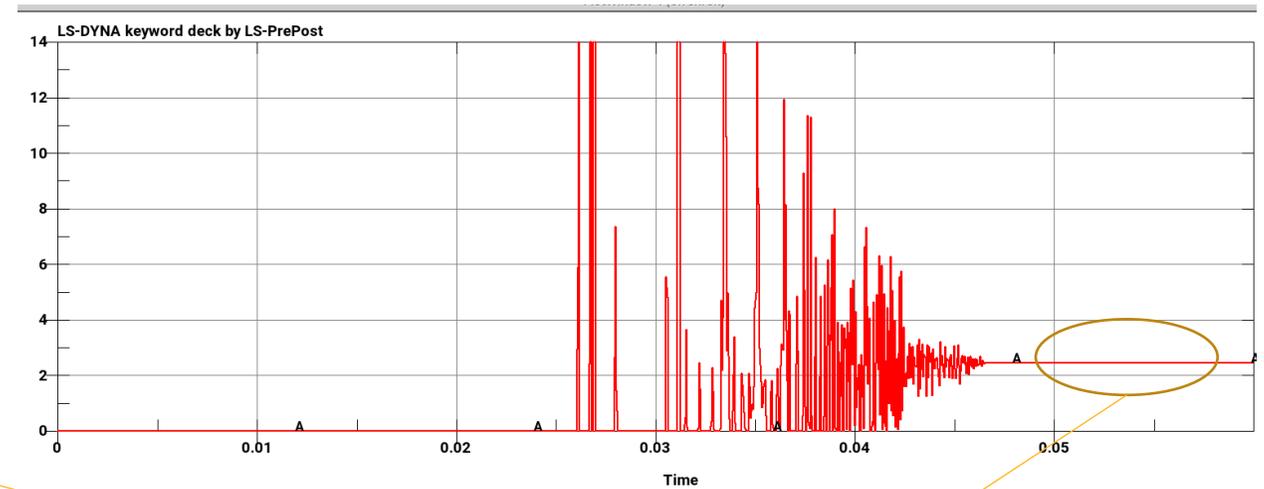
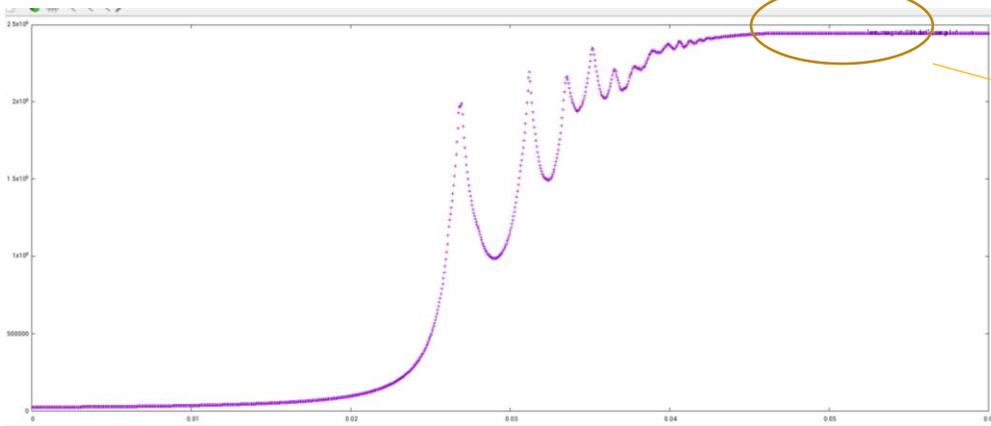


Case Study – Magnet snapping

Post :

Rcforc gives the contact force :

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

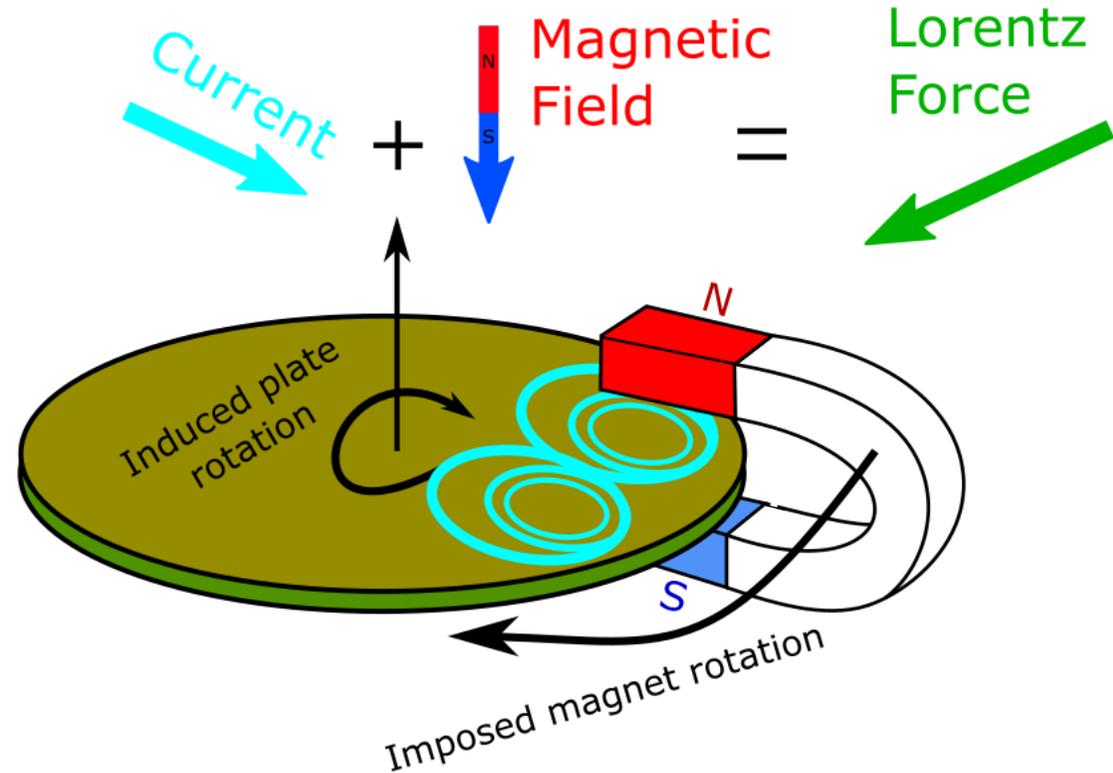


Matching results at equilibrium

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 :

*EM_PERMANENT_MAGNET

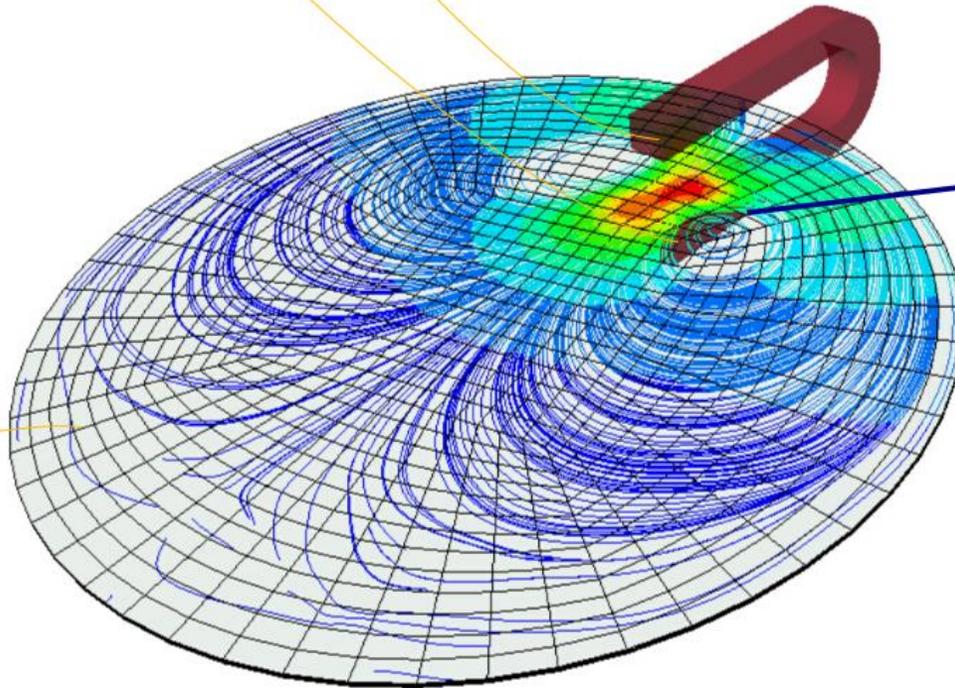
magid	pid	mtype	north	south	hc
1	1	0	1	2	1.0e6

*EM_MAT_002

mid	mtype	sigma	eosid	murel
1	2	1.e5		1.11

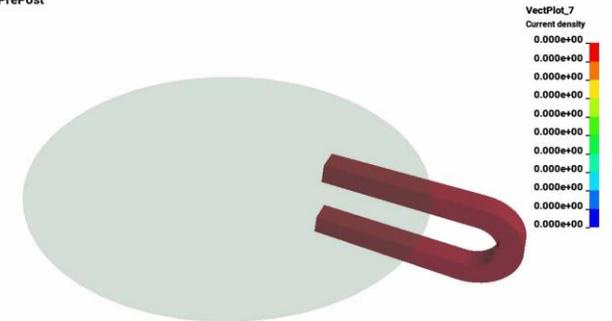
*EM_MAT_001

mid	mtype	sigma
3	2	6.e7



Current density streamlines

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

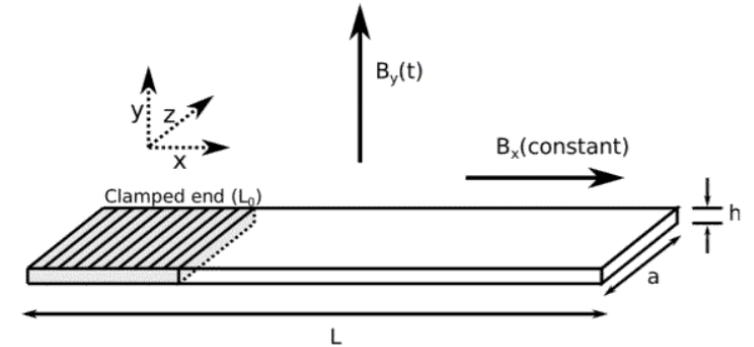


Case Study – Cantilever beam

Modified T.E.A.M 12 example :

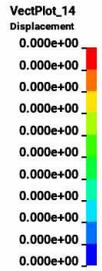
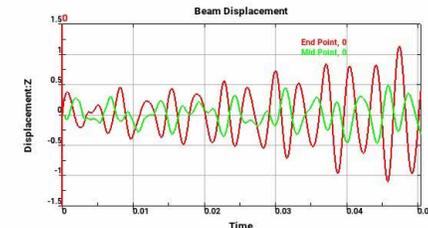
- In the original configuration the beam's oscillations are triggered by an external field. See *EM_EXTERNAL_FIELD.
- In this modified version, two magnets are placed at the end of the beam and a third magnet is attached to the beam.
- An initial displacement is applied on the beam's tip. The magnets 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 :

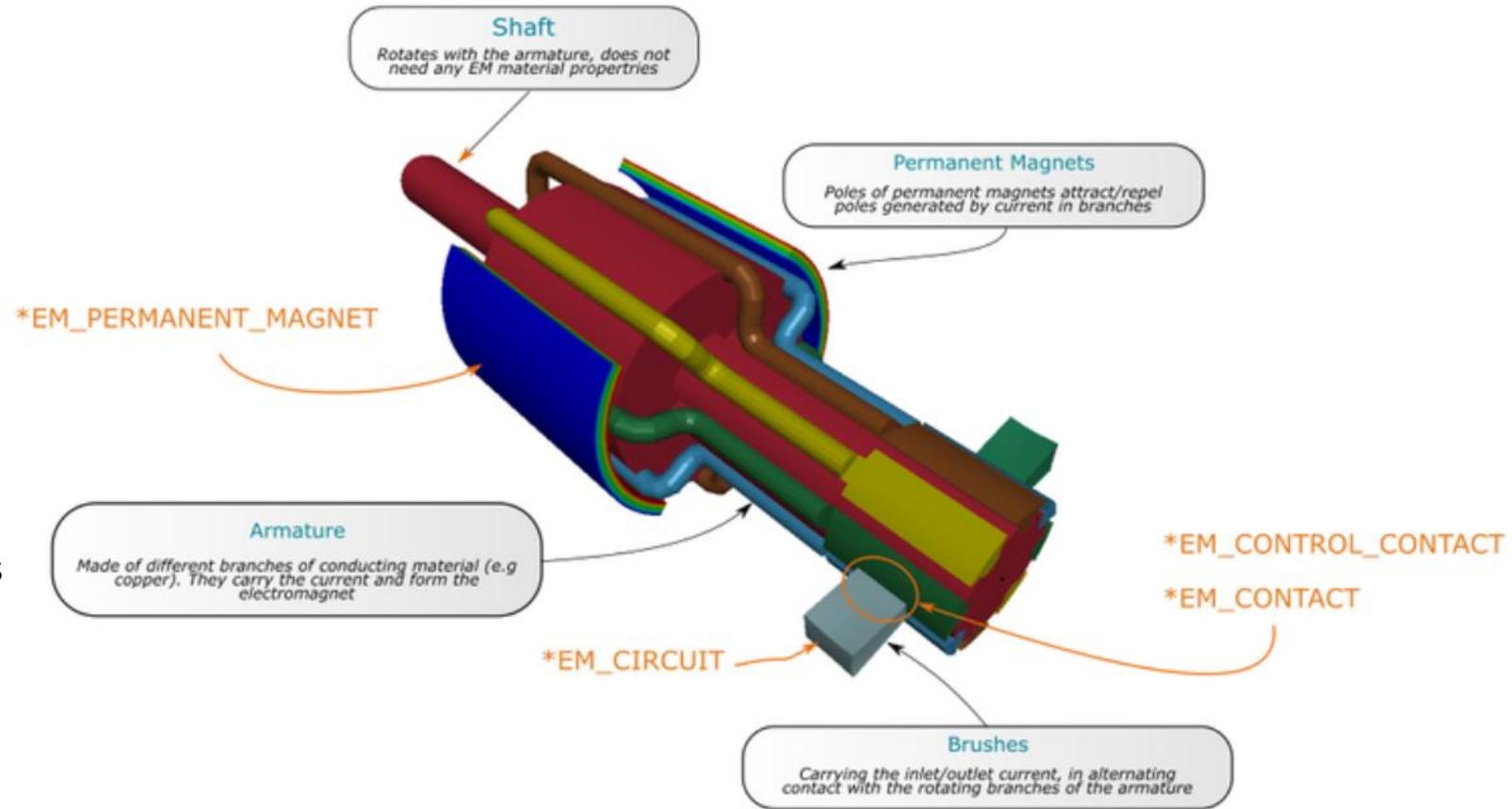
LS-DYNA keyword deck by LS-PrePost
Time = 0



Case Study – DC motor

Principle :

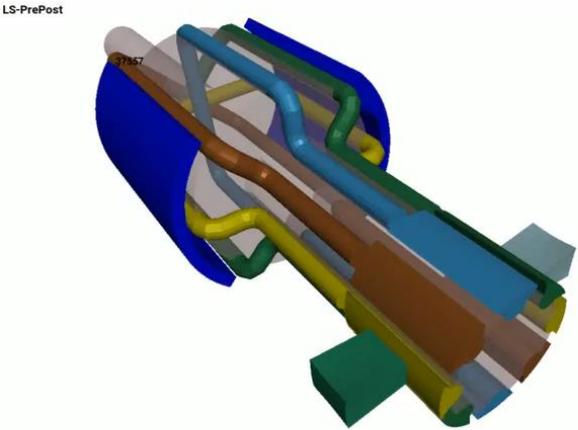
- A standard voltage of 12 V is applied between the two brushes of the motor.
- Permanent magnets located on each side of the armature cause the branches to start moving.
- The EM contact algorithm allows the current path to "switch" between the different branches and maintain the movement.
- The use 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



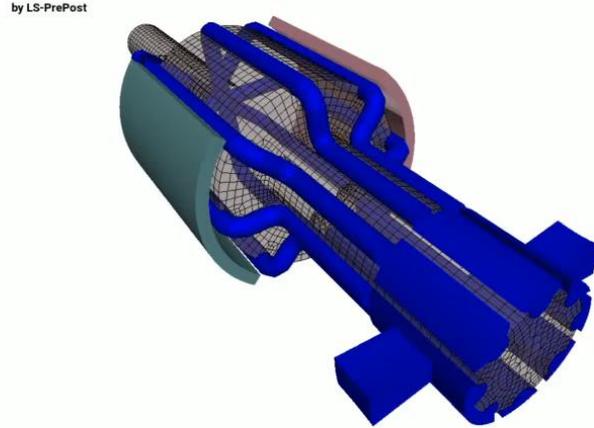
Case Study – DC motor

Post :

Magnetic potential in stator (permanent magnets)

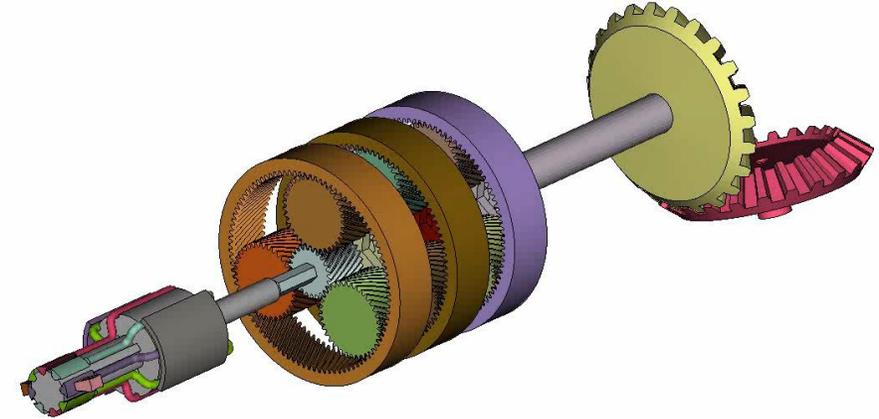


Scalar potential in armature branches and brushes



Increasing the complexity :

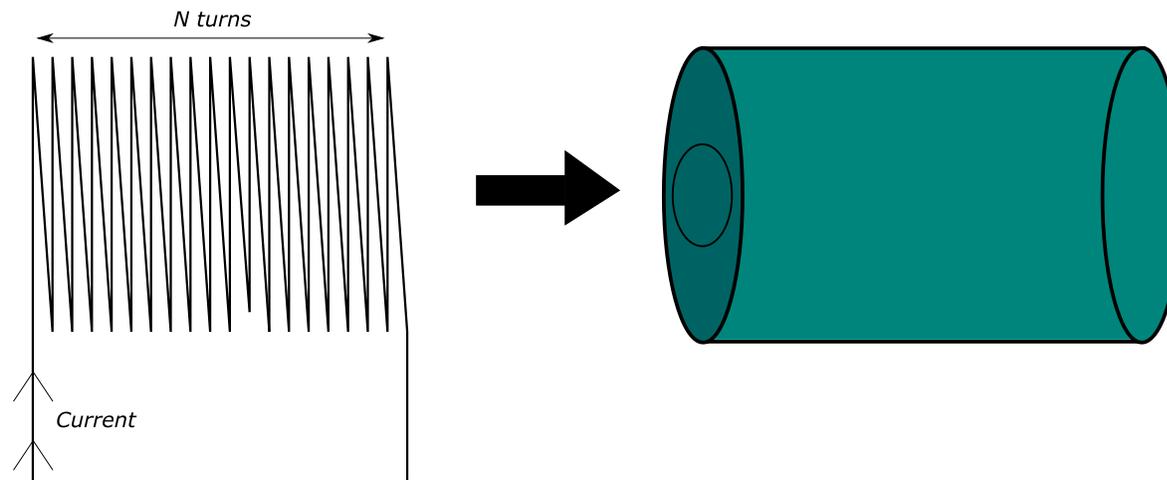
0:d3plot : LS-DYNA keyword deck by LS-PrePost : STATE 2 ,TIME 1.00000000E-04



**Stranded conductors,
magnetostatics and
ferromagnets**

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).



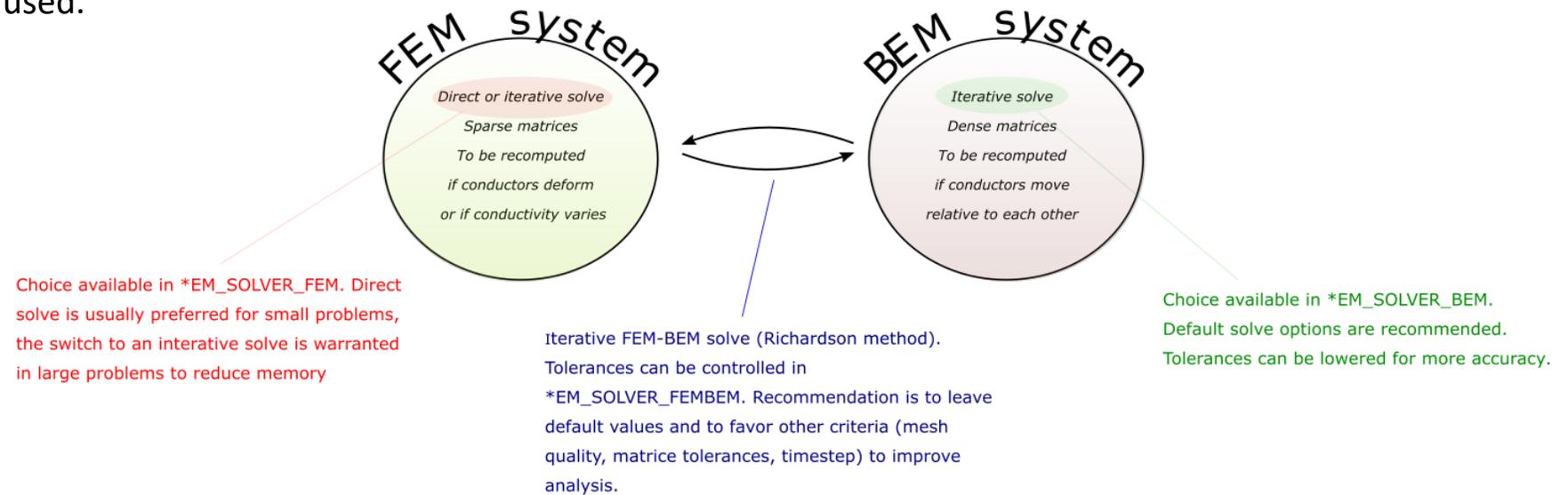
EM timestep considerations

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

Mesh size

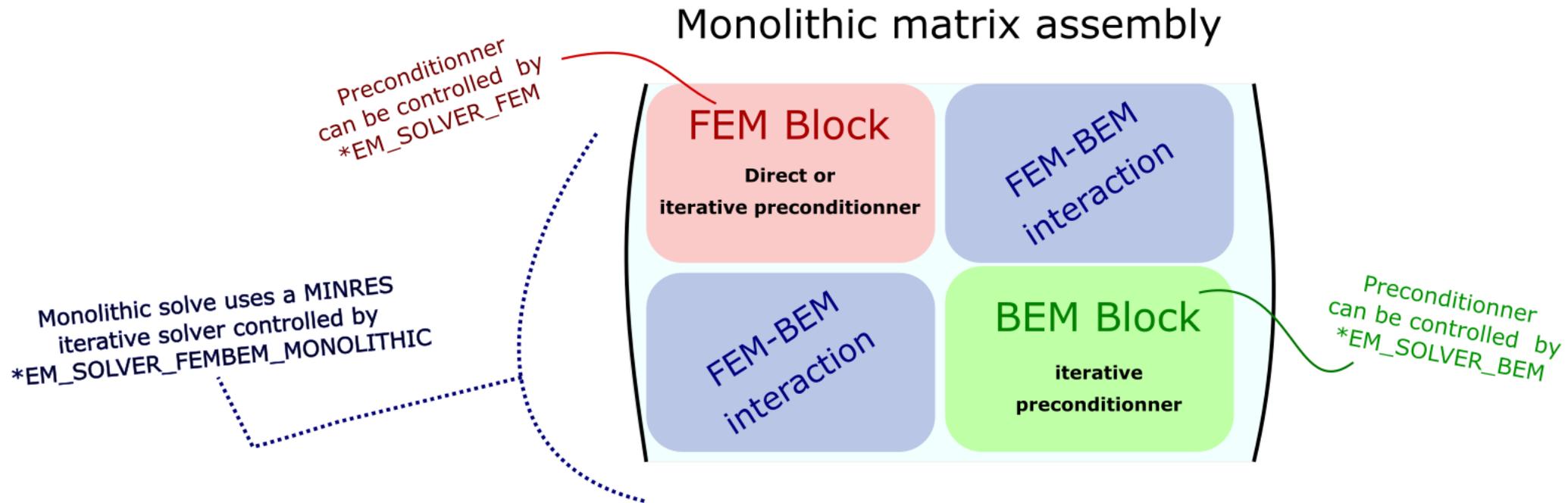
$$\Delta t \leq \frac{l^2}{2D} \quad D = \frac{1}{\mu\sigma}$$

- 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

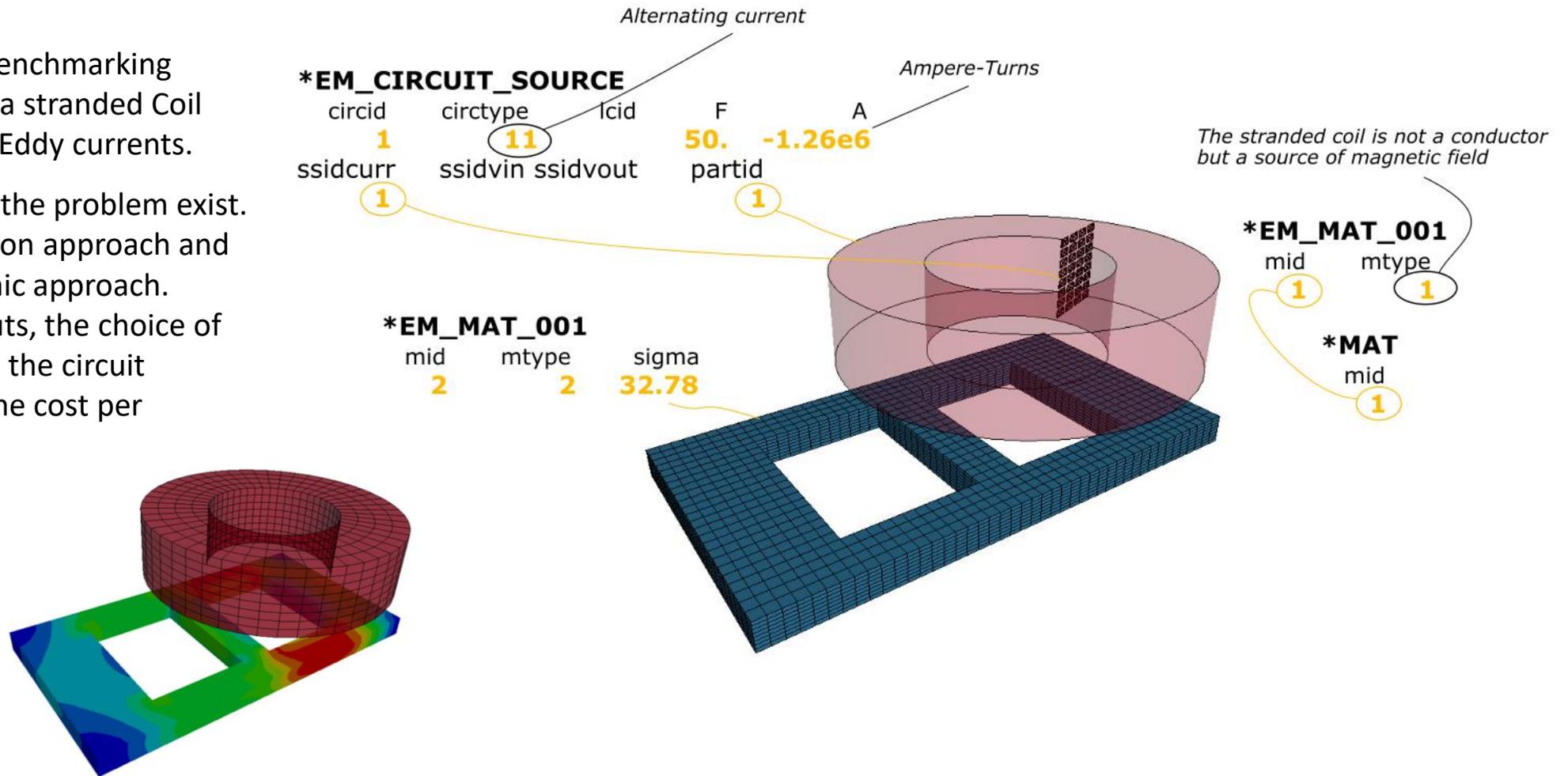
- FEM and BEM system are assembled and solved in a single matrix. This approach needs to be triggered by `*EM_SOLVER_FEMBEM_MONOLITHIC`.
- The advantage of such an approach is robustness, higher timesteps can be used, varying permeability problems can be solved as well as magnet interactions.



Case Study – TEAM 3 problem

Stranded Coil + workpiece

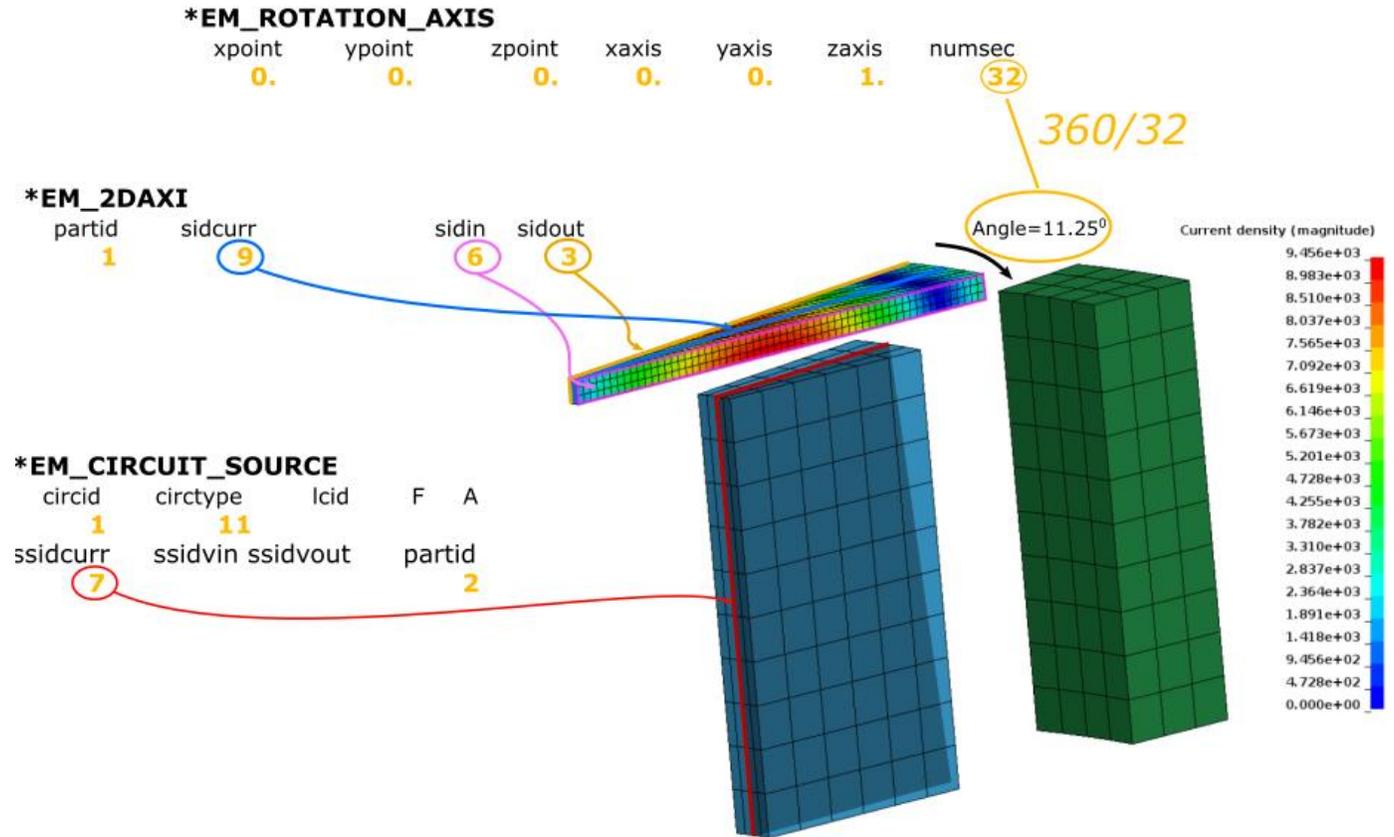
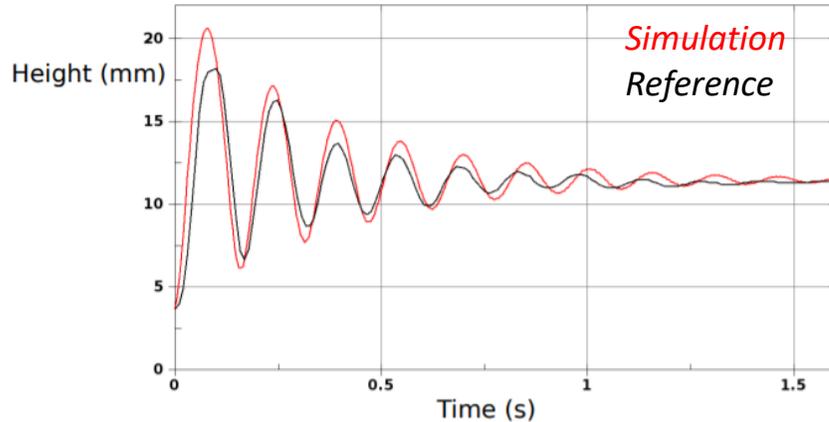
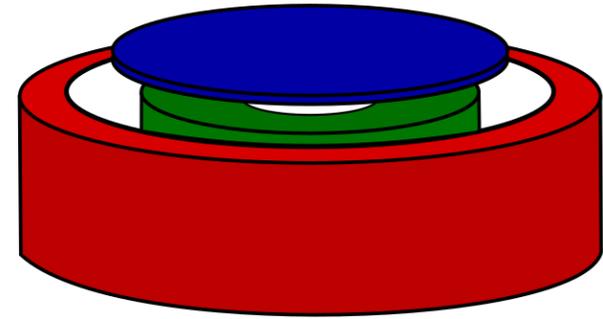
- Classic Eddy current benchmarking problem consisting of a stranded Coil and a workpiece with Eddy currents.
- Two configurations of the problem exist. One with the Richardson approach and one with the monolithic approach. Compare the two inputs, the choice of timestep compared to the circuit frequency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

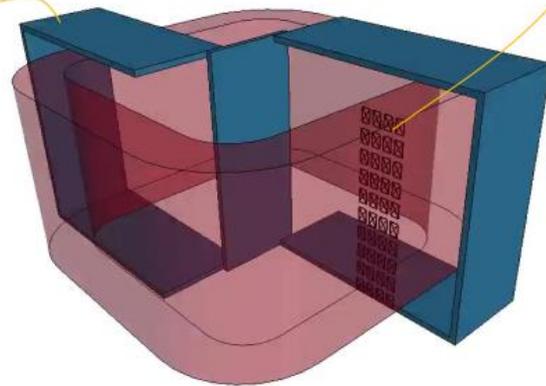
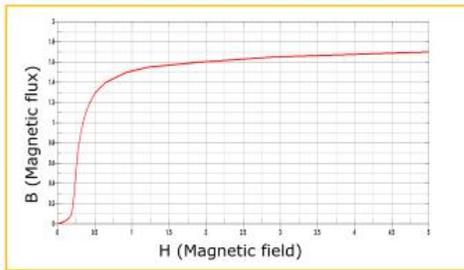
/ Magnetostatics

- 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.

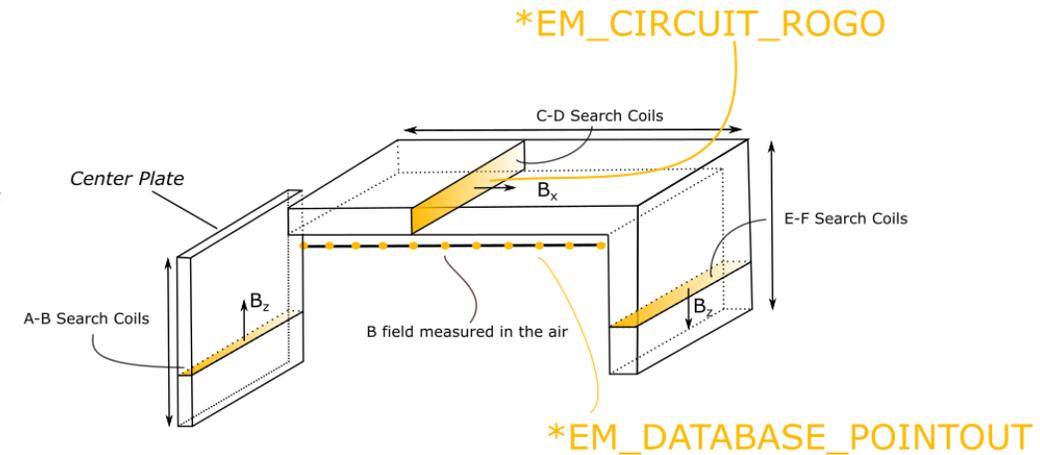
Case Study – T.E.A.M 13

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.

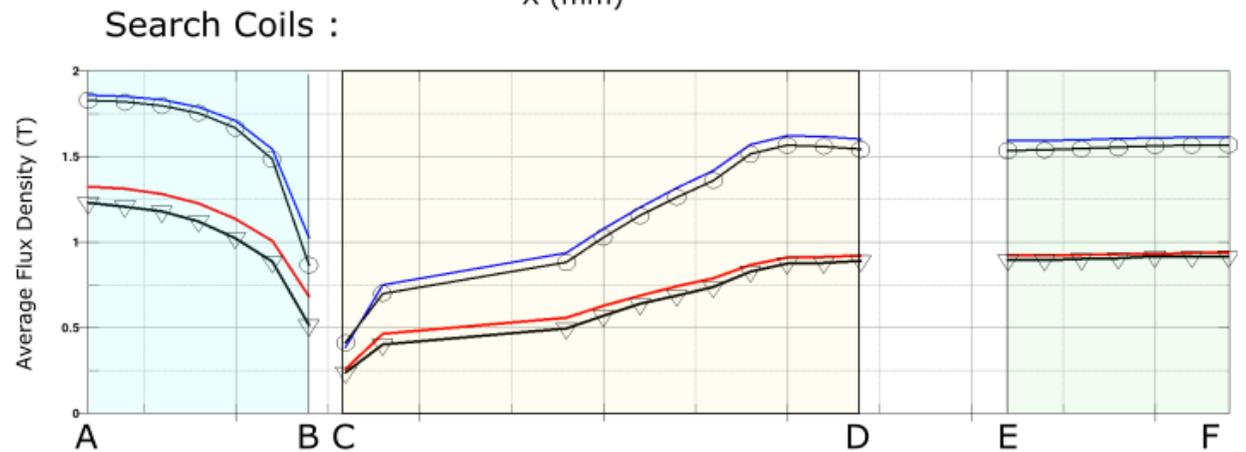
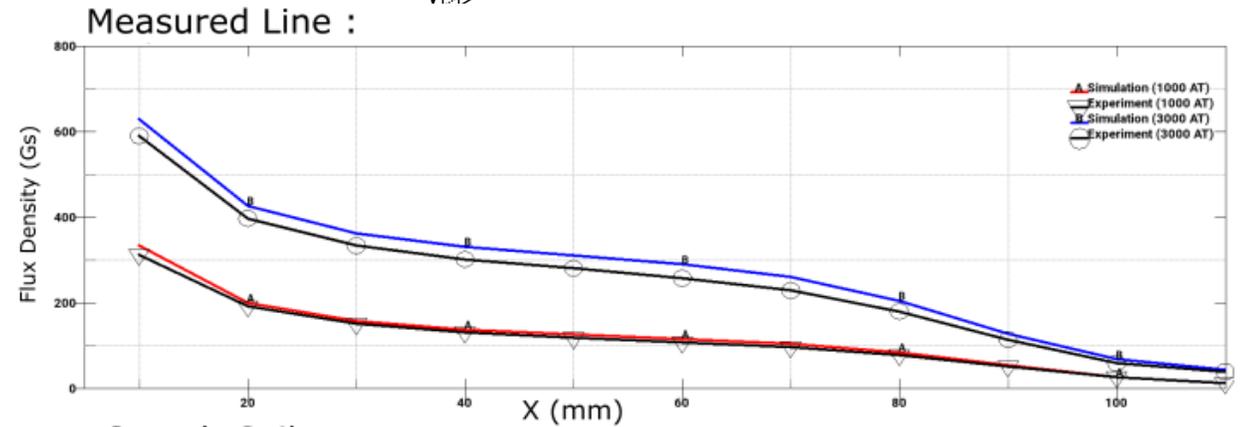
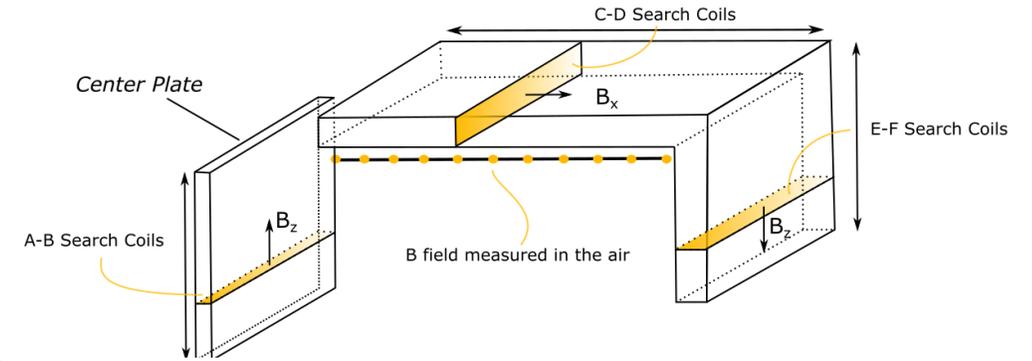
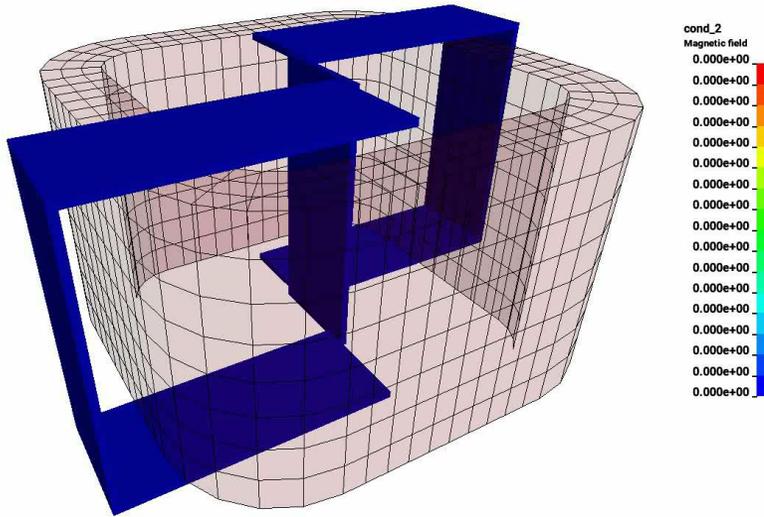
Default is 2 : Diagonal block preconditioner. For non linear material cases, try 4 : LLT factorization for speed up.

Case Study – T.E.A.M 13

Post :

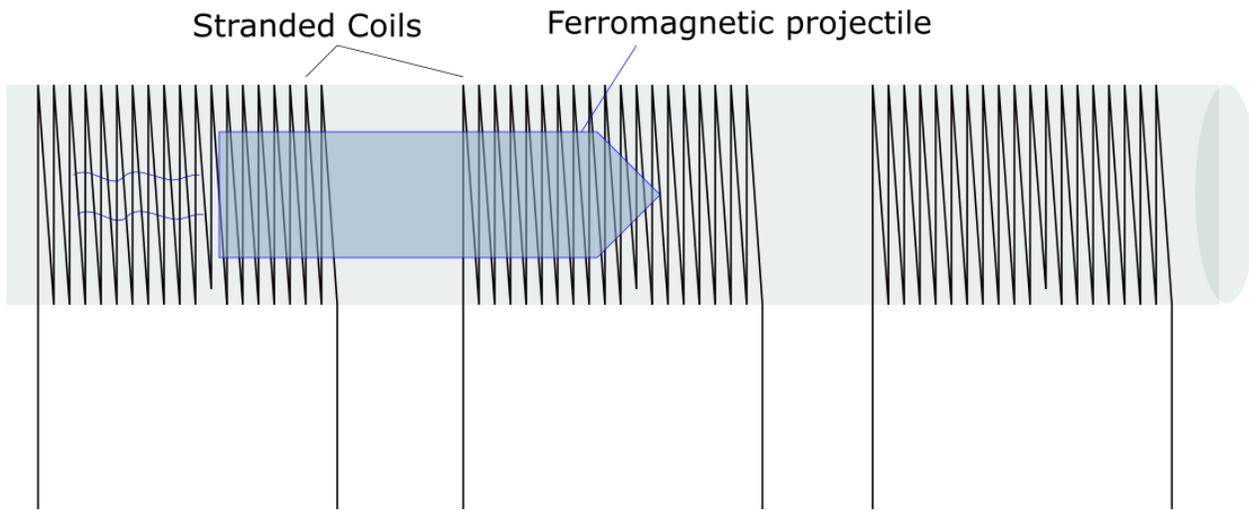
- Results are almost identical between the time dependent and the magnetostatic solve.
- Look for “NL newton” in the message file. Compare results between magnetostatic and time dependent case.

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

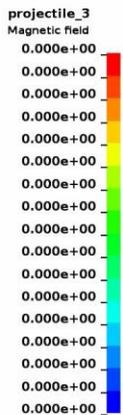
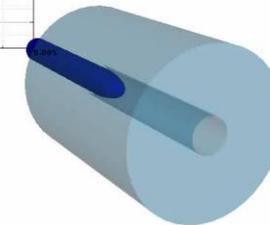
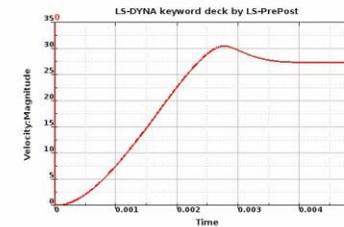


Coilgun

- A coilgun (also known as Gauss gun) is a type of projectile accelerator consisting of one or more coils used as electromagnets that accelerate a ferromagnetic projectile to high velocity as it passes through the center of the coils.
- The main difference with the railgun is that there is no sliding contact. Instead of relying on eddy currents and a Lorentz force, the projectile is made of a ferromagnetic (i.e relative permeability $\neq 1$.) material which generates sufficient magnetization force to propel the solid slug.



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

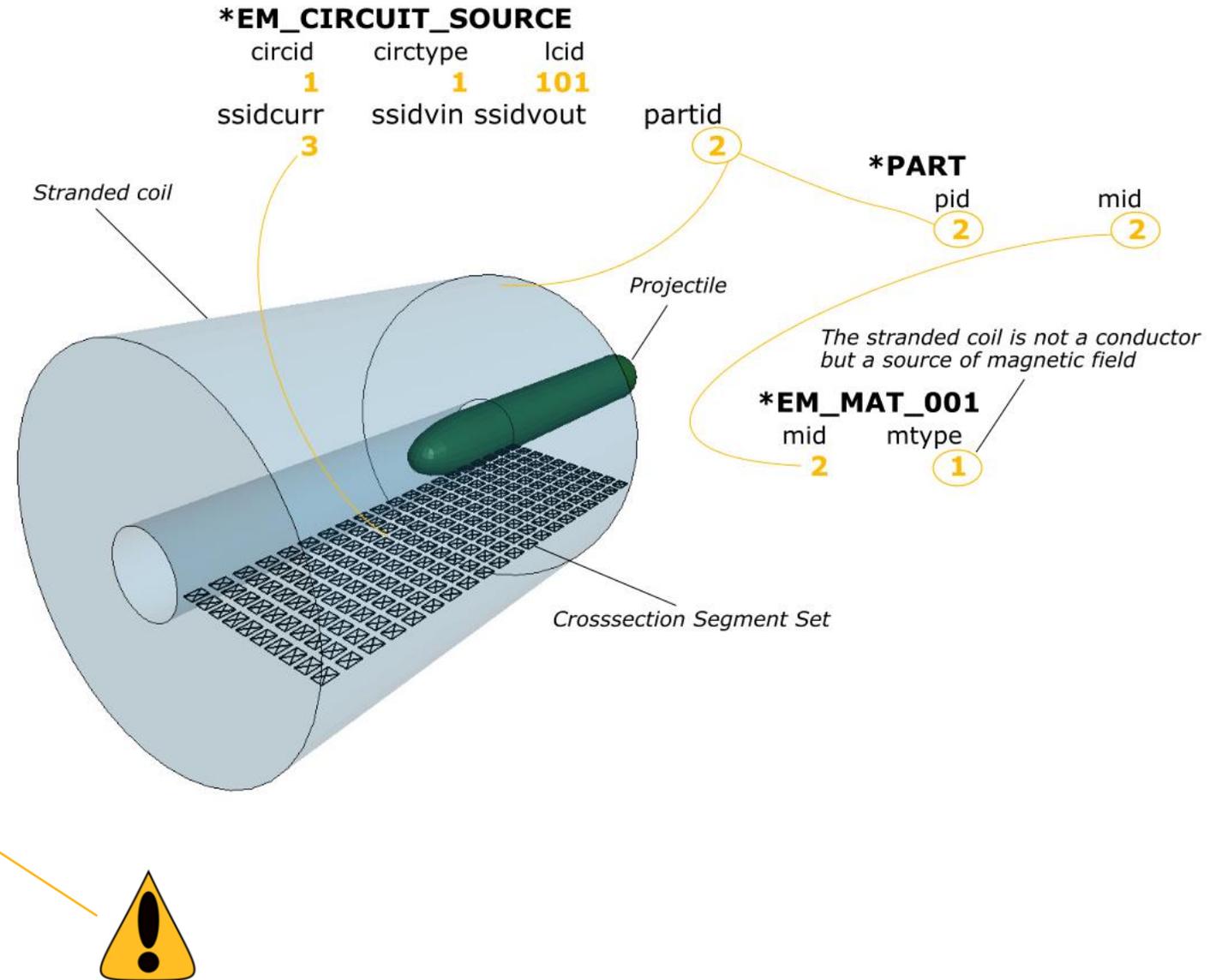


Case Study – Coilgun

The coil– modelled stranded conductors a.k.a

Source circuit

- Due to the ferromagnetic material, *EM_SOLVER_FEMBEM_MONOLITHIC must be used. The solve can either be magnetostatic or consider the electrical conductivity of the projectile
- 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).

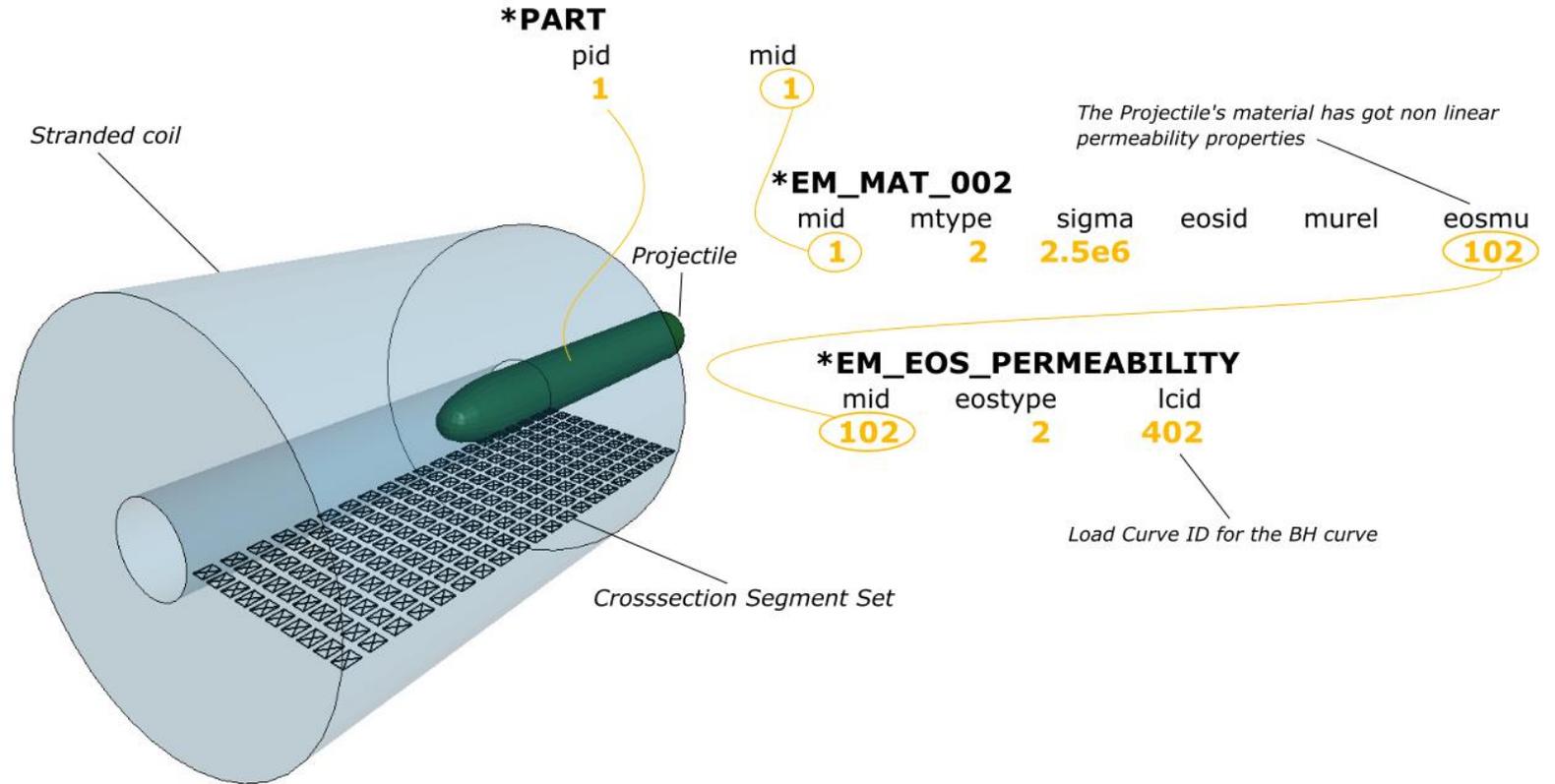


Case Study – Coilgun

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

*EM_CONTROL_COUPLING

THCPL	SMCPL
	2



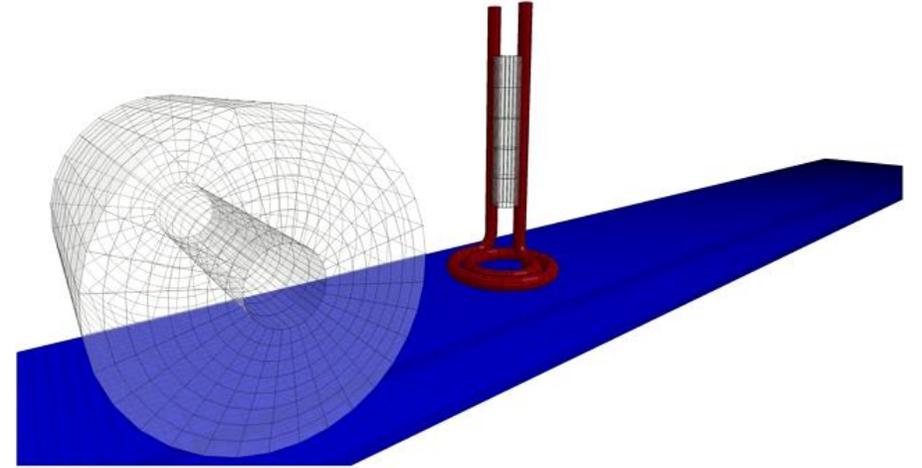
SMCPL = 2 replaces the traditional Volumetric Lorentz Force by the Magnetic surface force, to be used in conjunction of the monolithic solver and to be preferred in cases involving non linear permeabilities.

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

Inductive heating

/ Introduction

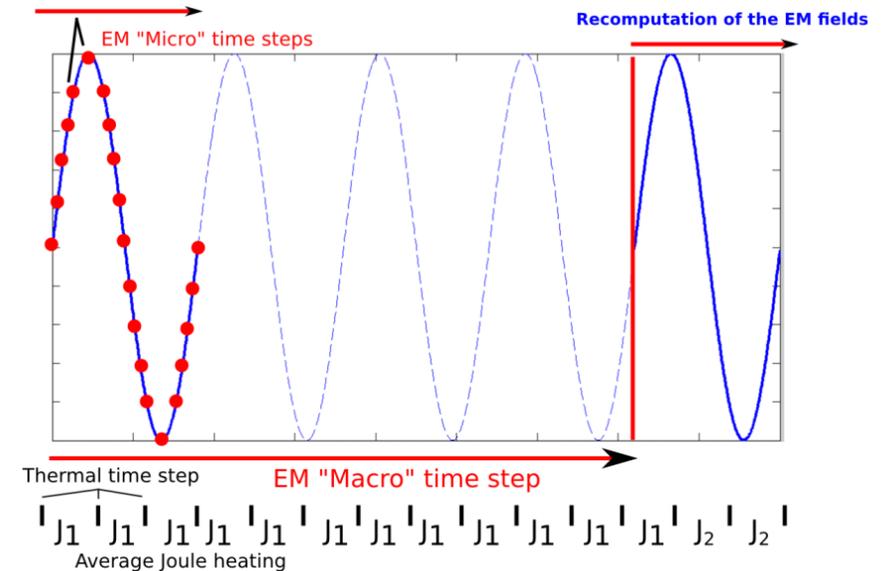
- Induction heating is the process of heating an electrically conducting object (usually a metal) by electromagnetic induction, through heat generated in the object by eddy currents. It has applications in diverse industries such as induction welding, inductive charging or even cancer therapy.
- Compared 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 $1/(NUMLS * F)$

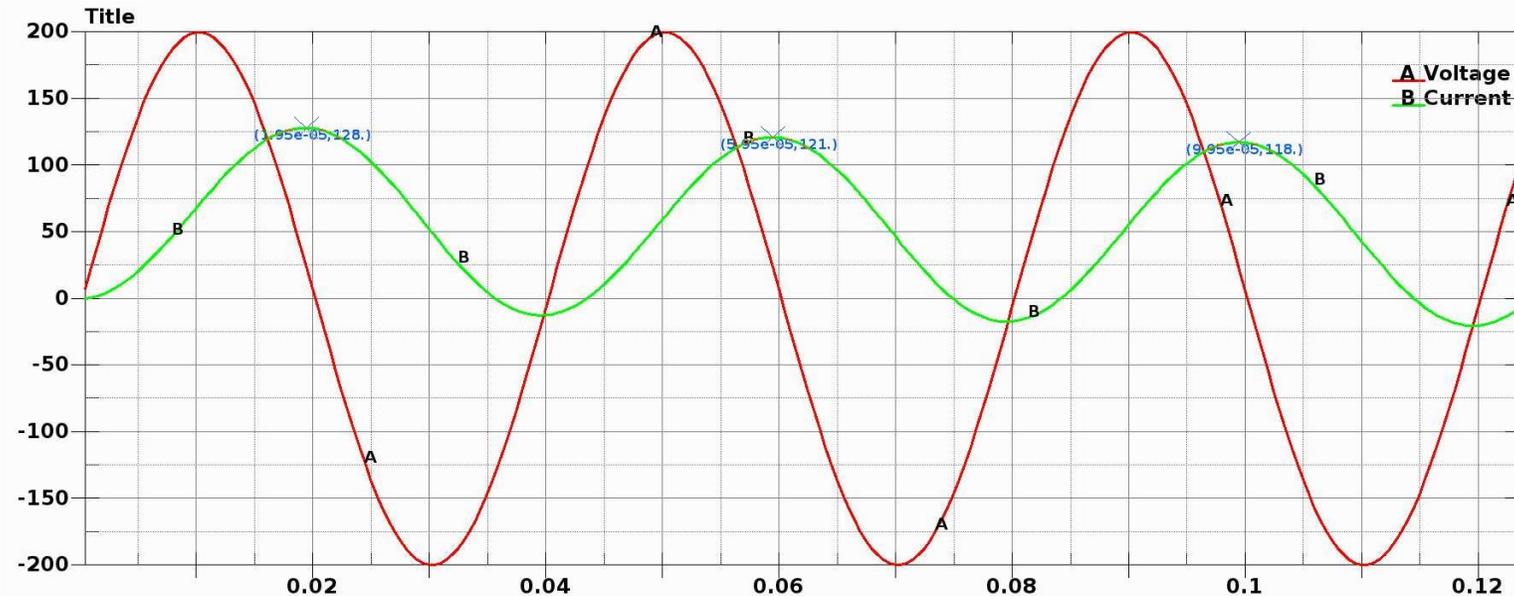
In order to have NUMLS vary in time, a load curve can be used by defining a negative value for each of those quantities (the negative value will refer to the LCID).

/ 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.



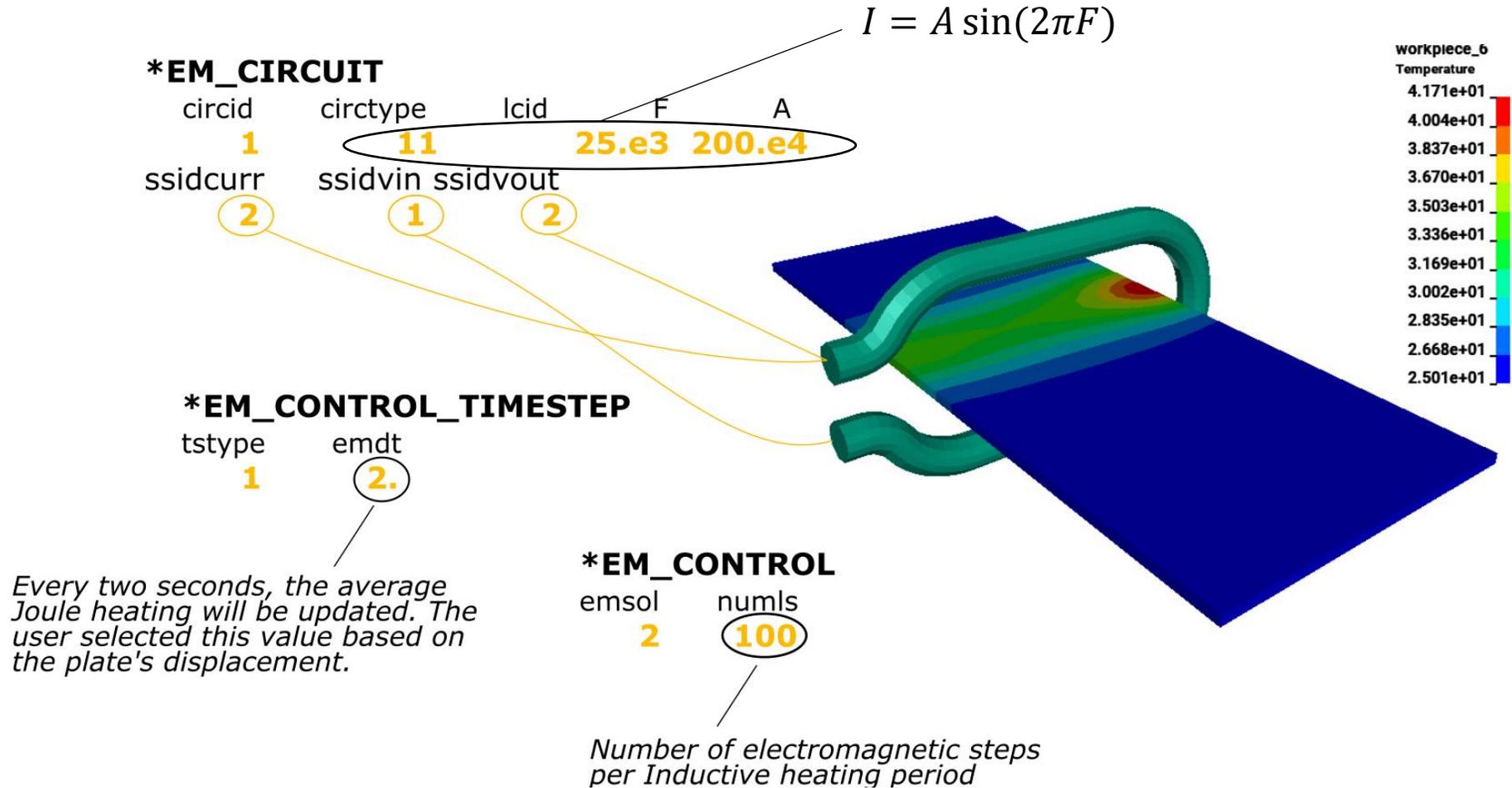
/ The switch option

- 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 :

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

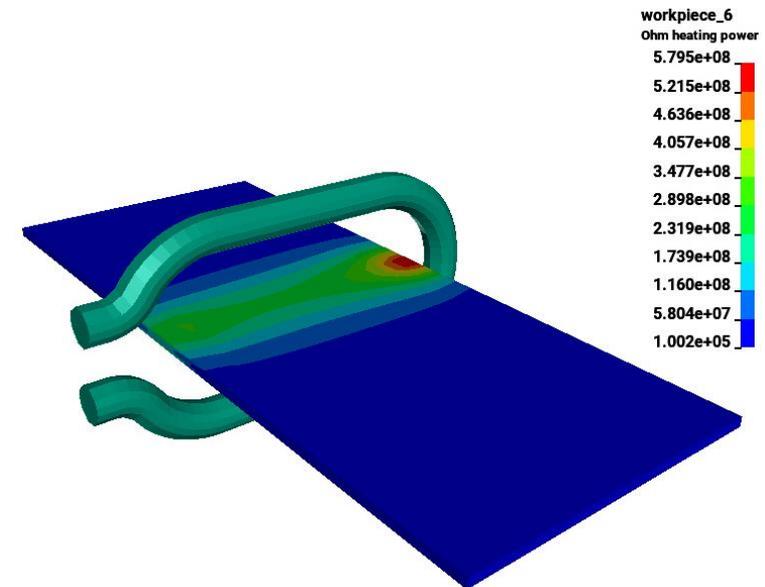
Average Magnetic flux :

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

- The most important post treatment quantity is the temperature !

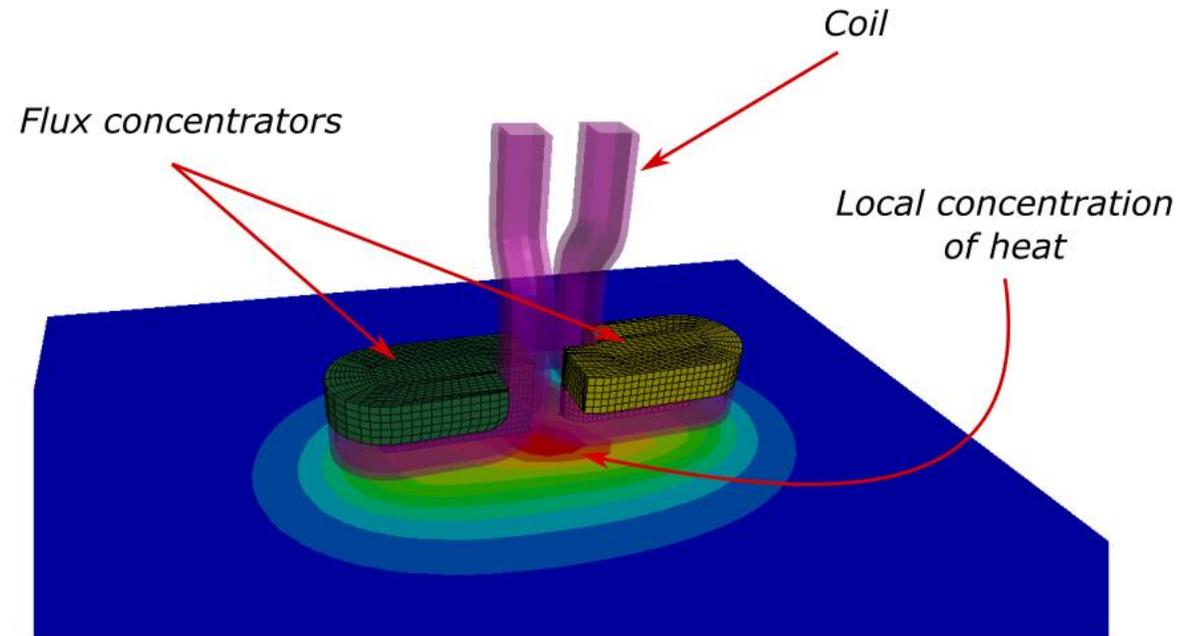
Check the EM-IH step to track the Electromagnetic micro steps :

```
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.

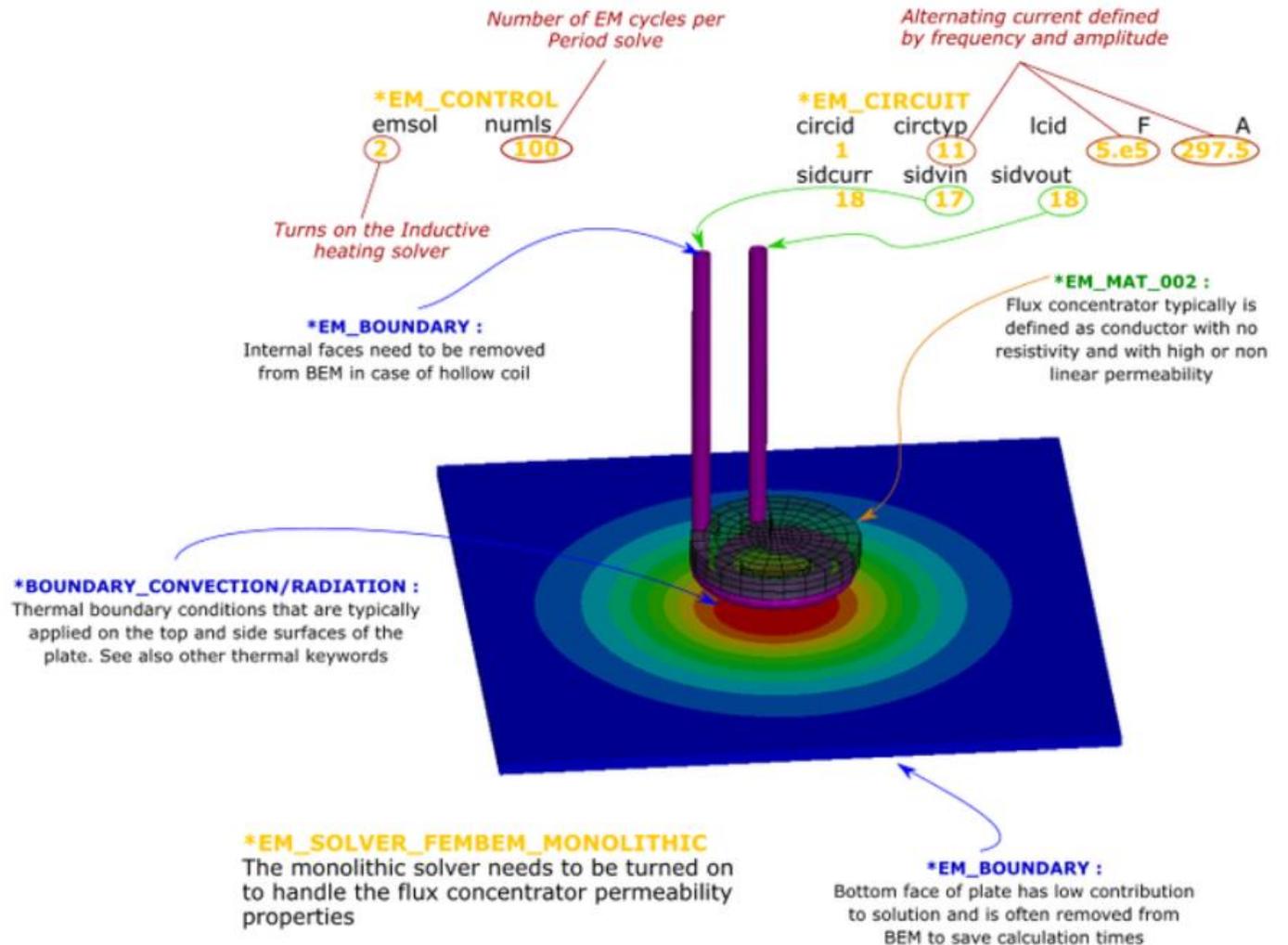
Default uses a diagonal block preconditioner. For cases involving materials with high or non-linear permeability cases, it is recommended to switch to 4 : LLT factorization for improved computation times.



Case Study – Pancake coil with flux concentrator

Hollow coil : Using *EM_BOUNDARY

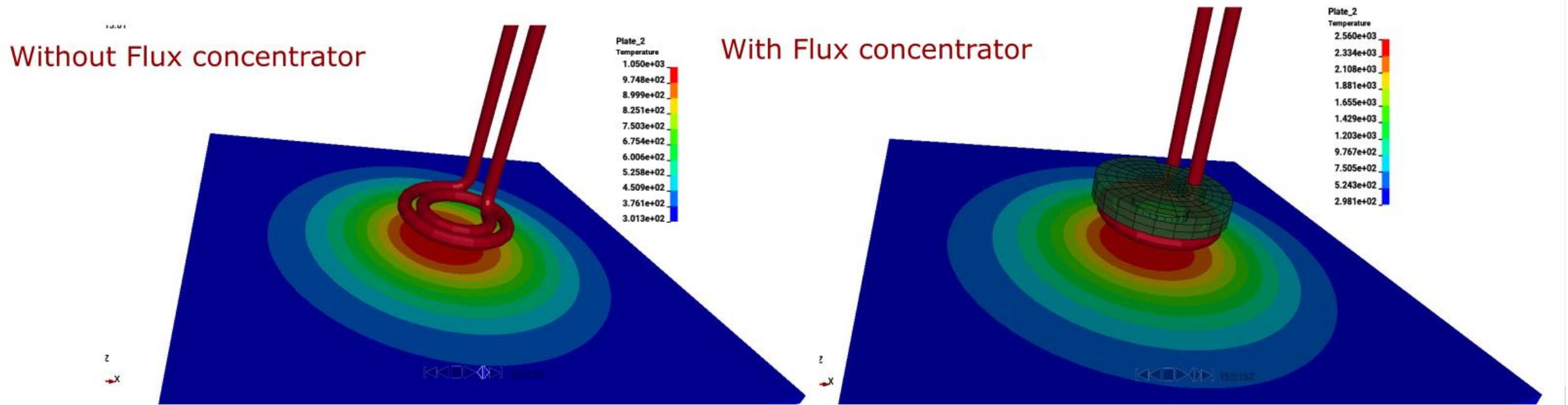
- The coil in this application is hollow. Two closed loops can be formed (one inner, one outer) at the intersection of the inlet segment set faces and the rest of the BEM surface mesh.
- The boundary condition imposed by *EM_CIRCUIT relies on providing one and only one intersection between the boundary 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

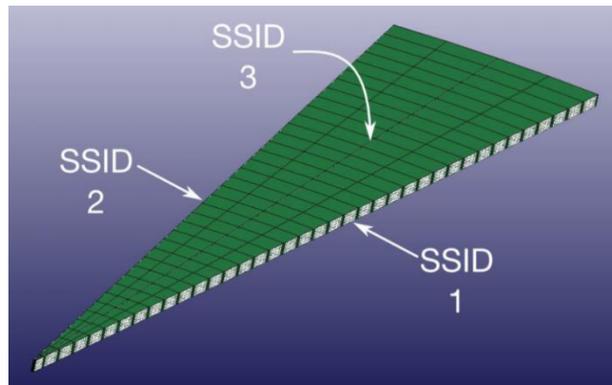
- The axisymmetric feature has been developed in order to simplify certain types of cases and save some calculation time . Inductive heating cases where a helicoidal coil surrounds a cylindrical workpiece a common and could therefore be modelled using the 2D axisymmetric solver.
- Since LS-DYNA is primarily 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

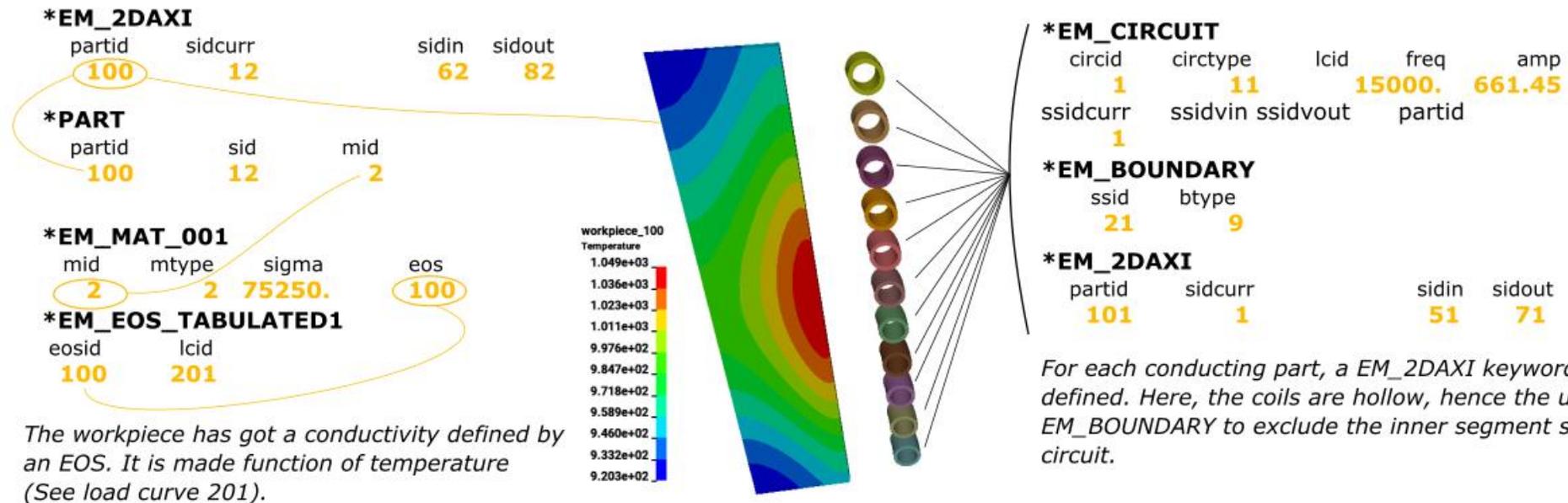
PID	SSID			STARTSSID	ENDSSID	NUMSEC	
3	3			1	2	32	



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.



Upcoming Developments

- Voltage Driven Coils
- Loudspeaker simulations
- Improvements of solve times in magnetostatic cases
- FMM method for BEM

Thank you

