Snapping magnets with LS-DYNA :

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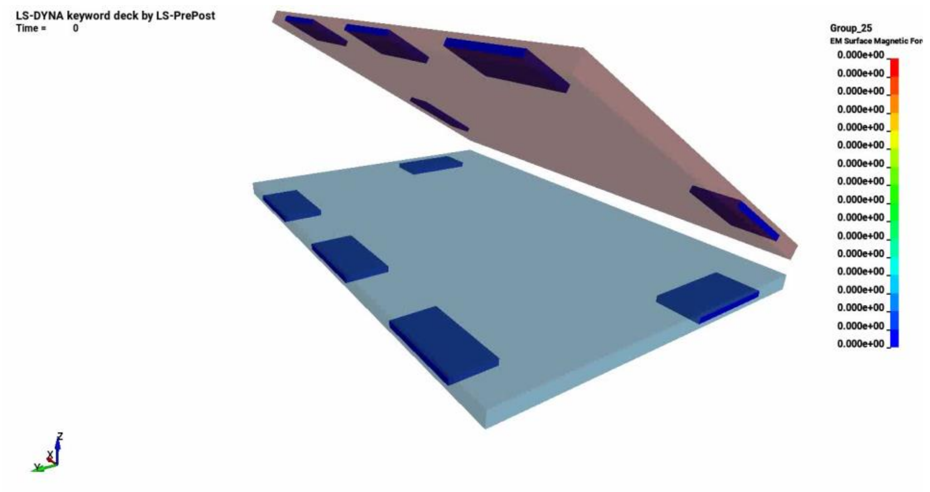
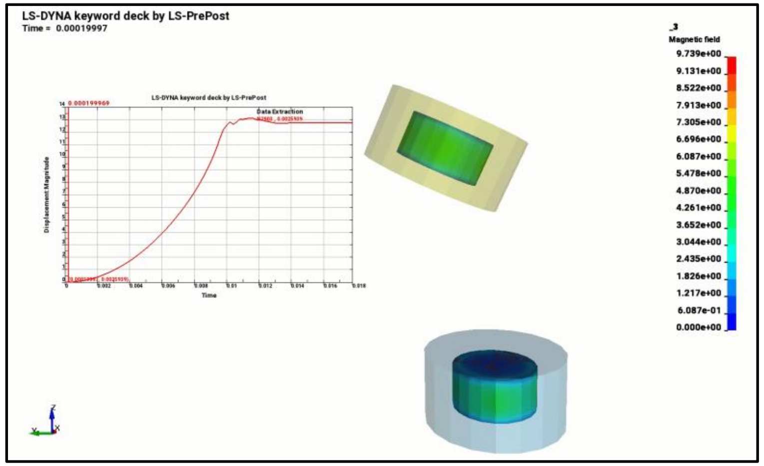
Ansys

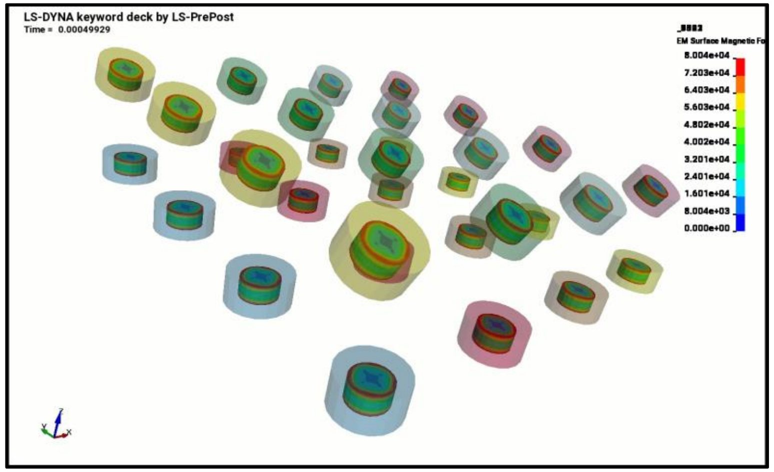
Numerical Solution: LS-DYNA EM Solver

Background :

- LS-DYNA includes an **Electromagnetic** (EM) solver.
- Allows coupling with **Thermal** and **Mechanical** Solvers and the coupling is **seamless** and in part automatic.
- Development has been ongoing for the **past 15 years** and since version **R13**, permanent magnets can be simulated.

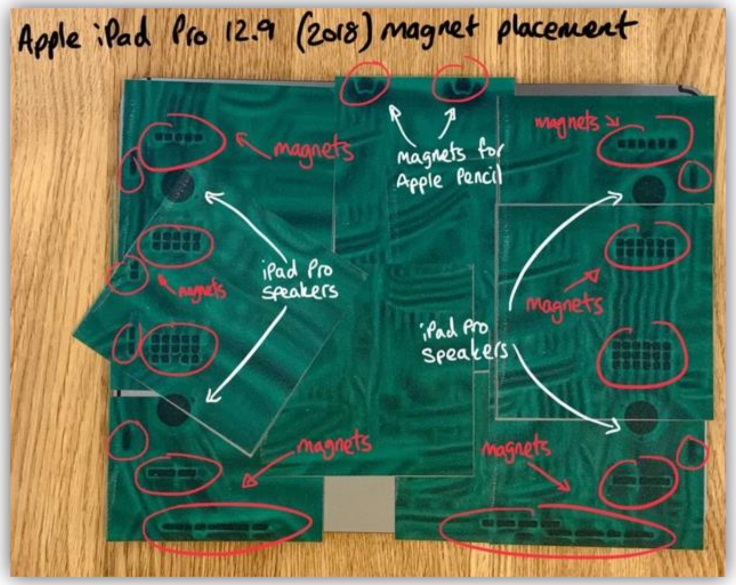






Industry Background

- 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.



FEM-BEM Approach & FEM-FEM Approach

FEM-FEM

- Air mesh used to model interaction between conductors.
- Quantities solved and displayed on the mesh : magnetic field lines visible.
- Sparse matrices : direct and iterative solving methods available.
- Frequently encountered in commercial FEA software.

FEM-BEM

- No air mesh required : simplification of input. No remeshing and mesh distortion in moving mesh cases, less mesh effects on solution : better consistency.
- No artificial approximation needed at domain boundaries.
- BEM method implies dense matrices. Special techniques needed for both the matrix assembly and the solve (compression techniques like low Rank approximations, advanced preconditioners).
- Primary approach adopted by LS-DYNA's EM solver

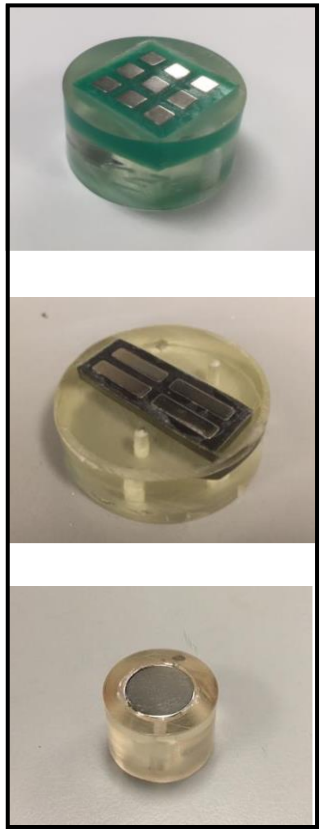
Experimental Testing: Work at Ansys DfR 'RES' Lab

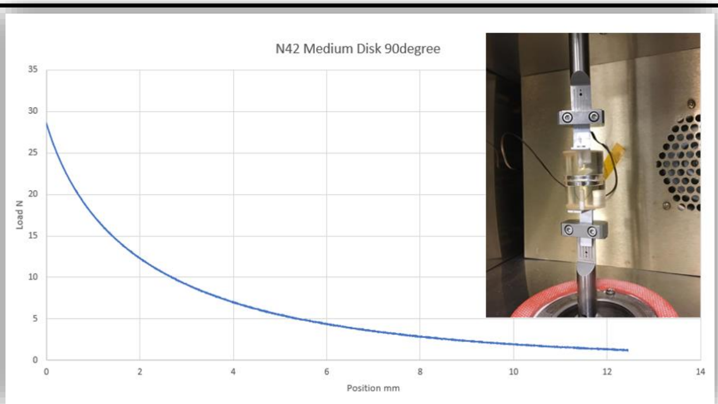
Objective

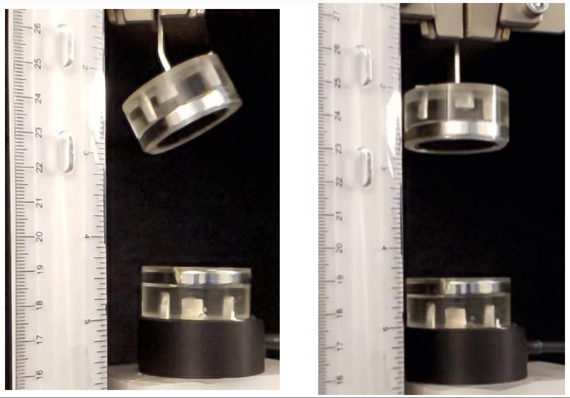
Perform experimental validation studies of magnetic motion to address industry needs and build confidence in Ansys Solutions

But why was experimental testing is needed initially?

- Evidence: Generates **Confidence** in the Numerical Solution. New solver/method.
- Properties: Helps **calibrate** numerical parameters, identify characteristics which the manufacturer might miss.
- Hole in Literature: Not a whole lot of **publications** with **validations**.



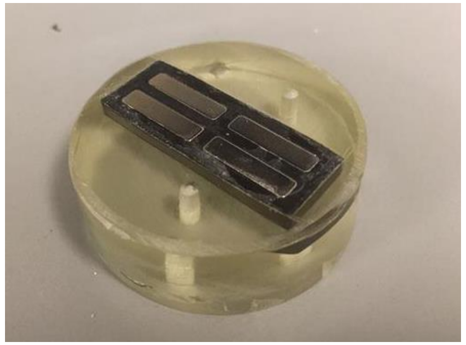


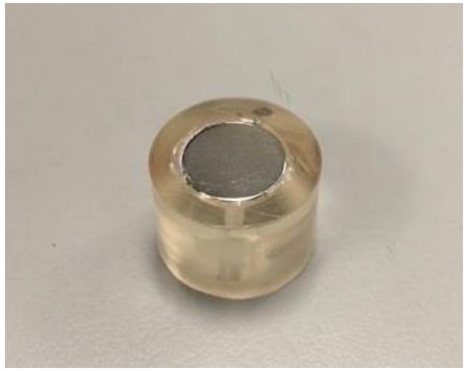


Developed custom fixturing, setup, and operating procedures to obtain accurate validation results

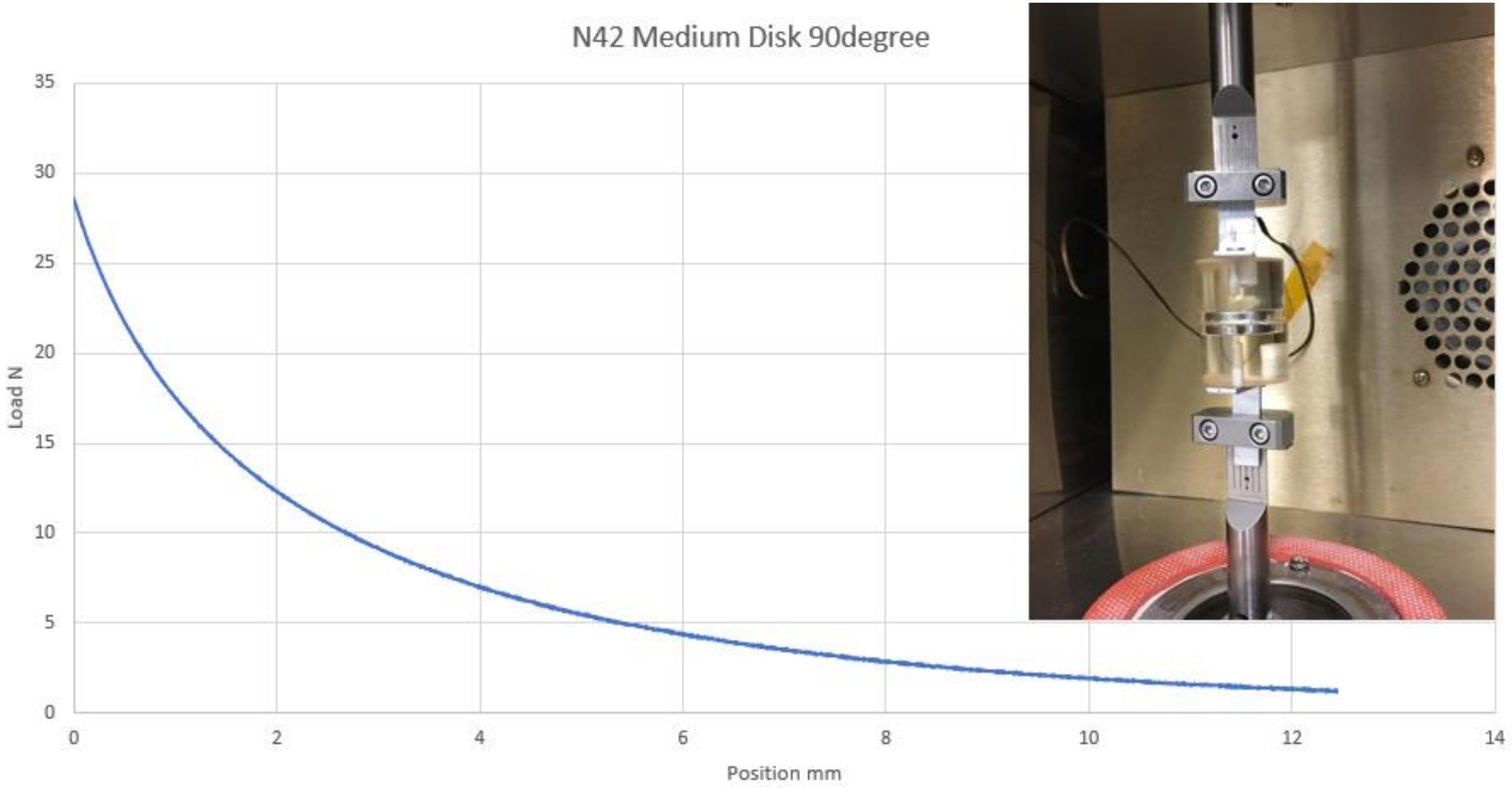
Experimental Procedure (Static Testing – Pull Forces)

- Test 1a (**3x3 small block magnet grid**)
  - To conduct the pull tests, a 3x3 grid was constructed using a 3D printer so that the magnets could be situated in the manner as described in the test procedure.
  - The magnetic grid was then encapsulated in an epoxy puck with the top face of the magnets guarded with tape. When the puck was finished curing the tape was removed, which exposed the top face of the magnets to the environment flush with the top of the puck.
- Test 1b (**2x2 medium block magnet grid**)
  - A similar process was conducted using a 2x2 3D printed grid fixture.
  - Once again, tape was applied during the potting process and removed after curing which exposed the top face of the grid to the environment such that it was flush with the top of the puck.
- Test 2 (**circular disk magnet**)
  - For the circular disk magnet, no grid was needed prior to encapsulation. Once again, tape was applied during potting and removed after curing which exposed the top face of the magnet to the environment such that it was flush with the top of the puck.



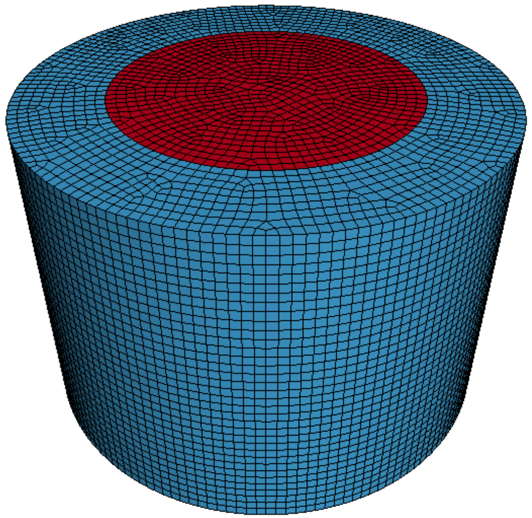


N42 Static Pull Testing Circular Disk (Test 2)

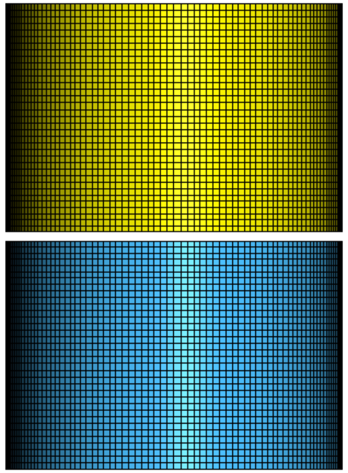


- A Tbar was affixed to the pucks via aluminum screws, allowing for the samples to be mounted onto grips within the DMA system. A pull test was then performed with both pucks starting together at the lowest position of the DMA (-6.5mm).
- Samples were then pulled apart with the bottom puck stationary until the top puck reached the maximum height allowed within the DMA (+6.5mm).

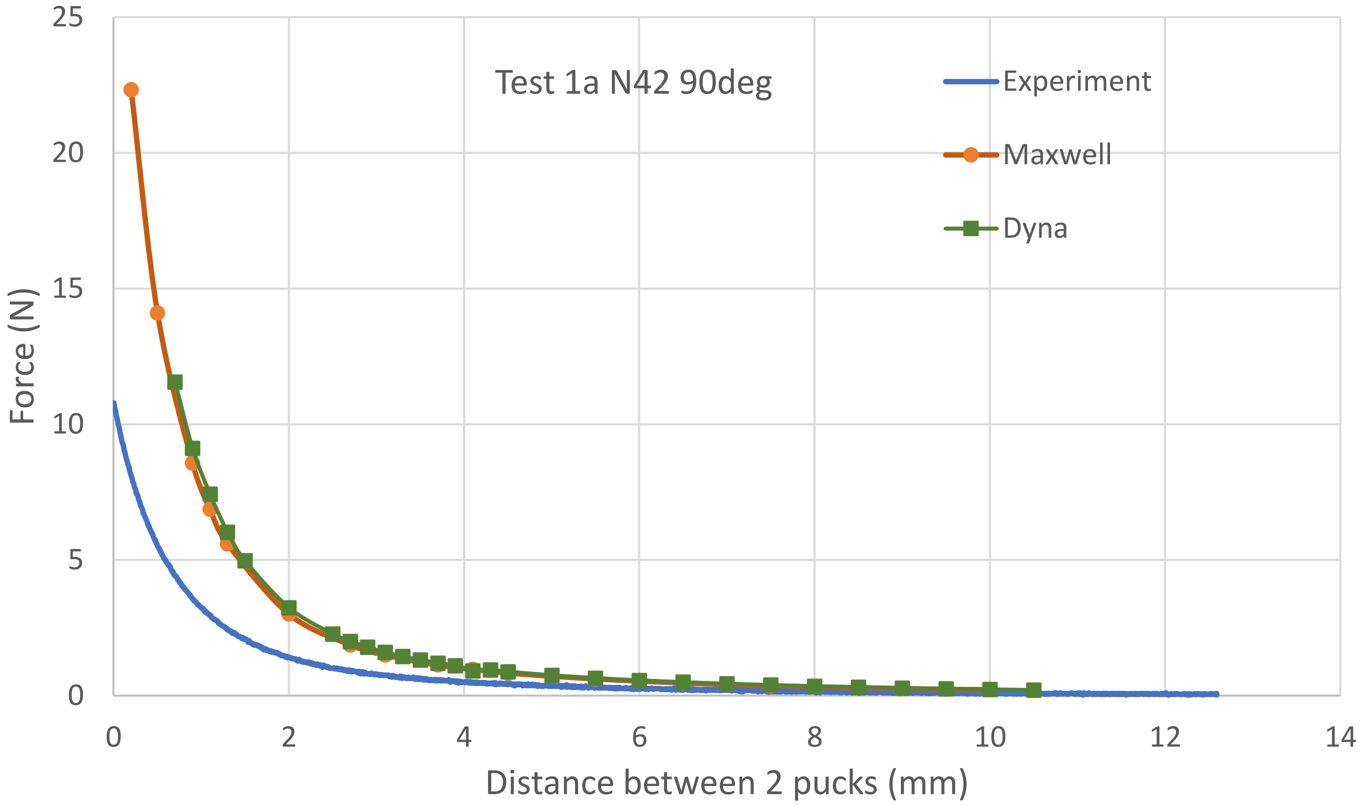
First comparison simulation/experiment



1 magnet encapsulated in a puck. LS-DYNA Mesh



2 pucks of 1 magnet encapsulated in a puck. LS-DYNA Mesh



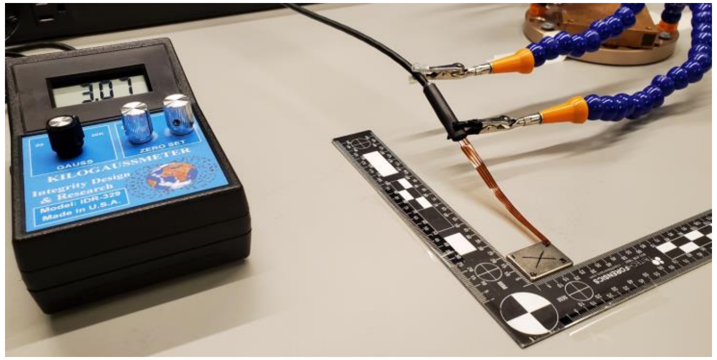
Very good agreement between LS-DYNA and Maxwell.

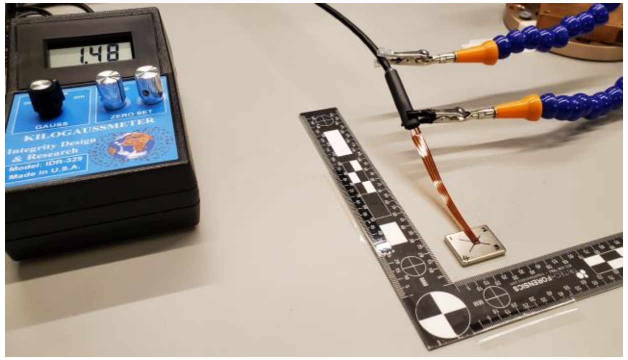
Factor of 2 between simulation and experiments.

Magnetic field measurement

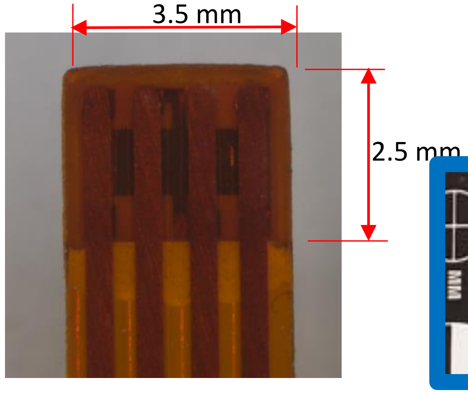
- **Tracking down the mystery:** measuring the magnetic field on top of the magnet with a Hall probe and see if it matches the magnet coercive force value given by the manufacturer.

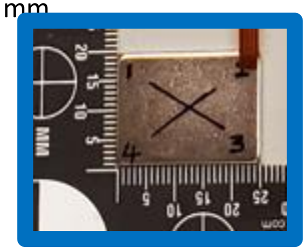
Measurement on large block

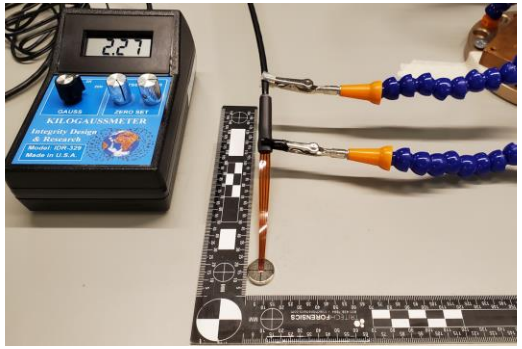




Transverse probe (top view):







~2 mm x 1 mm hall plate

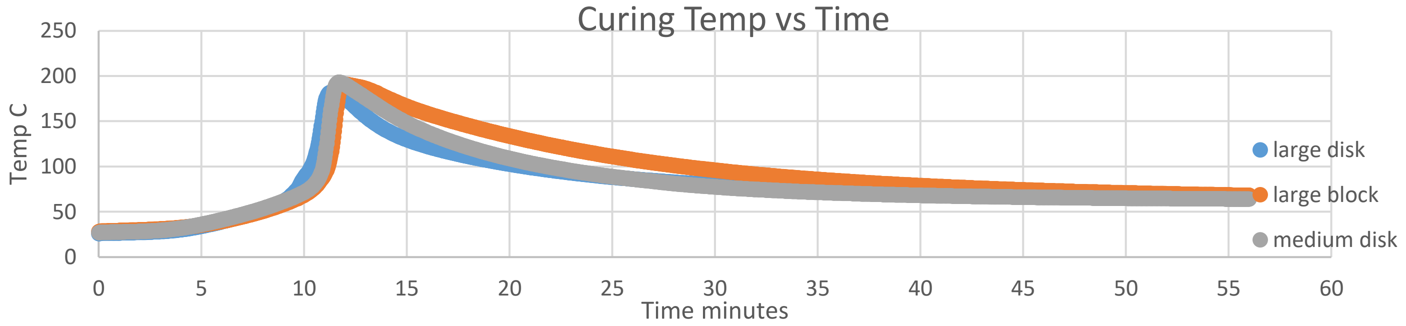
Measurement on magnetic field Pre/Post cure

Data collected between 3/4 - 3/7/2022			Position					Variance Percentage across 3 Measurements				
N42		**Measurement**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
	Sample		**B (kG)**	**B (kG)**	**B (kG)**	**B (kG)**	**B (kG)**					
Medium Disk pre cure	6	1	2.84	2.86	2.89	2.83	2.24	0.35%	0.35%	0.35%	0.35%	0.45%
		2	2.84	2.85	2.88	2.82	2.24					
		3	2.83	2.85	2.88	2.82	2.23					
Large Disk pre cure	7	1	3.54	3.72	3.58	3.52	2.04	0.28%	0.54%	0.28%	0.28%	0.98%
		2	3.55	3.71	3.58	3.51	2.06					
		3	3.55	3.70	3.59	3.52	2.05					
Large Block pre cure	8	1	2.99	3.34	2.99	3.33	1.42	0.33%	0.30%	0.67%	0.91%	0.71%
		2	3.00	3.35	3.00	3.30	1.42					
		3	3.00	3.34	3.01	3.32	1.41					
Medium Disk post cure	6	1	1.59	1.57	1.57	1.56	0.68	0.63%	1.28%	0.00%	1.29%	1.47%
peak temp 193C		2	1.58	1.58	1.57	1.55	0.68					
		3	1.58	1.56	1.57	1.57	0.69					
Large Disk post cure	7	1	2.82	2.80	2.81	2.84	0.77	0.35%	0.36%	0.71%	1.06%	1.32%
peak temp 182C		2	2.83	2.80	2.83	2.87	0.76					
		3	2.82	2.79	2.83	2.84	0.77					
Large Block post cure	8	1	1.87	1.79	1.85	1.82	0.45	0.54%	1.13%	1.63%	1.10%	0.00%
peak temp 191C		2	1.86	1.78	1.87	1.84	0.45					
		3	1.87	1.77	1.84	1.82	0.45					

An internal study was conducted in order to measure the effect of the epoxy's curing temperature on the magnetic field strength of several untested samples. It was observed that curing the pucked samples at 65C in a thermal chamber significantly reduced the measured field strength.

Note:
Position 5 is center

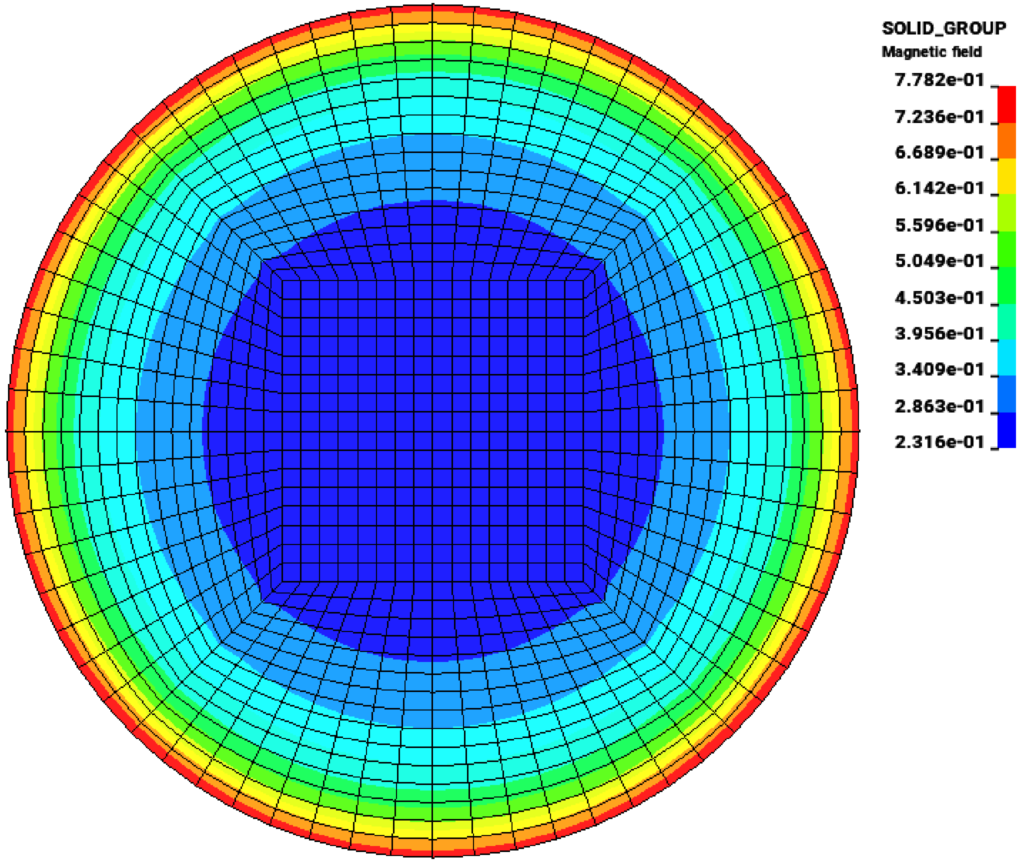
- Conclusion : the magnet coercive force must be adjusted in our simulations to obtain matching magnetic fields



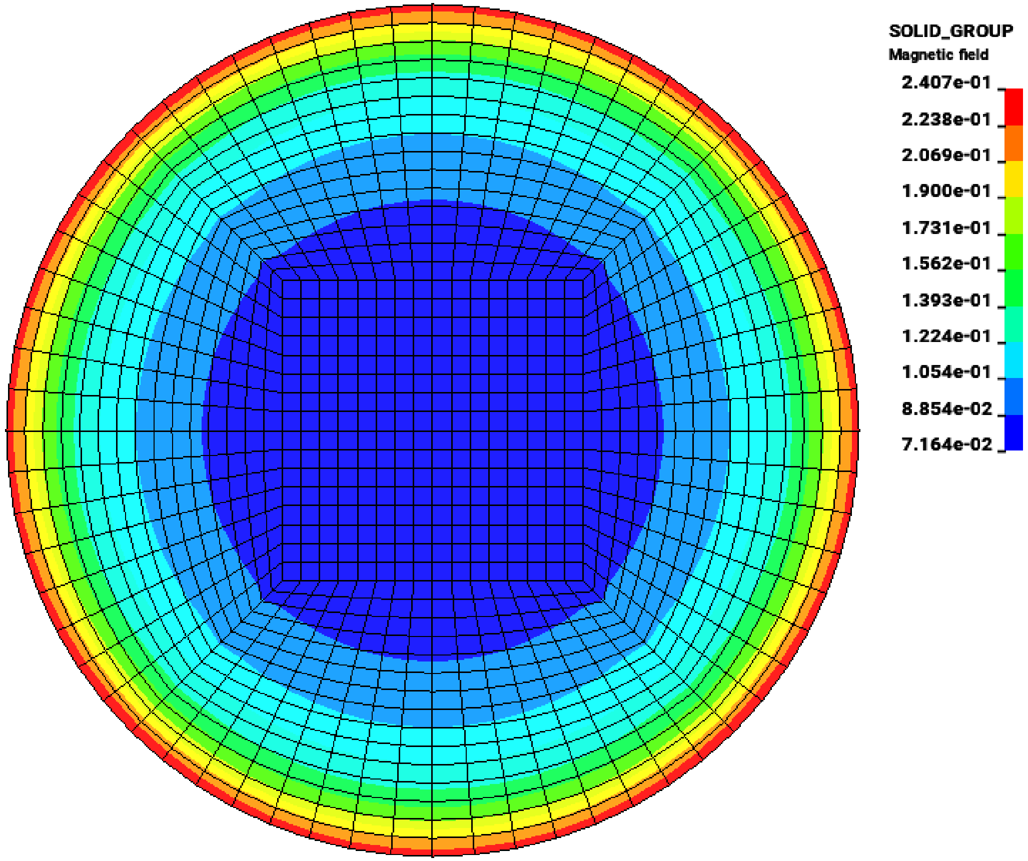
Modification of the coercivity value

Simulation output shows that a B field modification at the center of a magnet dropping down from 2.3 kG (pre cure) to 0.71 kG (post cure) means the coercivity of the magnet goes from 9.7E5A/m to 3E5A/m => effects on results can be significant.

Pre cure

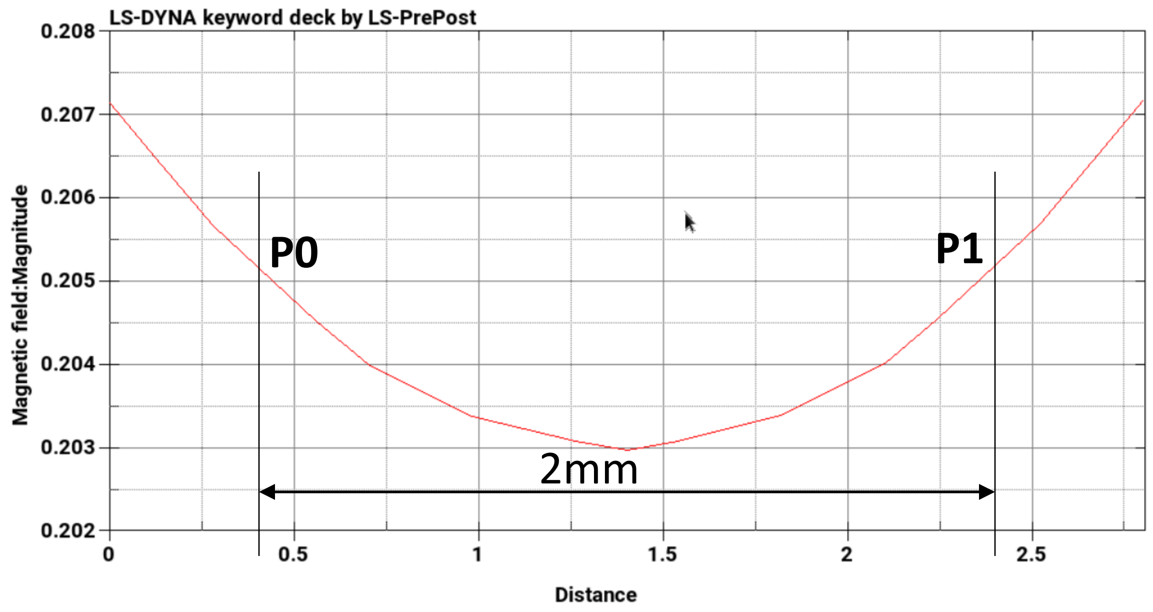


Post cure

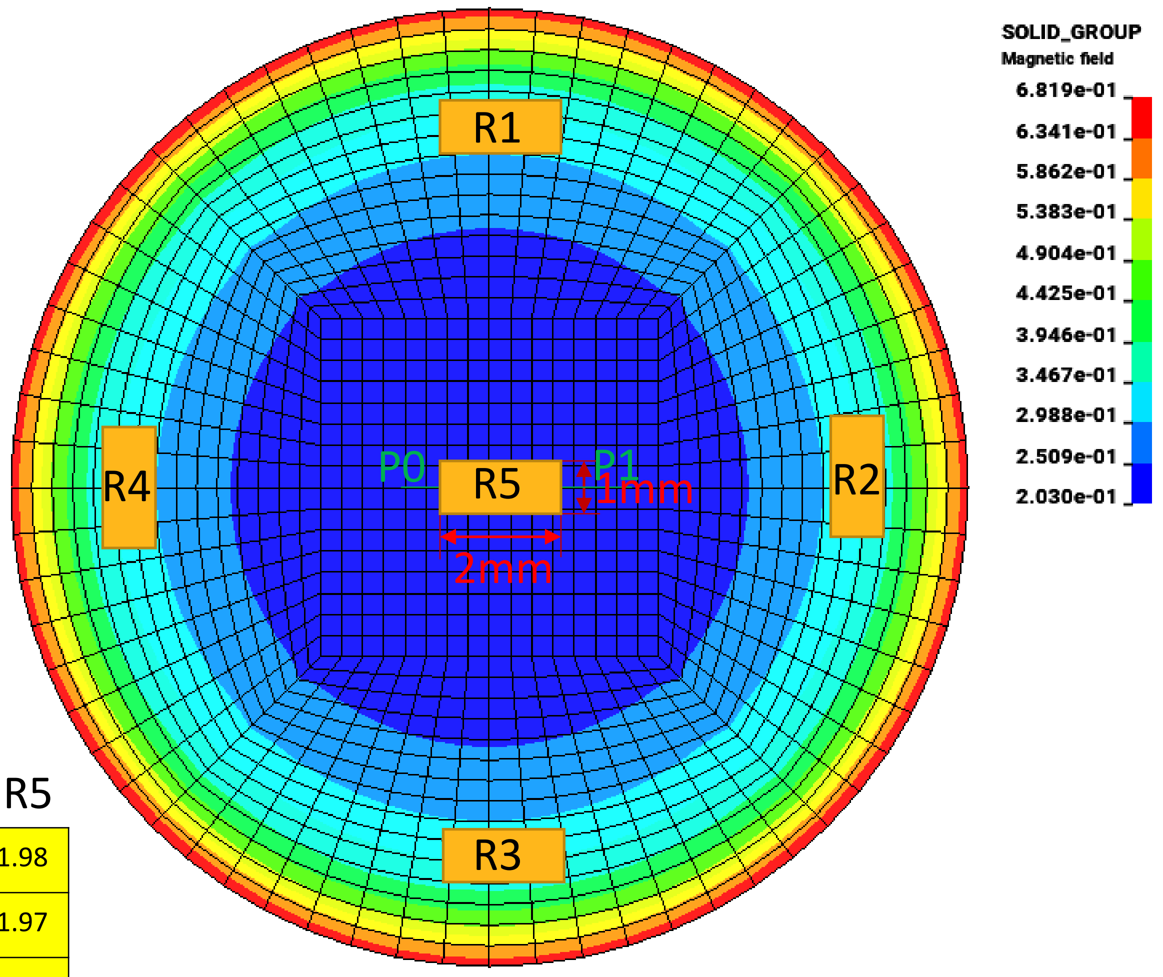


Calibration by magnetic field measurement

Magnet coercivity goes from 9.7E5 to 8.5E5



Magnetic field from P0 to P1



Simulation R5

R5
2.03

Experimental measurement

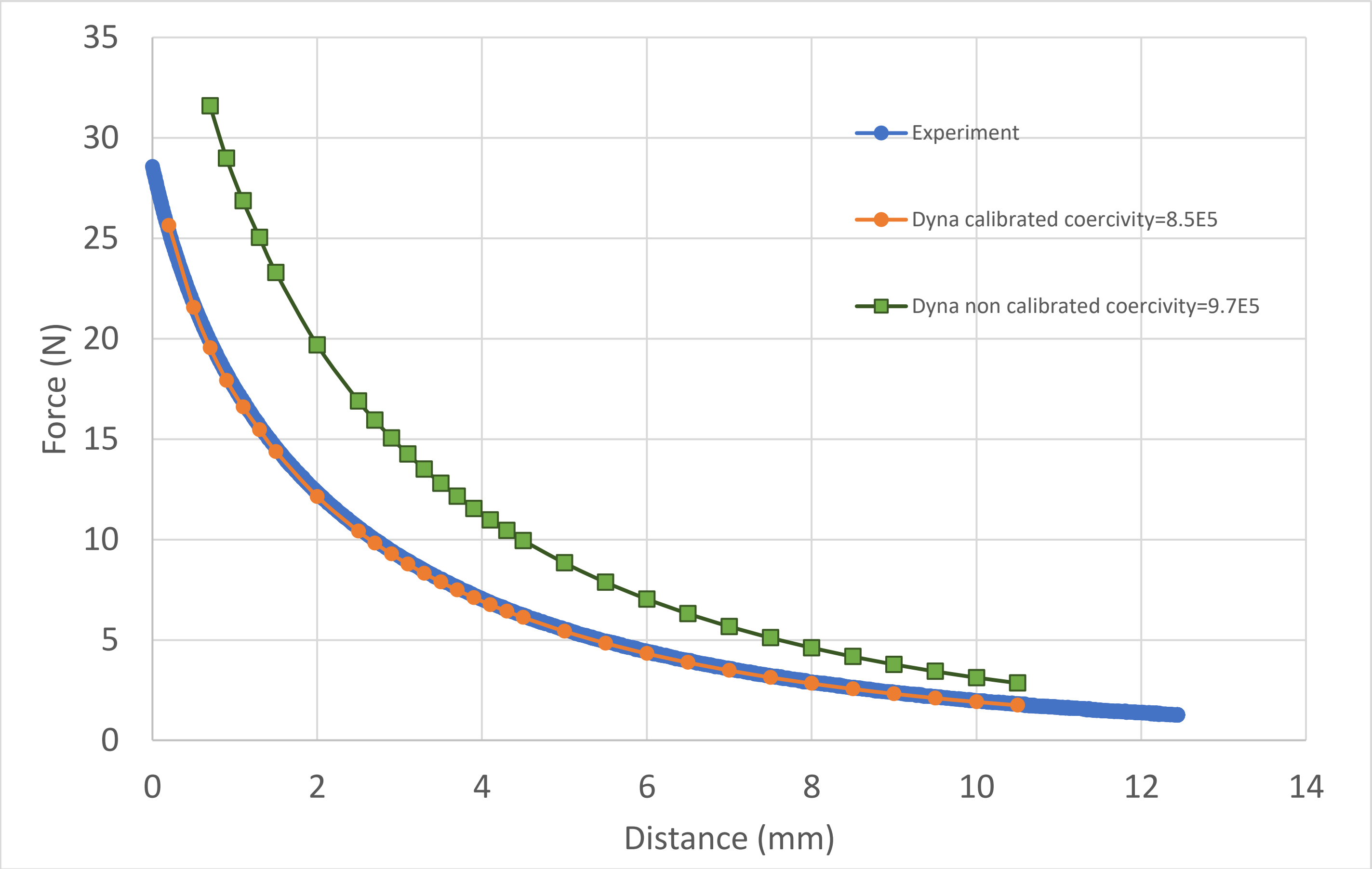
	R1	R2	R3	R4	R5
M1	3.13	2.89	3.05	3.08	1.98
M2	3.11	2.88	3.04	3.08	1.97
M3	3.11	2.89	3.03	3.06	1.99

Points R1, R2, R3, R4 are more difficult to calibrate due to strong gradient.

Local fluctuations suggest magnets may have not always been uniformly damaged.

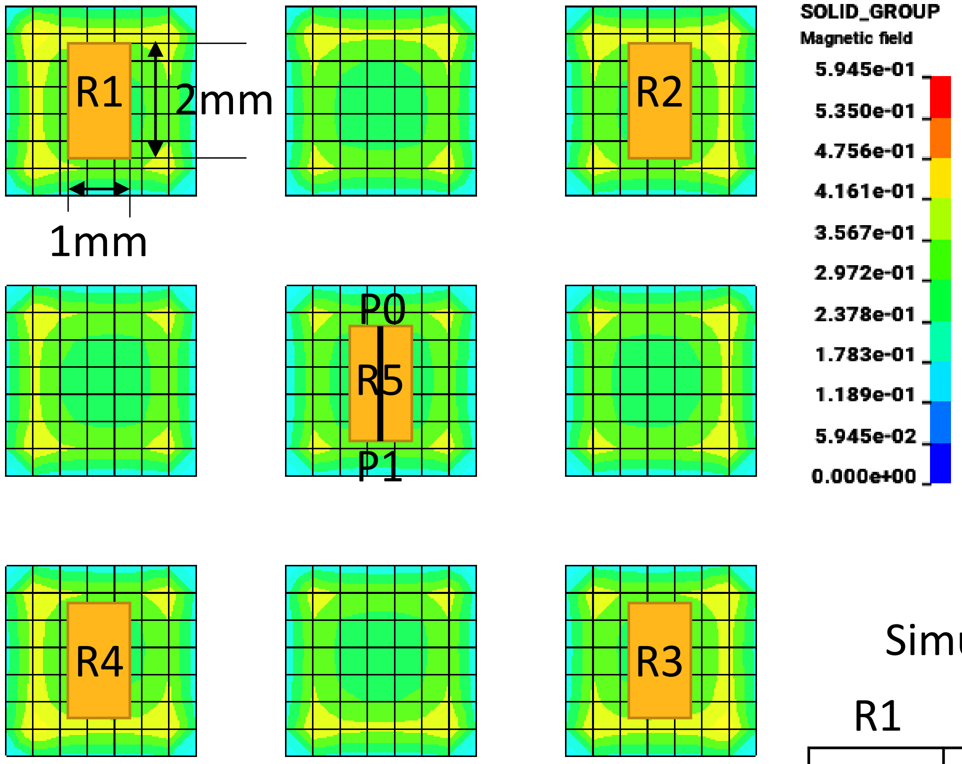
Final results

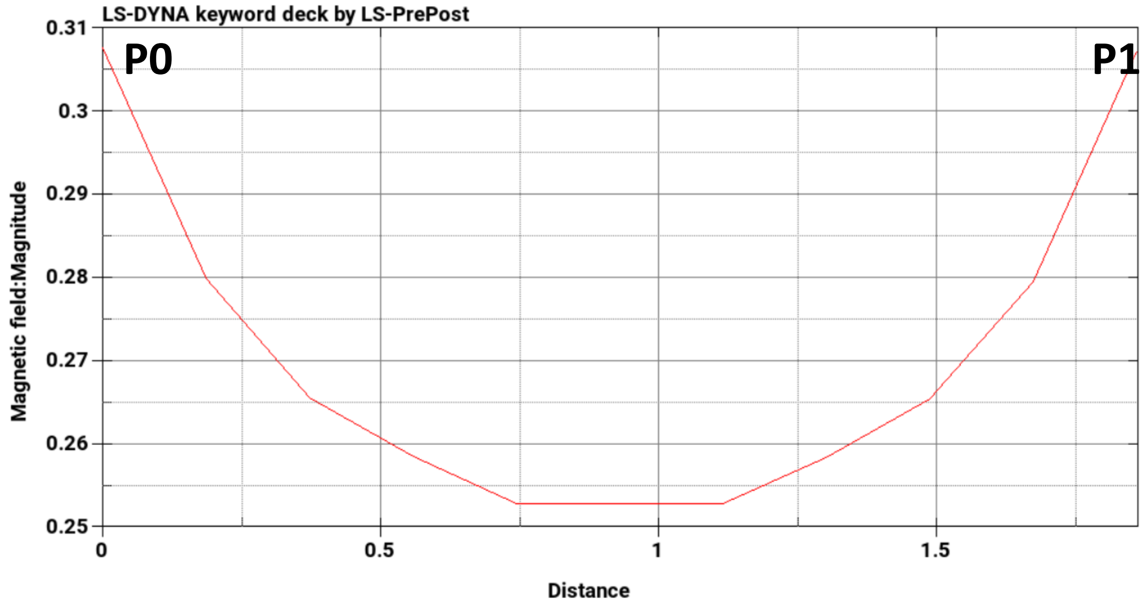
Significant improvement in the results is achieved after calibrating the magnet coercive force to account for magnet deterioration during curing process



Other static tests (Test1a)

The coercivity drops down from 9.7E5 to 6.5E5





Magnetic field from P0 to P1

Simulation

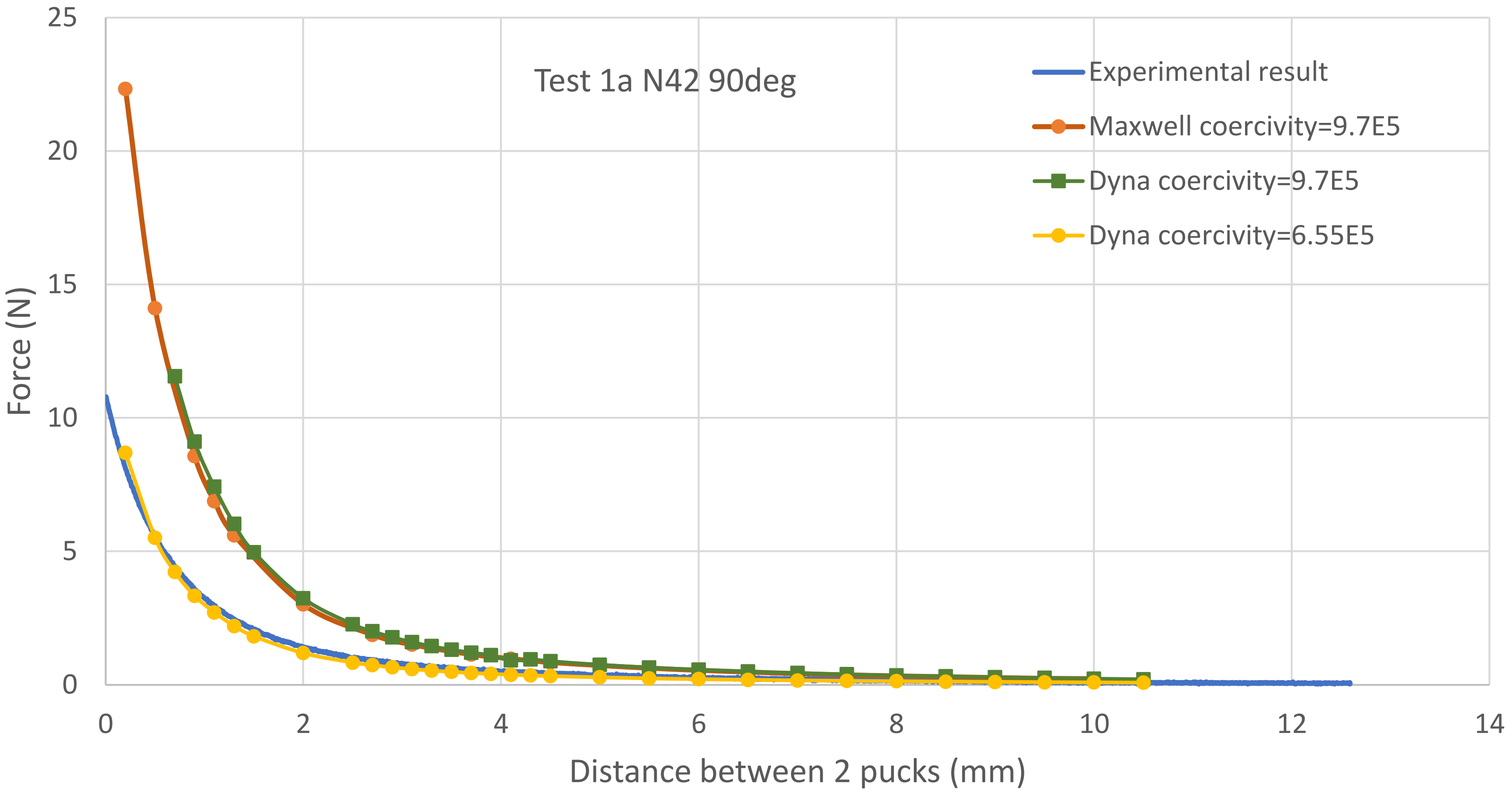
R1	R2	R3	R4	R5
3.06	3.06	3.06	3.06	2.73

Experimental measurement

	R1	R2	R3	R4	R5
M1	3.02	2.70	2.41	2.82	2.55
M2	3.00	2.68	2.41	2.84	2.57
M3	2.99	2.65	2.44	2.84	2.57

Results

Similar trend is observed : correctly adjusting the coercive force thanks to magnetic field measurements significantly improves the results

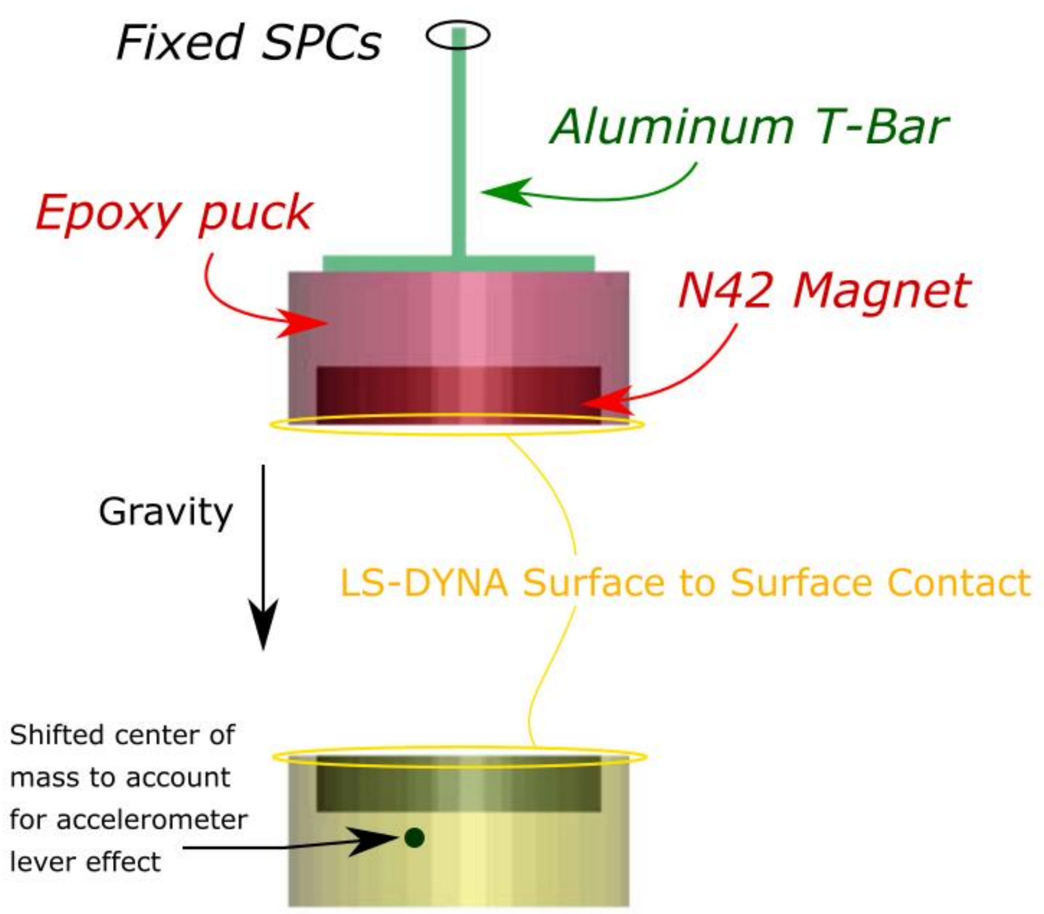


Experimental Procedure (Dynamic Impact Test)

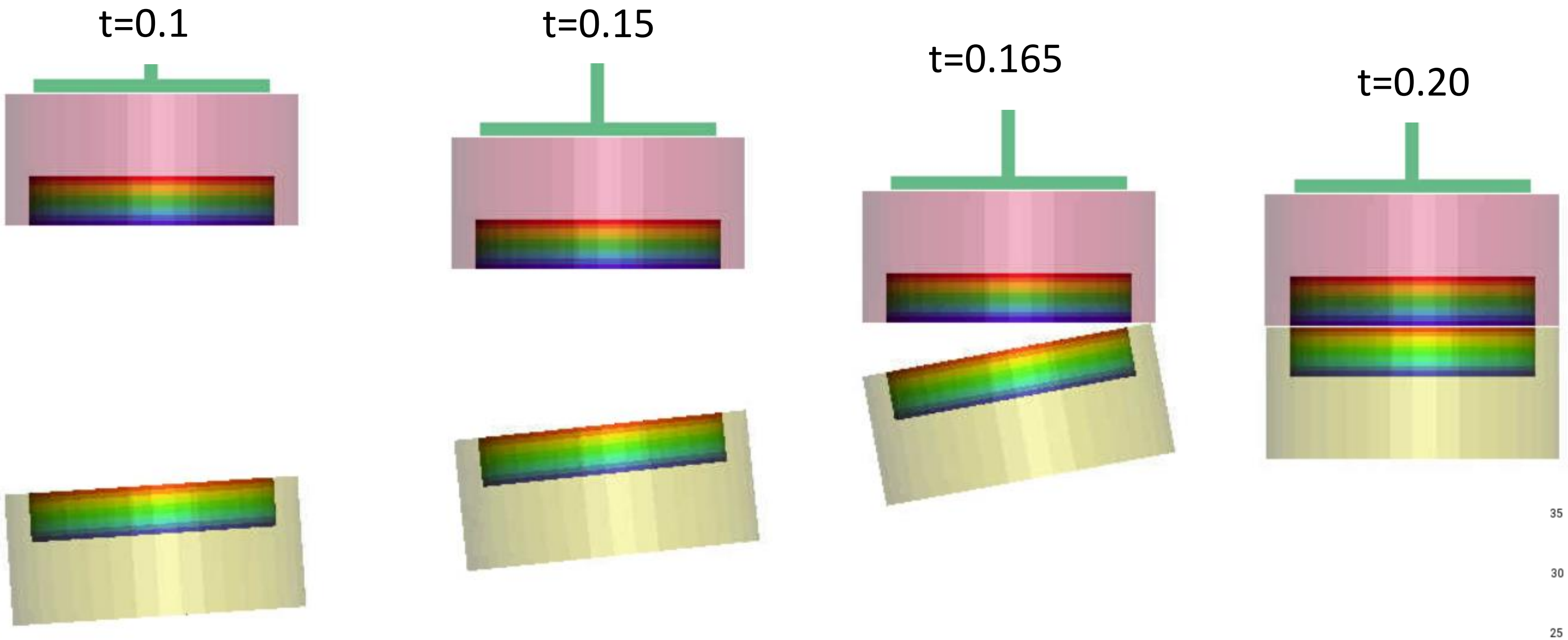
- Test 4 (Dynamic impact with accelerometer)
  - To perform the accelerometer test, a **Dytran 3023A** accelerometer rated for 10,000G was affixed to the bottom stationary puck.
  - A **Tbar**, affixed via aluminum screws to the puck, was used to attach the top puck to the **MTI grips**. A 3d printed fixture was used to situate the bottom **puck+accelerometer** system flush with a machined polymer block spacer. A spirit level was used to ensure the system was level and perpendicular to the axis of motion.
  - An MTI-2k crosshead and grip system with a travel speed of **10 inches per minute** was used to bring the top puck down until the bottom puck lifted off the fixture and impacted the top puck.

LS-DYNA model

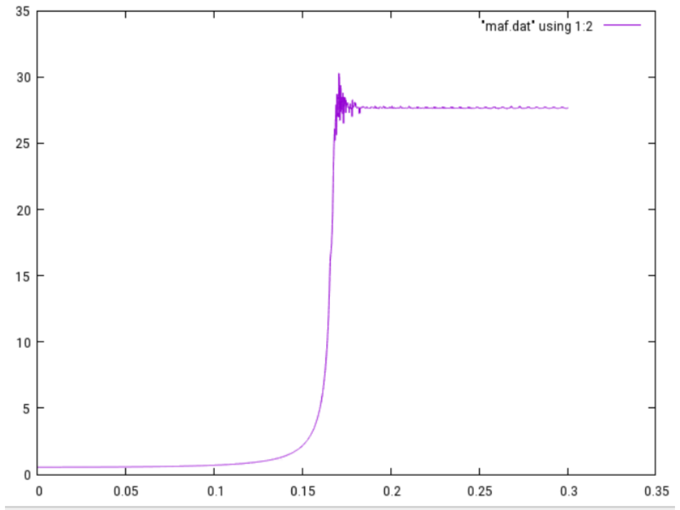
- The two Large Disk magnets facing each other configuration was tested.
- Both solvers retain their **own timesteps** but automatically exchange information during each of their respective solves (Magnetic forces, Displacements and positions).
- **No air mesh** means the input deck definition is similar to the static case (only BEM matrices need to be reassembled as the magnets are moving).
- In this analysis the LS-DYNA structural implicit solver was used.



Results



Magnetic force (Newton) in Z- direction



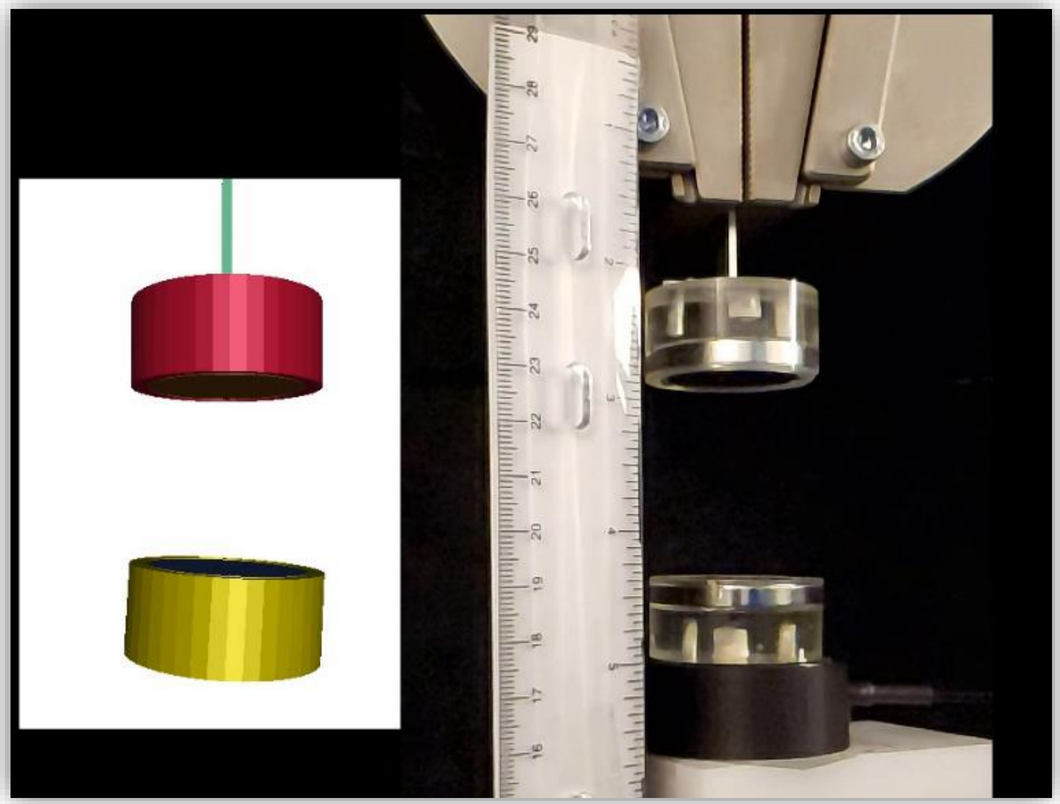
Displacement is small at the initial stages (magnet force barely above gravity) but quickly ramps up and impacts the other magnet at a high acceleration

Results for acceleration and impact force.

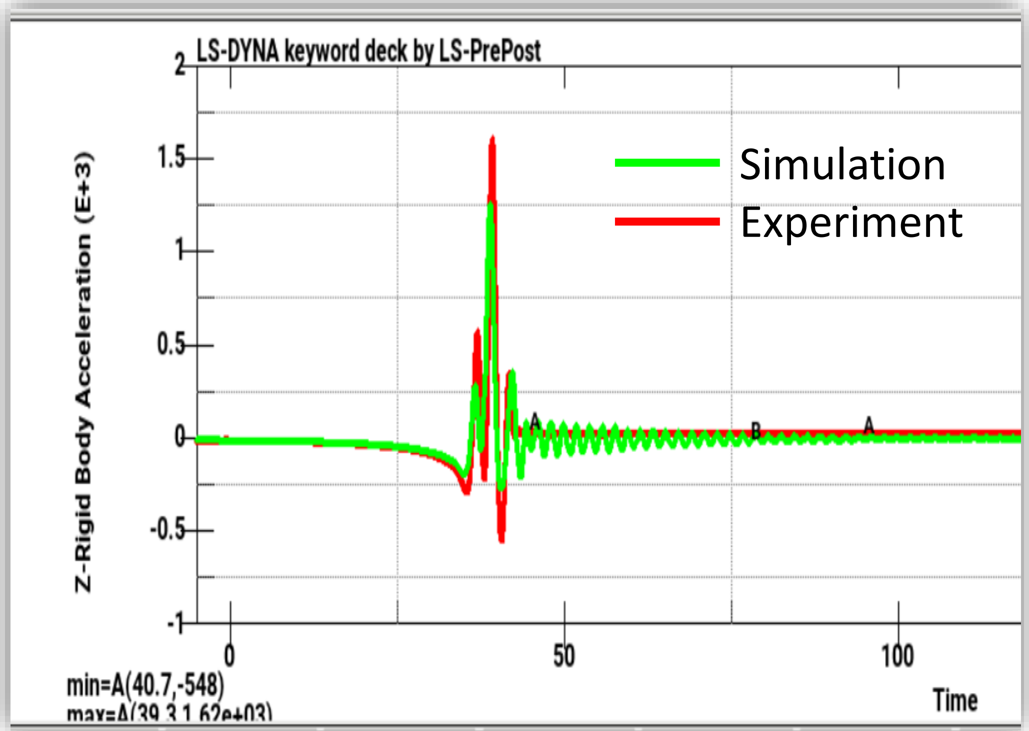
- A remarkably accurate (**qualitative** and **quantitative**) prediction has been achieved in this dynamic impact scenario.

Numerical Model Setup and Analysis
~ 1 Day

Experimental Fixture Setup and Testing
~ 1 Month



Impact acceleration (Butterworth Filter applied)

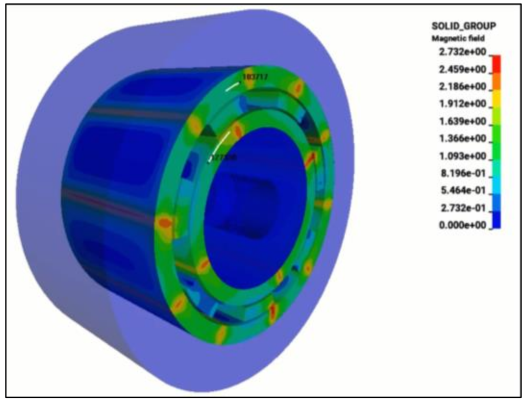


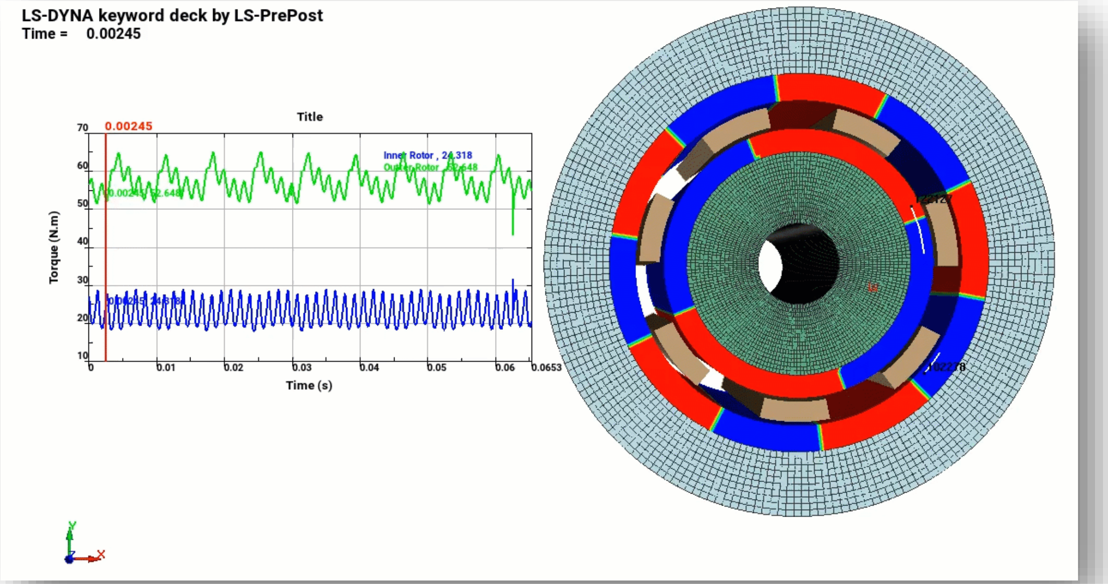
Conclusions

- LS-DYNA EM technology offers some unique advantages:
  - 1 solver, instead of 2 or 3 or more.
  - Data transfer is seamless.
  - EM Meshing is automatically taken care of by the EM Solver. Makes pre-processing much simpler.
  - Analysis and data transfer happens in the RAM, so much faster.
  - Setup is much quicker in comparison (1 tool vs 3 tools).
  - The solution is highly scalable using HPC Clusters.
- Shines as true multi-physics solver for highly non-linear problems (unique advantage).
- Ansys developed custom experimental procedures for magnet snapping validation including fixturing, setup, and operating procedures to obtain accurate validation results (New Testing Protocols) to instill confidence to future users about our simulation technologies.
- Examples can be found at www.dynaexamples.com

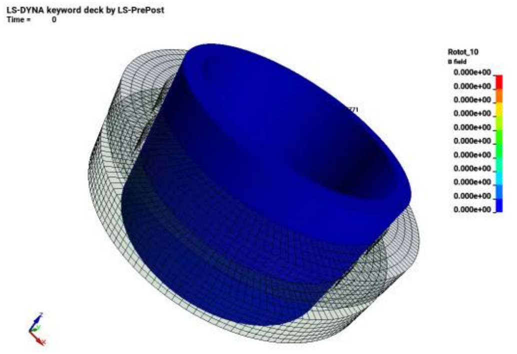
Misc magnet Applications

Magnetic Gears :

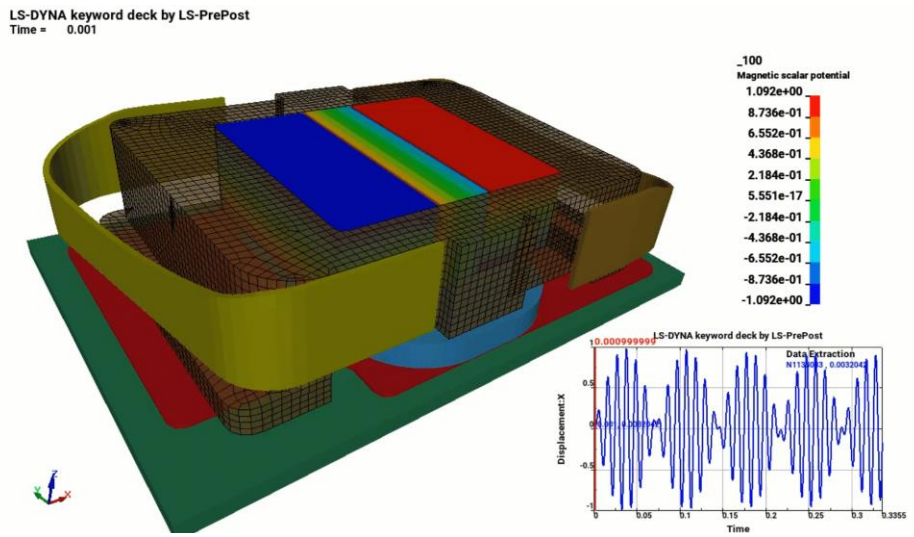




Magnetic bearings :



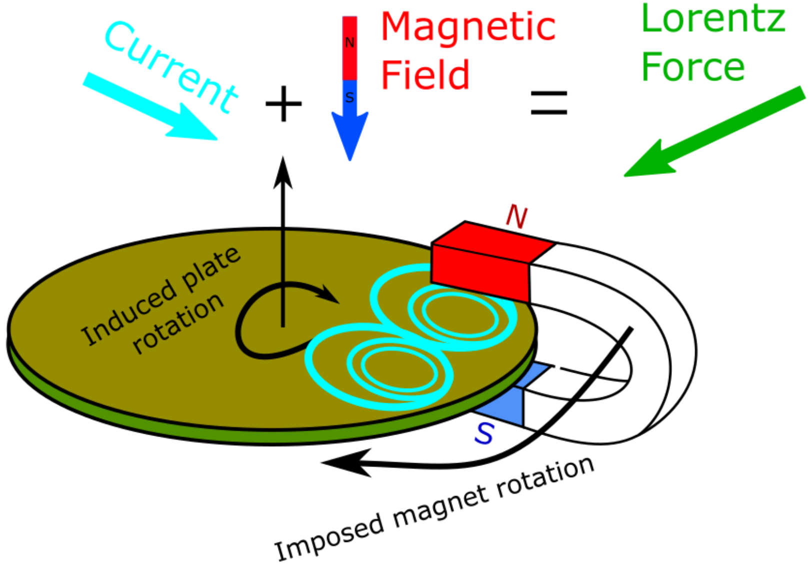
Magneto-haptics :

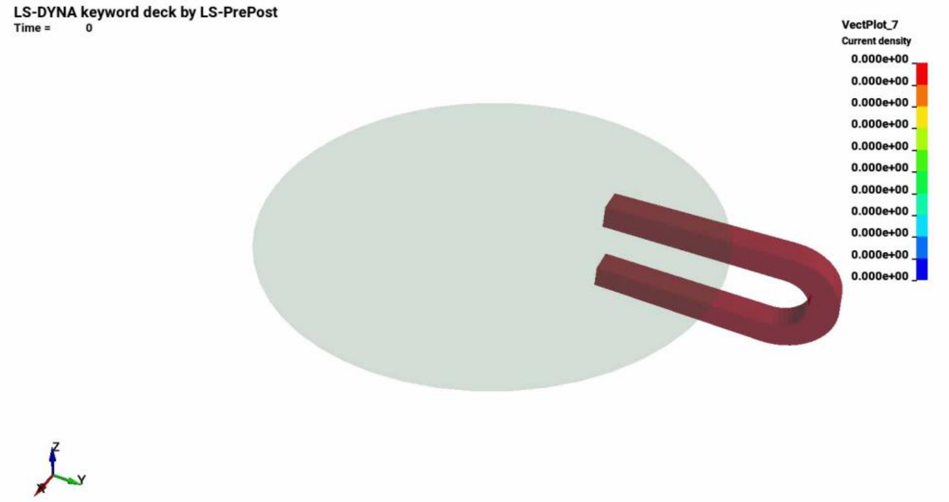


Case Study – Arago’s disk

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.

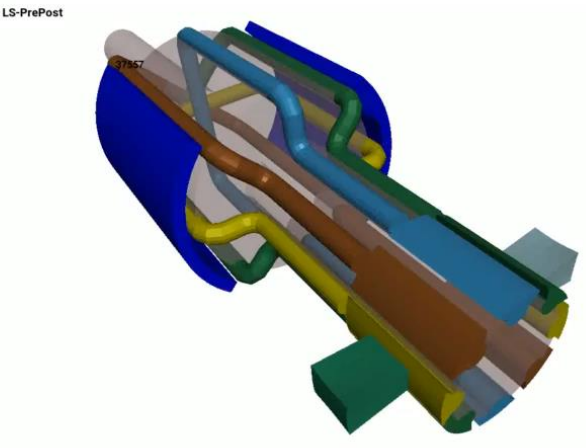




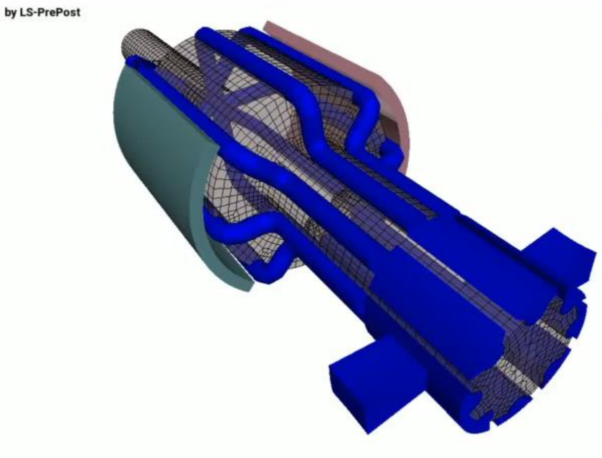
Case Study – DC motor

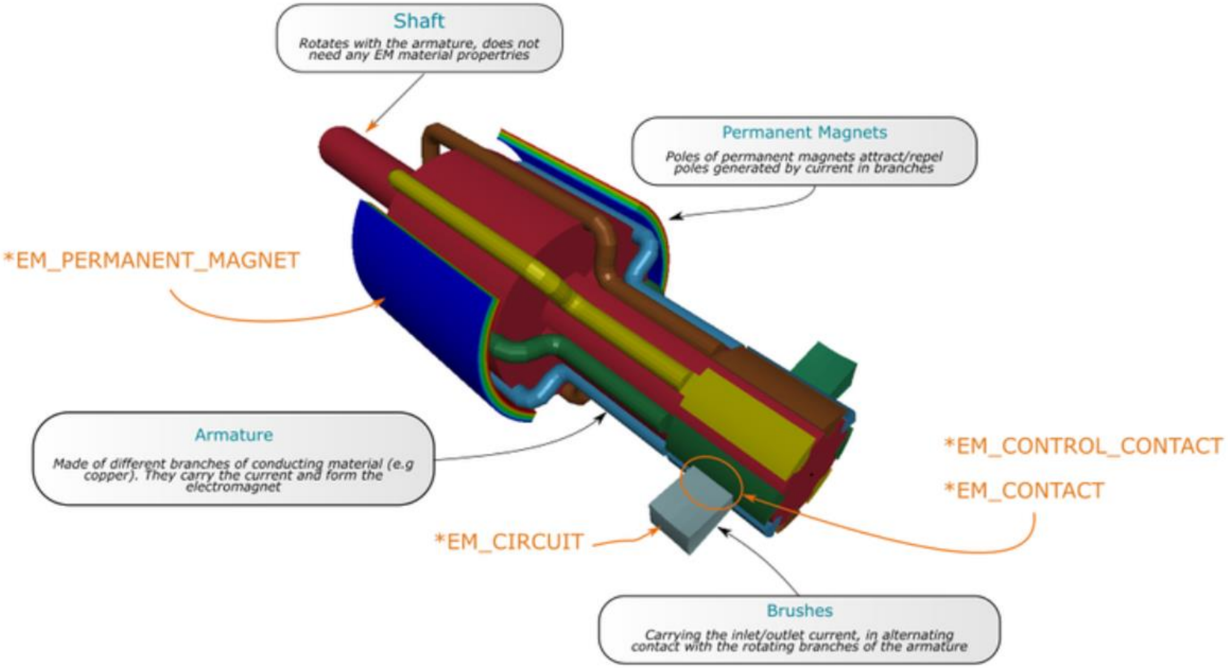
Post :

Magnetic potential in stator (permanent magnets)



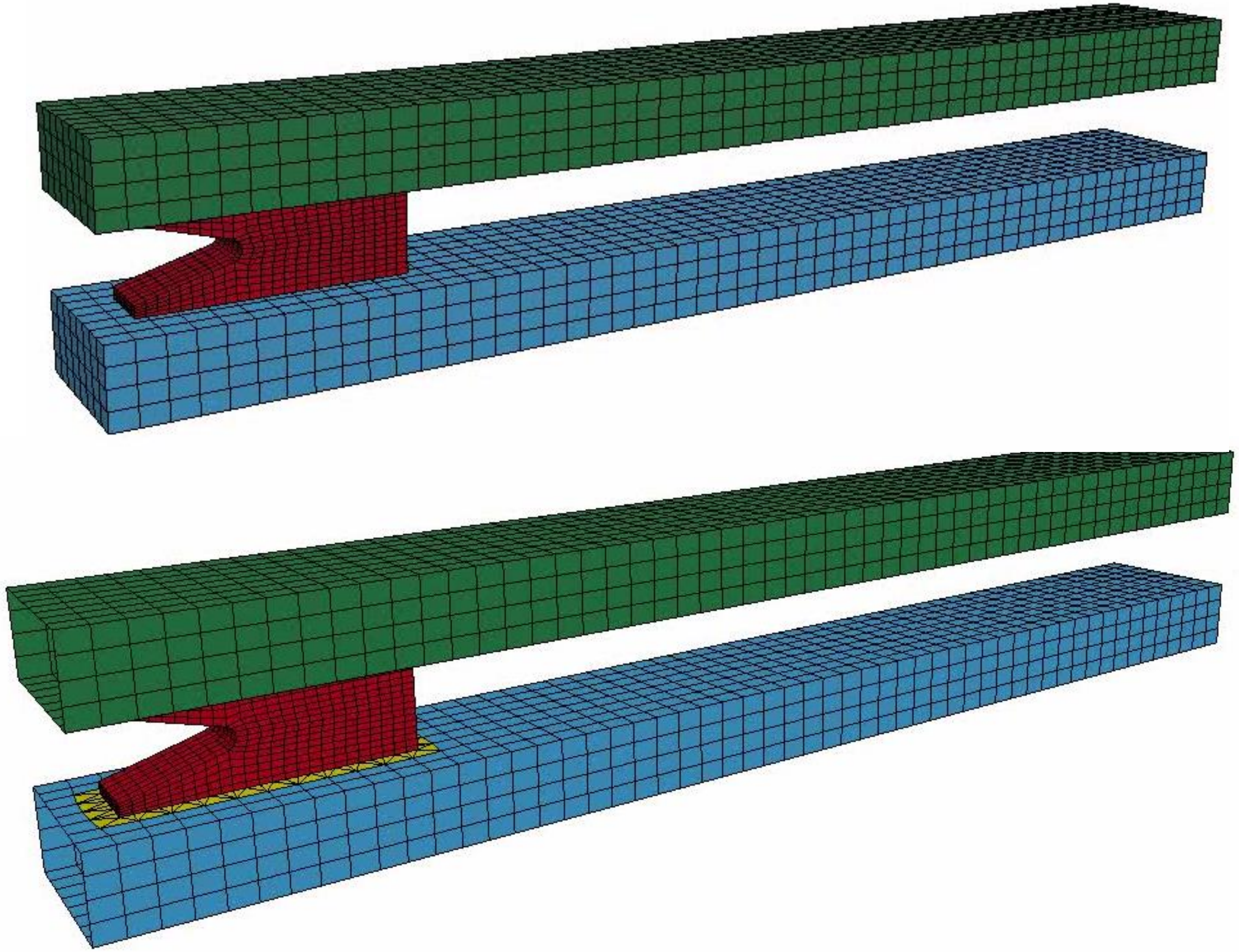
Scalar potential in armature branches and brushes





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).



Thank you