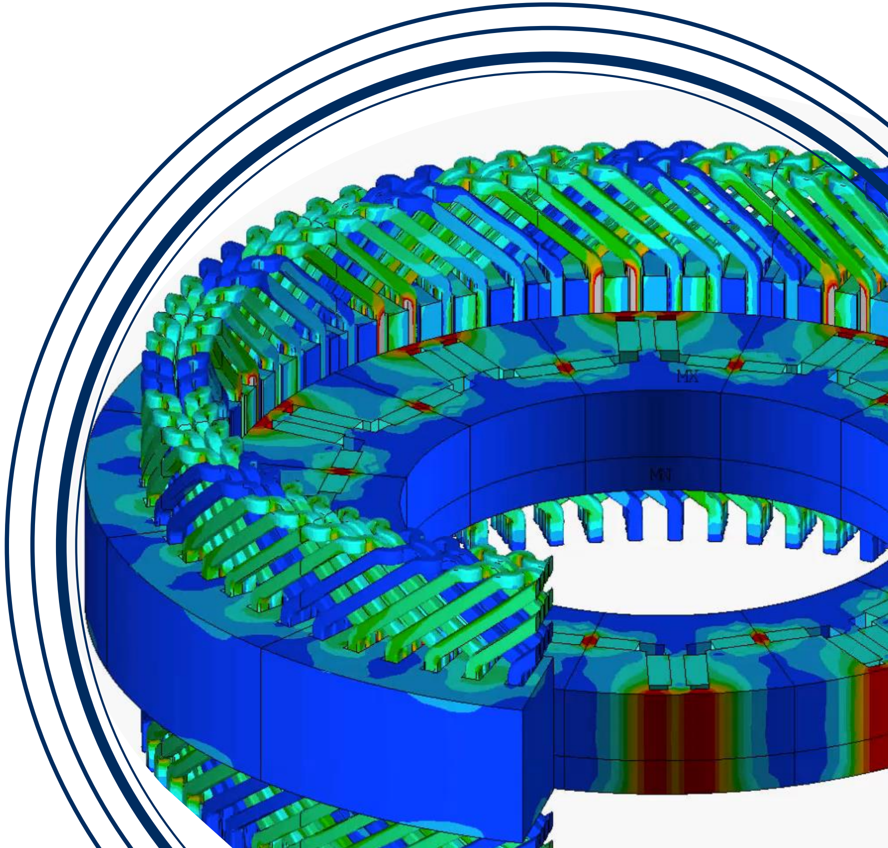
End Winding Impedance Calculation for Motor-CAD Usage Comparison of Four Different Approaches



Technologietag E-Motoren Juni 2020
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CADFEM ANSYS

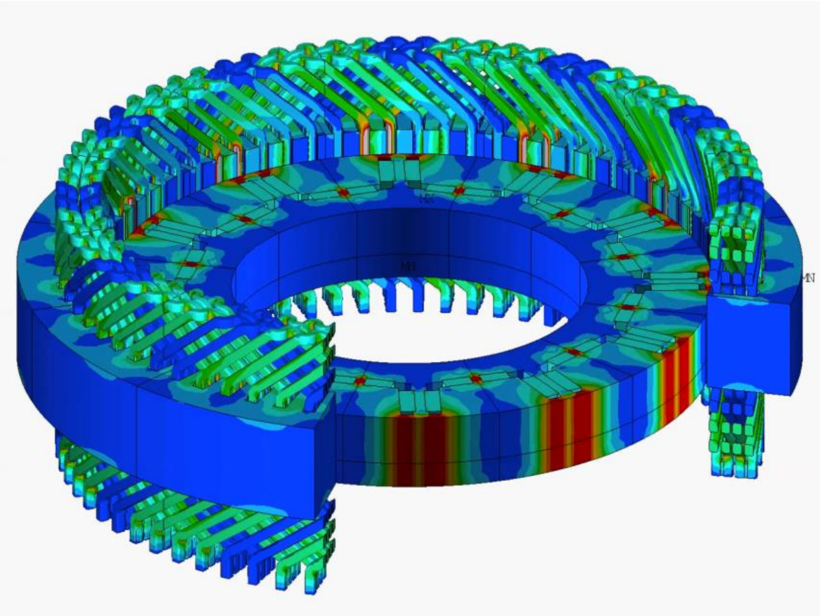
Problem Description

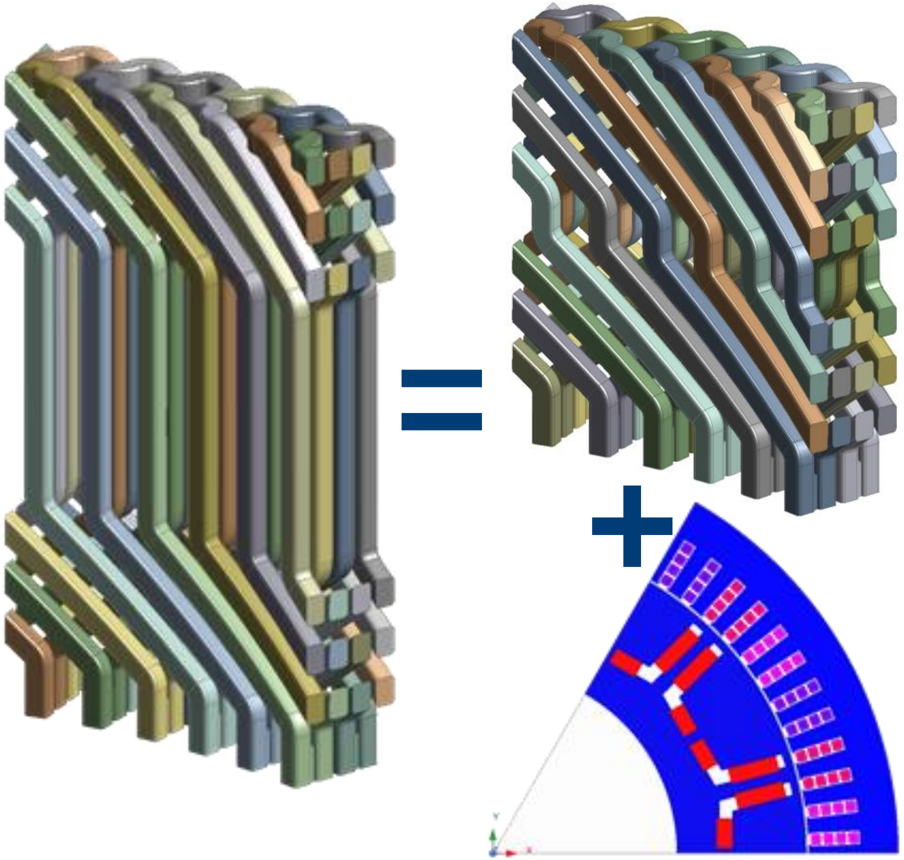
Demo Problem: Short PMSM, 6 Pole Pairs, 72 Slots, Hairpin Winding

End winding‘s influences shall be accounted for in 2D simulations, special case hair pin.

Assume no iron in the end winding region.

Approximate flux parallel at the end of active region.





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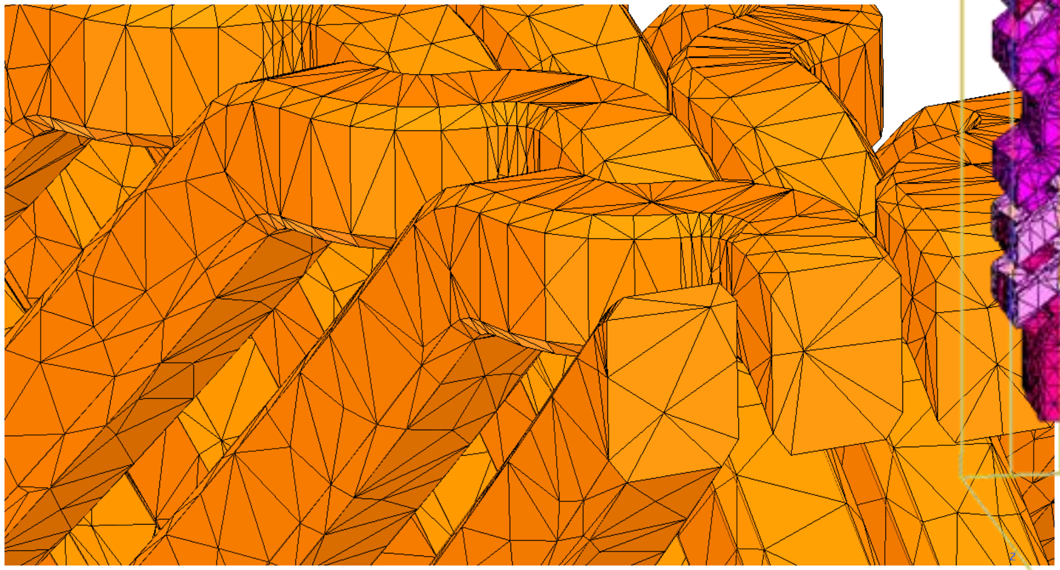
Model

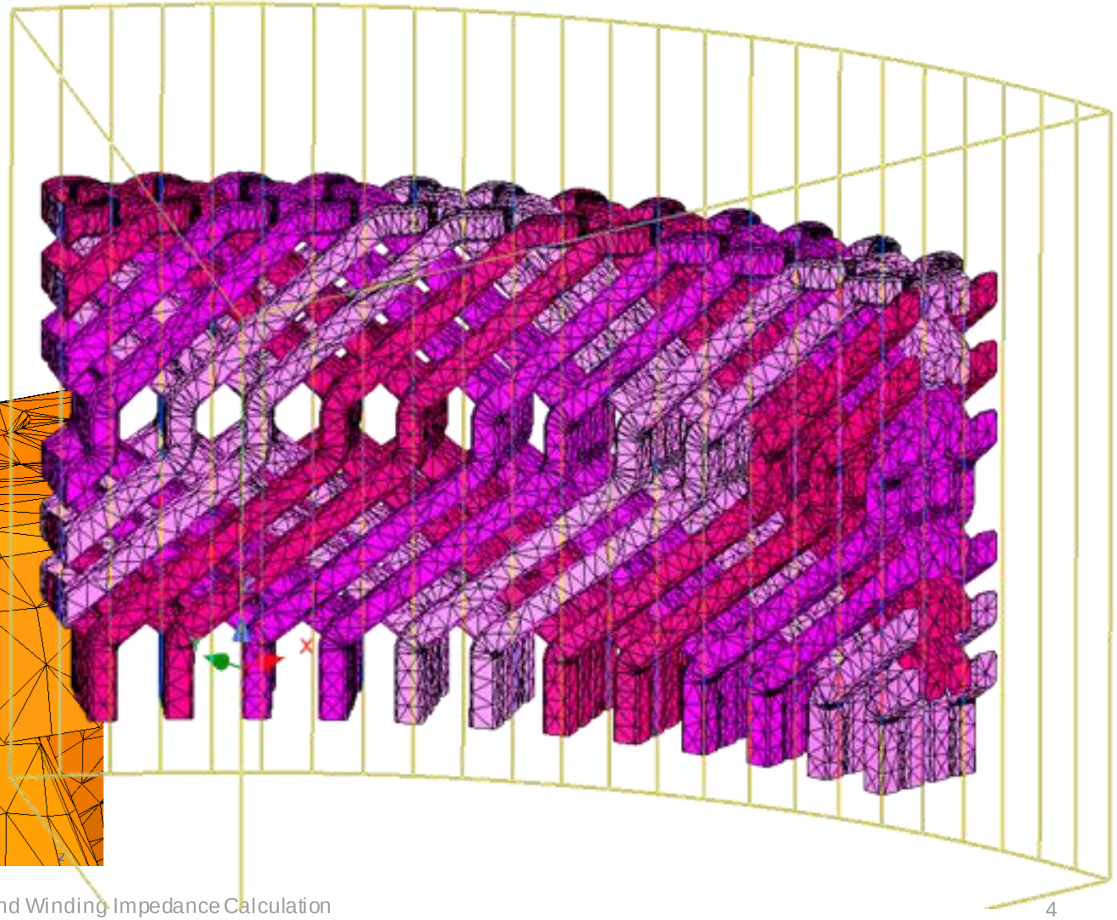
1/6 sector model, wires and region

Periodic boundary conditions

Wire edge fillets replaced by chamfers

275641 tetrahedra





1) Inductance from Static Maxwell Analysis, T-Ω

Solution

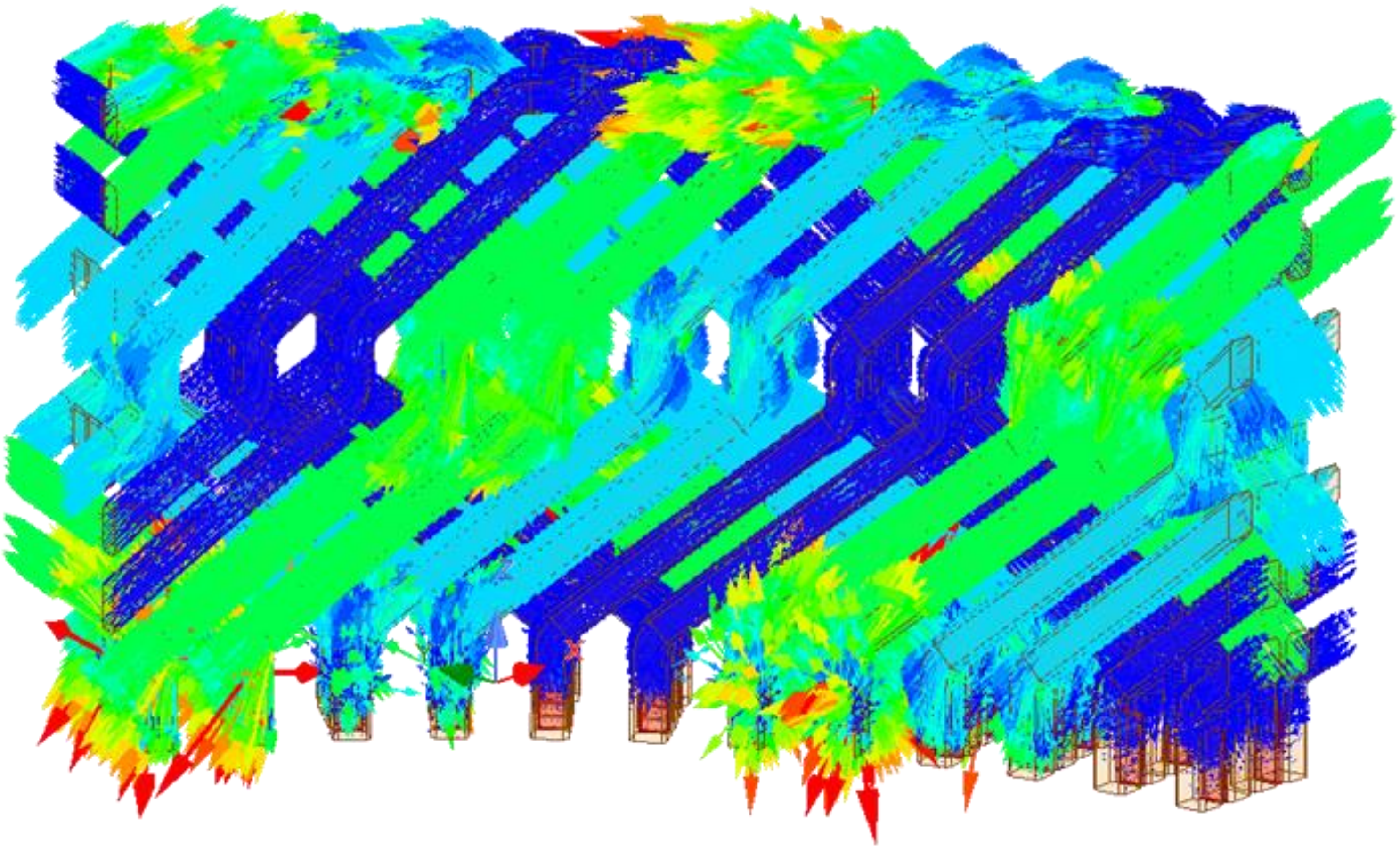
90‘ mesh time

15‘ solution time

60‘ matrix time

Current density shown from phase currents

1A, 2A, 3A



1) Inductance from Static Maxwell Analysis, T-Ω

CADFEM

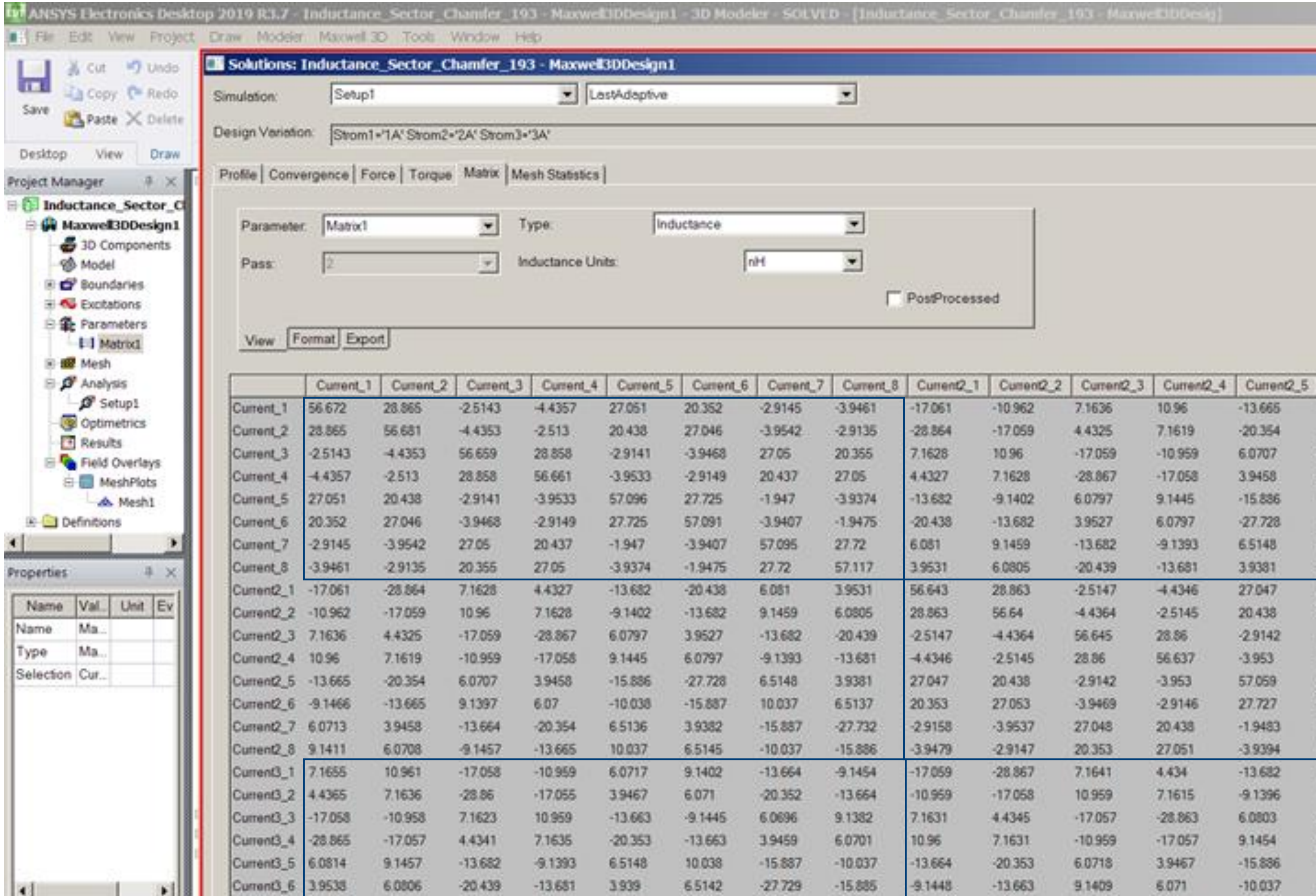
Results

Inductance in nH

from blocks of

induction matrix:

981.3044	-313.2853	-313.2927
-313.2853	980.9968	-313.2863
-313.2927	-313.2863	980.8626



	Current_1	Current_2	Current_3	Current_4	Current_5	Current_6	Current_7	Current_8	Current2_1	Current2_2	Current2_3	Current2_4	Current2_5
Current_1	56.672	28.865	-2.5143	-4.4357	27.051	20.352	-2.9145	-3.9461	-17.061	-10.962	7.1636	10.96	-13.665
Current_2	28.865	56.681	-4.4353	-2.513	20.438	27.046	-3.9542	-2.9135	-28.864	-17.059	4.4325	7.1619	-20.354
Current_3	-2.5143	-4.4353	56.659	28.858	-2.9141	-3.9468	27.05	20.355	7.1628	10.96	-17.059	-10.959	6.0707
Current_4	-4.4357	-2.513	28.858	56.661	-3.9533	-2.9149	20.437	27.05	4.4327	7.1628	-28.867	-17.058	3.9458
Current_5	27.051	20.438	-2.9141	-3.9533	57.096	27.725	-1.947	-3.9374	-13.682	-9.1402	6.0797	9.1445	-15.886
Current_6	20.352	27.046	-3.9468	-2.9149	27.725	57.091	-3.9407	-1.9475	-20.438	-13.682	3.9527	6.0797	-27.728
Current_7	-2.9145	-3.9542	27.05	20.437	-1.947	-3.9407	57.095	27.72	6.081	9.1459	-13.682	-9.1393	6.5148
Current_8	-3.9461	-2.9135	20.355	27.05	-3.9374	-1.9475	27.72	57.117	3.9531	6.0805	-20.439	-13.681	3.9381
Current2_1	-17.061	-28.864	7.1628	4.4327	-13.682	-20.438	6.081	3.9531	56.643	28.863	-2.5147	-4.4346	27.047
Current2_2	-10.962	-17.059	10.96	7.1628	-9.1402	-13.682	9.1459	6.0805	28.863	56.64	-4.4364	-2.5145	20.438
Current2_3	7.1636	4.4325	-17.059	-28.867	6.0797	3.9527	-13.682	-20.439	-2.5147	-4.4364	56.645	28.86	-2.9142
Current2_4	10.96	7.1619	-10.959	-17.058	9.1445	6.0797	-9.1393	-13.681	-4.4346	-2.5145	28.86	56.637	-3.953
Current2_5	-13.665	-20.354	6.0707	3.9458	-15.886	-27.728	6.5148	3.9381	27.047	20.438	-2.9142	-3.953	57.059
Current2_6	-9.1466	-13.665	9.1397	6.07	-10.038	-15.887	10.037	6.5137	20.353	27.053	-3.9469	-2.9146	27.727
Current2_7	6.0713	3.9458	-13.664	-20.354	6.5136	3.9382	-15.887	-27.732	-2.9158	-3.9537	27.048	20.438	-1.9483
Current2_8	9.1411	6.0708	-9.1457	-13.665	10.037	6.5145	-10.037	-15.886	-3.9479	-2.9147	20.353	27.051	-3.9394
Current3_1	7.1655	10.961	-17.058	-10.959	6.0717	9.1402	-13.664	-9.1454	-17.059	-28.867	7.1641	4.434	-13.682
Current3_2	4.4365	7.1636	-28.86	-17.055	3.9467	6.071	-20.352	-13.664	-10.959	-17.058	10.959	7.1615	-9.1396
Current3_3	-17.058	-10.958	7.1623	10.959	-13.663	-9.1445	6.0696	9.1382	7.1631	4.4345	-17.057	-28.863	6.0803
Current3_4	-28.865	-17.057	4.4341	7.1635	-20.353	-13.663	3.9459	6.0701	10.96	7.1631	-10.959	-17.057	9.1454
Current3_5	6.0814	9.1457	-13.682	-9.1393	6.5148	10.038	-15.887	-10.037	-13.664	-20.353	6.0718	3.9467	-15.886
Current3_6	3.9538	6.0806	-20.439	-13.681	3.939	6.5142	-27.729	-15.885	-9.1448	-13.663	9.1409	6.071	-10.037

2) Impedance from Harmonic Mechanical, A-Φ
Theory

Harmonic current 1A is fed into winding k

Time integrated voltage V is measured at winding j

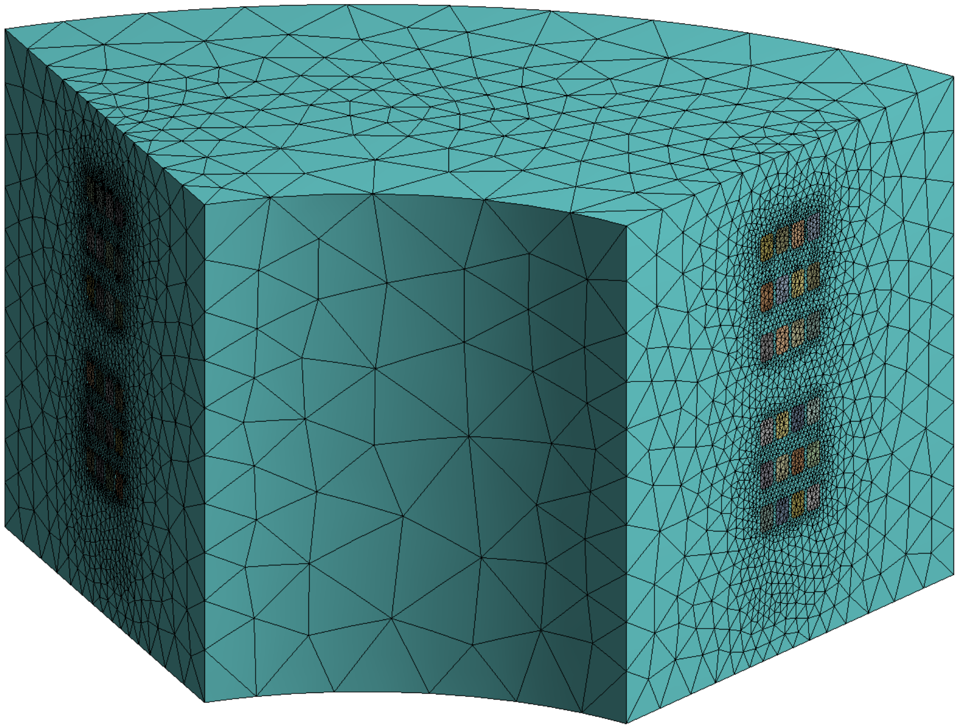
$$V(t) = \int U(t')dt'$$

$$V = {}^{U}/_{i\omega}$$

$$U = (R + i\omega L) \cdot I$$

$$i\omega(V_{Re} + iV_{Im}) = (R + i\omega L) \cdot I$$

Real part of time integrated voltage gives inductance.



2) Impedance from Harmonic Mechanical, A-Φ

Model, Result

Periodic sector

Electrical periodic and inner terminals with APDL

419605 elements: solid236/237 magnetic edge

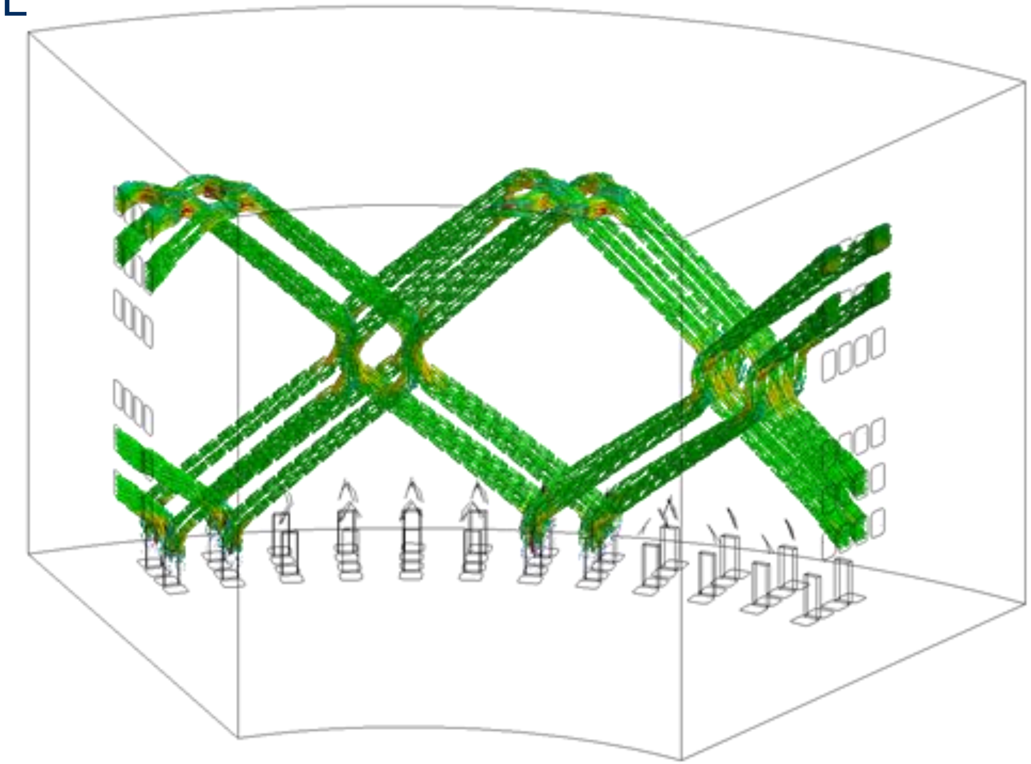
10‘ elapsed time for 3 load steps

10 Hz:

0.988831E-06	-0.328137E-06	-0.328223E-06
-0.328137E-06	0.989335E-06	-0.328096E-06
-0.328223E-06	-0.328097E-06	0.988927E-06

1000 Hz:

0.986678E-06	-0.327491E-06	-0.327564E-06
-0.327491E-06	0.987071E-06	-0.327471E-06
-0.327564E-06	-0.327471E-06	0.986721E-06

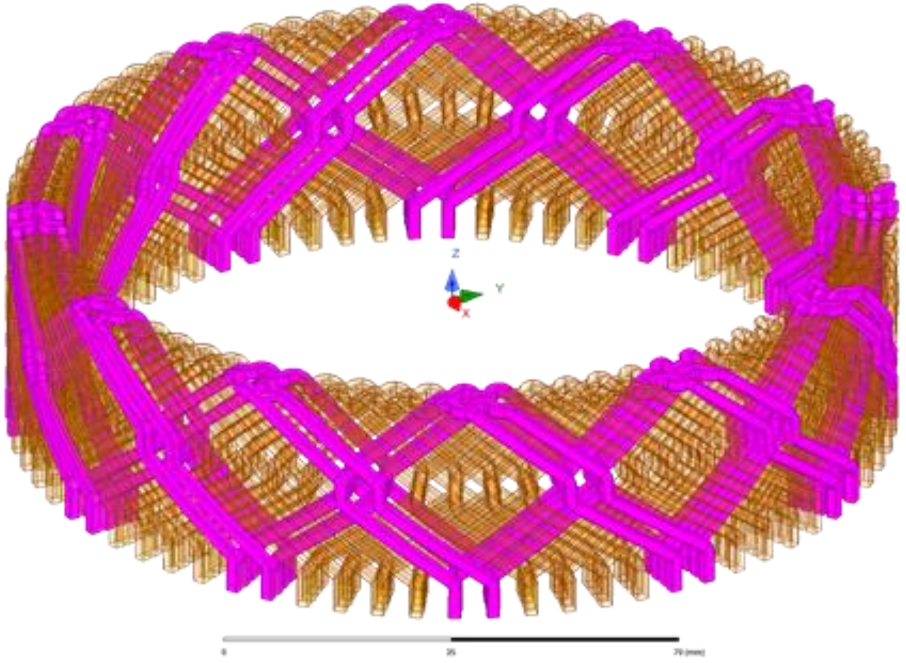


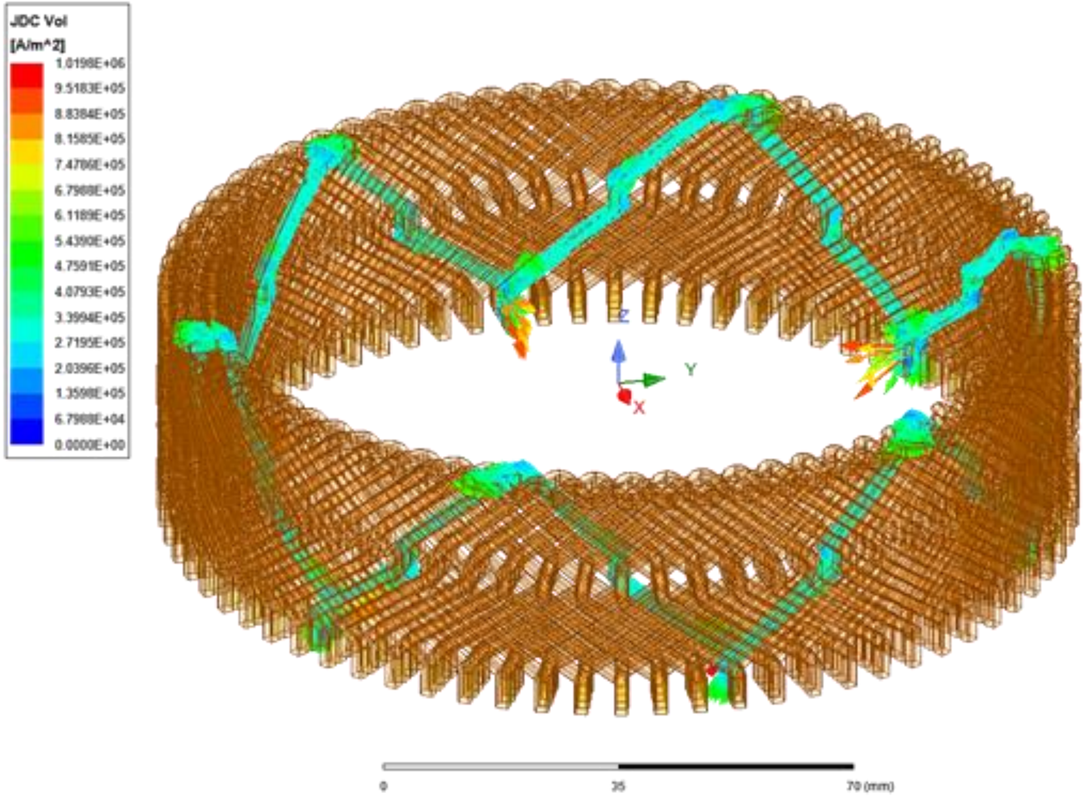
3) Impedance from Q3D, Method of Moments

Model

Full model of wires only

24 signal nets with source and sink pairs





3) Impedance from Q3D, Method of Moments

Result

Result is full inductance Matrix after 98‘

Projection with winding number matrices give winding inductance

Inductance in nH per sector:

1003.5	-325.6	-325.3
-325.6	1003.6	-325.3
-325.3	-325.3	1002.7

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	420	254	182	143	119	102	90	102	119	143	182	254	255	214	172	142	122	107	101	107	122	142	172	214
2	254	420	254	182	143	119	102	90	102	119	143	182	214	255	214	172	142	122	107	101	107	122	142	172
3	182	254	420	254	182	143	119	102	90	102	119	143	172	214	255	214	172	142	122	107	101	107	122	142
4	143	182	254	419	254	182	143	119	102	90	102	119	142	172	214	255	214	172	142	122	107	101	107	122
5	119	143	182	254	420	254	182	143	119	102	90	102	122	142	172	214	255	214	172	142	122	107	101	107
6	102	119	143	182	254	420	254	182	143	119	102	90	107	122	142	172	214	255	214	172	142	122	107	101
7	90	102	119	143	182	254	420	254	182	143	119	102	101	107	122	142	172	214	255	214	172	142	122	107
8	102	90	102	119	143	182	254	420	254	182	144	119	107	101	107	122	142	172	214	255	214	172	142	122
9	119	102	90	102	119	143	182	254	420	254	182	143	122	107	101	107	122	142	172	214	255	214	172	142
10	143	119	102	90	102	119	143	182	254	419	254	182	142	122	107	101	107	122	142	172	214	255	214	172
11	182	143	119	102	90	102	119	144	182	254	420	254	172	142	122	107	101	107	122	142	172	214	255	214
12	254	182	143	119	102	90	102	119	143	182	254	420	214	172	142	122	107	100	107	122	142	172	214	255
13	255	214	172	142	122	107	101	107	122	142	172	214	450	274	200	161	136	118	105	118	136	161	200	274
14	214	255	214	172	142	122	107	101	107	122	142	172	274	450	274	200	161	136	118	105	118	136	161	200
15	172	214	255	214	172	142	122	107	101	107	122	142	200	274	450	274	200	161	136	118	105	118	136	161
16	142	172	214	255	214	172	142	122	107	101	107	122	161	200	274	450	274	200	161	136	118	105	118	136
17	122	142	172	214	255	214	172	142	122	107	101	107	136	161	200	274	450	274	200	161	136	118	105	118
18	107	122	142	172	214	255	214	172	142	122	107	100	118	136	161	200	274	450	274	200	161	136	118	105
19	101	107	122	142	172	214	255	214	172	142	122	107	105	118	136	161	200	274	450	274	200	161	136	118
20	107	101	107	122	142	172	214	255	214	172	142	122	118	105	118	136	161	200	274	450	274	200	161	136
21	122	107	101	107	122	142	172	214	255	214	172	142	136	118	105	118	136	161	200	274	450	274	200	161
22	142	122	107	101	107	122	142	172	214	255	214	172	161	136	118	105	118	136	161	200	274	450	274	200
23	172	142	122	107	101	107	122	142	172	214	255	214	200	161	136	118	105	118	136	161	200	274	450	274
24	214	172	142	122	107	101	107	122	142	172	214	255	274	200	161	136	118	105	118	136	161	200	274	450

	A	B	C
1	1	0	0
2	1	0	0
3	0	0	-1
4	0	0	-1
5	0	1	0
6	0	1	0
7	-1	0	0
8	-1	0	0
9	0	0	1
10	0	0	1
11	0	-1	0
12	0	-1	0
13	1	0	0
14	1	0	0
15	0	0	-1
16	0	0	-1
17	0	1	0
18	0	1	0
19	-1	0	0
20	-1	0	0
21	0	0	1
22	0	0	1
23	0	-1	0
24	0	-1	0

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A	1	1	0	0	0	0	-1	-1	0	0	0	0	1	1	0	0	0	0	-1	-1	0	0	0	0
B	0	0	0	0	1	1	0	0	0	0	-1	-1	0	0	0	0	1	1	0	0	0	0	-1	-1
C	0	0	-1	-1	0	0	0	0	1	1	0	0	0	0	-1	-1	0	0	0	0	1	1	0	0

W^T*L*W

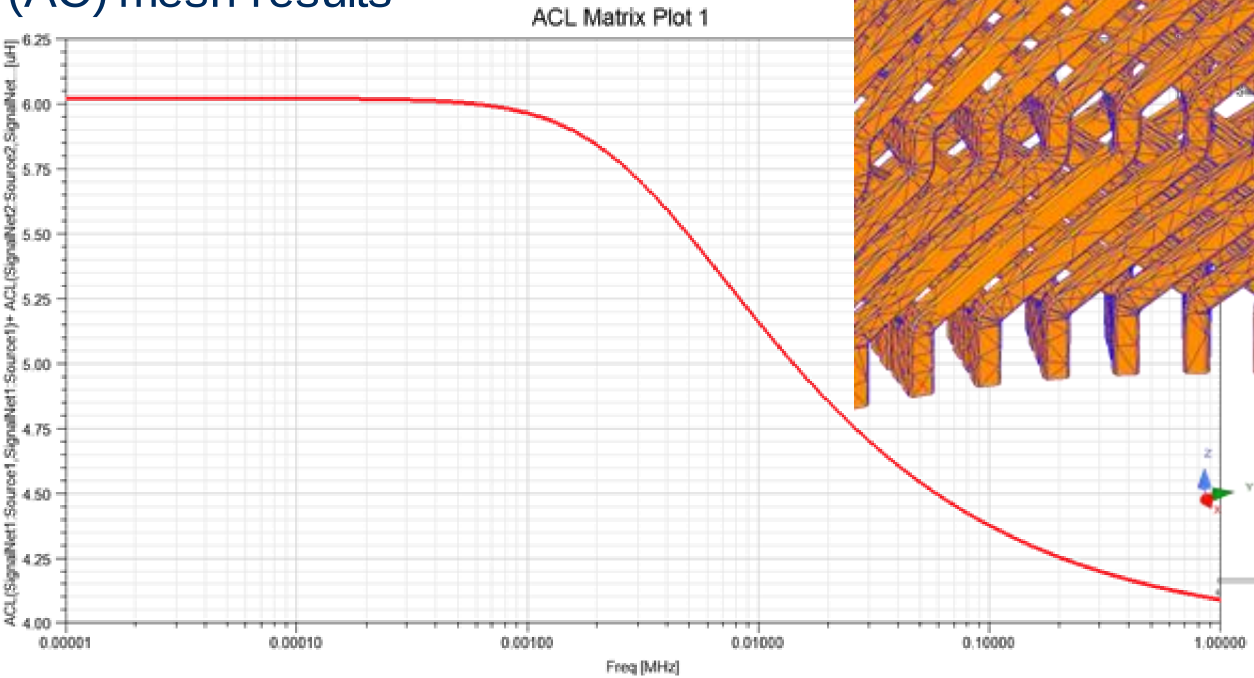
6020.8	-1954	-1952
-1953.6	6021.6	-1952
-1952	-1952	6016

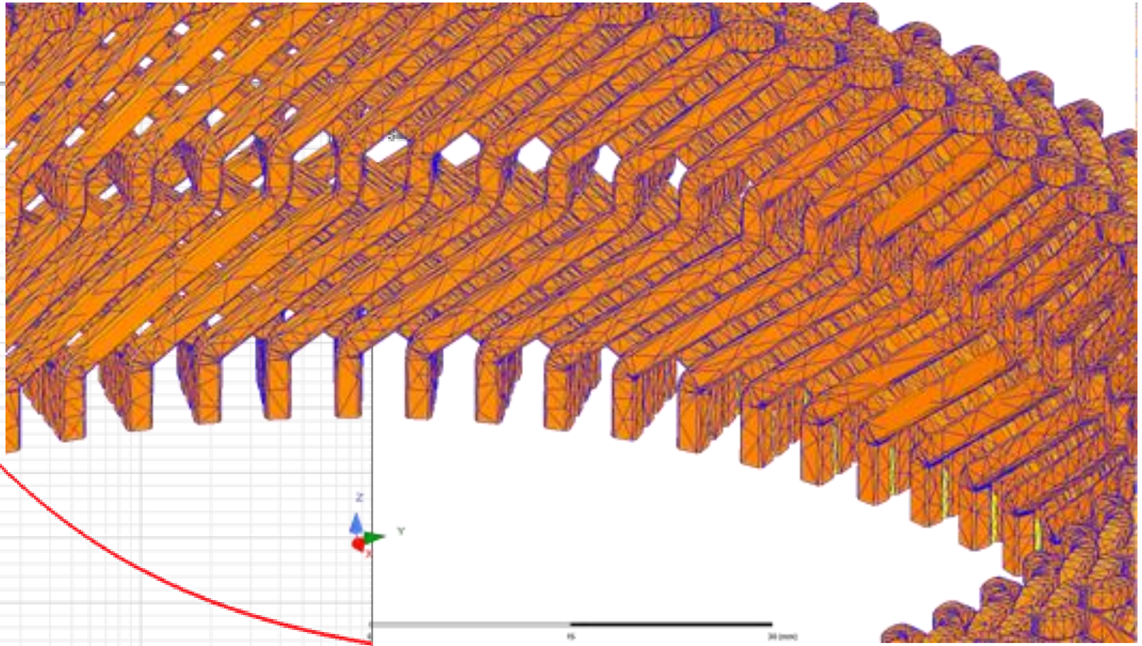
3) Impedance from Q3D, Method of Moments

Frequency Dependence

Frequency dependence full end winding

Interpolation from volume (DC) and surface (AC) mesh results





4) Static Inductance from Biot-Savart's Law

Theory

$$\vec{A}(\vec{r}) = \frac{\mu_0}{4\pi} \iiint \frac{\vec{j}(\vec{r'})}{|\vec{r} - \vec{r'}|} \cdot d^3\vec{r'}$$

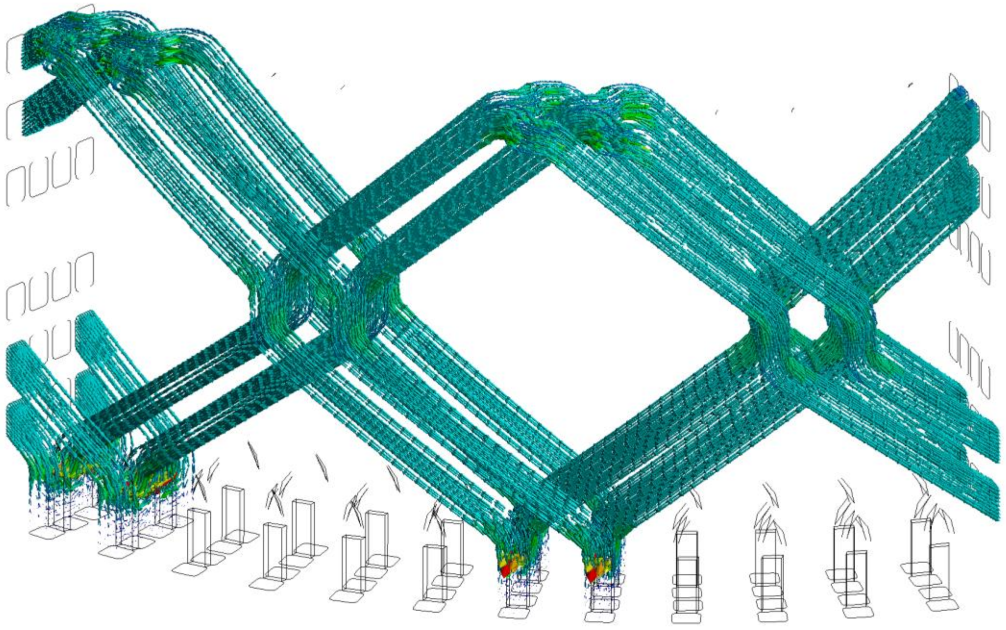
executed over all periodic sectors is solution of

$$\Delta \vec{A}(\vec{r}) = -\mu_0 \cdot \vec{j}(\vec{r}).$$

If $\vec{j_k}$ is the turn density vector for load case k coming from 1A current in winding k and $\vec{A_l}$ is the vector potential from excited winding l then we find the flux linkage matrix element:

$$\Phi_{kl} = \iiint \vec{j_k} \cdot \vec{A_l} \cdot d^3\vec{r}$$

by integration over winding k only.



4) Static Inductance from Biot-Savart's Law

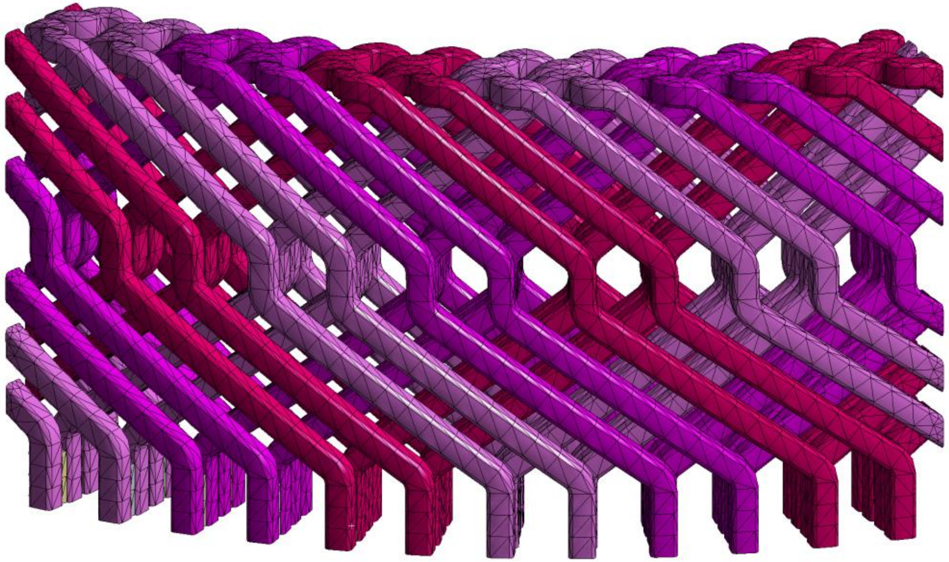
Numerics in Ansys Mechanical

39801 elements: solid232 current conduction

Solve three load cases: 24'' elapsed time

Postprocessing: 18' to find one row of static flux linkage matrix in Wb:

```
MY_FLUX11 =     0.9884747759E-06
MY_FLUX12 =    -0.3249750294E-06
MY_FLUX13 =    -0.3249925750E-06
```



Summary: Inductance Calculation Methods

Method	Pro	Con	Best
Maxwell T-Ω	Easy to use	Simplified geometry Singly connected conductors Long meshing time	Easy to use
Mechanical A-Φ	Fast Inflation mesh for skin effect	Scripting needed	Fastest
Q3D MoM	Mesh for conductors only Frequency dependence Direct circuit export	Full geometry Frequency interpolation	Most convenient
Mechanical Biot-Savart	Mesh for conductors only Sector geometry	Scripting needed Integration for vector potential takes long time DC only	Easiest mesh