A 60 KW ISA Problem
and
how to take advantage of Maxwell 3D

Andrew Hirzel
andy@lightengineering.com
LE Incorporated
8158 Zionsville Road
Indianapolis, IN 46268
USA

October, 2004

Presentation Outline

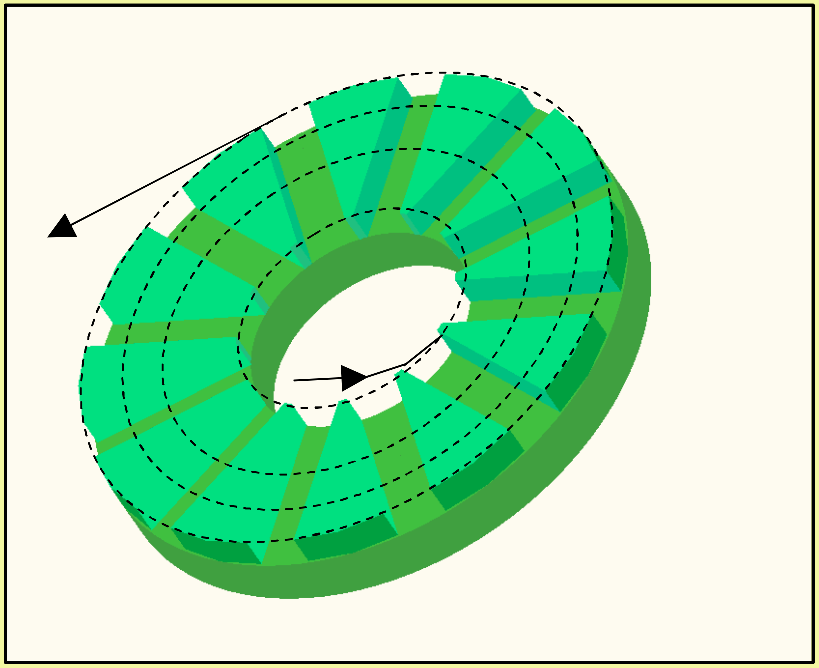
- Background
  - Axial Airgap Machine Topology
- Maxwell 3D Quasi-Dynamic
- Maxwell 3D Transient
- Results

Example of Axial Airgap Stator

•Single “tape-reeled” amorphous metal ribbon

•Slotted after “reeling” operation

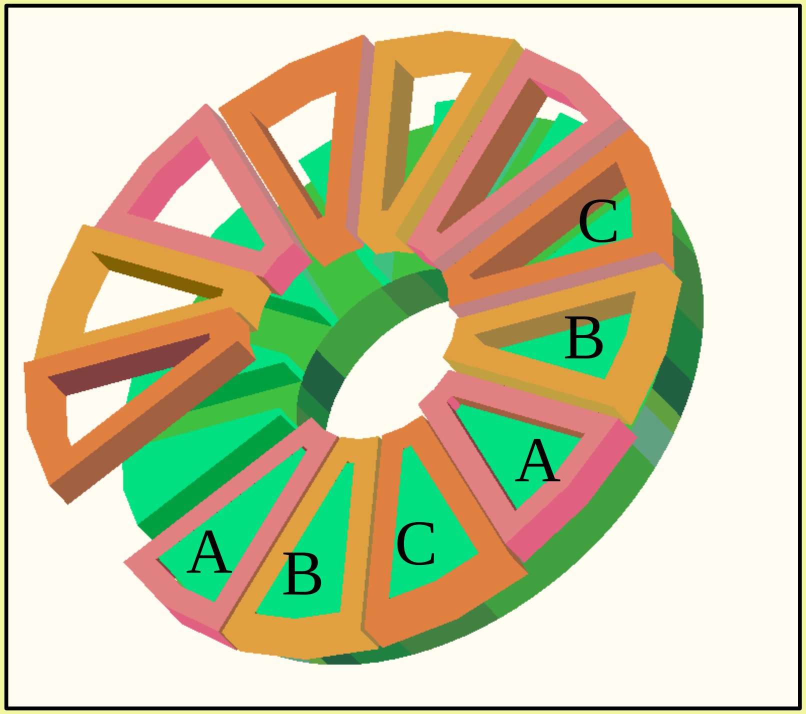
•Unibody Design



Example of Stator shown with Phase Coils

•Discrete, modular 3-phase coils with concentrated windings

•Non-distributed A-B-C, A-B-C windings

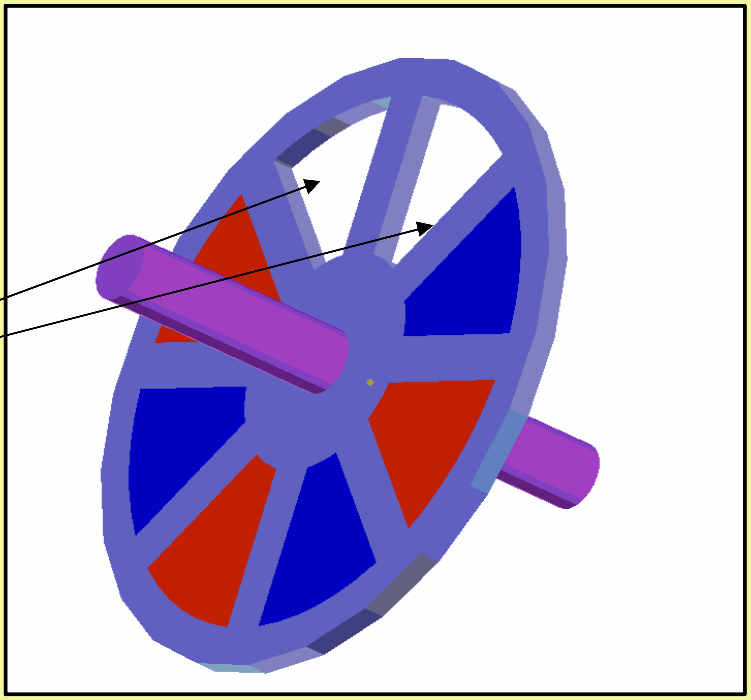


Example of Axial-Gap Rotor and Shaft

- Rotor material; non-magnetic

- NdFeB Magnets through rotor "windows" (magnets missing)

- Shaft material; conventional



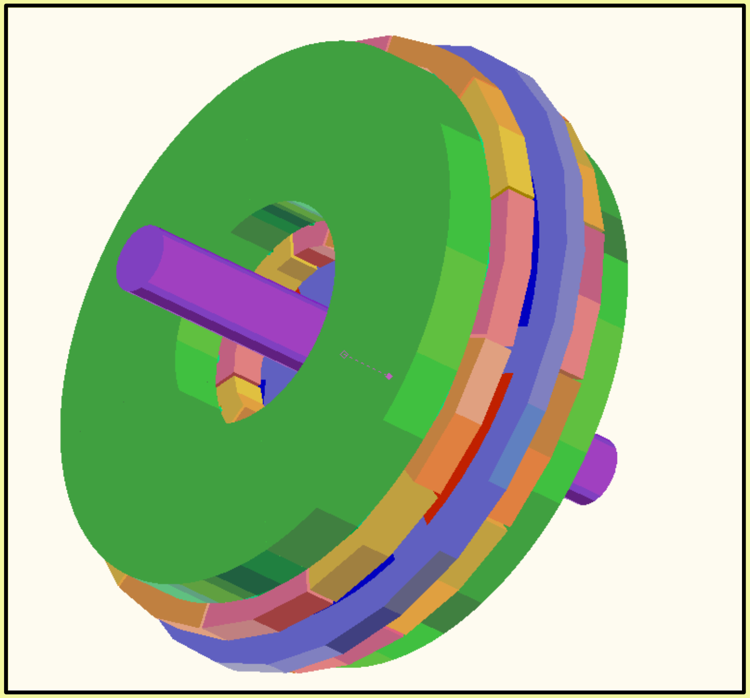
Example of Complete Axial-Gap Machine

•One rotor assembly

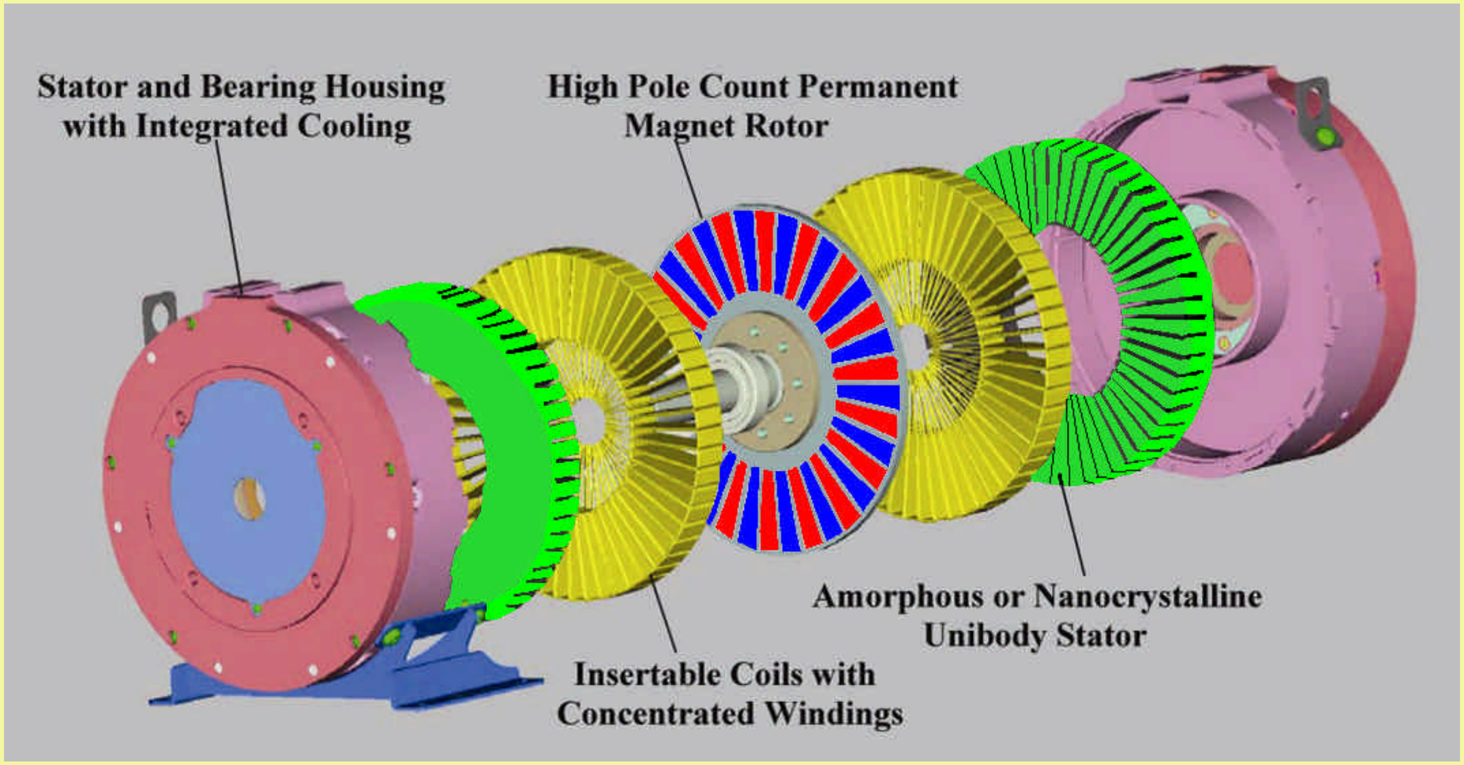
•Two stator assemblies

•Housing not shown

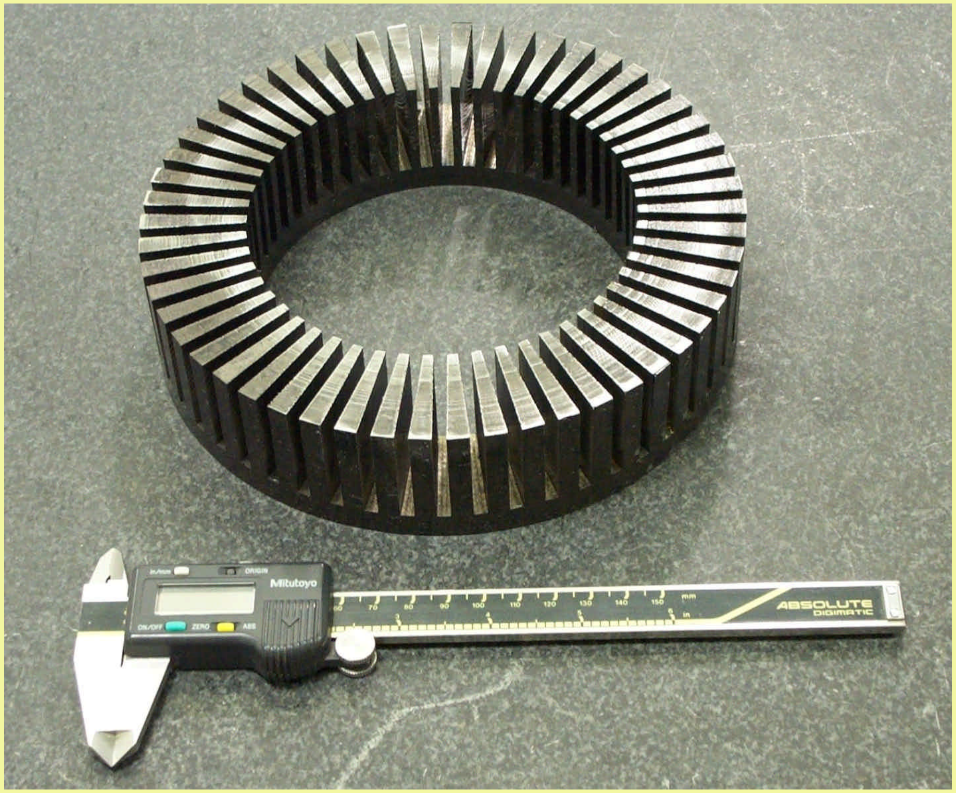
•Magnets, coils and amorphous stators = Active Material



Axial Machine M32

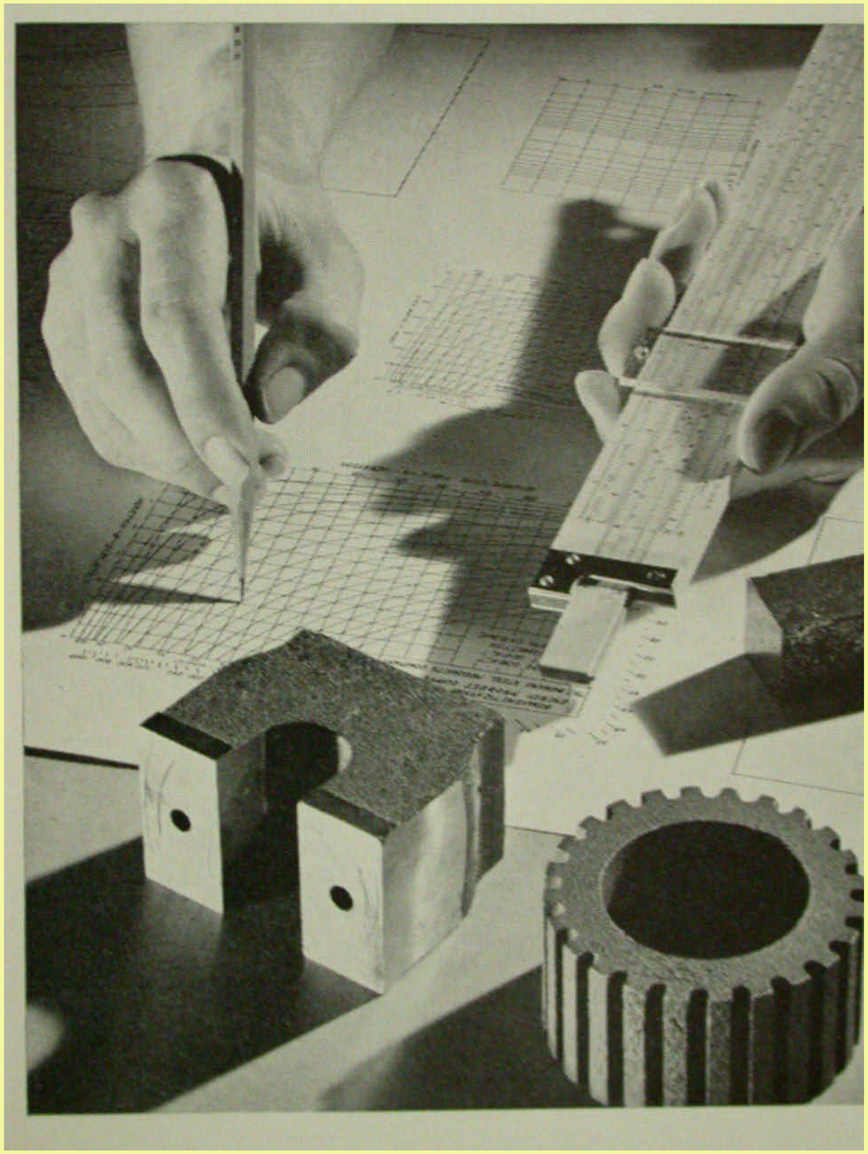


Typical 54 slot, 22 cm stator



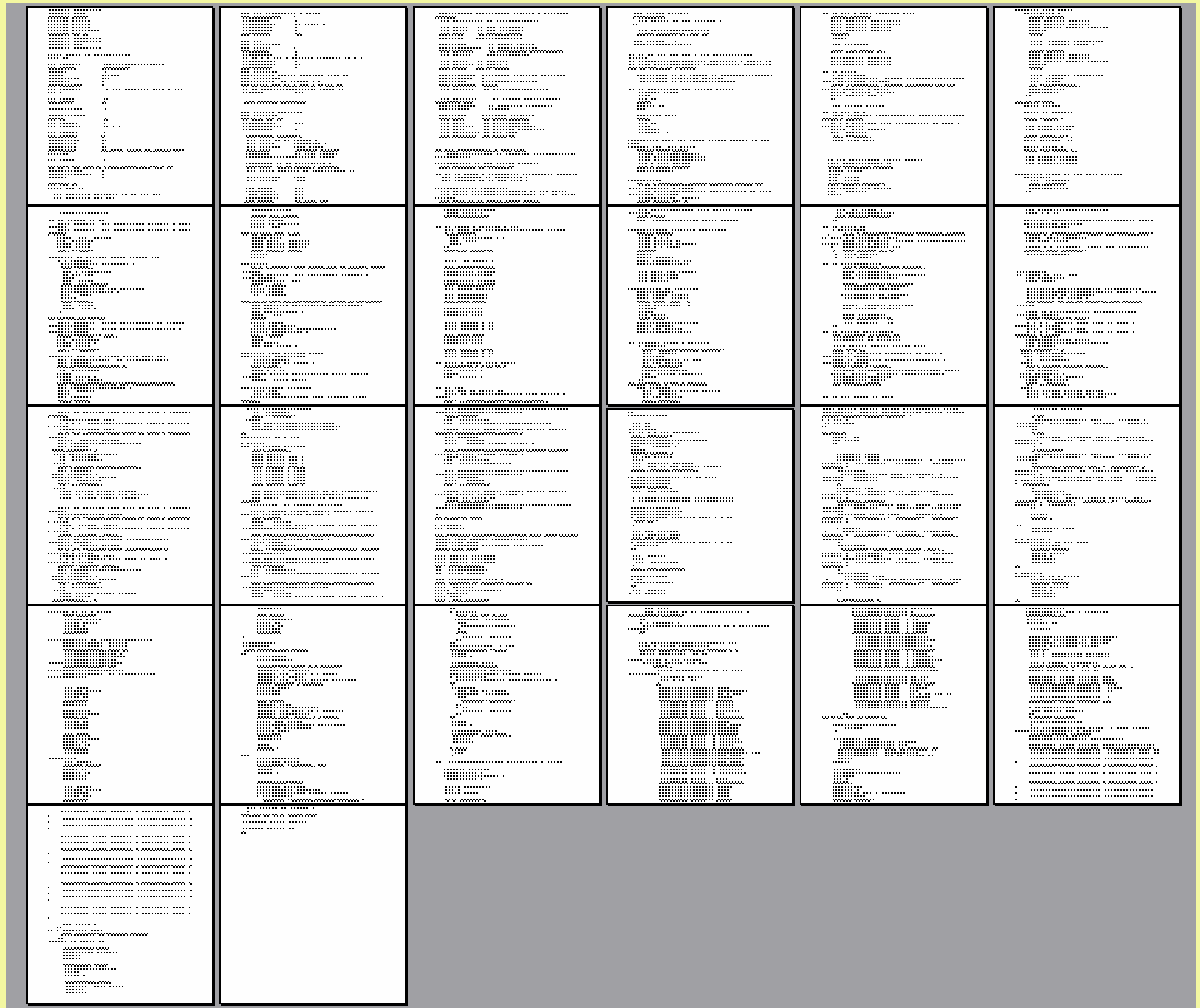
Presentation Outline

- Background
- Maxwell 3D Quasi-Dynamic
  - Before Transient Solvers
  - Flux Density
  - Ripple
  - De-Magnetization
- Maxwell 3D Transient
- Results



Don't laugh too hard …
This technology took us to the moon and back.

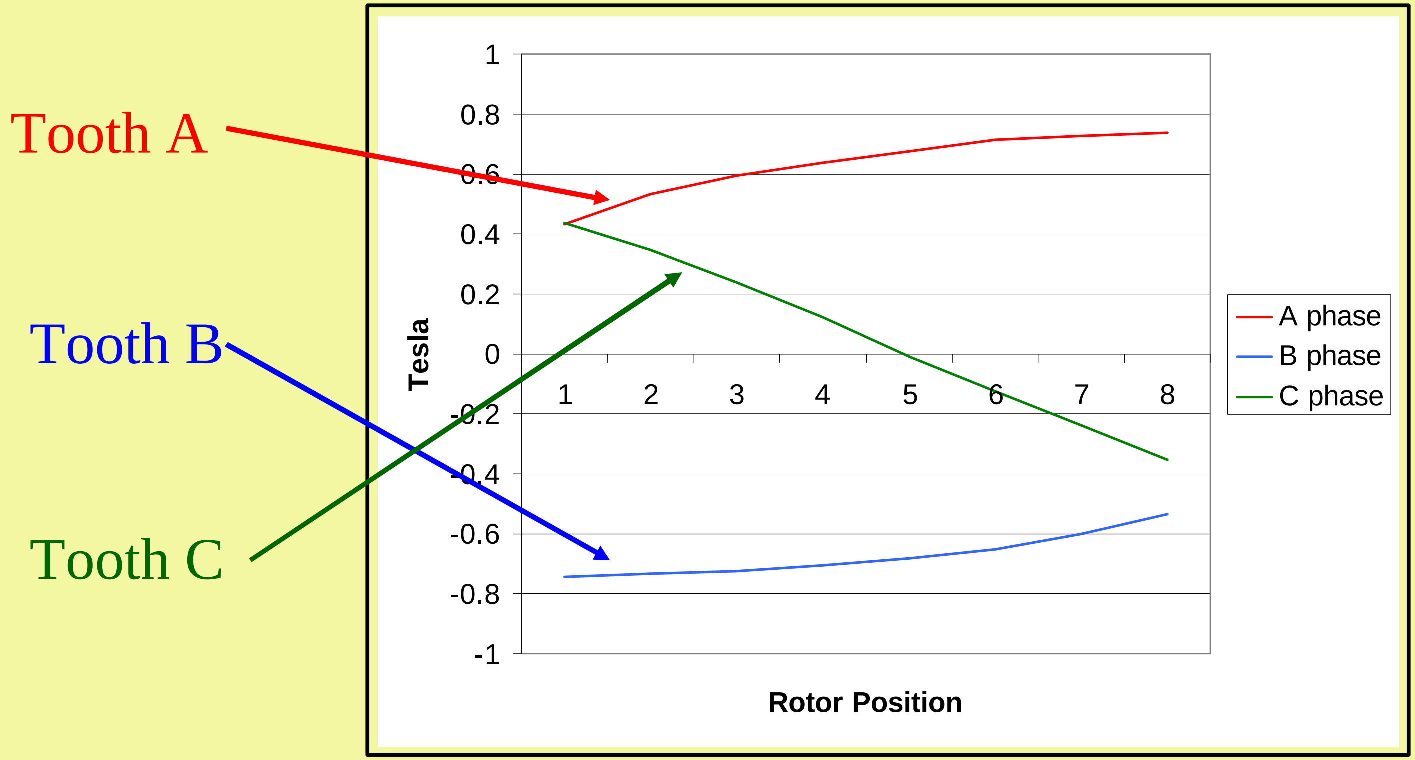
26 pp Optimetrics macro will setup and solve all designs, and iterate on parameters of interest



Variation in Flux Density Inside Coils

Analysis for 1/6 of synchronous cycle, i.e. 1/6 of pole-pair angle.

Observation of symmetry concludes that this is all the analysis needed.



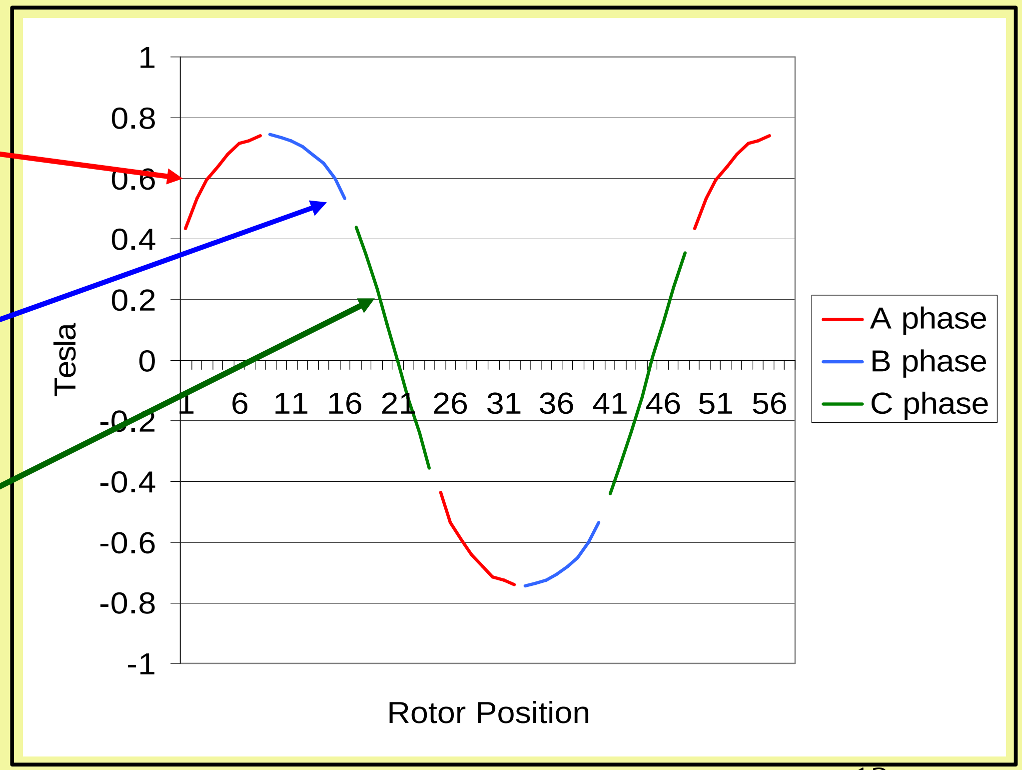
“Assembled” Variation in Flux Density

- Assembly of synchronous cycle from 1/6 analysis
- Makes macro code much faster and much easier to write

Tooth A

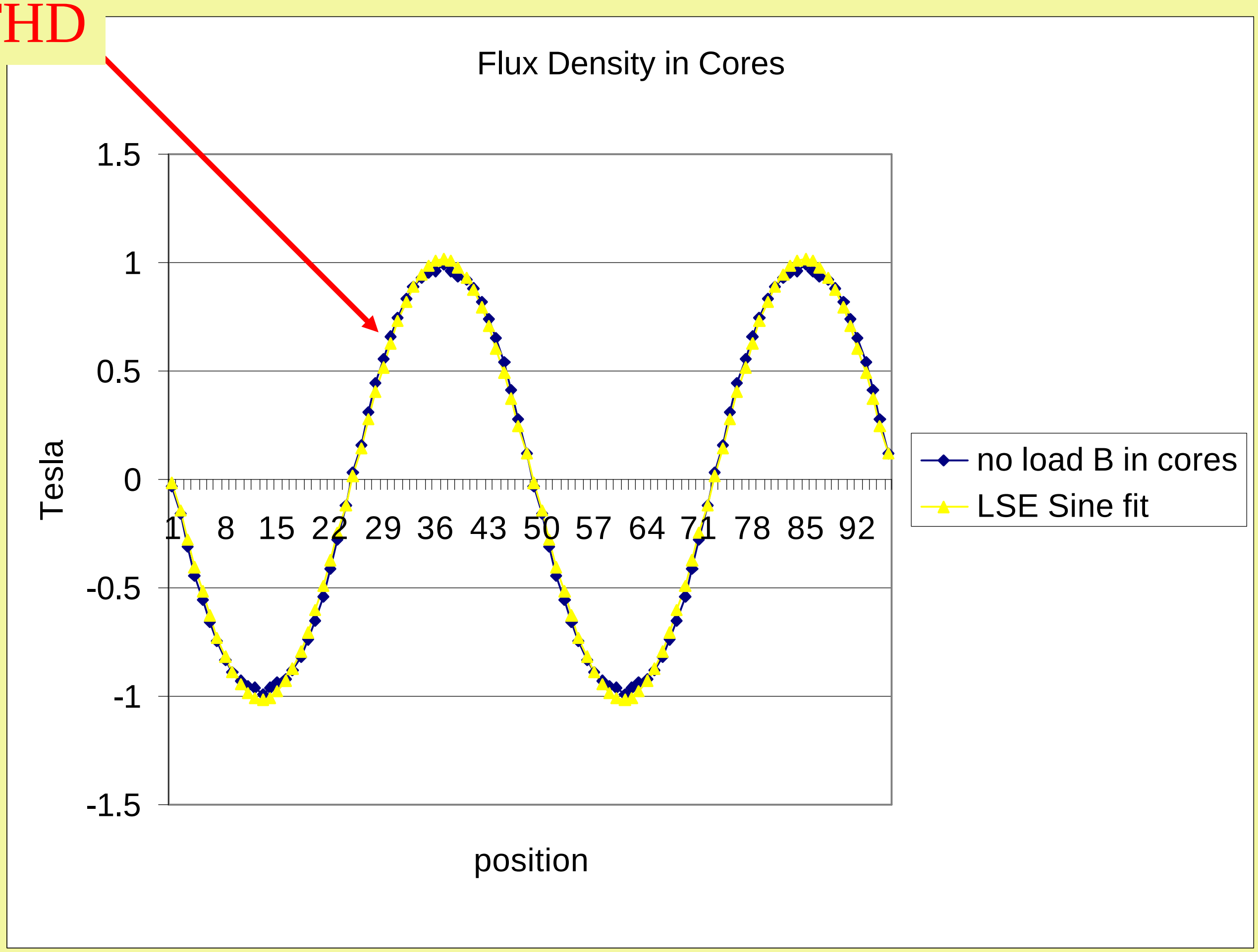
Minus Tooth B
Shifted once

Tooth C
Shifted 2X



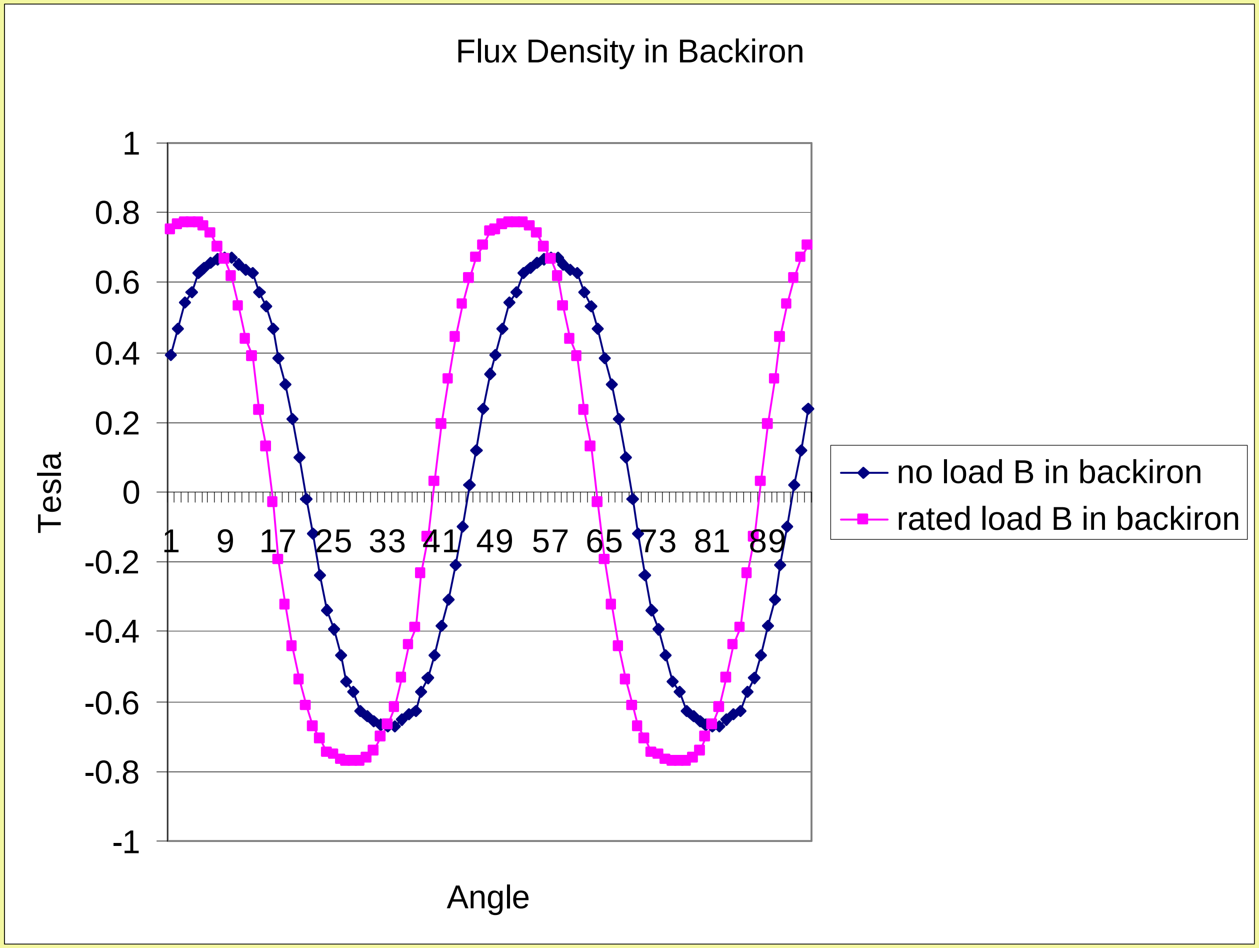
Check flux density,
this directly determines EMF

4% THD

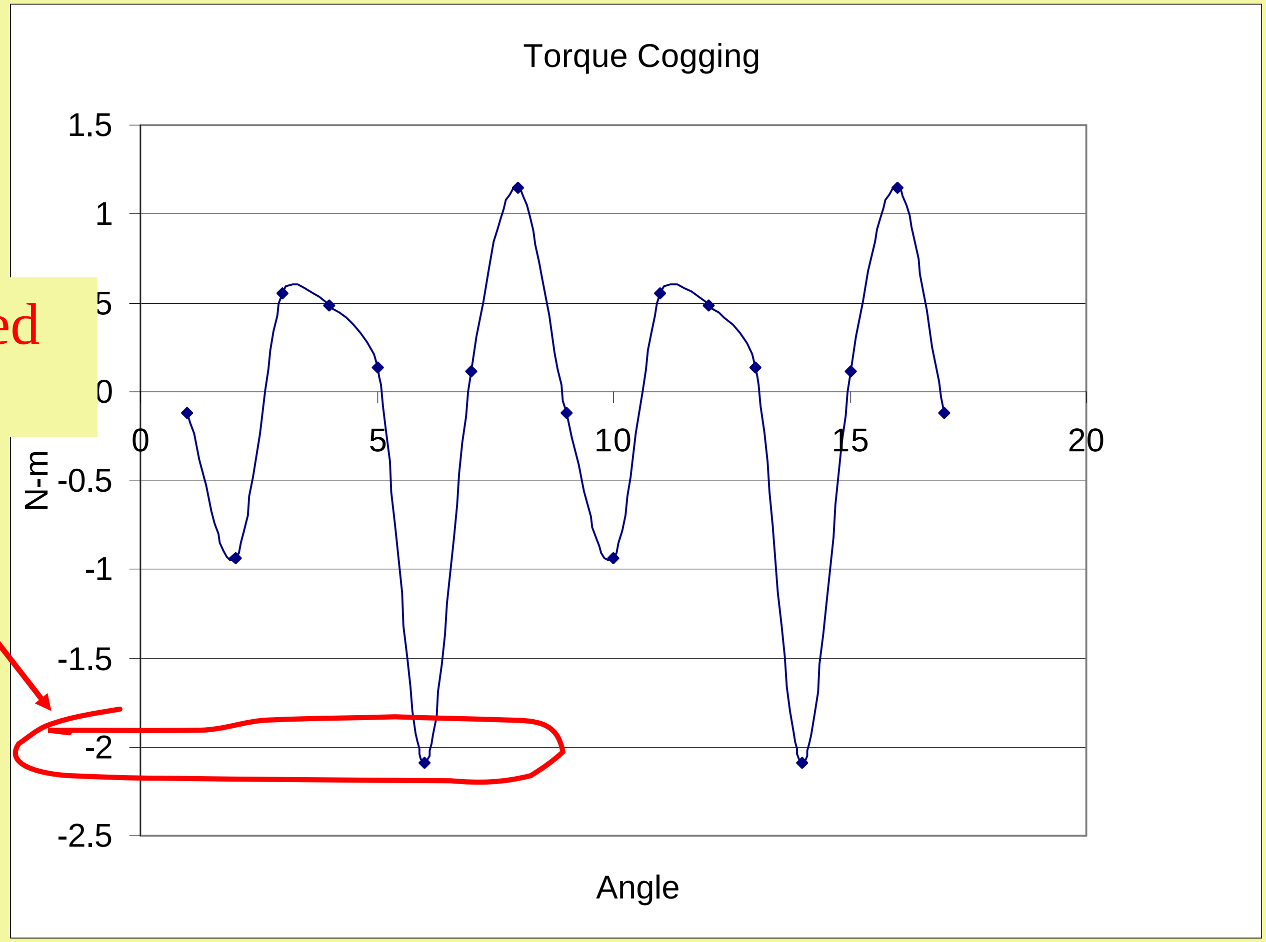


Check Saturation

You can easily check any pre-defined surface this way



Check Torque Cogging

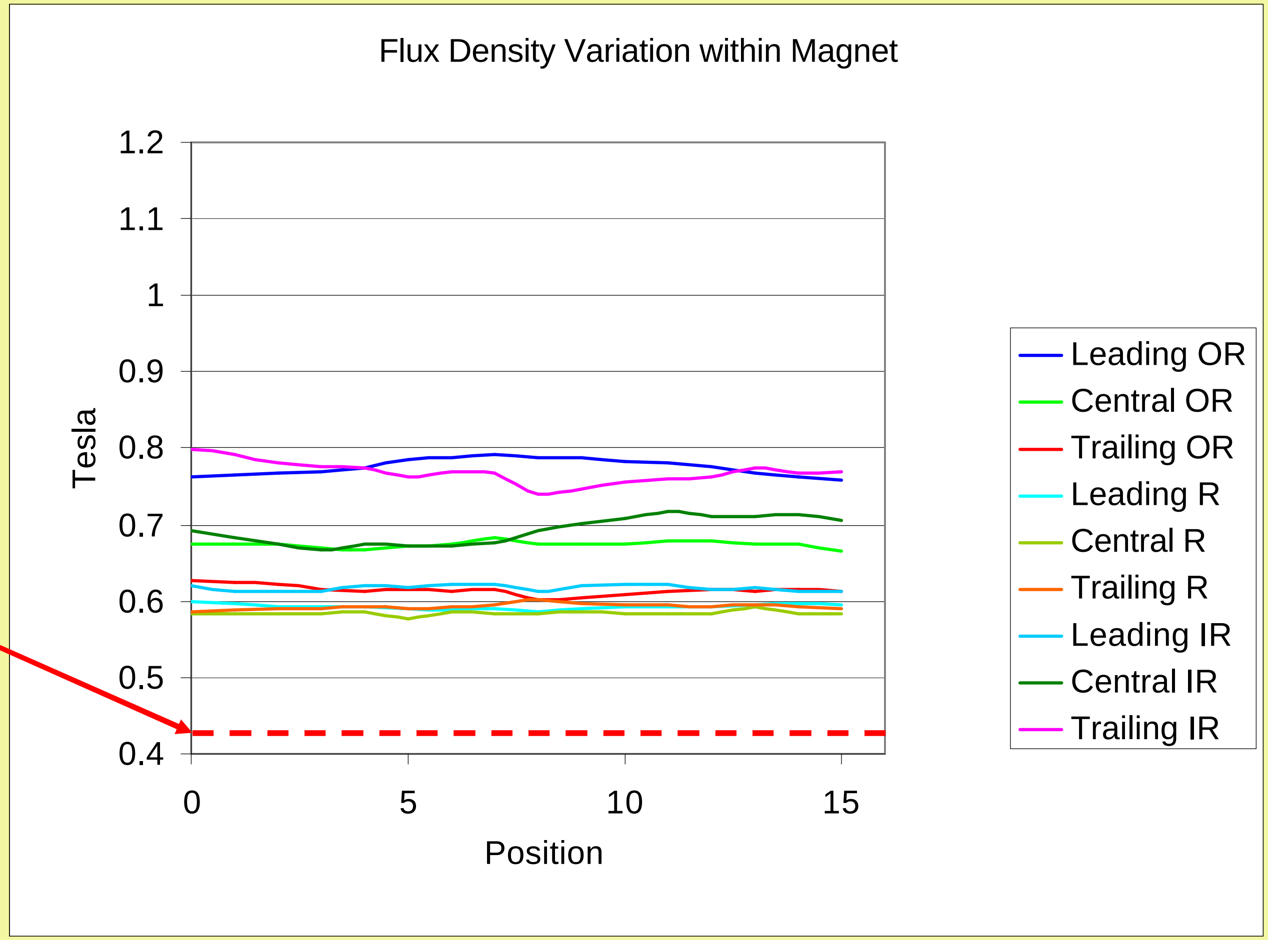


1% rated torque

Check Worst Case Potential for Demagnetization

Analysis @ rated current, in D axis
Shows very safe operation

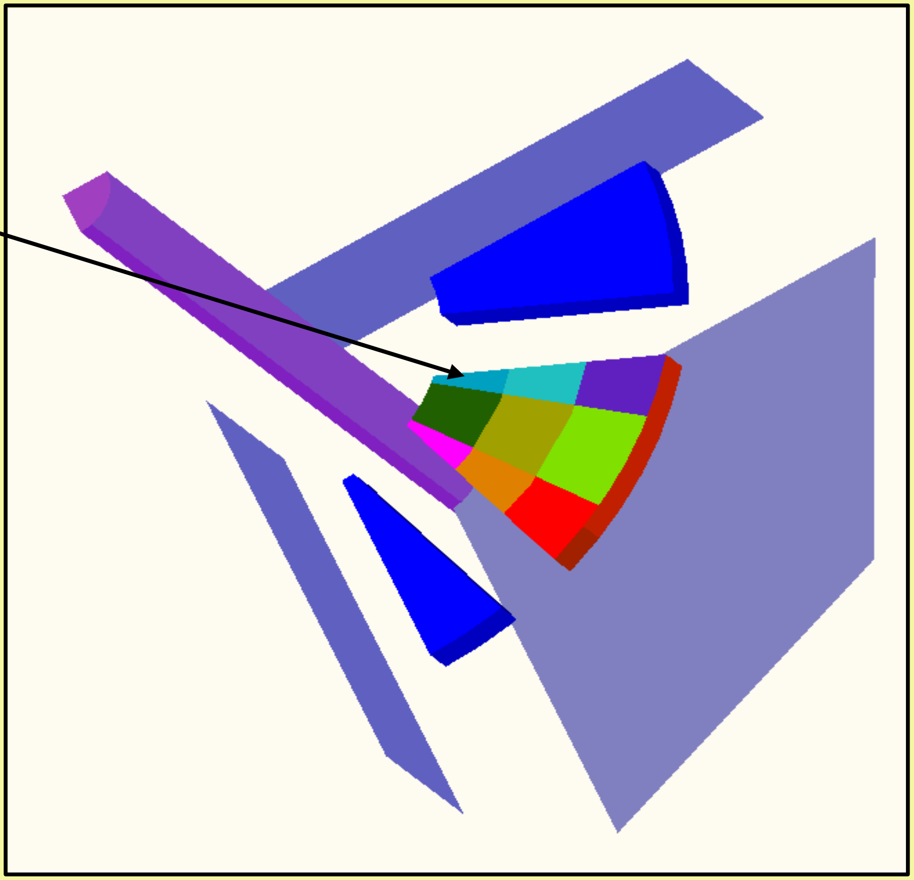
Danger of De-mag!



Surfaces Setup in Advance for Analysis Needs

•Analysis surfaces; orthogonal grid.

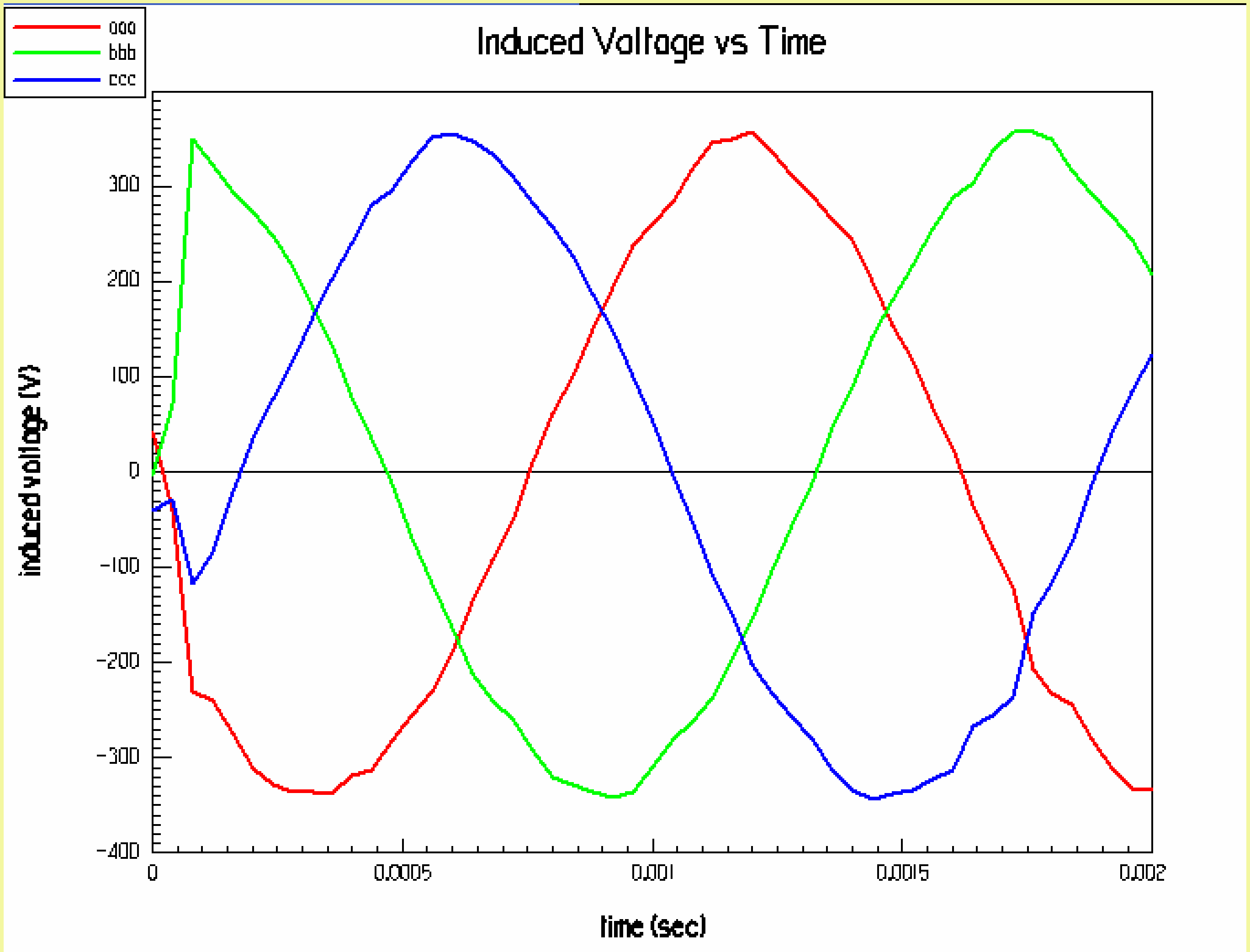
Again, make the surfaces useful to you.



Presentation Outline

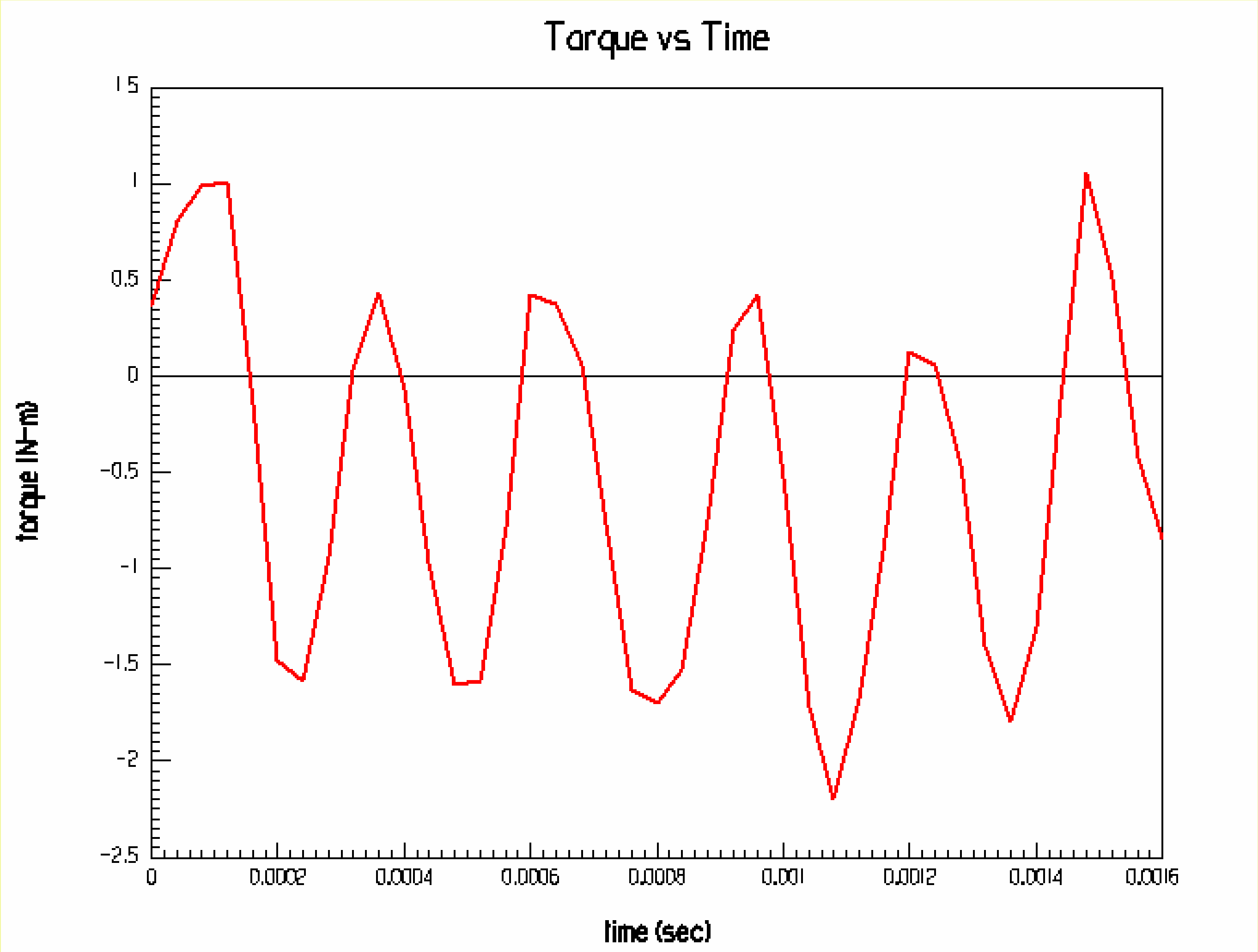
- Background
- Maxwell 3D Quasi-Dynamic
- Maxwell 3D Transient
  - BEMF
  - Cogging
  - Core Loss
  - Magnet Eddy Current Loss
- Results

BEMF



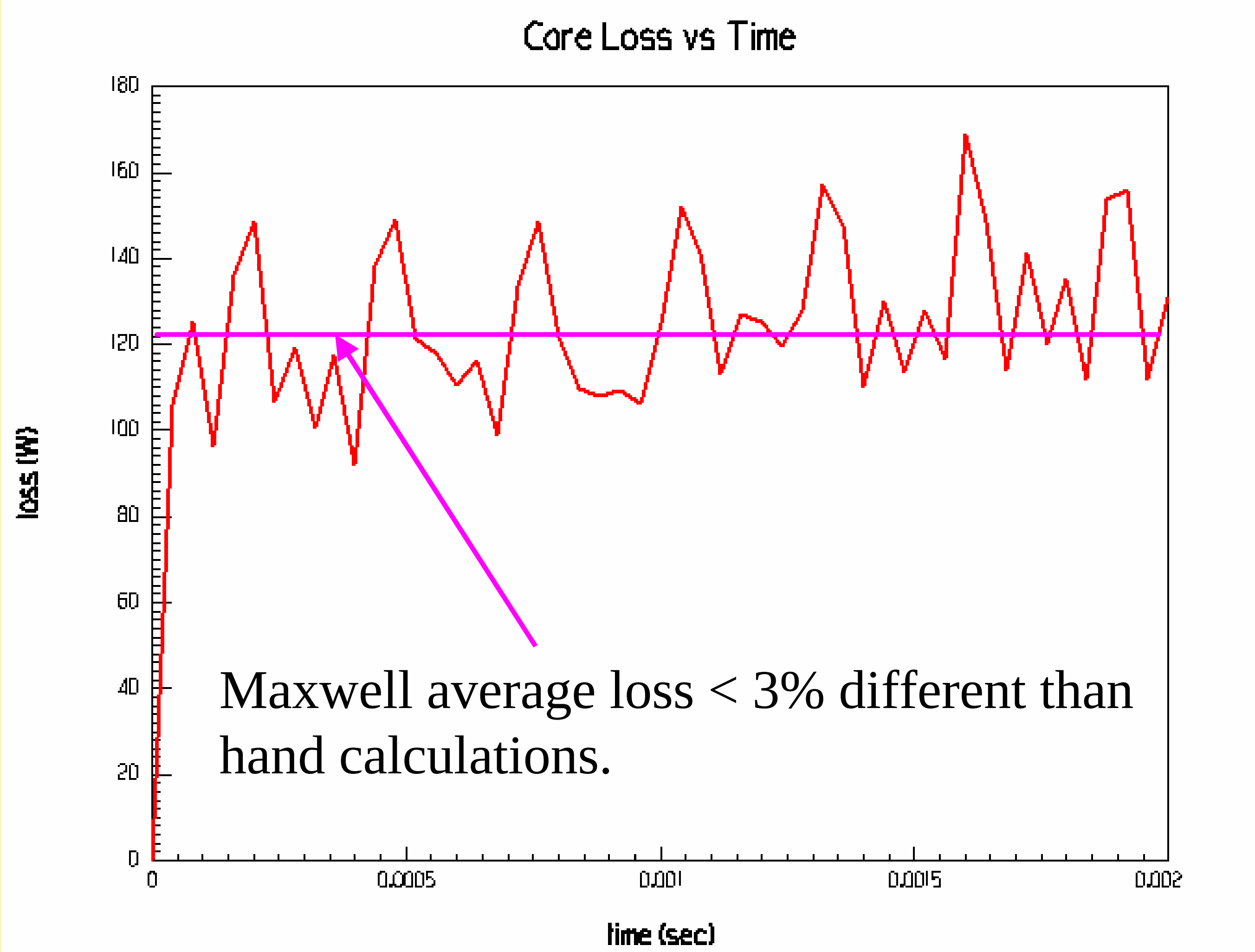
Induced Voltage vs Time
aaa
bbb
ccc
induced voltage (V)
300
200
100
0
-100
-200
-300
-400
0
0.0005
0.001
0.0015
0.002
time (sec)

Cogging

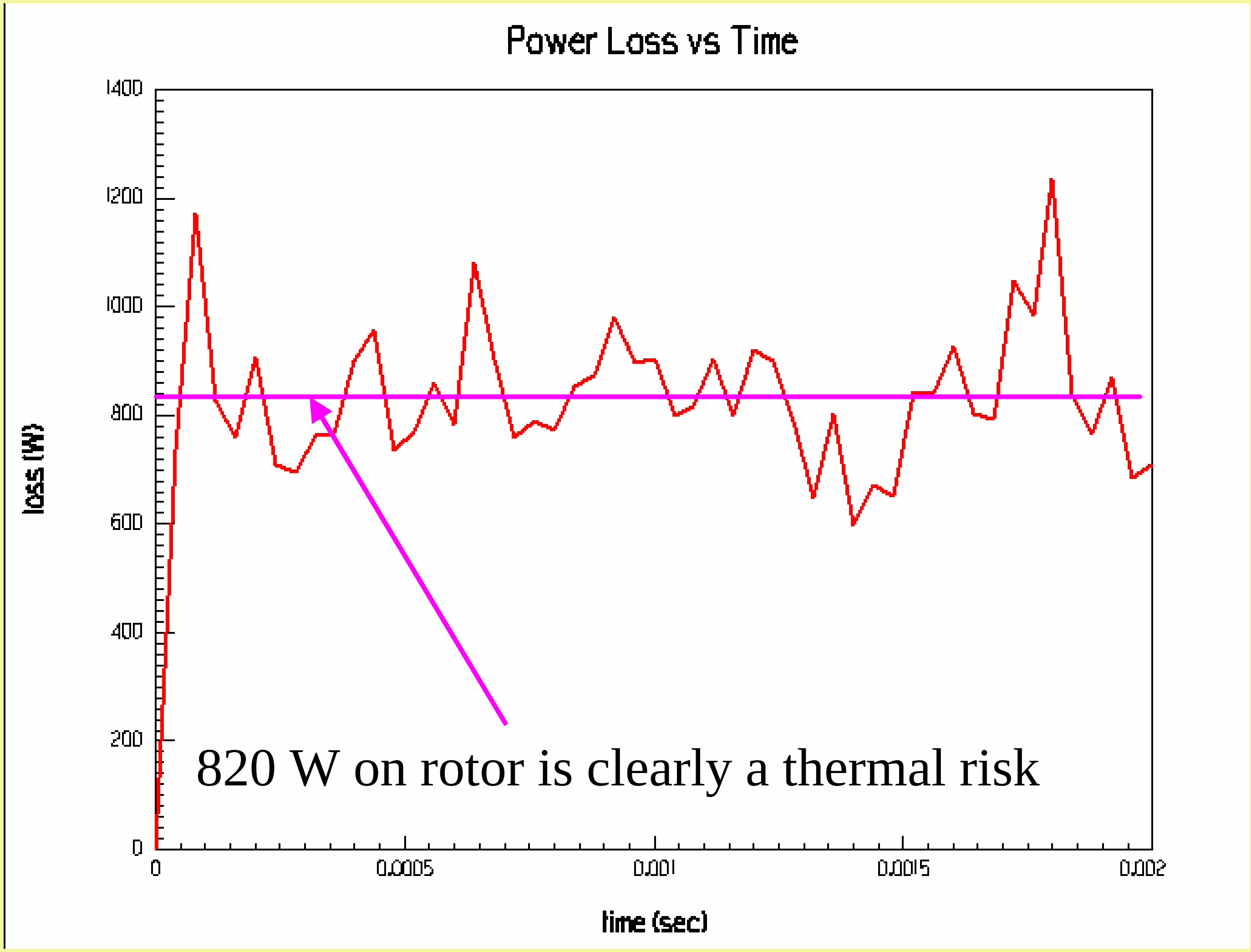


Torque vs Time
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
torque (N-m)
0
0.0002
0.0004
0.0006
0.0008
0.001
0.0012
0.0014
0.0016
time (sec)

Core Loss


Core Loss vs Time
loss (W)
180
160
140
120
100
80
60
40
20
0
0
0.0005
0.001
0.0015
0.002
time (sec)
Maxwell average loss < 3% different than hand calculations.

Magnet Eddy Current Loss - Ouch!

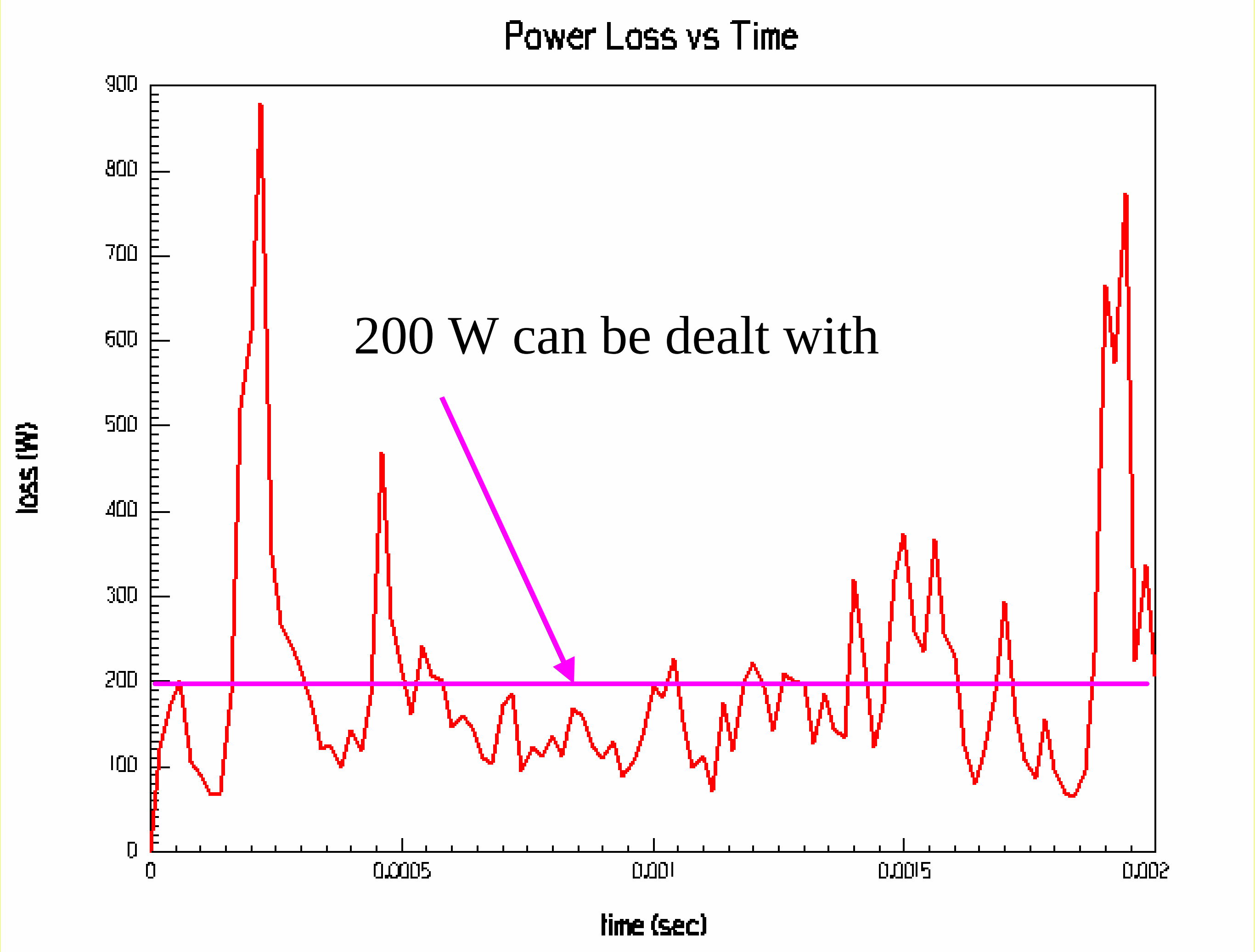


Iterations to Success:
Do you really want to see them all?

version	Lm	Lg
v3	10	1.5
v4	13	2
v5	16	2.5
v6	13	2.5
v7	...	...

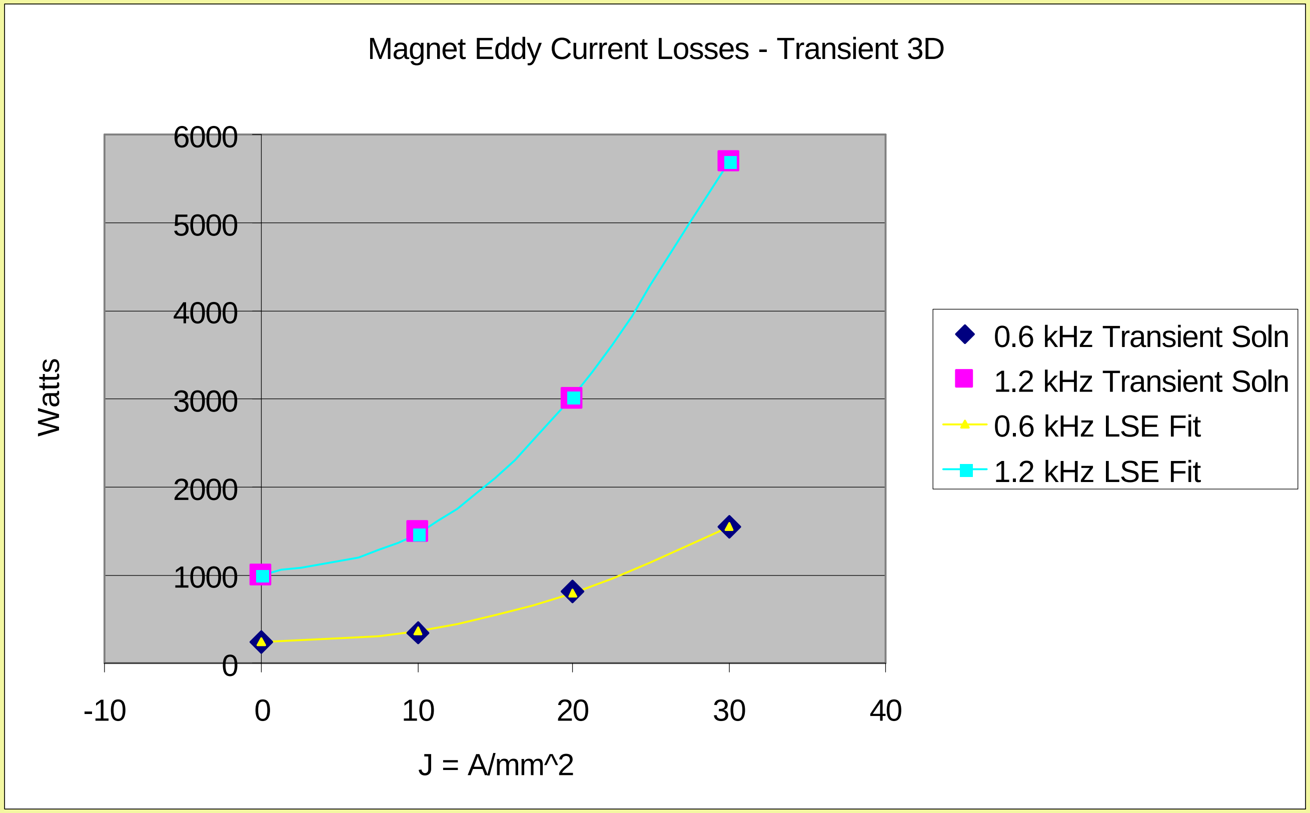
With Optimetrics tool it’s easy to study potential for demagnetization, magnet eddy current loss and output torque to reach a balanced decision.

Magnet rotor Losses After Improvement

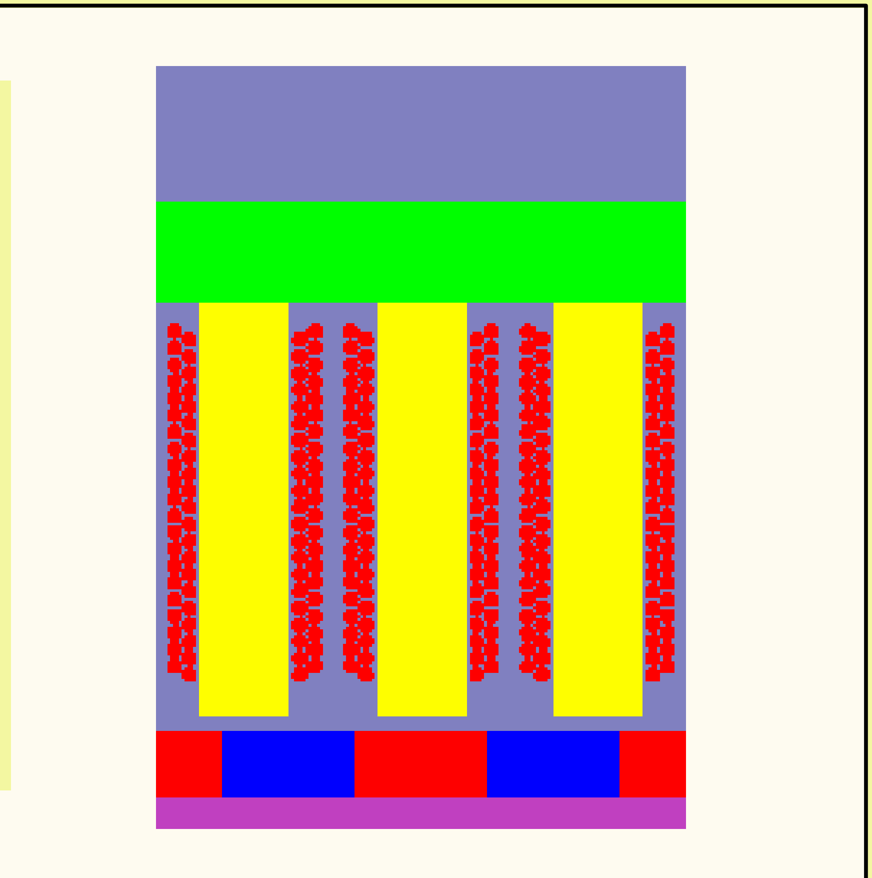


Perform LSE on a few virtual data points to find modified[2] Steinmetz equation

$$L = a \cdot Speed^{b} + c \cdot Speed^{d} \cdot CurrentDensity^{e}$$

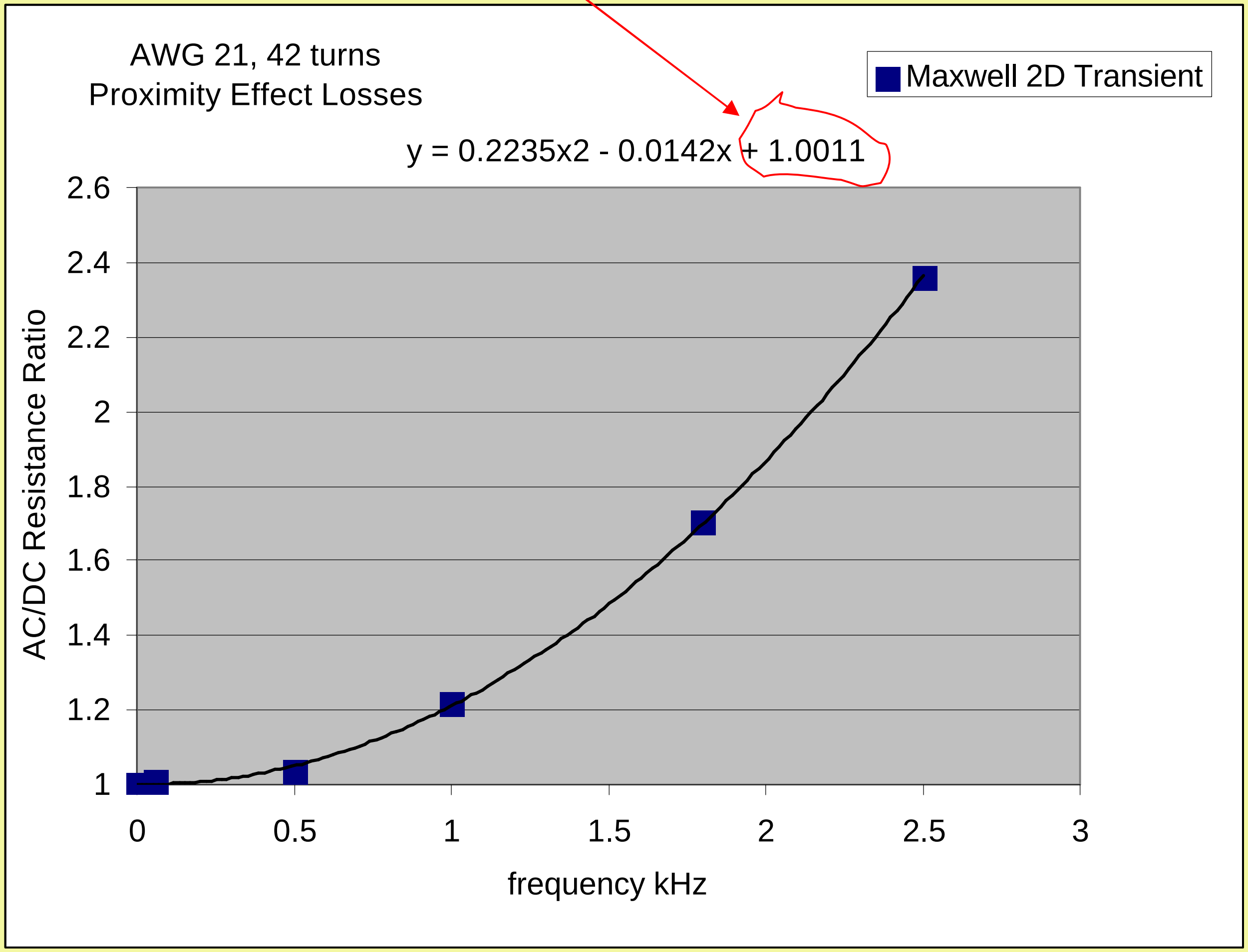


- 2D transient analysis
- Determines AC losses
- Due to proximity effects on adjacent phases, and within phases



Maxwell 2D Transient Relationship curve

Should be 1.0, but close enough for engineering!



Presentation Outline

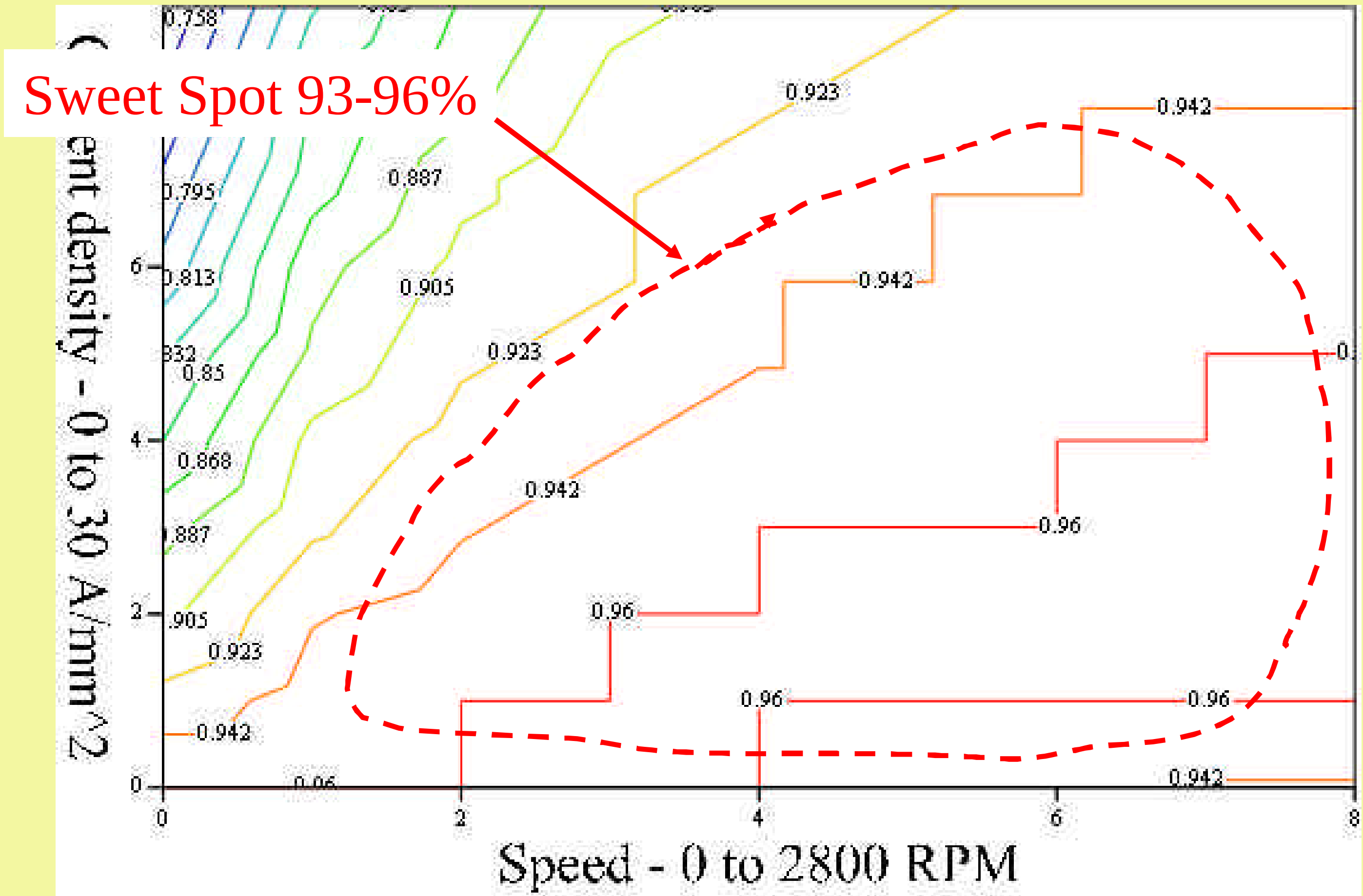
- Background
- Maxwell 3D Quasi-Dynamic
- Maxwell 3D Transient
- Results

60 kW ISA Performance

At 2500 RPM	Rated	Peak (at .70 P.F.)	
Shaft torque	239	638	N-m
KVA	70	255	kW
Power	63	167	kW
Efficiency	96%	91%	
active mass	23.9		kg
Outside Diamter	34.8		cm
Axial Length	9.1		cm
N-m/kg active matl	10.0	26.7	
N-m/liter total	27.6	73.6	

Would not have reached such high efficiency without the transient simulations

60 kW ISA Efficiency Plot



Eff

Conclusion

- Early LE designs had:
  - severe torque cogging – Maxwell 3D resolved this issue in numerous ways
  - no method to predict proximity effect losses – Maxwell 2D solved this
  - rotor-related heating failures – these were cured with Maxwell 3D Transient