Experimental evaluation of a high-speed multi-megawatt SMPM machine

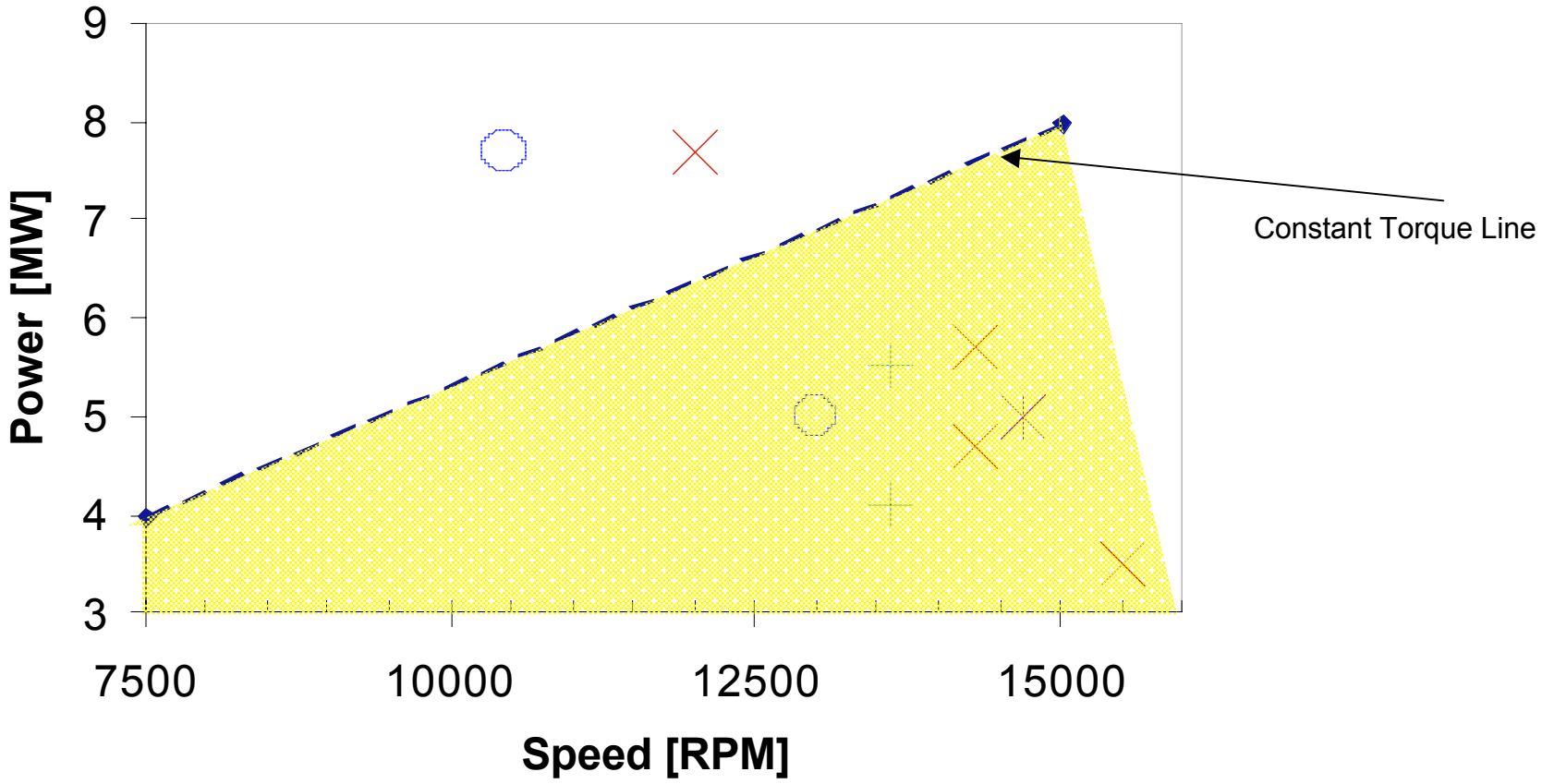
Daniel M. Saban, PE PhD
saban@ieee.org

Agenda

- Machine Description
- Testing
  - Stator-only
  - Open circuit
  - No-load
  - Short circuit
  - Partial load, full speed generating
- Analysis
- Conclusion

Frame 8 Product Family

- Highlighted area is capability envelope of product family
- Maximum electrical loading along constant torque line



DIRECTDRIVE SYSTEMS

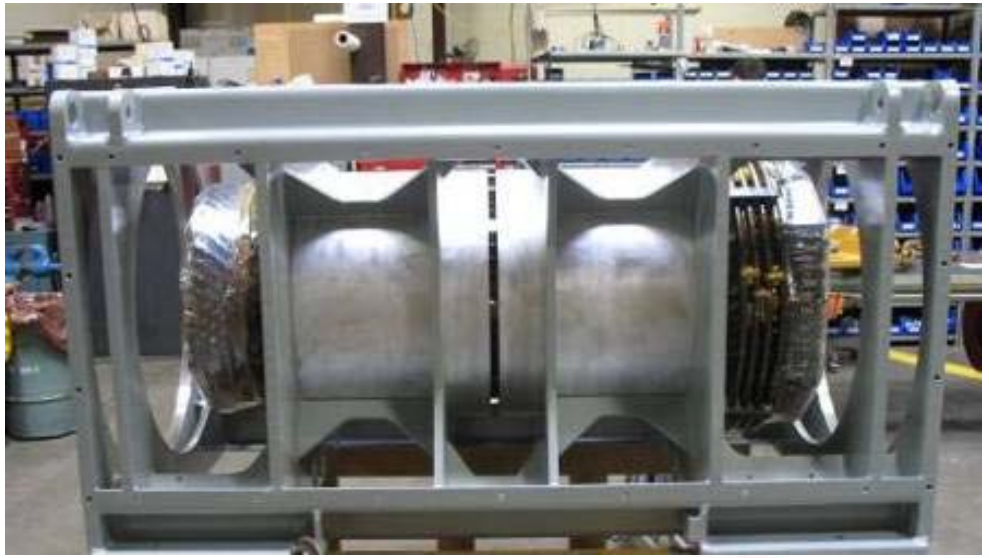
Frame 8 Machine

- Envelope
  - 43.8 in (13350mm) tall
  - 41.5 in (12469mm) wide
  - 85.4 in (25969mm) long
- Weight 8,975 lbs (4,071kg)

DIRECTDRIVE SYSTEMS

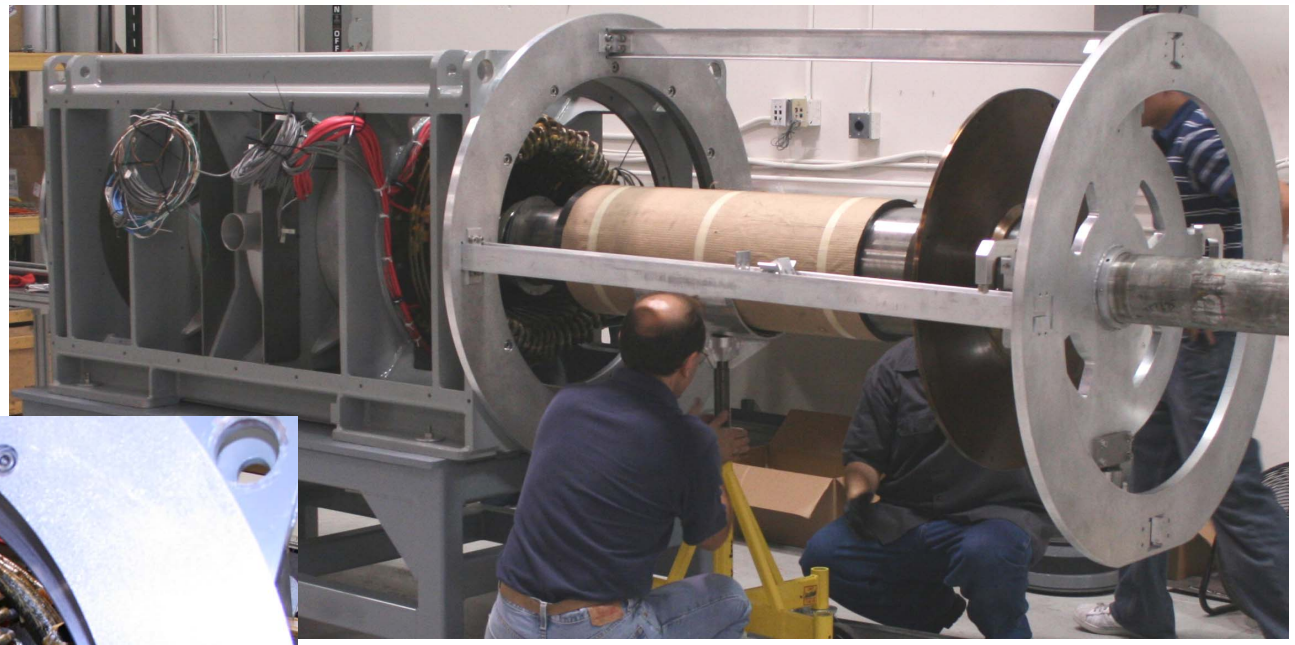
Frame 8 Stator and Housing

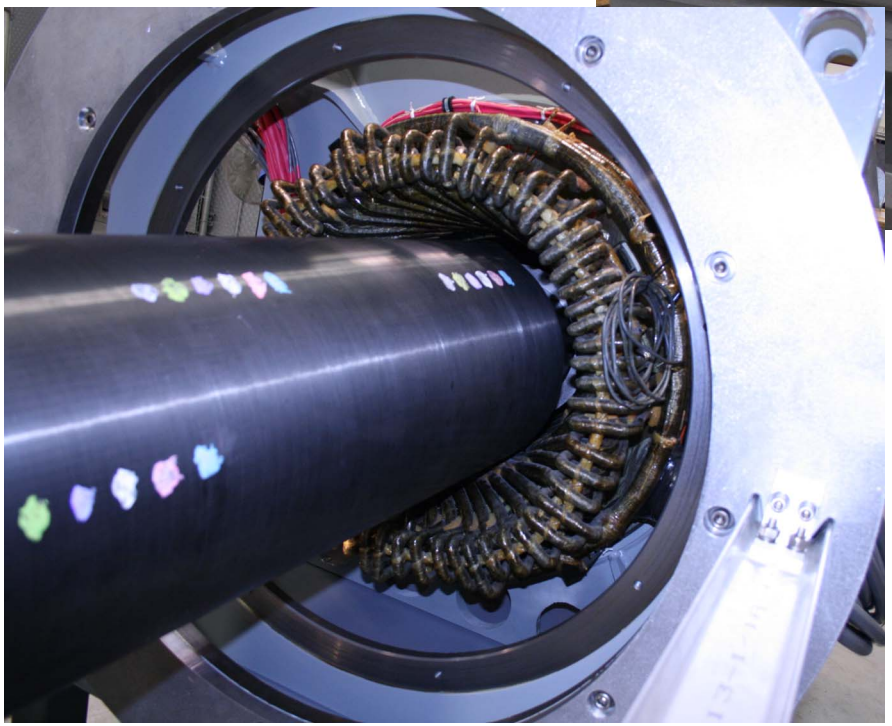
- Built by Kato Engineering
  - Collaborative design
  - Robust stator design and manufacture
  - Proven insulation system



DIRECTDRIVE SYSTEMS

Frame 8 Final Assembly





- Rotor insertion at DDS facility
- Special insertion tooling developed by DDS

DIRECTDRIVE SYSTEMS

Frame 8 Demonstration Unit

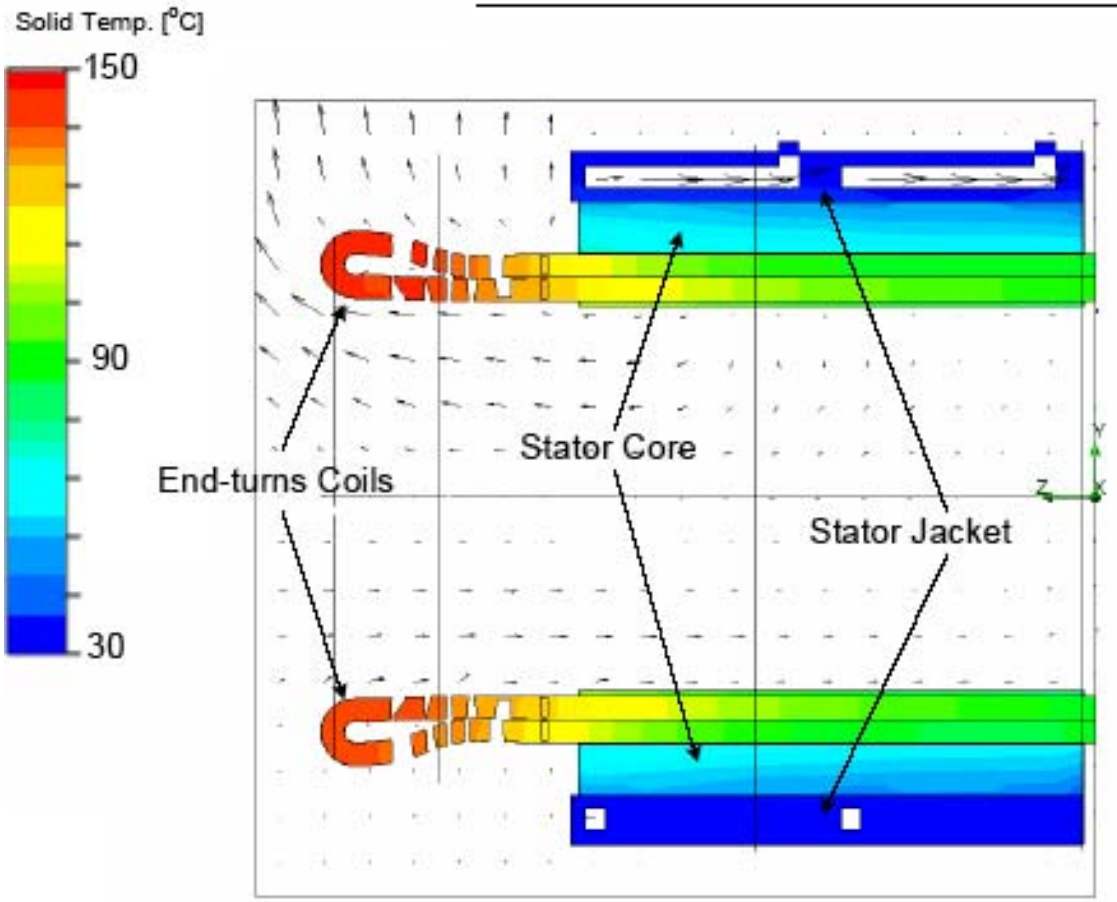
- Insulation system
  - Class H designed for class F temperature rise
  - Tested up to 10kV and 800Hz
- Oil lubricated ceramic ball bearings in squeeze film damper resilient mounts
- Machine Rating
  - Generator (demo): 4.2kV, 2.8MW, unity PF, 97.5% eff, 15kRPM
  - Generator (expected): 3.6kV, 6.1MW, 0.98 PF, 98.2% eff, 15kRPM
  - Motoring (expected): 5.5kV, 7.5MW, 0.80 PF, 98.1% eff, 15kRPM
- Cooling System
  - Forced air cooling over each end turn and through mid-stack vent
  - Closed circuit water/glycol cooling through pressed-on aluminum cooling jackets over stator back iron
  - Individual valves per each cooling jacket
  - Separate fans for mid-stack and end-turn air

Electromagnetic Design

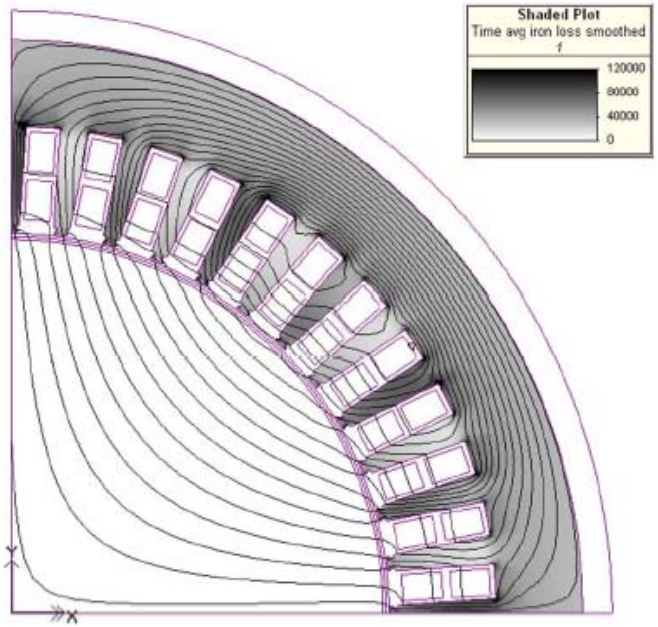
- High-frequency considerations
  - Iron core loss (eddy and hysteresis)
  - Copper eddy loss
  - Rotor eddy loss (magnets and hub/shaft)
- Stator configuration
  - Thinly laminated, low-loss silicon steel
  - Multi-stranded, form-wound coils
- Rotor configuration
  - Pre-magnetized, segmented magnets
  - Large magnetic gap
- Need to balance manufacturing costs and complexity with loss reduction
  - Wroebel conductors or Litz wire
  - Magnetic slot wedges
  - Size of rotor segments

Stator Only Thermal Model

	Iron Loss [kW]	Slot Cu Loss [kW]	End-turn Cu Loss [kW]	Total losses [kW]
CFD Model	10.52	8.28	3.72	22.52

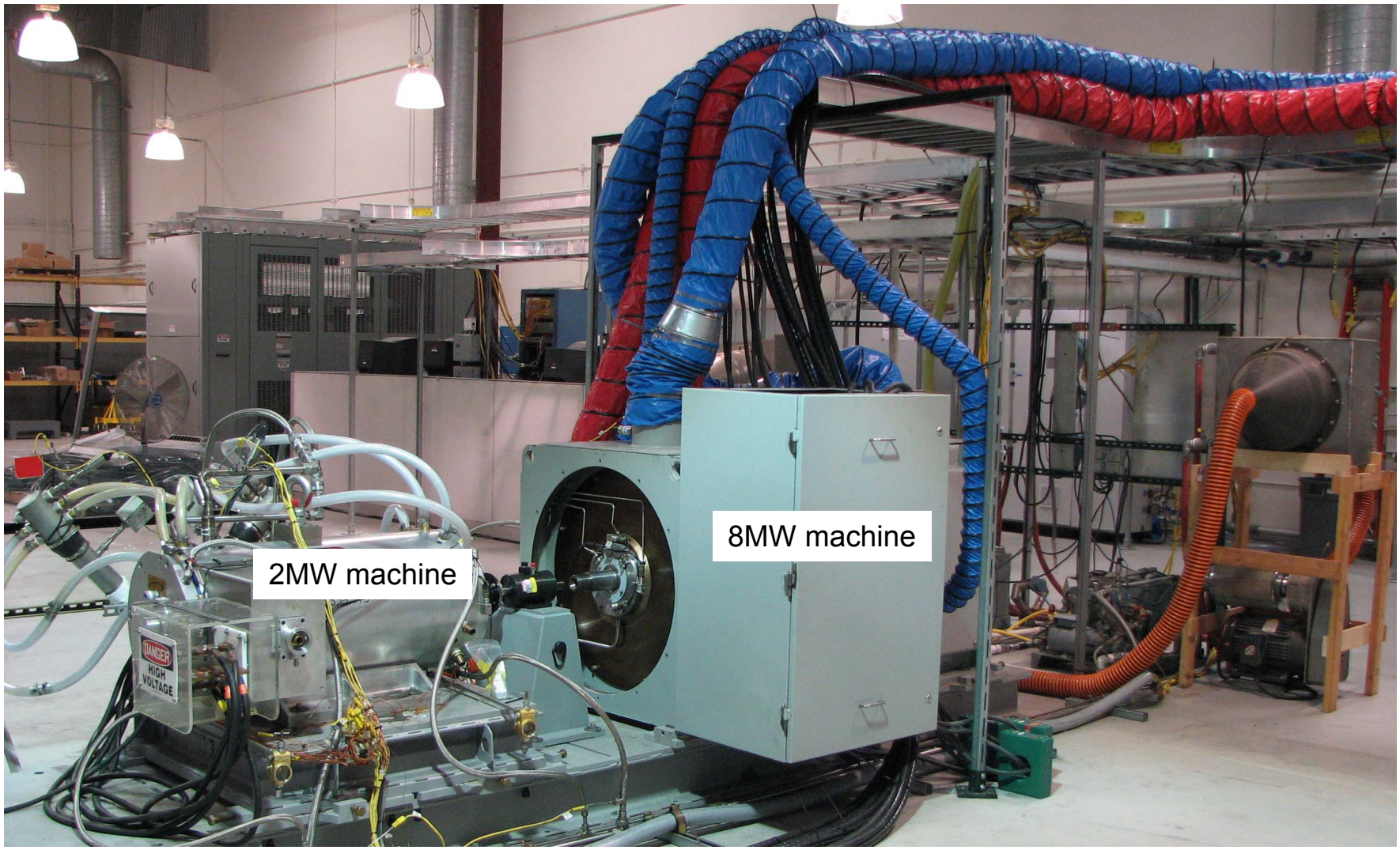


- 60Hz, 1000A
- FE model predicts <10kW of total loss



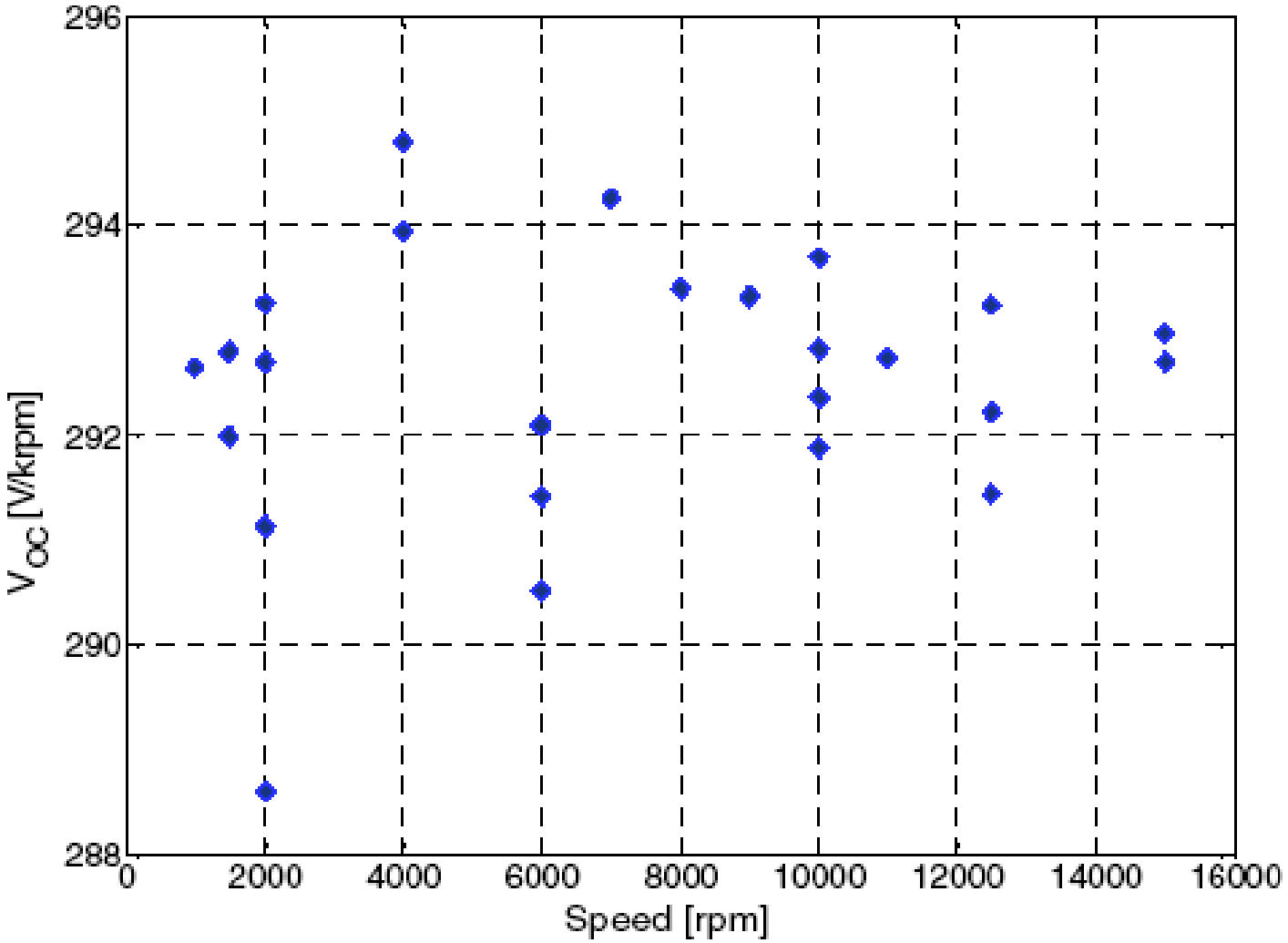
DIRECTDRIVE SYSTEMS

Back-to-back tests



DIRECTDRIVE SYSTEMS

Open Circuit Voltage

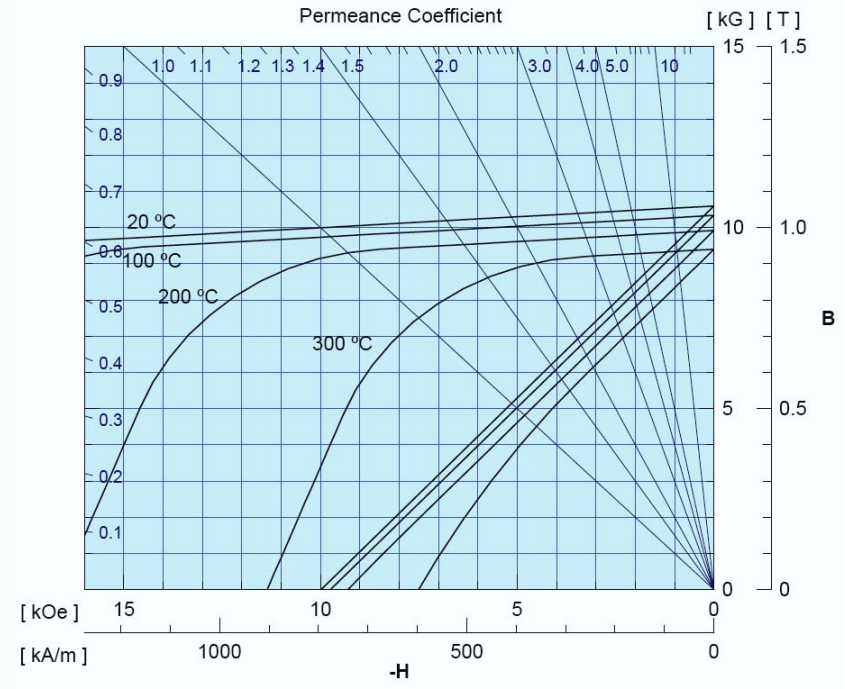


DIRECTDRIVE SYSTEMS

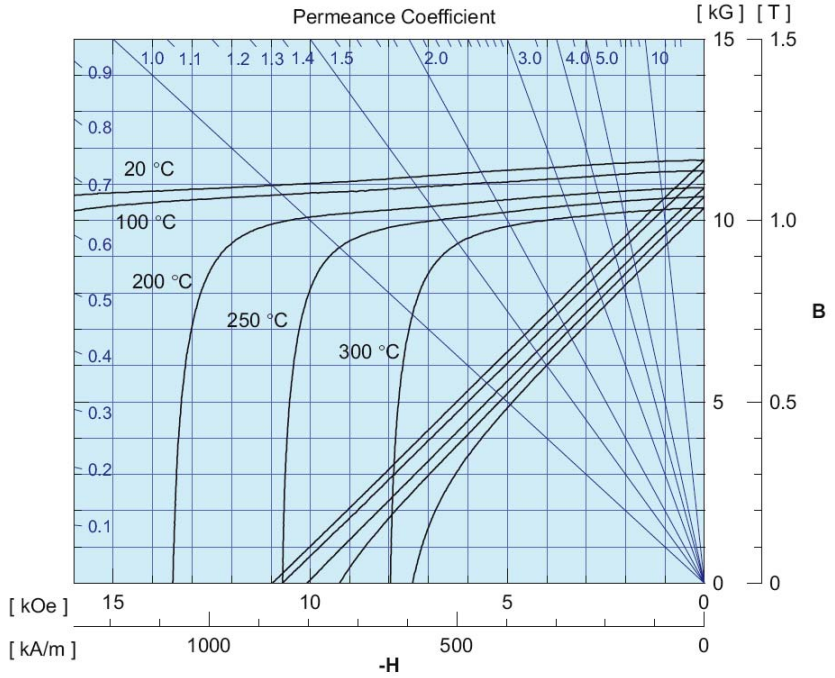
Magnet Material Data

- Demagnetization curves at elevated temperature
- Modern hard magnetic materials resistant to demagnetization within normal operating temperatures

26 MGOe nominal



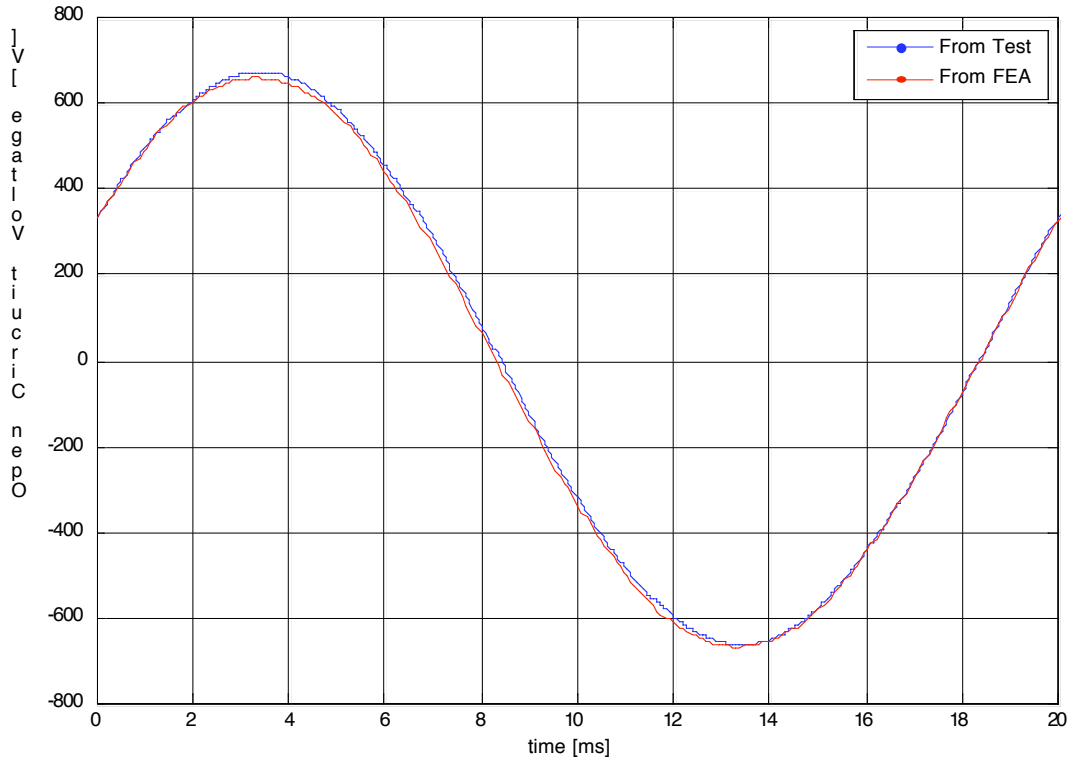
32 MGOe nominal



DIRECTDRIVE SYSTEMS

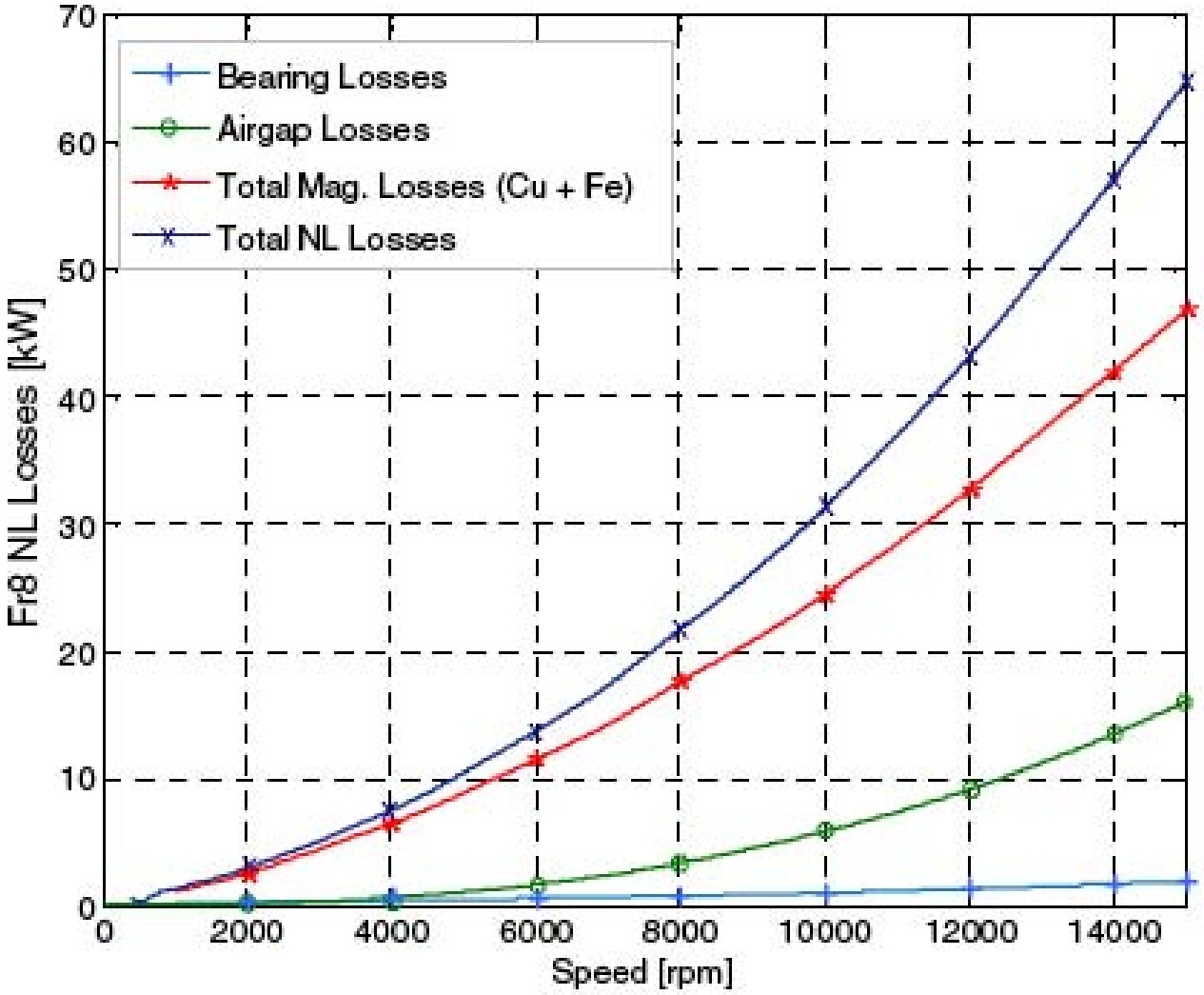
Open Circuit Voltage

- FEA pre-build, 20 °C: 4685 V_{rms} line-to-line
- FEA post-build, 20 °C: 4392 V_{rms} line-to-line
- Measured, average: 4378 V_{rms} line-to-line



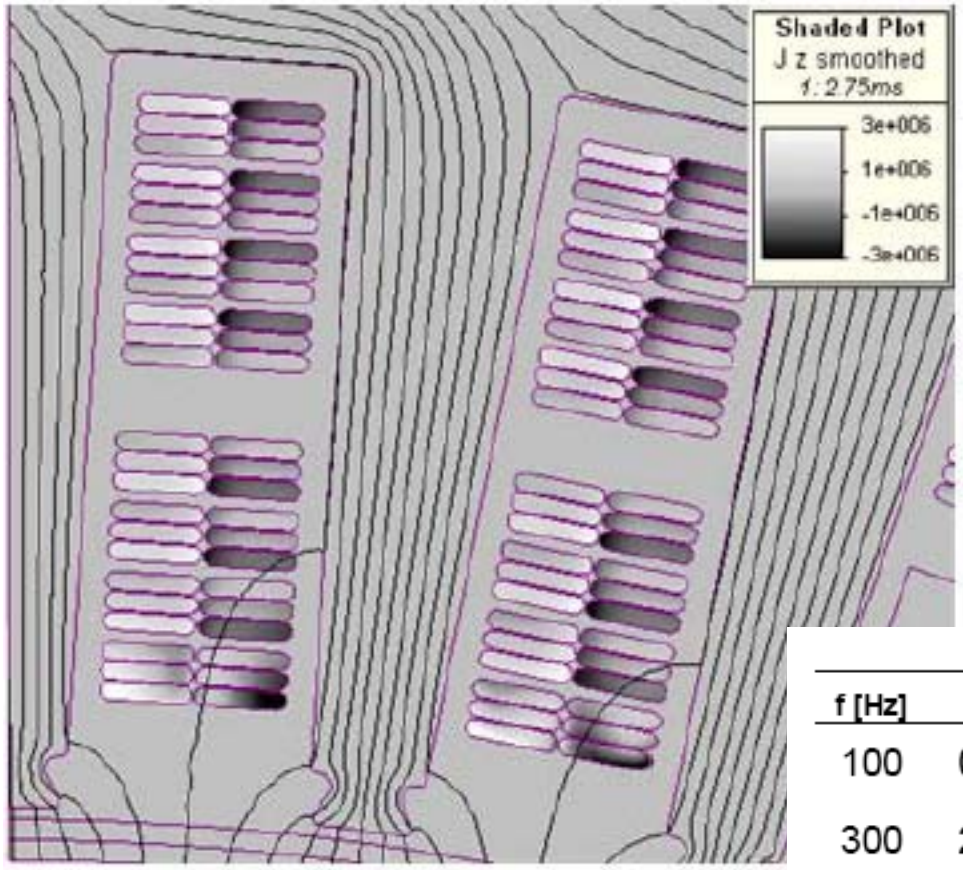
DIRECTDRIVE SYSTEMS

No-load loss curves



DIRECTDRIVE SYSTEMS

No-load stator eddy currents



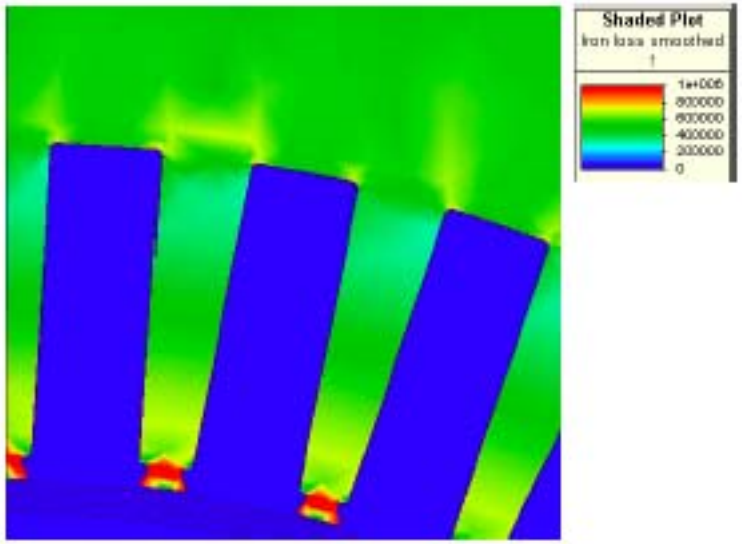
- Analytical methods widely varied
- FE ~10kW lower prediction than experimental (correlated w/ CFD)

EDDY CURRENT LOSS IN STATOR COILS

f [Hz]	FE	CFD	Say [14]	Walker [15]	Shanks [16]	Fink [17]
100	0.32	1.58	18.13	0.08	0.22	4.08
300	2.39	7.47	23.96	0.72	1.99	36.74
400	3.99	11.71	29.07	1.23	3.53	65.34
500	5.91	16.80	35.63	1.98	5.52	102.05

Iron loss discrepancies

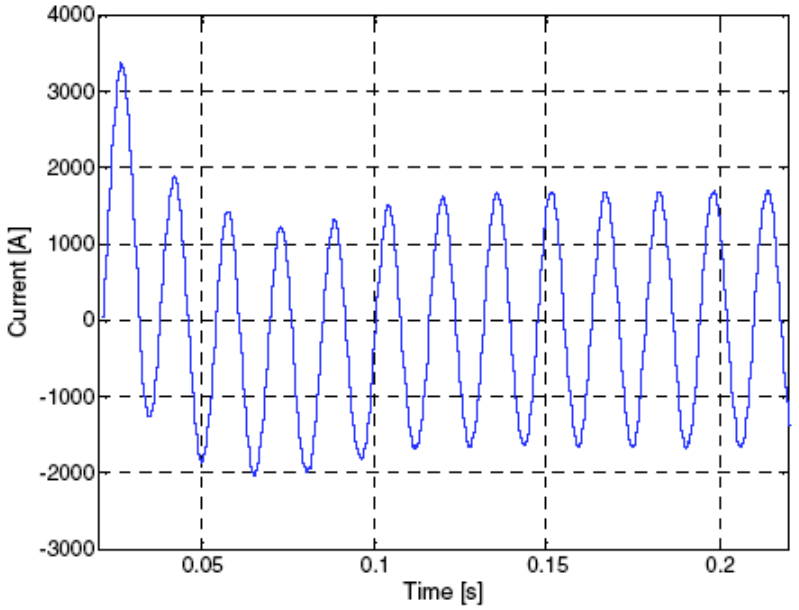
- University Epstein tests 26% above manufacturer data
- Independent material testing lab, higher still
- Independent material lab data used in FE model predicts ~ 9kW lower loss than justified with CFD



DIRECTDRIVE SYSTEMS

End-reactance & Short Circuit

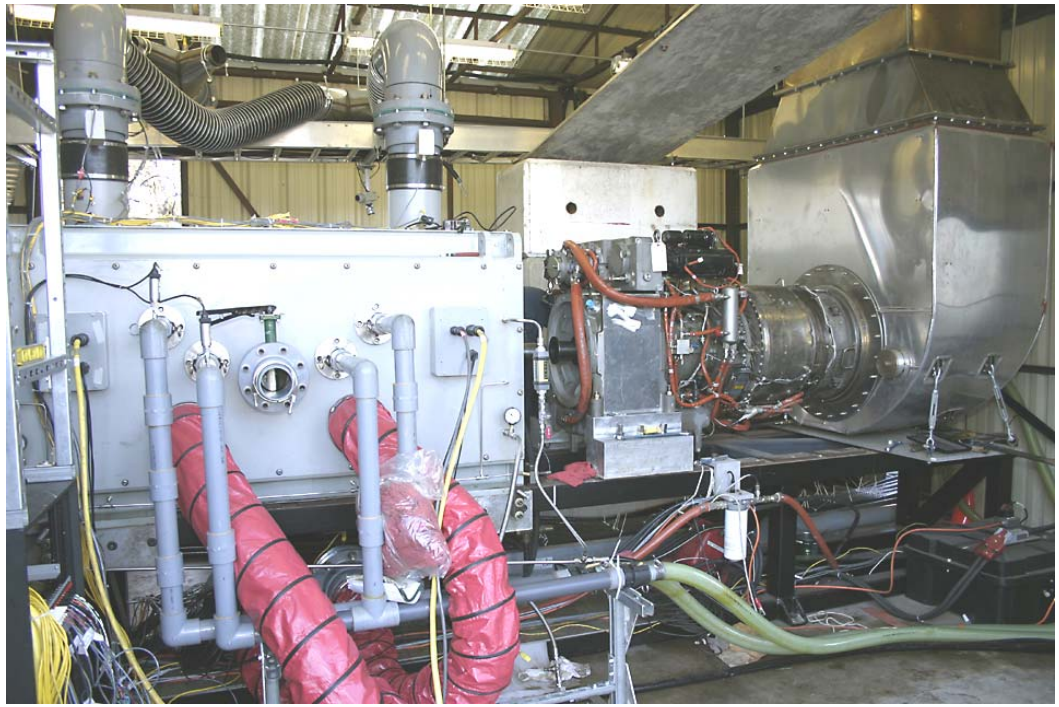
- Analytical methods
  - Liwschitz-Garik & Whipple (41.95 μH)
  - Puchstein (38.31 μH)
  - Fowler (41.84 μH)
  - Langsdorf (46.28 μH)
  - Still (125.83 μH)
  - Lipo (84.0 μH)
- PC-BDC: 8 μH
- SC test - 2D FE: 150 μH



DIRECTDRIVE SYSTEMS

UT Test Configuration

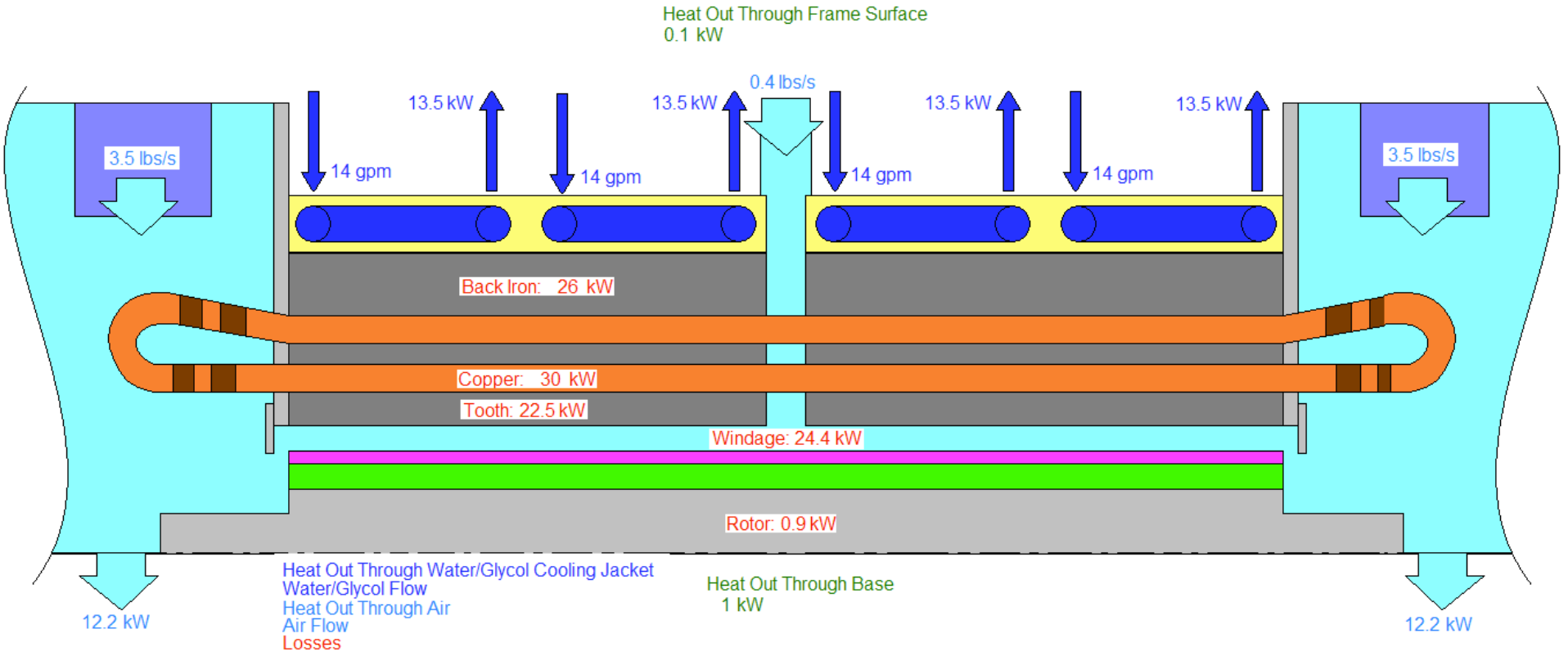
- Frame 8 demonstration unit tested as a generator
  - TF-40 turbine as prime mover
    - ISO rating 3MW at 15kRPM
  - 3 MW resistive load bank
  - Disc pack flexible coupling



DIRECTDRIVE SYSTEMS

Machine Cooling

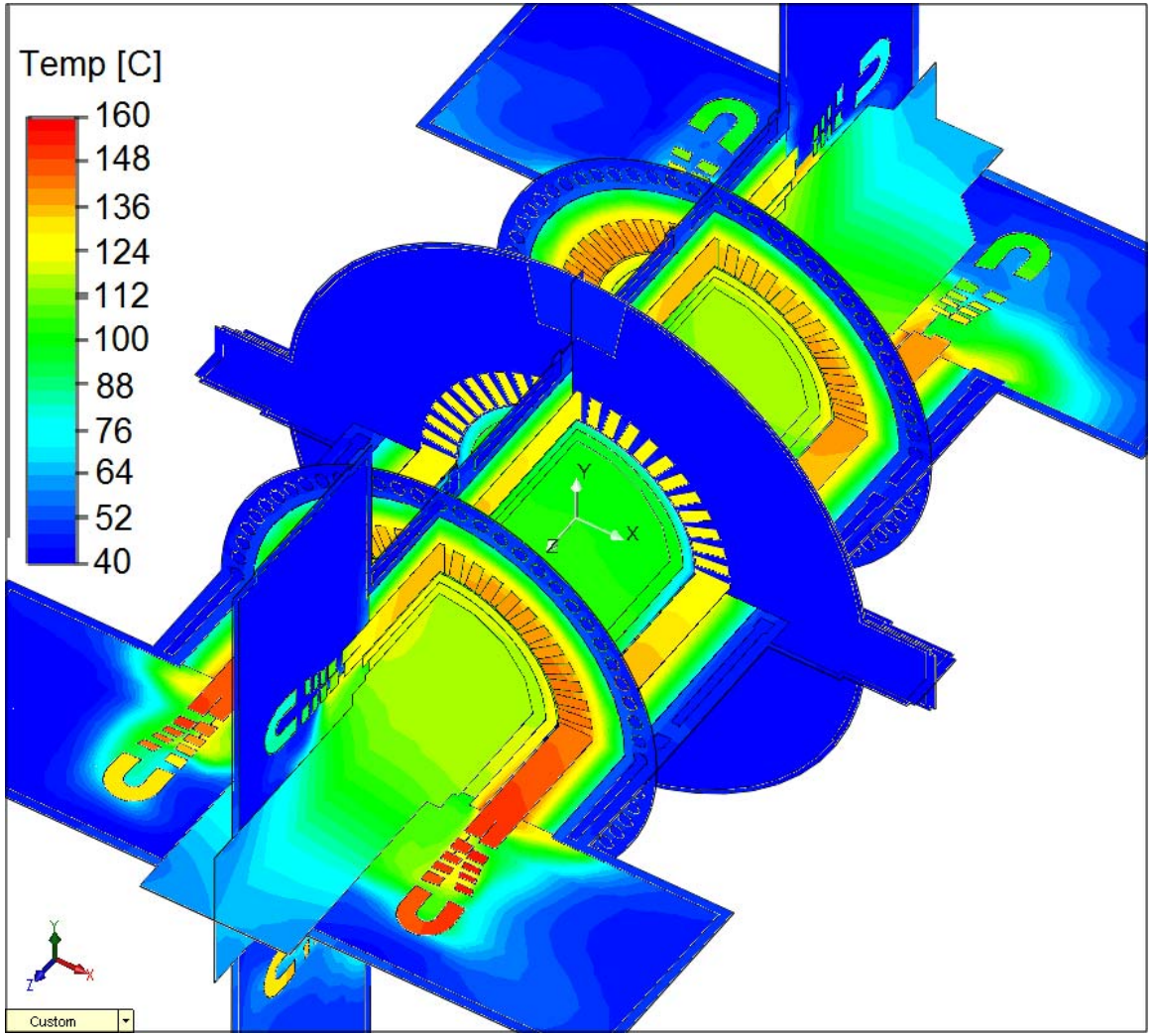
- Heat Balance Figure



DIRECTDRIVE SYSTEMS

Machine Cooling

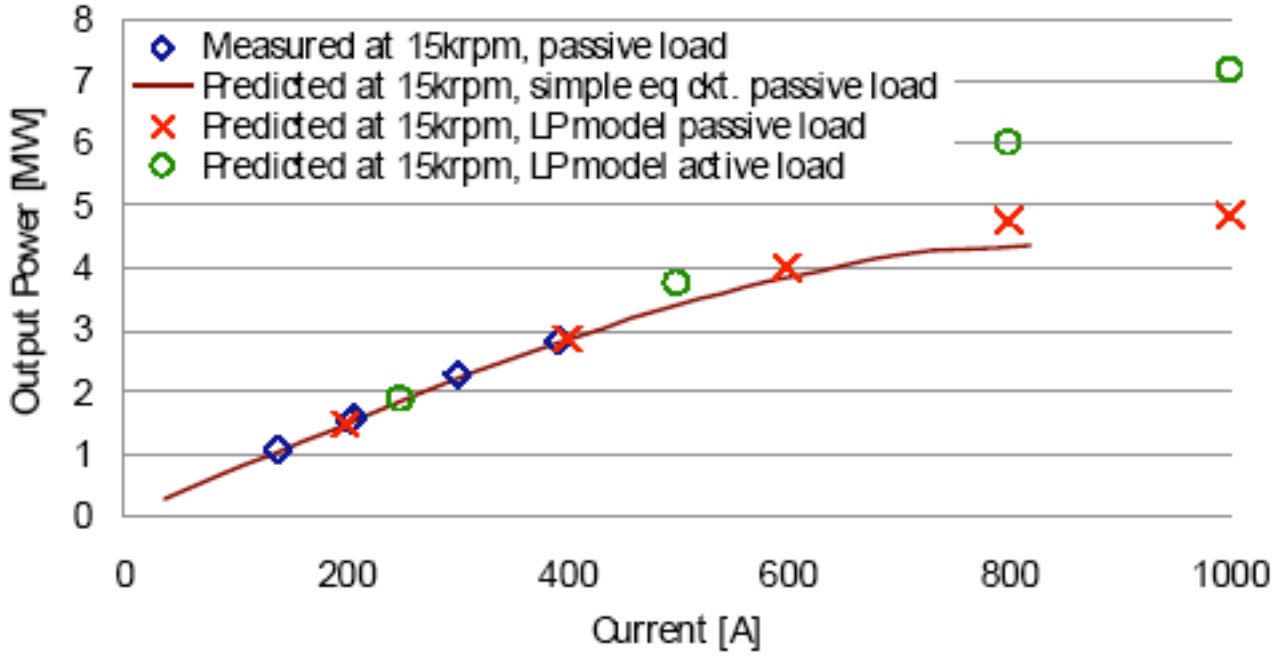
- Computational fluid dynamics model results



DIRECTDRIVE SYSTEMS

Generating performance

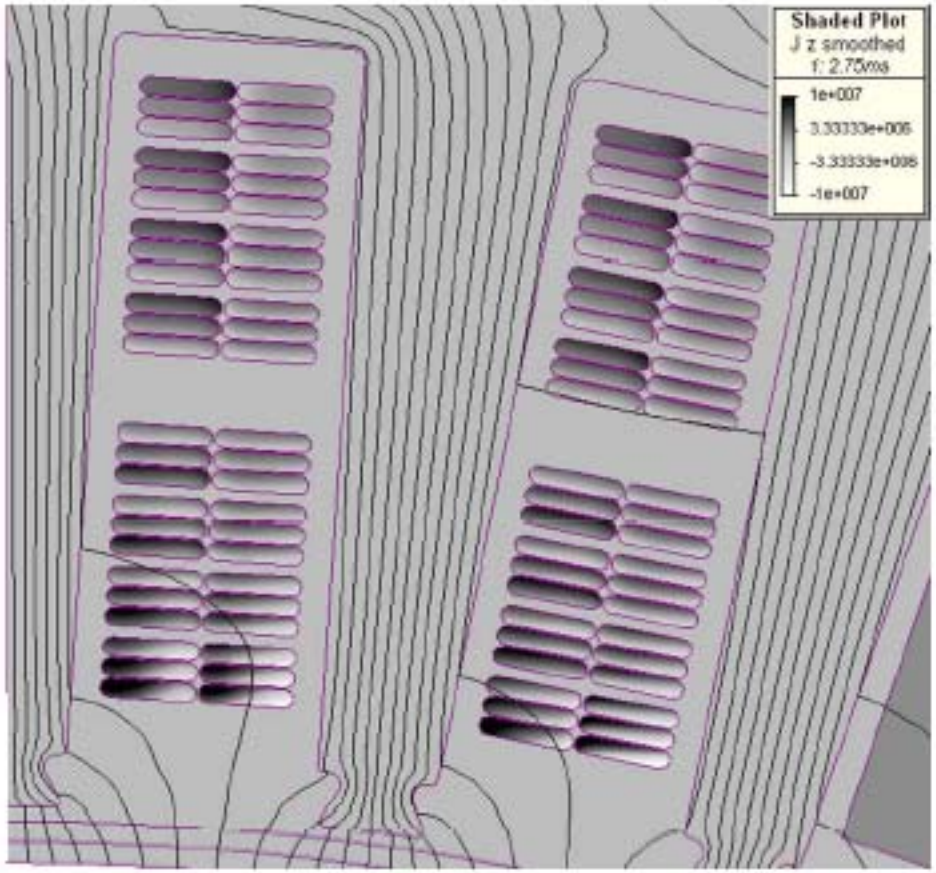
- Active load significantly improves output power
- Simple circuit model diverges from LP model
- Both models track well for low currents



DIRECTDRIVE SYSTEMS

Stator eddy currents

- Includes tooth ripple, skin and proximity effects
- Dwarfs losses due to fundamental, net current



DIRECTDRIVE SYSTEMS

Loss Segregation

- Thermal model (CFD) identifies significantly more loss than other tools (FE, LP) predict
- Both Iron and copper loss miss by ~10kW
- Discrepancy not principally changed from no-load

LOSS SEGREGATION FOR 3 MW, 15 krpm OPERATION

	Iron Loss [kW]	Slot Cu Loss [kW]	End-turn Cu Loss [kW]	Windage [kW]	Total loss [kW]
CFD Model	33.60	21.2	1.77	17.80	74.37
FE Model	23.77	9.95	1.72	n/a	n/a
LP Model	24.46	1.91	1.71	20.0	48.08

Conclusions

- Thermal models can be used for effective allocation of machine losses
- Commercially available tools are not successful in predicting machine losses *a priori*
- Both parameter and physics based models can be modified after prototype testing to predict losses
- Calibrated models can be used to design similar machines