Evaluation and Mitigation of AC Losses in a Fully Superconducting Machine for Offshore Wind Turbines

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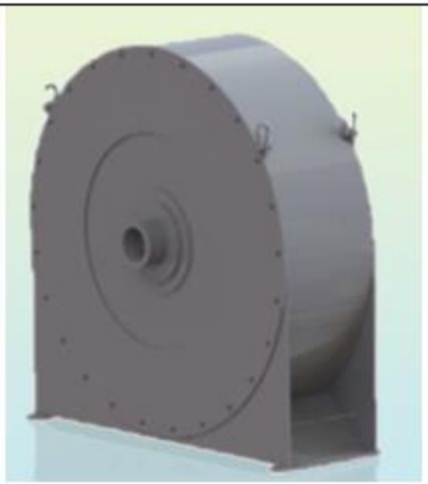
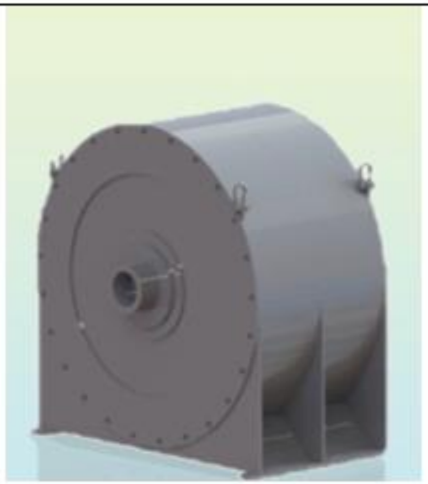
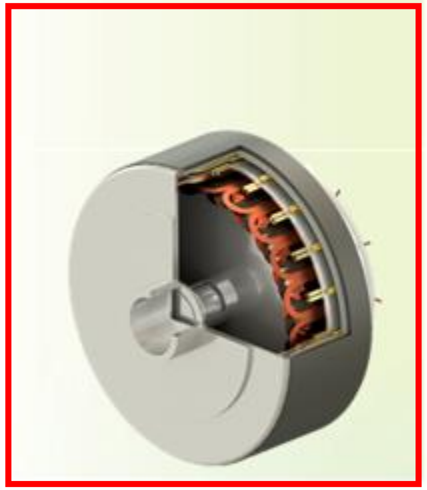
Advantage of Fully Superconducting Turbines

	Coper wound with gear box	Permanent Magnet	Partially superconducting	Fully superconducting with iron yoke/shield	Actively Shield Design (Preliminary design)
size					
Weight	500 Tons	320 Tons	>150 tons	<150 tons	<50 Tons

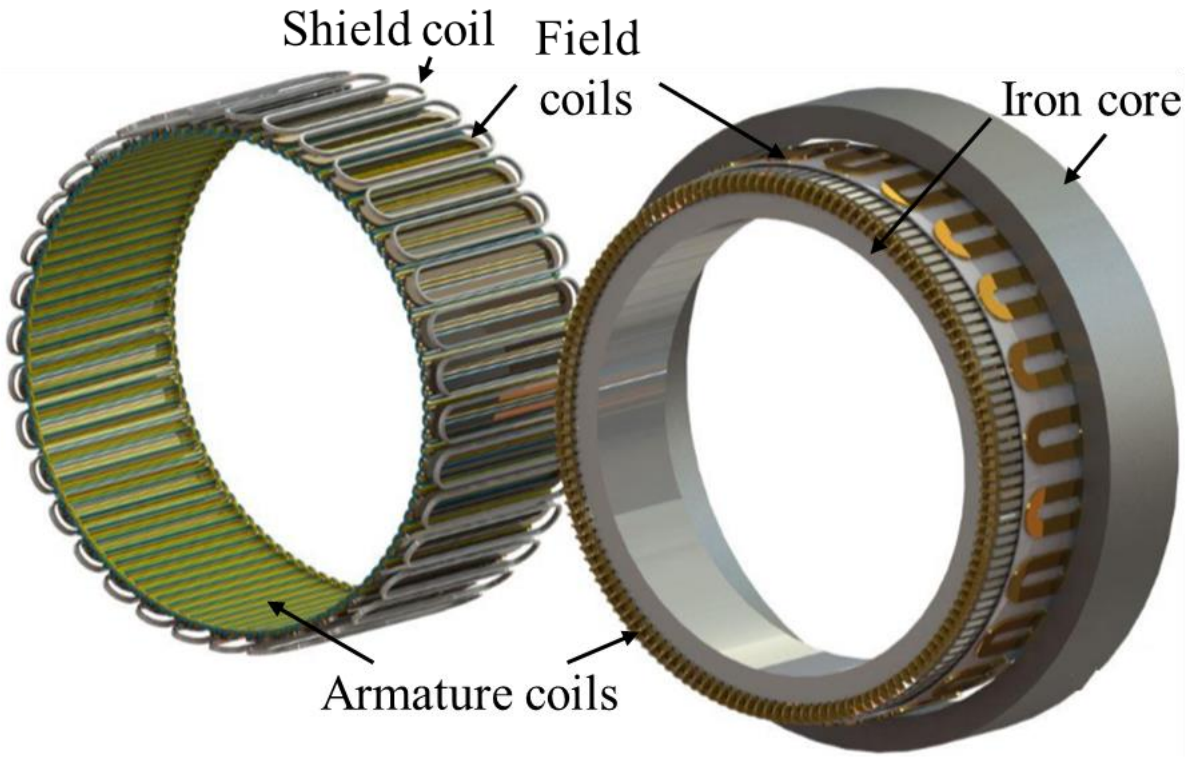
- Direct drive and larger capacity 10MW to 20MW
- Increased efficiency up to 99%.
- Weight 30 -50% less than a permanent magnet machine.
- 10-20 % reduction in capital cost.
- Reduction in maintenance cost
- Efficient energy capturing capability at partial loads.

} Reduced levelized cost of energy (LCOE)

[1] http://amlsuperconductivity.com/wordpress/wp-content/uploads/2015/07/Next-Generation-of-Wind-Turbine-Generators-U.S.-Department-of-Energy.pdf

[2] B. Maples, M. Hand, and W. Musial "Comparative Assessment of Direct Drive High Temperature Superconducting Generators in Multi-Megawatt Class Wind Turbines," NREL 2010

Proposed Machine Specification – Active Shield



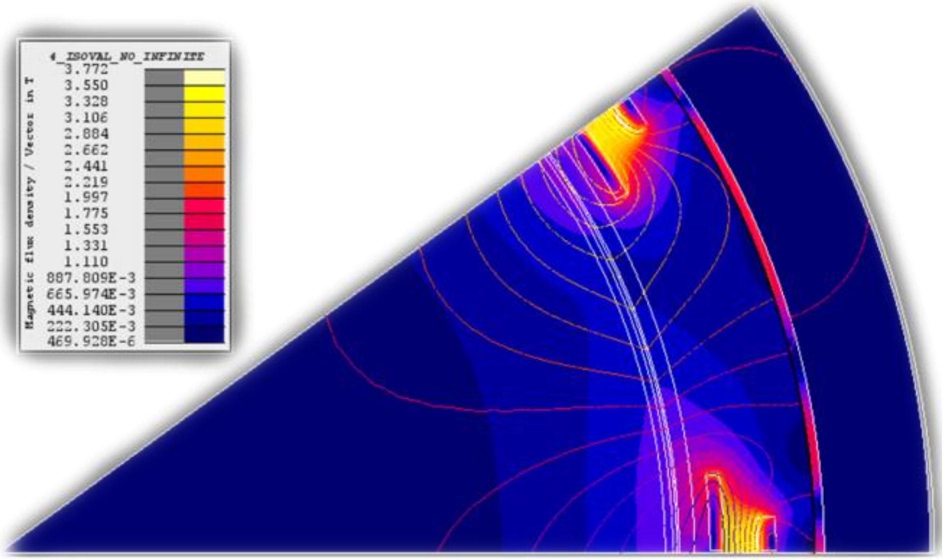
Specification	Value
Power	10MW
Speed	10 rpm
Weight	Less than 50 Ton
Ac loss	Less than 1 kW
Pole number	10 / 20 /30 / 40/50/60
Superconductor	MgB_2
Operating temperature	20 K
Armature Current density	Max 200 A_{rms}/mm^2
Field current density	200 A/mm^2
Shield current density	200 A/mm^2

- Active magnetic shield to contain the flux within the machine
- No core loss or core saturation - explore peak fields up to 10T ??
- Further weight reduction – explore low pole count designs
    - Estimated low ac loss ??

Fully Superconducting Machines

Actively-Shield Fully Superconducting Motor for Wind Turbine Conceptual Design

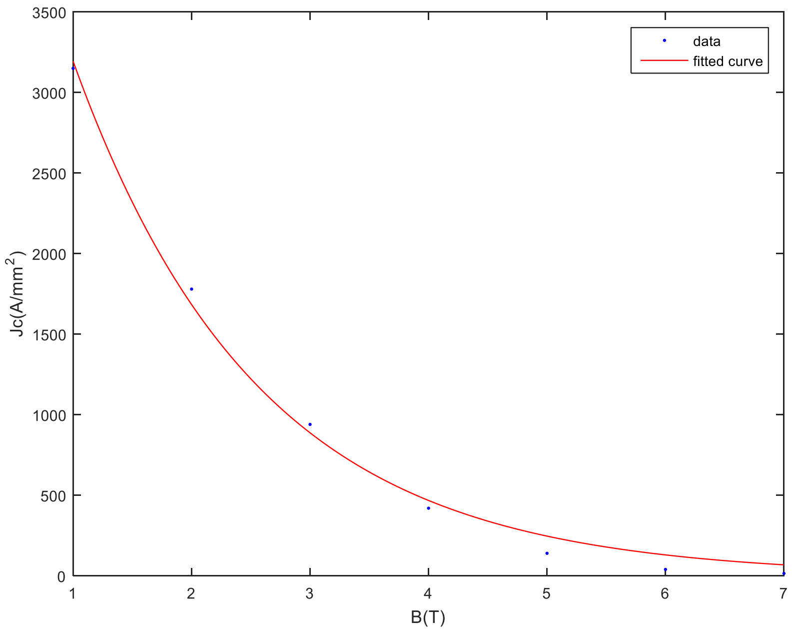
Low ac loss MgB_2 superconductors (HyperTech)

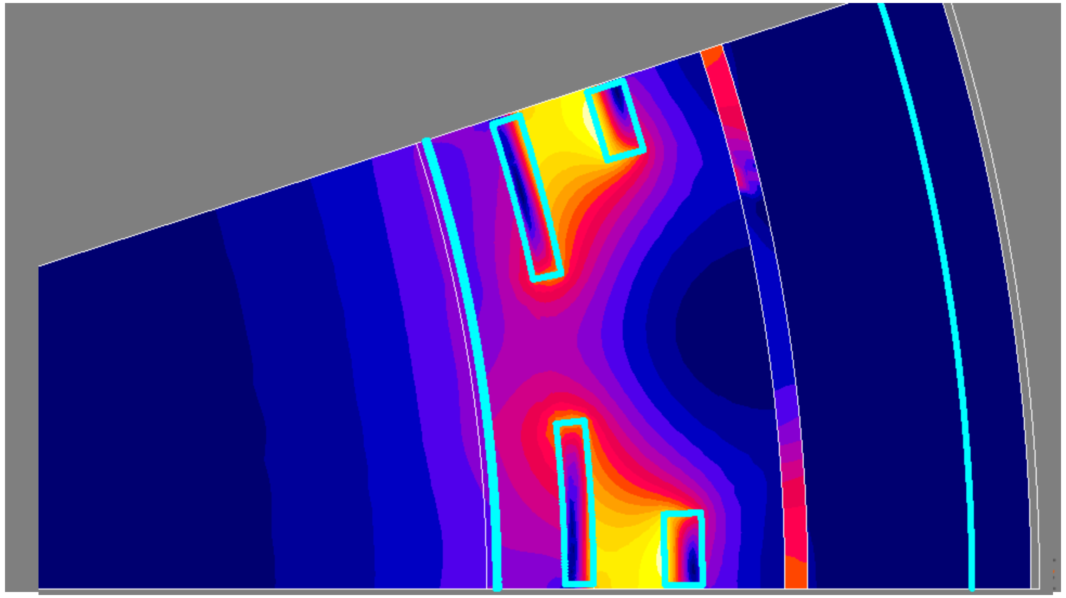


Symbol	Parameter	Conductor I 0.32/10/5
J_c	Critical current density at 0.4 self-field at 20K [A/m^2]	6.6e9
D_O	SC diameter [mm]	0.32
d_f	Filament diameter [μm]	10
n	Number of filaments	114
λ	The area fraction of the wire that is SC	0.15
λ_{eff}	Effective fill factor	0.49
ρ_{eff}	Effective transverse resistivity [Ω-m]	12.5e-8
L	The twist pitch (mm)	5

Flux density Vs Critical Current Density

Measured B Vs Jc for MgB2 conductors at 20 K





$$J_E = \lambda * \pi * \frac{D^2}{4} * J_C$$

At 20K and 2T field density $J_E = 200A/mm^2$ at 20K and 3T $J_E = 113A/mm^2$

Operating current – Safety margin $I_A = .50 * Ic$, $I_F = .70 * Ic$

AC Losses – Carr's Model

- Penetration field

$$B_p = 0.4 * \mu_0 * J_c * d_f$$

- Hysteresis loss

$$P_h = \left(\frac{4}{3}\right) * B_m * J_c * d_f * f$$

- Eddy current loss

$$Pe = \left(\frac{\pi^2}{k * \rho_{eff}}\right) * (B_m * D_o * f)^2$$

- Coupling loss

$$Pc = \left(\frac{1}{n * \rho_{eff}}\right) * \left(f * L_p * B_m\right)^2$$

- Transport current loss

$$PI = \left(\mu_0 * \frac{f}{\pi}\right) * (Ic^2) * \frac{\left(1 - \left(\frac{I_0}{I_c}\right)\right) * log\left(1 - \left(\frac{I_0}{I_c}\right)\right) + \left(\frac{I_0}{I_c}\right) - .5 * \left(\frac{I_0}{I_c}\right)^2}{\pi * \left(\frac{D_o}{2}\right)^2}$$

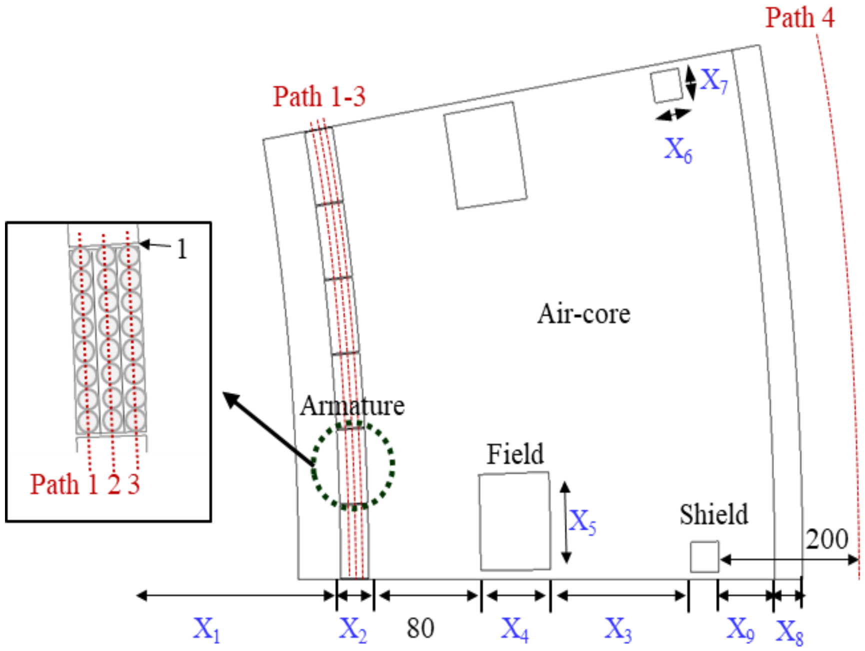
- K=4, n=2 constants

J_c	Critical current density [A/m^2]
D_O	SC diameter [mm]
d_f	Filament diameter [μm]
n	Number of filaments
λ	The area fraction of the wire that is SC
λ_{eff}	Effective fill factor
ρ_{eff}	Effective transverse resistivity [Ω-m]
L	The twist pitch (mm)

- Develop conductors with low losses
- Design machine to minimize losses
  - Reduce operating frequency – low pole count
    - weight
  - Reduce operating field
    - size
  - Optimize between electrical and magnetic loading
  - Optimize between volume and w/cm^3 losses

M. D. Sumption, "AC Loss of Superconducting Materials for Very High Density Motors and Generators of Hybrid-Electric Aircraft," 2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), Cincinnati, OH, 2018, pp. 1-6. – Experimental data presented on ICMC 2019 conference and EATS 2019 conference.

Optimization



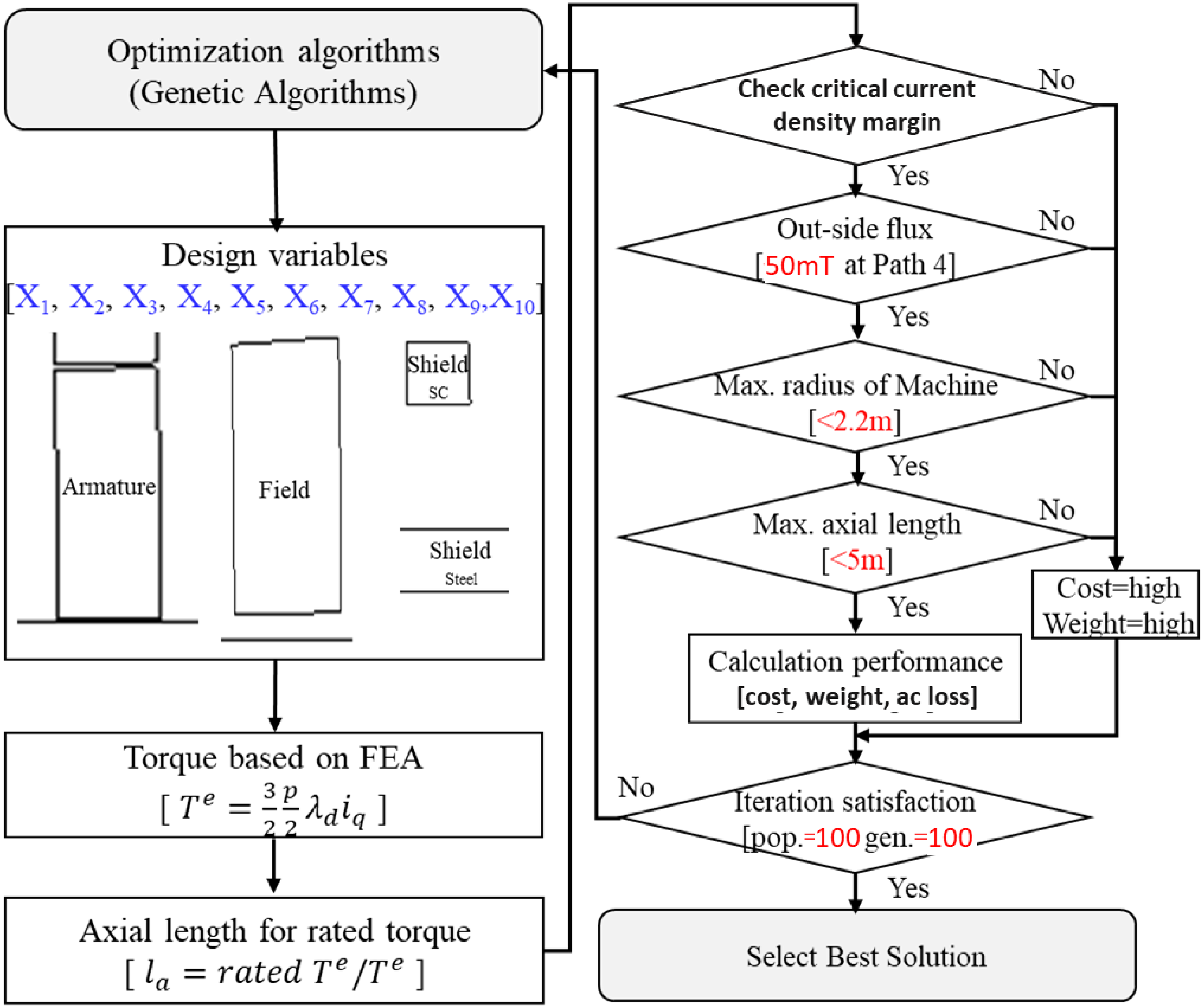
$$X = [X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}]$$

- Magnetic loading
- Electrical loading

$$X_{optimal} = \underset{X}{\text{Minimize}}(Weight, ac\ loss)$$

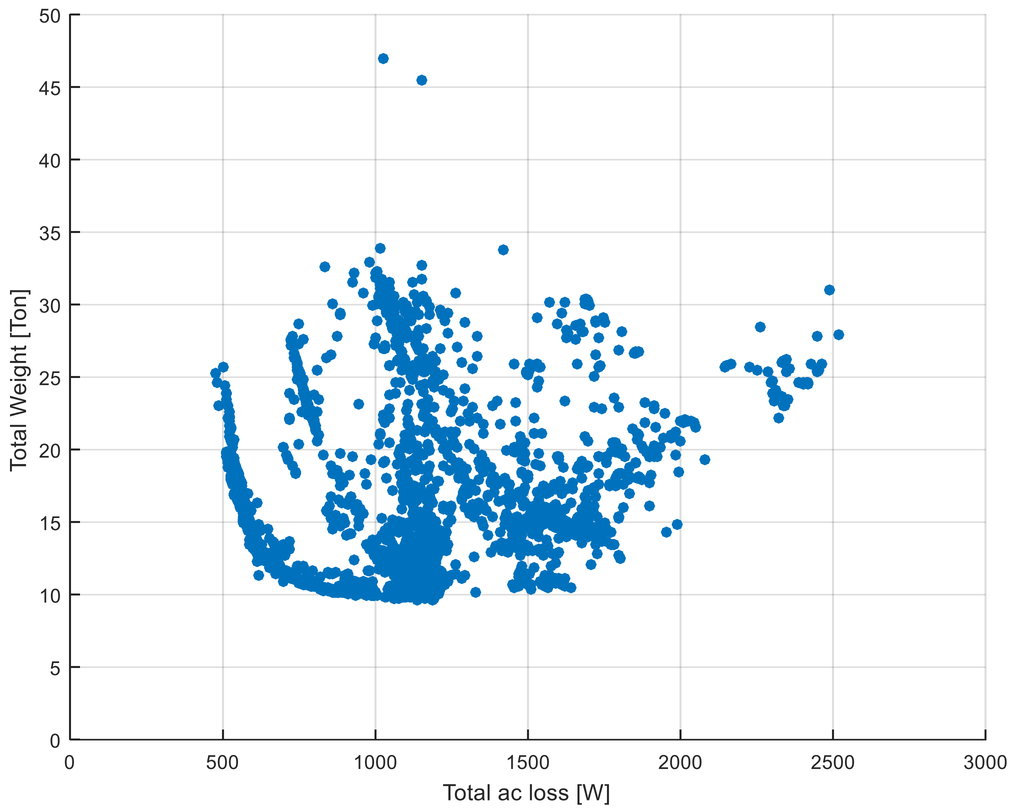
Parameter	min	max
Armature slot inner radius [X1](mm)	1500	2000
Armature slot radial height [X2](mm)	1	100
Radial distance between field coils and shield coils [X3] (mm)	1	100
Field slot radial height [X4] (mm)	1	100
Field slot circumferential width [X5] (Angle Degree)	0.2	$f(pole)$
Shield slot radial height [X6](mm)	1	100
Shield slot circumferential width [X7](mm)	1	$f(pole)$
Radial distance between shield coil and iron shield [X9] (mm)	1	100
Radial iron shield height [X8] (mm)	1	100
Armature current density [X10] (A/mm2)	50	200

Optimization

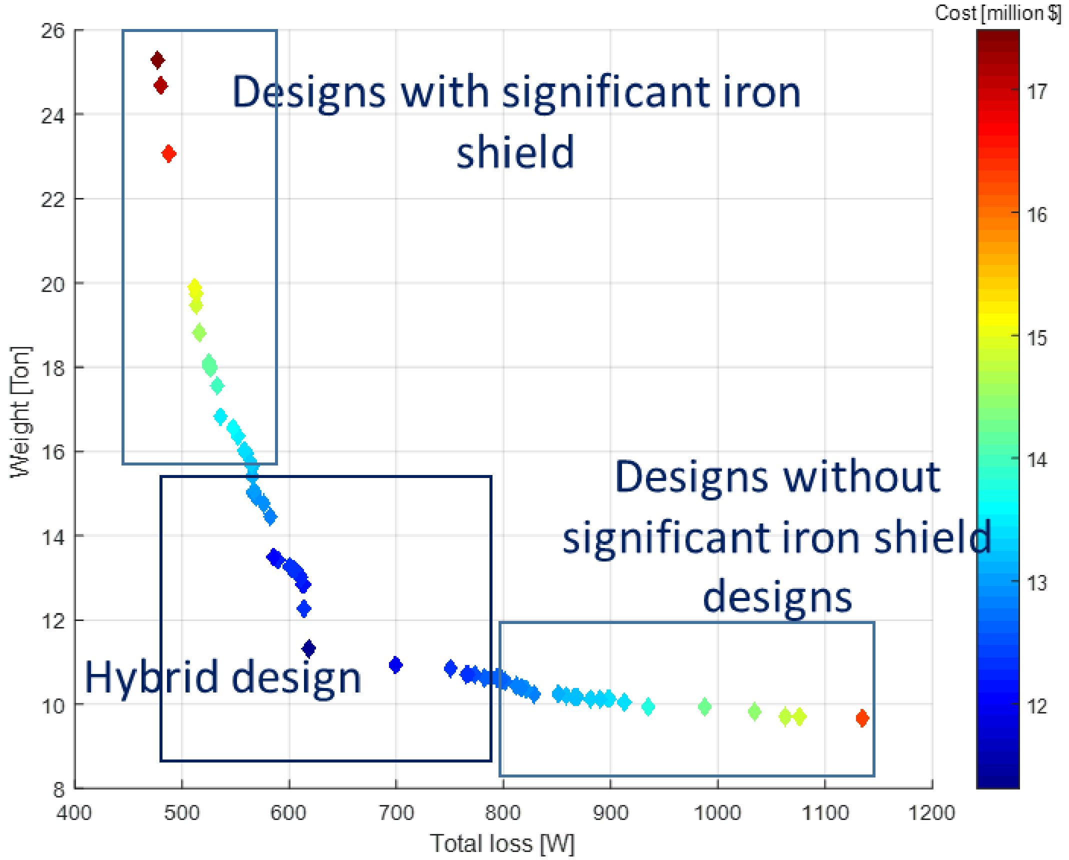


Optimal front - 10 Pole machine designs

All machine designs satisfying constraints



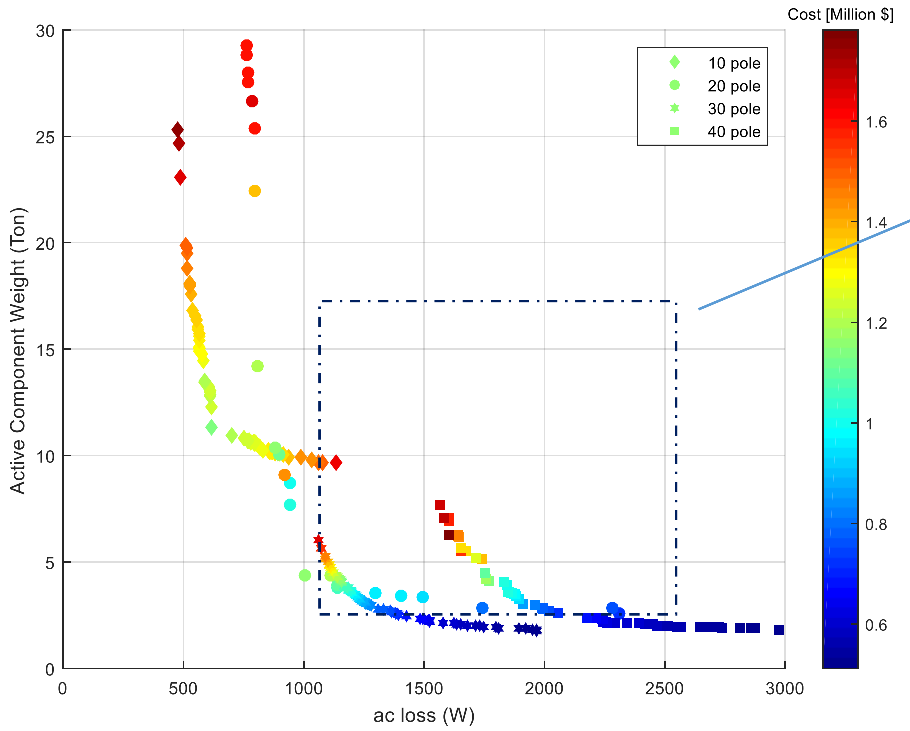
Optimal-front

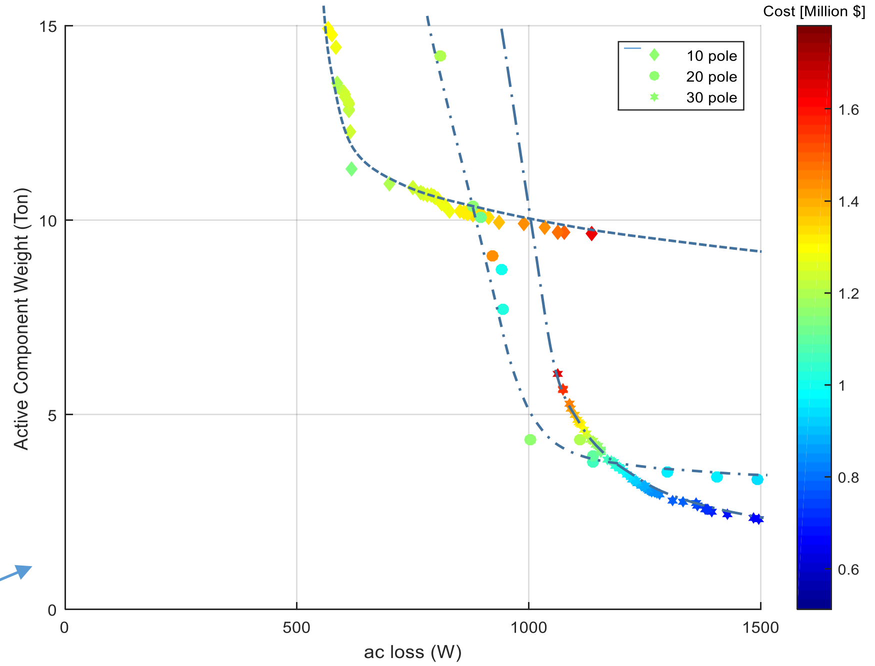


- Active shield designs reduce weight significantly
- Air-gap field density and stack length of the motor has significant tradeoff
- Different stack length designs can be chosen with corresponding change in ac loss.

Results - Pareto fronts

- AC loss is estimated in the armature axial length as well as in the end windings.
- Only active mass is considered for the weight.
- Optimal-pareto front for 10,20,30 and 40 pole count designs.
- Weight and ac loss has the tradeoff

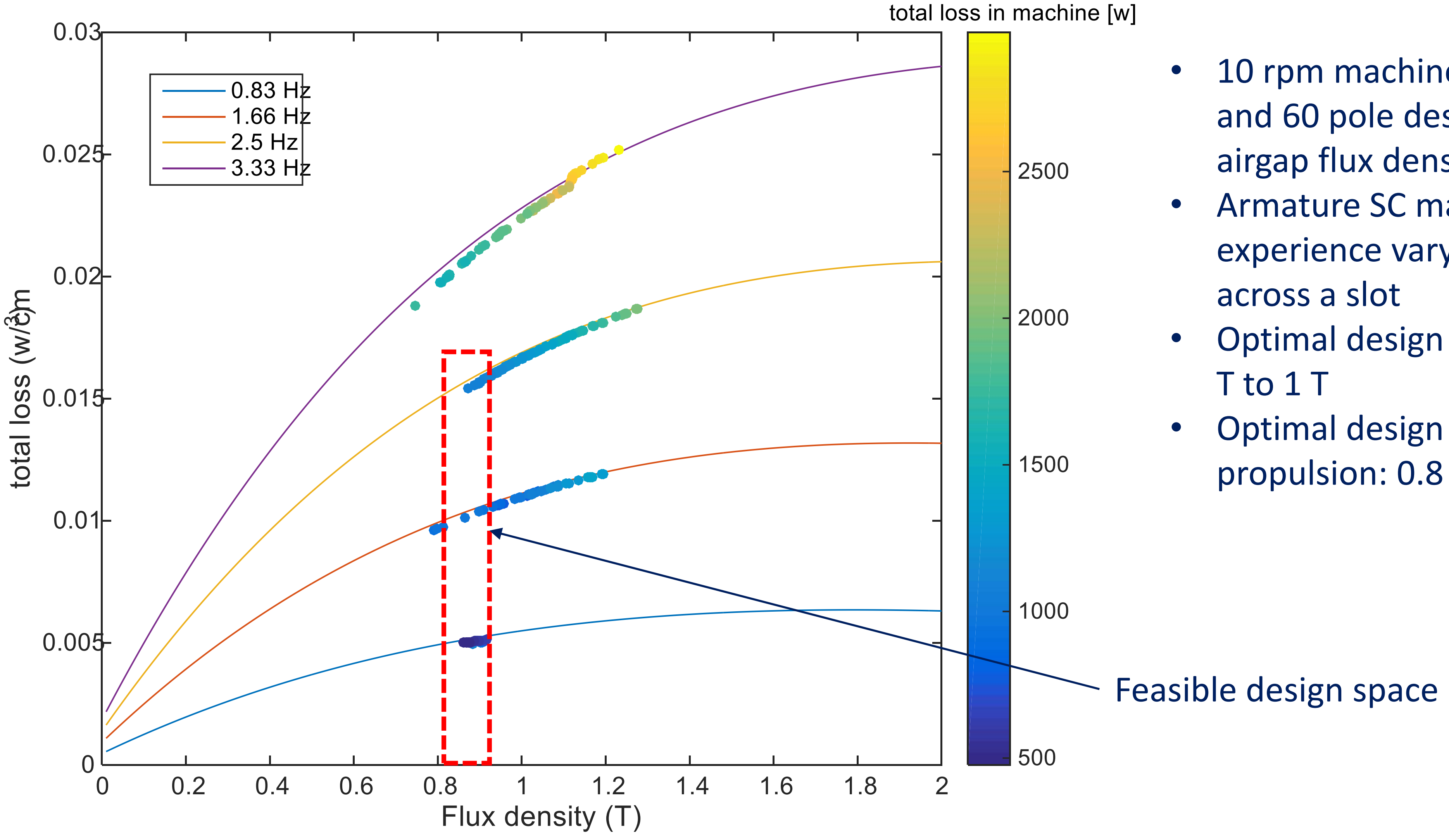




- As pole count increases weight decreases and ac losses increases
- Between optimized pole counts low pole counts looks desirable due to their low ac loss performance.

Comparison of ac losses – Design Space

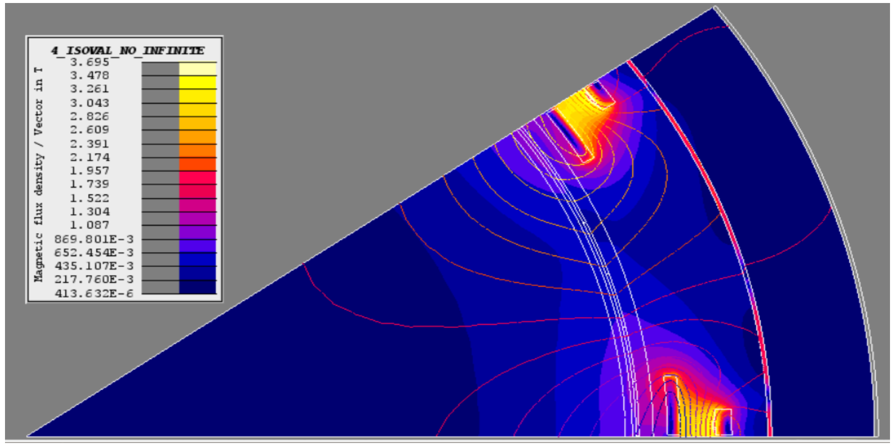
Assuming armature current density is 50% of the J_c at applied field density **0-2T**



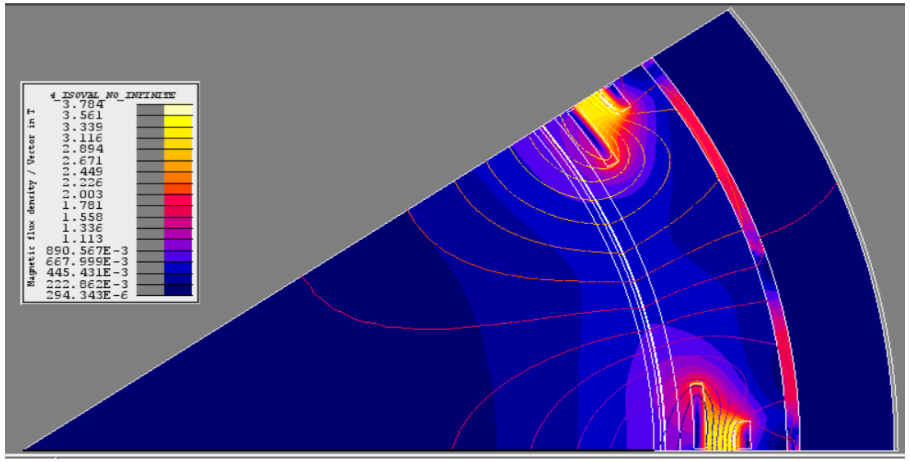
- 10 rpm machine with 10 20 30 40 and 60 pole designs with 0T to 2T airgap flux density
- Armature SC machine conductors experience varying flux density across a slot
- Optimal design space for wind: 0.8 T to 1 T
- Optimal design space for electric propulsion: 0.8 to 1 T

Optimization Results –10 pole

10 pole Machine designs – Comparison			
Parameter	Lowest weight	Lowest Ac loss	Optimal design
Outer Diameter [m]	4.18	4.34	4.29
Axial length [m]	3.34	4.72	2.45
Air-gap flux density [T]	0.88	0.86	0.91
Outside flux density [T]	0.049	0.048	0.044
Armature SC length [km]	2852	1190	1494
Field SC length [km]	3316	4850	2610
Shield SC length [km]	1656	2683	1544
Total SC length [km]	8125	7917	5648
Iron shield weight [Ton]	4.27	19.51	7.57
Total loss [W]	1135	477	618
Weight (Iron and SC) [Ton]	9.7	25.3	11.4
Cost (Iron and SC) [million $]	16.2	17.5	11.3



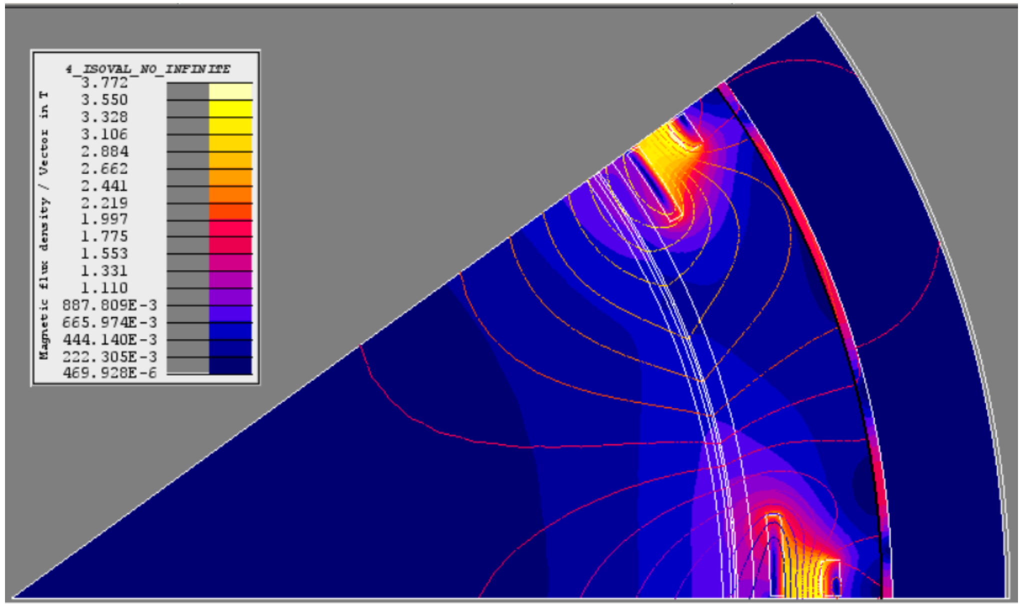
High Loss = 1135 W, Low weight = 9.7 Ton

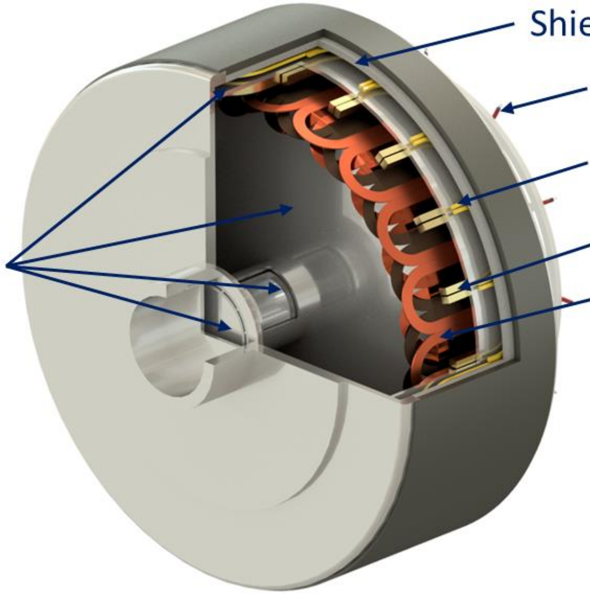


Low ac loss = 477 W, High Weight = 25.3 Ton

- All the designs converge towards active shield designs
- Air-gap flux density and active length affect ac losses

AC Loss summary

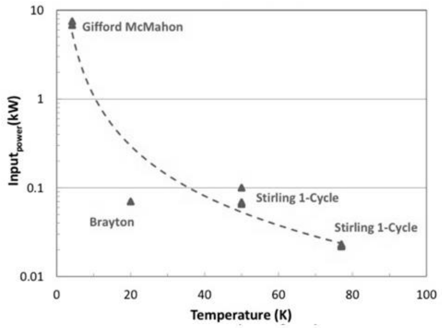




Machine designs with ac losses 477W and weight 25.3 Ton could be achieved with 10-poles

Best design ac loss 618 W, weight 11.3 Ton, axial length is 2.45 m and diameter is 4.29 m.

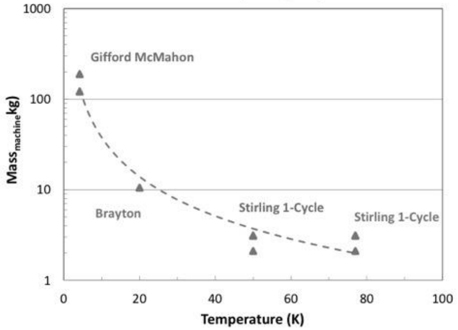
Total system weight and efficiency considering cryogenic system



$$Required\ cryocooler\ power \approx \frac{90}{1.5} * 618 = 37.08KW$$

$$efficency \approx \frac{1MW - 37.698kW}{1MW} * 100 = 99.6\%$$

$$System\ weight \approx 11.3 * 200\% + \frac{10}{1.5} * 618 = 38\ Ton$$



Conclusion and future works

- Fully superconducting machines attractive for 10 MW scale wind turbines.
- Armature winding ac losses and associated added cryogen system weight are significant challenges.
- Relatively low field, low pole-count designs preferred. AC loss data close to operating conditions needed for more rigorous analysis.
  - Machine design with ac losses less than 1KW
- Iron yoke weight dominates in passively shielded designs. Actively shielded designs give lowest weight.
  - Machine design with weight less than 50 Ton
- Mechanical design needs to be refined to estimate total weight including non-active components.
- TRL increase will be sought within ac loss measurement with race track winding build and test under rotating magnetic setup.