Electric Motors for Non-Cryogenic Hybrid Electric and Turboelectric Propulsion

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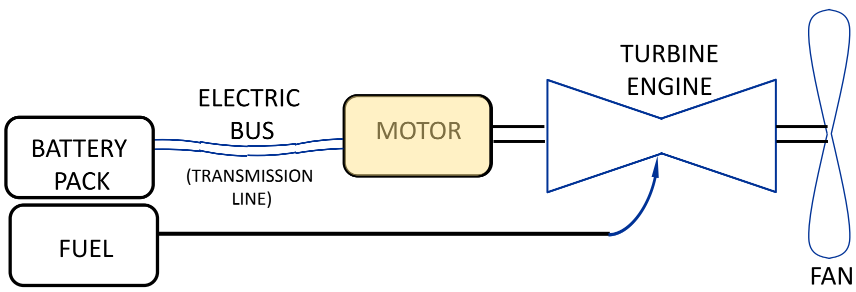
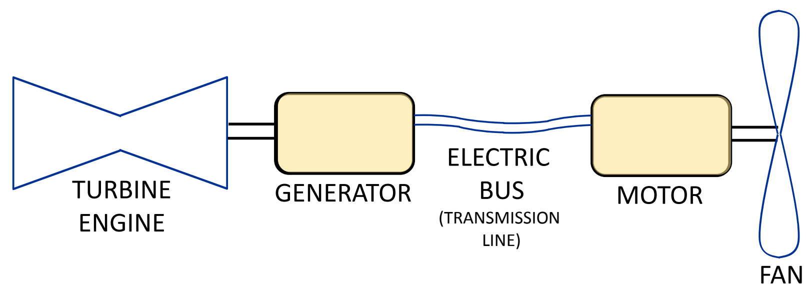
Background

Hybrid Electric Propulsion



Turboelectric Propulsion



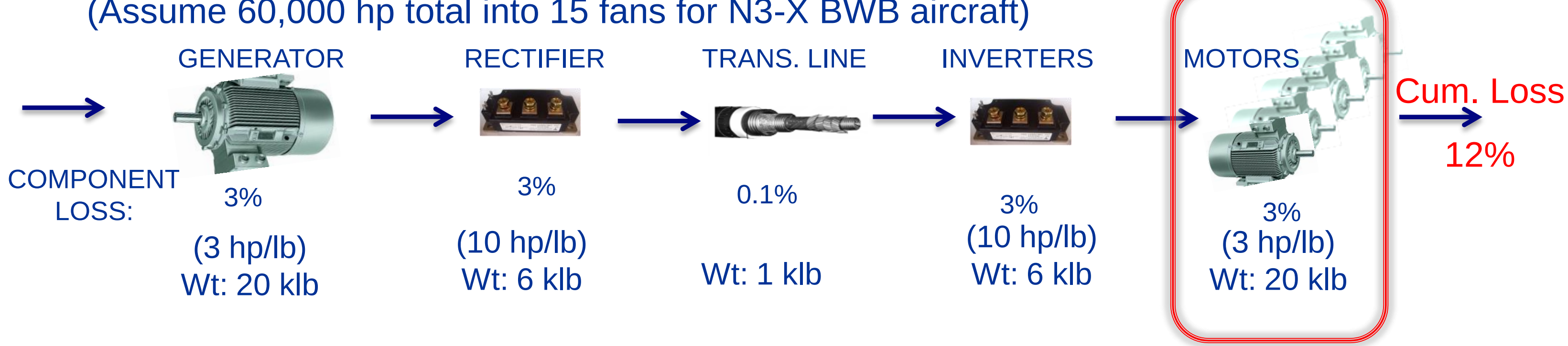
“N3-X” Distributed Turboelectric Propulsion System

From Dr. Gerald Brown “Efficient Flight-Weight Electric Systems”

Background

Room Temperature Turboelectric Propulsion

(Assume 60,000 hp total into 15 fans for N3-X BWB aircraft)



Net extra fuel burn: 8% *increase!* (before iterating)

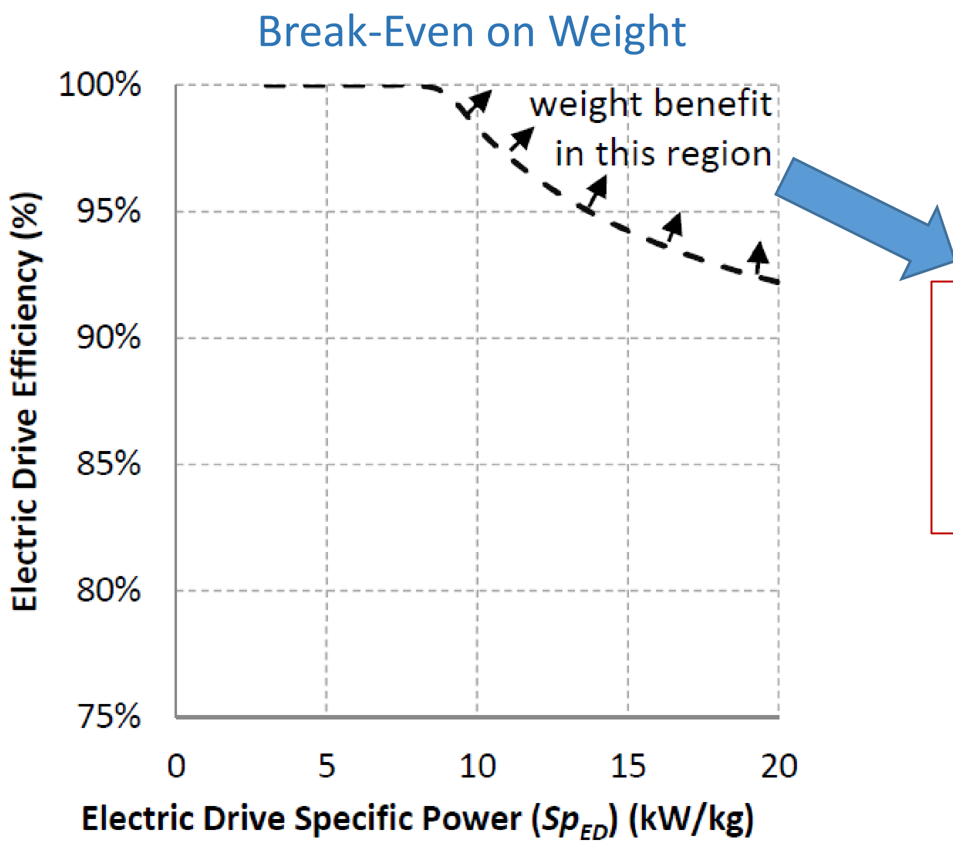
Need to determine combination of power density
And efficiency to give net benefit

From Dr. Gerald Brown "Efficient Flight-Weight Electric Systems"

Background

Turboelectric Propulsion Benefits

Electric drive = motor + other electrical components



Each aircraft configuration will yield combinations of power density and efficiency required to achieve net benefit

From Jansen et al. "Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements"

Application

- 1 MW motor application
  - Small eight-passenger aircraft, or distributed fans for larger aircraft
  - 7000 RPM fan speed
  - 0.8-meter fan diameter
- Motors
  - Permanent magnet, induction, synchronous reluctance
  - Target baseline motor performance
    - 5.8 kW/kg (3.5 HP/lb) power density
    - 96% efficiency
    - *Based on electromagnetic weight and electromagnetic losses*

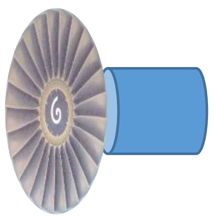
Application

- How can motor performance be improved by using better component materials?
  - Conductor
    - Copper windings → windings with CNT
    - *Assume double conductivity*
  - Permanent magnets
    - NdFeB → nanocomposite material
    - *Remanence flux increase to* $B_r = 2.0\ T$
  - Core material (soft magnetic material)
    - Hiperco 50 → composite material with hard and soft magnetic materials
    - *Assume 50% loss, 75% saturation compared to baseline*
  - Structural materials – composite sleeve
    - Carbon fiber composite → materials with CNT
    - *Assume double strength*

Electromagnetic analysis: Conductor, Permanent magnets, Core material

Structural analysis: Structural materials

Assumptions



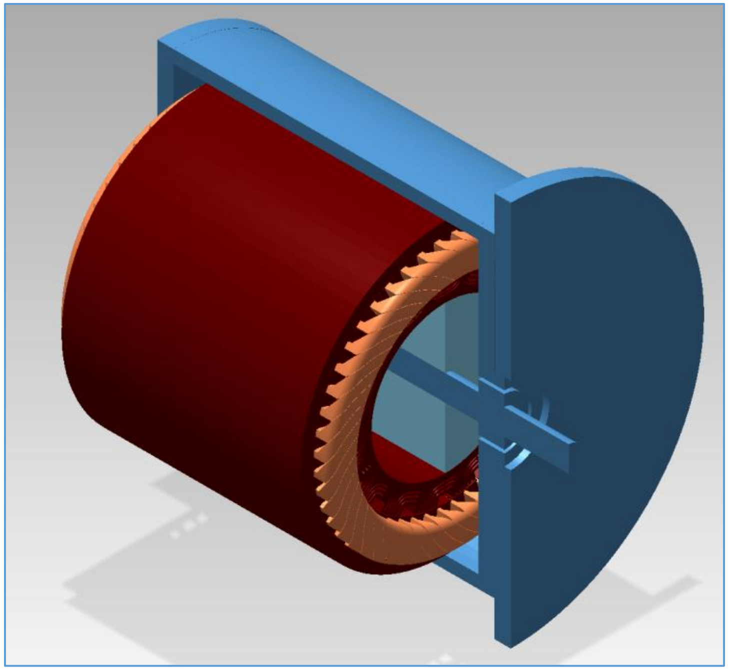
Standard Motor

Tip Drive Motor

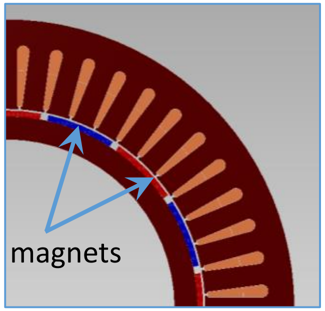
Parameter	Value
Standard motor outer diameter, OD	0.5 m maximum
Tip drive motor inner diameter, ID	0.8 m minimum
Stator winding current density, J	10 A/mm^2 rms maximum
Target flux density in teeth, B	2.0 T rms maximum
Target flux density in backiron, B	1.5 T rms maximum
Frequency, f	1 kHz

Increases power density, but also increases losses

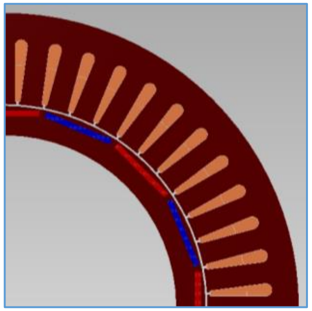
Baseline Motor Designs



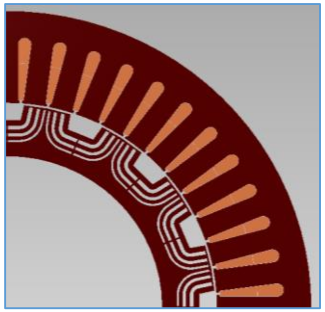
Standard Motor



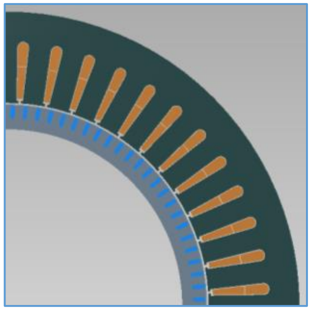
Surface-Mounted PM Motor (SPM)



Interior PM Motor (IPM)

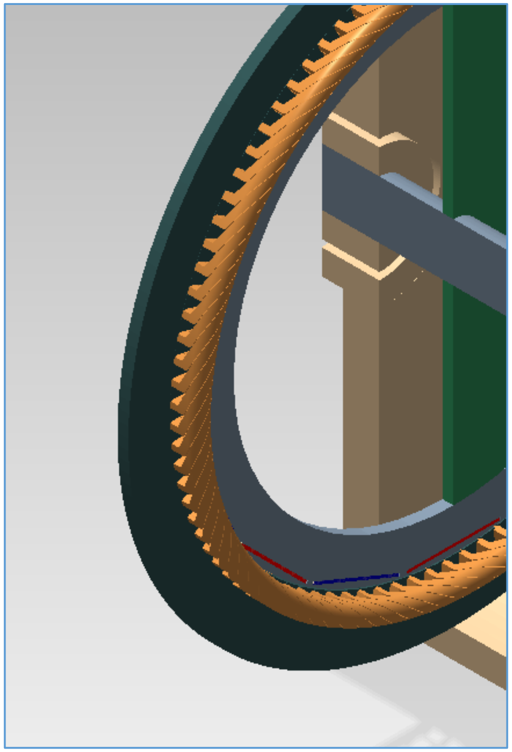


Synchronous Reluctance Motor (SRM)

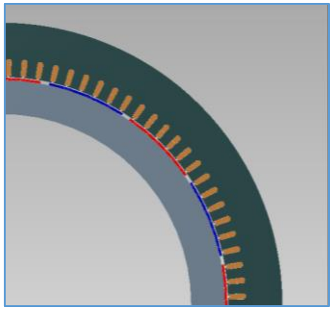


Induction Motor (IM)

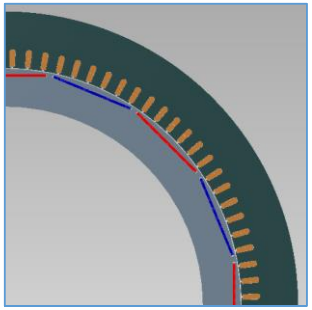
Baseline Motor Designs



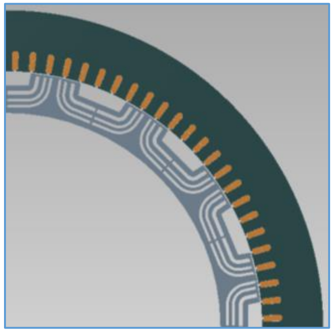
Tip Drive Motor



Surface-Mounted PM Motor (SPM)



Interior PM Motor (IPM)



Synchronous Reluctance Motor (SRM)

Baseline Motor Designs

Parameter	Standard Motor				Tip Drive Motor		
	SPM	IPM	SRM	IM	SPM	IPM	SRM
Outer diameter, OD (mm)	500	500	500	500	1184	1184	1184
Inner diameter, ID (mm)	292	292	255	290	800	800	800
Length, L (mm)	97	99	234	310	16.0	15.5	22.5
Stator copper mass (kg)	18.4	18.5	29.4	38.0	40.3	40.2	41.9
Stator core mass (kg)	58.3	59.5	140.7	186.8	39.3	38.1	55.3
Rotor copper mass (kg)	0.0	0.0	0.0	12.4	0.0	0.0	0.0
Permanent magnet mass (kg)	3.4	3.5	0.0	0.0	1.6	1.6	0.0
Rotor core mass (kg)	13.9	14.5	45.9	50.1	22.9	22.3	20.6
Total mass (kg)	94.0	96.1	216.0	287.2	104.1	102.2	117.7
Power density (HP/lb)	6.4	6.3	2.8	2.1	5.8	6.0	5.2
Power density (kW/kg)	10.6	10.4	4.6	3.5	9.6	9.8	8.5

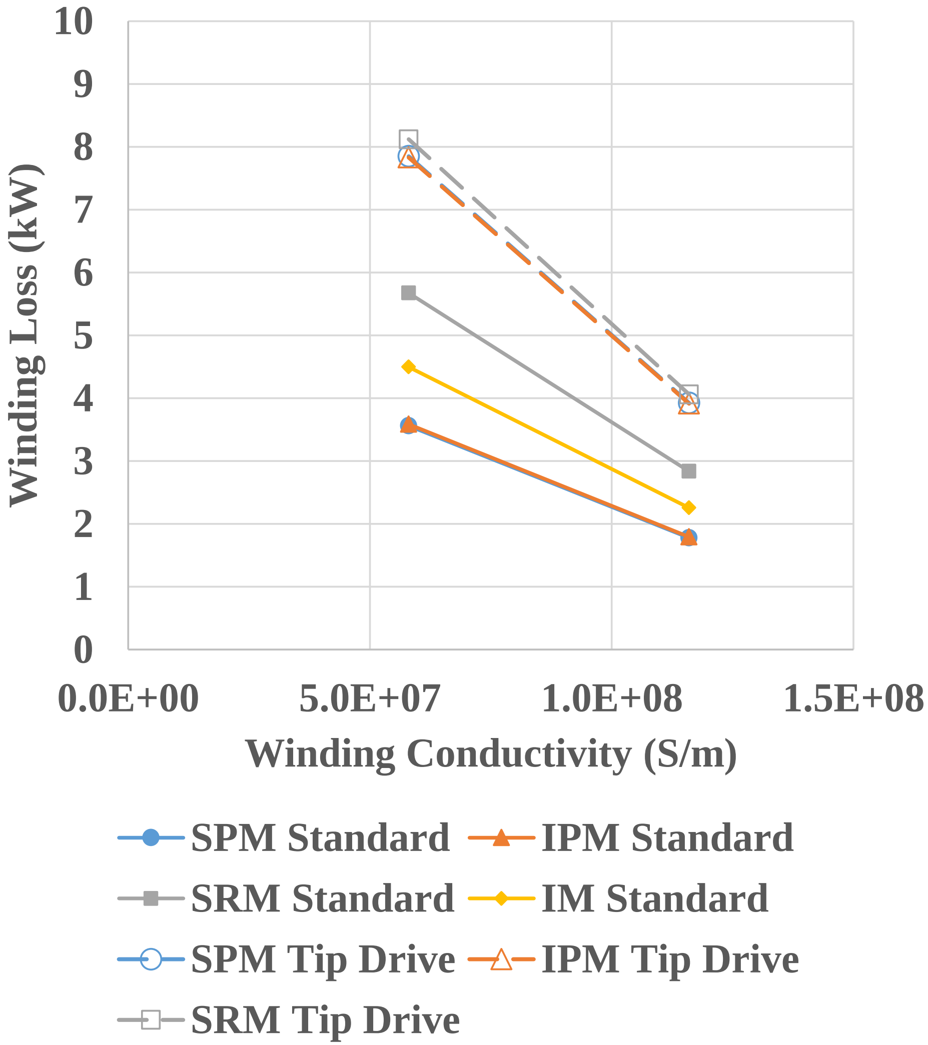
SPM = surface-mounted PM motor
IPM = interior PM motor
SRM = synchronous reluctance motor
IM = induction motor

Baseline Motor Designs

Parameter	Standard Motor				Tip Drive Motor		
	SPM	IPM	SRM	IM	SPM	IPM	SRM
Winding Loss (kW)	3.6	3.6	5.7	4.5	7.9	7.8	8.1
Core Loss (kW)	20.4	20.5	59.7	41.7	12.4	12.8	28.0
Solid Loss (kW)	24.9	9.7	0.0	6.1	70.6	13.9	0.0
Efficiency (%)	95.3%	96.8%	93.7%	95.0%	91.6%	97.3%	96.8%

SPM = surface-mounted PM motor
IPM = interior PM motor
SRM = synchronous reluctance motor
IM = induction motor

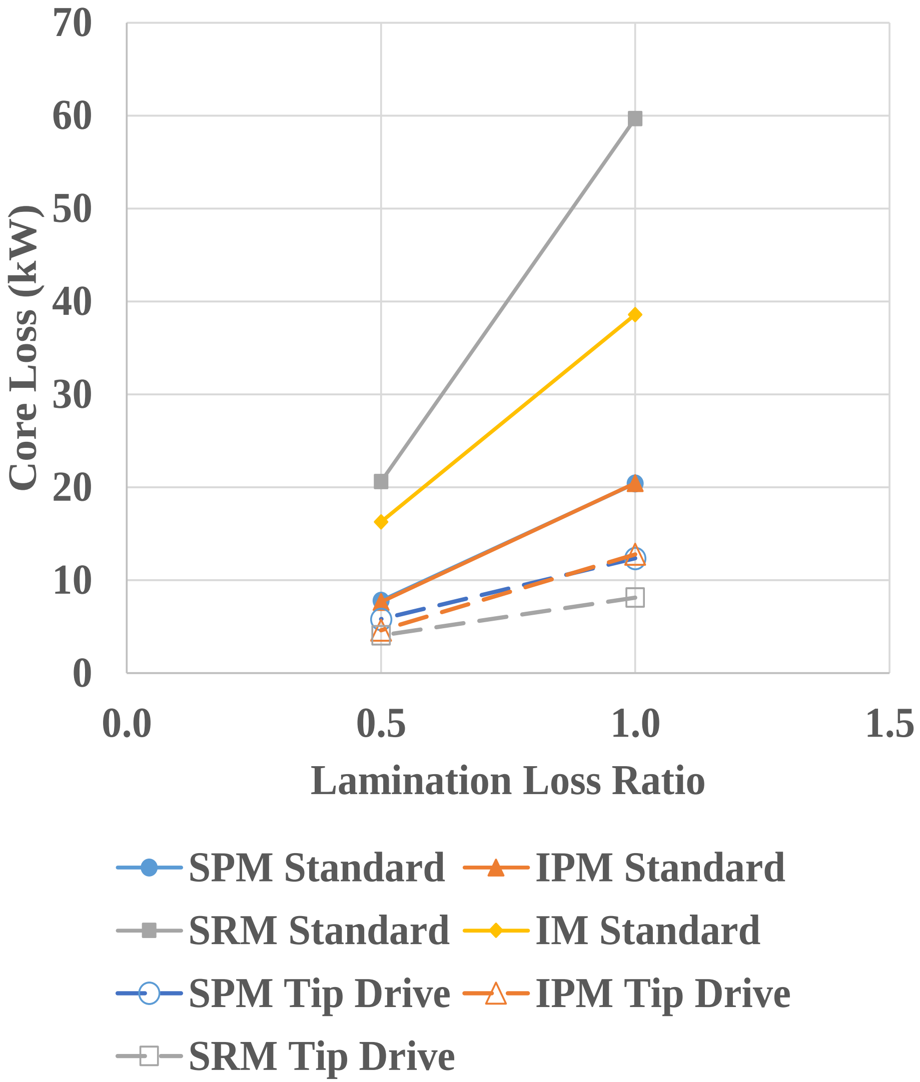
Improved Motor Performance



Conductor:

- *Efficiency benefit with increased conductivity*
- *Power density benefit if winding loss kept constant*

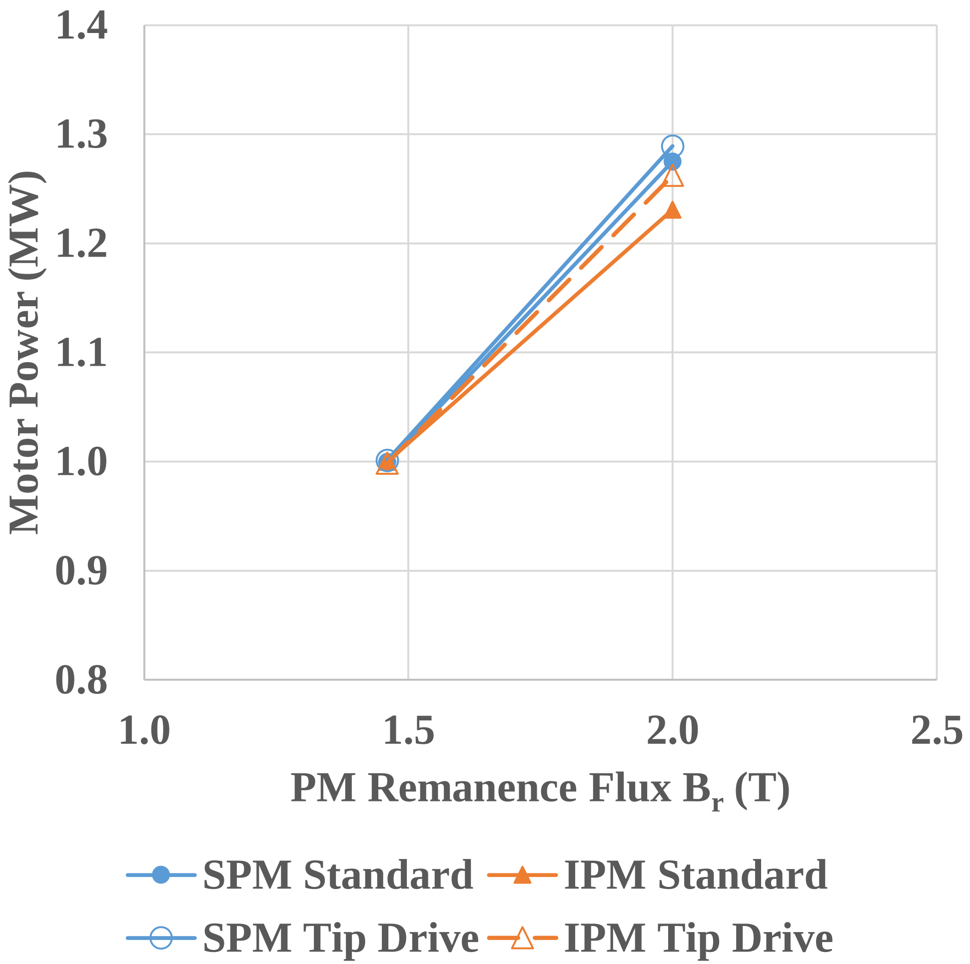
Improved Motor Performance



Core material:

- *Efficiency benefit with decreased loss*
- *Torque reduction with decreased saturation B_{sat}*

Improved Motor Performance

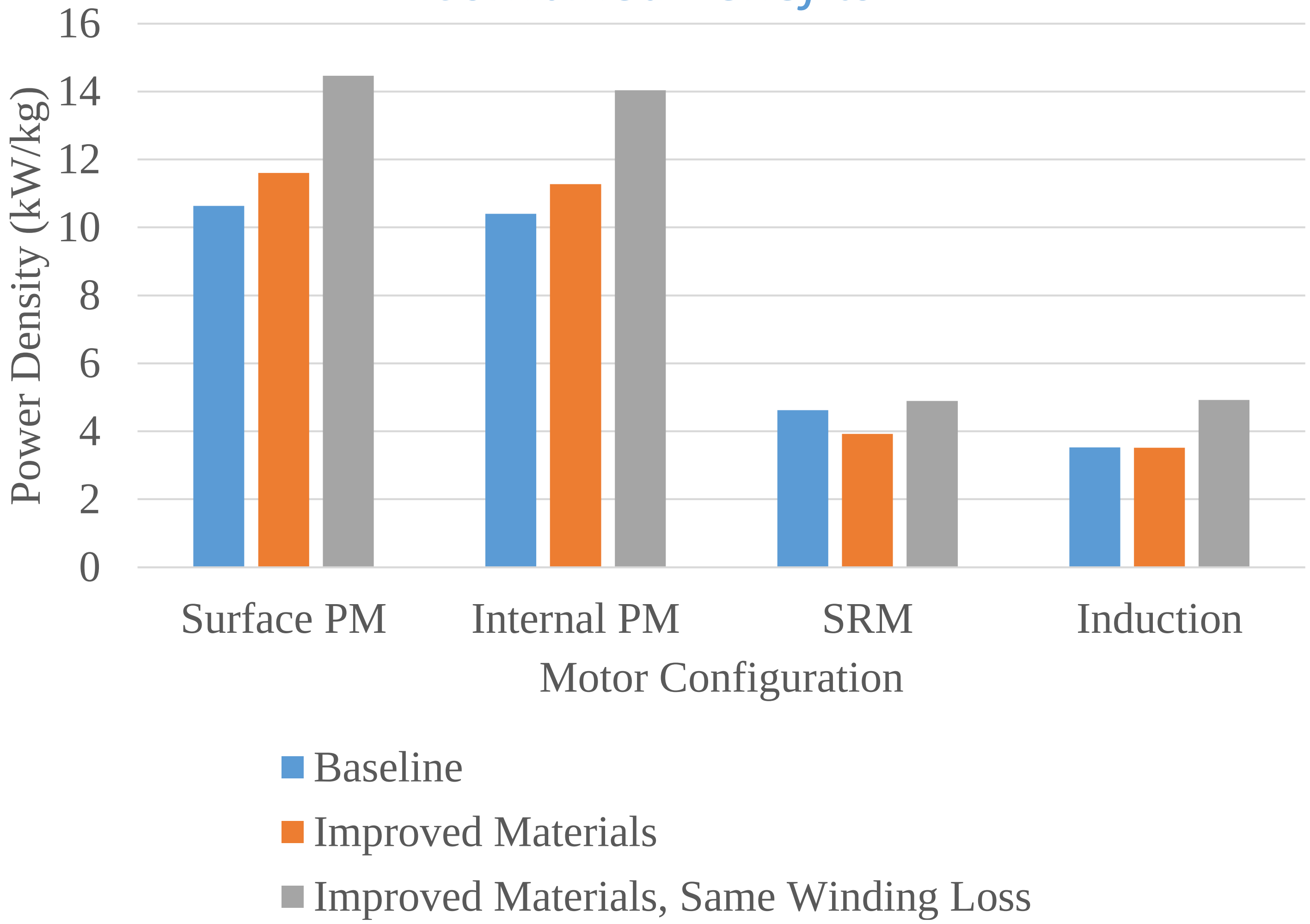


Permanent magnet:

- *Power density benefit with increased remanence flux B_r*

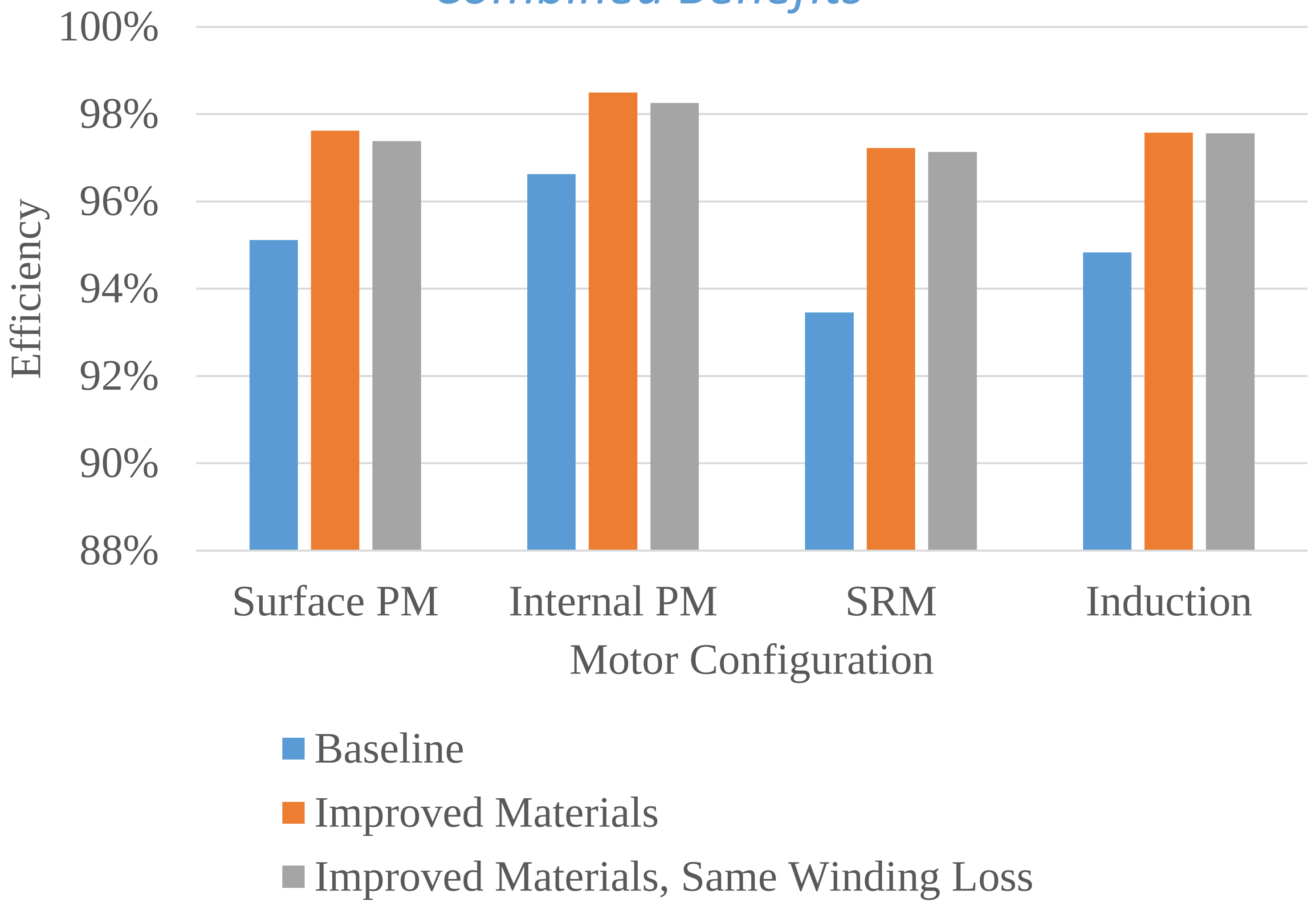
Improved Motor Performance
Standard Motors – Power Density

Combined Benefits



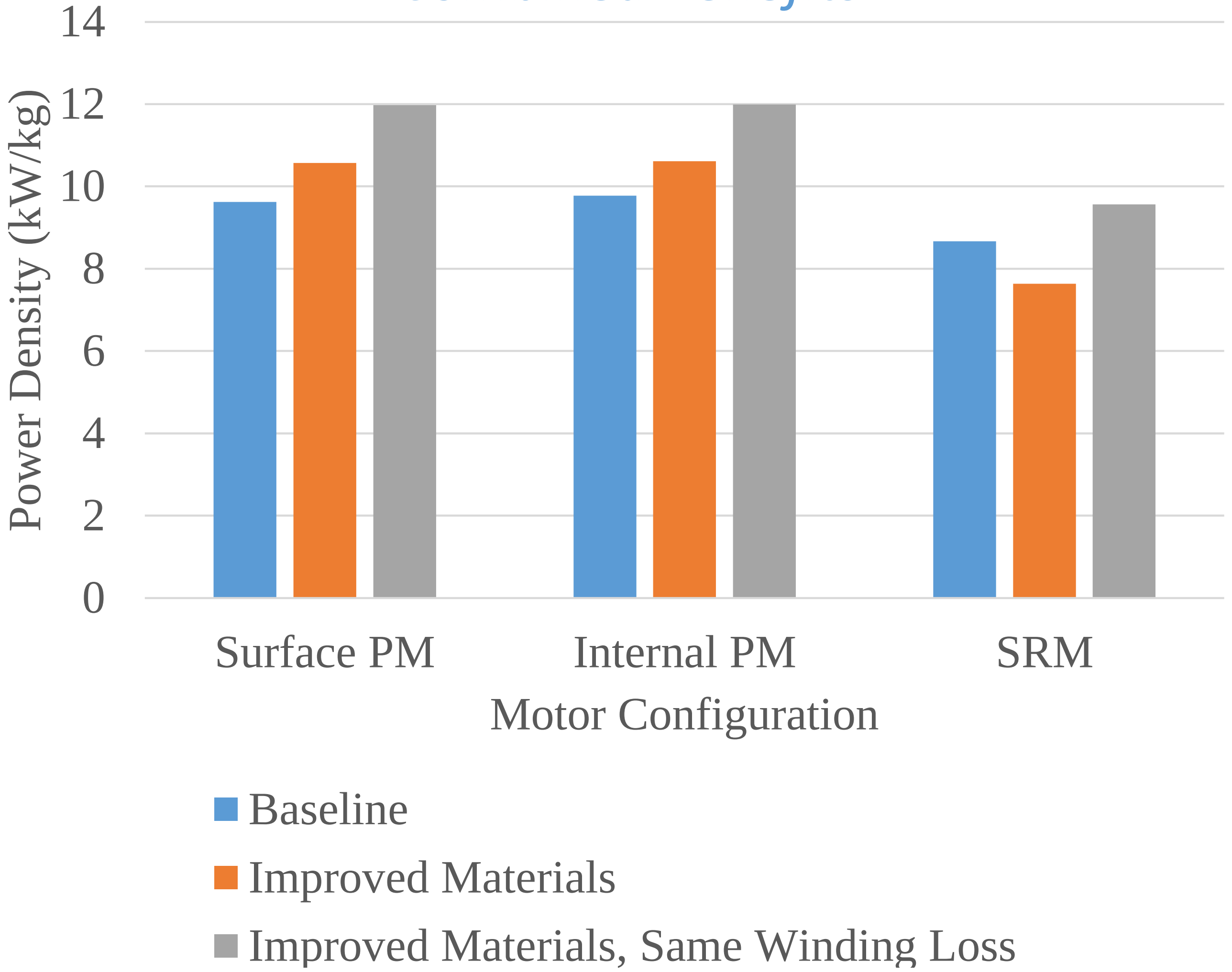
Improved Motor Performance
Standard Motors – Efficiency

Combined Benefits



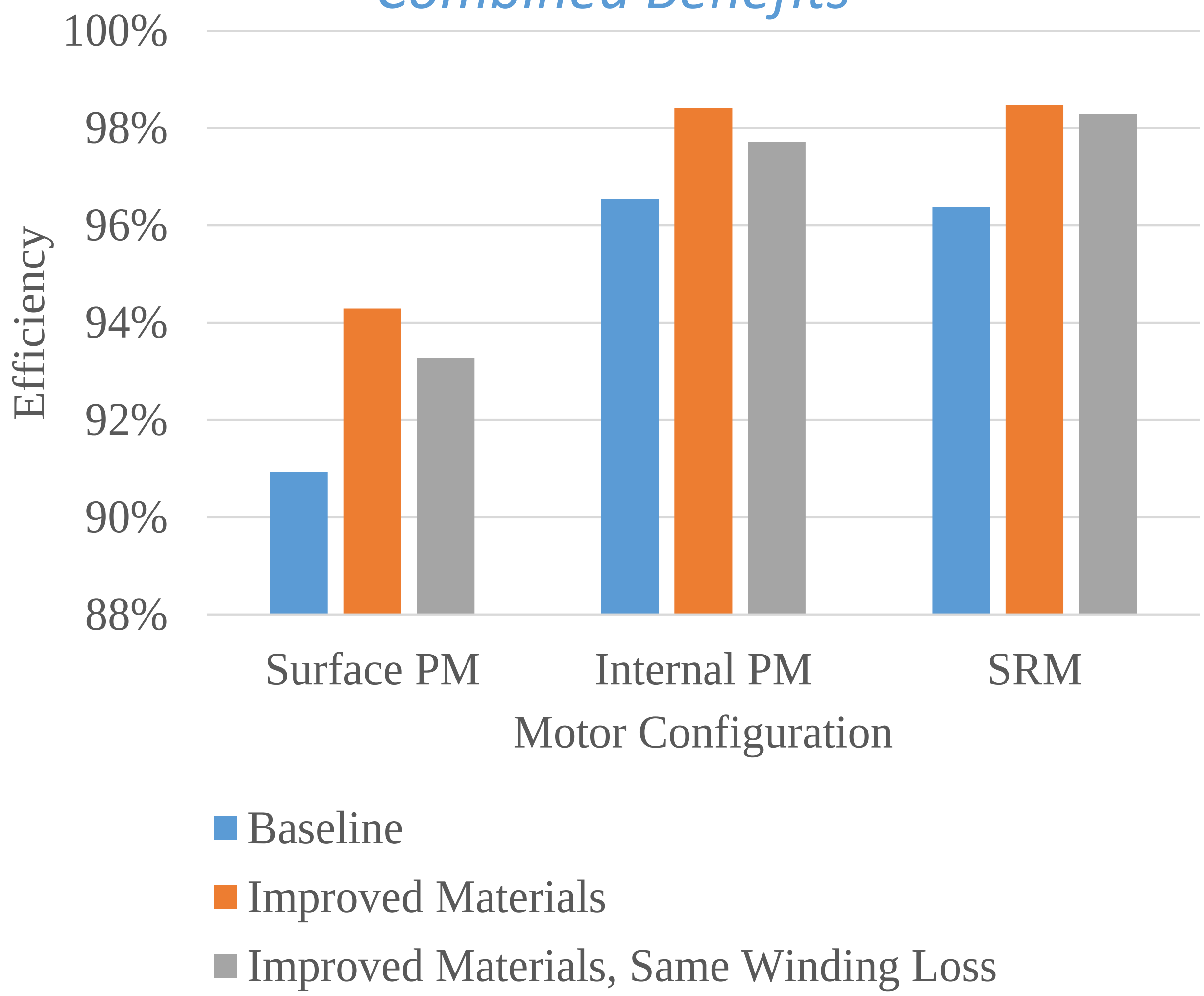
Improved Motor Performance
Tip Drive Motors – Power Density

Combined Benefits



Improved Motor Performance
Tip Drive Motors – Power Density

Combined Benefits



Summary

- 1 MW Application – Target 5.8 kW/kg, 96% efficiency

Drive	Motor Type	Baseline Materials		Improved Materials	
		Power Density kW/kg (HP/lb)	Efficiency	Power Density kW/kg (HP/lb)	Efficiency
Standard	SPM	10.6 (6.4)	95.1%	**14.5 (8.8)**	**97.4%**
	IPM	**10.4 (6.3)**	**96.6%**	**14.0 (8.5)**	**98.3%**
	SRM	4.6 (2.8)	93.5%	4.9 (3.0)	97.1%
	IM	3.5 (2.1)	94.8%	4.9 (3.0)	97.6%
Tip Drive	SPM	9.6 (5.8)	90.9%	12.0 (7.3)	93.3%
	IPM	**9.8 (6.0)**	**96.5%**	**12.0 (7.3)**	**97.7%**
	SRM	**8.7 (5.3)**	**96.4%**	**9.6 (5.8)**	**98.3%**

Summary

- 1 MW Application – Benefits

Drive	Motor Type	Power Density Increase	Winding Loss + Core Loss Decrease
Standard	SPM	37%	14.3 kW / 60%
	IPM	35%	14.4 kW / 60%
	SRM	7%	36.7 kW / 56%
	IM	40%	27.6 kW / 60%
Tip Drive	SPM	25%	8.1 kW / 40%
	IPM	22%	8.6 kW / 42%
	SRM	10%	19.0 kW / 53%

Next Steps

- 1 MW motor design and analysis
  - Combine effects of materials into re-design
  - Tradeoffs
- Design, *build, and test* high performance non-cryogenic motors
  - State-of-the-art materials
  - New configurations
  - Maximize power density and efficiency