National Aeronautics and
Space Administration

High-Efficiency Megawatt Machine Rotating Cryocooler Conceptual Design

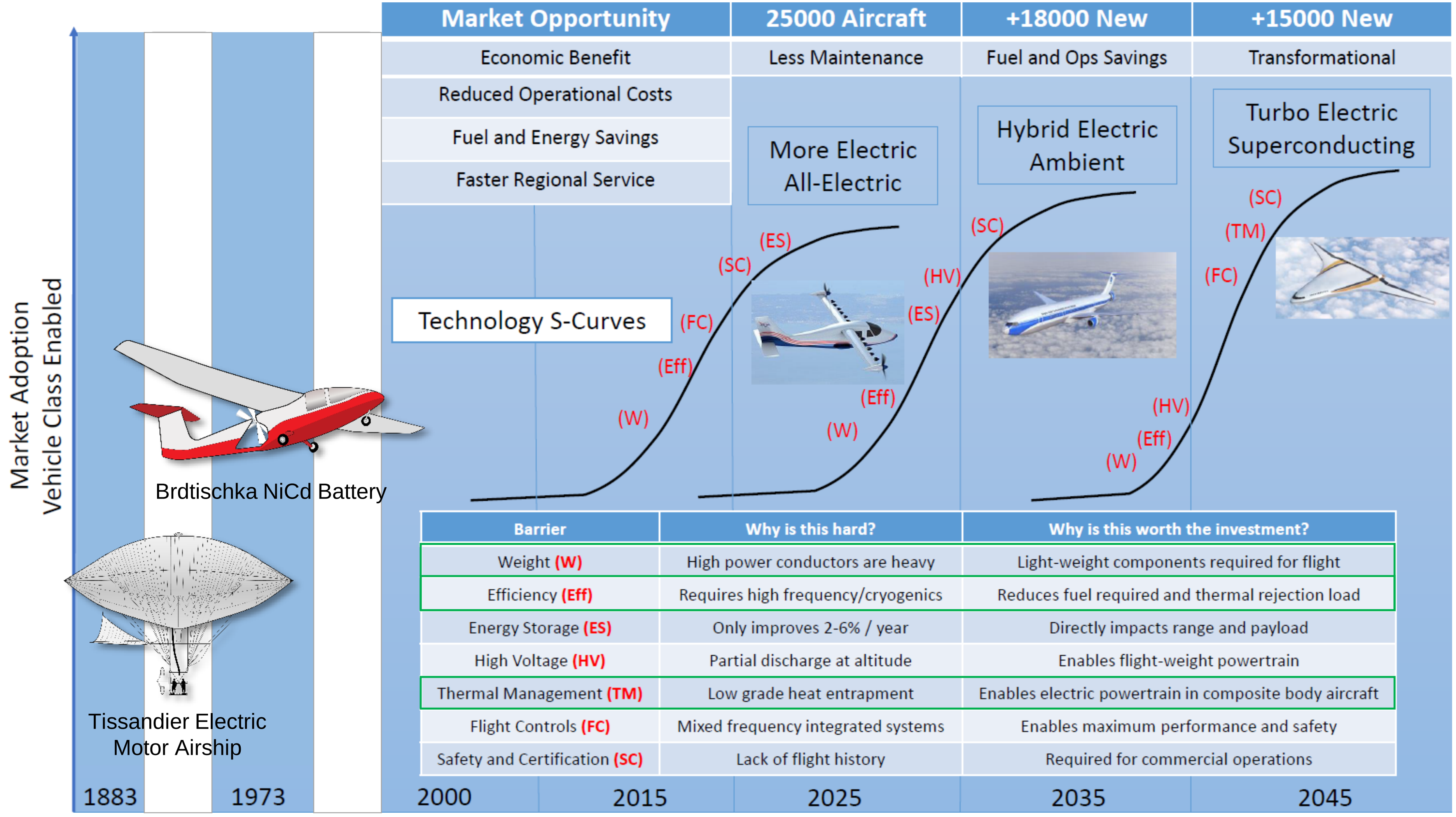
Rodger Dyson, Ralph Jansen
NASA Glenn Research Center
Cleveland, OH

Kirsten Duffy
University of Toledo
Toledo, OH

Paul Passe
Vantage Partners, LLC
Cleveland, OH

AIAA/IEEE Electric Aircraft Technology Symposium
Session V, Topic 2: Megawatt-Scale Motor Systems
1300-1530, August 24, 2019

Electric Aircraft Propulsion Technology Adoption



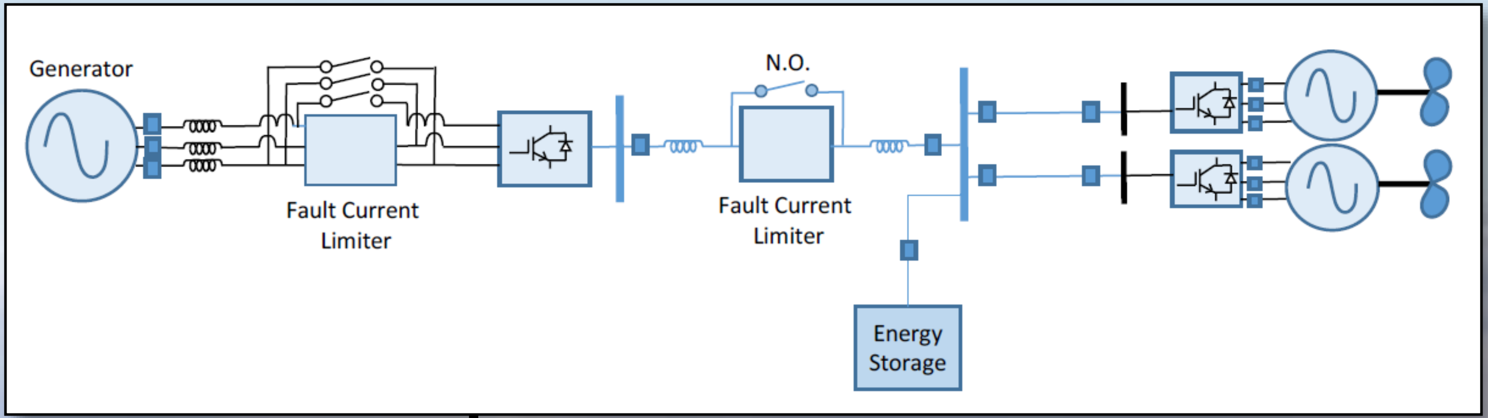
Market Opportunity	25000 Aircraft	+18000 New	+15000 New
Economic Benefit	Less Maintenance	Fuel and Ops Savings	Transformational
Reduced Operational Costs			
Fuel and Energy Savings			
Faster Regional Service			

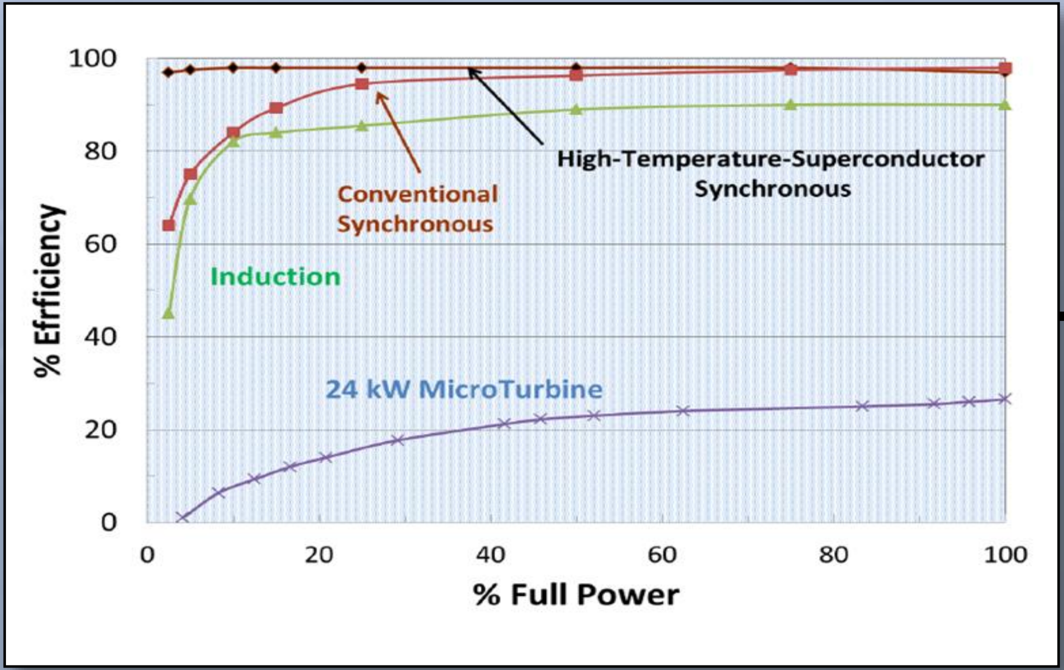
Barrier	Why is this hard?	Why is this worth the investment?
Weight **(W)**	High power conductors are heavy	Light-weight components required for flight
Efficiency **(Eff)**	Requires high frequency/cryogenics	Reduces fuel required and thermal rejection load
Energy Storage **(ES)**	Only improves 2-6% / year	Directly impacts range and payload
High Voltage **(HV)**	Partial discharge at altitude	Enables flight-weight powertrain
Thermal Management **(TM)**	Low grade heat entrapment	Enables electric powertrain in composite body aircraft
Flight Controls **(FC)**	Mixed frequency integrated systems	Enables maximum performance and safety
Safety and Certification **(SC)**	Lack of flight history	Required for commercial operations

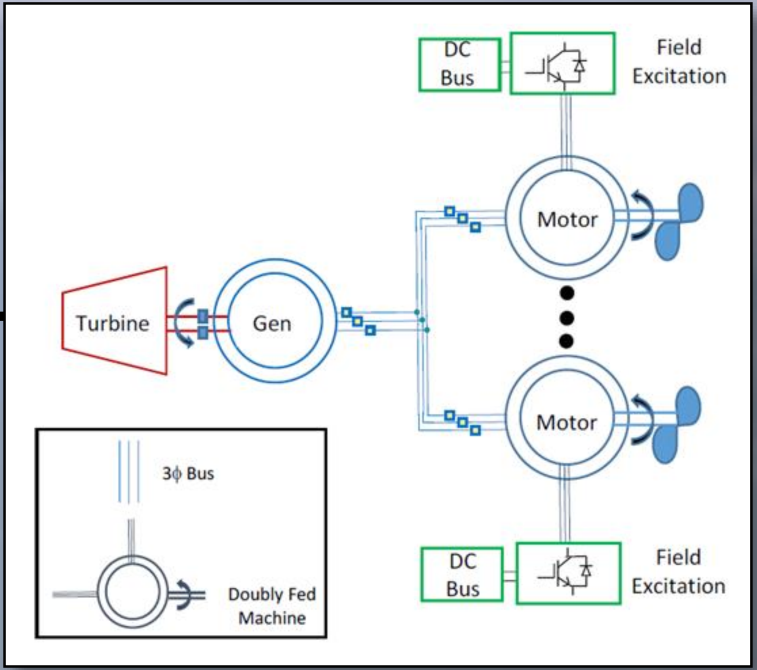
HEMM addresses weight, efficiency, and thermal management technology barriers.

Electric Propulsion Machine Options

- Fully Superconducting
- Partially Superconducting
- PM Synchronous
- Single-fed Induction
- Double-fed Induction

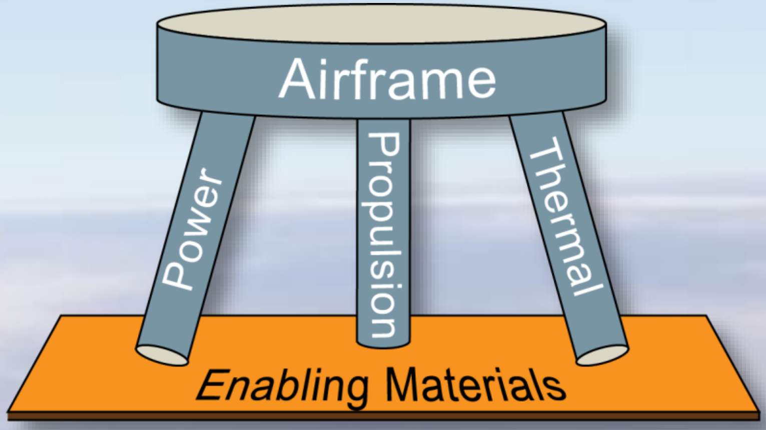




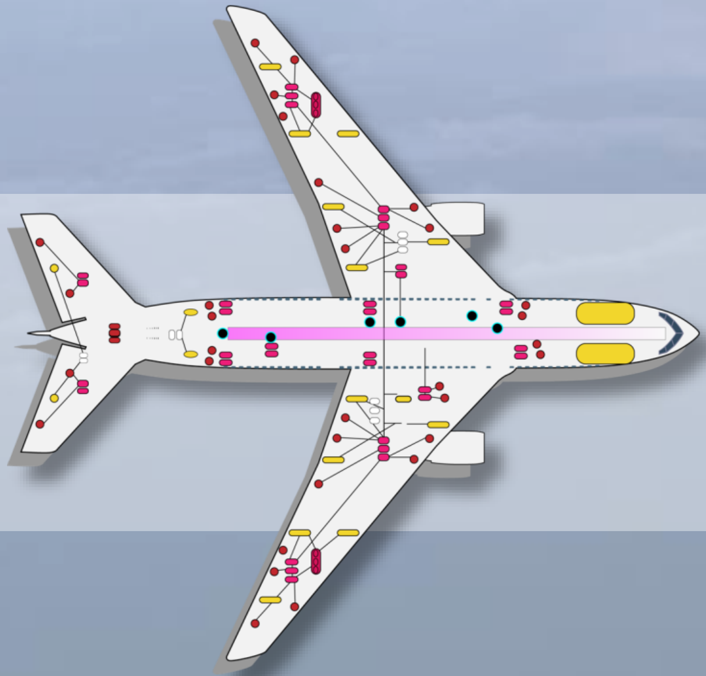


Power, Propulsion, Thermal, and Airframe Integration

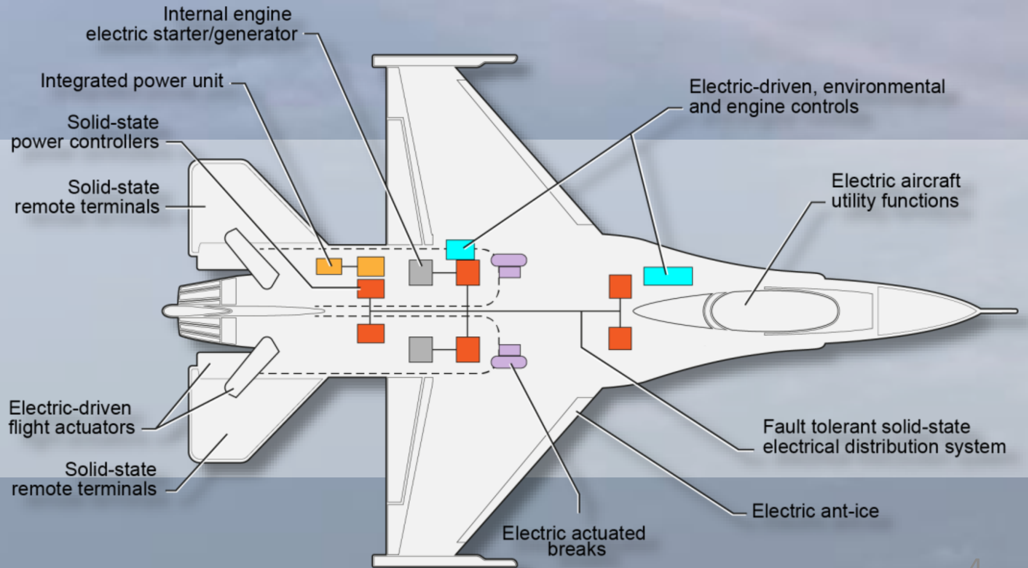
- **Challenge is to highly integrate all systems:**
  - improves fuel efficiency
  - reduces emissions
  - reduces low grade waste heat
  - reduces vehicle mass



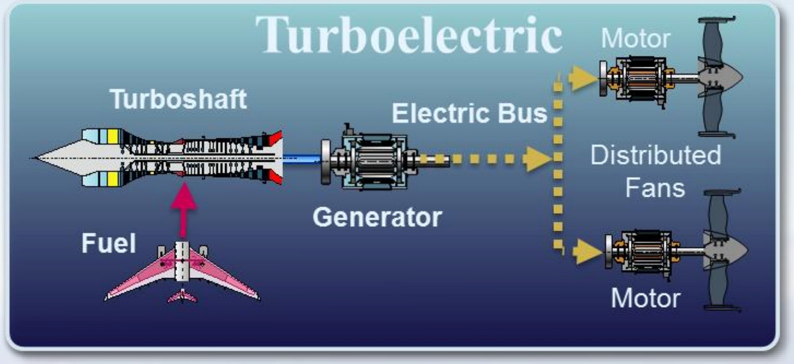
All components must integrate



Partially Superconducting Machine is a Near-term Technology



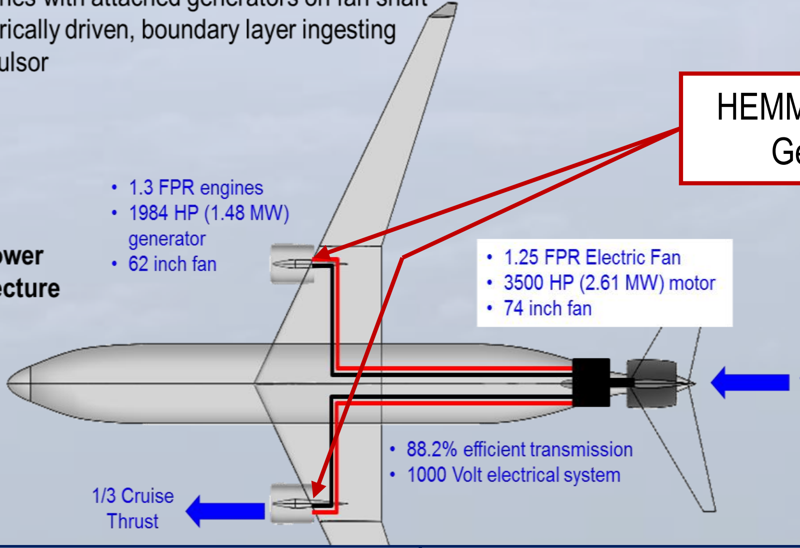
Electric Machine Integration



Single-aisle **T**urboelectric **AiRC**raft with **A**ft **B**oundary **L**ayer propulsion (STARC-ABL)

- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted N+3 (Far-term) geared turbofan engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor

STARC-ABL Power System Architecture



HEMM 6800 RPM Generator

- 1.3 FPR engines
- 1984 HP (1.48 MW) generator
- 62 inch fan

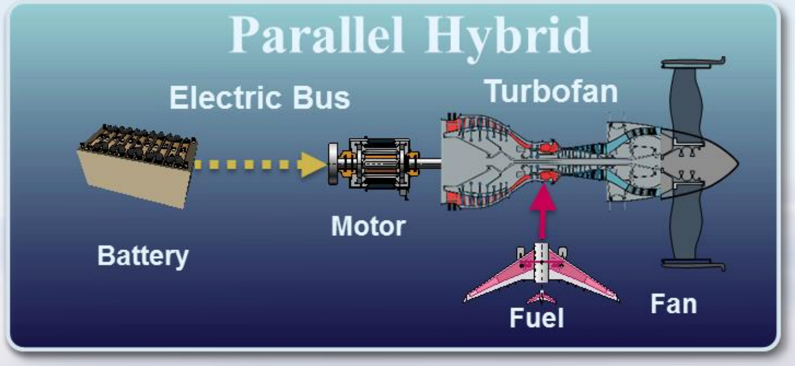
- 1.25 FPR Electric Fan
- 3500 HP (2.61 MW) motor
- 74 inch fan

1/3 Cruise Thrust

- 88.2% efficient transmission
- 1000 Volt electrical system

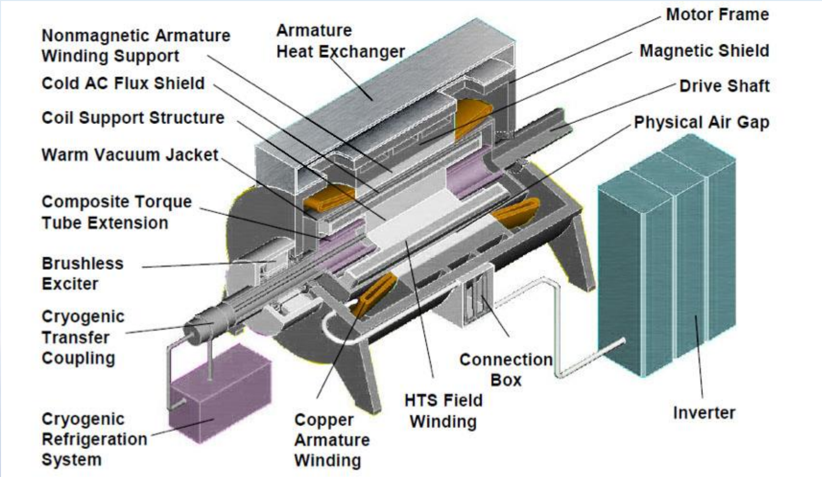
1/3 Cruise Thrust

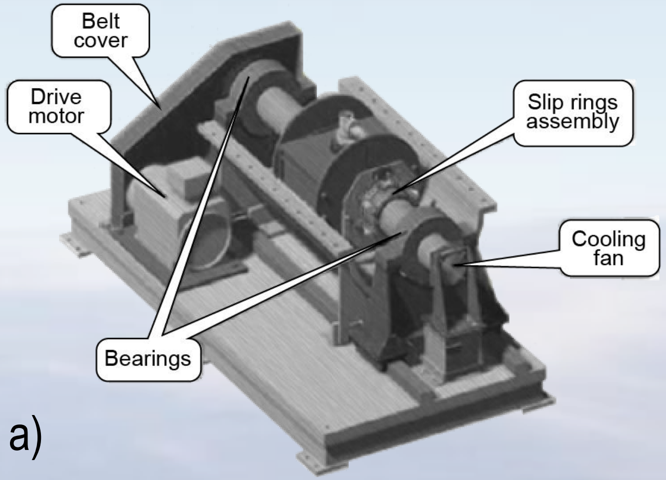
Partial Turbo-electric Benefits From Efficient Generator



Parallel Hybrid Performance Improves with Energy Storage

Related Prior DOE Effort and Recommendation





a)

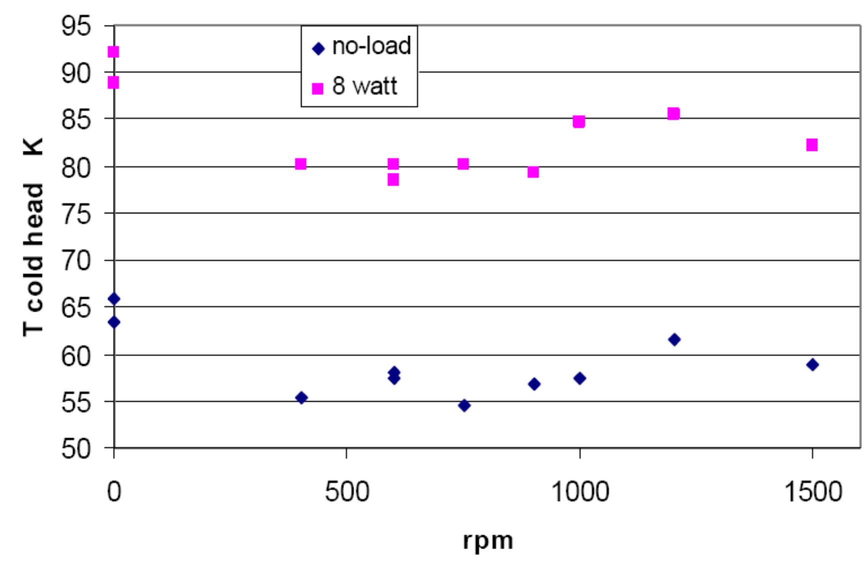
b)

“**A pulse-tube cryocooler** is suitable for usage in a rotating environment. The demonstrated test rig allowed testing to 1500 rpm. There is no evidence that a pulse-tube based rotating cryocooler would not be successful at speeds exceeding 1500 rpm. Our belief is that the integration of the cryocooler into the rotor structure may be done for any rotational speed and such an integration will not increase the complexity of the rotor design.”

Development of Ultra-Efficient Electric Motors
April 2002- Sept. 2007
Reliance Electric Company
26391 Curtiss Wright Parkway, Suite 102
Richmond Heights, OH 44143
Date Published – May 2008

Prepared for the United States Department of Energy
Under Cooperative Agreement – No. DE-FC36-93CH10580
Baldor-DODGE-Reliance

Challenge: Design high aspect ratio symmetrical cryocooler for higher speed operation.
Solution: Redlich Alternator with Single-Stage Pulse-Tube Cooler



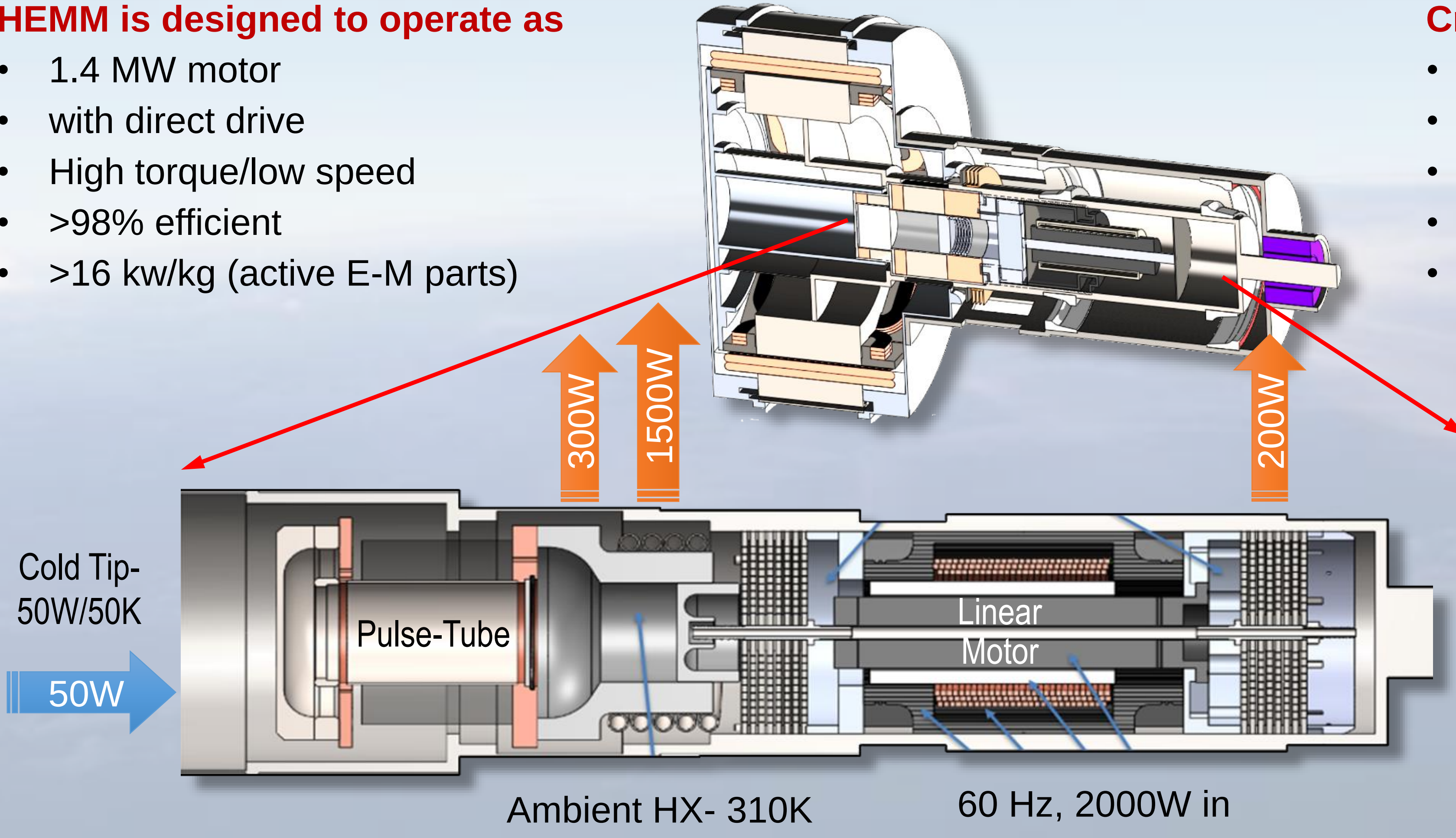
HEMM w/Embedded Cryocooler

HEMM is designed to operate as

- 1.4 MW motor
- with direct drive
- High torque/low speed
- >98% efficient
- >16 kw/kg (active E-M parts)

Cryocooler Key Features:

- Cool superconducting rotor
- Fit inside rotating motor
- Integrates cooler and linear machine
- Operate rotating or stationary
- No cold moving parts



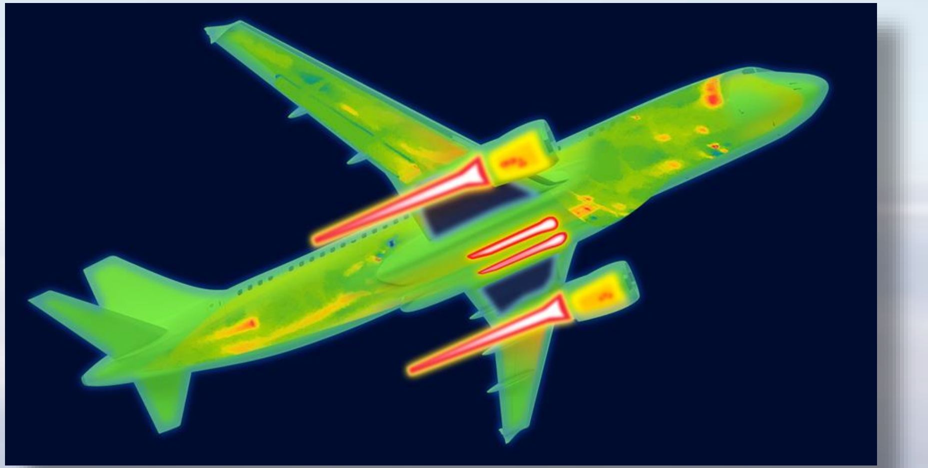
Top Level Parameter	Value
Frequency	60 Hz
Gas	Helium
Pressure	6.2 MPa
Heat Lifted @ 50K	55W
Heat Rejected	2000W
Electrical In	2000W
Mechanical PVin	1661W
Coil Current Density	4 A/mm2
Piston Amplitude	1.3 cm

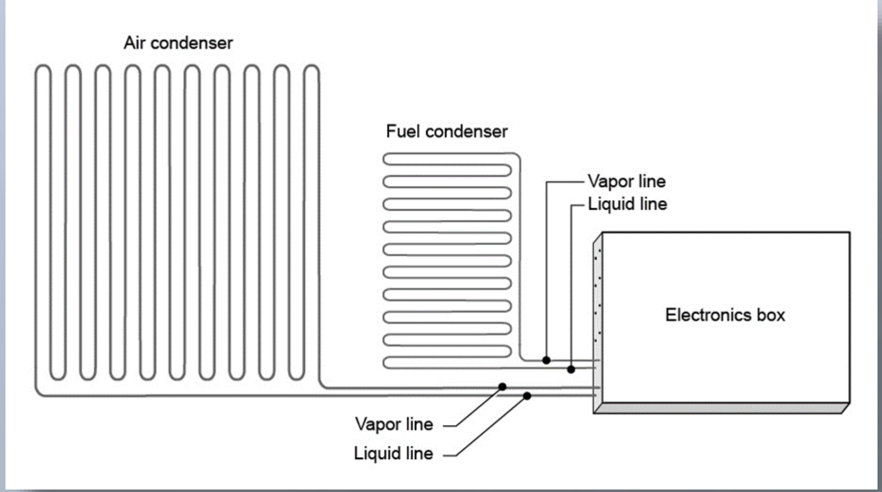
Machine is superconducting inside the rotor, but integrates with aircraft conventionally

Electric Aircraft Thermal Challenge

Current proposed solutions include:

- Ram air HX
  - – adds weight and aircraft drag
- Convective skin cooling HX
  - – adds weight, drag, and inefficient
- Dumping heat into fuel
  - – limited thermal capacity
- Dumping heat into lubricating oil
  - – limited thermal capacity
- Active cooling
  - – adds weight and consumes engine power
- Phase change cooling
  - –adds weight and limited thermal capacity
- Heat pipe, pumped multiphase, vapor compression
  - – adds weight and consumes engine power



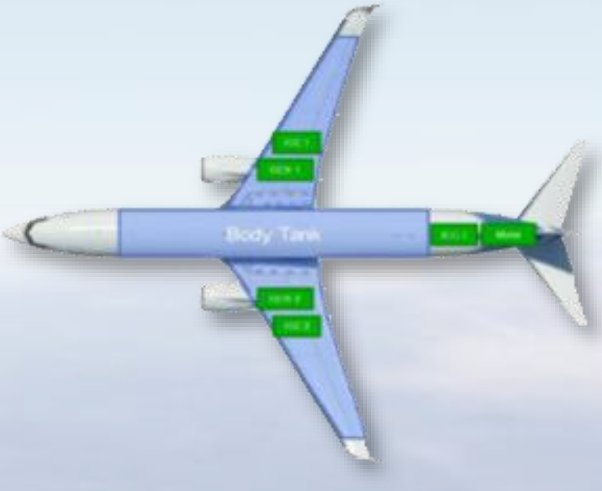


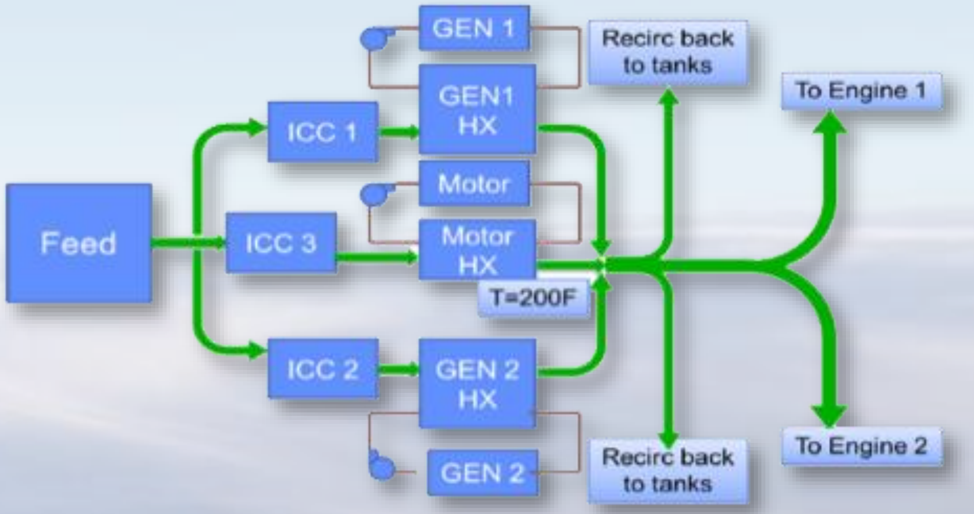
50kW to >800kW of low grade thermal heat trapped within composite aircraft body

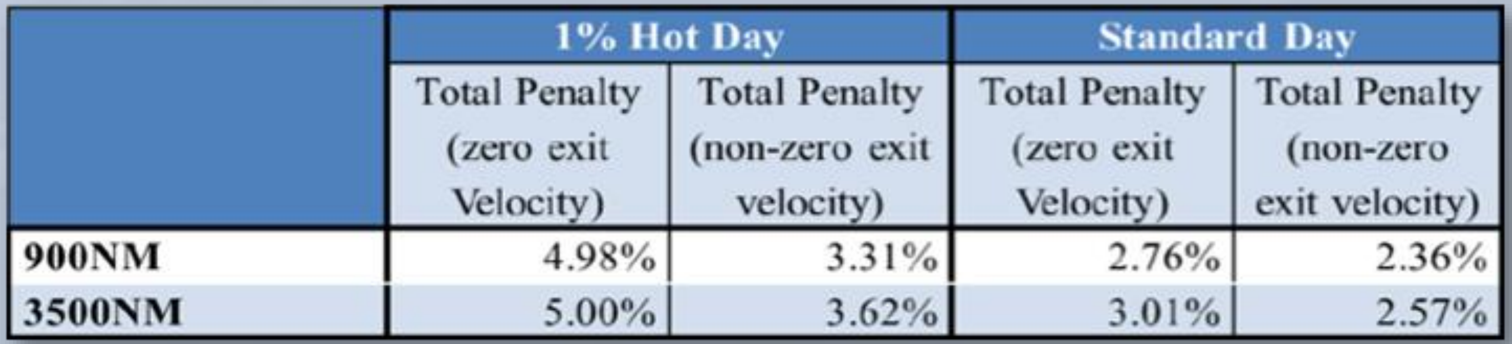
Thermal Management Limits

Dumping heat into:

- Fuel (limited 50 kW)
- Outer mold line (limited 300 kW)
- Ram air (see below for losses)
- By-pass air (see below for losses)

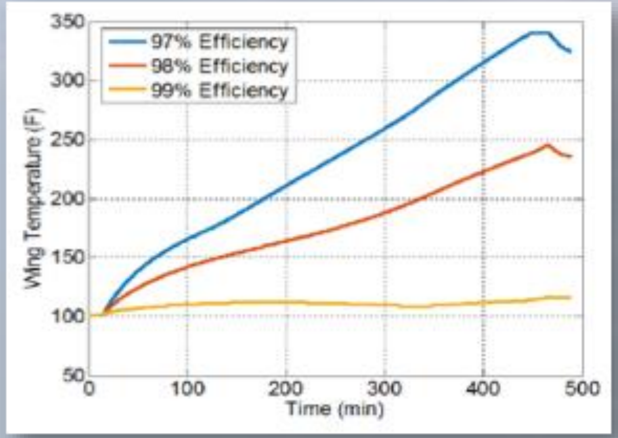






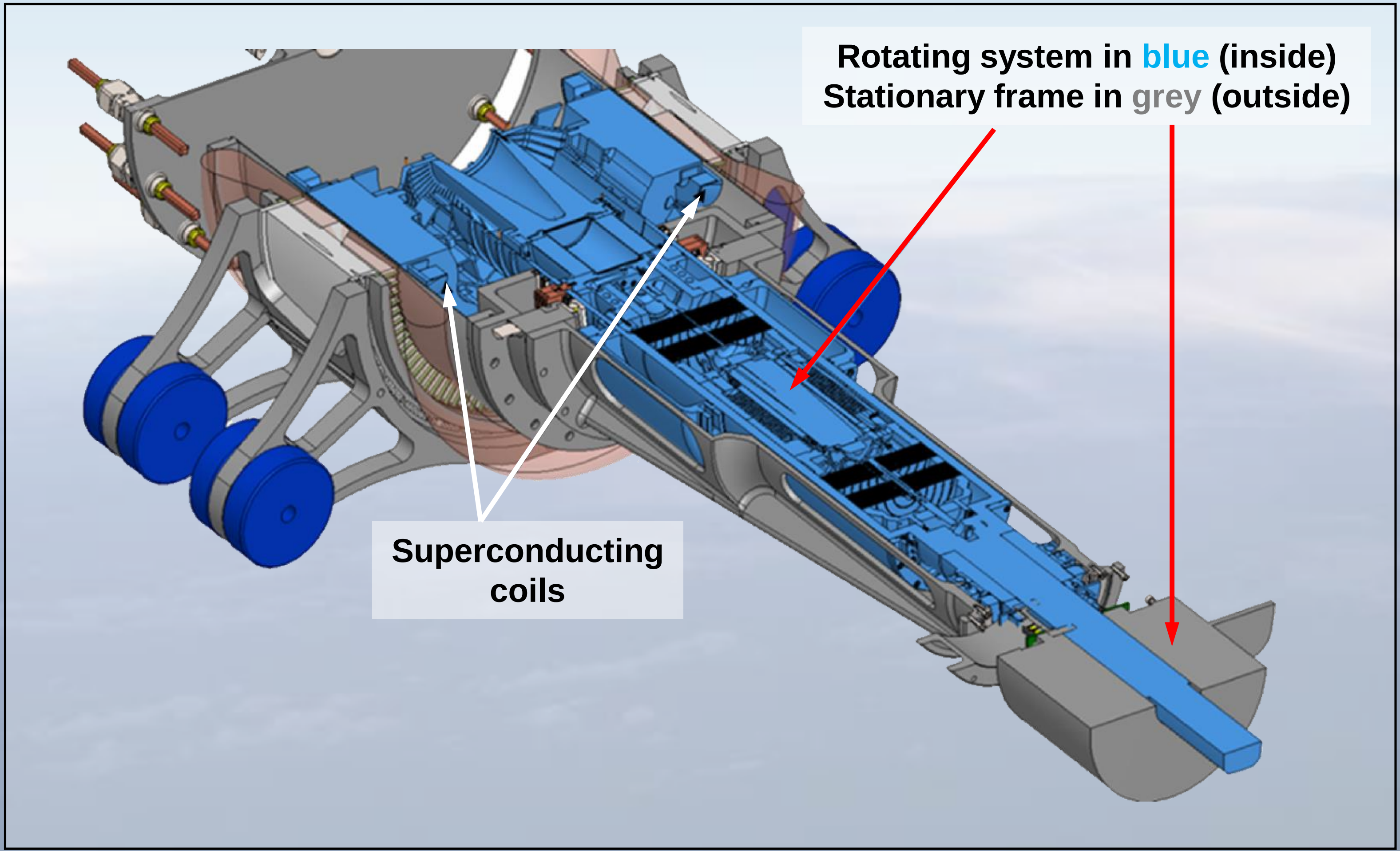
	1% Hot Day		Standard Day	
	Total Penalty (zero exit Velocity)	Total Penalty (non-zero exit velocity)	Total Penalty (zero exit Velocity)	Total Penalty (non-zero exit velocity)
900NM	4.98%	3.31%	2.76%	2.36%
3500NM	5.00%	3.62%	3.01%	2.57%

Thermal Runaway with Composite Fuselage



Electric Aircraft Propulsion Thermal management technology impacts performance and safety certification

HEMM Thermal Loads (Cryogenic and Ambient)



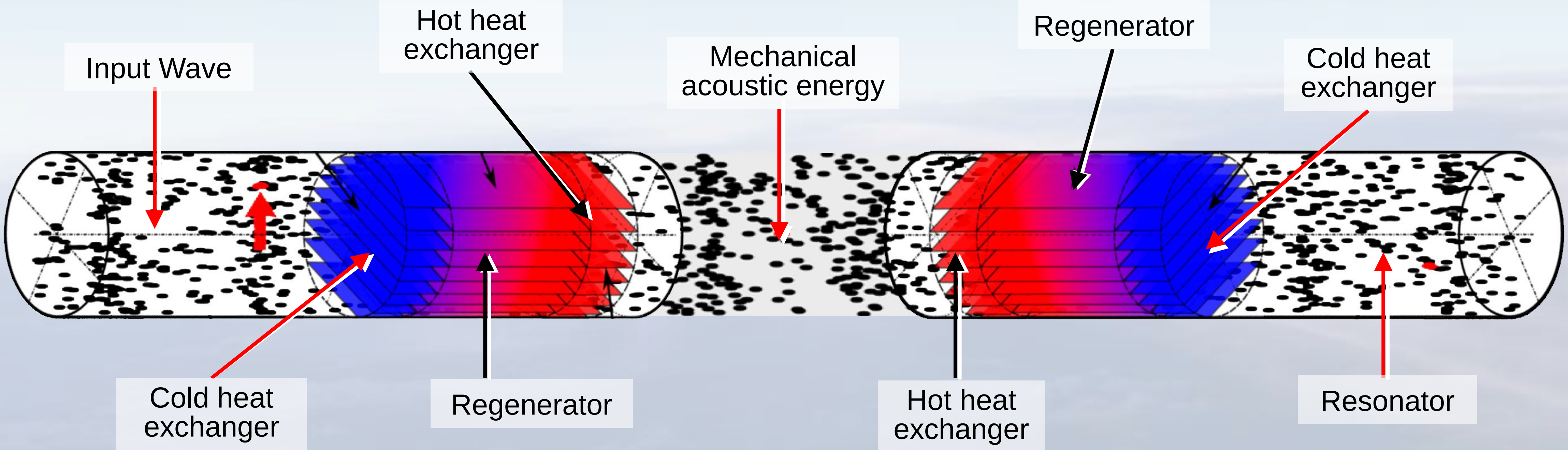
Rotating system in blue (inside)
Stationary frame in grey (outside)

Superconducting coils

Component	Loss (kW)
Electromagnetic Losses	9.3
Stator Core	3.9
Stator winding (I^2R)	4.6
Stator winding proximity	0.8
Rotor core	0.009
Rotor coils	0
Other Losses	4
Cryocooler Power	2
Bearings	1
Vacuum Seals	1
Total Losses	13.5
Total Losses(+20% margin)	16.2

Under 50W Cryogenic Heat Load Expected

Basic Building Block for Electric Aircraft: Thermo-Acoustic Engine and Heat Pumping

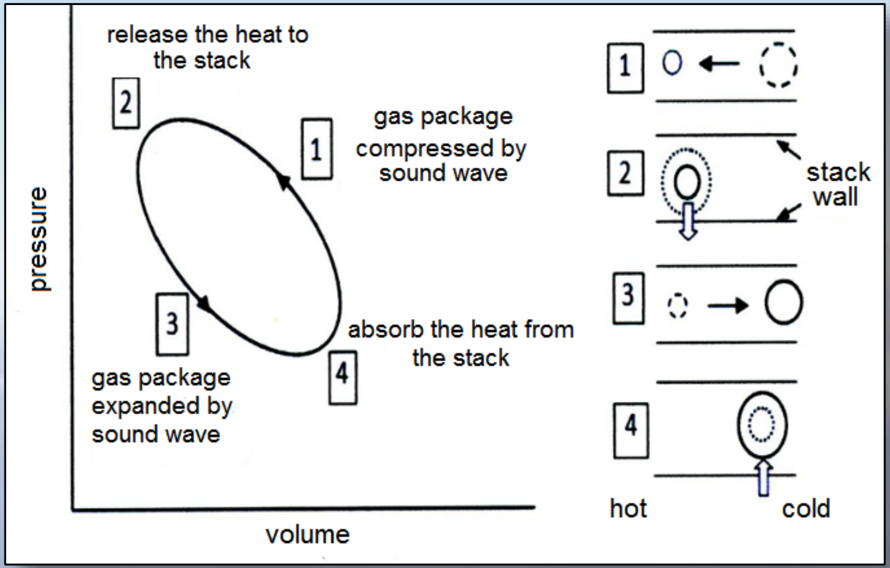


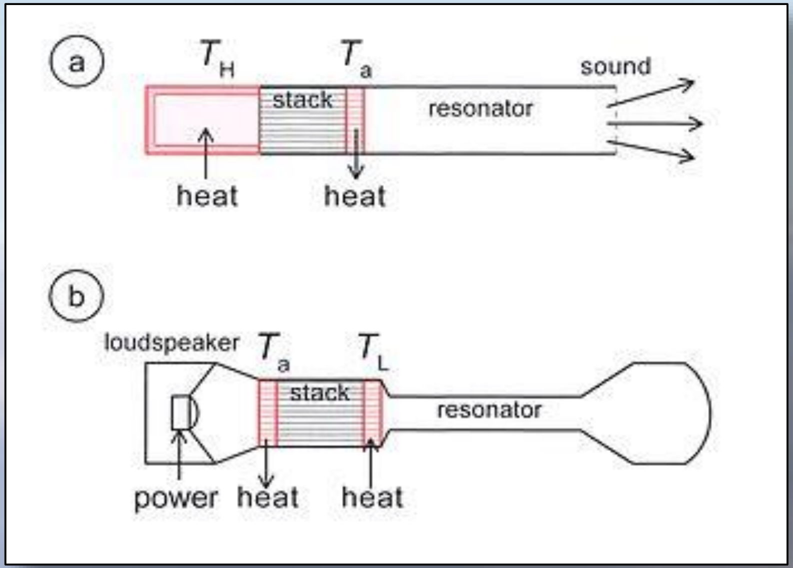
KEY PROPERTIES

Can be used for thermal energy conversion:

- From heat to mechanical power
- From mechanical power to cooling
- From heat to heat pump when used in double configuration shown

No Moving Part Acoustic Heat Pump





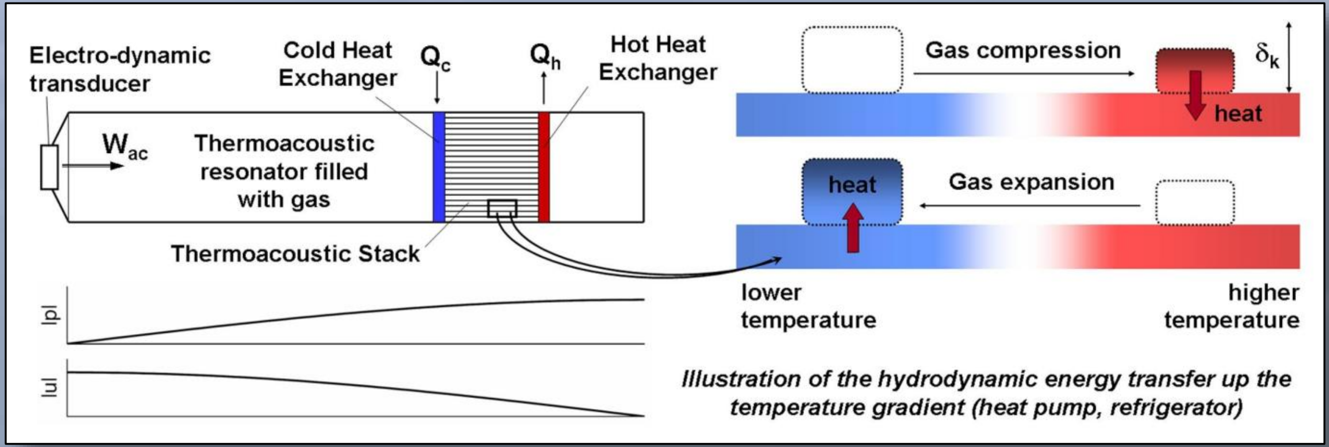
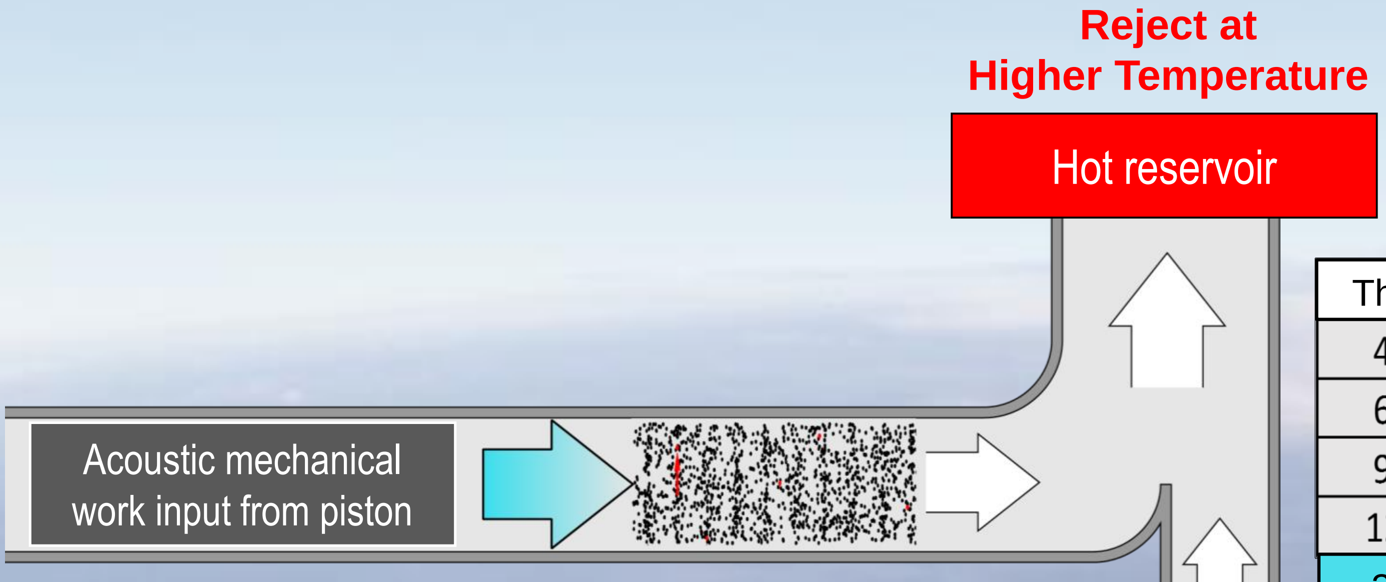


Illustration of the hydrodynamic energy transfer up the temperature gradient (heat pump, refrigerator)

Acoustic Mechanical Work Energy Moves Heat From Cold to Hot

Acoustic Heat Pump Efficiency



Reject at Higher Temperature

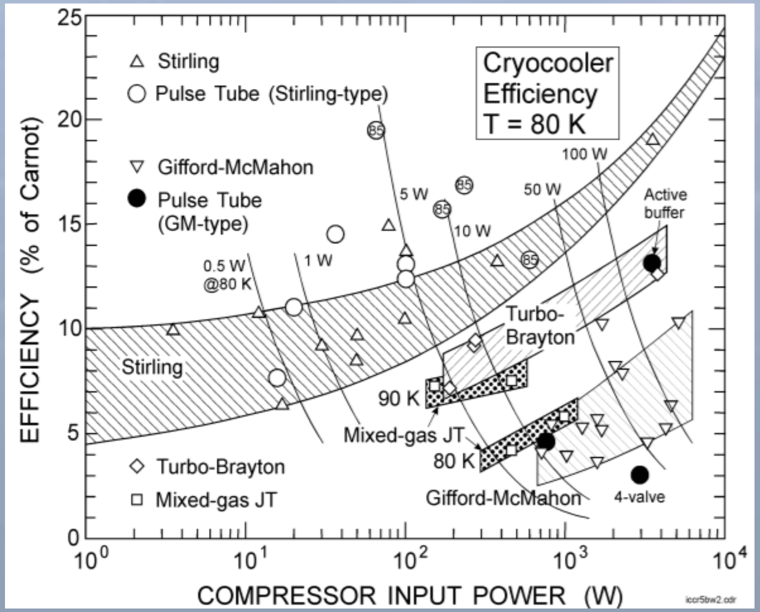
Hot reservoir

Acoustic mechanical work input from piston

Cold reservoir

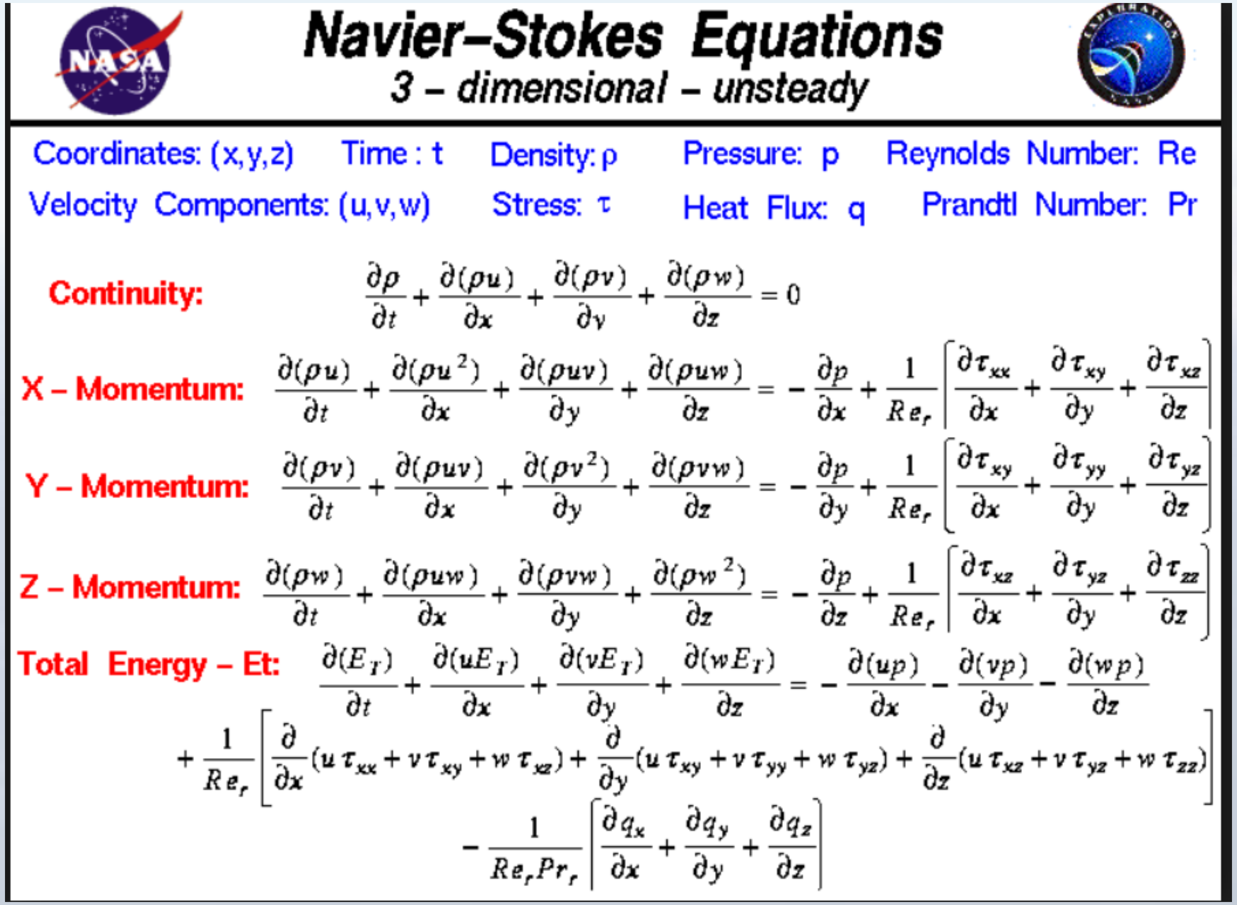
Accept at Lower Temperature

Th (k)	Tc (k)	Ratio (W/Qc)	Qout (W)	WorkIn (W)	Qin (W)
400	300	1:3	1000	250	750
600	300	1:1	1000	500	500
900	300	2:1	1000	666.66667	333.3333
1200	300	3:1	1000	750	250
300	50	40:1	1025	1000	25



More input acoustic power required as the heat lifted from the cold reservoir increases and/or as temperature gap increases

Governing Thermo-Acoustic Equations and Modeling



Navier–Stokes Equations

3 – dimensional – unsteady

Coordinates: (x,y,z) Time : t Density: ρ Pressure: p Reynolds Number: Re

Velocity Components: (u,v,w) Stress: τ Heat Flux: q Prandtl Number: Pr

Continuity:
$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

X – Momentum:
$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right]$$

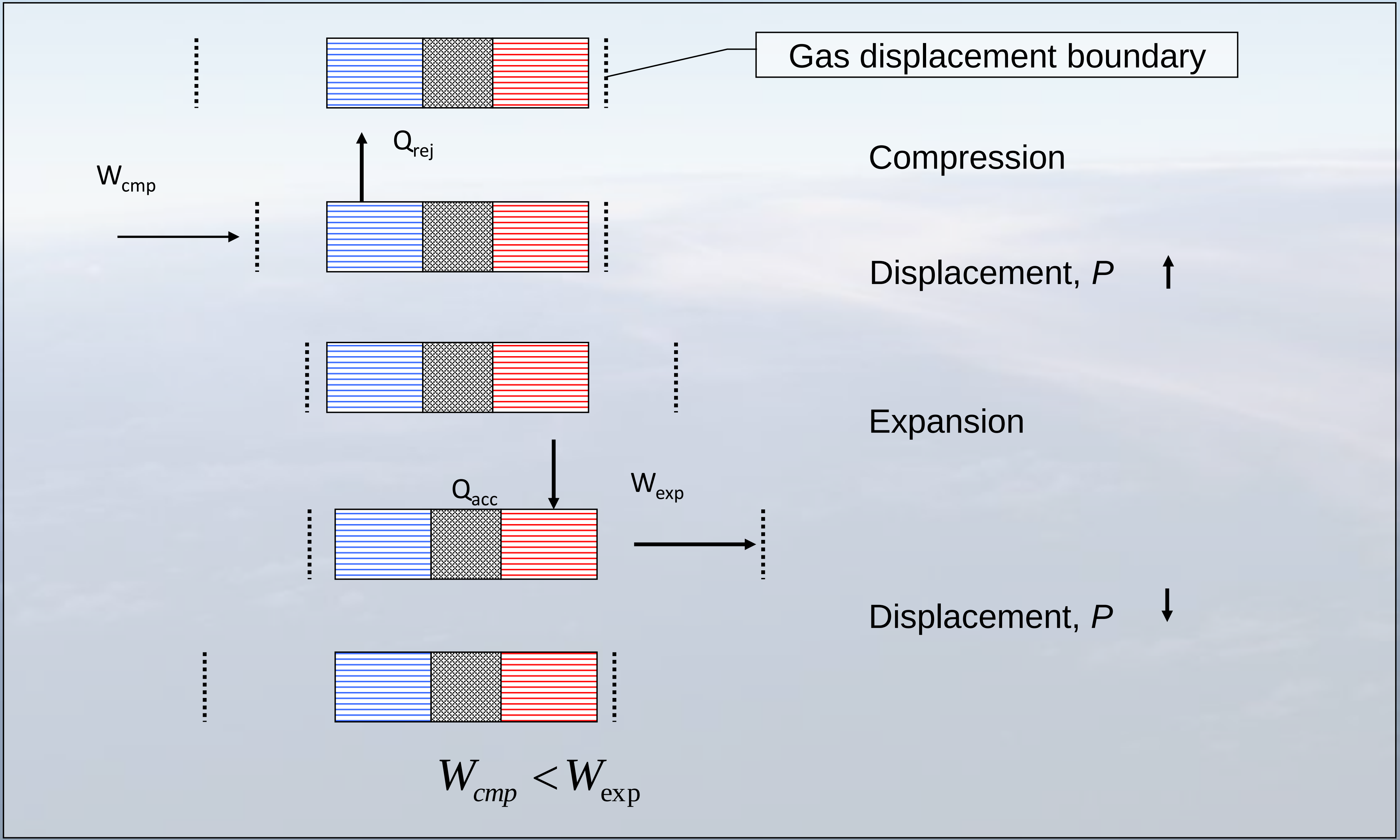
Y – Momentum:
$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum:
$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right]$$

Total Energy – Et:
$$\frac{\partial(E_T)}{\partial t}+\frac{\partial(uE_T)}{\partial x}+\frac{\partial(vE_T)}{\partial y}+\frac{\partial(wE_T)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}$$
$$+\frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx}+v\,\tau_{xy}+w\,\tau_{xz})+\frac{\partial}{\partial y}(u\,\tau_{xy}+v\,\tau_{yy}+w\,\tau_{yz})+\frac{\partial}{\partial z}(u\,\tau_{xz}+v\,\tau_{yz}+w\,\tau_{zz})\right]$$
$$-\frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]$$

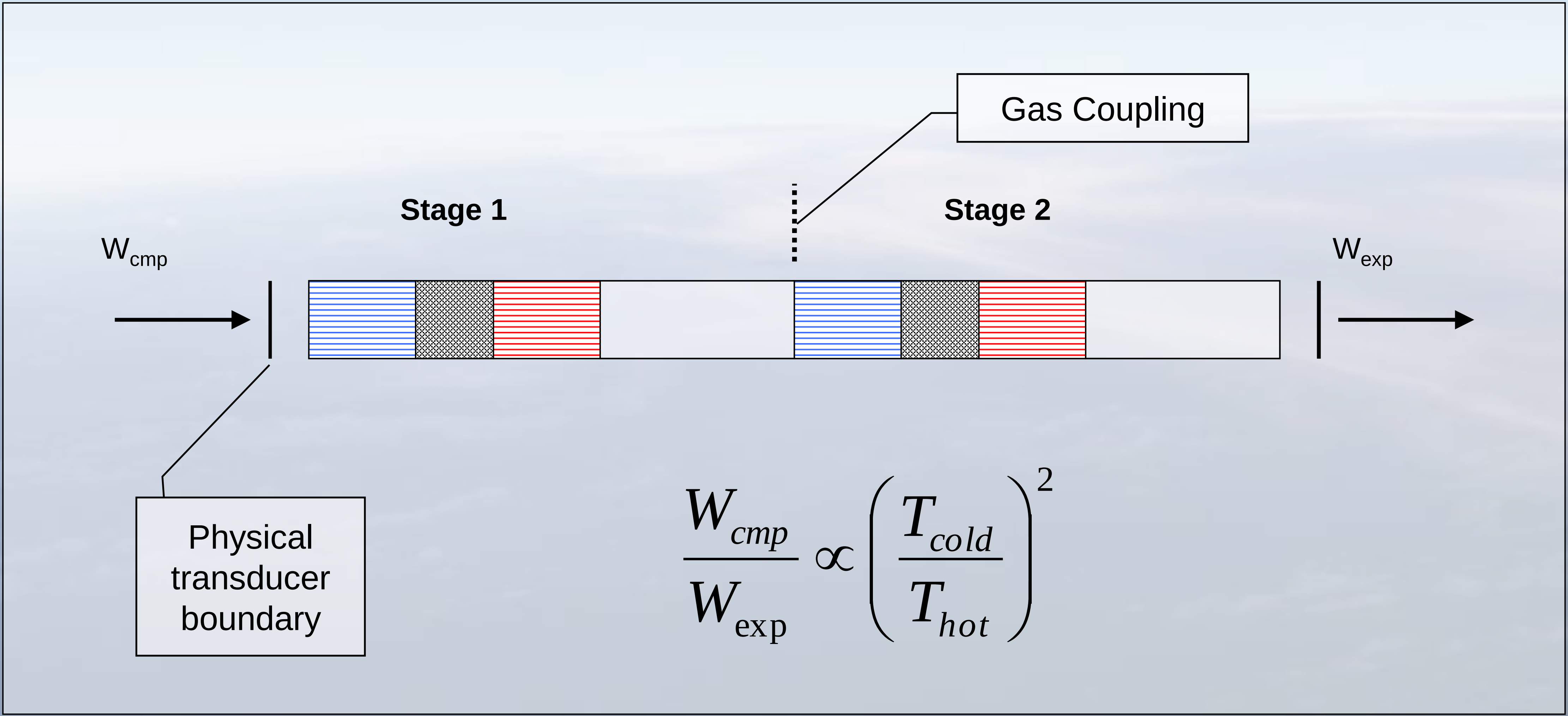
- Represent all known physics in the Stirling Cycles and Maxwell Equations for Generator
- Require specialized numerical resolution to combine hydrodynamics with acoustics
- COMSOL cannot solve system for example
- DELTAE frequency domain LANL
- SAGE time-periodic domain GRC/Gedeon
- Numerical Schemes
  - Discontinuous Galerkin FE
  - Compact Schemes
  - Absorbing Boundary Layer
  - Low Order Diffusion a Problem
  - Space and Time Together Works with sinusoidal basis functions
- Gas Bearing Hydrodynamics with Fluent FV

Basic Acoustic Traveling Wave Thermodynamic Cycle



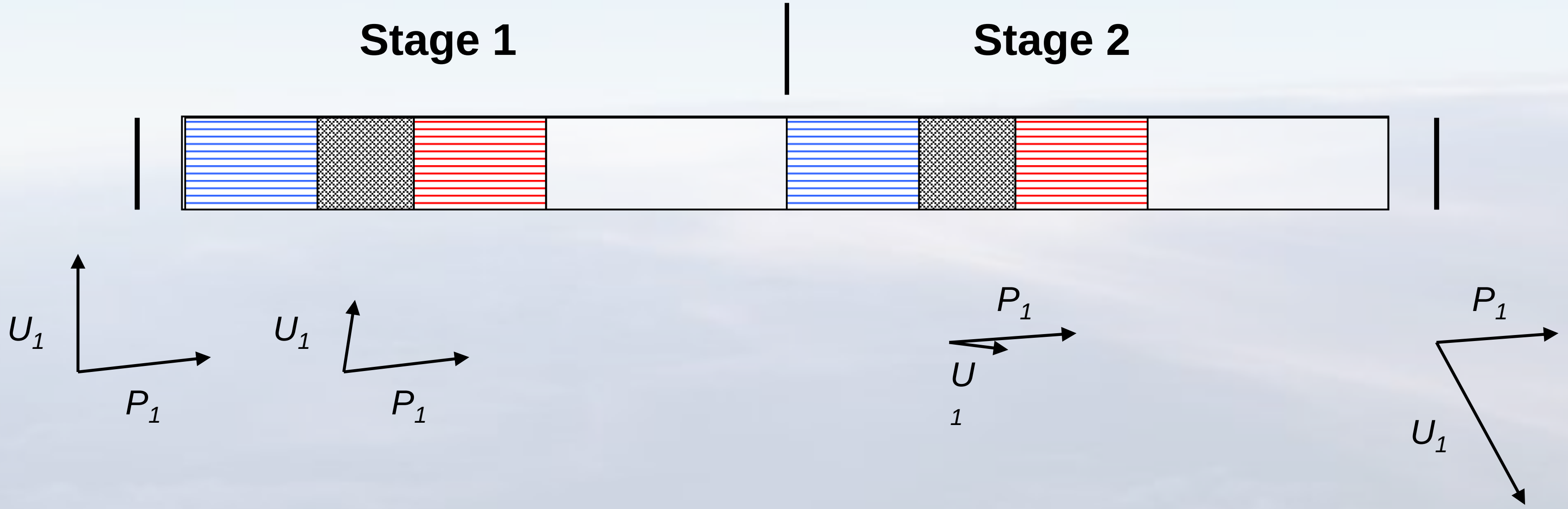
$$W_{cmp} < W_{\exp}$$

Two-Stage Cascade



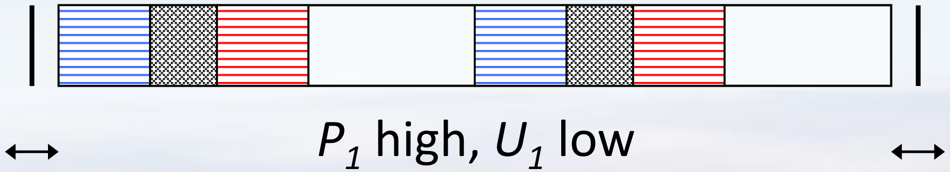
$$\frac{W_{cmp}}{W_{\exp}} \propto \left(\frac{T_{cold}}{T_{hot}}\right)^2$$

PV Phasing



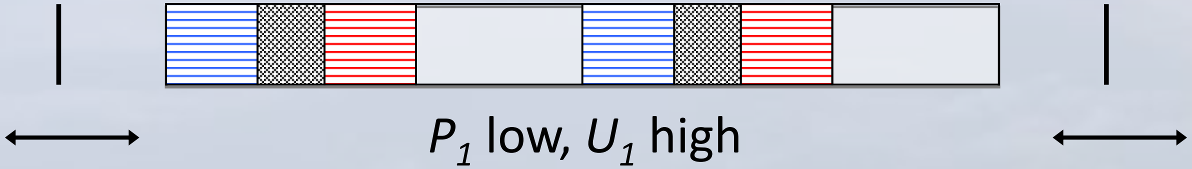
- P_1 phasors everywhere nearly constant
- U_1 phasors progressively lag due to volume (compliance)
- Ideally, P_1 and U_1 in phase in regenerators
- Gas inertia (inertance) can be used to counter U_1 lag
- E.g. Swift inter-stage inertance tube (see reference 4)

End Transducer Options



P_1 high, U_1 low

High Impedance (Piezo or magnetorestrictive)

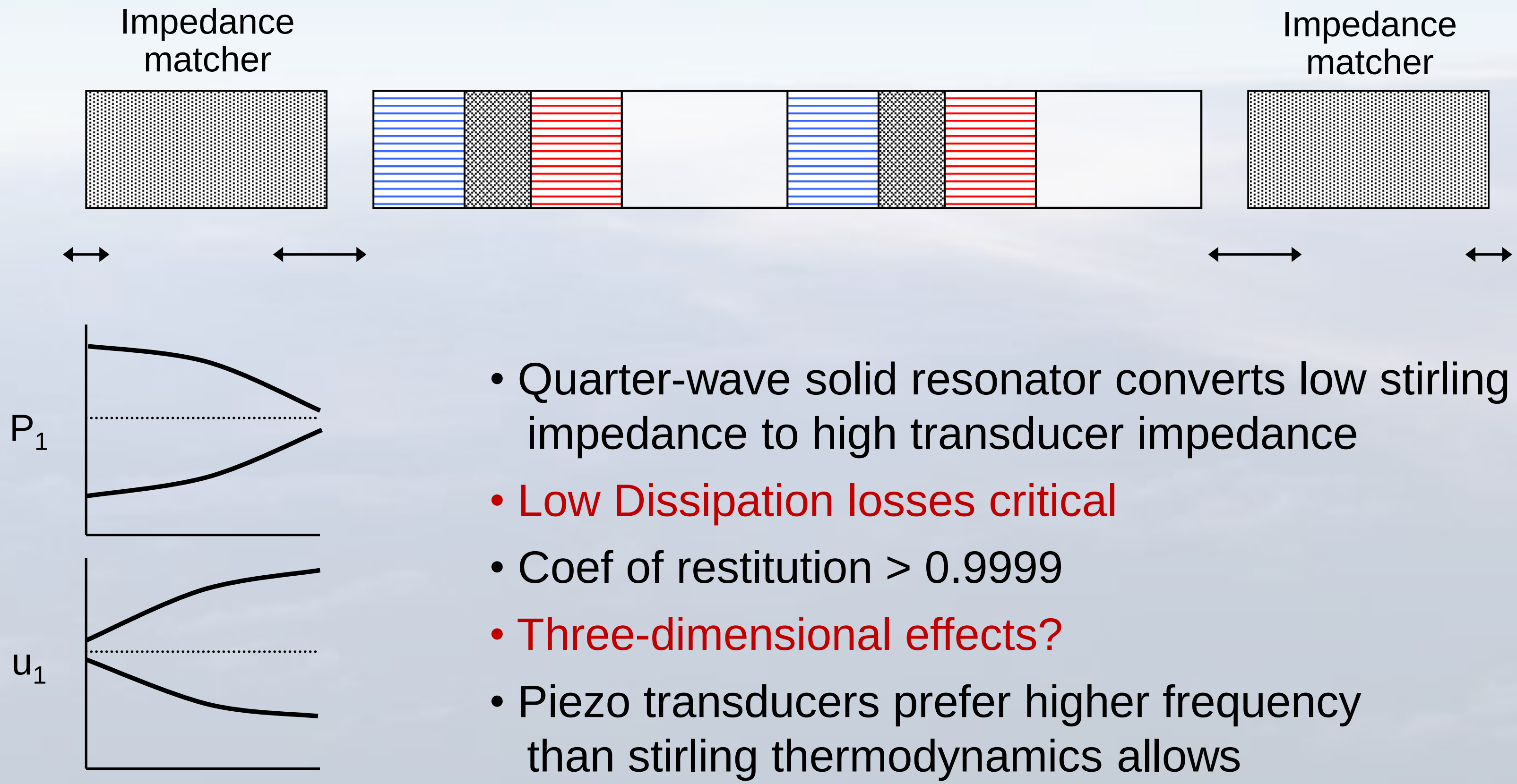


P_1 low, U_1 high

Low Impedance (Moving Magnet actuator)

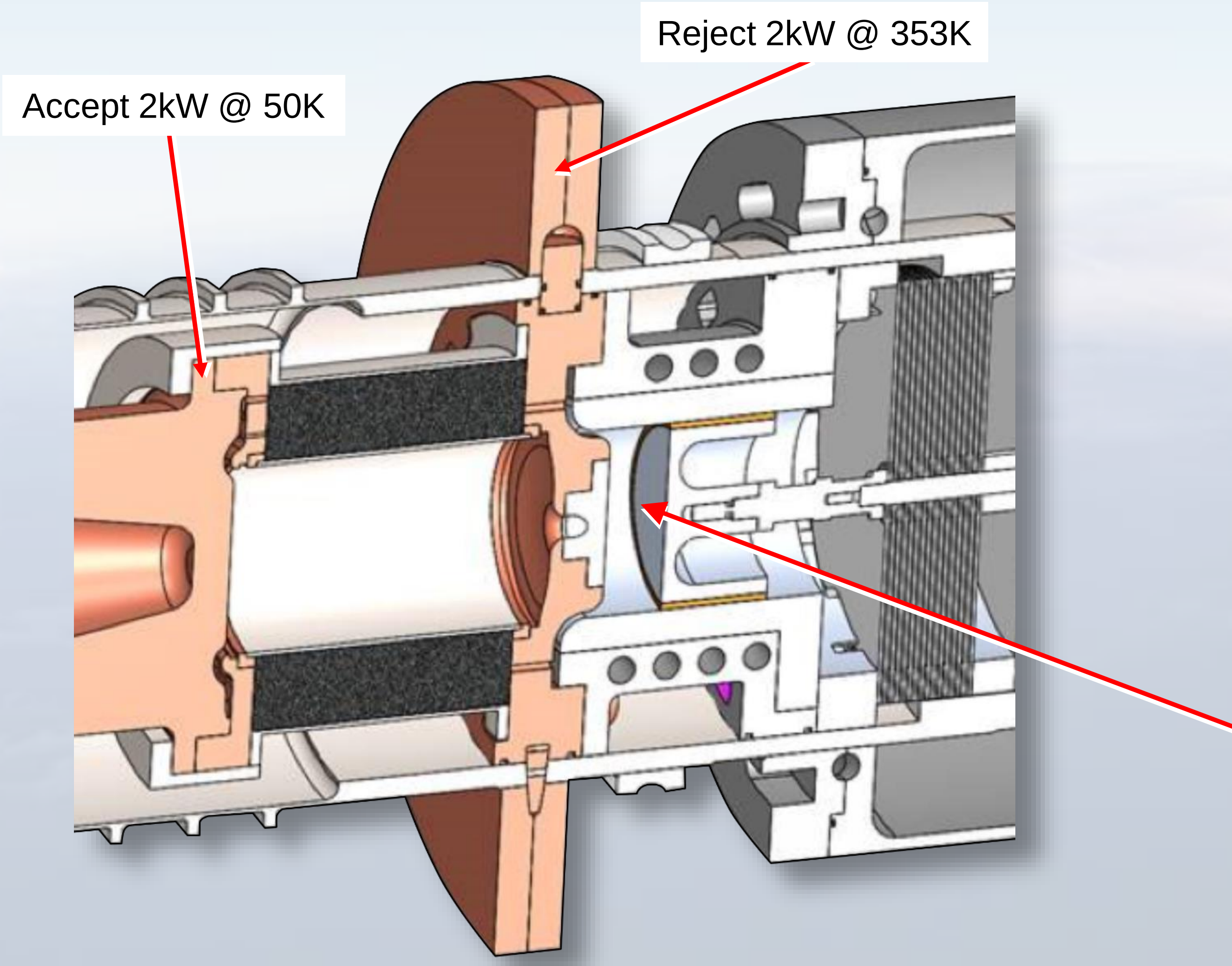
Impedance is P_1 / U_1

High Impedance Matching

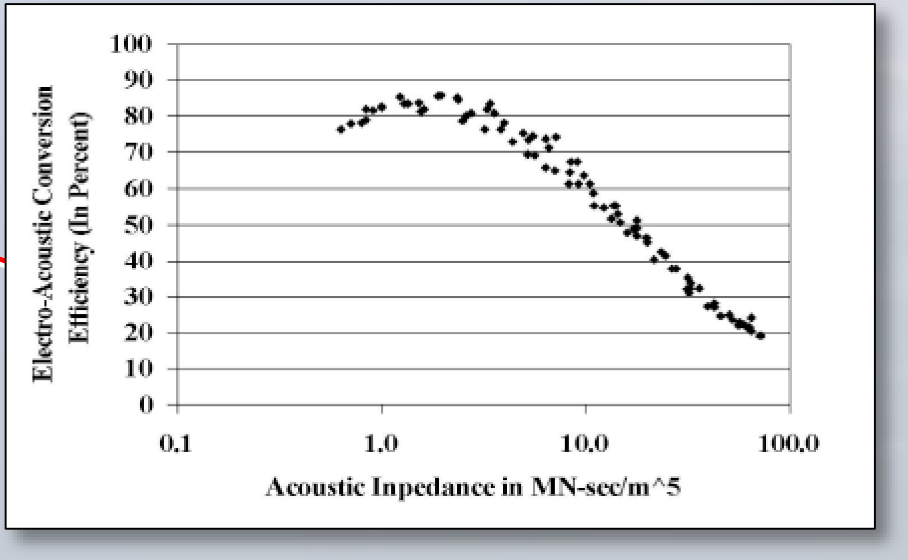


- Quarter-wave solid resonator converts low stirling impedance to high transducer impedance
- Low Dissipation losses critical
- Coef of restitution > 0.9999
- Three-dimensional effects?
- Piezo transducers prefer higher frequency than stirling thermodynamics allows

Low Impedance Matching



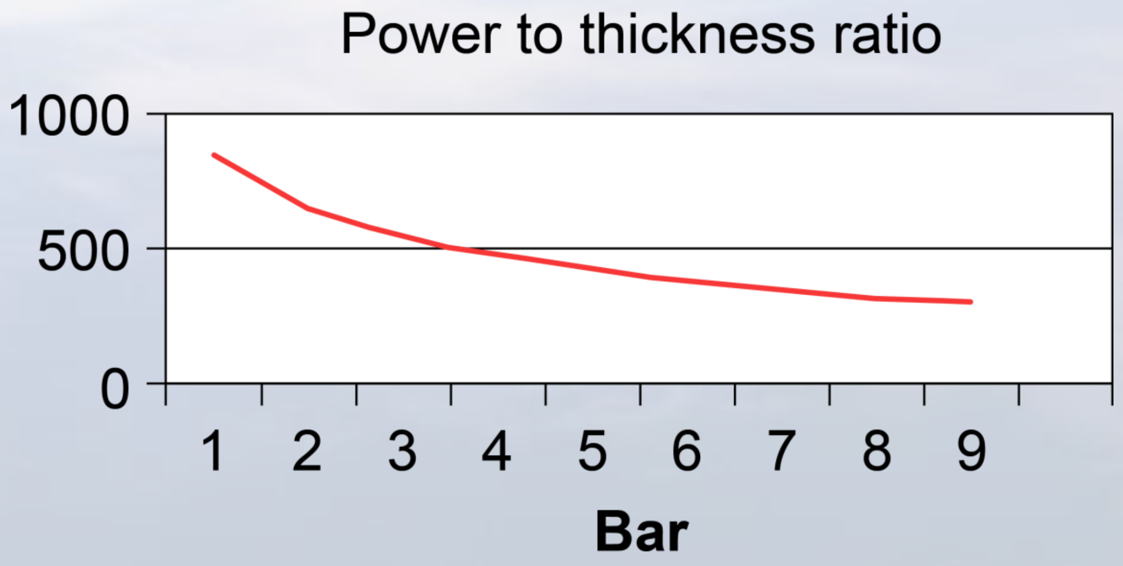
- Moving magnet linear transducers can intrinsically match stirling impedance
- But have relatively high reciprocating mass compared to piezo transducers
  - F=m w^2 A
- Limiting maximum operating frequency without external springs



System Optimization

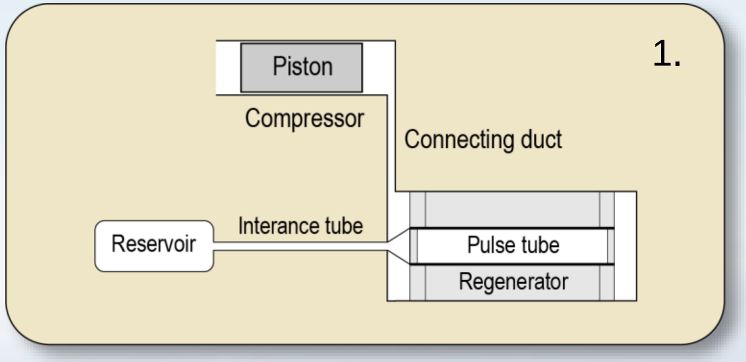
Optimization examples

- Increased frequency
  - alternator efficiency ↑
  - thermo-acoustic efficiency ↓
- Increased pressure
  - Mass of containment ↑
  - Power output per volume ↑
- TAE topology
  - Standing wave less complex, (Hence lighter for given efficiency)
  - Travelling wave more efficient (Hence less weight per Watt)
- Working Gas
  - Air is cheapest
  - Helium allows higher frequency (Hence lighter alternator and TAE)



Heat Pump Trade Study

1.



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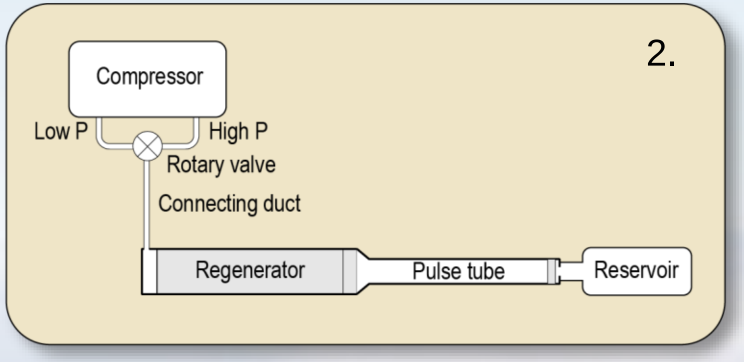

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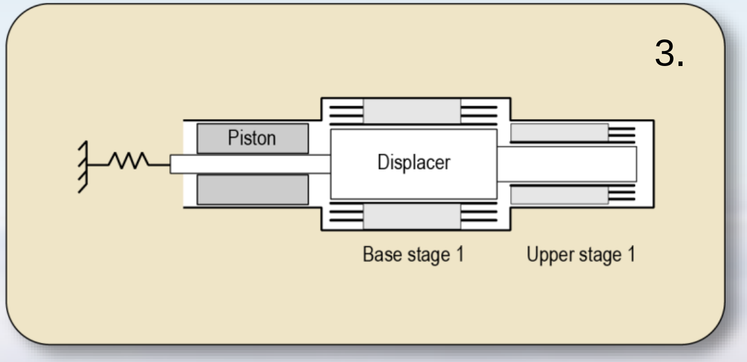

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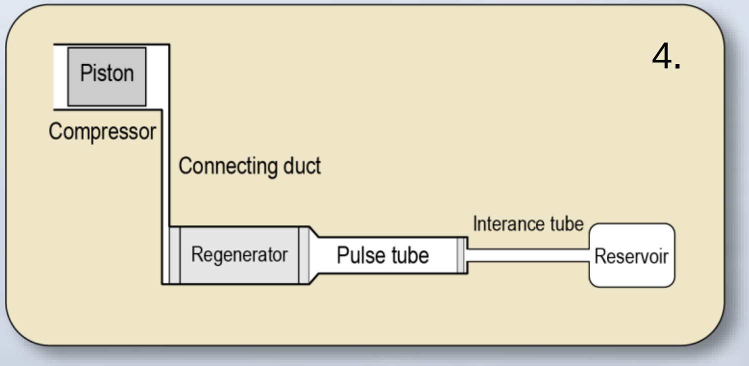

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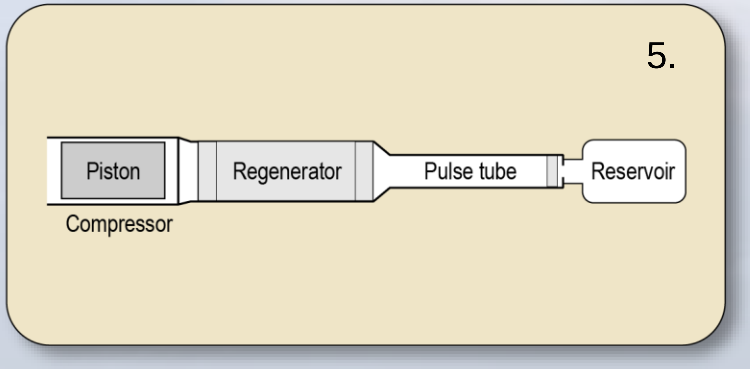

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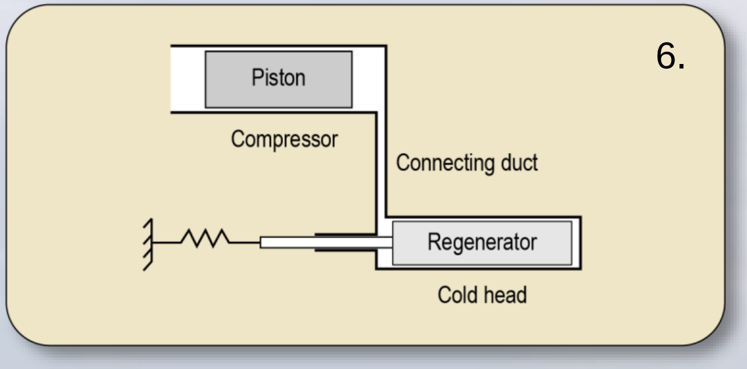
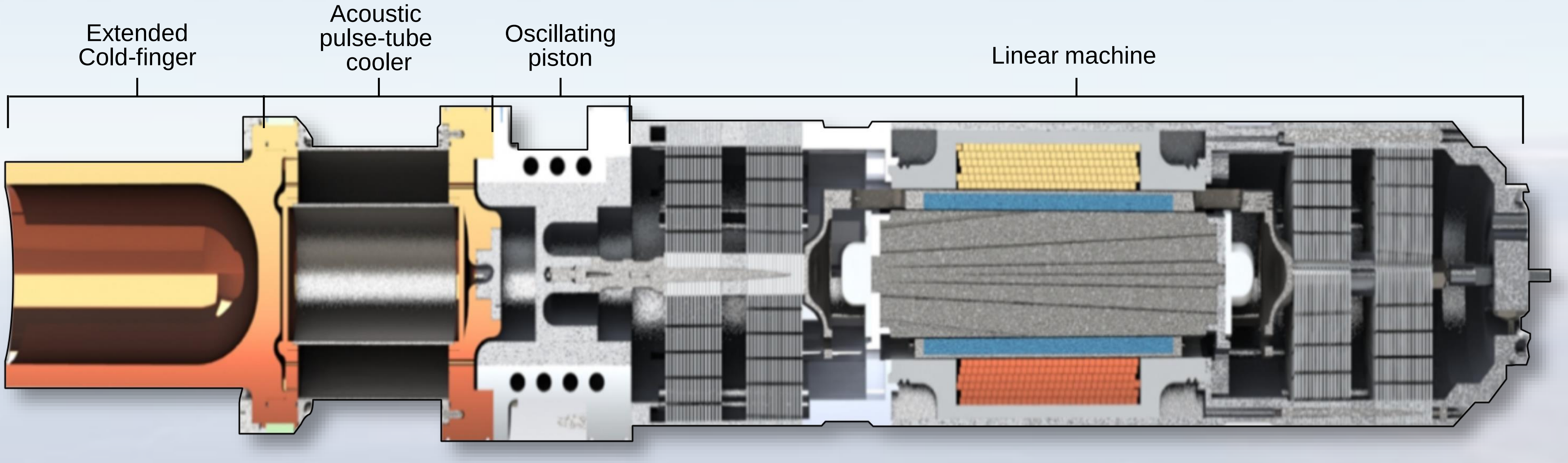


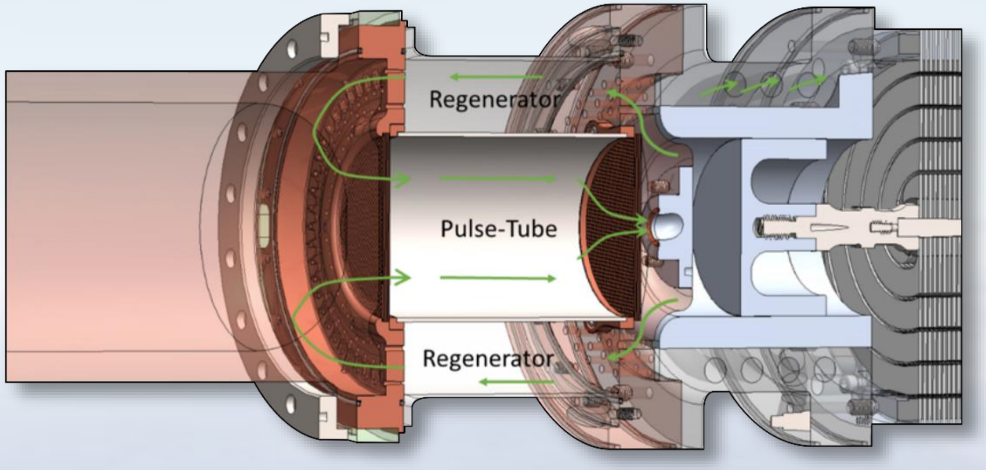
Cryocooler Type	Property
1. Co-axial Pulse Tube	Efficient enough and fits in rotating shaft
2. GM-Pulse Tube	Not Efficient
3. Two-Stage Stirling Displacer	Very efficient, but challenging to rotate displacer
4. Inline Pulse Tube	Too long vs. Co-axial
5. Pulse Tube	Not as efficient as two-stage, Too long
6. Split Cycle	Not axi-symmetric for high speed rotation

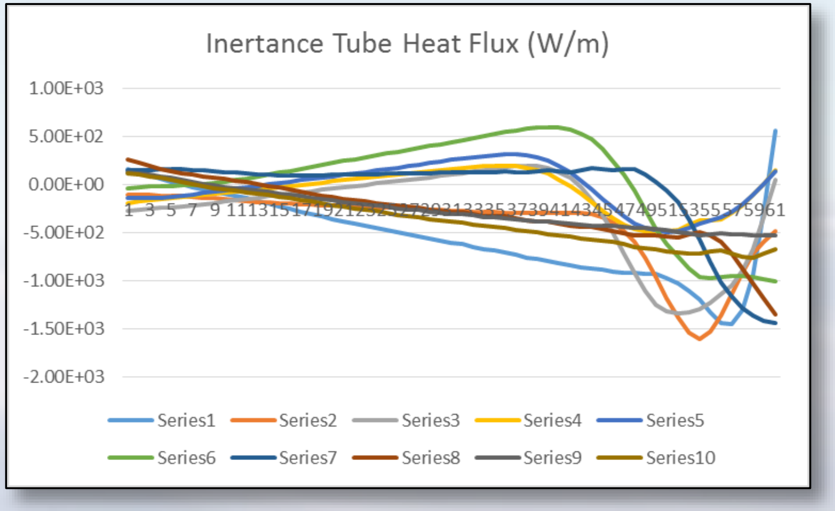
Selected Configuration

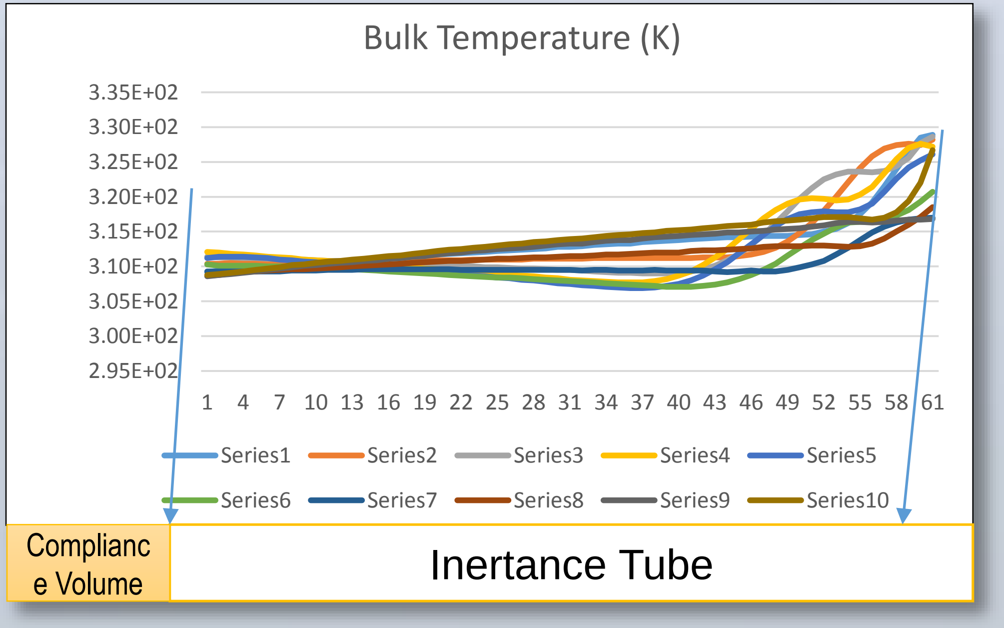


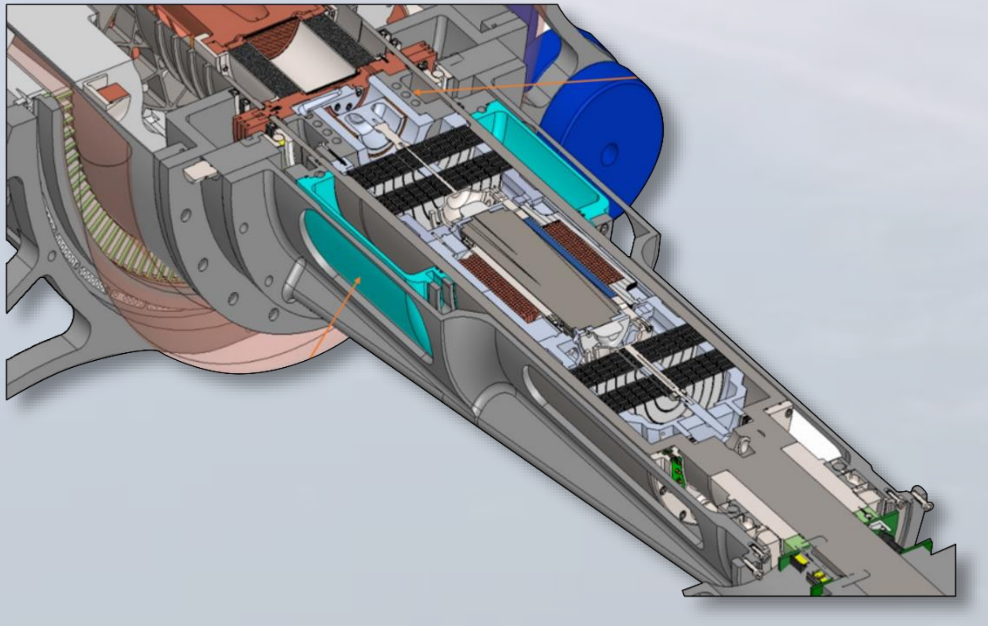
- Overall design is axisymmetric for dynamic stability under rotation
- Redlich style permanent magnet linear machine increases force with axial length increases (high aspect ratio)
- No cold moving parts or bearings
- Single tight-clearance seal that can be supported with many radially stiff flexure bearings
- Fits within 100mm diameter torque tube
- Can be designed to lift 50W at 50K with reasonable efficiency and size
- Thermal rejection can be located outside the vacuum enclosed rotor area

Acoustic Circuit

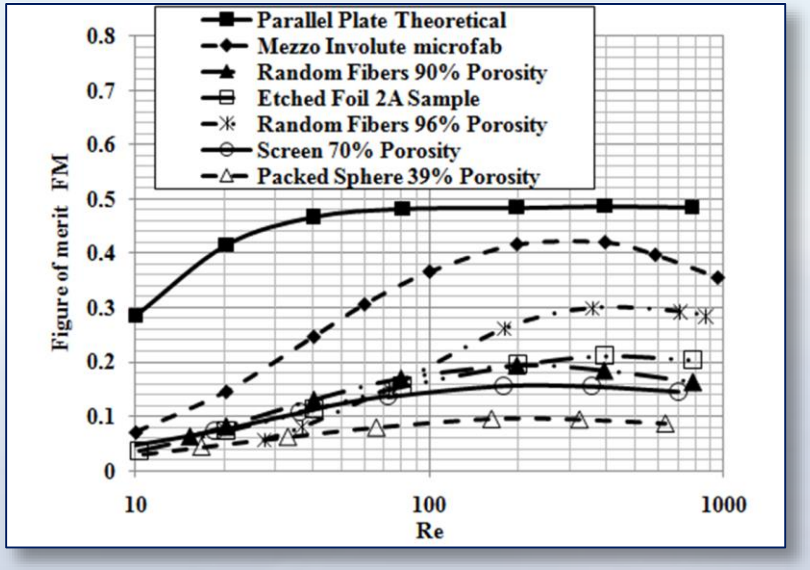




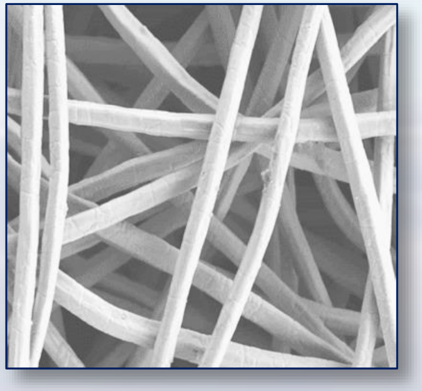




Regenerators

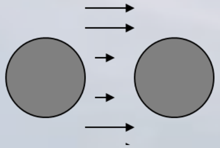


$$F_M = \frac{1}{f\left(\frac{R_e P_r}{4N_u} + \frac{N_k}{R_e P_r}\right)}$$



- *f*=Darcy friction factor
- N_u=Nusselt Number, *hd/k*
- N_k=effective gas conductivity due to thermal dispersion as a Fraction of molecular conductivity
- R_e=Reynolds number, *pud/k*
- P_r=Pradtl number, $C_p\mu/k$
- *d*-hydraulic diameter

Wakes and Eddies

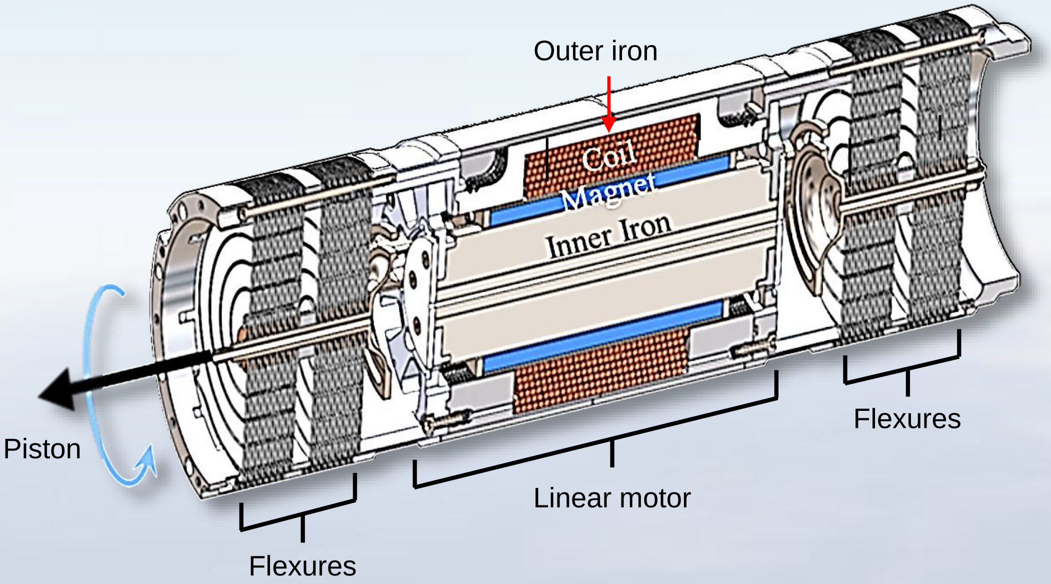


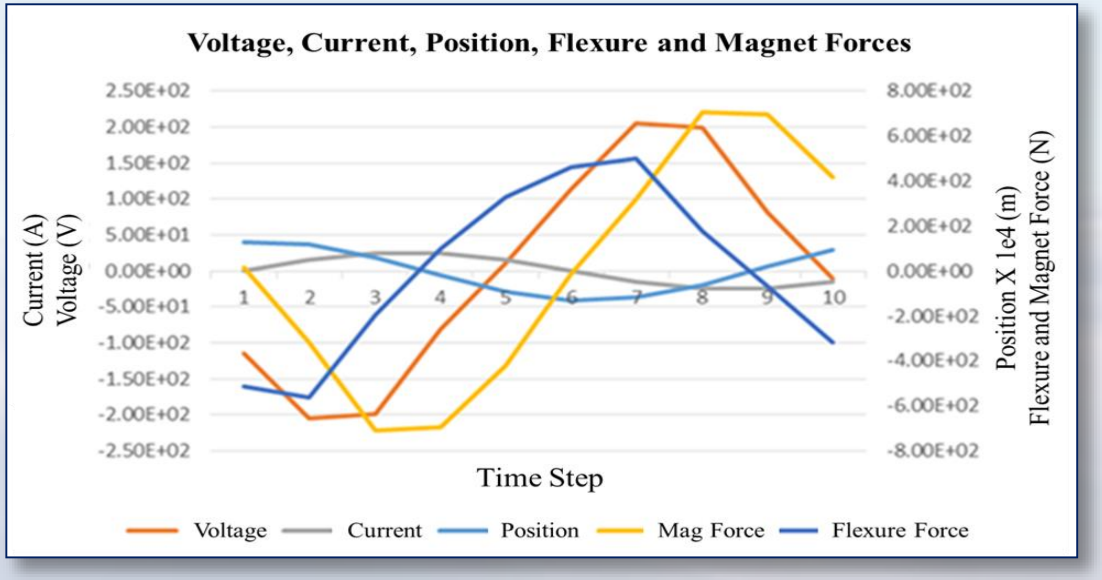
Stagnation Zones

- Wakes and eddies increase ∆P and thermal dispersion (axial conduction losses)
- Thermal dispersion was measured/simulated during DOE amd NASA efforts
- Stagnation zones tend to decrease heat transfer
- Blowby at wall, wall-caused flow non-uniformities found to be potential random-fiber/wire screen regeneration losses

Piston Heat Flux Higher Fidelity Distribution

Redlich Linear Machine Cycle Performance





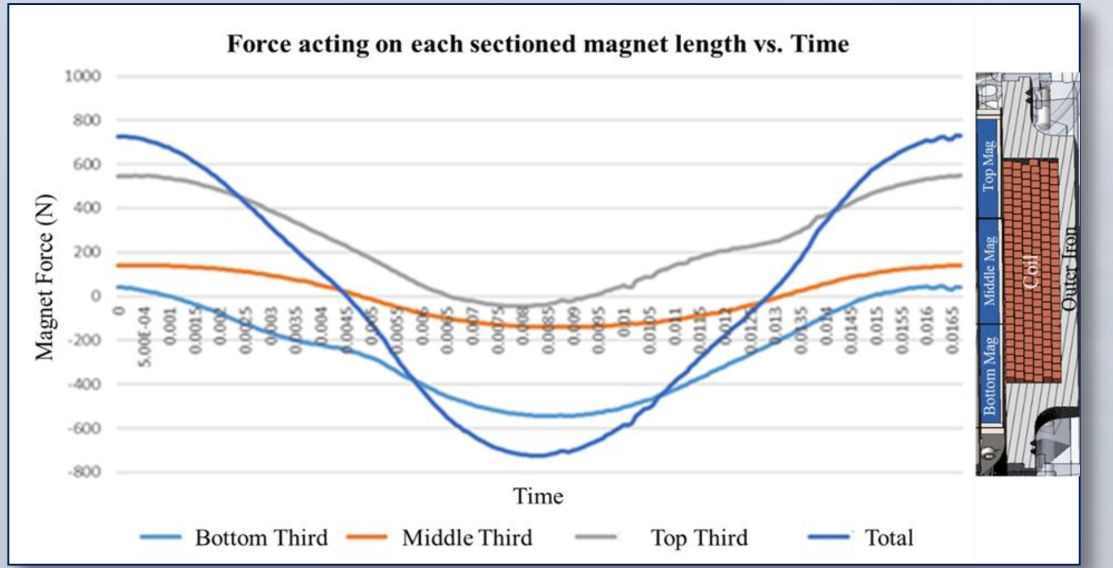
And after combining equations (1) and (2) we find:

$$F_p = C_f\, I \tag{1}$$

$$P = F_p V_x = VI \tag{2}$$

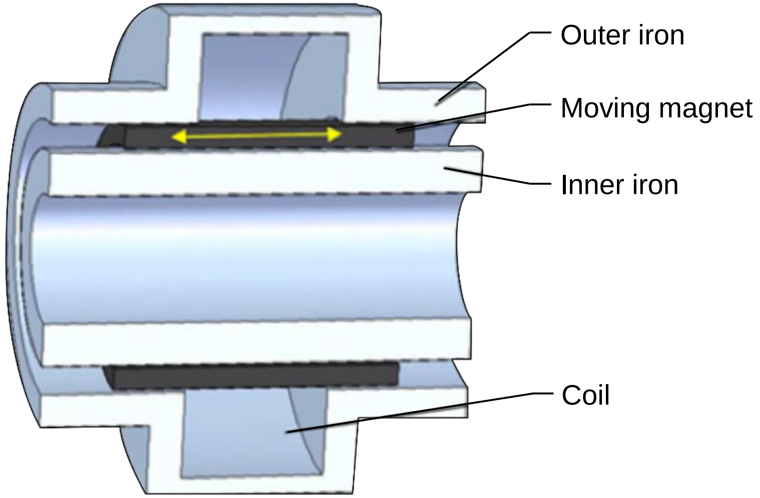
$$V_x C_f = V \tag{3}$$

$$V_x = A_x\, 2\pi\, f \tag{4}$$



Increasing frequency and magnet length enables high aspect ratio geometry to fit inside narrow shaft

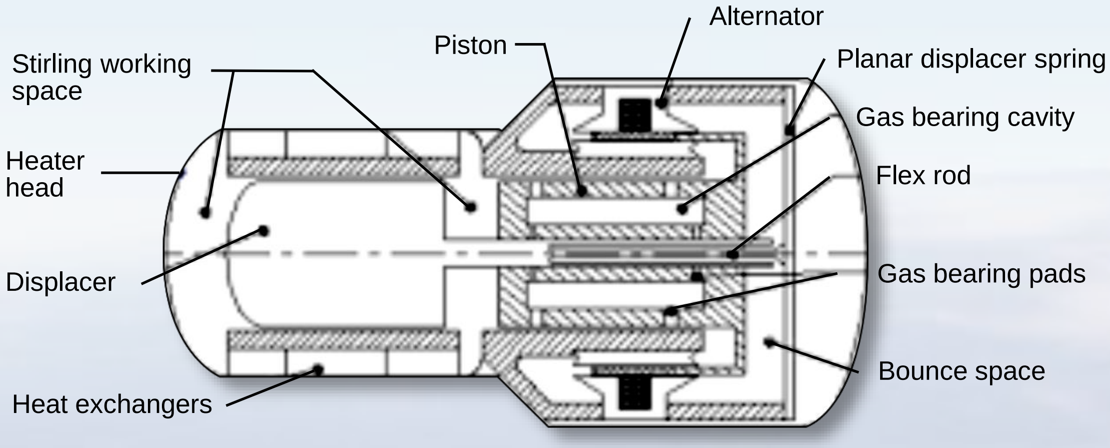
Redlich Linear Machine Design Considerations

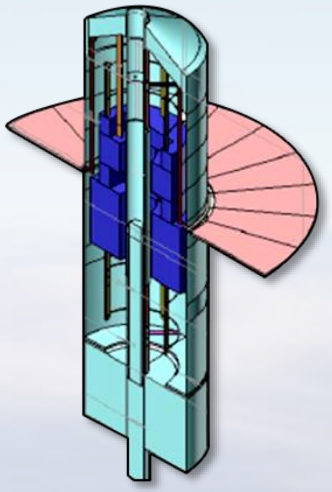


- Have some freedom in lamination thickness for structural and manufacturing
- All components are symmetrical about rotation axis
- Drilled copper used instead of screen mesh for strength
- Rotor shaft provides outer pressure vessel

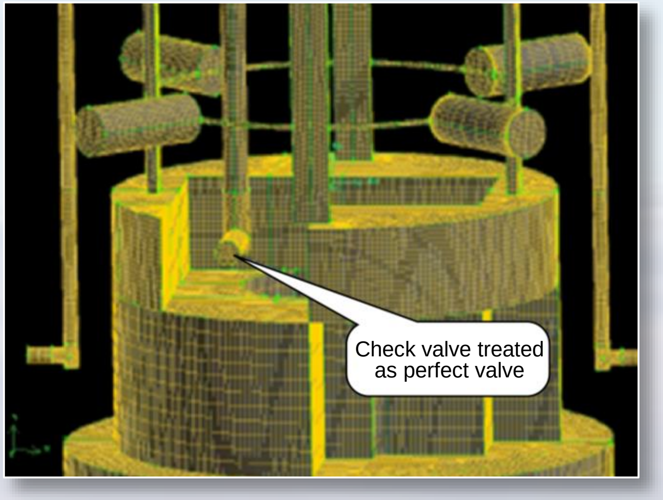
Lamination Thickness (mm)	Alternator Efficiency	Heat Lift at 50K (W)	Electric Power In (W)	Coil Current Density (A/mm2)
0.5	0.83	55	1900	4
1	0.826	55	2000	4
3	0.79	53	1992	4
5	0.74	48.6	1940	4
6	0.71	45	1884	4
7	0.67	40.7	1806	4
10	0.58	27.5	1562	4

Bearing Options

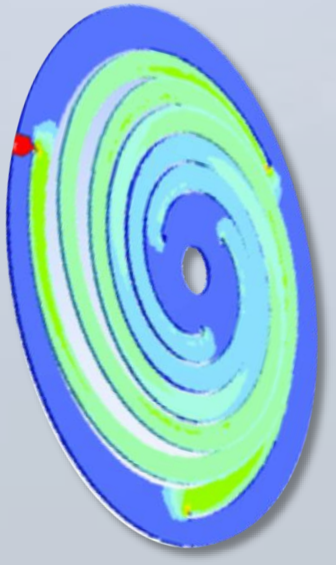


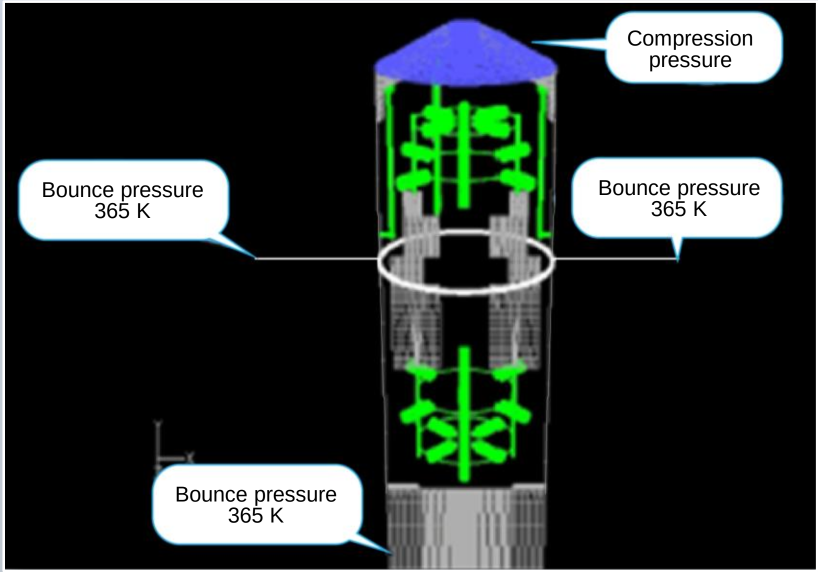


Laser bearing design



Gas Bearings – Hydrostatic and hydrodynamic
Flexure Bearings – Spiral and other
Rotating Bearings - Foil





Flexure Selected

Material Properties

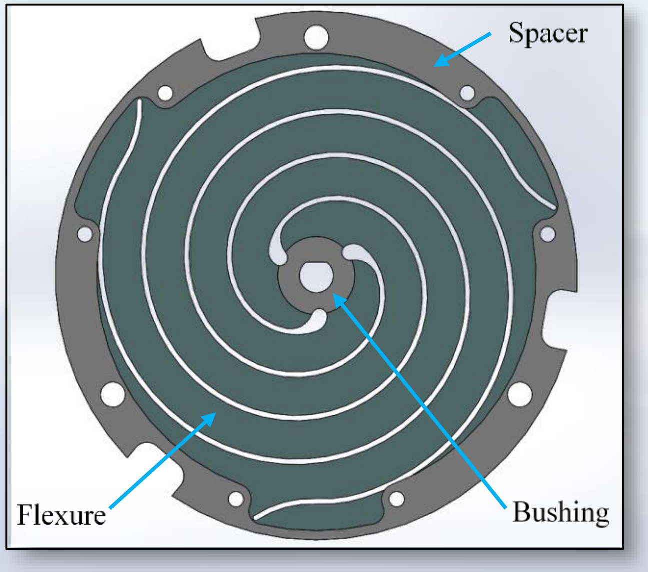
Property	Value
Tensile Strength (MPa)	1900
0.2% Yield Strength (MPa)	1500
Fatigue Strength (MPa) 5% Failure Rate	±750
Young’s Modulus (GPa)	210
Density (kg/m^3)	7700

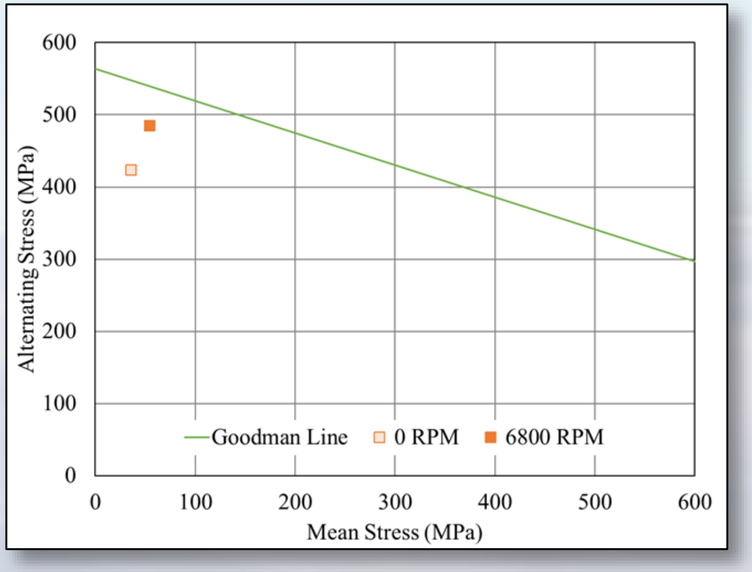
Flexure Properties

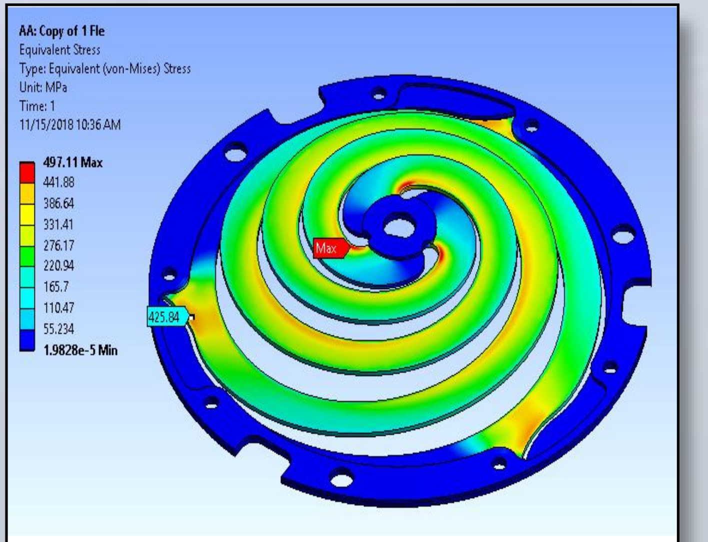
Property	Value
Number of arms	3
Outer diameter	100 mm
Number of revolutions in a spiral arm	1.3
Spiral inner diameter (without stress relief)	20 mm
Spiral outer diameter (without stress relief)	85 mm
Spiral pitch	25 mm
Arm width	6.98 mm
Slot width	1.0 mm

T Single flexure stiffness and moving mass

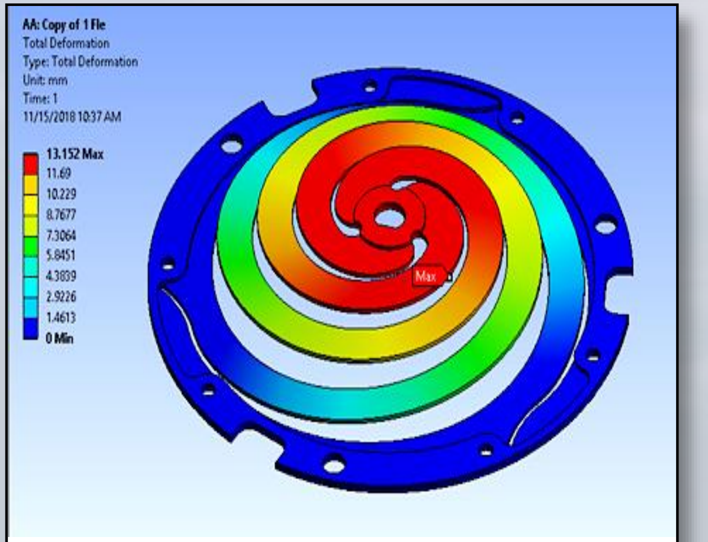
Property	0 RPM Test (n=3 samples)	0 RPM FEA prediction	6800 RPM FEA prediction
Stiffness (N/m) at 13 mm displacement	2642	2601	2937
Moving mass (g)	17.0	16.3	16.5







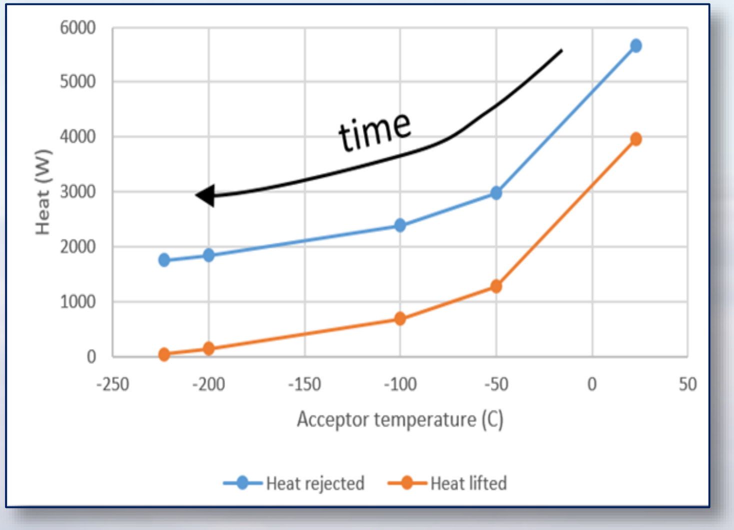
Von Mises Stress

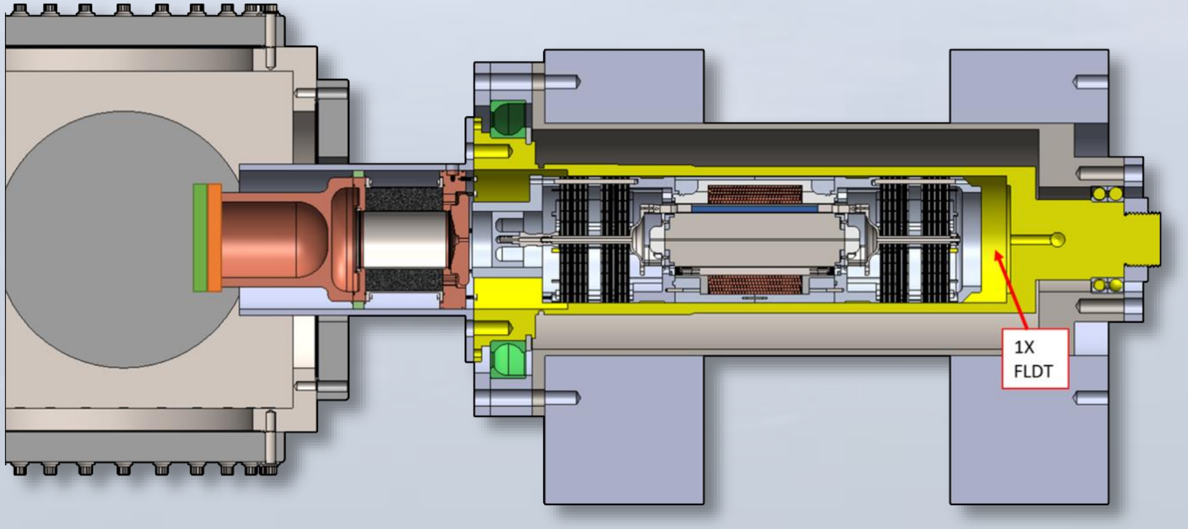


Deformation

Next Step: Testing and Operations

Stationary and Rotational Operating Parameters		
Property	0 RPM	6800 RPM
Piston Oscillation Freq (Hz)	56	56
Heat Lifted at 50K (W)	51	51
Electric Power In (W)	1860	1774
Effective Flexure Stiffness (N/m)	1.57e5	1.78e5
Reactive Power In (W)	2531	3121
Voltage (V)	154	176
Current (A)	20.4	20.4
Power Factor	0.59	0.49





Supports 60 Hz Single-Stage Pulse-Tube Cooler

Summary

- Maximum benefit with electric aircraft is achieved by integrating at both the component level and the system level.
- Thermal energy conversion technologies provide a fundamental building block for this integration.
- **HEMM** enables flight-weight, high efficiency at MW-scale
- Internal rotating cryocooler design identified that successfully installs inside the rotor shaft
- Next step is prototype build and test