IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), July 2015.
Plenary presentation M3PL given at CEC-ICMC 2015, Tucson, USA, June 28 – July 2, 2015.

Superconducting Turboelectric Distributed Aircraft Propulsion

Michael Armstrong
Rolls-Royce North American Technologies Inc

- Cryogenic Engineering Conference / International Cryogenic Materials Conference
- July 1, 2015

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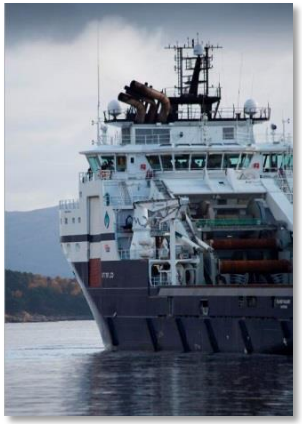


Civil Aerospace

Our engines keep up **400,000** people in the air at any one time

Defence Aerospace

160 armed forces around the world depend on our engines

Marine

30,000 commercial and naval vessels use our marine equipment

Power Systems

Develop, produce and service energy markets under the MTU and Bergen engine brands

Nuclear

Design authority for the Royal Navy's naval nuclear plant

A brief history of Rolls-Royce

1884 FH Royce & Co
1899 Royce Ltd

1906 Rolls-Royce Ltd

1931 'R' Engine wins Schneider Trophy

1940 Merlin helps win Battle of Britain

1969 1st run of RB211
1990 1st run of Trent

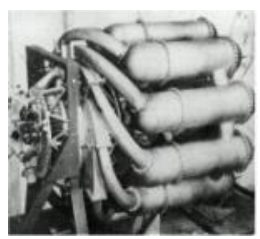
2013 TrentXWB Certification

1880 1900 1920 1940 1960 1980 2000

1904 Rolls meets Royce

1914 1st R-R Aero Engine

1940s R-R begins Gas Turbine Development



1953 Dart & Avon enter Civil Market

1966 Bristol Aero Engines acquired

"Bristol"

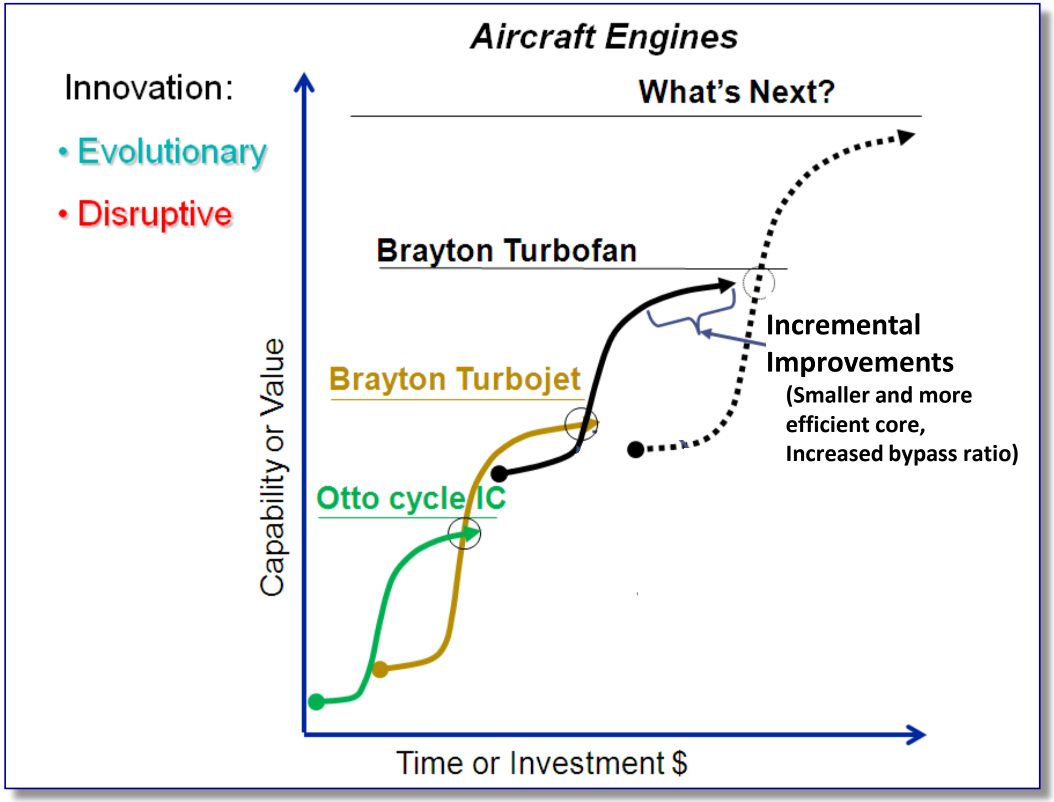
1999 Vickers acquired

Vickers

2000 BMW Aero Engs acquired

1995 Allison acquired

The move to the More Electric Engine & more!
The S-Curve of Technology Cycles



Presentation Outline

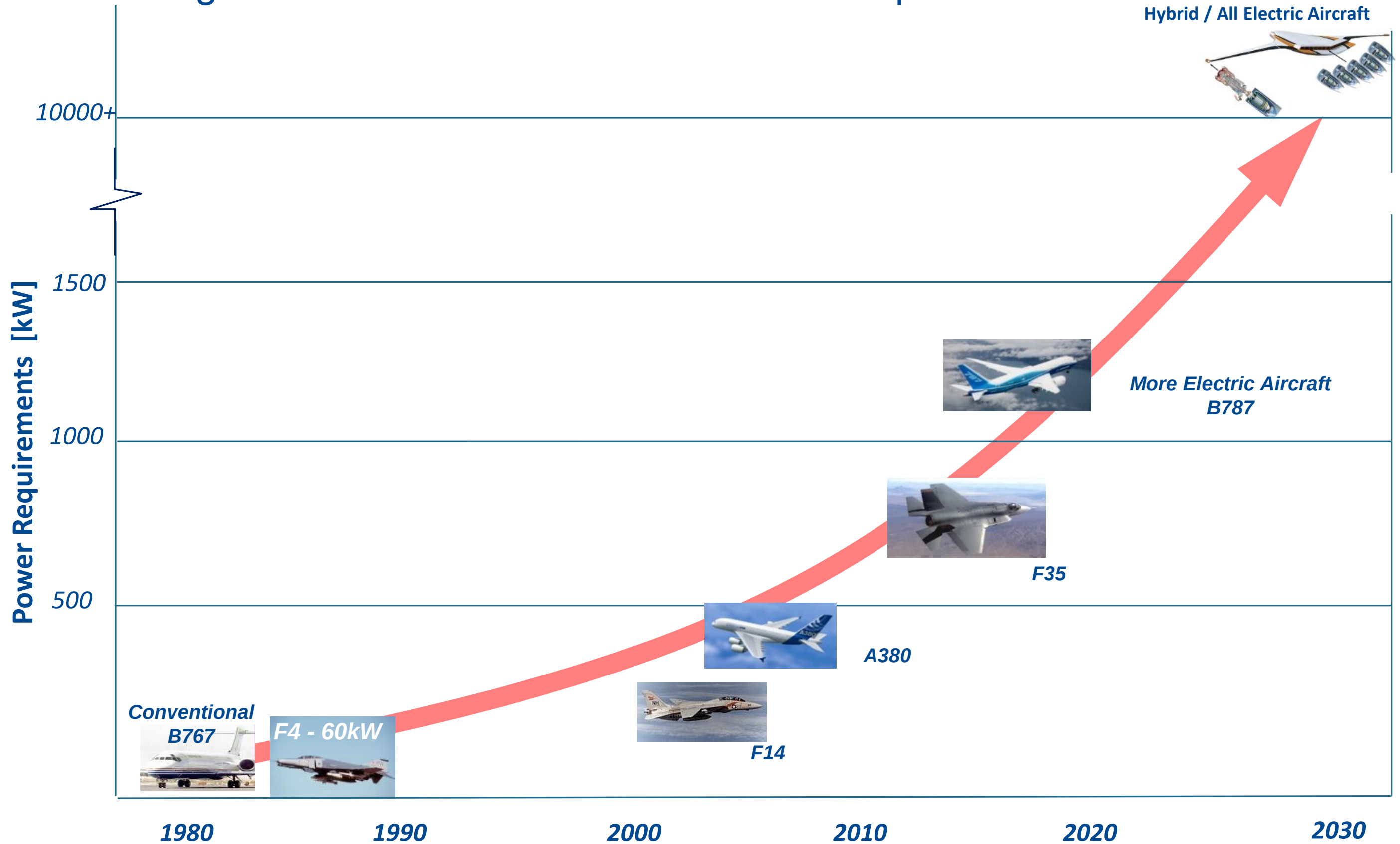
- Hybrid/Distributed Propulsion Aircraft
- TeDP Superconducting Electrical System Architecture
- Electrical System Requirements and Sensitivities
- Cryogenic Systems Targets

The move to a Electric Aircraft Propulsion

- Over the last 100 years transportation has become increasingly electrified
- Increased sharply over the last decade with the Boeing 787 'More Electric Aircraft'
- As we look to the future this trend will only increase…
- … and the Engineering challenges are great!

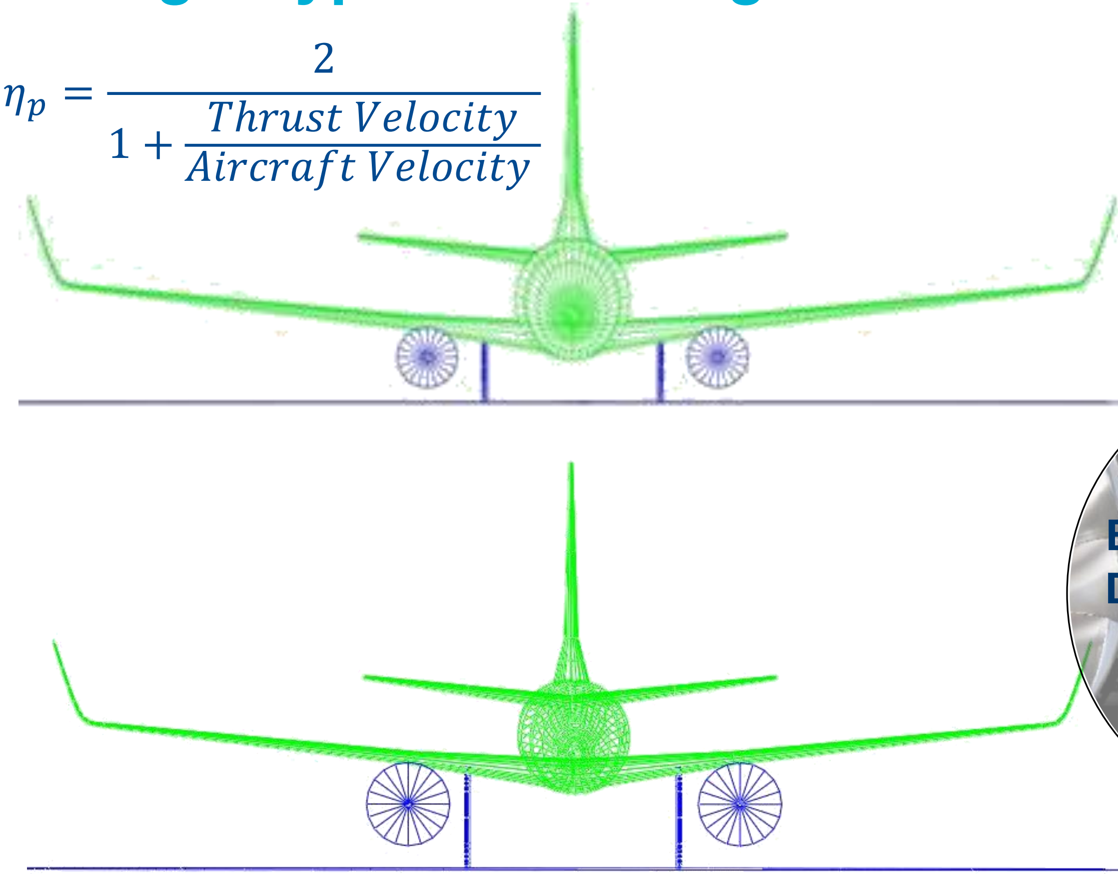
How the More Electric Aircraft has changed the Gas Turbine

Progression of Aircraft Electrical Power Requirements



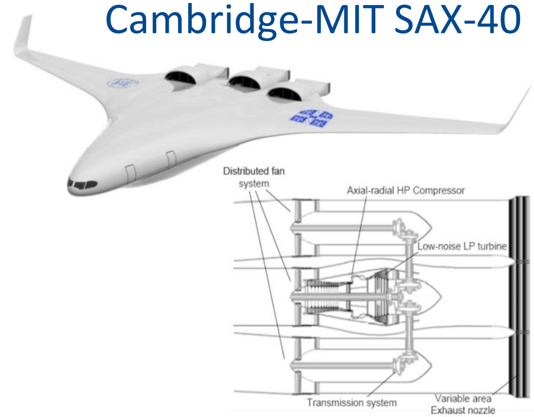
Large Bypass Challenges

$$\eta_p = \frac{2}{1 + \frac{Thrust\ Velocity}{Aircraft\ Velocity}}$$



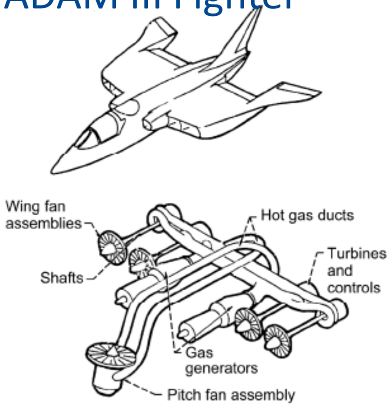
Thrust Distribution

Cambridge-MIT SAX-40



(mechanical shafting/gears)

ADAM III Fighter

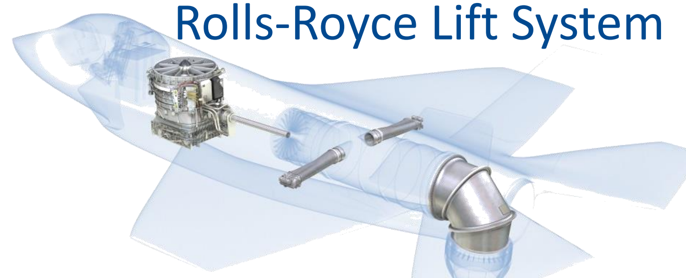


(hot gas redirection)

NASA CESTOL Aircraft

(multiple engines)

Rolls-Royce Lift System

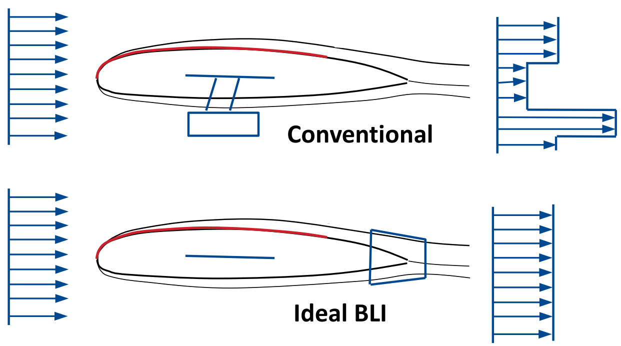


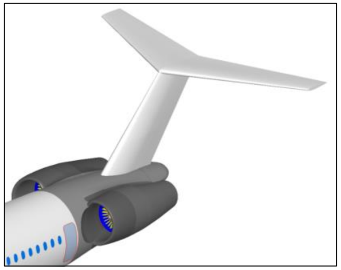
(mechanical, bleed, and hot gas redirection)

Distributed Propulsion with Boundary Layer Ingestion

Benefit of BLI:

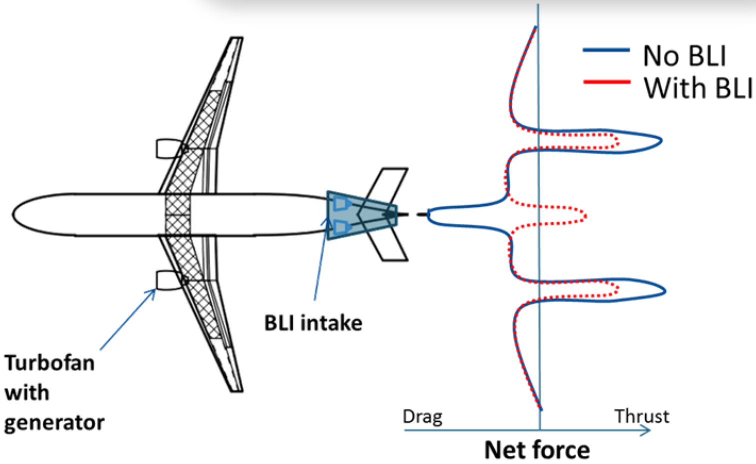
- **Improves overall vehicle propulsive efficiency by reenergising low energy low momentum wake flow**



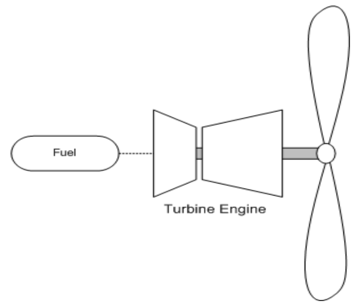


Distributed Propulsion Benefits

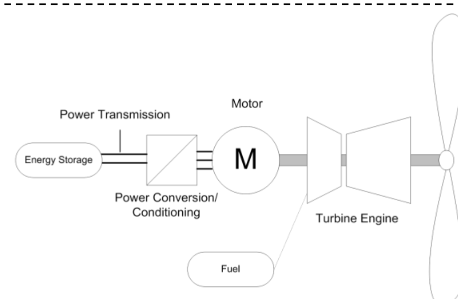
1. Maximises opportunity for BLI
2. Facilitates of installation of low specific thrust propulsion
3. Structural efficiency/optimised propulsion system weight
4. Minimises asymmetric thrust, reducing vertical fin area
5. Reduced jet velocity & jet noise



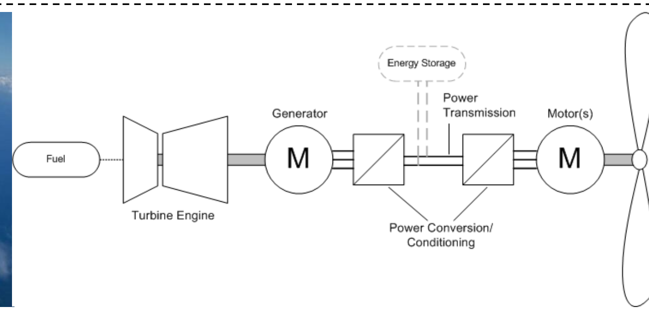
Functional Implementation of Electric Propulsion



- Coupled Power Production and Propulsion Functions
- Decoupled Propulsion and Aircraft Aero Functions



- Coupled Power Production and Propulsion Functions
- Largely Decoupled Propulsion and Aircraft Aero Functions
- Alternative Source For Energy Storage

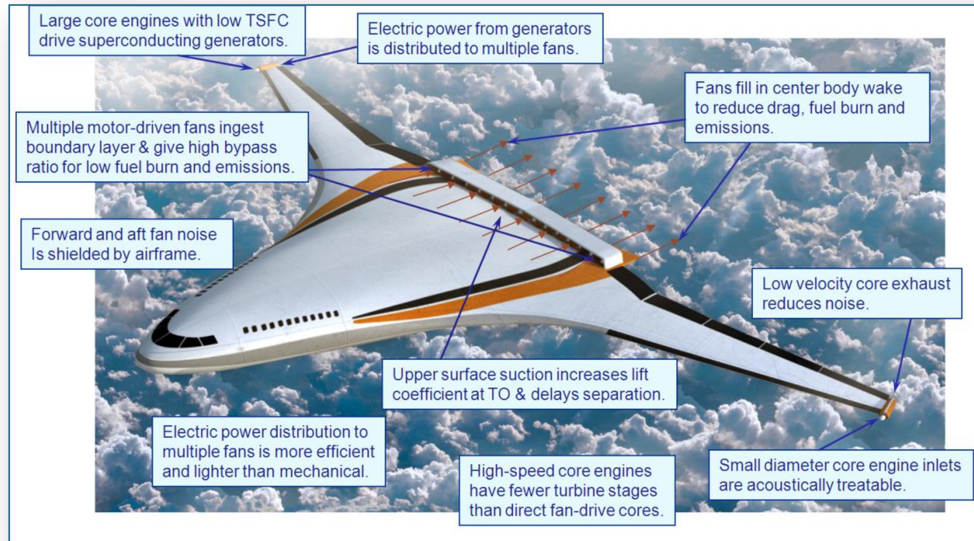


- Decoupled Power Production and Propulsion Functions
- Coupled Propulsion and Aircraft Aero Functions
- Optional alternative Source For Energy Storage

N3-X TeDP Vehicle Concept

Aircraft Attributes		
Range	7500nm	
Payload	118100 lbm	
M_{cruise}	0.84	
Cruise alt	34,000 ft	
	RTO	TOC
Fn - lbf	85,846	33,405
TSFC – lbm/hr/lbf	0.2174	0.3125
Effective BPR	36.1	30.1
Empty Weight (Baseline B777-200LR)	420,000 lbm (Δ69,197)	
Block Fuel Weight (Baseline B777-200LR)	**76,171 lbm** **(Δ203,629)**	
Number of Propulsors	16 (function of aircraft width, FPR, boundary layer, and net thrust)	
Thrust Power Required	~50MW	
Motor/propulsor	~3.3 MW	

Revolutionary Aeropropulsion concept for Sustainable Aviation - Turboelectric Distributed Propulsion ISABE-2013-1719



Cryogenically Cooled Superconducting DC TeDP Electrical System

- Tasked with providing aircraft propulsion and some level of differential thrust for directional control

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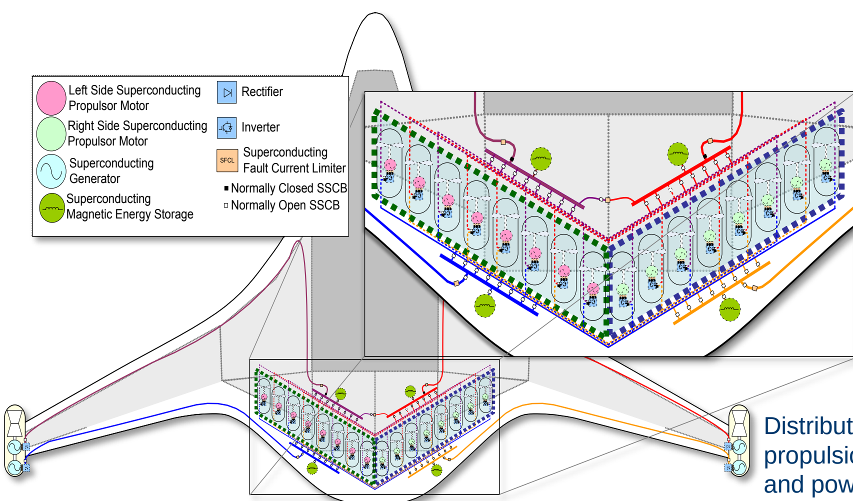
Power Systems Architectures

- Multi-kVpower system architecture and associated control system for transmission and use of multi-MW power in aircraft
- Integrated thermal management and motor control schemes
- Enabling materials and manufacturing technologies

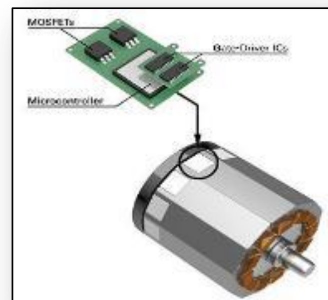


Distributed propulsion control and power systems architectures

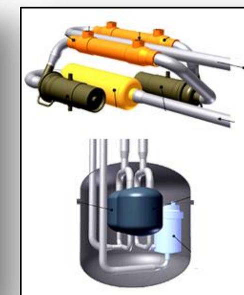
Superconducting transmission line

Lightweight power transmission

Integrated motor with high power density power electronics



Lightweight Cryocooler



Lightweight power electronics

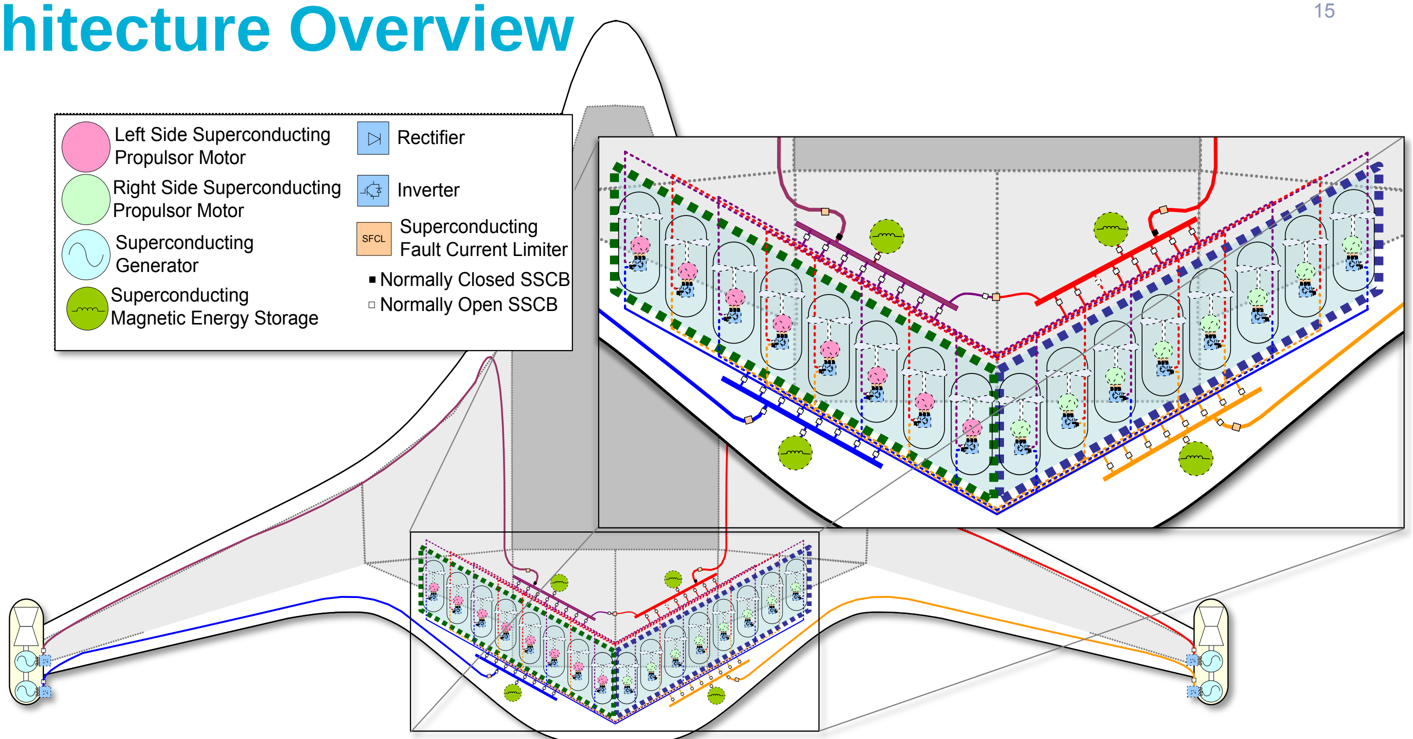
TeDP Architecture Design

Challenge in defining a Safety Critical, Flight Weight, Superconducting, DC Microgrid

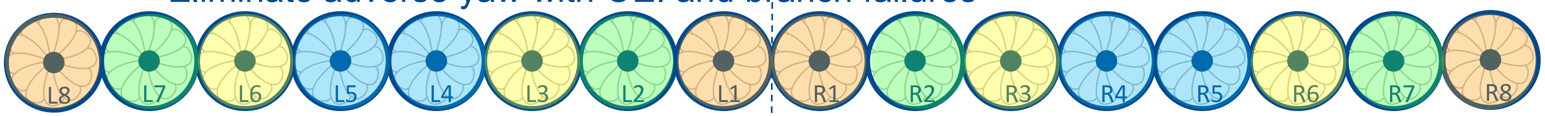
- Off-nominal requirements drive the overall mass and efficiency of the system

Architecture Requirements	Dynamic Requirements
• Reliability	• Regulation
• Redundancy	• Response
• Reconfigurability	• Recovery

Architecture Overview



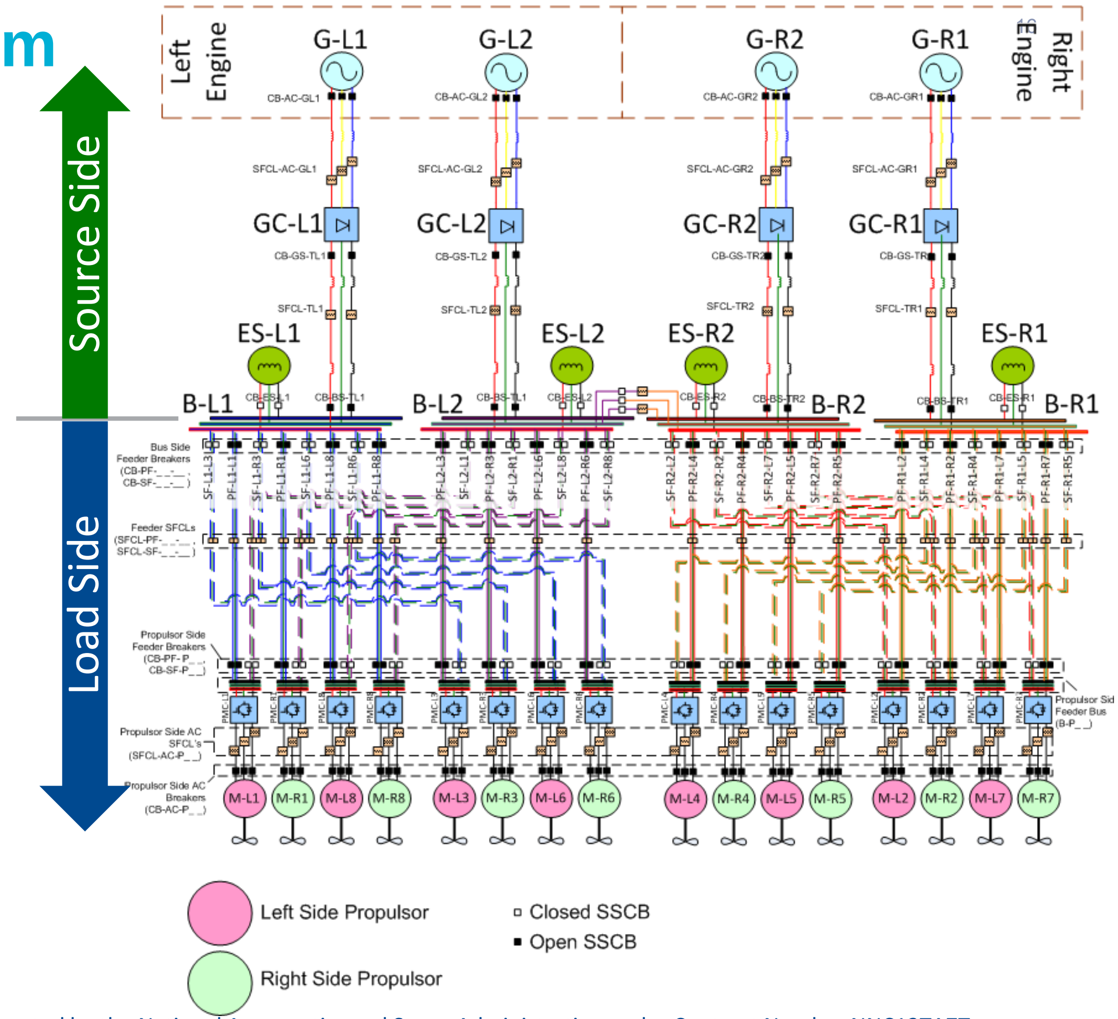
- Multiple transmission lines and feeders provide spatial redundancy
- Decoupling power and propulsion function provides beneficial flexibility
    - Eliminate adverse yaw with OEI and branch failures



The material is based upon work supported by the National Aeronautics and Space Administration under Contract Number NNC13TA7T.

Overall System

- Definitions
  - Turbogen (x2)
    - Turbine Engine
    - Generator (x2)
  - Branch (x4)
    - Generator
    - Rectifier
    - Transmission Lines
    - Associated Protection
    - Bus
    - Primary Feeders (x4)
    - Propulsor (x4)
  - Feeder (x32)
    - Primary (x16)
    - Secondary (x16)
  - Propulsor (x16)
    - Motor
    - Converter
    - Fan



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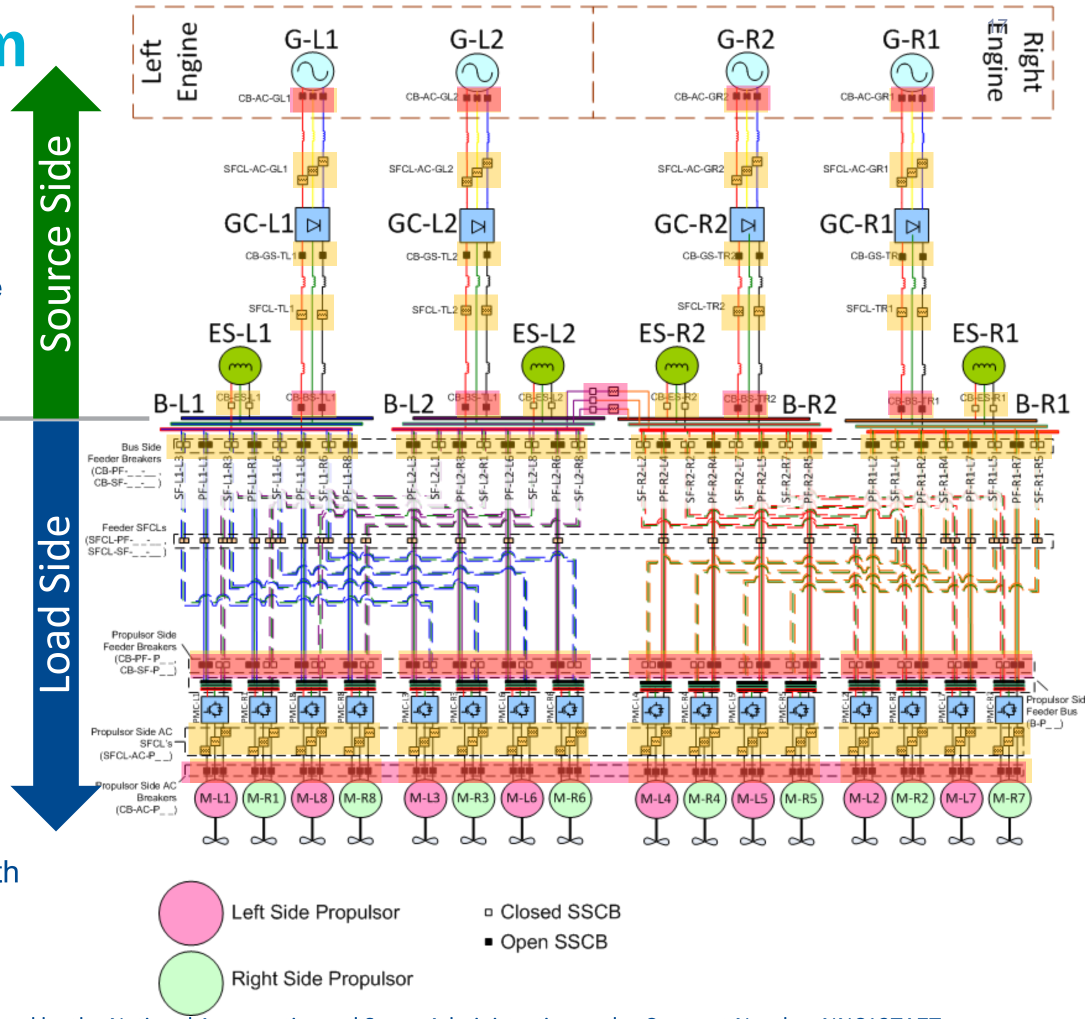
Overall System

- Protection Equipment
  - Coordination of Superconducting fault current limiters (SFCL) and solid state circuit breakers (SSCB)
- Reconfigurability
  - Distribution Interconnectivity
  - Primary/Secondary Propulsor Feeders
  - UPS (SMES Energy Storage)
- Branch Similarity
  - Equivalent number of propulsors per bus and per engine
  - Common component rating between branches
  - Similar performance lapse with failures



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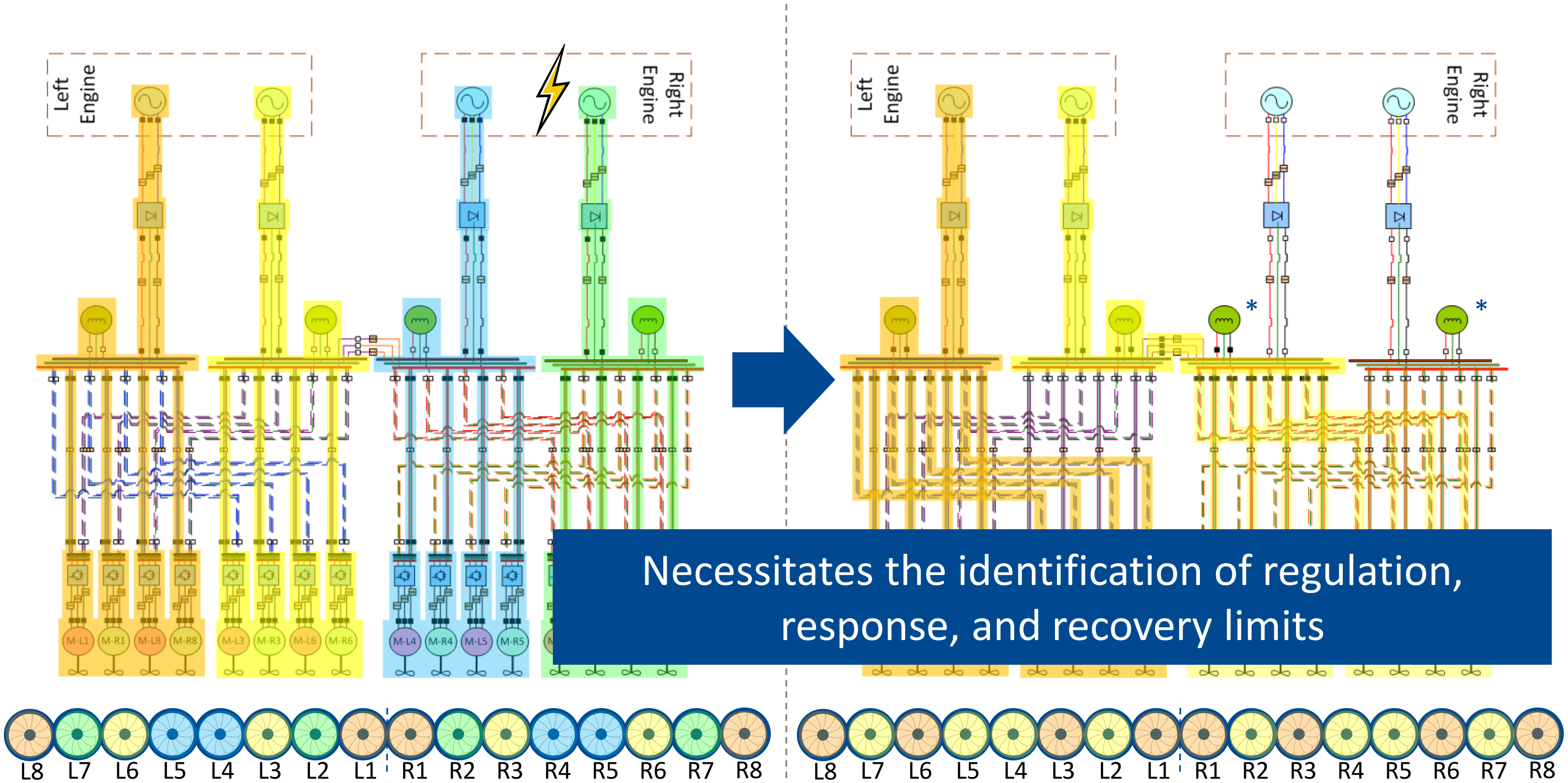
OEI Power Rerouting



- Engine sees step change in power required from 50% to 100%
- System sized by fail safe requirements

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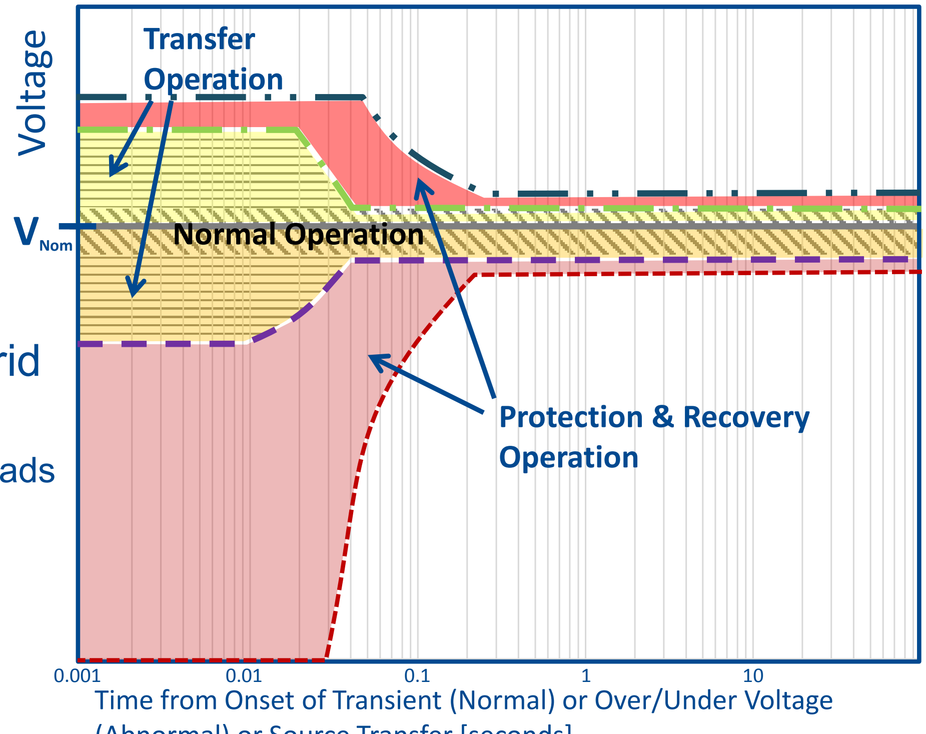
Operating Voltage Standards

- Bulk Power, Microgrid, Marine, and Aerospace voltage standards have repeating themes:
  - Steady state regulation
  - Transient behavior
  - Fault tolerance and recovery
  - Distortion and harmonics



- Unique airborne, flight critical, superconducting TeDP microgrid considerations:
  - Regulated utilization equipment loads
  - FAR imposed segregation, redundancy, response
  - Pressurized fluid environment

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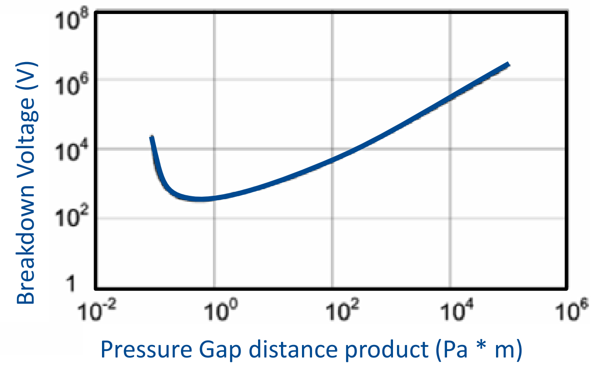
Operating Voltage Standards

- Aircraft electrical safety has not been designed to optimize the electrical system but resulted from either what has always been done or conservative estimates
  - The electrical system has not considered what is possible but what has been
  - The TeDP system has to opportunity to be designed by what is possible and requires this to achieve the benefits of the TeDP

- Why current voltage levels?
  - First airplanes used car batteries which had cell voltage that were in multiples of 6 so a voltage of 24VDC was initially used
  - The 270 voltage level result of Paschen's curve

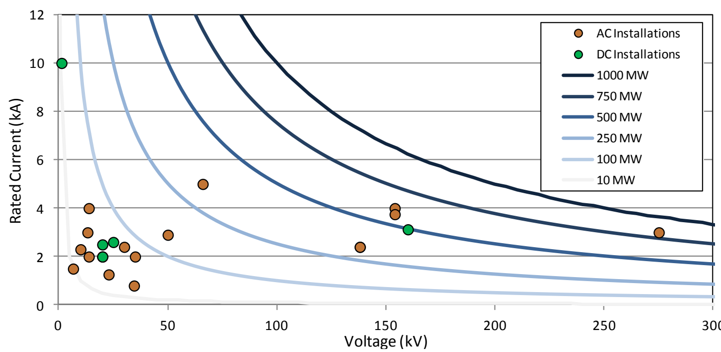
- Standards typically evolve slowly. TeDP systems are a radical departure.
  - IEEE Std. 1709

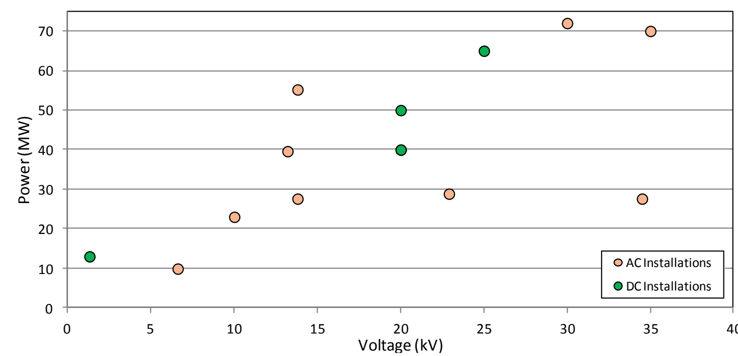


Terrestrial Superconducting Systems Voltage Range

- Preliminary voltage range baselined against conventional terrestrial systems
  - Min of 0.8kA, Max of 10kA*
  - Preliminary voltage range of 2.5 kV to 40kV

*EPRI discusses a 100kA upper limit for terrestrial power distribution, Adopting this range would yield a lower limit of 250V





Eckroad, S., “Superconducting Power Equipment: Technology Watch 2012,” Electric Power Research Institute, Technical Update 1024190, December 2012.
Sato, Ken-ichi, “Present Status of International Standardization Activities for Superconductivity,” SEI Technical Review Number 74, pg 4-7, April 2012.
Sato, Ken-ichi, “Present Status and Future Perspectives of High-Temperature Superconductors,” SEI Technical Review Number 66, pg 55-67, April 2008.

Integration of superconducting component into normally conducting system

Architecture Decomposition

- 440 pieces of electrical equipment
  - 20 machines
  - 20 converters
  - 20 AC Cables
  - 36 DC Cables (bi-polar)
  - 206 SSCBs (1 per phase, 1 per pole)
  - 136 SFCLs (1 per phase, 1 per pole)
  - 4 SMES (w/ h-bridge)

- Each component to be decomposed to the device level for system sizing and sensitivity trades

Complete microgrid configuration with unique sizing objectives

Baseline system equipment list for 25MW thrust power rated system

Equipment		Count	Single engine out rating at takeoff (MW)	Nominal rating at cruise (MW)
Electric Machines	Generator	4	12.5	6.25
	Motor	16	1.79	1.5625
Converter	AC/DC converter	4	12.5	6.25
	DC/AC inverter	16	1.79	1.5625
	DC/DC converter for SMES	4	12.5	0
Cables	AC	4	12.5	6.25
		16	1.79	1.5625
	Transmission	4	12.5 (2x30m, 2x40m)	6.25
	Feeder	16	1.79 (16x5m)	1.5625
		16	1.34 (16x5m)	0
Breakers	AC	12	12.5	6.25
		48	1.79	1.5625
	DC	16	12.5	6.25
		64	1.79	1.5625
		64	1.34	0
		2	12.5	0
SFCL	AC	12	12.5	6.25
		48	1.79	1.5625
	DC	8	12.5	6.25
		32	1.79	1.5625
		32	1.34	0
		2	12.5	0
En. storage	SMES	4	12.5	0
Total		440		

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Voltage Sensitivity Model Integration

Architecture

Requirements and Configurations

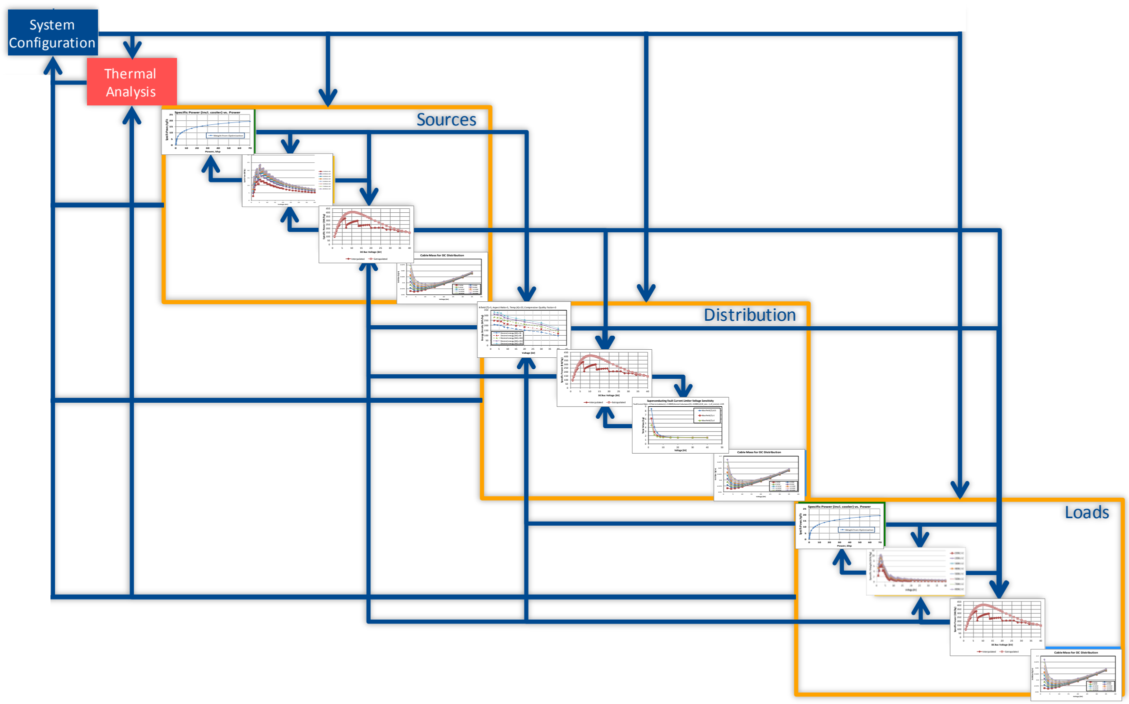
Systems

Interactions and Interdependencies

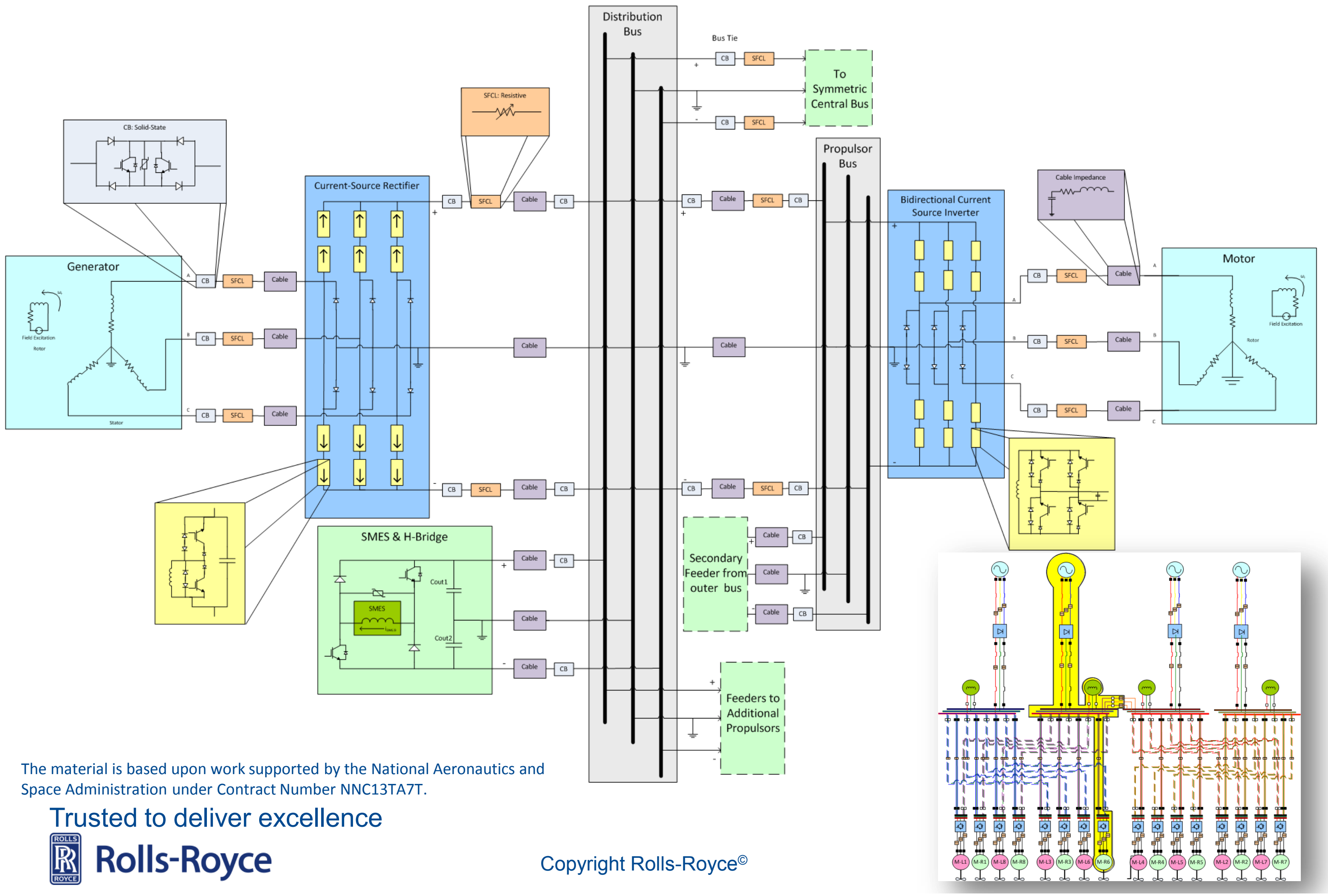
Components

Derived Requirements

Subcomponents



Architecture Decomposition



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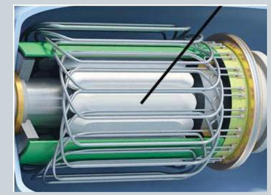
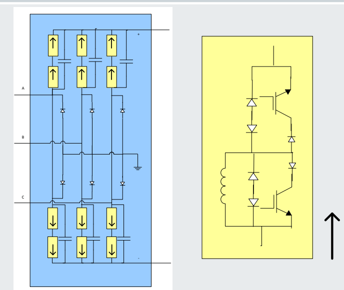
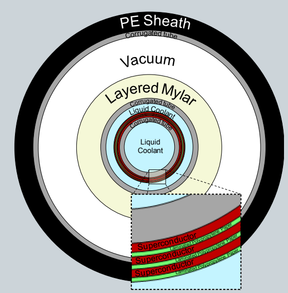
Component Descriptions

Component	Assumptions	Image/Diagram
Electric Machines	• Superconducting machines with BSCCO rotor and stator windings • Sizing models provided by NASA	
Power Electronics	• Current source converters with low temperature IBGT switching operation (*scaling from state of the art IGBT data*) • Presspack diodes for overvoltage protection (*scaling state of the art diode data*) • Layered aluminum polypropylene film capacitor • LN_2 cooled superconducting inductor • Packaging estimates by extrapolation from state of the art	
Cables	• Nexans triax bipolar DC cable topology with YBCO tape superconductor • Vacuum jacket insulation with heat leakage • Conduction losses sensitive to critical current margin • Laminated Polypropelyne Paper dielectric protection • LN2 cooled • Weight and geometry sensitive to required layer thicknesses	

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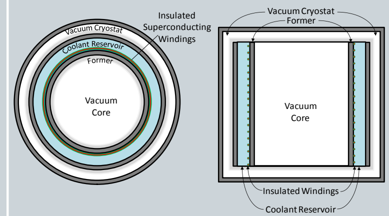
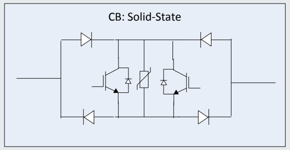
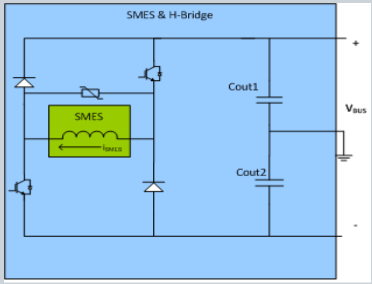
Component Descriptions

Component	Assumptions	Image/Diagram
SFCL	• Solonoidal resistive type SFCL • BSCCO windings with quench transition dynamics sensitive to fault current ratio • LN_2 sub-cooling (*assuming no boil-off cooling*)	
SSCB	• Solid state circuit breaker with surge arrestor, • Low temperature IGBT switching operation • (*Similar sizing approach to converter sizing*)	
SMES	• Toroidal SMES inductor with layered Force Balance Coil (FBC) winding configuration • Application of Moone's approach using virial theorem to estimate structural mass • H-bridge for charge and discharge • Hydrogen cooled YBCO superconductor	
Cryo Systems	• Estimated 30% Carnot efficiency Brayton cycle • Assumed 3 kg/kW power density for cryocooler	

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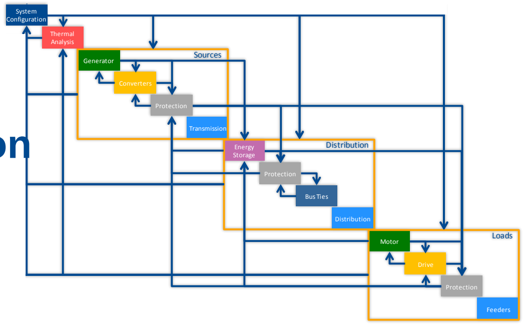
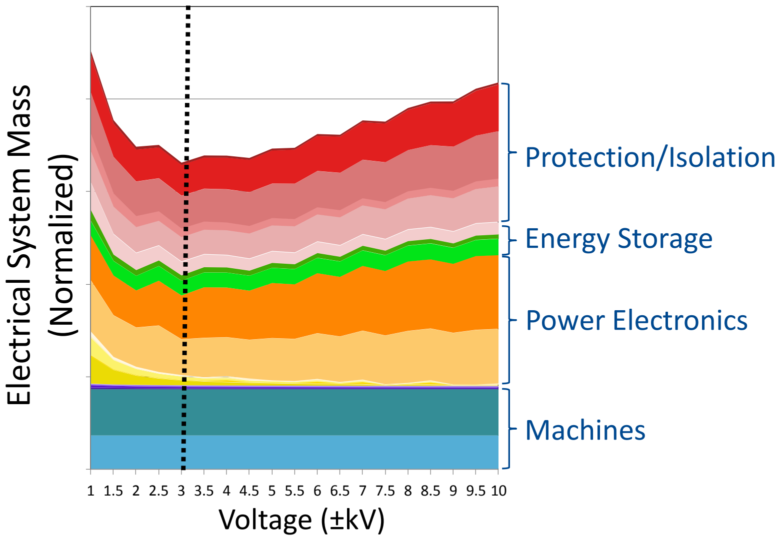
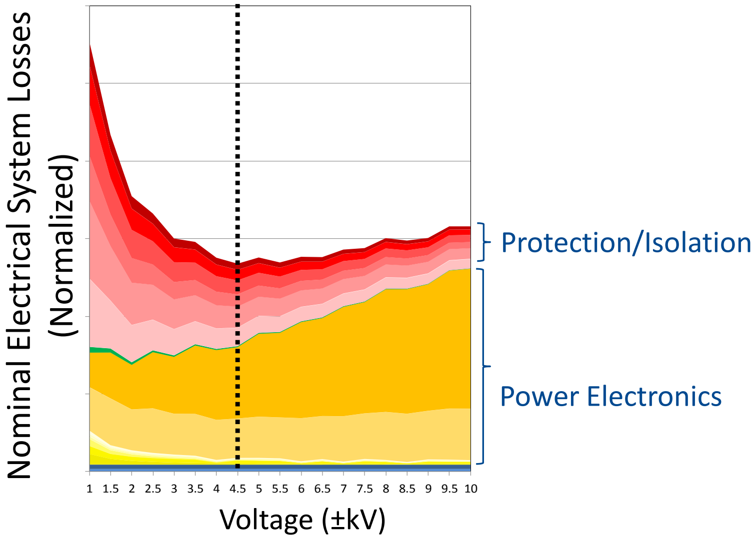
Selection of V_{nom}



- **Trends are dominated by the mass and the conduction and switching losses from semiconductors**
  - SSCB's and Power Electronics
  - Inefficiency → Cryocooling requirements





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Effect of Protection Solution Architecture and Technology Improvements

Nominal Voltage Range Selection

- Semiconductor efficiency characteristics play a major role in sizing system
- Minimize mass by improving component performance or removing semiconducting equipment from the system

Technology Improvement →

Architecture Improvement ↓

± *Optimal Voltage* / Overall Mass (Cryogenic System, Electrical System)	Baseline switching loss	50% improvement in converter losses	90% improvement in converter losses
Baseline system	*±4.5 kV*	*±4.5 kV*	*±4.5 kV*
W/o protection SSCBs and all SFCLs	*±3 kV*	*±3 kV*	*±4.5 kV*
W/o energy storage, protection SSCBs and SFCLs	*±2 kV*	*±3 kV*	*±4.5 kV*

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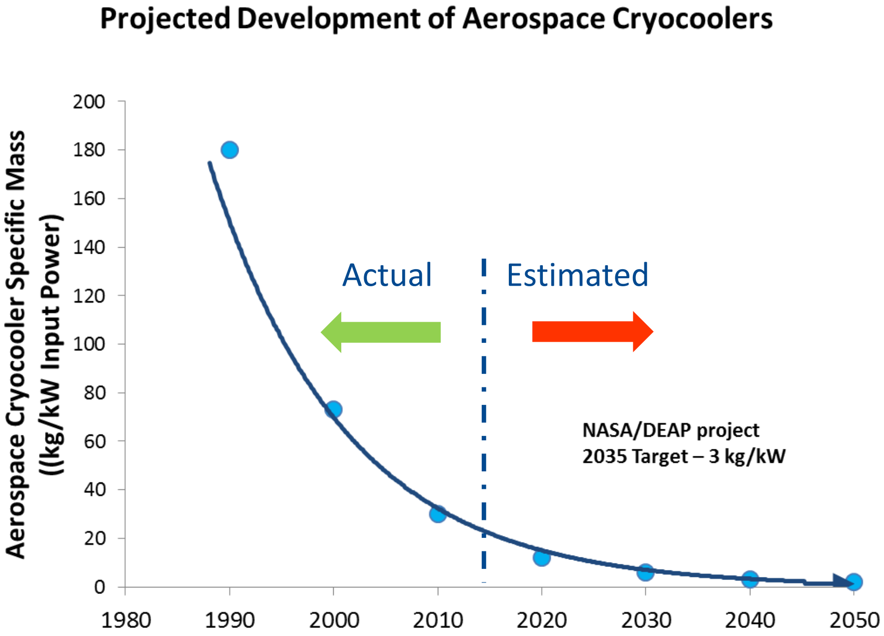
Challenge: Lightweight, Efficient, Reliable, >1kW Cryocoolers

Cryogenic Cooling for
Distributed Propulsion



Courtesy of NASA

Lightweight Cryogenic Technology Needs

Cryocooler

Compressor

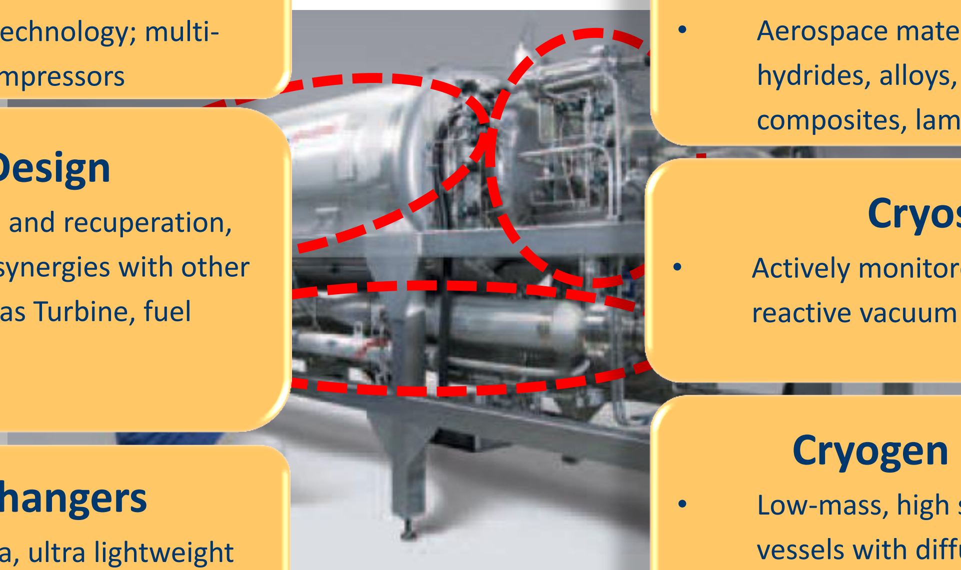
- Use of aerospace technology; multi-stage axial flow compressors

Cycle Design

- Combined cycle and recuperation, exploitation of synergies with other systems (ECS, Gas Turbine, fuel systems)

Heat Exchangers

- High surface area, ultra lightweight heat exchangers



Cryogenic System

Materials

- Aerospace materials and coatings; hydrides, alloys, ceramics, composites, laminates

Cryostat

- Actively monitored cryostat with reactive vacuum and boil-off control

Cryogen Storage

- Low-mass, high strength storage vessels with diffusion protective coatings

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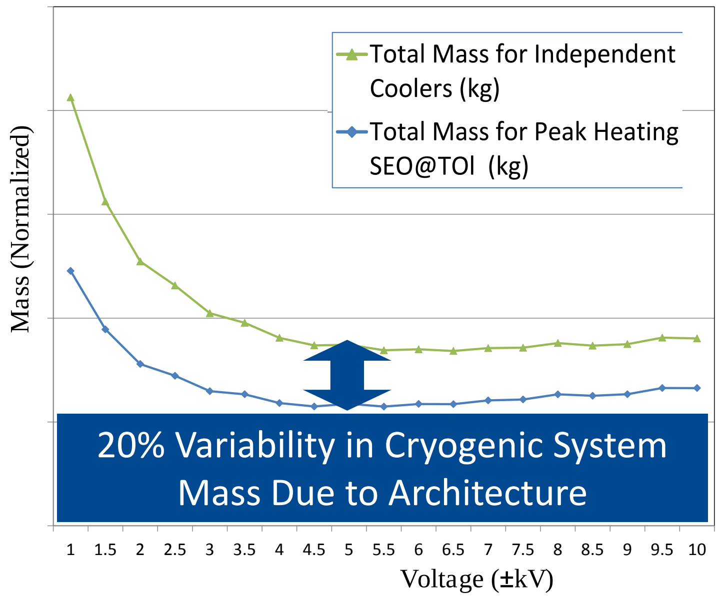
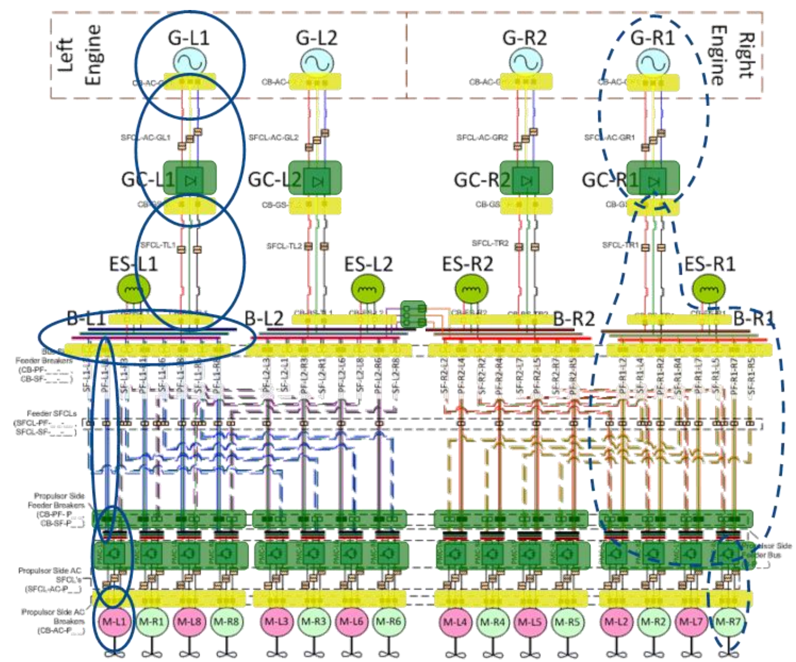
Cryogenic System

- Coordinated Design of Cryogenic Cooling System and Electrical System Zonal Protection
  - Distributed and/or Centralized Cryo-Cooling Systems
  - Fault accommodation and cascading failures
  - Mass minimization





TeDP Electrical Systems Observations

Architecture Requirements	Dynamic Requirements
• Reliability • Redundancy • Reconfigurability	• Regulation • Response • Recovery
Medium voltage system balances electrical equipment weight with cryocooling penalties	Dynamic protection and conversion requirements have large impact on overall system mass and efficiency
Need for semiconductor technology improvements and protection system architectures to minimize mass, losses, and cryocooling requirements	Need coordinated cryogenic system and electrical system transient analysis to verify and ensure safety, stability, and efficiency and confirm protection requirements

Conclusions

- Advancements in superconducting technologies and cryocooling solutions have the potential to provide revolutionary improvements air vehicle performance
- Many technical challenges remain to realize large platform hybrid/distributed electric propulsion
- Many of the TeDP electrical systems design challenges are cryogenic challenges
- Feasibility/viability of TeDP systems require light weight solutions which afford the required redundancy, reliability, and maintainability
- An integrated architecting approach (electric and cryo systems) is necessary to realize potential vehicle benefits

Thank you for your time & attention

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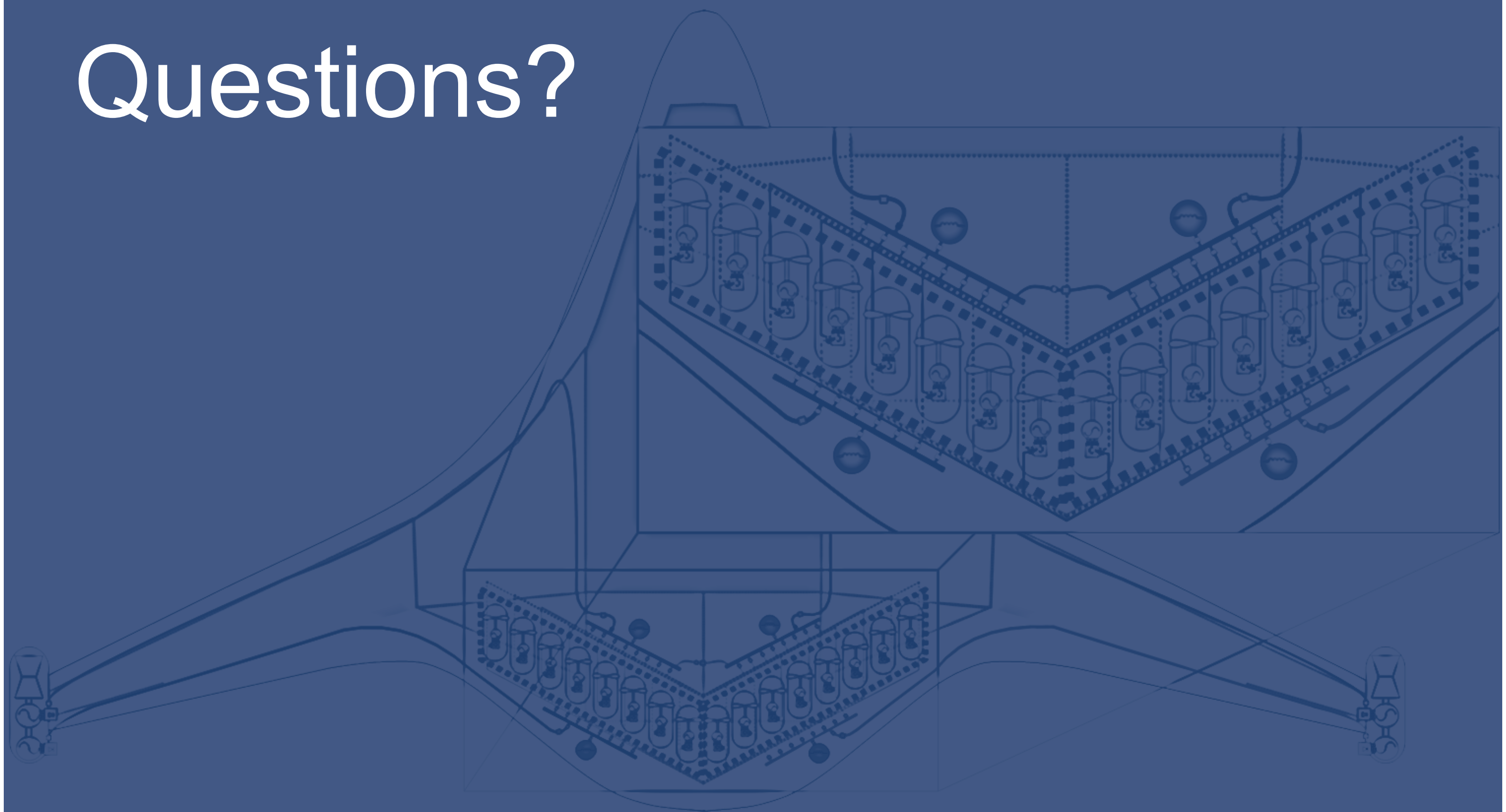
Questions?



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