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Sustainability through Cryogenic Hydrogen-Electric Aviation: Research of the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)

CEC-ICMC 2021

Phil Ansell, University of Illinois at Urbana-Champaign

July 22, 2021

CHEETA
Center for High-Efficiency Electrical Technologies for Aircraft

Agenda

- Introduction
- CHEETA Team and Technical Challenges
- Research Components and System Definition
- Technical Work at CEC-ICMC 2021
- Acknowledgements

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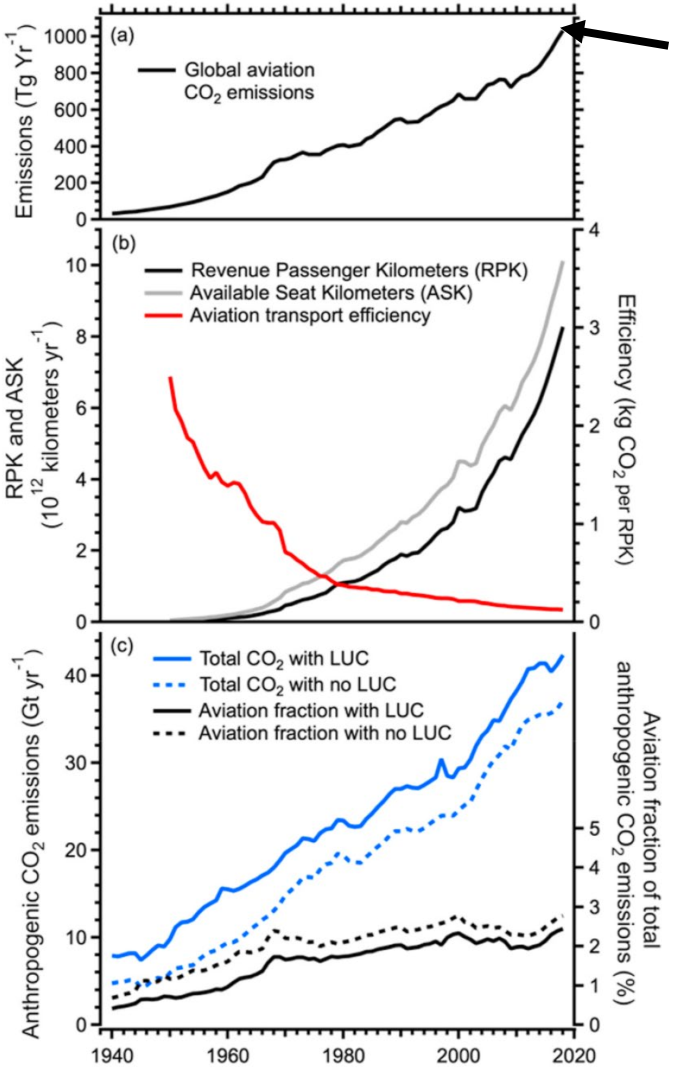

Lee et al. (2021)

CO_2 emissions mass produced by aviation: 1,000,000,000,000 kg in 2018 alone

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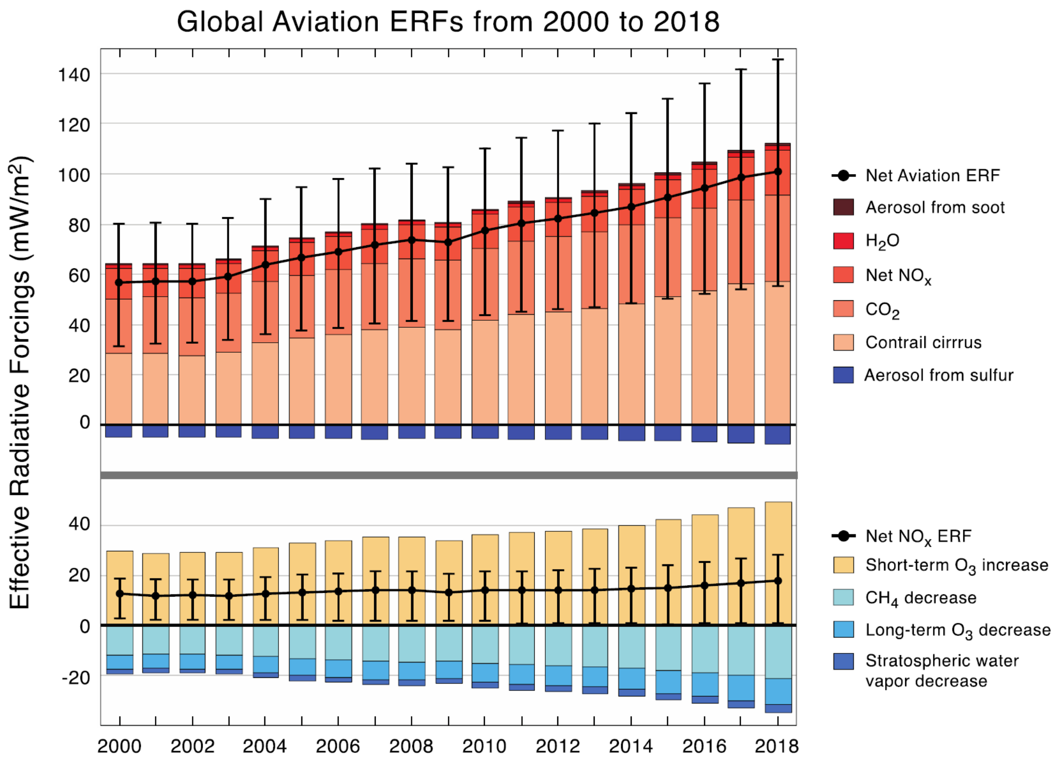
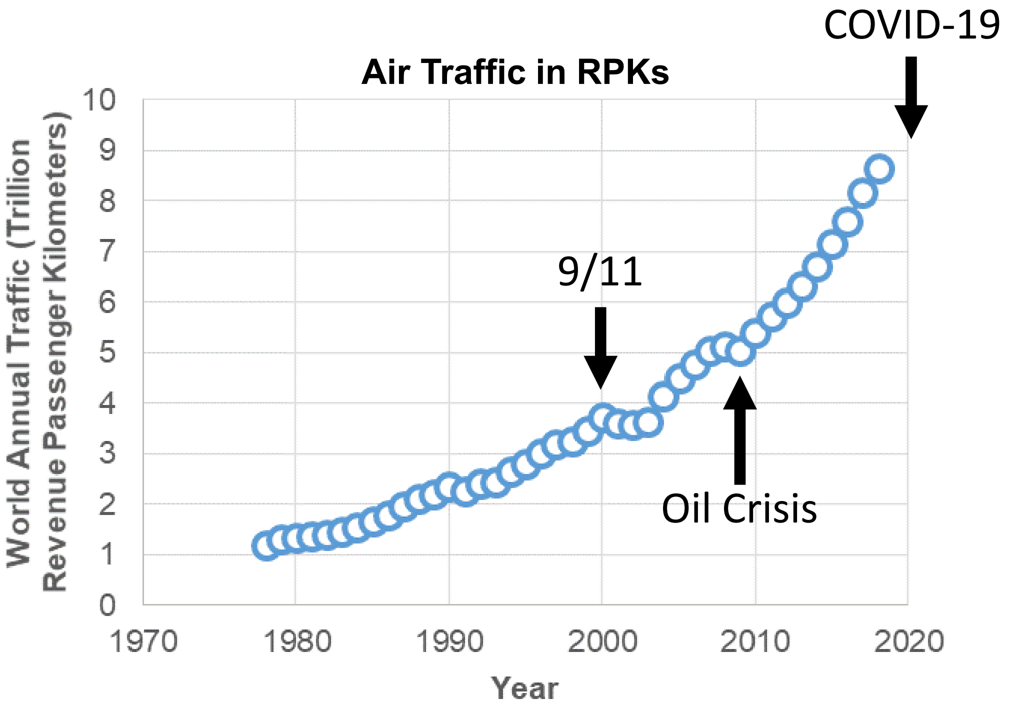
Aviation and the Global Climate Crisis



Lee et al. (2021)



Ansell and Haran (2020)

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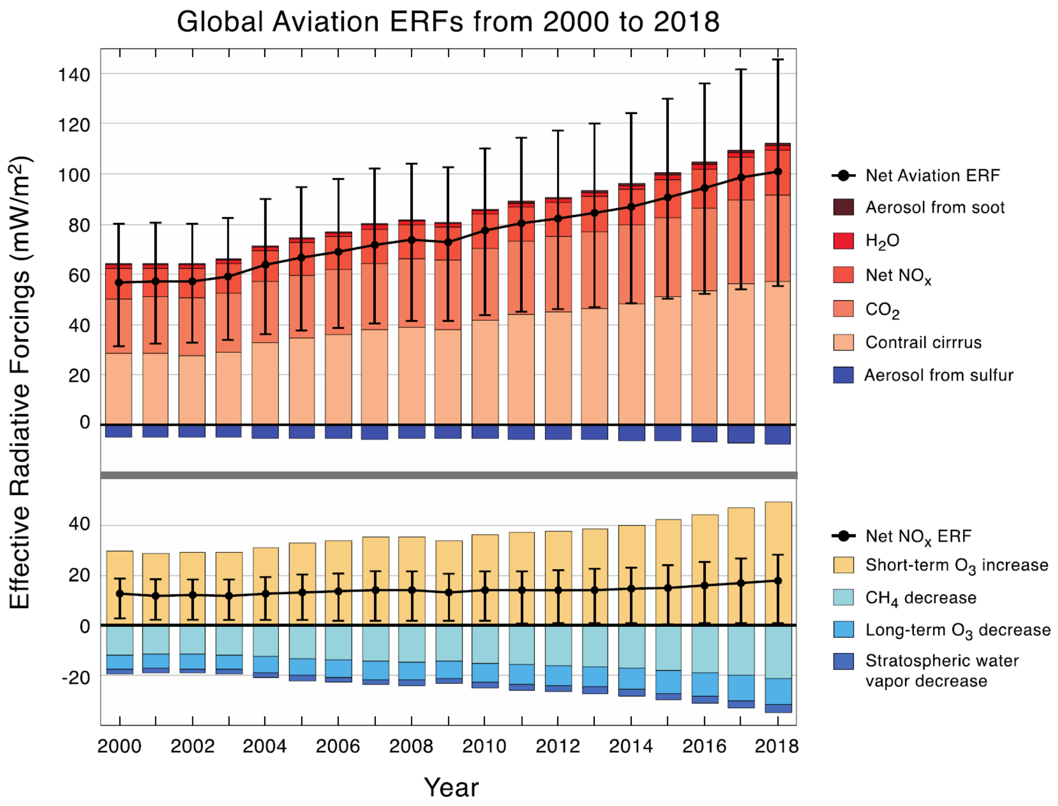
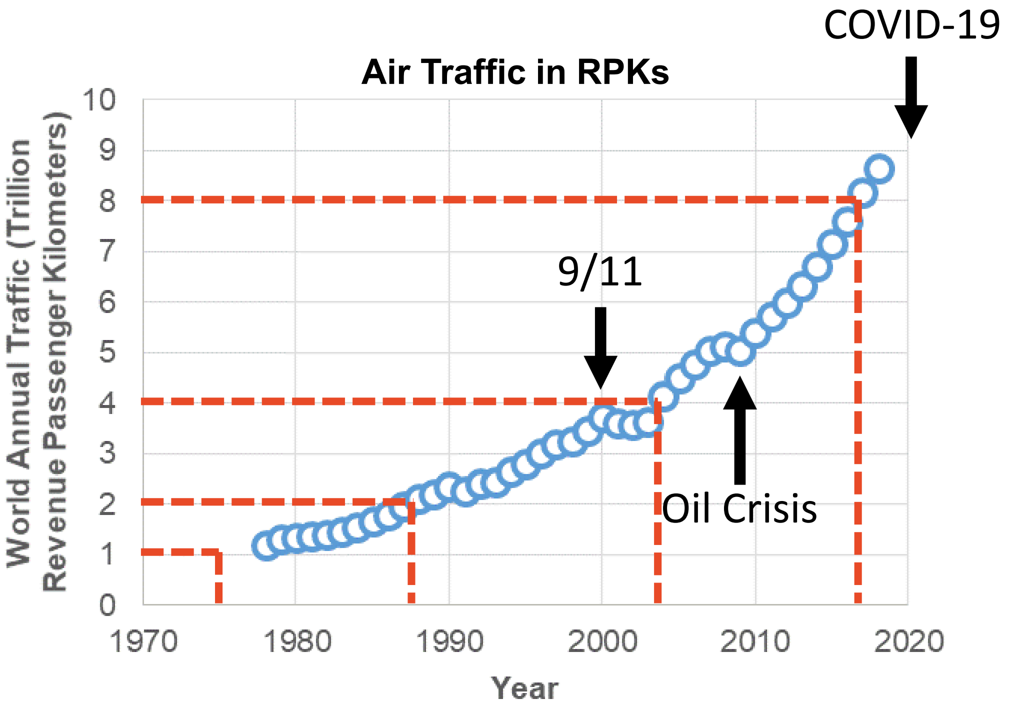


Lee et al. (2021)



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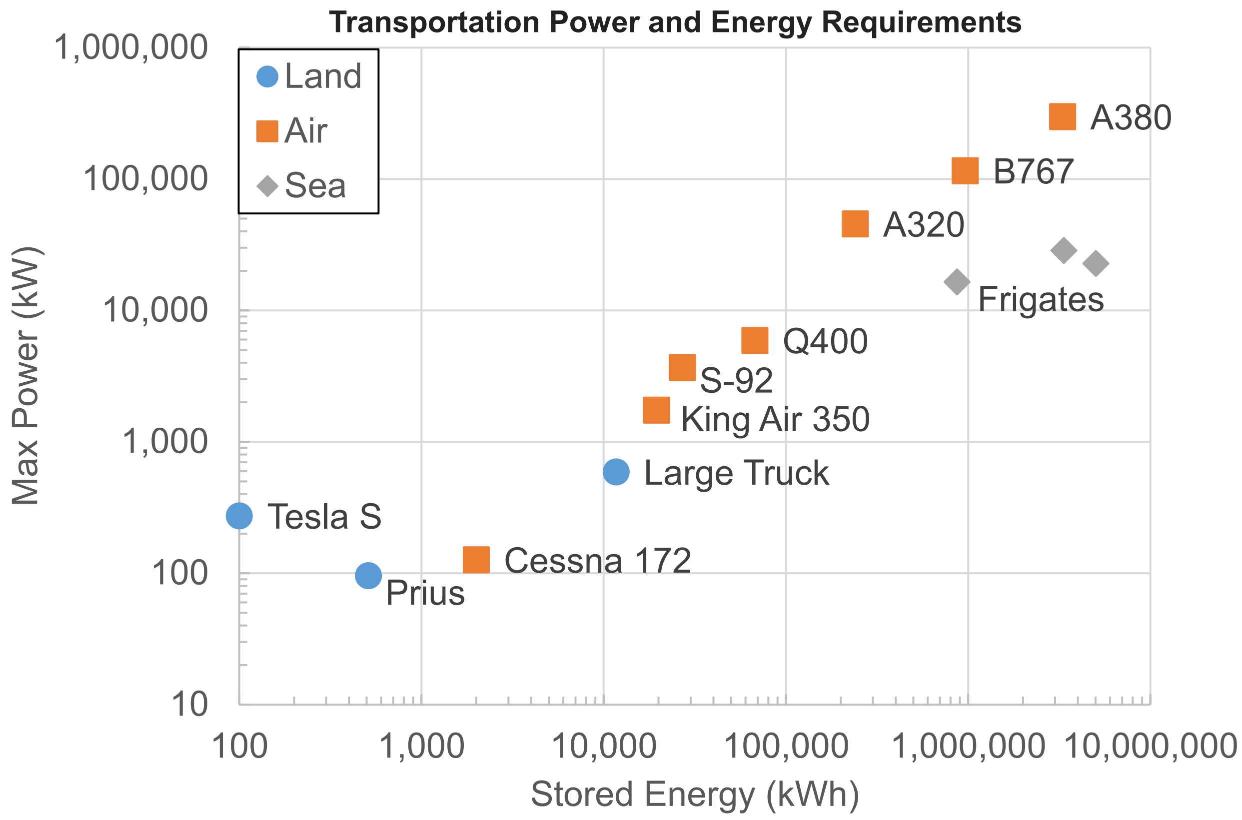
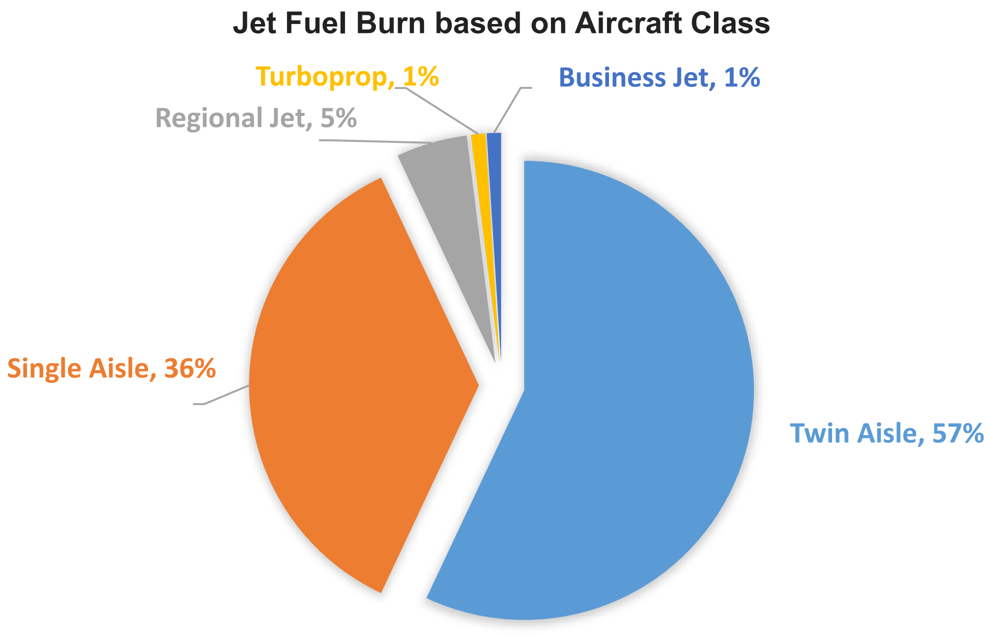
What are the Emissions?

- Atmospheric process creates additional chemical changes
  - Ocean uptake (CO_2), chemical reactions (CH_4, O_3), microphysical process (H_2O, aerosols, clouds, contrails)
  - Chemical lifetime differences at high altitudes
- Long-term and short-term impacts produced

The Challenge…



Epstein and O'Flarity (2019)



Yutko and Hansman (2011)

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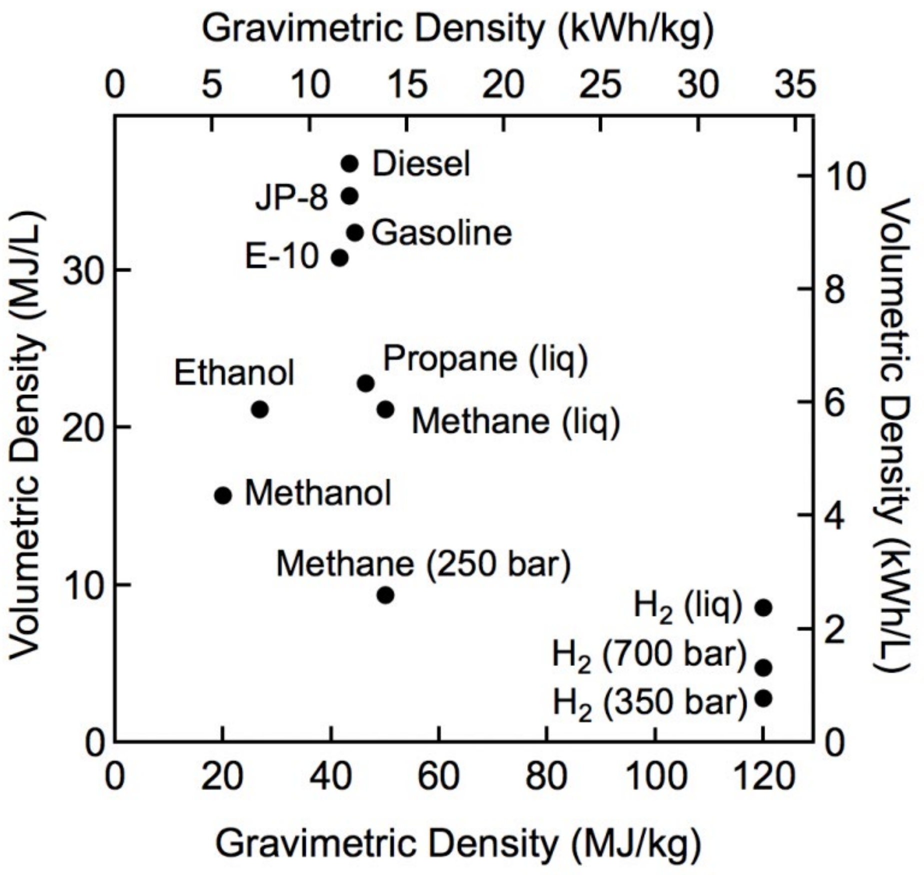
Why Hydrogen?

- Specific Energy of:
  - Jet A: 43.0 MJ/kg
  - LH_2: 119.93 MJ/kg (LHV)
  - Modern Li-Ion battery: 0.9 MJ/kg (250 Wh/kg)
- Energy Density of:
  - Jet A: 35 MJ/L
  - LH_2: 8.491 MJ/L (LHV)
  - Modern Li-Ion battery: 2.6 MJ/L
- Cryogenic LH_2 system enables high power and energy with low weight
  - **Are LH_2 aircraft feasible?**



DOE

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H_2 Aircraft Studies

- Brewer/Lockheed (1970's)
  - Concept studies of transport-class aircraft using LH_2 energy
- Tupolev Tu-155 (1980's)
  - Experimental version of production transport aircraft
  - Just over 100 flights on LH_2 and LNG
- CRYOPLANE (2000-2003)
  - Technically feasible and equivalent safety as conventionally-fueled aircraft
- NASA (2004-2006)
  - Fuel cells too heavy (at 0.3 kW/kg) to make system feasible, indicating 4× increase in power density required for feasibility
    - ★ Recent order-of-magnitude increase in specific power (> 2kW/kg)
- Many others…

Ion Tiger UAV (LH_2 with Fuel Cell)

CRYOPLANE Concept (LH_2 Combustion)

Phantom Eye Aircraft (LH_2 Combustion)

DLR HY2 (LH_2 with Fuel Cell)

ZeroAvia Piper M (GH_2 with Fuel Cell)

Tupolev Tu-155 (LH_2 Combustion)

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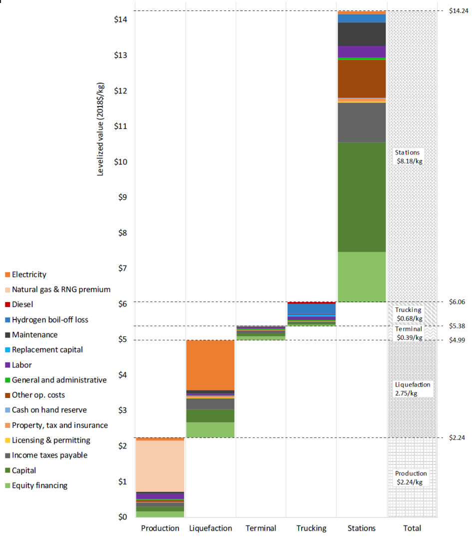
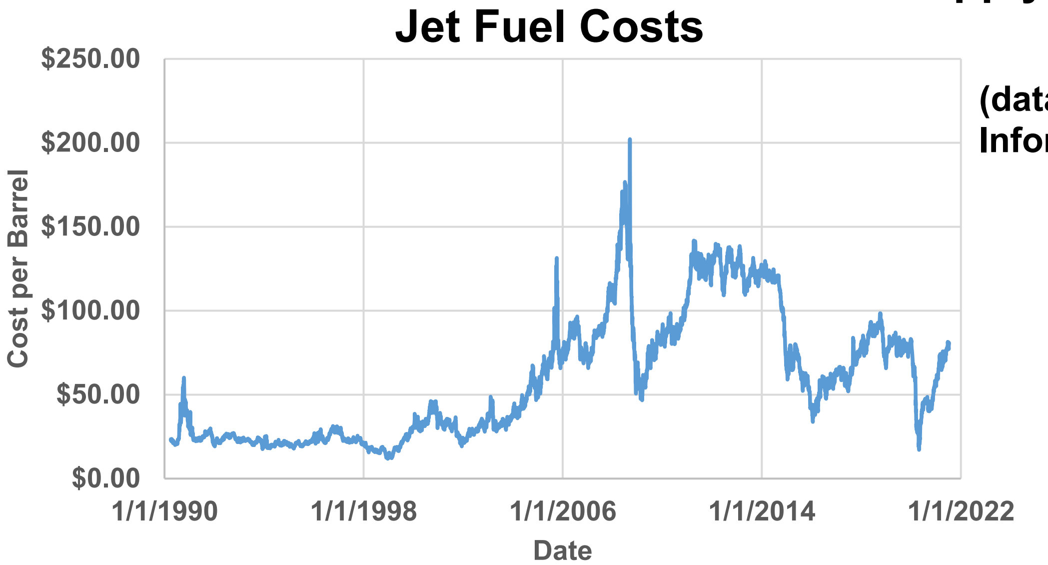
Economic Viability

- DOE goal (2021):
  - $1 for 1 kg of clean hydrogen in 1 decade
  - **80% decrease** from current values
- Cost per unit energy:
  - Jet A @ $80.77/bbl
    - 1 bbl = 158.99 L
    - 1 L = 35 MJ
    - **= $0.0145/MJ**
  - H_2 @ $1/kg
    - 1 kg = 119.93 MJ
    - = **$0.00834/MJ**
- Need to determine LH_2 liquefaction, handling, and delivery costs!
  - Critical cost in infrastructural development

DOE Earthshot Initiative



LH2 Supply Chain Costs (DOE)



(data source: US Energy Information Administration)

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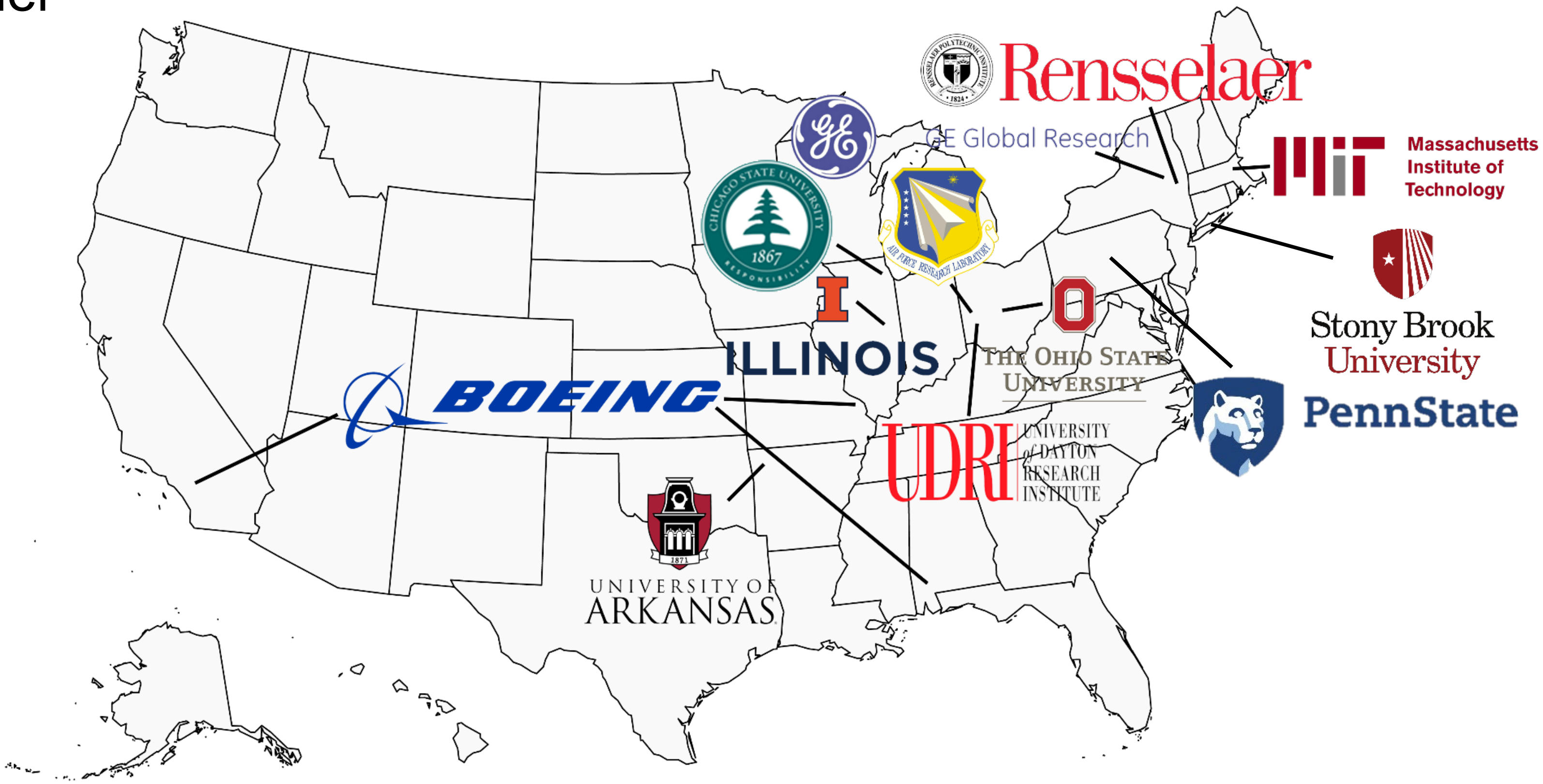
Our Team

- CHEETA
  - Established in 2019 under NASA ULI program
- Bringing together world experts in
  - Aeronautics
  - Electrical Systems
  - Material Science
- Multi-institutional
  - 9 Universities
  - 2 Industry groups
  - Government research collaboration



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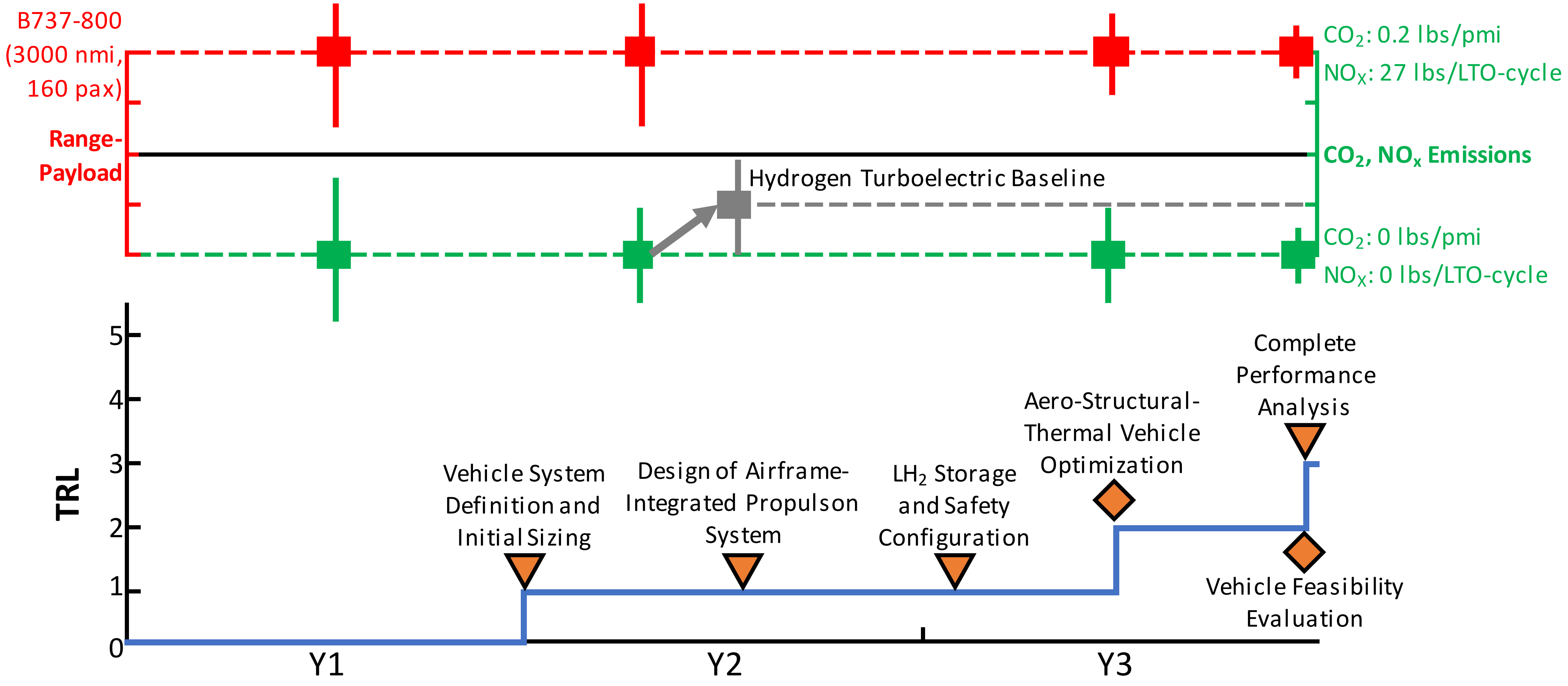
Technical Challenges (Aircraft)



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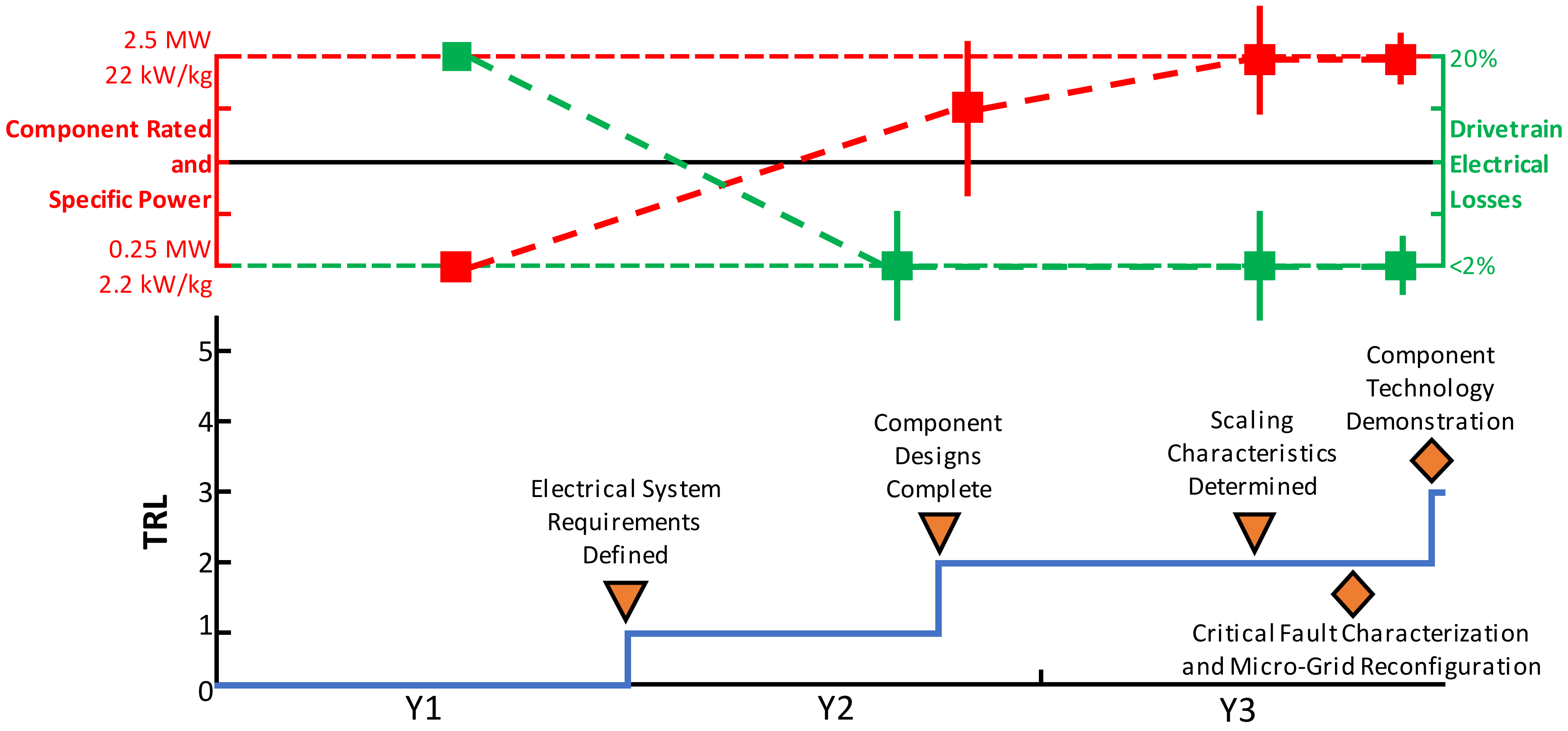
Technical Challenges (Electrical System)



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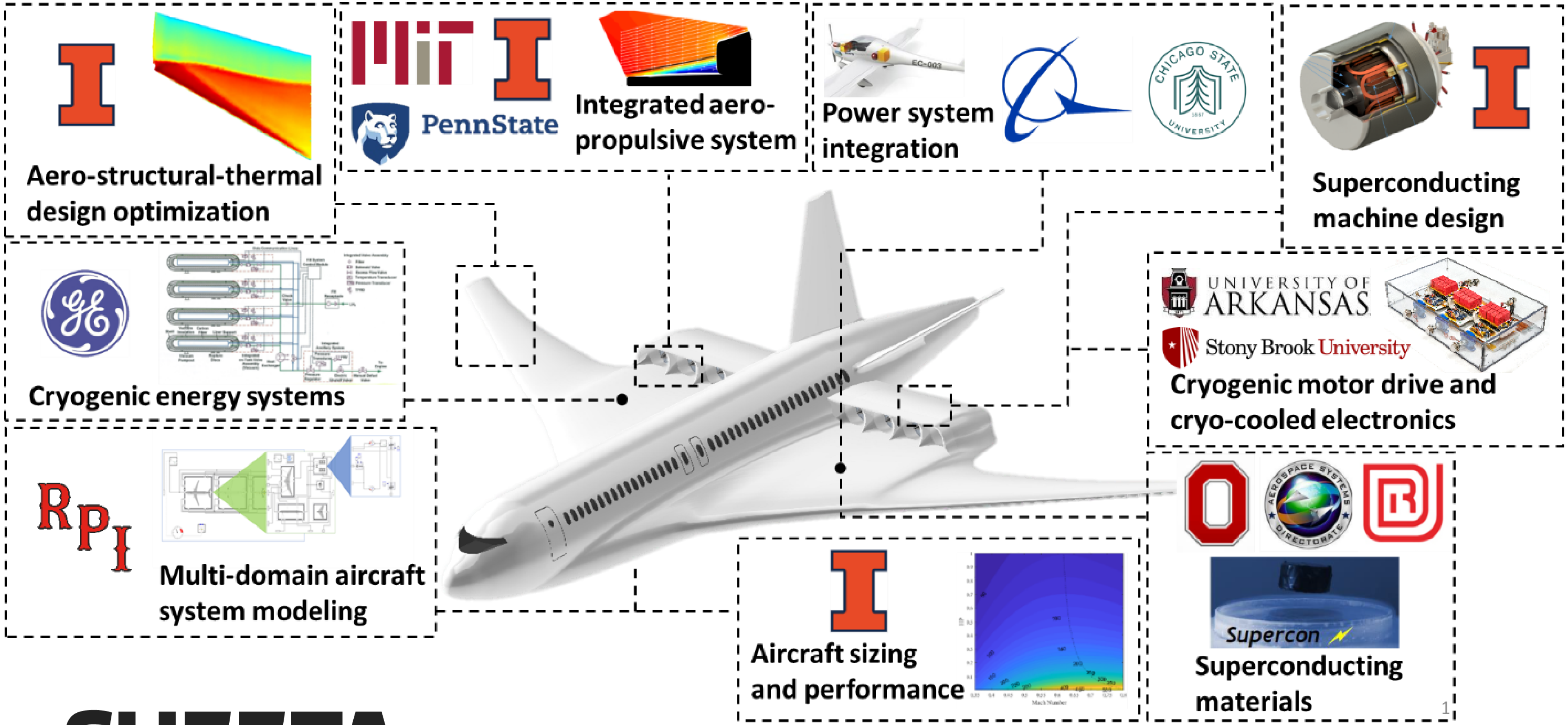
Research Components



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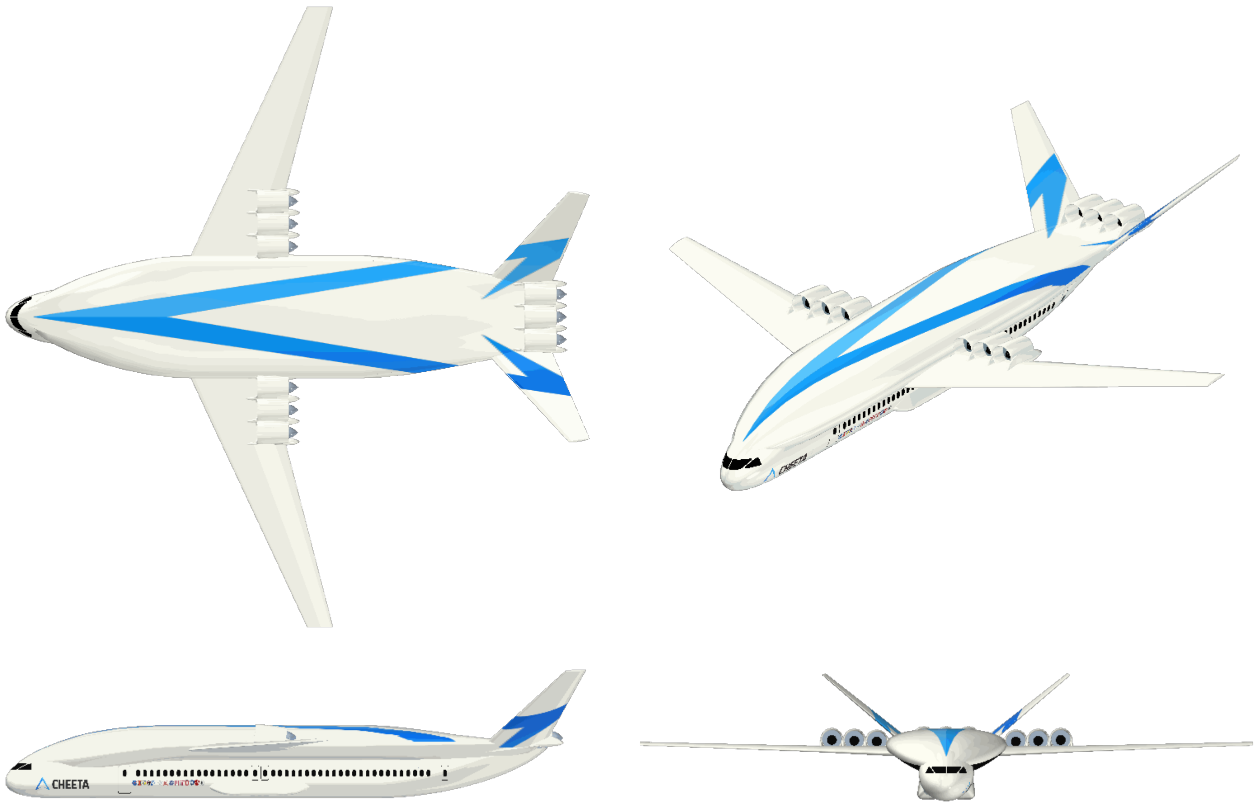
System Definition

- Configuration defined to guide technology development programs
- Fully hydrogen-electric power and energy system
- Distributed-electric propulsion system integration
- 180-pax single-aisle aircraft
  - Group III (with 15%-span folding wingtips)
- Consistent mission as B737-800 (M_∞, range, reserves)
- Assumed EIS: 2050



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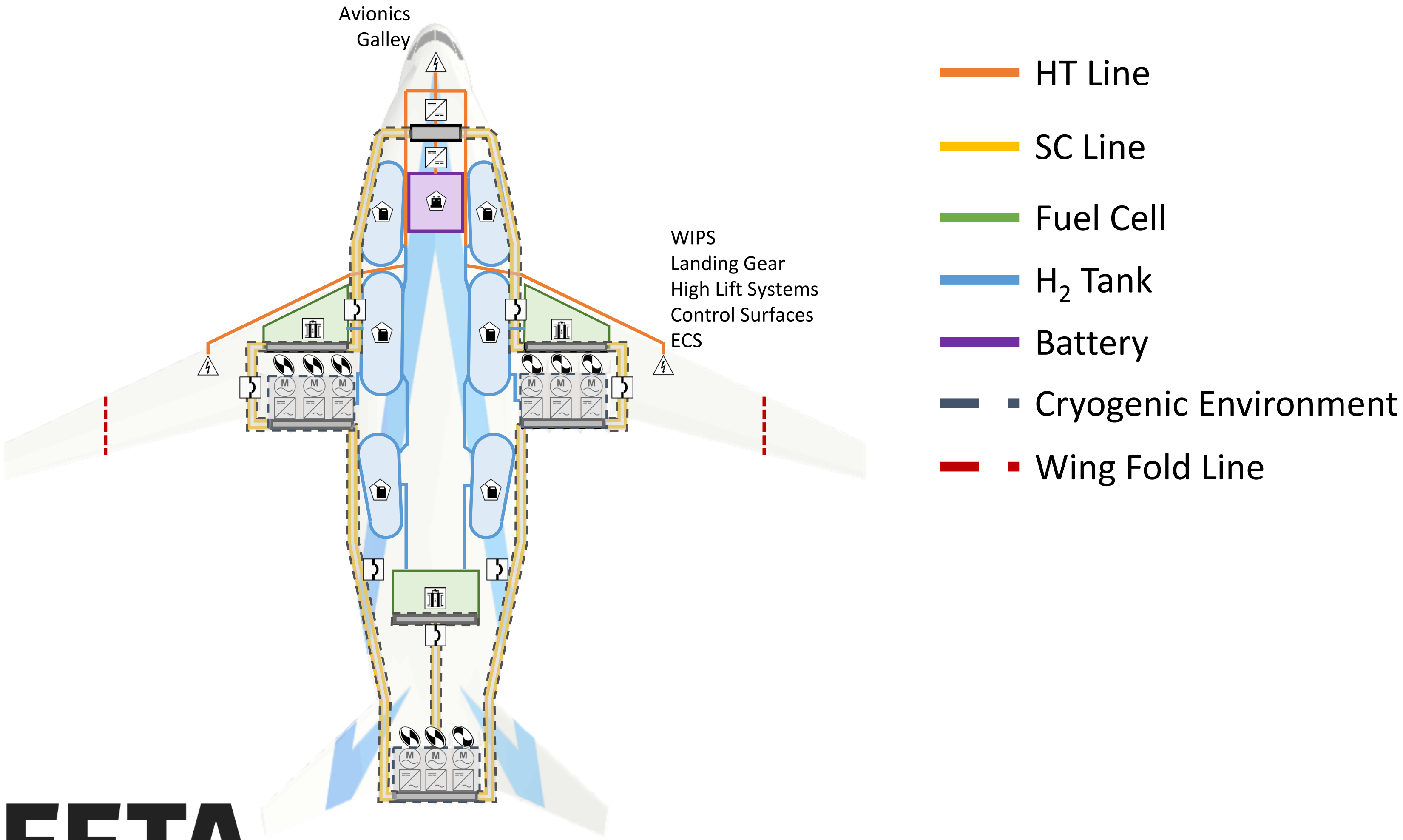
Power System Configuration



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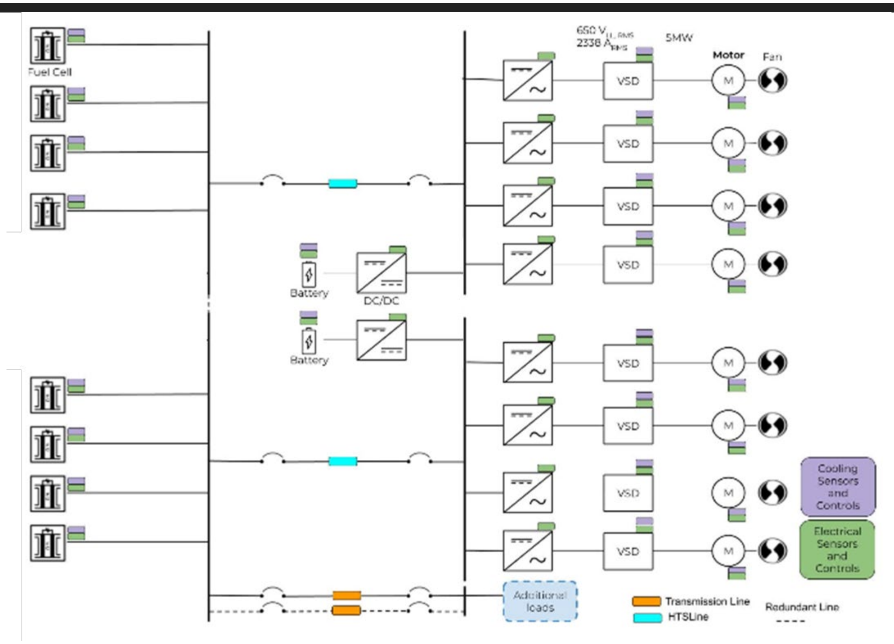
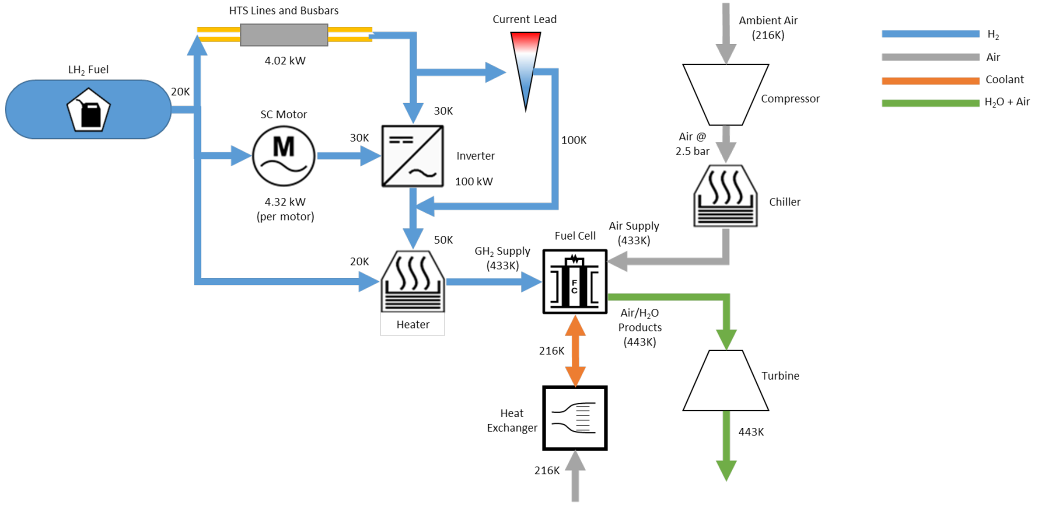
Power/Thermal System Architecture

- Architecture:
  - Hybrid centralized/distributed
  - Peak DC power: 25 MW
- Power Transmission:
  - Redundant superconducting power transmission
  - ± 270 VDC
- Motors:
  - Peak shaft power: 2.5 MW
- Cooling:
  - Liquid: Motor and transmission cable
  - Gaseous: Inverter, FC supply





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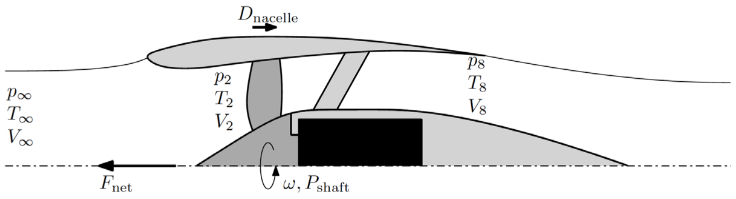
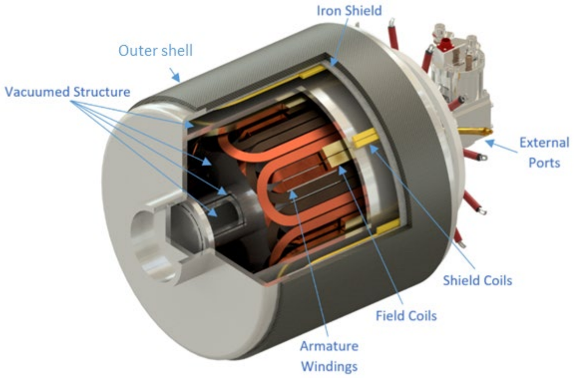
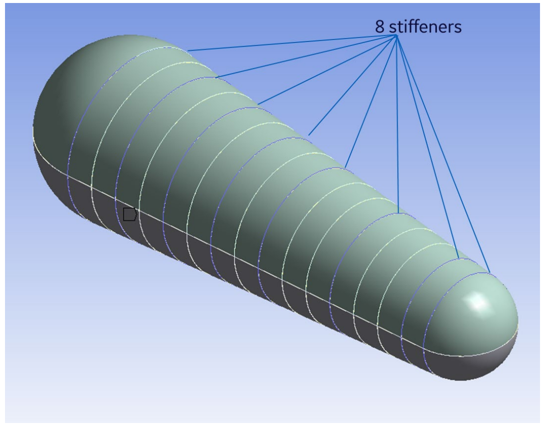
Key Technologies in Development

- **Aircraft System:**
  - LH_2 Aircraft concept synthesis
  - High-temperature PEMFC system integration
  - Boundary-layer ingesting propulsor design optimization
- **Electrical System:**
  - Ultra-efficient, power-dense superconducting motors
  - Cryogenically-cooled power inverters
  - Superconducting materials and power systems
- **Power and Energy System:**
  - Lightweight LH_2 tank designs
  - Cryogenic circuit components and subsystems
  - Electro-thermal system designs







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Here at CEC-ICMC 2021

- M2Or2A-03 A Pressurized, Flexible, Variable Temperature Aerospace Cable Demonstration
- M2Or5A-01 Design and Optimization of Rotating Cryogenic Machine Topologies for a Hydrogen-Powered, Electric Propulsion Commercial Aircraft
- C3Or1A-05 Liquid hydrogen tank design for medium and long range all-electric-airplanes
- C3Or1B-06 Design and Analysis of Cryogenic Cooling System for Superconducting Motor
- M3Or1B-02 Comparison of Cryogenic Technologies for Electric Aircraft Power Transmission
- M3Or2B-01 Cryogenic Performances Comparisons Among Si MOSFET, SiC MOSFET, Cascode GaN, and GaN Devices
- M3Or2B-04 Electrical characterization of a 1200V GaN HEMT at cryogenic temperatures
- M3Or3A-01 Comparative Evaluation of Different DC-AC Converter Topologies for Cryogenic Applications Utilizing Superconducting Materials
- M5Or2A-01 Electro-Thermal Modeling of HTS Power Lines for Cryogenically-Cooled Electric Aircraft Design
- M5Or2A-02 Metal Composite T-Junction Terminals for Power Distribution
- M5Or2A-07 Current Sharing and Stability in an Extremely Low AC Loss MgB2 Conductor

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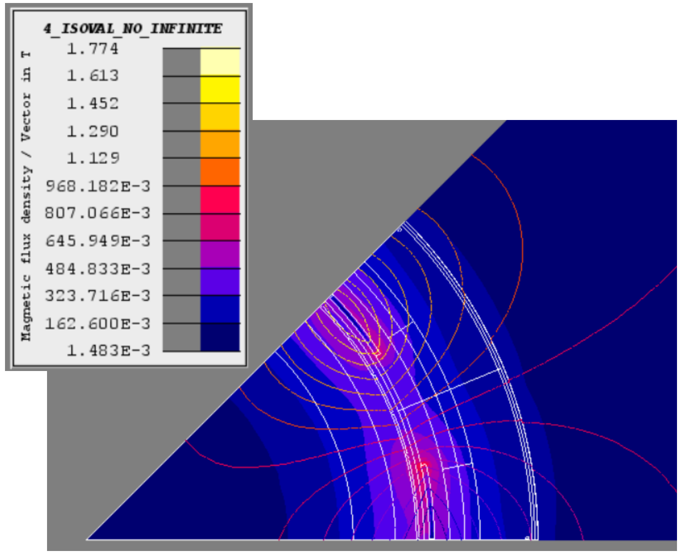
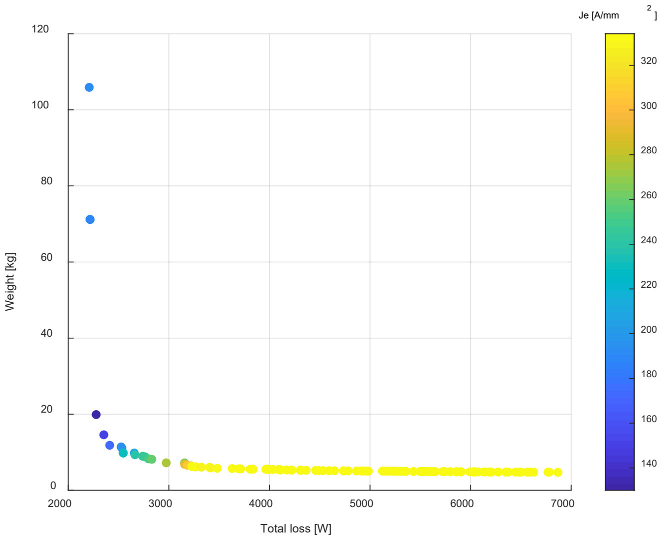
Superconducting Motor Design

- **Partial SC** demonstrates:
  - Smaller losses than fully-SC
  - Lighter weight than PM motor with SC armature coils
- Air-gap flux density range is 0.4-1.2T
- Current density at cable: 300-400 A/mm²



Optimal machine flux density diagram



Partial-SC motor design space

Parameter	'Optimal' design
Rated Power [MW]	**2.5**
Outer Diameter [m]	0.5
Machine total length [m]	0.75
Active length [m]	0.867
Average torque [Nm]	7045
Air-gap flux density [T]	0.63
Armature SC length [km]	12.11
Field SC length [km]	7.3
Shield SC length [km]	0.1
Total SC length [km]	7.3
Iron shield weight [kg]	1
Total loss [W]*	2656
Weight (Iron and SC) [kg]	13
Specific Power (Iron and SC) [kW/kg]	192

*Allocate 40% additional margin for losses considering uncertainty in loss prediction, field harmonics, time harmonics and losses in current lead, conduction and radiation.
Total losses: 4.3 kW

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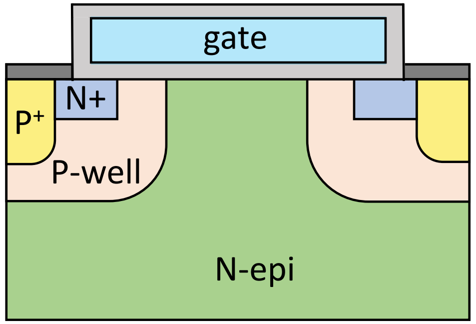
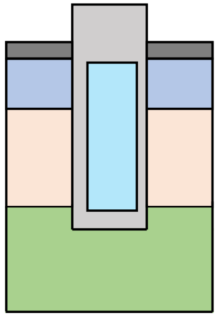
Electronics Component Characterization

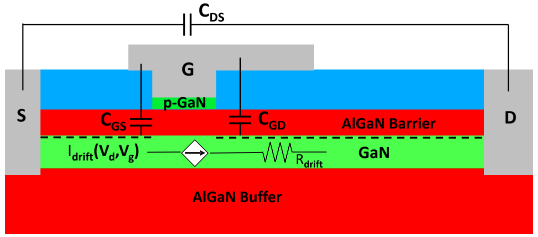
- Transistors at low temperatures:
  - Traditional Si: good conduction and switching performance
  - SiC MOSFET: increased on-resistance, variable switching speed
  - **Cascode/single-chip GaN HEMT**: reduced conduction and switching loss
    - No "carrier-freezeout" observed
    - Tolerable on-resistance at deep cryo temperatures
- Passive components
  - Variable performance
- Gate drivers
  - Lose functionality at low temperatures

Planar SiC

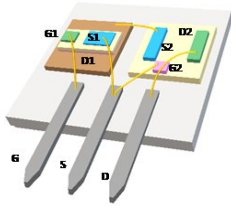


Trench SiC

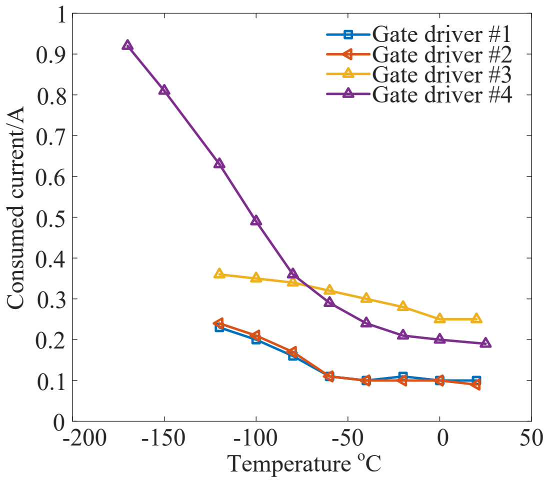


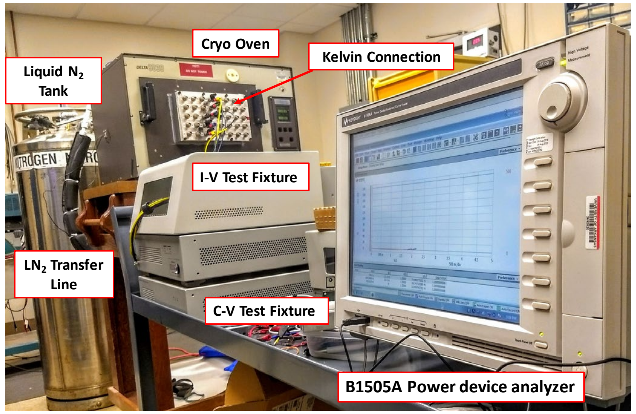


Single chip GaN HEMT

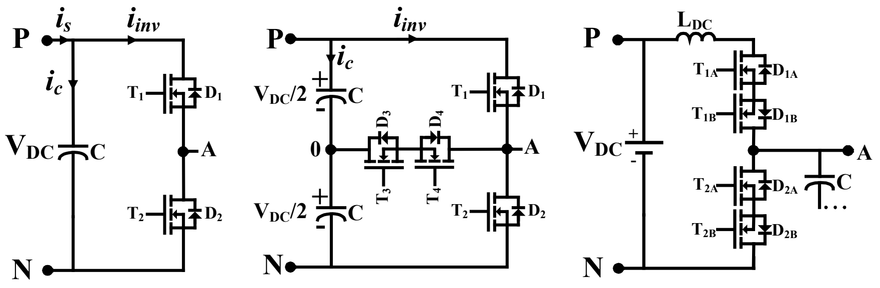


Cascode GaN





Power Converter Design



Two Level Voltage Source Inverter (2L-VSI)

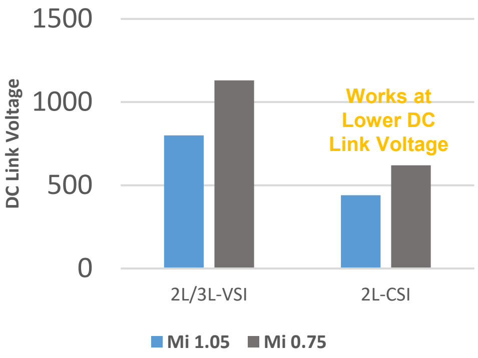
Three Level Voltage Source Inverter (3L-VSI)

Two Level Current Source Inverter (2L-CSI)

Property		2L-VSI (30 kHz)	3L-VSI (30 kHz)	2L-CSI (30 kHz)
DC Link Voltage	V_{DC} Max	1130 VDC	1130 VDC	620 VDC
	V_{DC} Min	800 VDC	800 VDC	440 VDC
DC Link Capacitance [1]-[4] (5 % Voltage Ripple and 1 switching frequency ride through)	@ V_{DC} Max	1500 uF, 1130 VDC	2 x 3000 uF, 565 VDC	---
	@ V_{DC} Min	2700 uF, 800 VDC	2 x 5400 uF, 400 VDC	---
DC Link Inductance [5] (5 % Current Ripple)	@ V_{DC} Max	---	---	25 uH, 4080 A DC
	@ V_{DC} Min	---	---	18 uH, 5710 A DC
O/P Filter Capacitance [6] (5 % THD)	@ V_{DC} Max	3 x 66 uF, 350 VAC	3 x 58 uF, 350 VAC	3 x 429 uF, 350 VAC
	@ V_{DC} Min	3 x 70 uF, 350 VAC	3 x 64 uF, 350 VAC	3 x 610 uF, 350 VAC
O/P Filter Inductance [6] (15 % Current Ripple)	@ V_{DC} Max	6.15 uH, 3402 A pk	4.61 uH, 3402 A pk	---
	@ V_{DC} Min	4.35 uH, 3402 A pk	4.27 uH, 3402 A pk	---

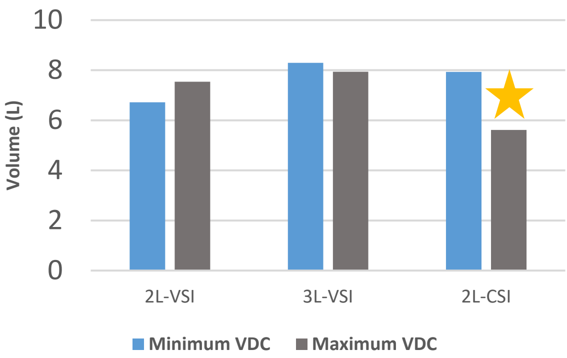
DC Link Variation

DC Link Required for Drive of 600 V_{LL-RMS}



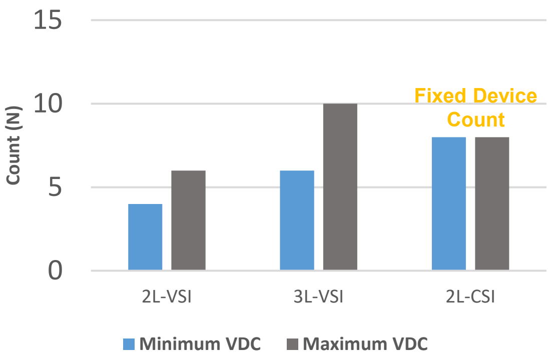
Overall Volume

Overall Volume of Passive Components

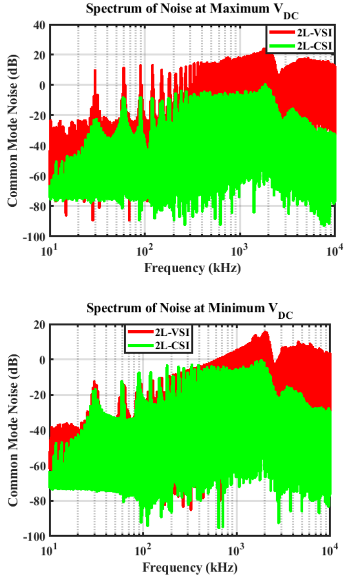


Device Count

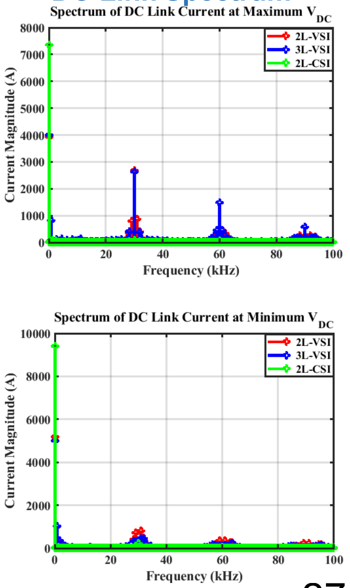
GaN Devices in a Phase leg



EMI Performance



DC Link Spectrum



- Current-source inverter suitable to handle voltage variation

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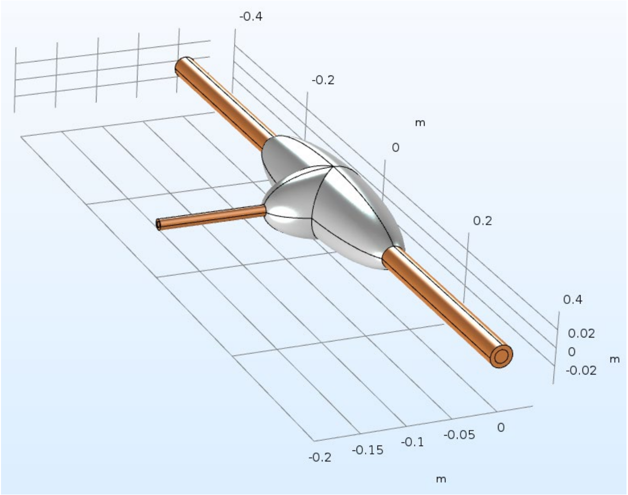
Superconducting Power Systems

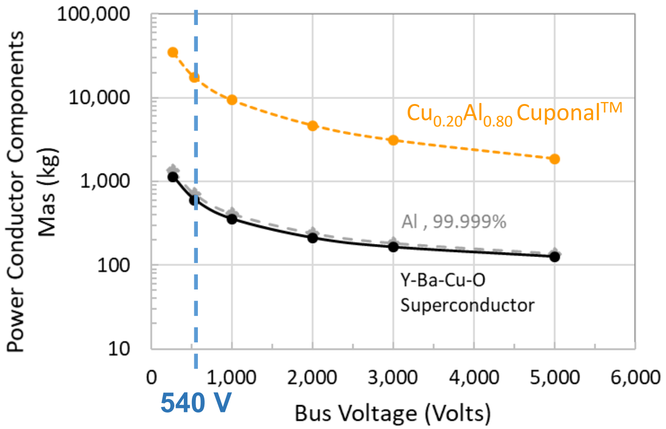
- Superconducting power transmission system:
  - Size, weight, and power (SWaP) trade studies for DC power system
  - Material selection (YBCO, hyperconducting Al)
  - Configuration and sizing of busbars, current leads
  - **± 270V bus is feasible**
- Configuration of current leads:
  - Heat Loss = 2–4 W @ 30K, 20 nΩ–m^2
  - Mass = 2.8–6.2 kg (varies with temp and power loss)



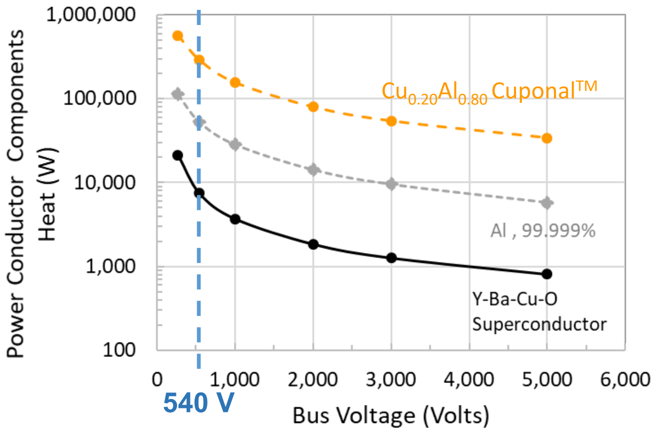
Bimetallic copper-aluminum T joint

	$Cu_{0.15}Al_{0.85}$ CupTM Cuponal™ @ 294K	Al > 99.999% Hyperconductor @ 20K	YBaCuO or MgB_2 Superconductor @ 20-65K
Weight	9,355 kg (heavy!)	411 kg (light)	357 kg (light)
Waste Heat	155 kW (hot!)	28.5 kW (hot)	3.7 kW (cool!)
Cost	medium	high	high
Complexity	low	medium	medium
TRL Level	9	4	4, aircraft 9, CERN
Protection Risks	high	high	medium, (FCL intrinsic)

Summary of technology solutions



Transmission system weight



Transmission system heat load

***Assumes 40MW system**

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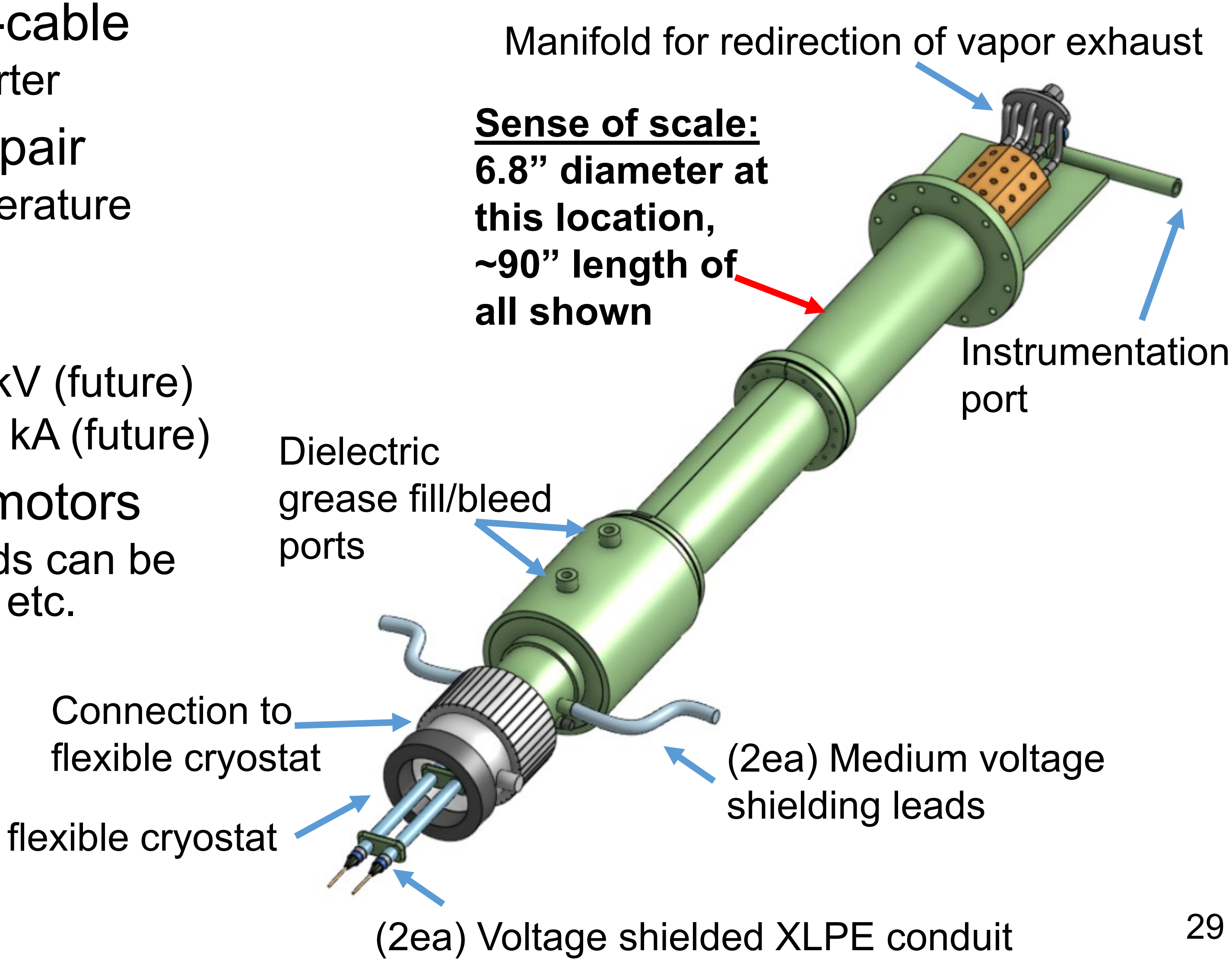
Drivetrain Technology Demonstrator

- Test of 1 kA Al, 99.999% cryo-cable
  - Connect/test a 20 kW cryo-inverter
- Vapor cooled +/- current lead pair
  - Gradient: 20 K to ambient temperature
  - Vapor pressure up to 30 psi
- Operating range:
  - Voltage = 1 kV (present), to 10 kV (future)
  - Currents = 1 kA (present), to 10 kA (future)
- Cryogen boiloff starting from motors
  - Cryogenic vapor exiting the leads can be redirected to power electronics, etc.



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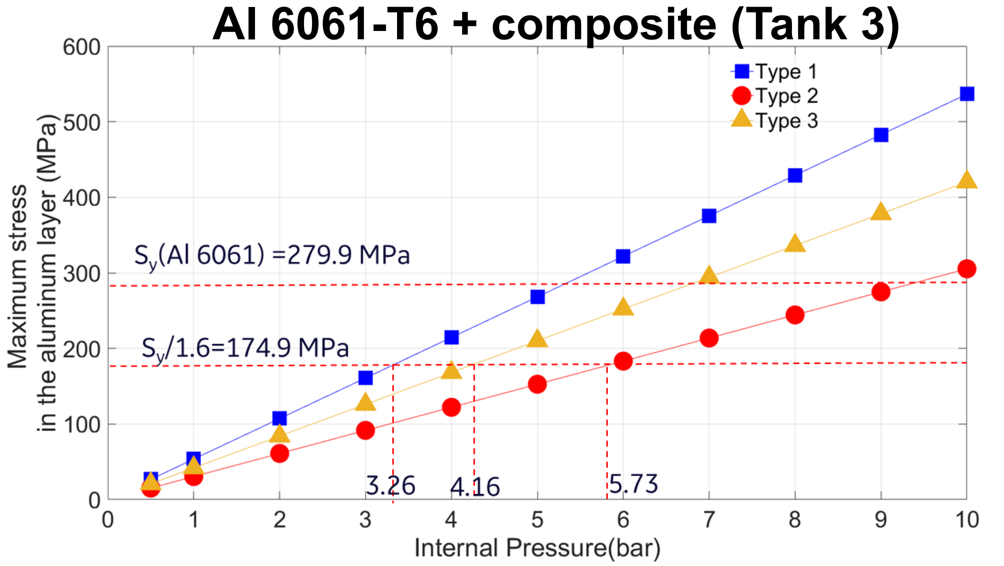
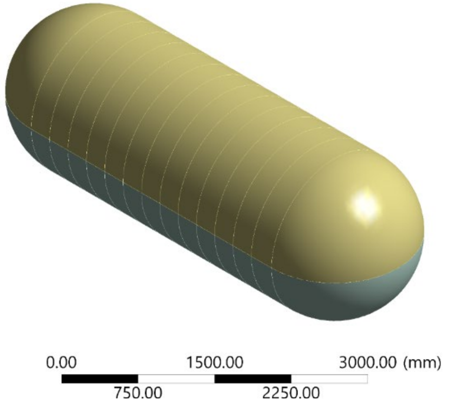
LH_2 Tank Design

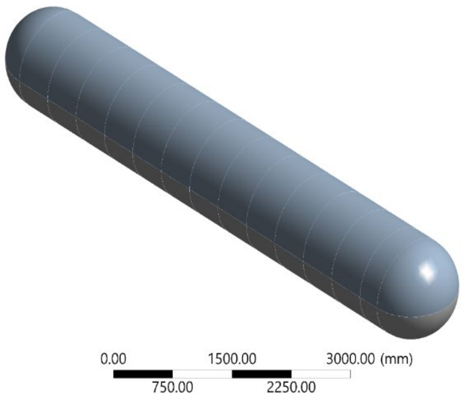
- Key design drivers
  - Integral vs. non-integral (modular)
  - Materials and insulation
  - Tank shape and size
  - Slosh, bulk-head baffles
  - Loads and multi-point operation
  - Safety considerations
  - Manufacturing, processing, inspection
- CHEETA design:
  - **Tank weight fraction (W_{tank}/W_{H2}) = 0.60-0.67**



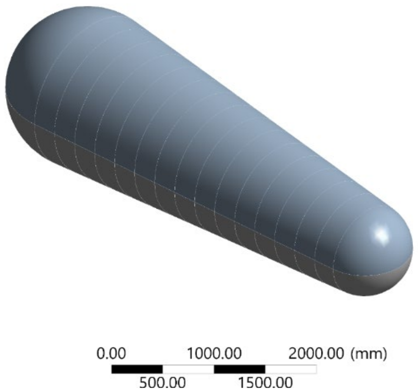
Tank 1 (Type 2)



Tank 2 (Type 2)



Tank 3 (Type 2)



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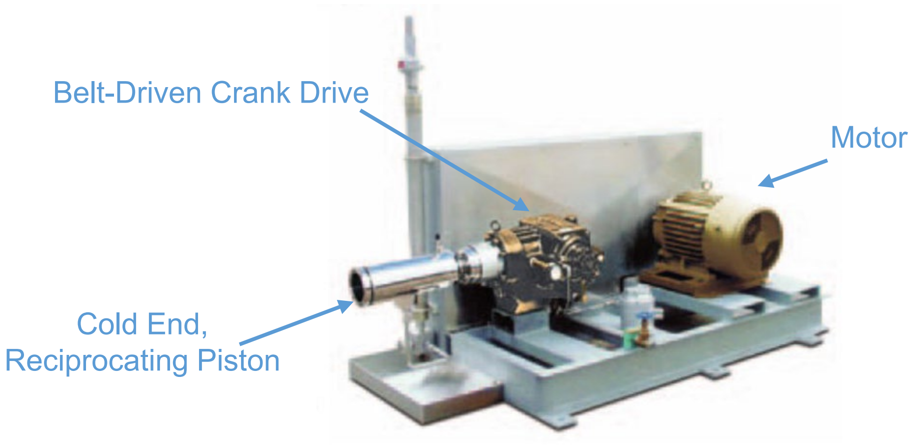
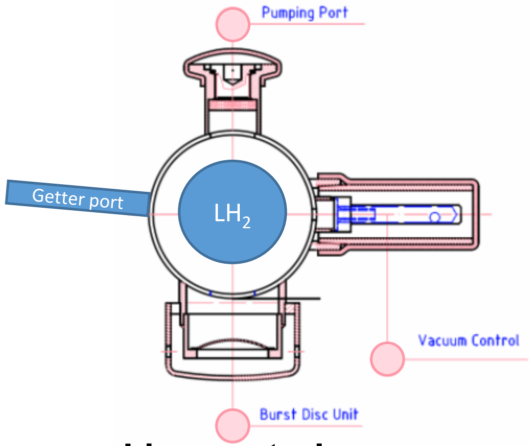
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 50, October 2021.
Invited presentation J4Or2A-01 given at CEC-ICMC 2021, July 19-23, 2021, Virtual.

LH_2 Pump, Distribution

- Pump selection (LH_2)
  - Piston pumps provide excessive pressure and insufficient flow
  - Centrifugal pumps provide insufficient pressure and excessive flow
  - Phase separation
  - **Opportunities for new aerospace-grade LH_2 pumps**
- Vacuum jacket distribution lines
  - Maintaining vacuum quality
  - Welded line designs
  - System controls
  - Purging and venting



Nikkiso 1-cylinder SGV Piston Pump



Line controls

Flexible vacuum jacket lines (cryostat)

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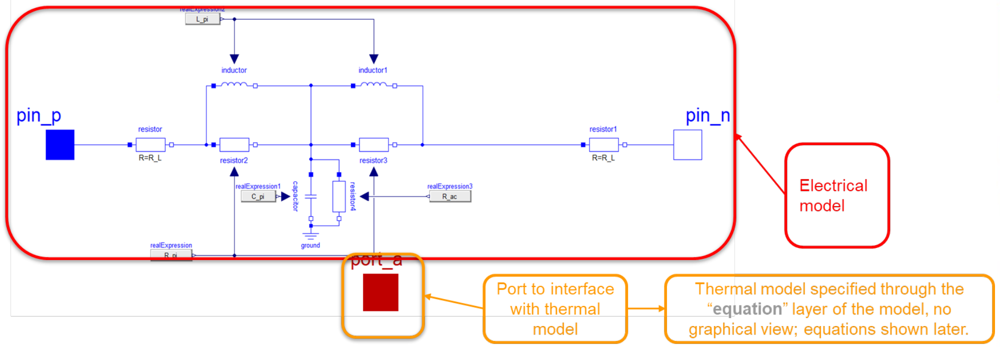
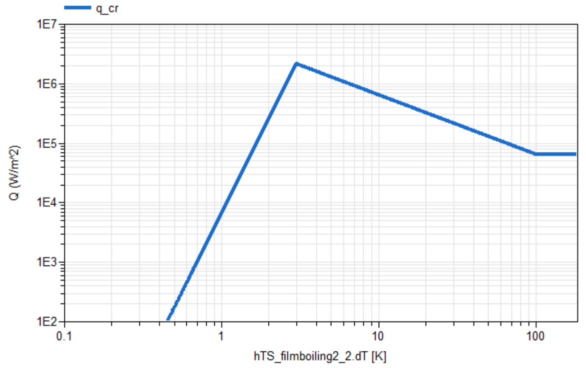
Multi-Domain Modeling Example: HTS

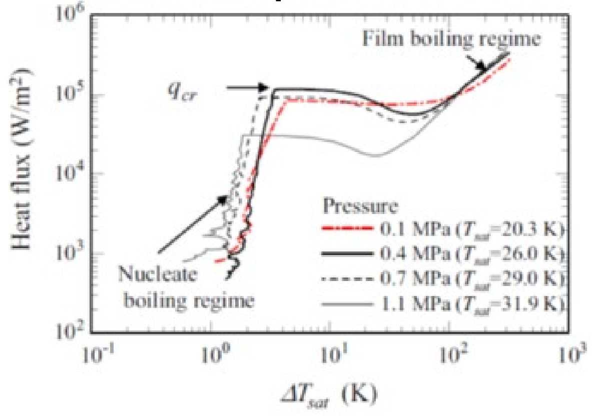
- Multi-domain transmission line
  - Co-axial cable model and Stekly cryostability equations (Mike Sumption, OSU)
  - Both gas and liquid cooled cables
  - Coaxial cable pi-line electrical circuit

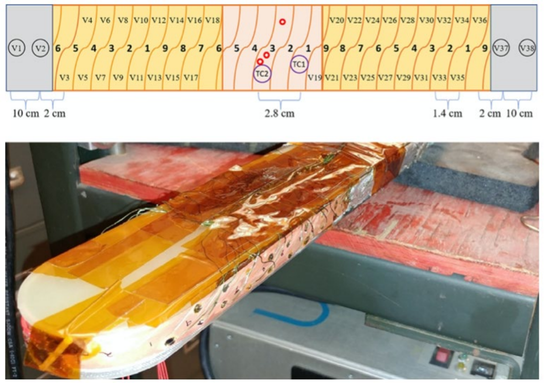


Simulation



Experiment





HTS Cable from: C.J. Kovacs, M. Majoros, M.D. Sumption, E.W. Collings, Quench and stability of Roebel cables at 77 K and self-field: Minimum quench power, cold end cooling, and cable cooling efficiency, Cryogenics, Volume 95, 2018.

- Simulation results
  - HTS line subject to current ramp input
  - **Liquid cooling provides superior stability**
  - Impedance limits on fuel cells

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Agenda

- Introduction
- CHEETA Team and Technical Challenges
- Research Components and System Definition
- Technical Work at CEC-ICMC 2021
- Acknowledgements

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  - 6 undergraduate students
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