P/O/E/T/S

CENTER FOR POWER OPTIMIZATION OF ELECTRO-THERMAL SYSTEMS

Cryogenics for conventional systems and for superconductivity

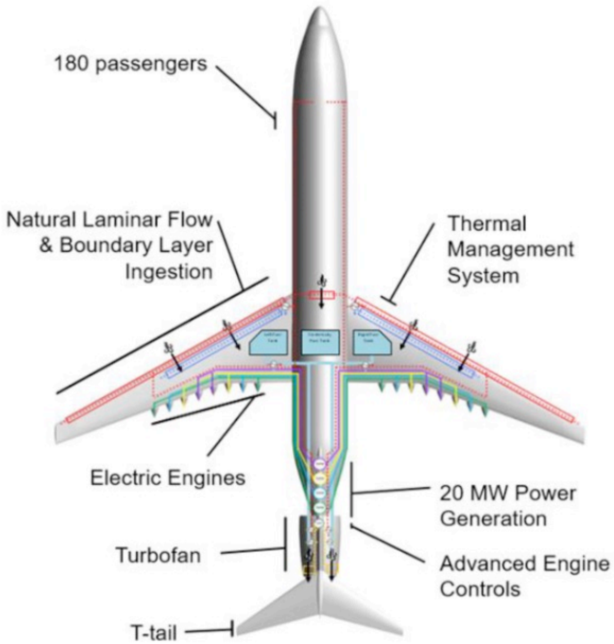
2022 Annual Meeting

October 18 – Noon to 2:00pm PDT

NASA 20 MW Electrical System Trade Study

Table 3: Specific Power and Efficiency Ranges Being Evaluated for SUSAN EPS Components

	Weight				Efficiency			
	Nominal	Min	Max	Unit	Nominal	Min	Max	Unit
Electric Machines								
Main Generator	25	15	50	kW/kg	99%	98%	99.5%	%
Turbine Control Motor/Generator (TCMG)	20	10	30	kW/kg	99%	98%	99.5%	%
Electric Engine Motor (EEM)	20	10	30	kW/kg	98.5%	97%	99.0%	%
Power Conversion								
Main Generator Converter (MGC)AC to DC	30	20	40	kW/kg	99%	97%	99.5%	%
Turbine Control M/G Converter (TCC) AC to AC	15	10	20	kW/kg	98%	94%	99%	%
Electric Engine Motor Converter (EEMC) DC to AC	20	10	40	kW/kg	99%	97%	99.5%	%
Batteries								
Rechargeable Battery	500	200	1000	w-hr/kg	97%	90%	98.0%	%
Single Use Battery	1500	700	3000	w-hr/kg	90%	50%	98.0%	%
Cables								
AC Distribution Cable	2	0.5	10	kg/m/MW	0.040%	0.080%	0.020%	% loss/m
DC Distribution Cable	2	0.5	10	kg/m/MW	0.040%	0.080%	0.020%	% loss/m
Circuit Interrupters								
AC Circuit Interrupters	300	200	600	kW/kg	99.5%	99.7%	99.9%	%
DC Circuit Interrupters	150	100	300	kW/kg	99.5%	99.7%	99.9%	%



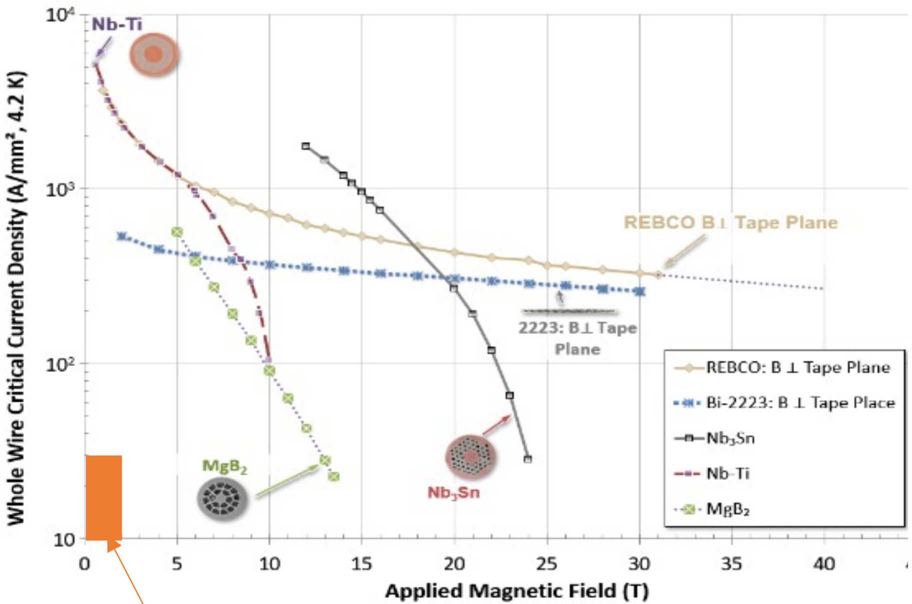
Powertrain Requirements

Device Power Density = 30-50 kW/kg

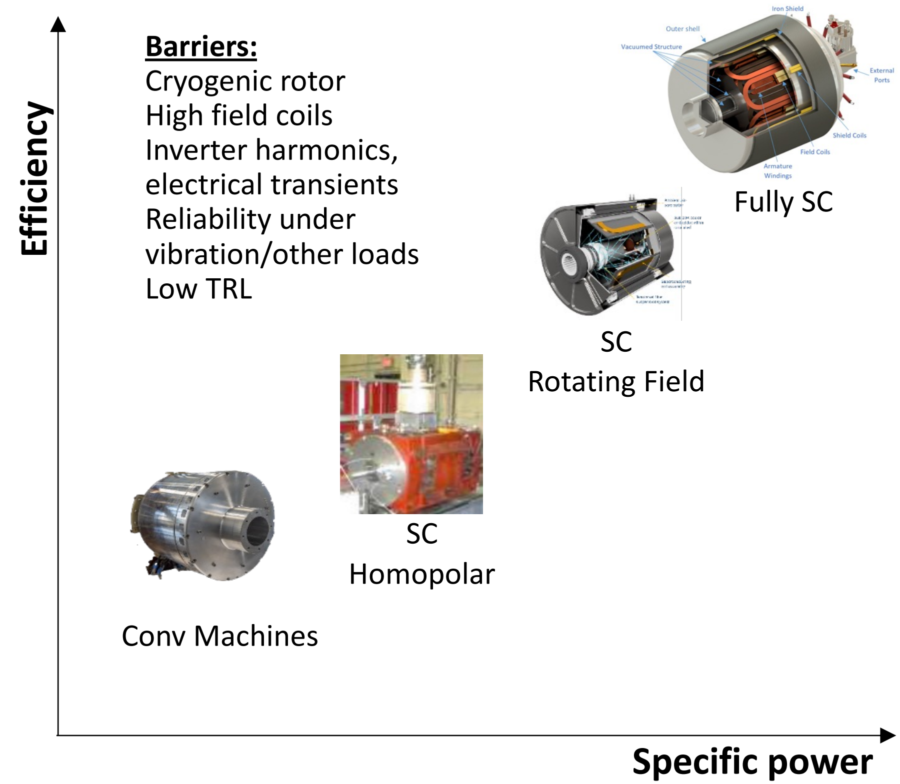
Device Efficiencies ≥ 99.5%

System Efficiency > 95%

$$Power = \frac{\pi^2}{4\sqrt{2}} k_{\omega 1} A B n D_{ag}^2 L_{stk}$$



Design space for ‘conventional’ machines

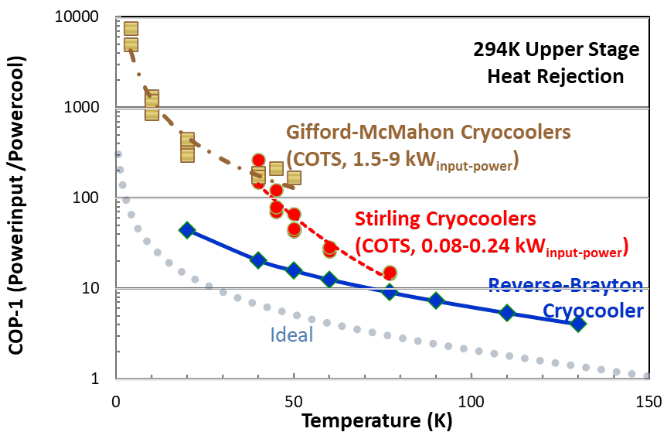


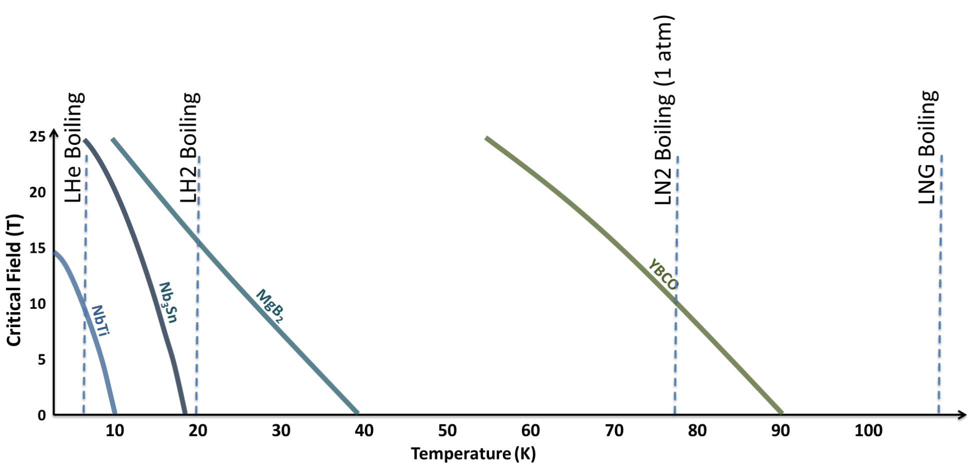
Design Considerations for a SC machine

I. Thermal Management (Cooling)
   - Open loop
   - Cryocoolers

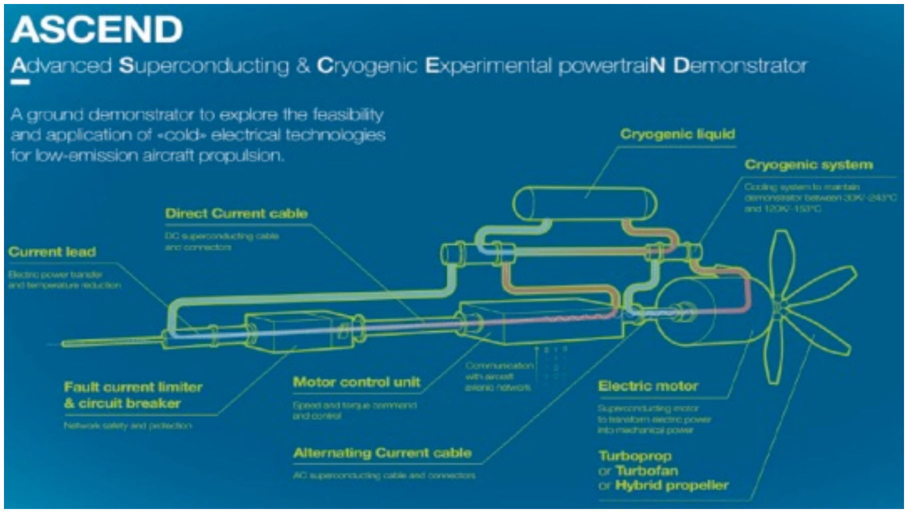
II. Electromagnetics
   - Fields, currents, stresses
   - Quench protection
   - Fault ride-through

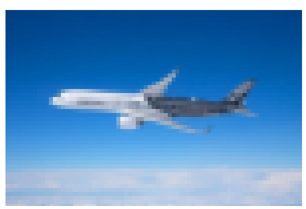
III. Mechanical design (incl. thermal)
   - Structural support
   - Thermal isolation
   - Heat transfer



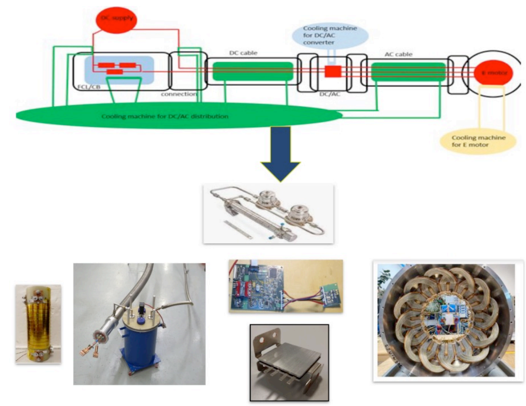


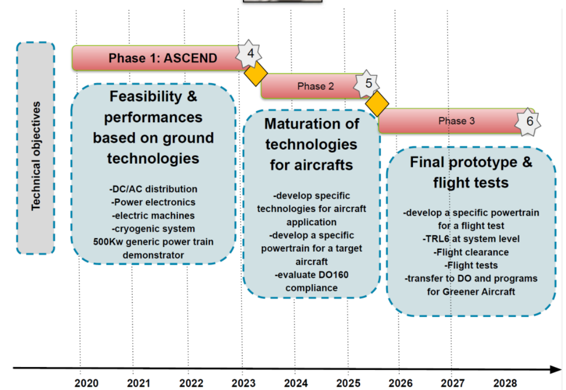
Airbus ASCEND





From 100 kW to 10 MW





EFATS ‘21

SC Motor Projects in the US

1. **NASA Glenn:** Superconducting motors [RebCO Rotor (77 K), Cu stator (RT)]

2. **SOARING*:*** Superconducting Motor (SC Stator, SC rotor) and Cryo-Cooled Inverter Engine (Raytheon, PNL, U Tennessee, Hyper Tech, OSU, KGP, Emvionic) 20 K operation, 120 K LNG heat sink

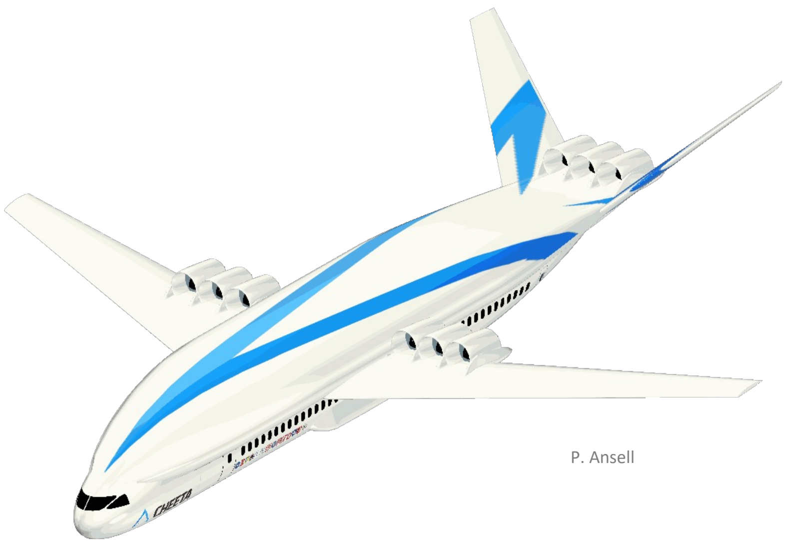
3. **Cryogenic Thermal Management of High Power Density Motors and Drives** (Hyper Tech, OSU, AFRL, Boeing, Raytheon, Tenn Tech) [120 K LNG operation and Heat sink]

4. **Flux-Switching Machine Based All-Electric Power Train for Future Aircraft :**(Flux Switching Superconducting Motor) (UCSC, ARFL)

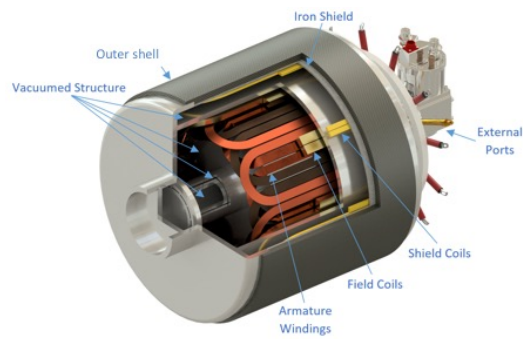
5. **CRUISE Motor:** Cryogen-free, conduction cooled, high field superconducting synchronous motor (Hinetics, UIUC/POETS Associated)

6. **NASA ULI - CHEETA**: Use LH2 in fuel cells to generate electricity to power an electrically driven aircraft propulsion system. LH2 also used to enable highly efficient superconducting electrical systems (UIUC, UArk, PennState, OSU, MIT, RPI, GE, Boeing/POETS Associated)

CHEETA NASA ULI (POETS Associated)

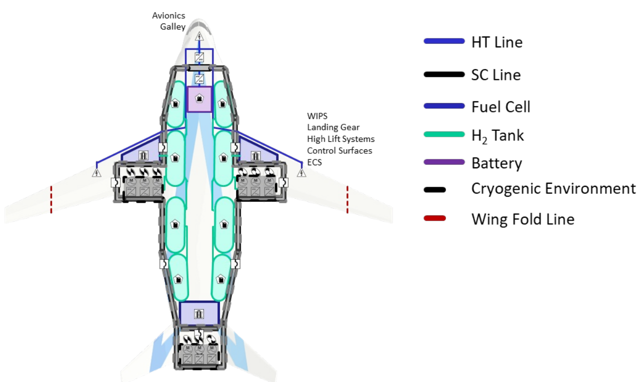


Fully Superconducting Machine

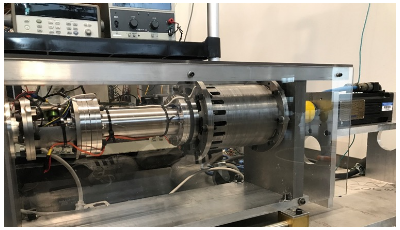


Main Parameters

Total Energy	1068 GJ
Propulsive power	40 MW
Mission length	8 hrs
Amount of fuel (LH2)	14833 kg
Number of motors	16
Motor Power	2.5 MW
Motor Speed	4500 rpm
LH2 Boil-off rate	0.01 kg/s
Cooling budget	4.3 kW
AC Losses	2260 W
Machine weight	60 kg

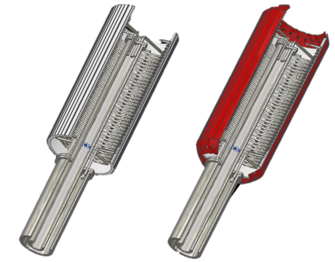


Component development:



Rotor mounted cryogenics

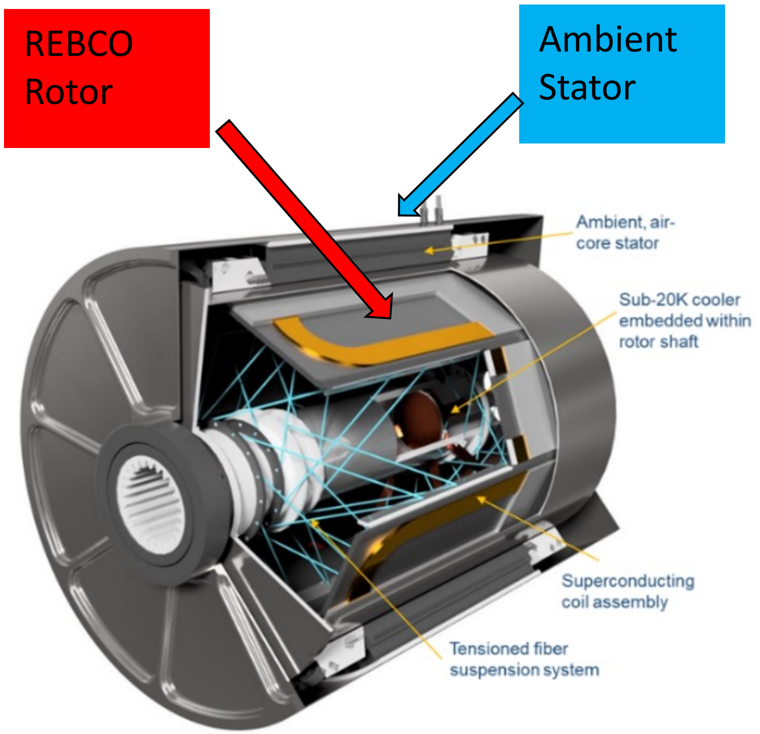
Superconducting coils



LH2 heat exchangers

ARPA-E: CRUISE motor (POETS Associated)

- Air-core, wound field synchronous motor
- Conduction cooled high temperature superconducting (HTS) field winding
- Sub-20 K Stirling-cycle cooler integrated with a low-loss rotor
- Magnetic fields an order of magnitude higher than conventional machines
- Novel coil suspension and torque transfer system with tensioned fibers that cut the cryogenic heat-load by a factor of 10 to eliminate the need for external coolers
- Goal: 10 MW, 3000 RPM aircraft propulsion motor weighing less than 250 kilograms that rejects up to 10 times less total heat to the ambient environment (>99% efficiency)

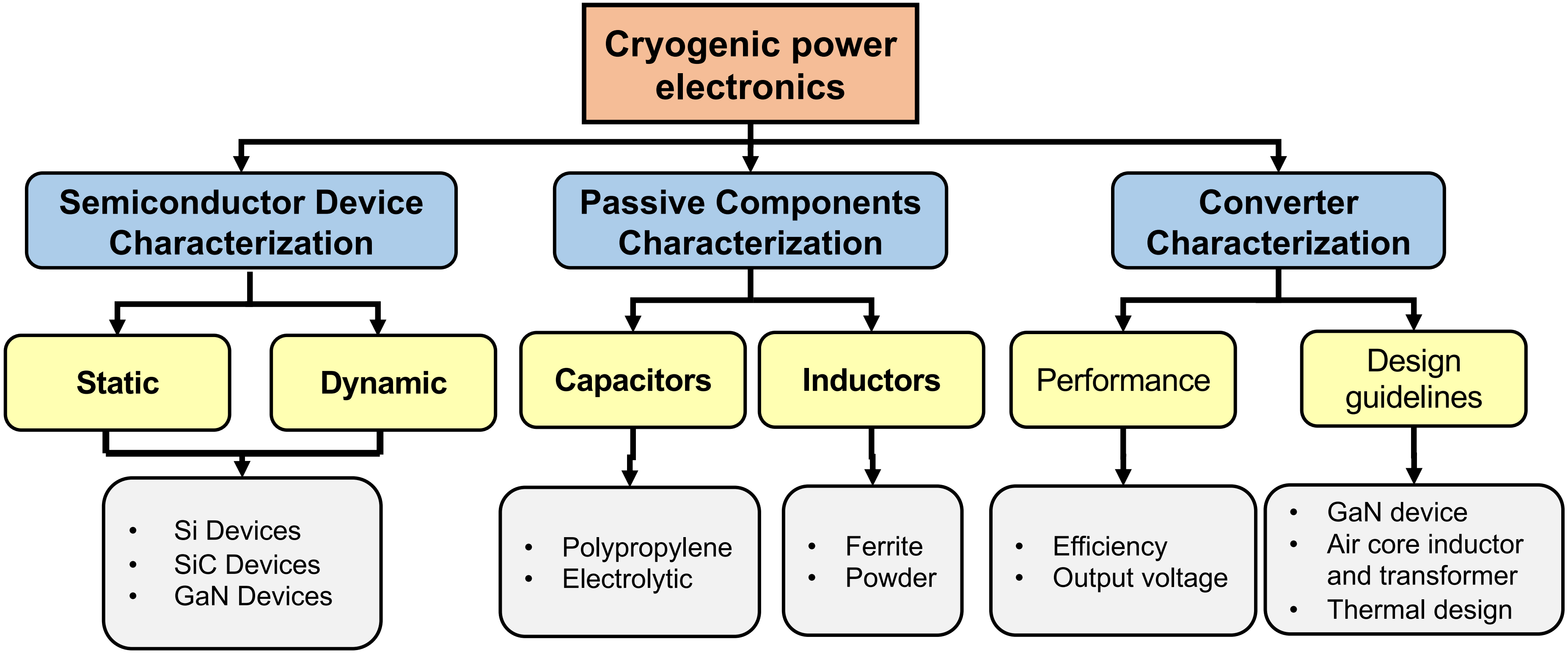


HINETICS SUNPOWER arpa·e

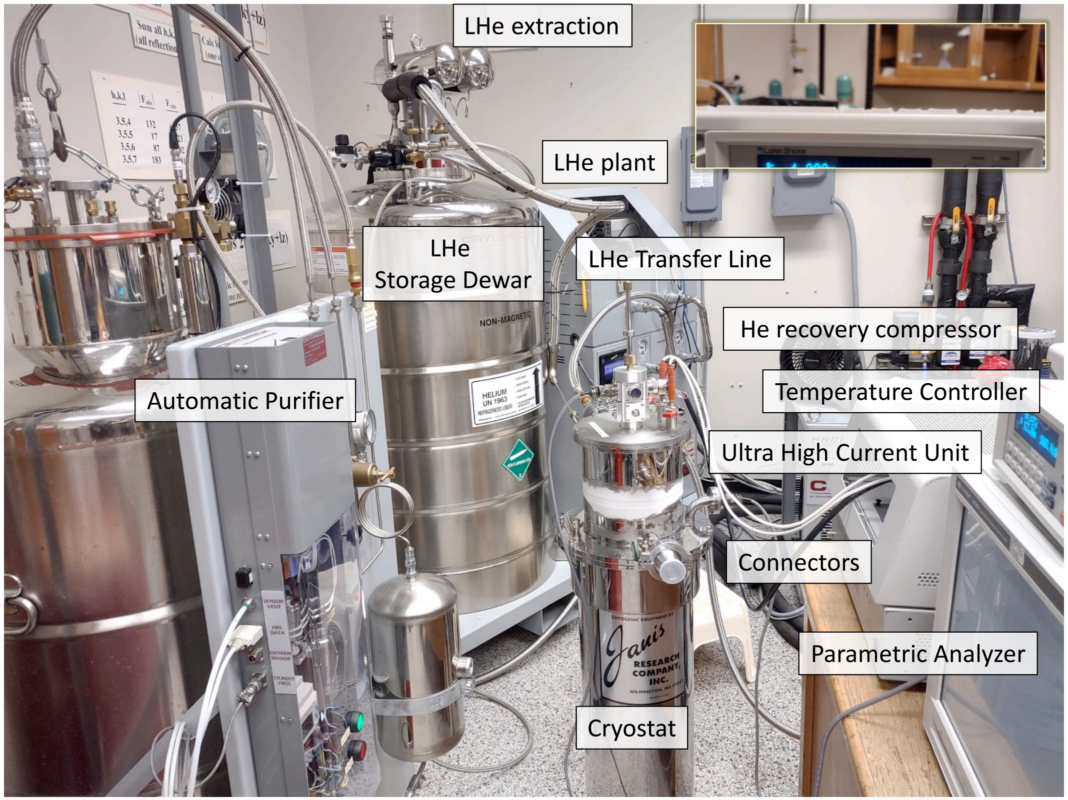
Material needs for SC machines

- Improved pinning, higher performance at higher temperatures (e.g. high J_e for >5T, >65 K)
- Low ac loss conductors at relatively high frequency (200-400 Hz) and fields (~1 T)
- Mechanically robust cryocoolers with increased SWAP (>3000 rpm, high g-loads, vibration)
- High strength, low thermal conductivity materials ($\sigma_{ys}/c >> 10^9$ Pa-m-K/W)
- Light weight high conductivity thermal bus
- Low loss stator assembly

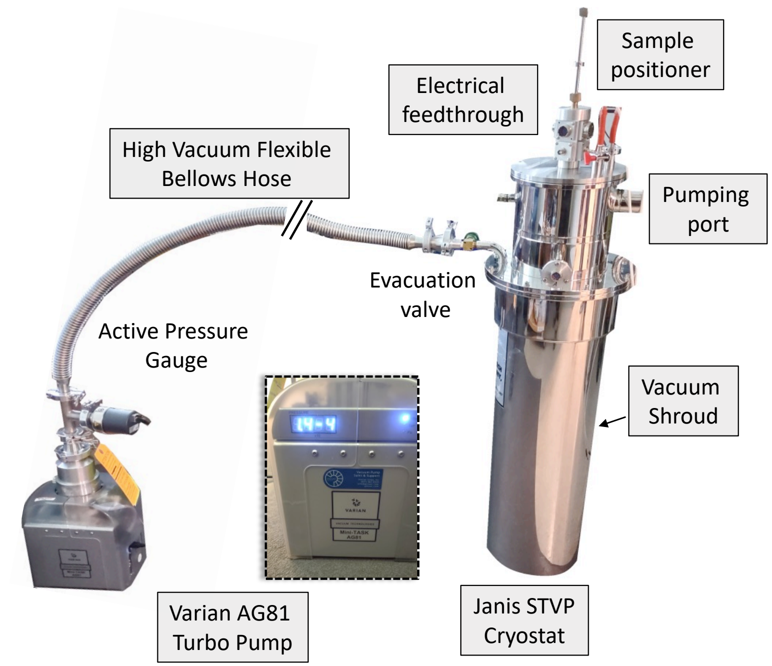
Cryogenic Power Electronics



LHe Characterization Setup



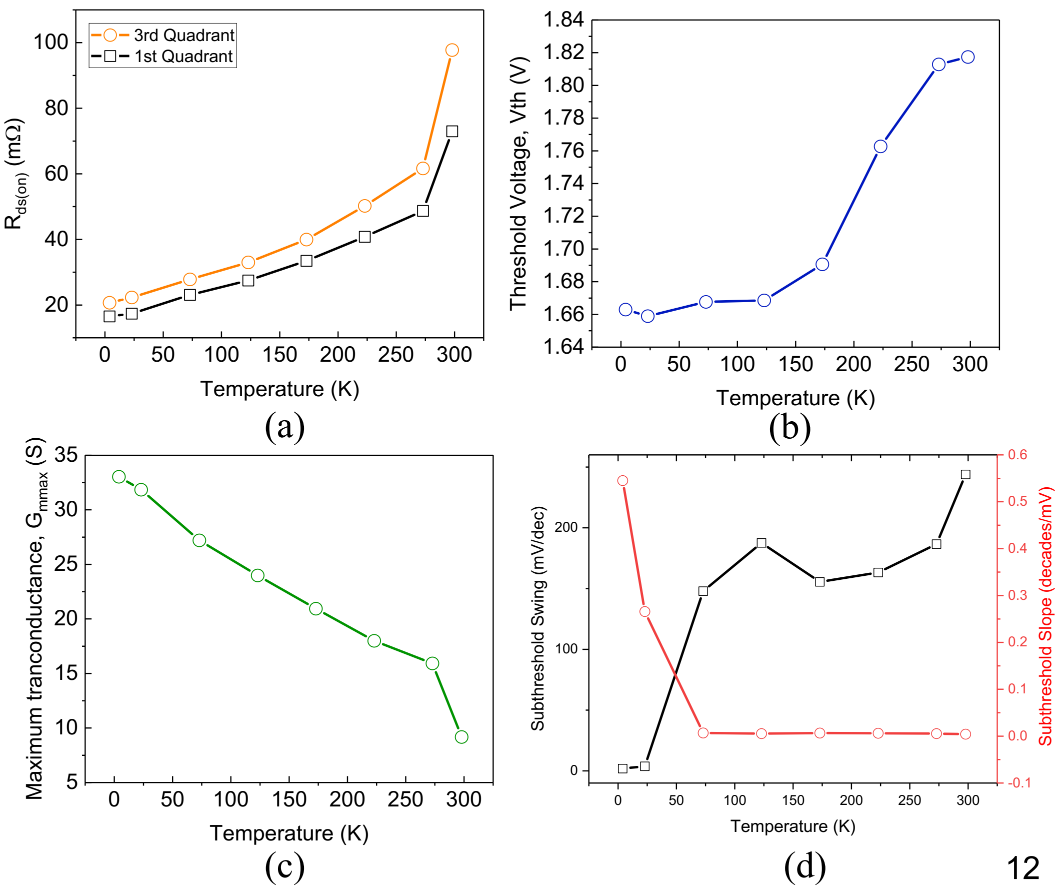
Static characterization setup



Vacuum shroud re-evacuation

Properties at Deep-Cryo 1200 V GaN

- The threshold voltage 8.5% reduced
- Transconductance increasing 3.6x with a decrease in temperature
- Reduced 1st Quadrant $R_{ds(on)}$ 4.4x
- Reduced 3rd Quadrant $R_{ds(on)}$ 4.7x
- Subthreshold slope increases 80.5x.
    - Smaller off-state current



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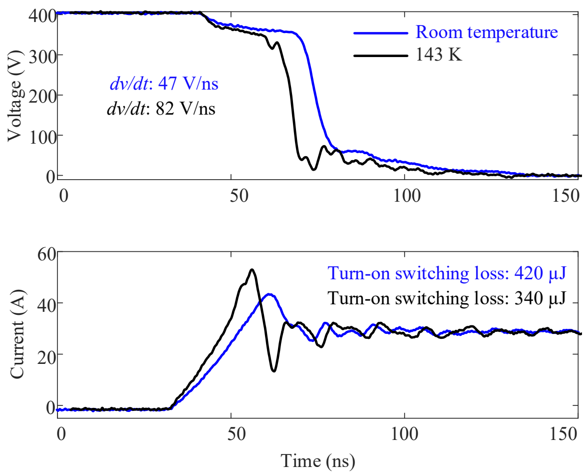
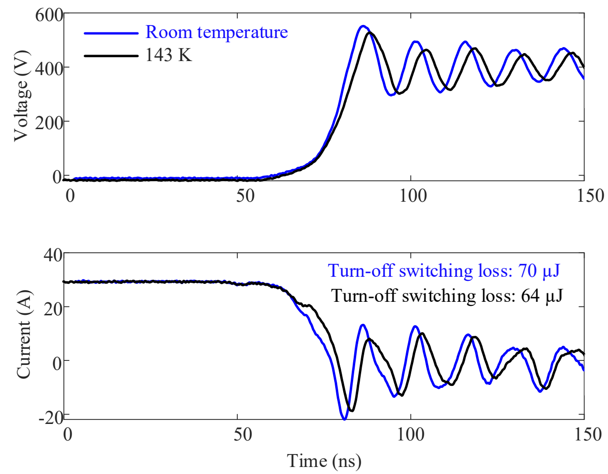
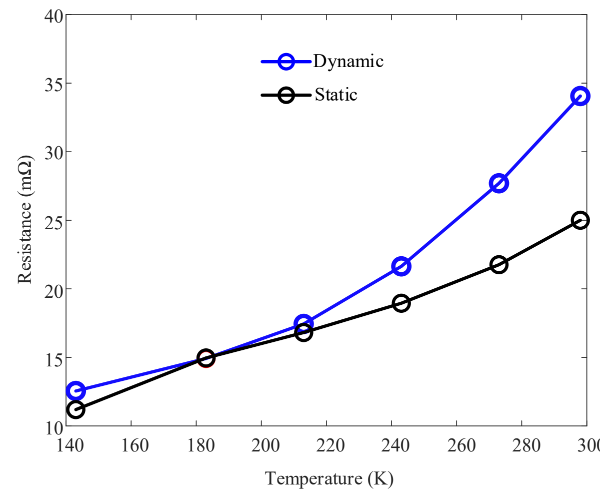
Dynamic Characterization of GaN HEMT



Turn-on process



Turn-off process



Dynamic $R_{ds(on)}$

- **Turn-on switching process is sped up**
- Turn-on dv/dt is increased from **47 V/ns at 298 K to 82 V/ns at 143 K**
- **Turn-on switching loss is reduced 19%**
- The turn-off performance is **almost unchanged**
- **The dynamic on-state resistance is reduced**

Semiconductor Cryo Comparisons

Semiconductor	Si IGBT[3]	Si MOSFET	SiC MOSFET (Trench)[6, 11]	Cascode GaN[5]	E-mode GaN[4]
Part number	FGA5065ADF	IXFH26N50P	SCT3120AL	TP65H035WSQA	GS66516B
On-state resistance/V_F+	5.6%	82.49%	126.36%	19.77%	53.32%
Threshold voltage+	25.86%	20.18%	25.88%	17.59%	29.4%
Dynamic on-state resistance*	-	-	-	Yes	Yes

RED: Indicates increase
GREEN: indicates a decrease

+: Comparisons between 298 K and 93 K
*: Comparisons between 298 K and 143 K

Device Compact Modeling

GaN HEMT modeling*

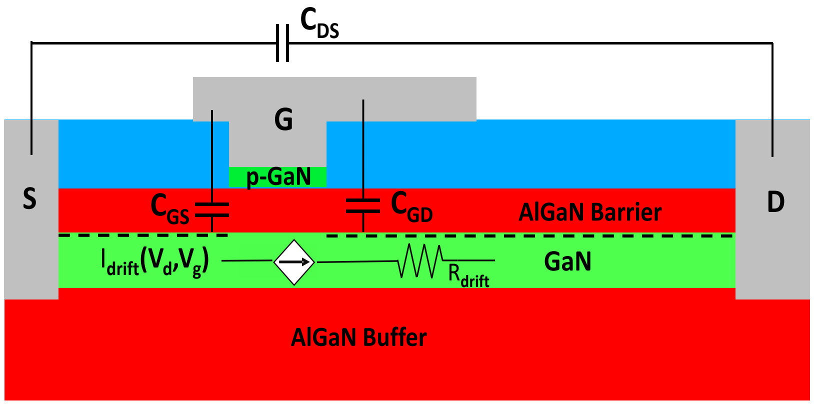
- Capacitance modeled as charge-equations
- Added temperature-dependent equations
- Convergence tested for buck, boost, 5-level CHB

Cascode GaN HEMT Cryogenic Modeling

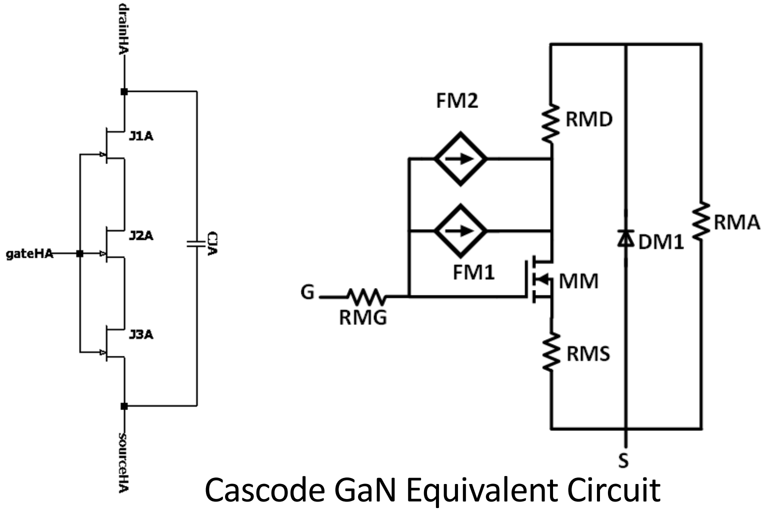
- Includes JFET to simulate the behavior of the normally-on HEMT and C-V dip
- Level-1 MOSFET to simulate the low-voltage Si MOSFET
- Diodes simulate the gate-leakage of the HEMT

Si Superjunction MOSFET and IGBT Cryogenic Modeling[**]

- Saber® power MOSFET / IGBT tool used for cryo-modeling



GaN HEMT Equivalent Circuit

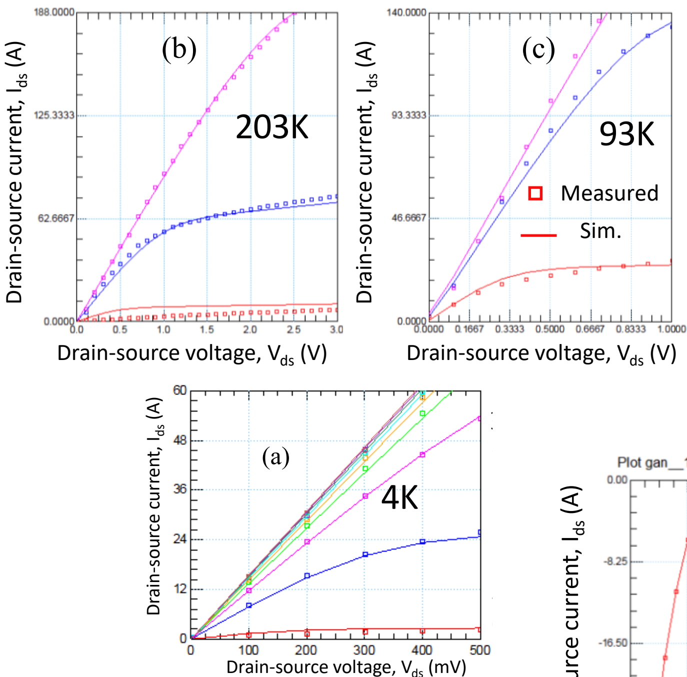


Cascode GaN Equivalent Circuit

* - R. M. Kotecha et al., "Compact Modeling of High-Voltage Gallium Nitride Power Semiconductor Devices for Advanced Power Electronics Design," in OJPEL.

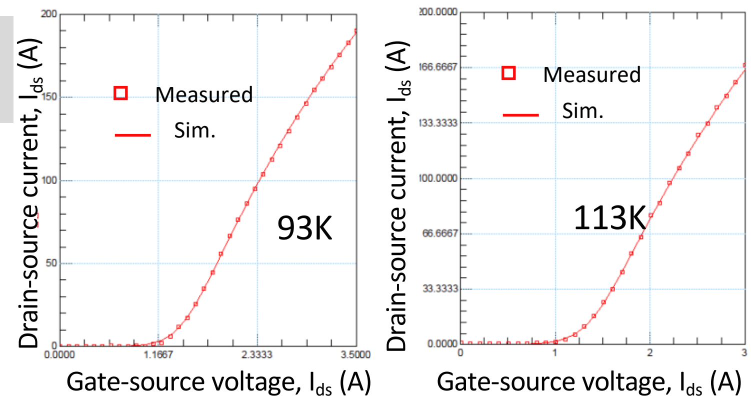
** - Md Maksudul Hossain et al, "Electrical characterization of a 1200V GaN HEMT at cryogenic temperatures," 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1241 012041

GaN HEMT Cryogenic Modeling

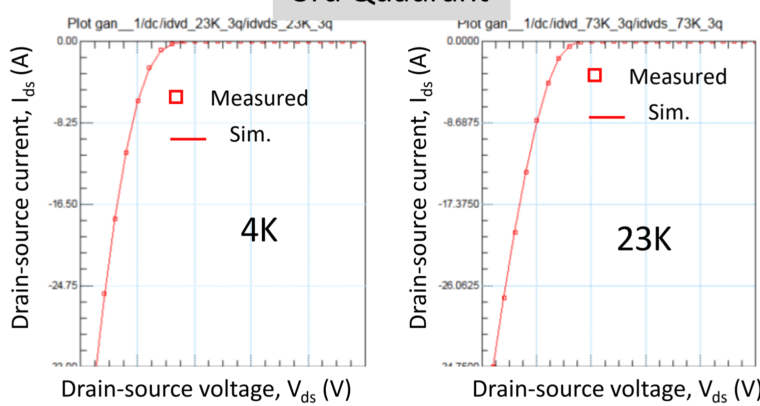


DC Output

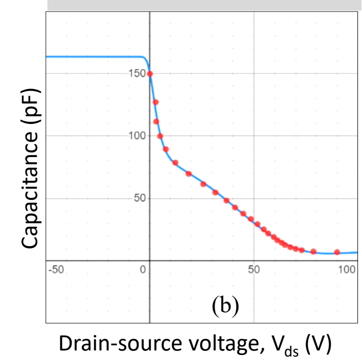
Transfer Characteristics



3rd Quadrant



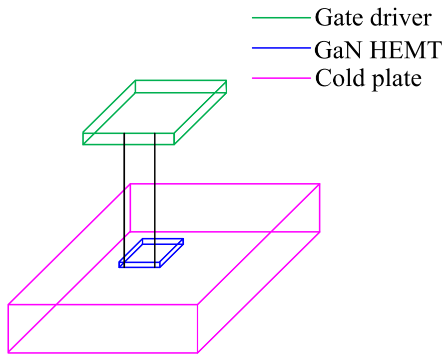
C-V Characteristics



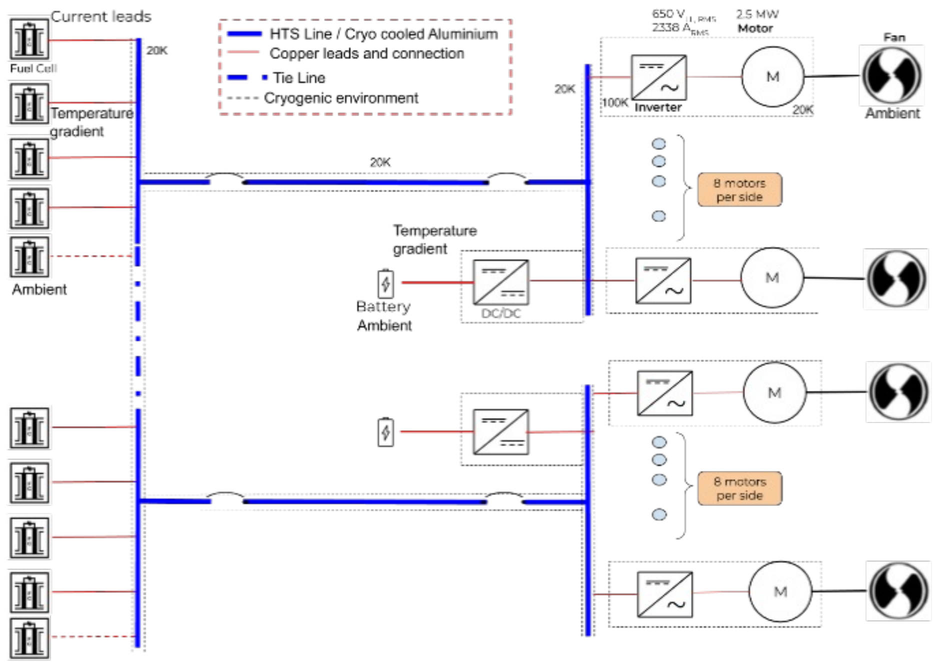
C-V Characteristics

Cryogenic Power Converter

- **Bi-directional DC/DC converter** for battery system
- **GaN HEMT** is selected due to its improved performances
- **Gate driver** is operating at **non-cryogenic temperature**
- **GaN HEMT is** operating at **cryogenic temperature to maximize efficiency**

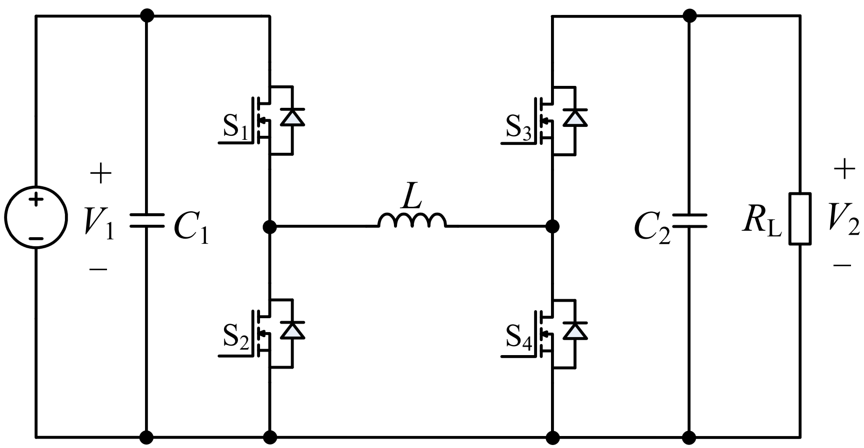


Cryogenic power electronics structure

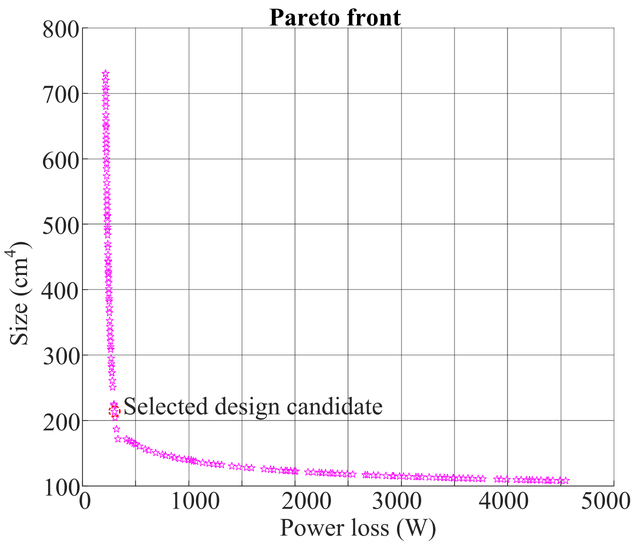


Aircraft structure

Cryogenic Power Converter



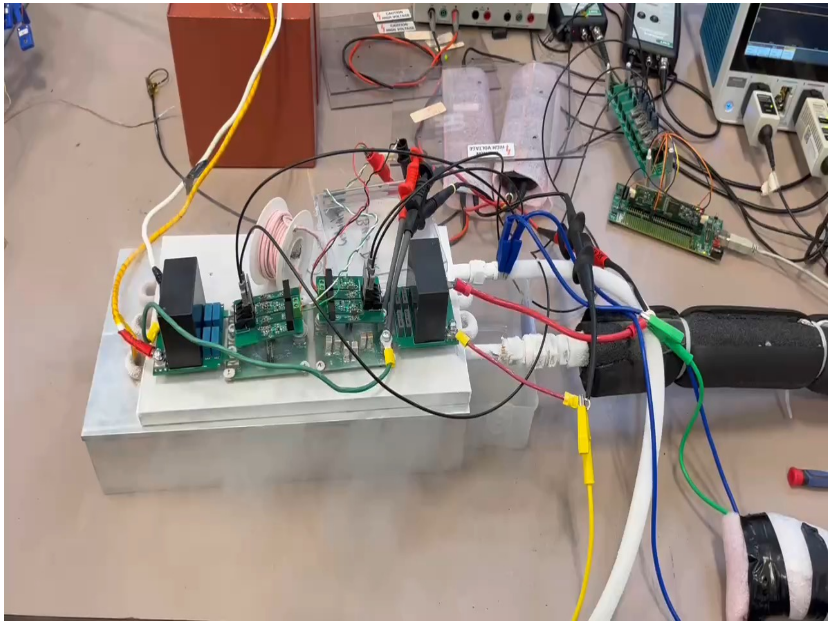
Four-switch buck-boost converter



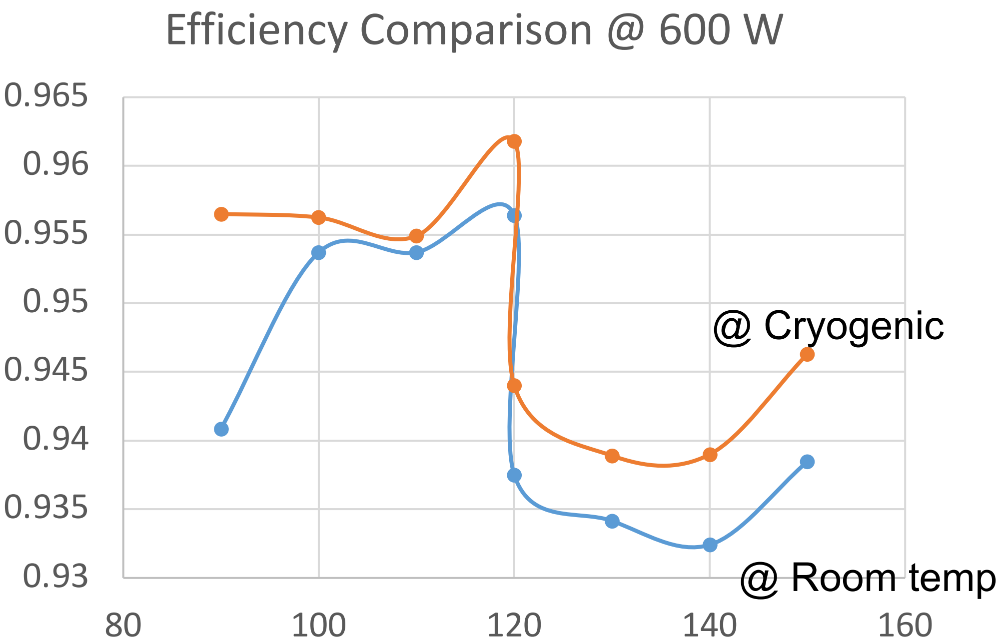
Optimal design

- Design variables: switching frequency, inductor current ripple, number of paralleling devices
- Design objective: **efficiency and size (only passive)**
- **Genetic algorithm**

Cryogenic Power Converter



Experimental Setup



Input Voltage (Output Voltage = 135 V)

- **Efficiency is improved at cryogenic temperature (orange)**
- **Efficiency is low in Buck-boost operation mode**