Design and Scaling Laws of a 40-MW class Electric-Wire-Interconnect-System (EWIS) for Liquid-H_2 Fuel-cell Propulsion

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Dr. Mary Ann Sebastian, Dr. Bang Hung Tsao, *University of Dayton Research Institute*

Dr. Chris Kovacs, *AFRL, Scintillating Solutions LLC*

2nd International Conference on Emissions Free Air Transport Through Electric Propulsion

Hybrid, 30,31 Aug 2022

CHEETA

Center for High-Efficiency Electrical Technologies for Aircraft

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.

CHEETA, Superconducting Materials Team

Senior Personnel

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Acknowledgment of Support

- NASA University Leadership Initiative (ULI) #80NSSC19M0125
- AFRL/RQ Aerospace Systems Directorate
- AFRL/AFOSR LRIR #18RQCOR100, Dr. Ken Goretta

Electric Aircraft Propulsion – the 3rd era in Aviation!

NASA X-57 Maxwell

www.nasa.gov/sites/default/files/thumbnails/image/x-57_maxwell_city.jpg

	Electric	2-12 Passenger	120-440 Passenger
Drivetrain Efficiency	90-95%	15-20%	35-40%
Energy Cost	$2.55/gge @ $0.07/kwh	AvGas $6/gal	JP8, $3.5-$4/gal
Carbon-free Fuel	yes	costly	costly
Operation Costs	80-90% lower		
Maintenance		10-100x higher	10-100x higher
Altitude cruise	100-40,000 ft	10,000-20,000 ft	30,000--40,000 ft
Noise	70% lower		
Airports to Use	13,000+ small/regional		

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Electric Aircraft Pre-Sales, as of 27 Apr 2022

Electric Aircraft Manufacturer	Model	Aircraft # seats	Vehicle Cost (each)	Goal for Operation (Year)	Company IPO, Total $	Airline Purchases	# Sales	Total Sales ($)	Reference Date	Reference
Archer Aviation			$5M	2025	$1.1B	United, Mesa	200 + 100 (option)	$1B	10-Feb-2021	techcrunch.com/2021/02/10/
Beta	Alia-250		$4.5M	2024	$0.796B	United Parcel Service (UPS)	10 firm + 140 (option)	$0.675B	20-Apr-2022	https://www.futureflight.aero/news-article/2022-04-20
Boom Aerospace	Overture 'supersonic'		$200M	2029		United	15 + 35	$3B	13-Dec-2021	www.prnewswire.com/news-releases
Bye Aerospace	eFlyer 2	2	$0.49M			many	~ 380	$0.19B	25-Apr-2022	https://byeaerospace.com/
Bye Aerospace	eFlyer 4	4	$0.63M			"	~ 385	$0.24B	25-Apr-2022	https://byeaerospace.com/
Bye Aerospace	eFlyer 800	8	$6M			"	135	$1.1B	25-Apr-2022	https://byeaerospace.com/
Eviation	Alice	6 to 9	$4M			Cape Air, many	150	$0.6B	18-Apr-2022	www.geekwire.com/2022/
Eviation	Alice	6 to 9	"	2026		DHL	12	$0.05	18-Apr-2022	www.geekwire.com/2022/
Joby Aviation				2024	$1.6B	Joby Aviation				
Lilium		7	$4.5M		$1.94B	Azul (Brazil), NetJets	370	$1.7B	8-Mar-2022	https://robbreport.com/motors/aviation/
EVE Urban Air Mobility			$8M			Azorra (Embraer), many	1,785	$14.28	16-Mar-2022	/www.reuters.com/business/aerospace-defense
Heart Aerospace	ES-19	19 seats	$8.8M	2026		United, Mesa	200	$0.9B	7-Jul-2021	www.bloomberg.com/news/articles/2021-07-13/
Textron Aviation	Cessna Grand Caravan EX	10-14 seats	$2.4M			Surf Air Mobility	150	$0.36B	20-Jul-2021	media.txtav.com/201086
Velos Electro, Pipestrel	Velis Electro	2	$0.094M			Europe, E-trainers	250	$0.024B	8-Feb-2021	https://www.electrive.com/2021/02/08
Vertical Aerospace	VA-X4	5	$4M	2024	$2.2B	many	1,350	$5.4B	4-Apr-2022	simpleflying.com/
Volocopter					$0.376B				4-Mar-2022	https://www.electrive.com/2022/03/04
ZeroAvia	ZA2000-RJ engines, e.g. for UA CRJ-550	100	$2M	2028		United	50 + 50 (engines)	$0.1B	13-Dec-2021	www.prnewswire.com/news-releases
					$8.00B	**Subtotals**	**5,562 +**	**$29.6B +**		

Presales
> 5,550 aircraft*
> $29B
IPO's > $8B

- **Compare to ~ 43,000 commercial aircraft worldwide in 2022**
- **Most Aircraft not built or certified yet**

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Center for High Efficiency Electric Aircraft (CHEETA)

Liquid-H_2 Fuel Cells + Battery, Design Study, FY20-22

- **NASA University Leadership Initiative (ULI)**
- **U. of Illinois UC,** Dr. Phil Ansell, Lead PI
  - Boeing Research and Technology (BR&T)
  - General Electric Global Research (GE Global)
  - Massachusetts Institute of Technology (MIT)
  - University of Arkansas (UARK)
  - Rensselaer Polytechnic Institute (RPI)
  - Ohio State University (OSU)
  - University of Dayton Research Institute (UDRI)
  - AFRL/RQ - collaboration, no $
- **Funding ~ $6M for 3 years, FY20-22**

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Boeing 737-800, CHEETA VO3 Comparison

178 Passengers

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	737-800	CHEETA VO3
Propulsion Fuel, Energy	JP-8	Liquid-H_2, Li-Battery
Operational Empty Weight (OEW)	91,300 lb	**138,000 lb**
Maximum Take Off Weight (MTOW)	174,000 lb	190,000 lb
Fuel Weight	47,570 lb	**16,700 lb**
Fuel Energy	917 GJ	1,074 GJ
Peak Motor Power	24,000 – 27,000 lbf	22.5 MW
Cruise Motor Power	5,960 lbf	16.4 MW

https://en.wikipedia.org/wiki/Boeing_737_Next_Generation

CHEETA Liquid-H_2+fuel-cell, 2020 drivetrain architecture V02

40 MW, 1 kV, 40 kA!, 43 m cable length

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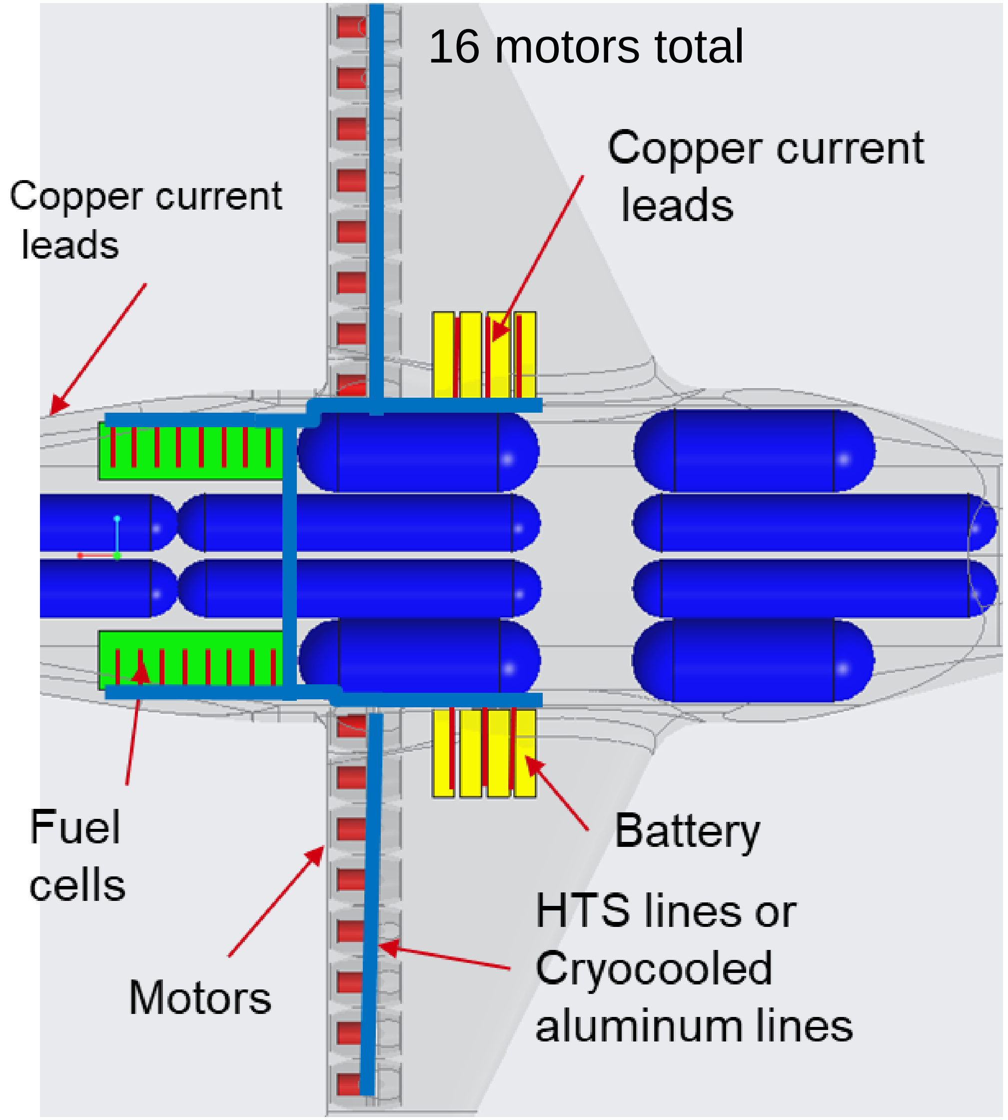

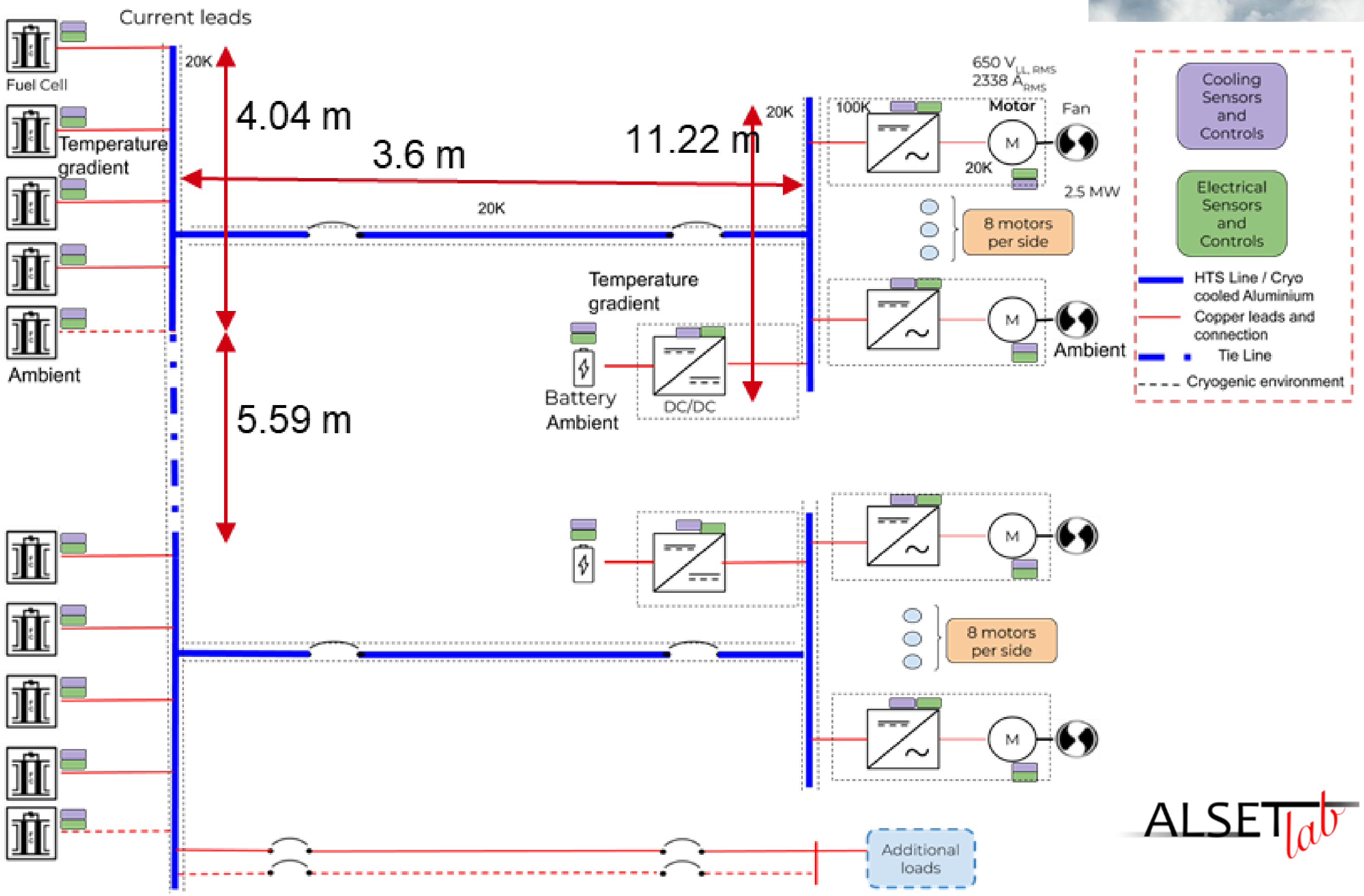

ALSET lab

Rensselaer
why not change the world?

CHEETA, Sept 2021 drivetrain architecture V03

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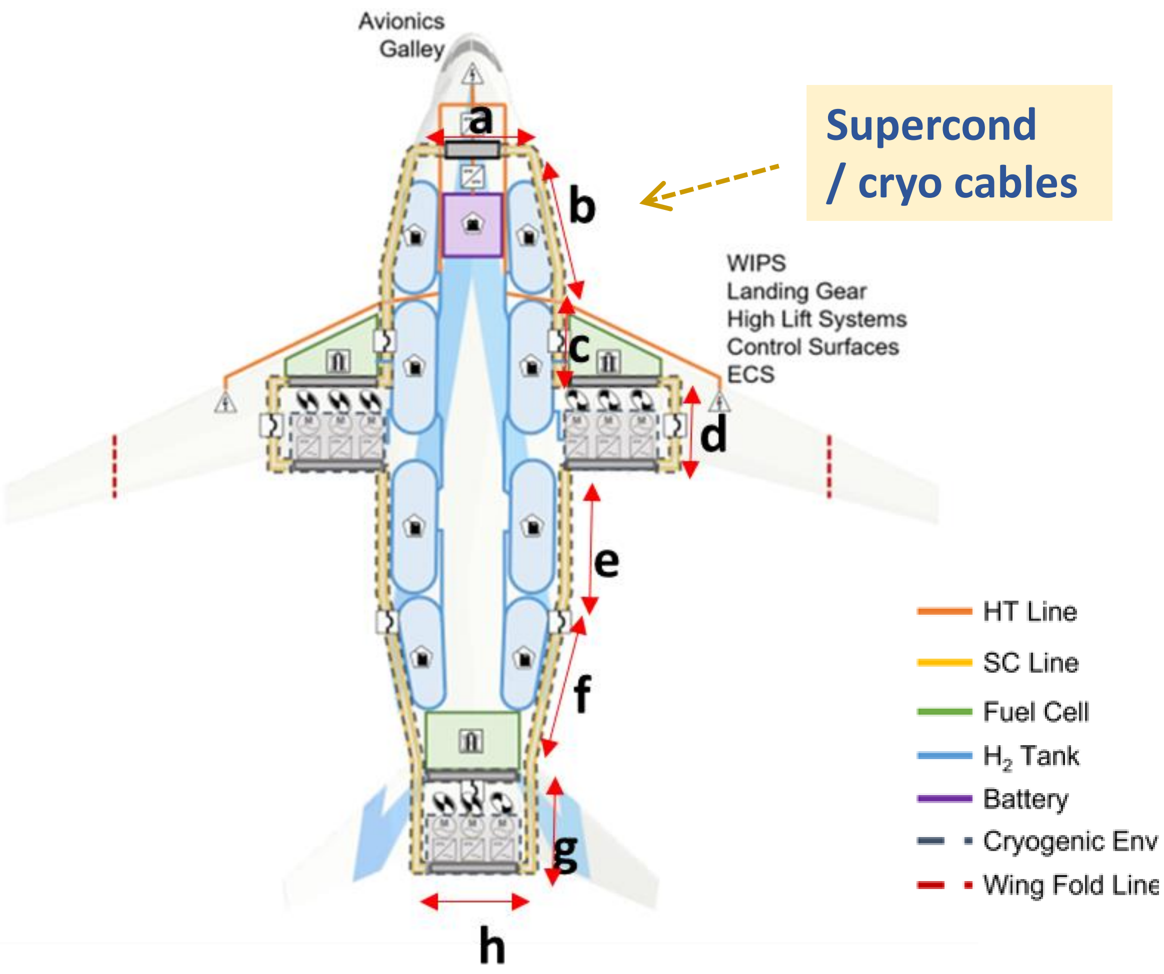
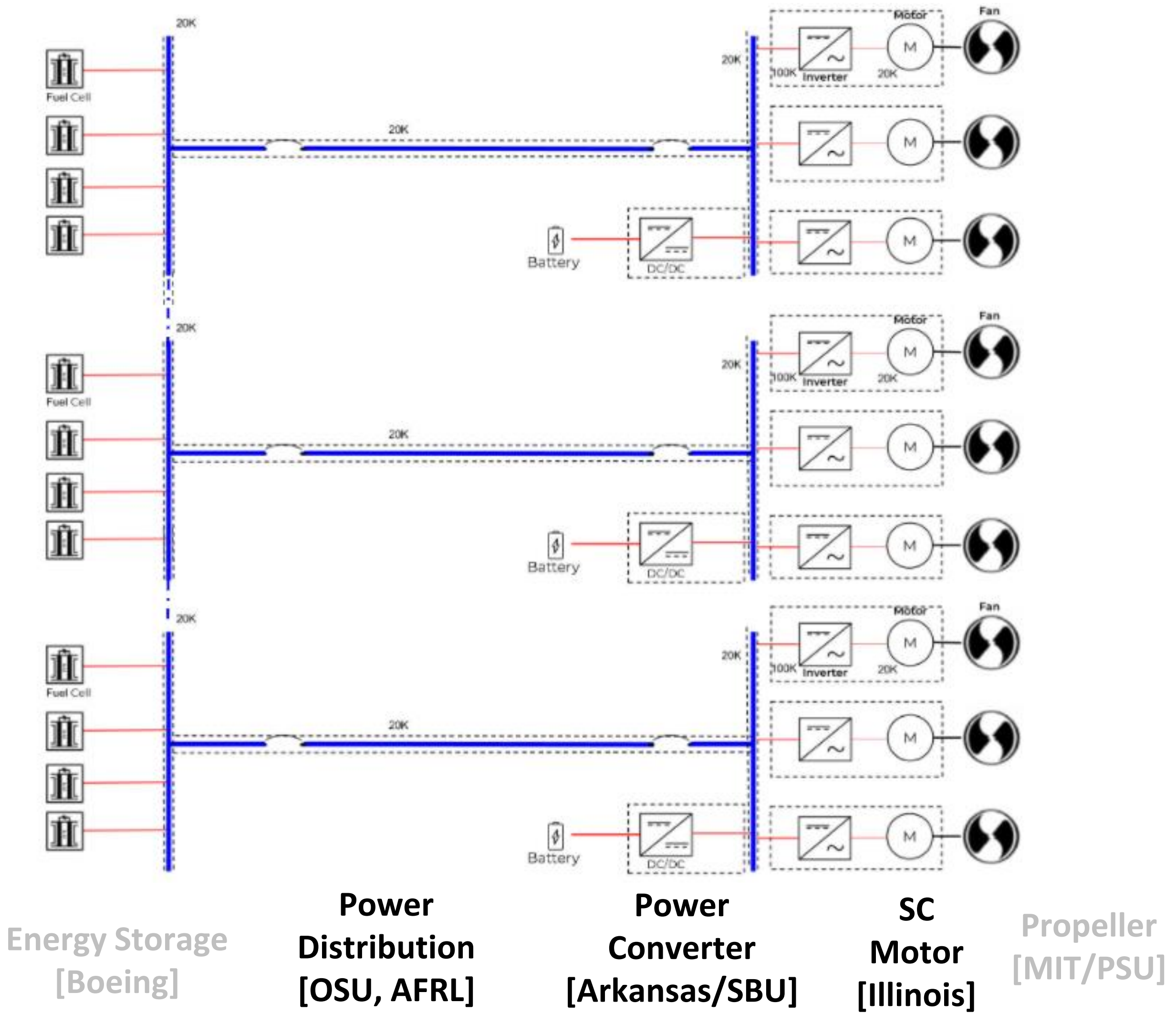
22.5 MW, ± 270V, (13.9 kA, ~75.5m to/from for ½ side) cable length





V03 tip-to-tip length = 41.91 m
V03 length = 37.59 m
Cable length one-side = (b+c+d+e+f+g)+(a+h)/2 = 37.72 m

AFRL/UDRI Project Task 1

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.

Power Distribution System: 22.5 MW, ± 270 V, 13.9 kA

- **Determine Scaling Laws for Major Components:** how mass, heat-loads vary
- **Goals:** compare different technologies, design options, sensitivities, and swaps

			Year 1	Year 2	Year 3
Metal Cable	Al-99.999% 'hyperconductor'	20K, 300K	X		
	Copper-clad Aluminum (CCA)	"	X		
Metal Cable Conduit		300 K		X	X
Superconductor Cable	YBCO, MgB_2	20K	X		
Current Leads	Metals, Cu or Al	300K <--> 77K	X		
Current Leads	Superconductor	77K <--> 20K	X		
Busbar	Superconductor or Metal	20K, 300K	X	X	
Cryoflex Tubing	Nexans, custom	20-80 K	X		X
T-Joint	YBCO <--> Copper-clad-Al	20-30 K		X	
High Voltage Cables		0-10 kV		X	X
Low --> High Voltage Insulation		0-10 kV			X
Circuit Breakers		DC			X
Switches, Fault Current Limiters					X
System Integration				X	X

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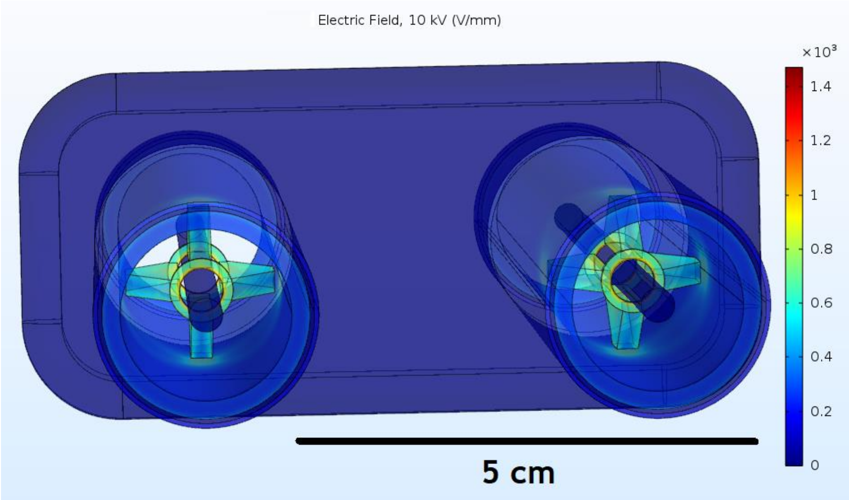
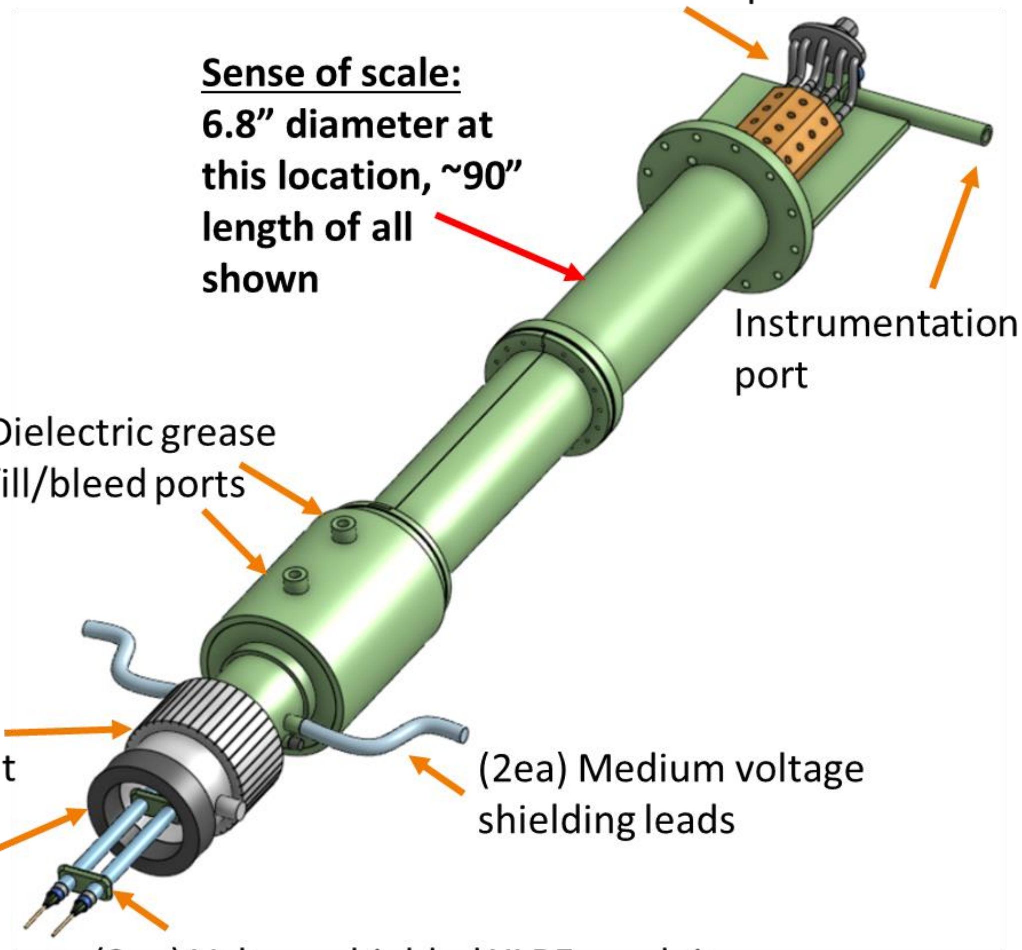
AFRL/UDRI Project Task 2

Power Distribution System, Demo: 1 MW, 1kV, 1kA

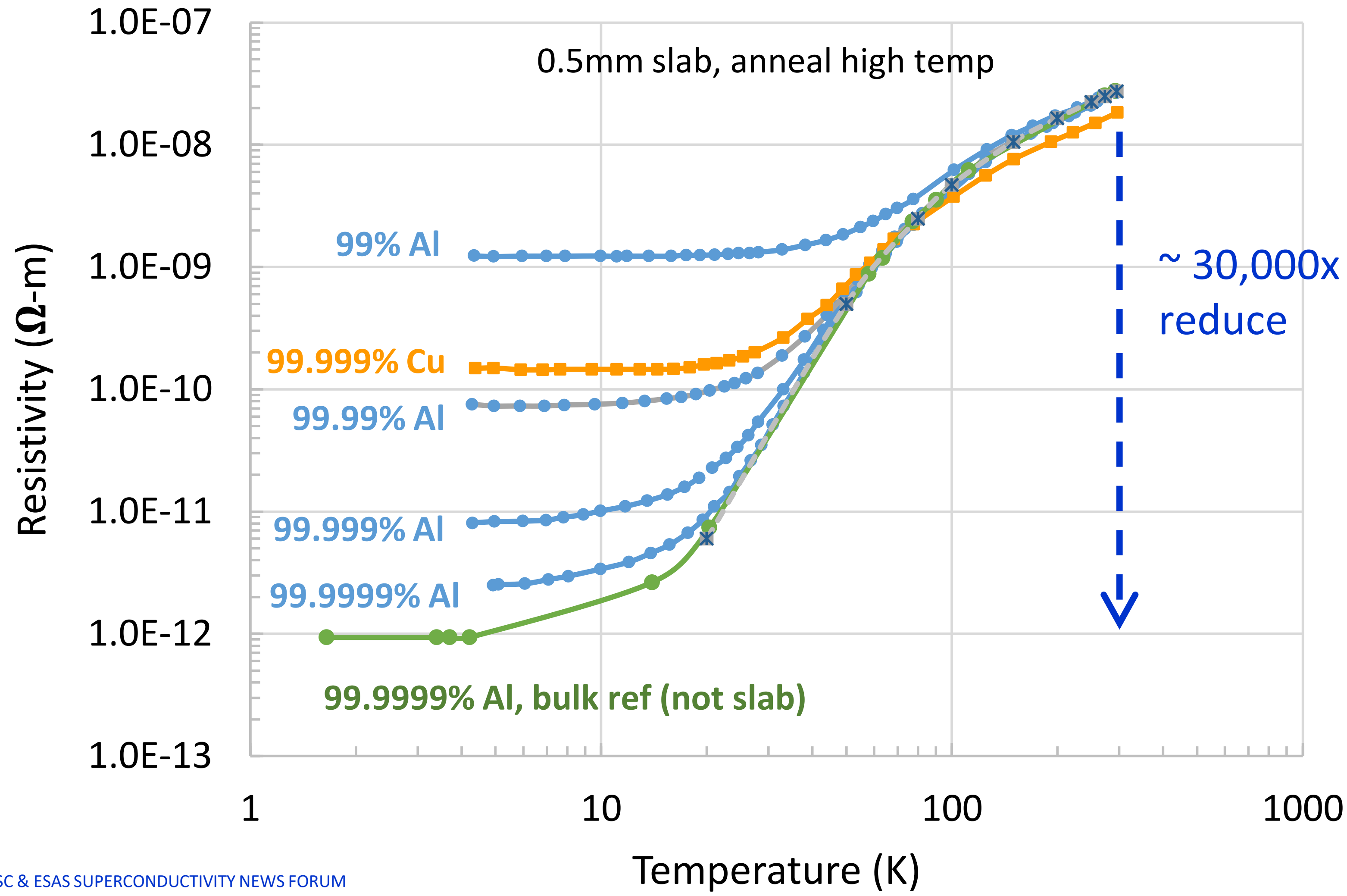
1 MW, 1kV, 1 kA Demo	Year 1	Year 2	Year 3
Hydrogen fluid flow modeling	X		
Cable Design	X	X	
Demo Design		X	
High Voltage Test, Cable			X
Purchase, Build, Demo		X	X
System Integrate			X





Ultrapure Al 99.999+% wire for Aerospace

lowest resistivity material that exists



Al,Cu Resistivity (ρ)

Cu ρ_{300K} = 1.68*E-08 (Sumitomo)
Al ρ_{300K} = 2,74*E-08 (Sumitomo)

Ohm's Law Heating of Wires

Q_{heat} = R*I^2

Q_{heat} = (ρ/Area)*L*I^2

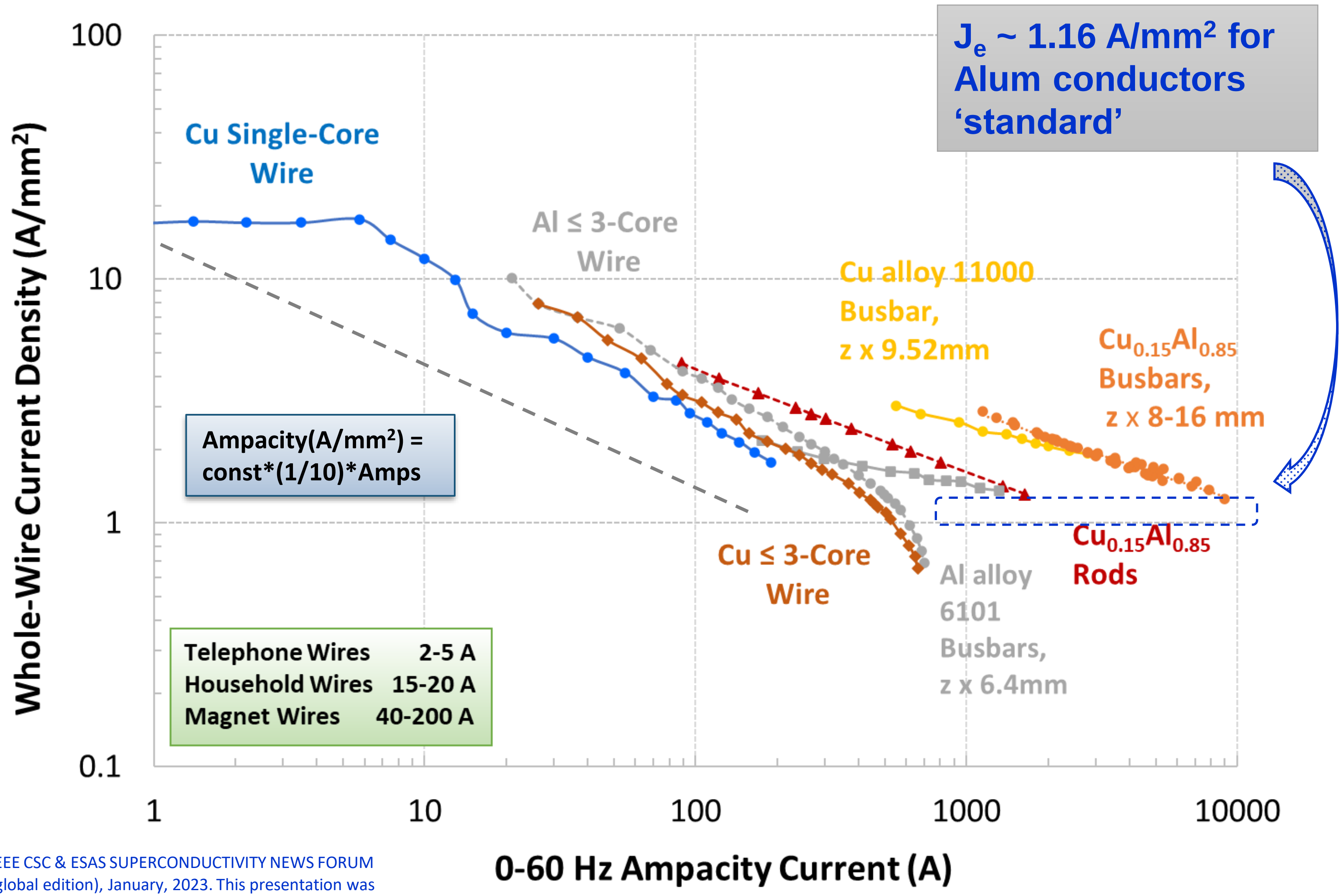
To maintain Q_{heat} **= const**, for RRR ↓ 30,000x, then **Wire Area (A)** ↓ 30,000x !!

1. Sumitomo Report "Refining Technology and Low Temperature Properties for High Purity Aluminum" 2013
2. L. A. Hall, NBS Technical Note 365 "Al-bulk"

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.

High Ampacity Metal Wire/Busbar Options

Ampacity Rating (A/mm²), 50°C Rise from ~ 294K



Conditions

- Air-cooled
- Ambient = 20-35°C
- Temp Rise = 40-50°C
- Amp values provided by companies, based on NEC rules

Ampacity Definition:

Controlled by Ohms Law:

$$Q_{loss} = R * I^2 ,$$

$$R = \rho * \frac{L}{A}$$

Therefore:

$$J_e = \frac{Q_{loss}}{\rho * I_c}$$

with Q_{loss} and ρ ~const. J_e is the current level at which Ohmic heat loss can be managed, to prevent thermal runaway; depends on time-duration; e.g. steady-state, pulsed, etc..

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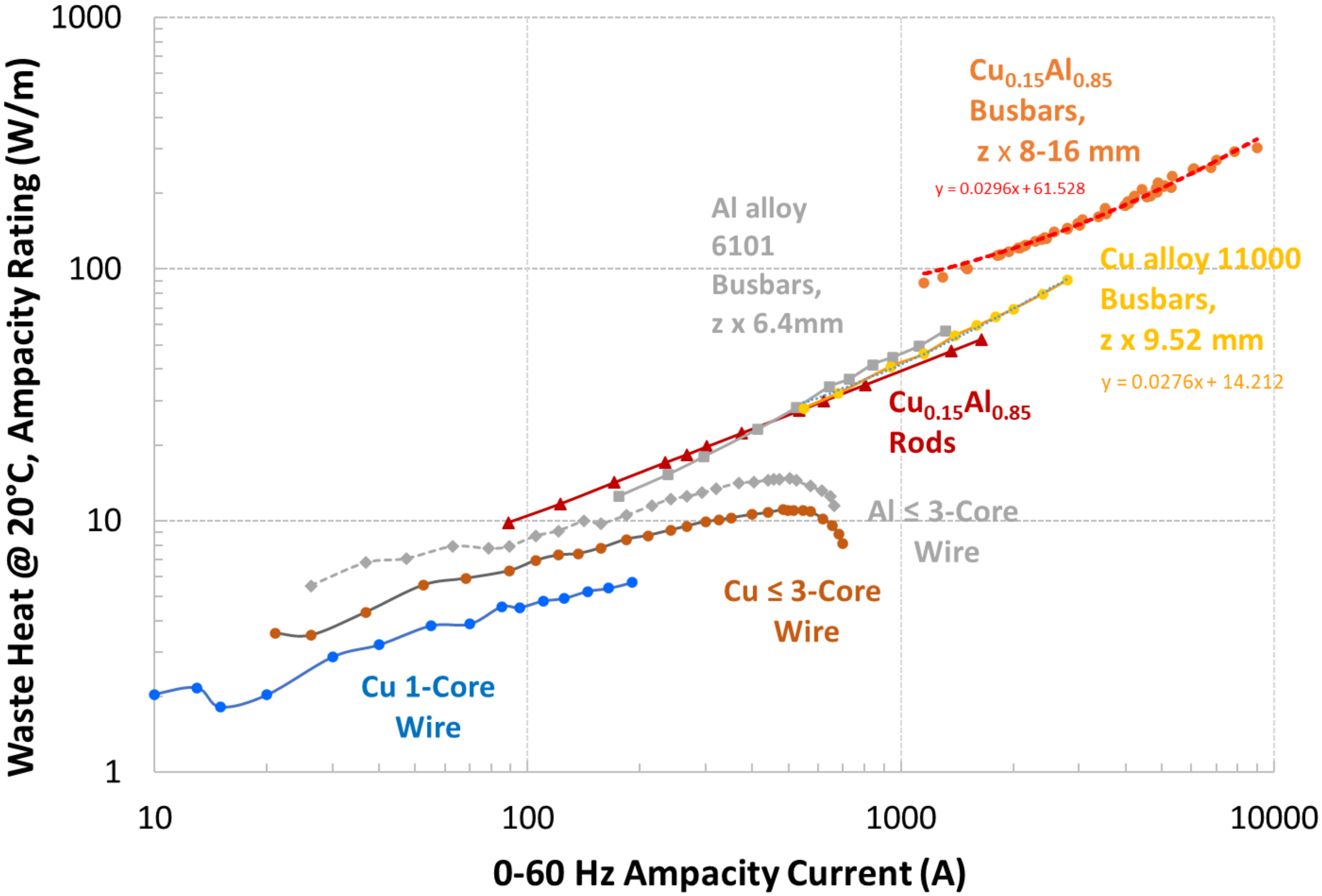
High Ampacity Metal Wire/Busbar Options

Waste Heat (W/m), 50°C Rise from ~ 294K



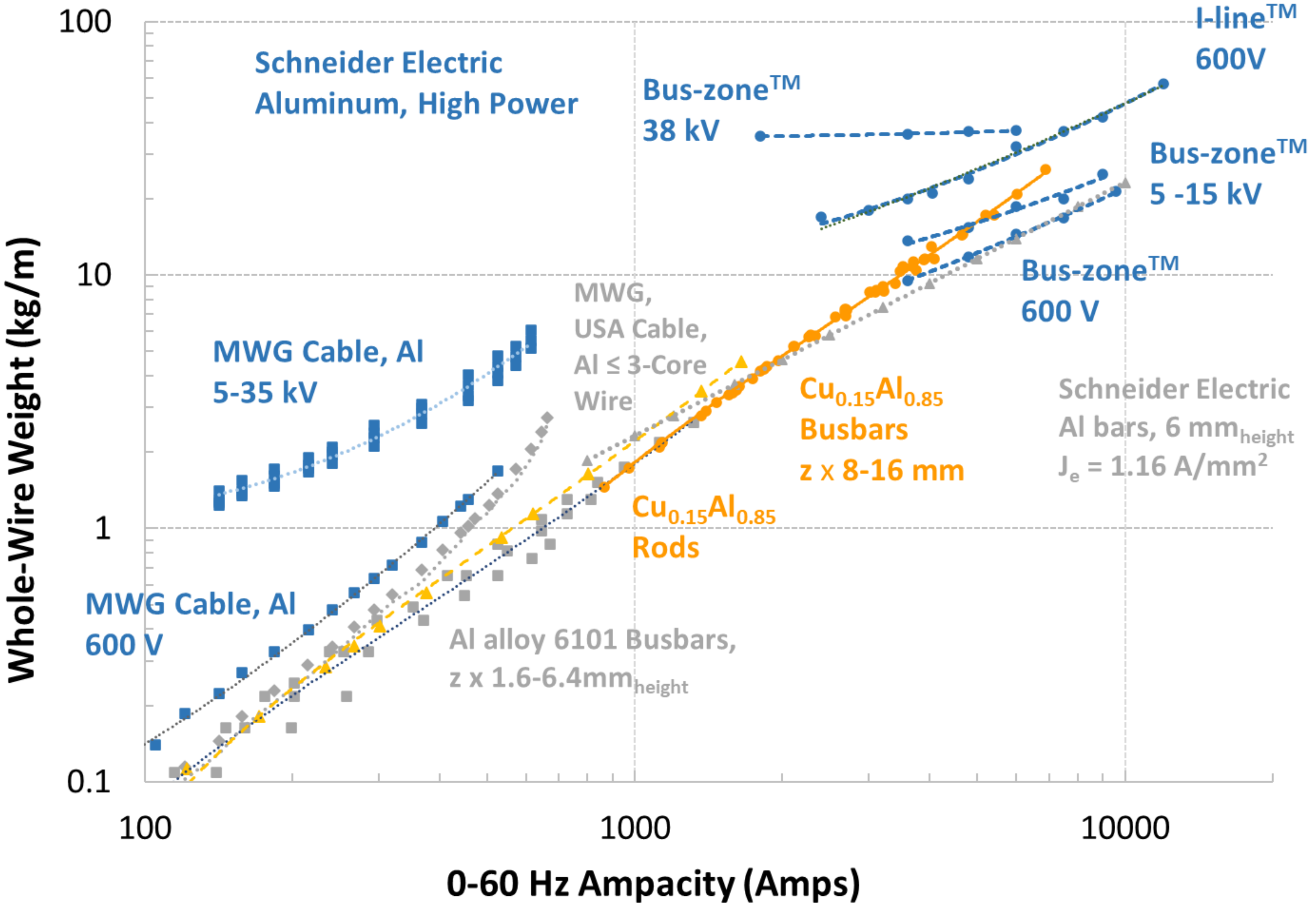
Conditions

- Insulated wires
- Ambient = 20-35°C
- Temp Rise = 40-50°C
- Amp values provided by companies, based on NEC rules

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.

High Power Al Busbars, with 0.6-38 kV conduits

Mass Density (kg/m), 50°C Rise from ~ 294K



Conditions

- Insulated wires
- Ambient = 20-35°C
- Temp Rise = 40-50°C
- Amp values provided by companies, based on NEC rules

- I-line™ 600V is ~2x heavier than Bus-zone™; 600V,much easier and lower cost connections

- Must compare full systems, and not just busbars

HTS Cable, Y-Ba-Cu-O (YBCO)
Conductor-Round-Core ($CORC^{TM}$)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.

Type HTS Cable	HTS Cable Mass	J_e @ 4.2K	I_c @ 4 K	I_c @ 20 K	I_c @ 77 K	HTS AC Loss	Reference
	(kg/m)	(A/mm²)	(A)	(A)	(A)	(W)	
CORC Cable C0b	0.036	1,198	12,402	~ 8,900	1,560	?	Wang X, Supercond. Sci. Technol. 31 (2018) 045007 (10pp)

Weight = 0.036 kg/m, for I_c(20K) = 8,900 A
- Mass includes Al 99.999% former

Advanced Conductor Technologies, LLC

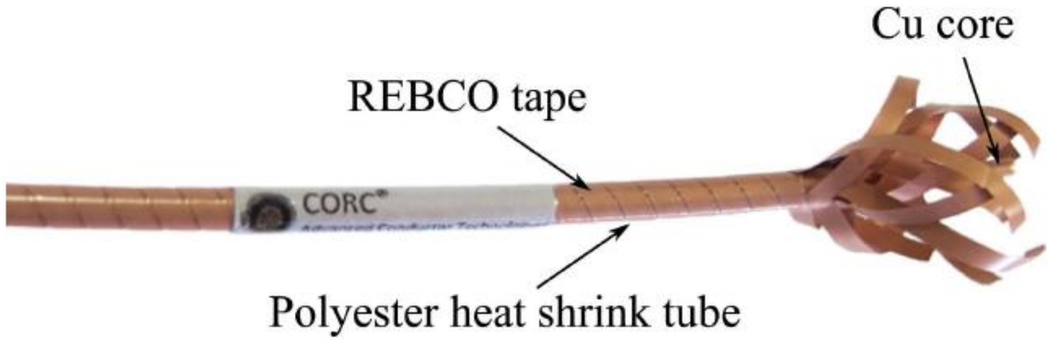


Table 1. Parameters of the two types of CORC® wires used for the three-turn CCT magnets C0a and C0b.

		16-tape wire	29-tape wire
Magnet name	—	C0a	C0b
Wire diameter	mm	3.09	3.63
Diameter of Cu core	mm	2.34	2.56
Number of tapes	—	16	29
Tape width	mm	2	2
Cu plating thickness	μm	5	5
Substrate thickness	μm	30	30
Cross sectional area	mm²	7.5	10.35
Percentage of Cu area	—	62%	55%
Wire length	m	2.3	2.9

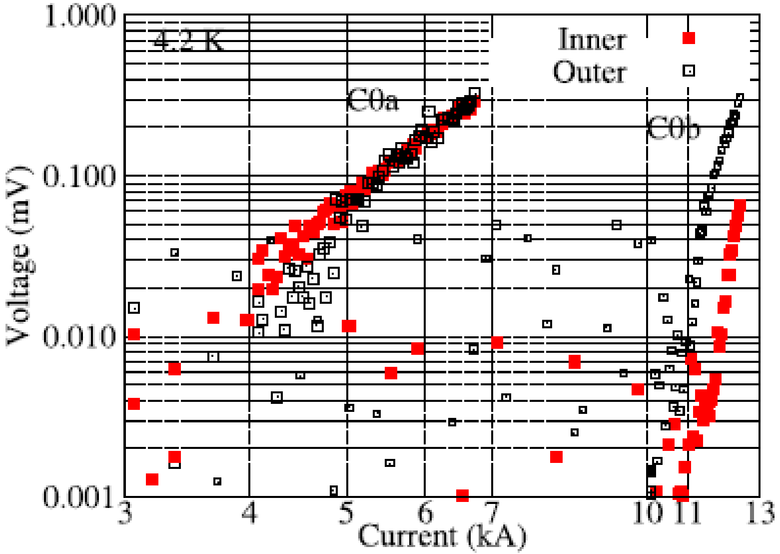
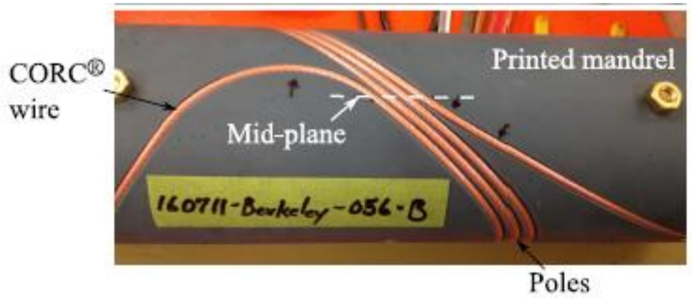


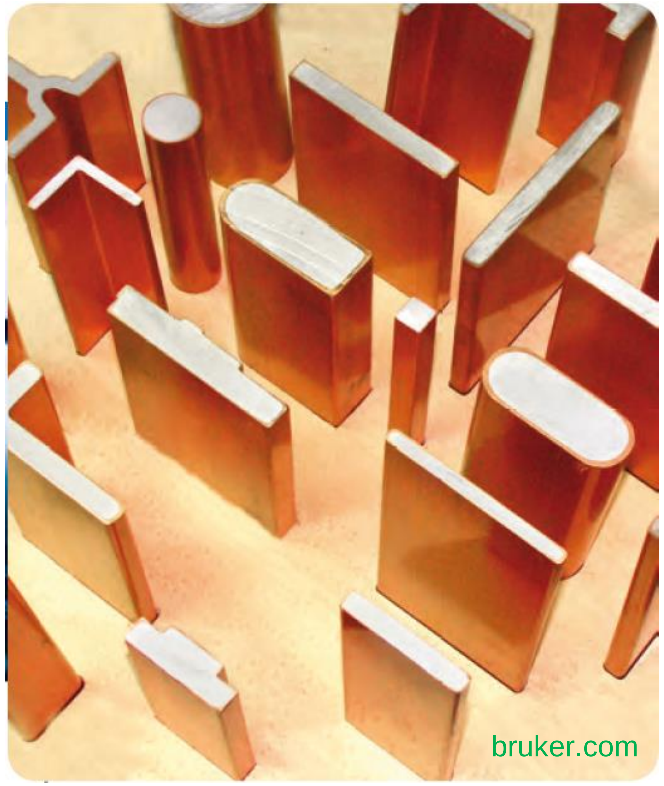
Figure 9. Layer voltage as a function of current for both magnets at 4.2 K, self-field, log–log scale.



C0a, I_c(4.2K,sf) = 6,748 A
C0b, I_c(4.2K,sf) = 12,402 A
~ 10x higher than 77K,sf

Metal Busbar Options for ~ 8,000 Amps

Liquid Cooling and Al 99.999% @ 20K



$Cu_{0.15}Al_{0.85}$ Cuponal™ @ 294K

Four bars ~ 7,000 Amps

J_e (8kA) = 1.6 A/mm²

Mass (8kA) = 20.7 kg/m

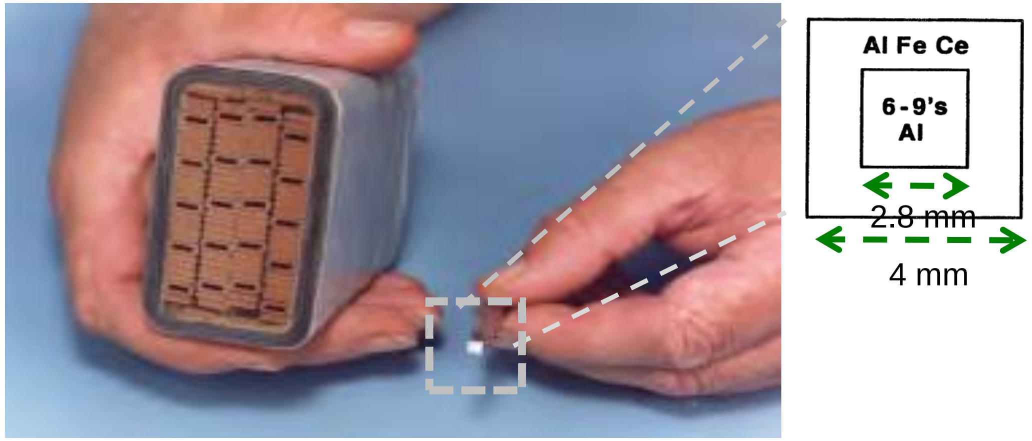
Waste Heat (8kA) = 307 W/m

Water-cooled Cu @294K

J_e (8kA) ~ 3 A/mm² @ 294K

For metals:

$$J_c = \frac{Q_l}{\rho * Ic}; \quad \rho_{Al} = \frac{\rho_{Cu}}{500 \dots 8{,}000}$$



Hyperconducting Aluminum @ 20K

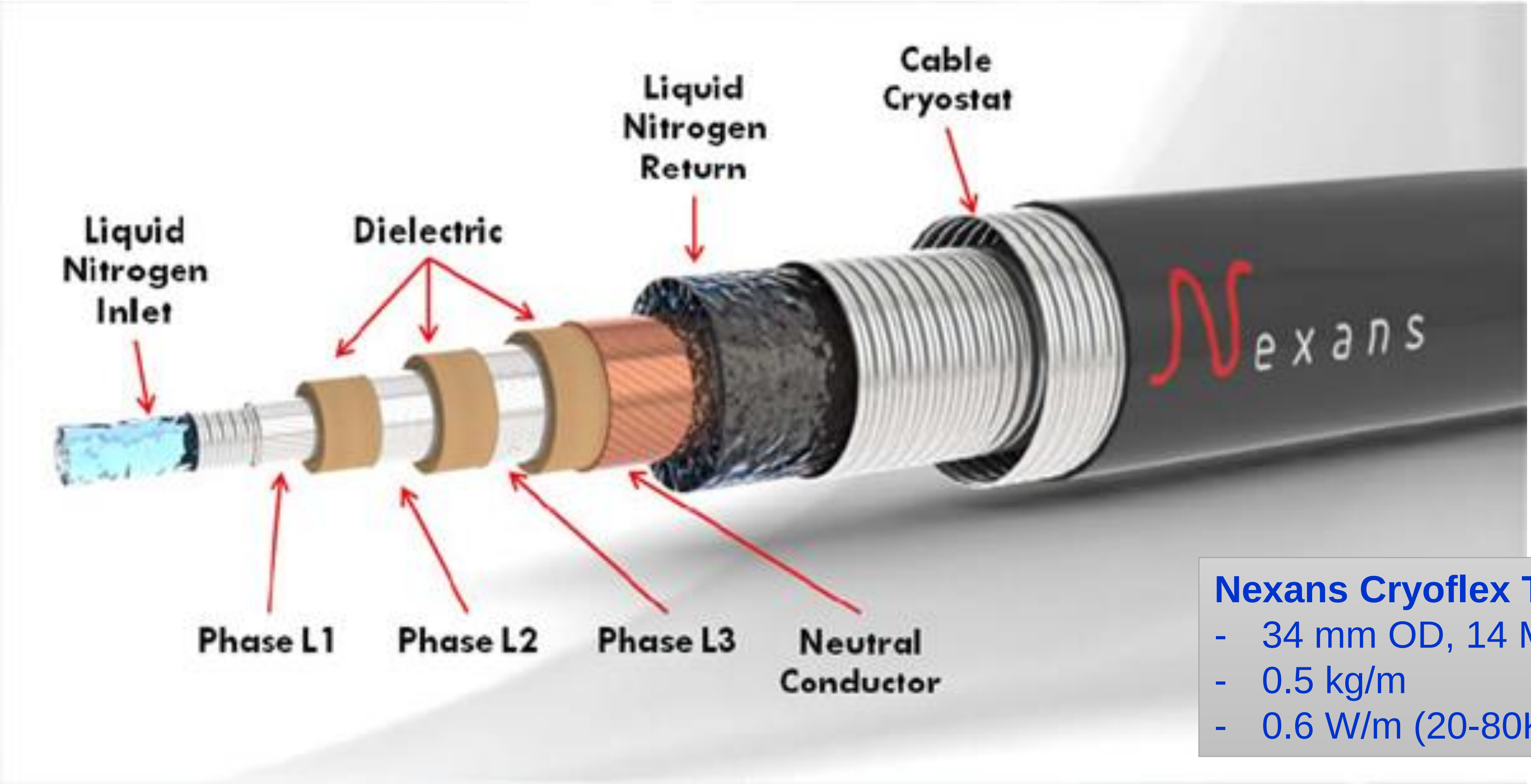
≥ 99.9999% purity, RRR > 1000

- J_e(20K,H=1-2T) = 450-**500** A/mm²
- Weight(8kA) = 0.042 kg/m
- Waste Heat (8kA) = 212 W/m
- Al = 3.3x lighter than Cu !
- Ref. C. Oberly (RQQM), IEEE Trans. Magn.. **27(1)**, 458 (1991)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.

Superconducting Cable Design, Nexans

Including Cryocooling, example Option



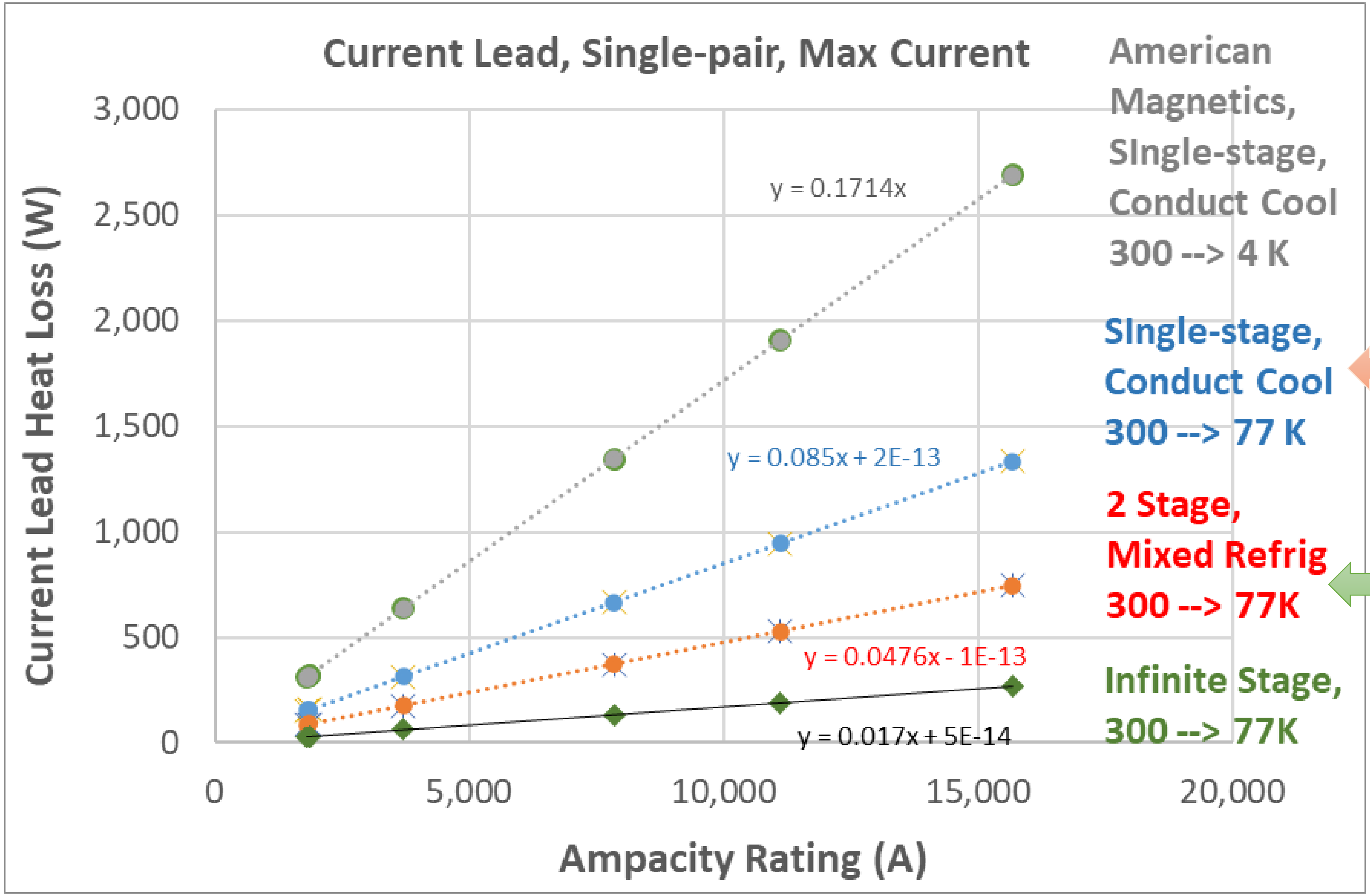
Nexans Cryoflex Tubing (COTS)

- 34 mm OD, 14 MM ID
- 0.5 kg/m
- 0.6 W/m (20-80K)

https://www.nexans.de/eservice/Germany-en/navigatepub_251736_-30212/

Cu Metal Current Lead Options
Waste Heat Generation (W)

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023. This presentation was given at EFATS 2022, August 30-31, 2022.



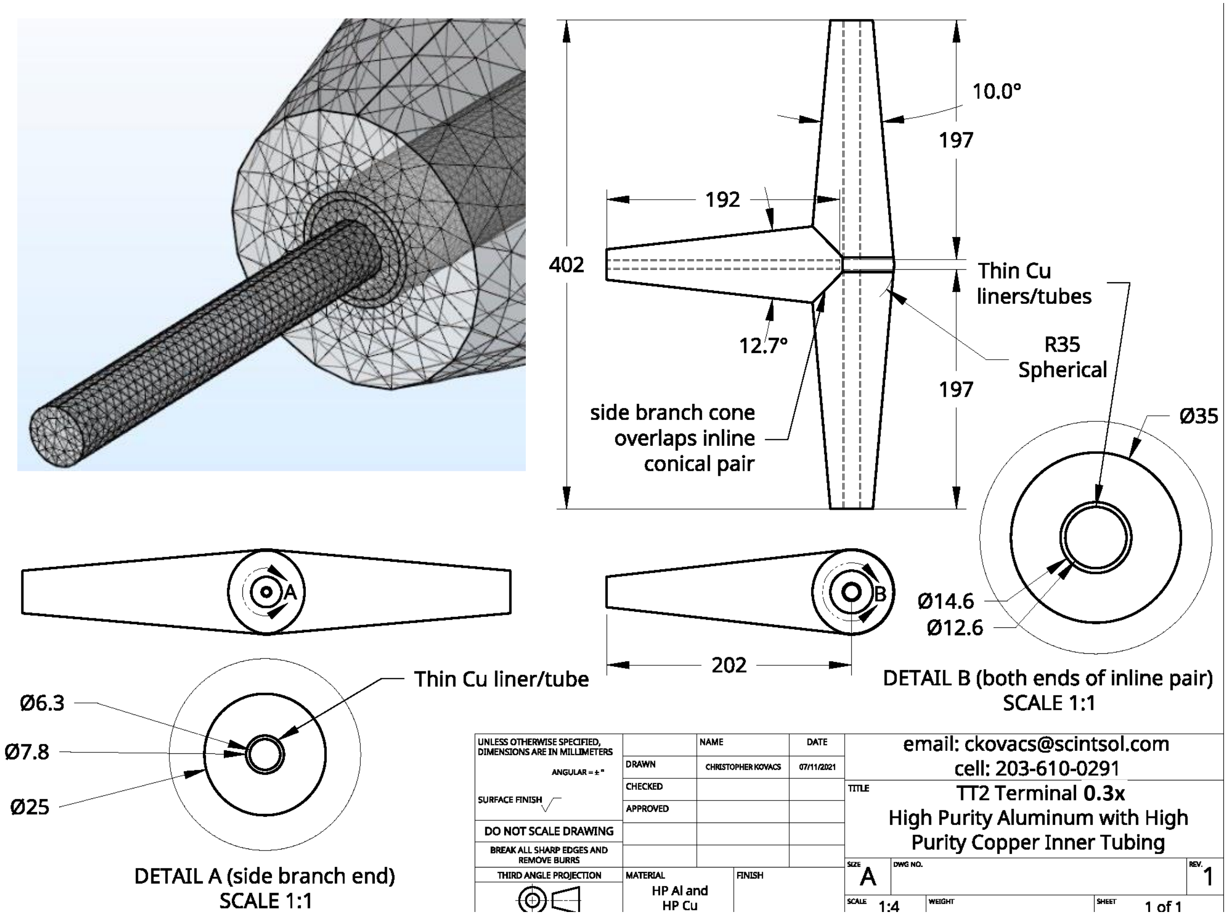
Classic Paper. 1-stage
R.McFee, Rev Sci Instr. 30, 98 (1959)
- Only needed if YBCO or BSCCO-2223 Cables.
- If MgB_2 then add YBCO or BSCCO current lead 77 K → 20 K
- Use this for spreadsheet

E. Shabagin et al, IOP Conf. Ser.: Mater. Science Eng., **v502**, 012136 (2019)

Note: Heat losses @ zero current (power) are ~ 60% of max current.

Multiphysics Simulation Details

- COMSOL 5.3.0.223
- Heat transfer, AC/DC, structural mechanics modules
- Electromagnetic heating, magnetic fields, electric currents, thermal stress interfaces
- Cryogenic Young's mod, Poisson ratio, coefficient of thermal expansion, electric resistivity, magnetoresistance, thermal conductivity found in literature
- Elastic regime (no plastic deformation)
- Volume integrated joule heating and density to find total power and mass
- Fixed surface temperatures 30, 40, 50 K
- Fixed contact resistivity 0, 20, 200 nΩ*cm^2
- Three different sizes 1x, ~0.6x, and ~0.3x mass



Y-Ba-Cu-O Conductor-on-Round-Core (CORC®)

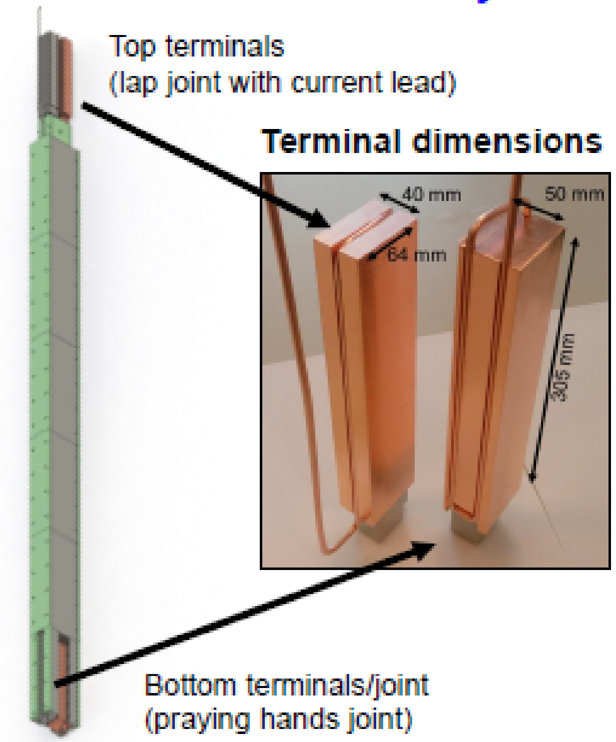
Mechanical Connector Joints

6x1 CORC® CICC terminations and joints

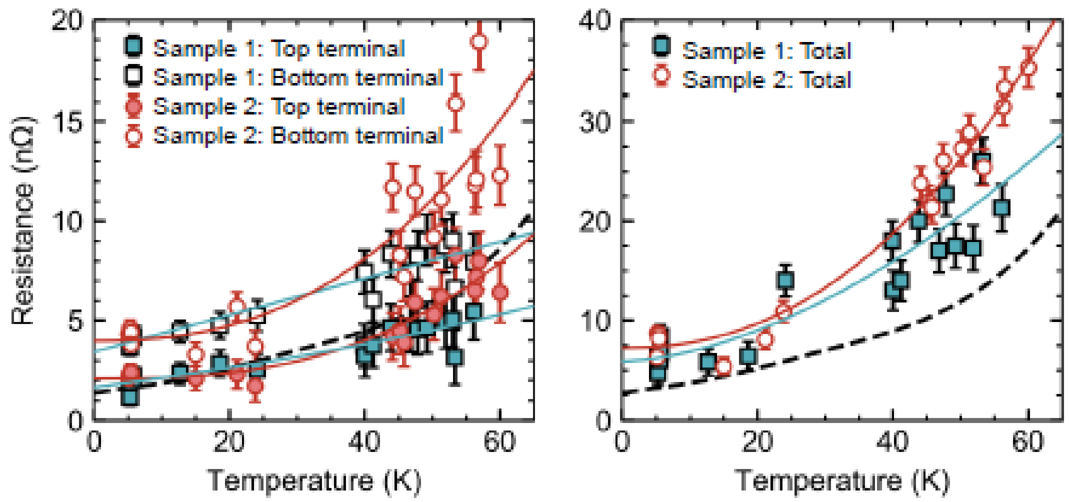
$Q_{loss} = R \times I^2$

$Q_{loss}(20K, 10kA) \sim 1$ W

Two samples tested in series at the SULTAN test facility



6x1 CICC terminations: R (5 K) = 2 to 4 nΩ
Splice between two samples: R (5 K) = 3.3 nΩ



Tim Mulder's thesis: *Advancing ReBCO-CORC Wire and Cable-In-Conduit Conductor Technology for Superconducting Magnets*
https://doi.org/10.3990/1.9789036546164

J. Weiss, et al, MT 2019

CORC “Tee” joint distribution:
1 kV, 20 kA Main-Line → 2.5 kA Motors

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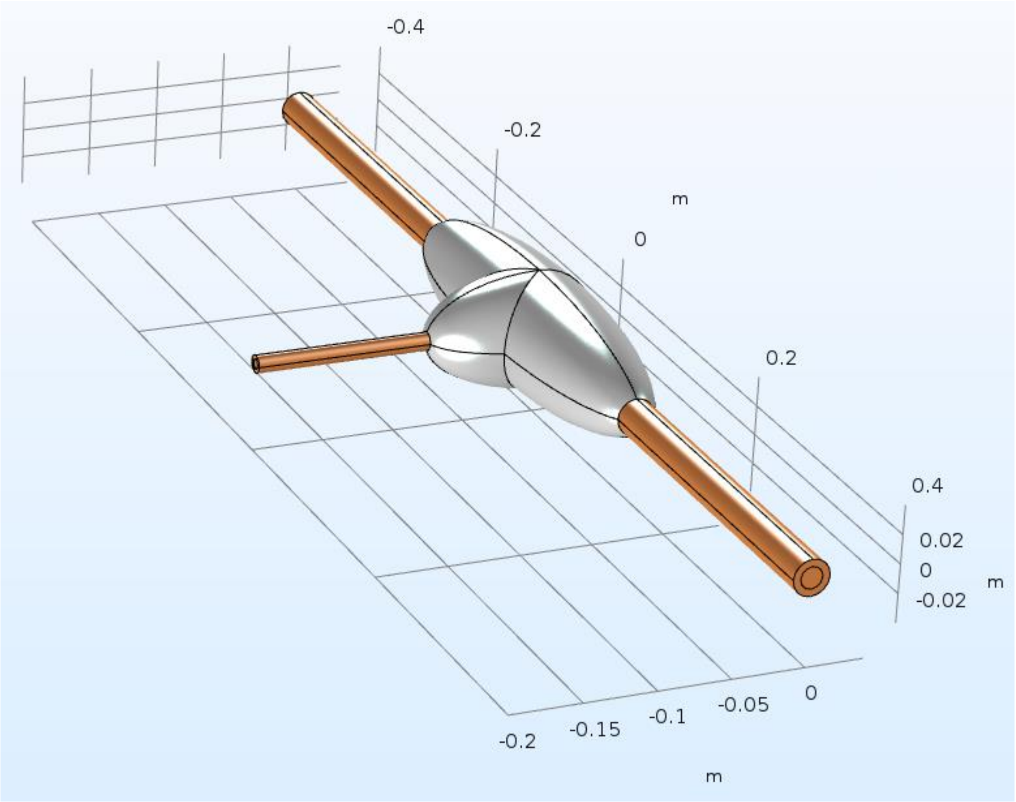
- To greatly reduce mass, use tapered and pre-tinned CORC cables and a staged T-shaped terminal.
- A bulge will be required near the junction to enhance current injection from the main cable to the 2.5 kA branch to a motor.
- Entire T-terminal can be made of Cu but more than 50% mass can be saved if the bulge volume is made of Al
- Bonding between Al/Cu is performed with shear and hydrostatic pressure



Lapovok “Bimetallic Copper-Aluminum tube by sever plastic deformation” (2012)

- **Heat Loss = 2-4 W @ 30K, 20 nΩ–m² (!)**
- **Mass = 2.8 – 6.2 kg, varying with temp and power loss choice (!)**

C. Kovacs, et al, *J. Phys. Conf. Series* **1975**, 012036 (2021)

Power Distribution Components

Parameterize Mass, Heat Loss Scaling for 0 → 20,000 Amps

Battery, Fuel-Cell → Motor

Pink = large mass, heat loss

Power Transmission Cable Component		Mass Parameterization	Heat Loss Parameterization	Reference, Comments
Metal Cable ~ 300K, single	$Cu_{0.2}Al_{0.8}$ Cuponal™	**Mass**(kg/m) = 0.0027***Wire**(A)	**Heat-Loss**(W/m) = 0.0437***Wire**(A)+45.14	**www.bruker.com**, ampacity tables
Metal Cable Conduit		don't have yet		
Current Lead 300K --> 77K	$Cu_{0.2}Al_{0.8}$ Cuponal pair™	**Mass**(kg) = 0.0062***Wire**(A)-3.8606		1st estimate, Cuponal current lead
Current Lead 300K --> 77K	Cu, pair	mass not provided	**Heat-Loss**(W) = 0.085***Wire**(A)	1-stage, R.McFee, Rev Sci Instr. **30**, 98 (1959), asked for mass Cu/Bronze
Supercon Lead 77K --> 20K	BSCCO ?, pair	**Mass**(kg) = 0.00066 ***Wire**(A)	**Heat-Loss**(W) = 0.00034***Wire**(A)	HTS 110, private communication
Metal to Supercond Joint	Cu to YBCO, pair	~ zero, cable plugs insert into lead	**Heat-Loss** ~3-10W, 5-20 nOhm@20K, 15kA	Adv Cond Tech., EUCAS 2019
HTS Cable, single, "to"	YBCO CORC™	**Mass**(kg/m) = 4.0438 E-6 ***Wire**(A)	DC loss = 0, AC Loss Transients?	X. Wang, SuST **31**, 045007 (2018), info..
HTS Cable, single 'from'	YBCO CORC™	**Mass**(kg/m) = 4.0438 E-6 ***Wire**(A)	DC loss = 0, AC Loss Transients?	" 8.9kA@20K, 3.63mm OD, 2.56 mm ID; Al
Hypercond Al Cable "to"	HP Al	**Mass**(kg/m) = 1.94 E-5 ***Wire**(A)	**Heat-Loss**(W/m) = 0.007155***Wire**(A)	C. Oberly, IEEE Tr. Magn. **27(1)**, 458 (1991)
Hypercond Al Cable "from"	HP Al	**Mass**(kg/m) = 1.94 E-5 ***Wire**(A)	**Heat-Loss**(W/m) = 0.007155***Wire**(A)	C. Oberly, IEEE Tr. Magn. **27(1)**, 458 (1991)
T-Connector, HTS to Metal	CORC™ to Cu/Al	**Mass**(kg) = 0.0006***Wire**(A)	**Heat-Loss**(W) = 0.00123***Wire**(A)	AFRL Calc @30K; 50K is ~4x higher
Cryoflex Tubing	OD=34 mm, ID= 14 mm	**Mass** = 0.50 kg/m	**Heat-Loss** = 0.5-0.63 W/m @ 77K --> 20K	Nexans COTS , other options possible

20,000 Amps for 1 kV = 20 MW Power; for one wing

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Power Distribution Cable, Excel Calculator, V02

Outputs: Mass, Heat Loss of Components/System

	Power Transmission Cable Component		Bus Power (kW)	Bus Voltage (V)	Bus Current (A)	Piece Length (m)	Piece Mass (kg/m)	Piece Heat (W/m)	Piece Mass (kg)	Piece Heat (W)
Depends on Length	Metal Cable ~ 300K, single "to"	$Cu_{0.2}Al_{0.8}$ Cuponal™	40000	1000	40,000	43.31	108.0	1,793	4,677	77,661
	Metal Cable ~ 300K, single "from"	$Cu_{0.2}Al_{0.8}$ Cuponal™	40000	1000	40,000	43.31	108.0	1,793	4,677	77,661
	Metal Cable Conduit, pair		40000	1000	40,000	43.31				
	HTS Cable, single, "to"	YBCO CORC™	40000	1000	40,000	43.31	0.16	0	7	0
	HTS Cable, single 'from'	YBCO CORC™	40000	1000	40,000	43.31	0.16	0	7	0
	Hypercond Al Cable "to"	HP Al	40000	1000	40,000	43.31	0.78	286	34	12,395
	Hypercond Al Cable "from"	HP Al	40000	1000	40,000	43.31	0.78	286	34	12,395
	Cryoflex Tubing	OD=34 mm, ID= 14 mm	40000	1000	40,000	43.31	0.50	1	22	27
				Subtotals			218.4	4,159	9,458	180,140
						# Pieces	kg/piece	W/piece		
Fixed (pieces)	Current Lead 300K --> 77K	$Cu_{0.2}Al_{0.8}$ Cuponal pair™	40000	1000	40,000	1			244.1	
	Current Lead 300K --> 77K	Cu, pair	40000	1000	40,000	1				3,400
	Supercon Lead 77K --> 20K	BSCCO ?, pair	40000	1000	40,000	1			26.40	24.00
	Metal to HTS Joint	Cu to YBCO CORC™, pair	40000	1000	40,000	1			0.00	24.00
	T-Connector, HTS to metal	CORC™ to Al/Cu @30K	2500	1000	2,500	32	1.600	3.075	51.20	98.40
				Totals	$Cu_{0.2}Al_{0.8}$ Cuponal™ Cable				9,355	155,322
					Al Hyperocnductor Cable				411	28,364
					YBCO CORC™ Cable				357	3,574

CHEETA V02
40 MW, 1 kV, 40 kA, 43.3m

Almost 'zero' mass

>70% of supercond/cryo system

Heavy, Hot!

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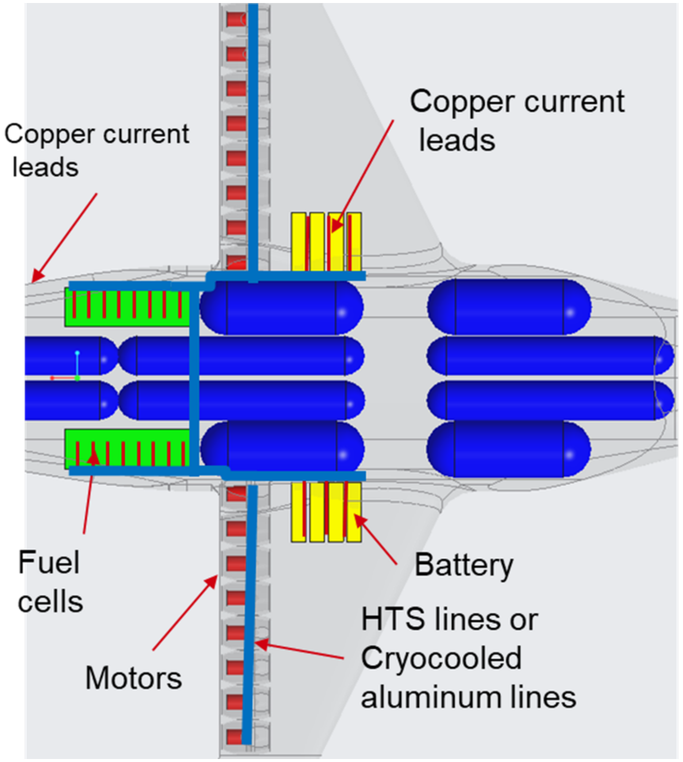
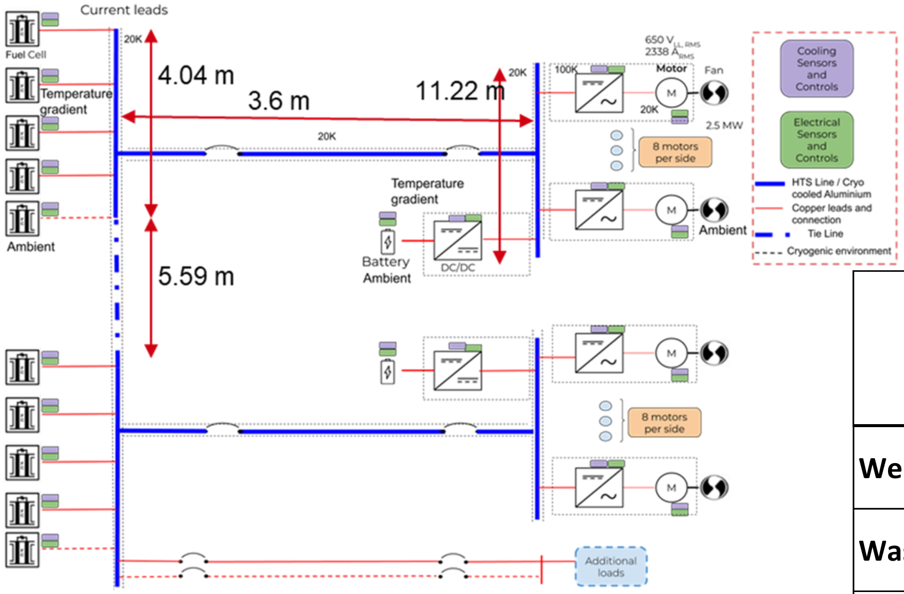
Power Distribution System - Mass, Heat Summary

CHEETA Liquid H_2 Fuel Cell, 40 MW, 1 kV, 40 kA, 43 m length





3 Technology Solutions

	$Cu_{0.15}Al_{0.85}$ Cuponal^{TM} @ 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)

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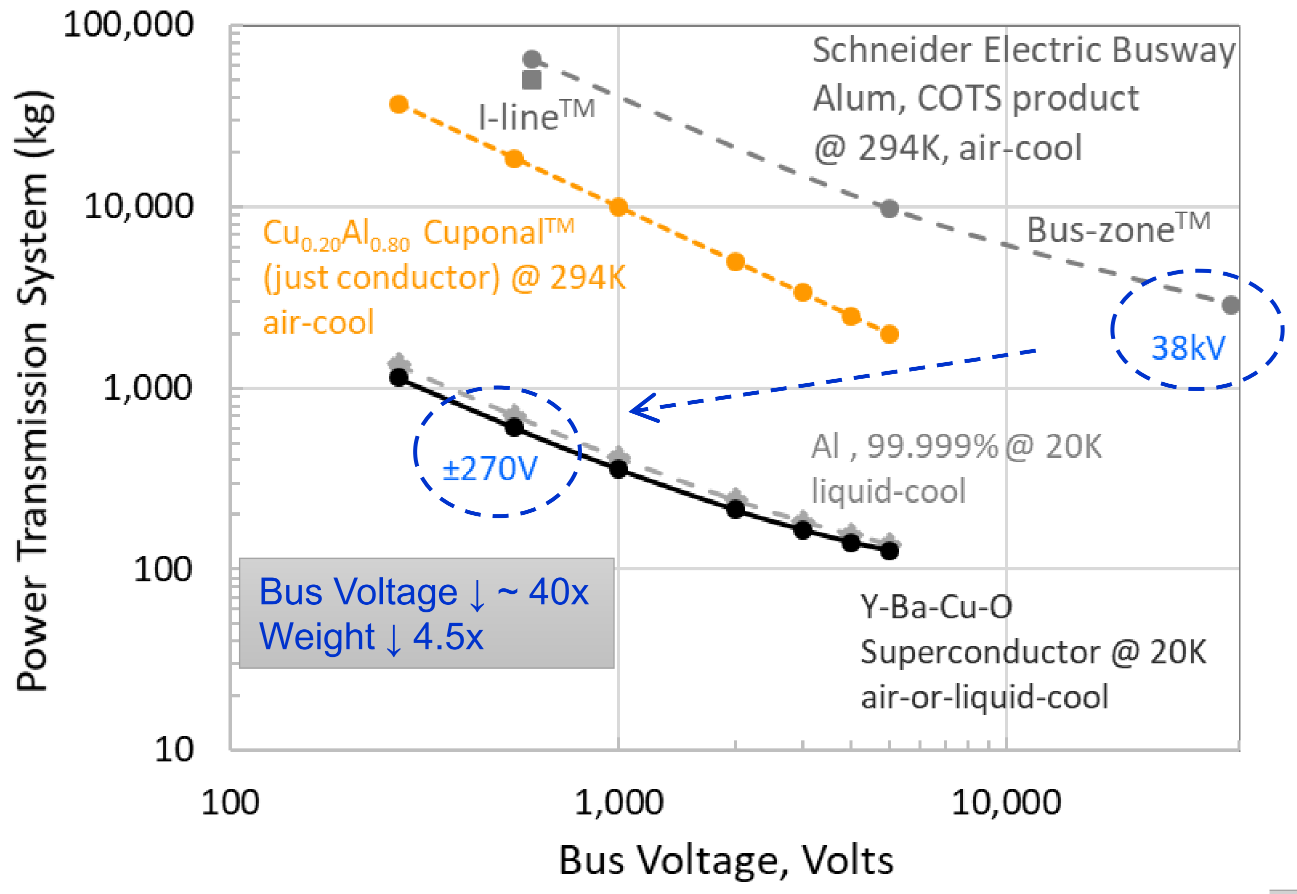
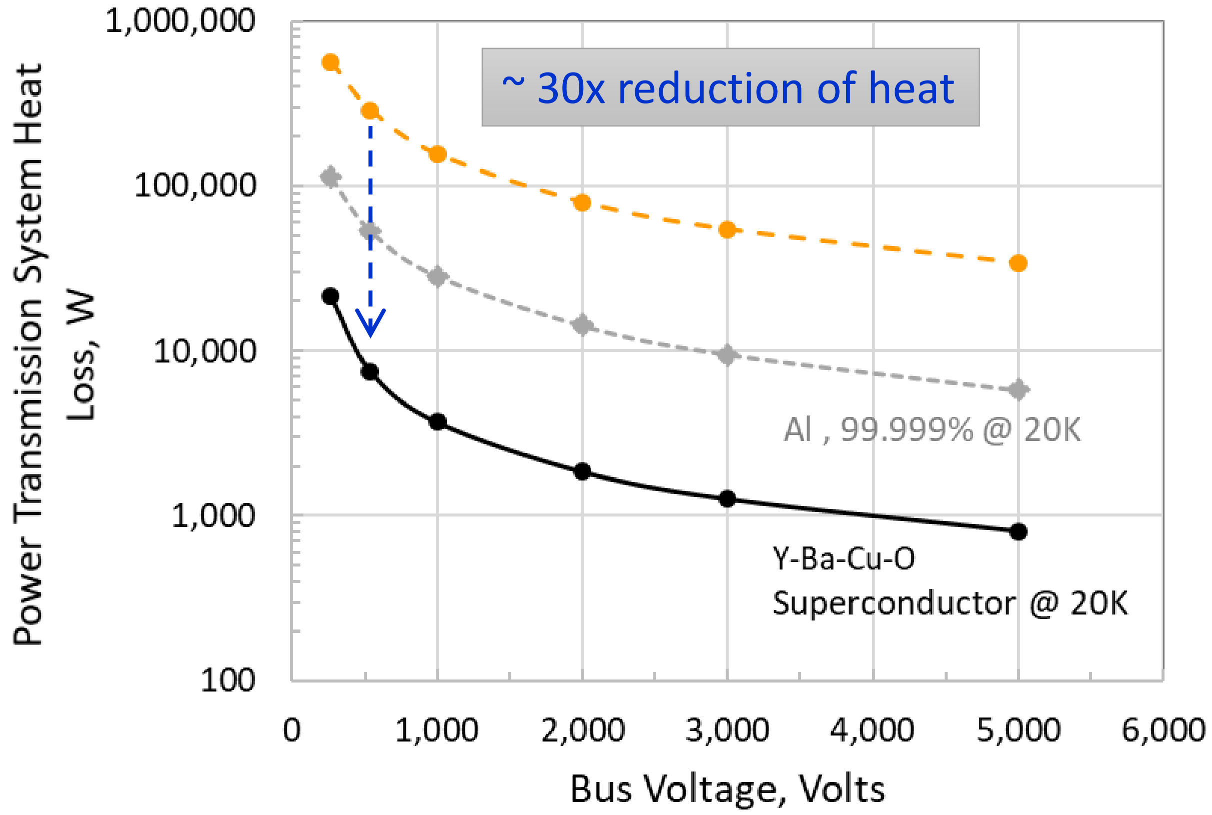
Power Distribution System - Mass, Heat Summary

CHEETA Liquid H_2 Fuel Cell, 40 MW, 40 kA, 43.3 m length

3 Technology Options





Ref. Schneider-Electric Cat # 5600CT9101, and email verify Wt(lb/ft) 5 Sept 2021

± 270 V Bus is 'feasible", and 4.5x lower mass than 38kV Bus-zones™, high voltage busway is ground not air-ready

Benefits of Superconductivity/Cryogenics for CHEETA VO2 Drivetrain System, *~ 8x lower mass, ~ 7x lower heat loads*

Boeing 737-800 Class, 178 Passenger

NASA ULI CHEETA V02, liquid-H_2 + fuel-cells

40 MW, 1 kV, 40 kA!, 43 m cable length

- Consider only major components so far

	Current Progress, Near-Term				CHEETA ULI Studies Future Investment			
	Power Density (kW/kg)	40 MW Power Mass (kg)	Efficiency	Waste Heat (kW)	Power Density (kW/kg)	40 MW Power Mass (kg)	Efficiency	Waste Heat (kW)
Generator	4	10,000	94	2400	40	1,000	99.8	80
Rectifier	20	2,000	98	800	40	1,000	99	400
Distribution	4.28	9,350	99.61	156	112.00	357	100	0
Motor Drive	20	2,000	98	800	40	1,000	99	400
Motor	13	3,077	96	1600	40	1,000	99.8	80
Thermal	4	10,000	98	800	150	267	100	0
Subtotals	**1.1 kW/kg**	**36,400 kg**	**83.6%**	**6,500 kW**	**8.7 kW/kg**	**4,600 kg**	**97.6%**	**960 kW**

Larger than Passenger Load = 13,700 kg !! (won't work)

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Summary Points, 22.5 MW EWIS Scaling Calculator

- **Superconductors arguably the best option**
  - very low heat loss, easiest to manage (gas cooling only)
  - ultralow volume and diameter, which reduces the impact of the cryoflex conduit
  - cables expensive (?)
- **Al 99.999% next best option**
  - provides large reduction of weight
  - heat loss is not insignificant, and must be cooled with liquid H_2. This adds greater complexity, and thermal management/control issues.
- **Operation at ±270 V @ 20K is considered a viable candidate,** and is even 30x lighter than Cu, Al at 294K, 30x less waste heat
- **Scaling for all components to higher powers is not necessarily linear -** must study each component
- **Design and operation of components can be complex -**
  - trade options possible; e.g. can swap mass and waste-heat

Acknowledgements

Questions?

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