Overview of Cooling Technologies for Cryogenic Transportation Machines

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System Cooling Modes – Direct / Remote

- Bath cooling / immersion cooling / subcooled / solid cryogens
- Thermosiphon cooling / heat pipes / pulsating heat pipes
- Forced-flow cooling / pumped / circulated with impellers
- Conduction cooled / directly bolted on or via cold plates

Cryogens* to Cool HTS Applications

Cryogen		BP (K) immersed	TP (K) – siphons, HP
Krypton	Kr	119.8	115.8
Methane	CH4	111.7	88.7
Oxygen	O_2	90.2	54.4
Argon	Ar	87.3	83.8
Fluorine	F	85.2	53.5
Carbon monoxide	CO	81.6	68.1
Air	N_2+O_2	78.8	59.8
Nitrogen	N_2	77.3	63.15
Neon	Ne	27.1	24.55
Hydrogen (normal)	H_2	20.4	13.95
Hydrogen (para)	H_2	20.28	13.8
Helium-4	He	4.215	5.22 (CP)
Helium-3	He	3.19	3.33 (CP)

T_c

BSCCO family,
1G HTS: **85-110 K**

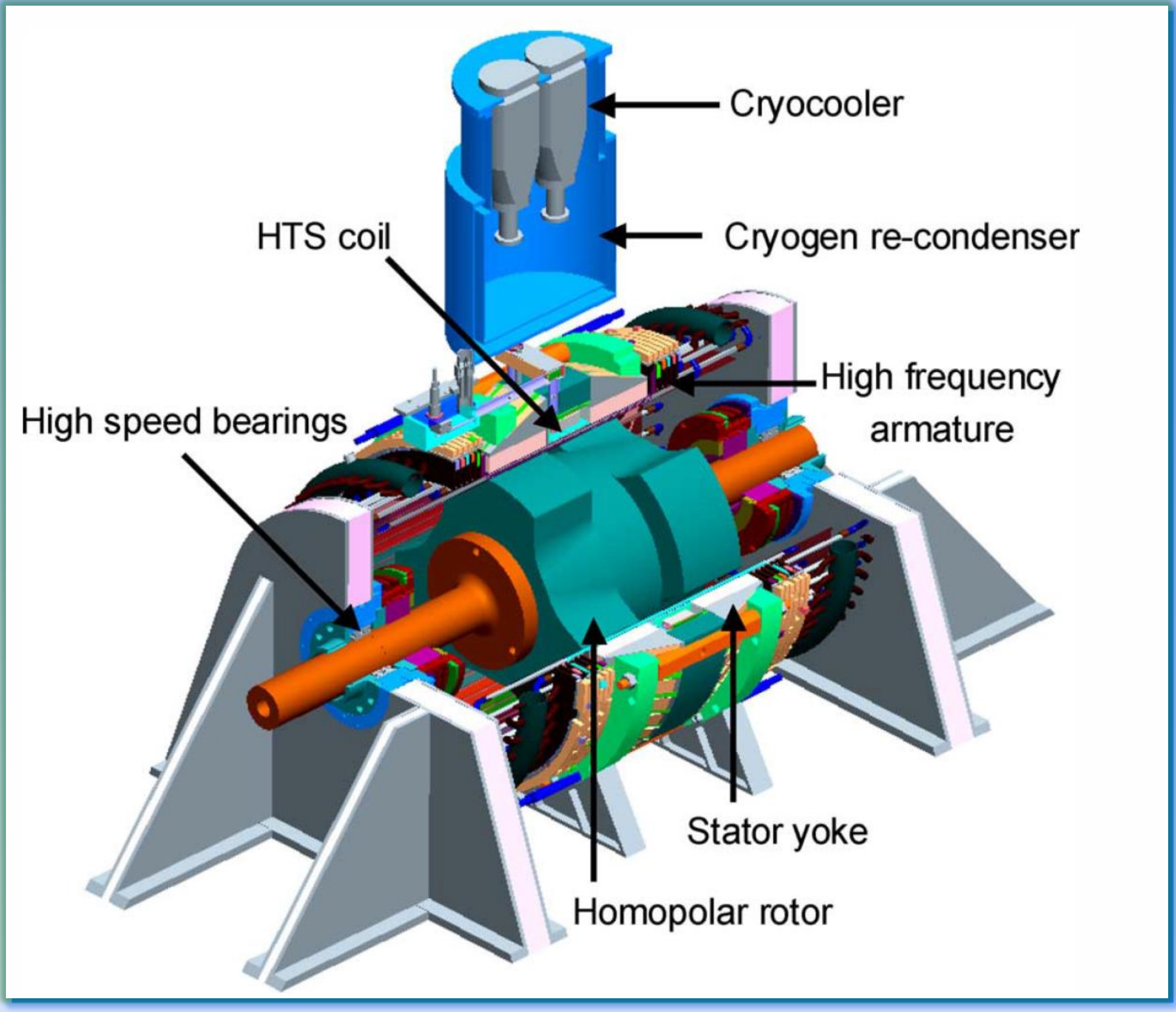
REBCO-123,
YBCO-123, Y-123,
2G HTS: **92 K**

MgB_2: **39 K**

*Mixtures excluded

Need cryocoolers to bridge the T-gaps

Technology Deployment – SC machines – Airborne Applications



Stationary HTS excitation coil,
LNe cooled,
BSCCO 2223,
Peak field 1 T, 5 MW,
10,000 rpm

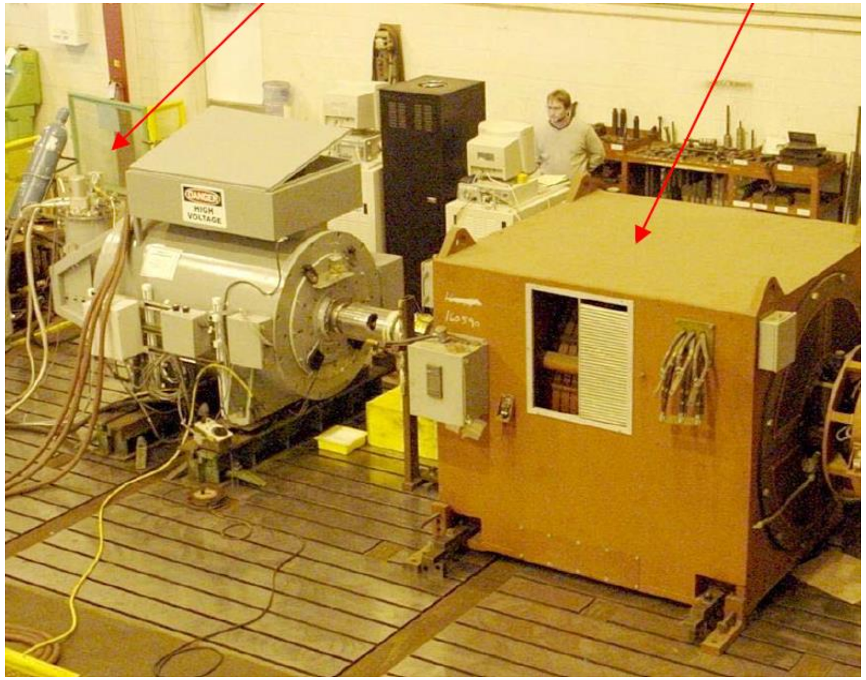
Airborne Applications
Homopolar Machine

GE 2009

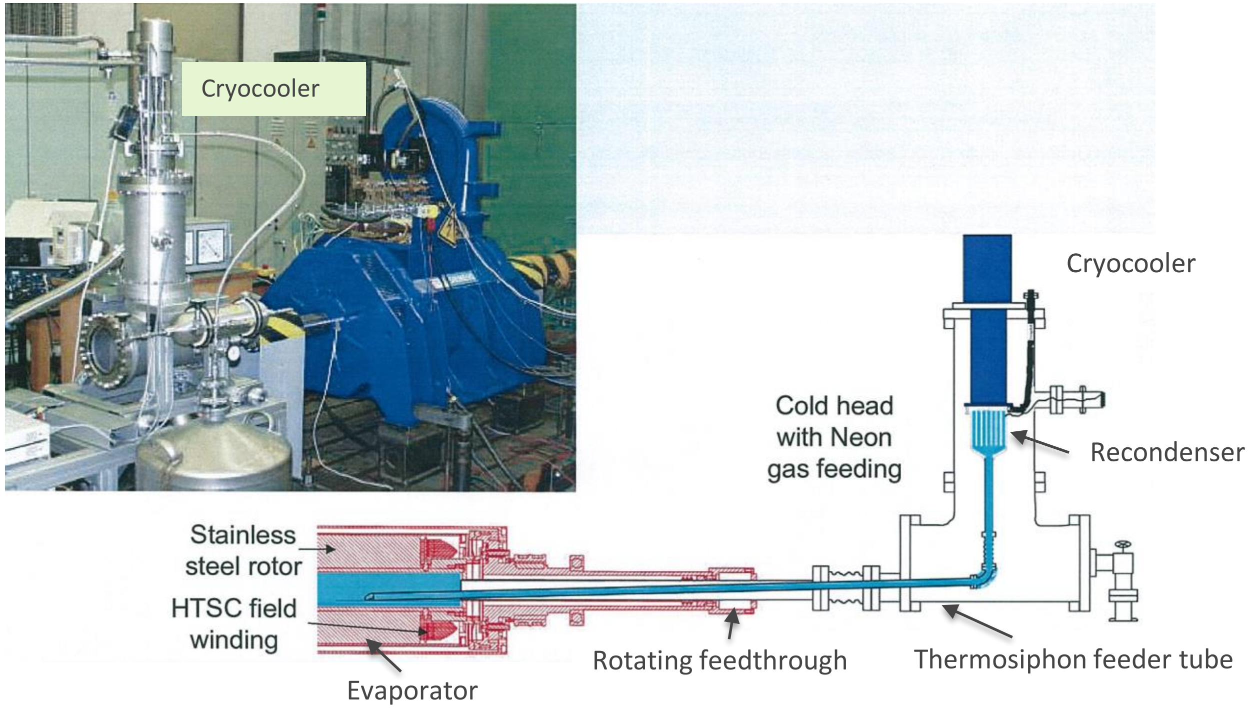
Further examples

AMSC

Cooler module and cryocooler 5000 hp motor



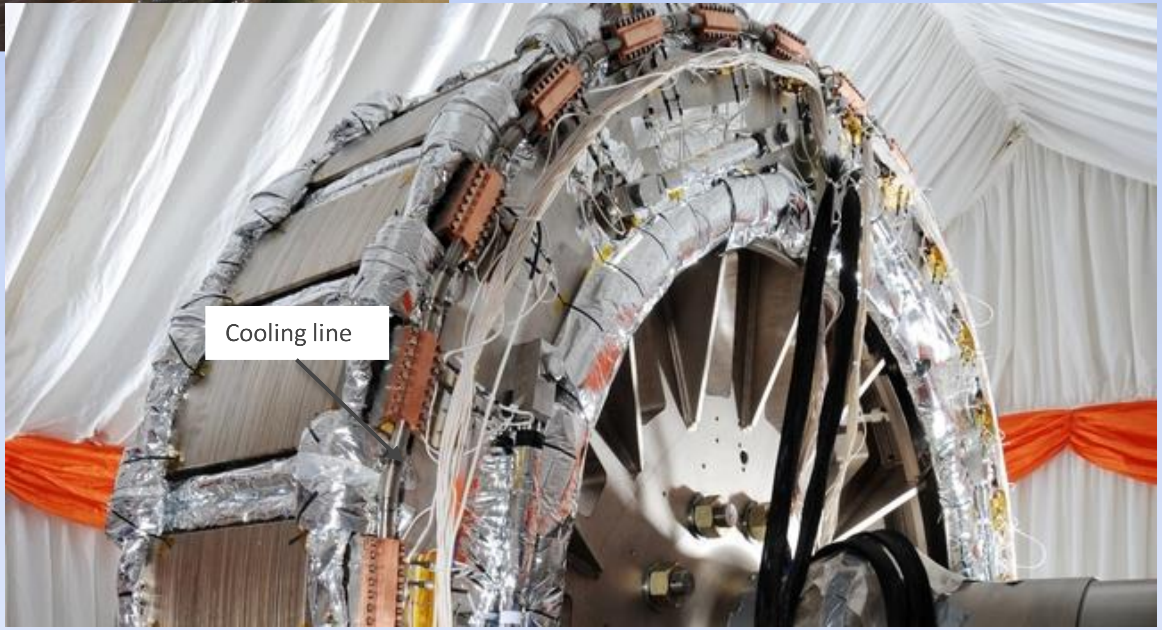
Siemens



J. Yuan, P. Winn, Cooling system for HTS Motors, International workshop on cooling systems for HTS, (IWC-HTS), Matsue, Japan, 2015
W. Nick, Siemens CT, Superconducting Motors and Generators, SCENET, Finland, 2005
See also: W. Stautner, “Cryocoolers for Superconducting Generators”, Chapter 5, in M. Atrey (ed.), Cryocoolers – Theory and Applications, Springer Publishing, 2017

Further examples

Supplier	Type
Power rating (nominal) (MW)	1.2 / 1.7
Zenergy conductor	Bi-2223
Rotational speed (rpm)	214
Number of poles	28
Line voltage (kV)	5.25
Design parameters	
Diameter (m)	3
Axial length (m)	1
Operating temperature (K)	30
Base temp. (with 1 cooler)	45
Coolers (2)	Cryomech
Impeller driven cooling	Cryozone



Typical component layout for coldbox remote cooling, GE Energy

Cryocooler Development Status for Transportation Machines

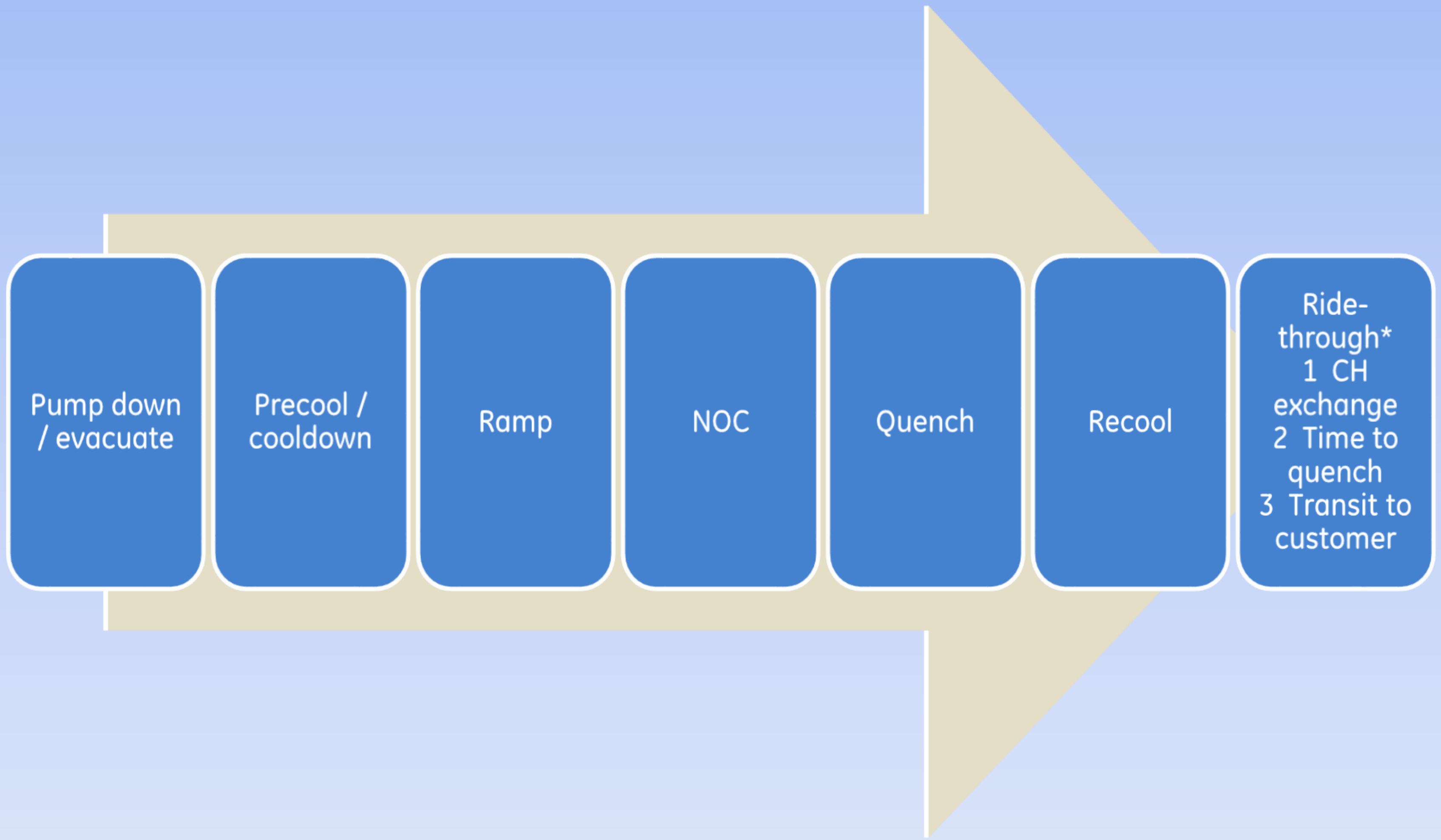
Supplier	Type	Single stage T-range	T_{bottom}	MTBF (hours)
Cryomech	GM type	600 W @ 80 K	26 K	15,000
Cryomech	PTR	100 W @ 80 K	9 K	25,000
Sumitomo	GM	200 to 600 W @ 80 K	20 K	15,000
Leybold/Oerl.	GM	140 W @ 80 K	18 K	n.a.
Chart/Qdrive	Stirling	Up to 1 kW @ 80 K	40 K limit	129,760
Creare+	Stirling	> 1 kW @ 80 K	(tbd.)	180,000
STI*	Stirling	Up to 100 W @ 80 K	45 K	>1 000,000
Sunpower	Stirling PTR	Up to 16 W @ 80 K	40 K limit	>1 000,000
Stirling SV	Stirling	Up to 1.3 kW @ 80 K	38 K	n.a.
Linde/Praxair	Rev Brayton	0.9 kW @ 20 K$	n.a.	n.a.
Taiyo Nippon Sanso	Turbo Brayton (Neon)	2 kW @ 70 K$ 10 kW @ 70 K	60 K	n.a.
Air Liquide	Turbo Brayton	50 kW and higher	35 K	n.a.

*design study, +under development, $with LN_2 subcool

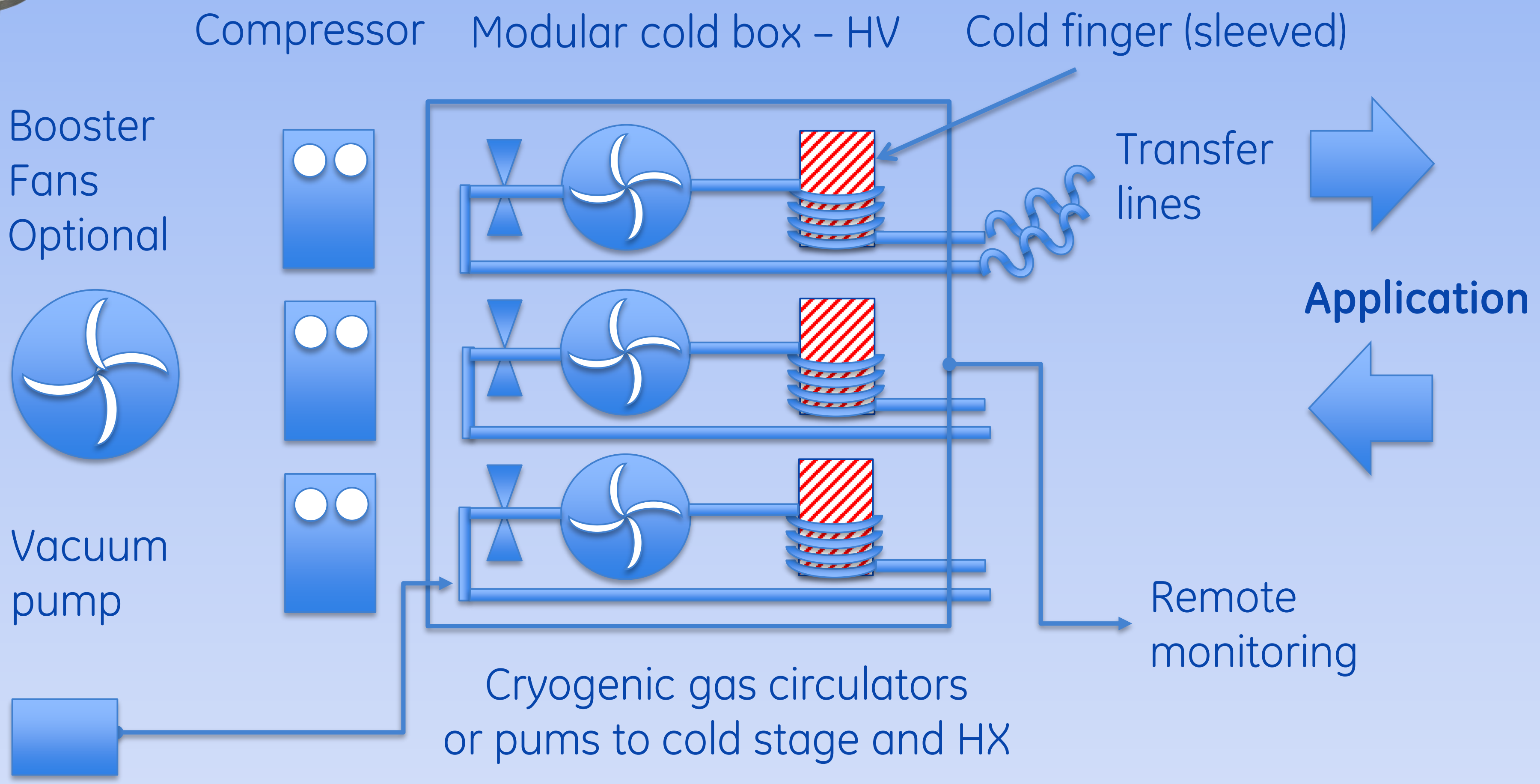
Cryogenic Topology of HTS Applications – Summary Status 2017

System	Conductor	T-range	Technologies
MRI	MgB_2/DI-BSCCO	4 to 10 K / 20 to 40 K, SN_2 < 30 K	Conduction cooled, thermo-siphons / heat pipes
Generators	YBCO/MgB_2 /BSCCO / DI-BSCCO	10 to 40 K, GHe, LNe solid/liquid gas mixes	Forced flow, LNe siphons, conduction-cooled (cooler mounted on rotor)
Motors	YBCO/BSCCO/GdBCO/MgB_2	20 to 40 K	CC via cold plate
AC cables	YBCO	LN_2@ 67 to 72 K	Pumped flow
DC cables	BSCCO/MgB_2	MgB_2: 2-walled @ 20 K, 4-walled 20 K / 70 K	Pressurized LN_2, He gas, LH_2, L_{air} (proposed), circulating siphons
SMES	YBCO/BSCCO/MgB_2	LN_2 / LHe / LH_2 / LNe	Immersion, 15 K CC-cooled, forced flow (1.5 - 10 K), siphon
SMB and flywheels	YBCO/BSCCO	10 to 20 K / 63 to 77 K or lower	Conduction cooled
Transformers	YBCO/BSCCO	66 to 77 K	Circulated LN_2/siphons
FCLs	BSSCO-2212 rods, YBCO/MgB_2	< 20 to 67 K	Immersed, CC, SN_2
Electr. comp.	YBCO film	30 to 70 K range	Conduction cooled
Cyclotrons	BSCCO-2212/YBCO	30 to 70 K range	Conduction cooled

Cryogenic Operating Conditions for HTS Transportation Machines



Emerging trend in cryogenic cooling for HTS applications



Distributed ➡ Modular ➡ Serviceable ➡ Simple maintenance

Fans: Cryozone, Barber Nichols, Creare, Mayekawa, Air Liquide, Linde/Praxair, R&D Dynamics

Evaluation of current HTS components

Solution	Status	KPI	Result
High power GM cooler	Cooling power avail. good, low eff.	Piston too heavy, low efficiency, oil	Maintenance issues
High power PTR cooler	Not available	Higher efficiency	Good, can be deeply embedded
High power Stirling	Available	Needs lower base T	Oil free, excellent
Turbo-Brayton	Available	Costly/maintenance	MTBF data?
Crycooler characterization	Inadequate	Adverse OP conditions	Transportation /vibration
Turbines and impellers	Available	Costly / HX needs improvement	MTBF – still need more data
Compressors for GM/PTR	Oil free, limited availability	Very little develop-ment effort only	MTBF not known yet
Liquid pumps	In development	Efficiency / no moving parts	MTBF not known yet

Key Enablers for Market Readiness - Industrialization

Cryocoolers

- Low maintenance or preferably maintenance-free at low cost
- Low susceptibility to vibration etc for some applications
- Able to withstand high 'g' forces
- Higher efficiencies at lower cost

Instrumentation and components

- e.g. high vacuum gauges in magnetic field, valves, etc. capable of withstanding high 'g' forces, acceleration and / or inclined operation

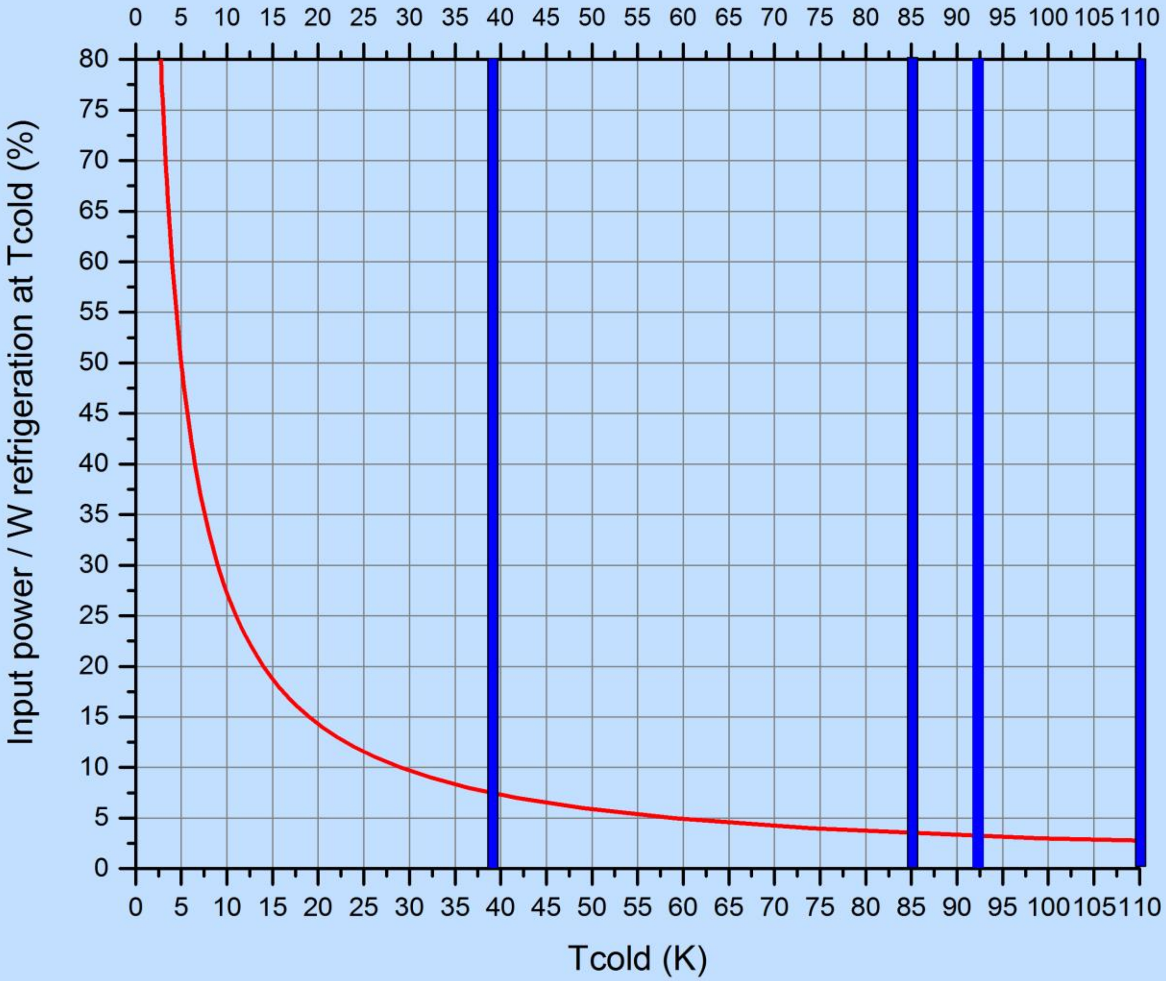
High-vacuum pumps

- Low maintenance / maintenance-free over years

Supplier chain and test facilities

- Need more highly specialized test facilities for components

Thank you!



0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110
80 75 70 65 60 55 50 45 40 35 30 25 20 15 10 5 0
Input power / W refrigeration at Tcold (%)
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110
Tcold (K)