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**Cooling topologies for superconducting power systems:
I. Short distance electric distribution**

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Abstract

In this and in accompanying reports, the topologies for cooling superconducting systems are investigated. The goal is to explore options that allow for flexibility of operation, low temperature rise in the superconductor and low refrigerator power consumption. A focus of this report is the study of means for cooling distribution systems with cryogenic loads dominated by current lead loss. Use of multiple fluids to decreased the refrigerator power requirements are described, and potential alternative candidate fluids are proposed.

I. Introduction

Short distance distribution systems have characteristics that make them very different from long-distance transmission lines. One of the main differences is that the cryogenic loads are dominated by the current leads losses, as opposed to long-distance transmission lines, where the heat load is dominated by distributed losses due to the cryostat. A second difference is that the short distance grid may be characterized by a large number of secondary feeders along the distribution line, as opposed to transmission, where there is a small number of feeders, or only terminations at each end.

There are two possible coolants of interest for cooling superconducting distribution lines: liquid nitrogen (subcooled), and gaseous helium. Liquid nitrogen has the advantage of much smaller temperature rise in the coolant for a given volumetric flow, but it is limited in the minimum temperature where it can operate, at around 65K. Gaseous helium is not limited by the temperature for expected temperatures of operation of the SC distribution grid, but it requires much larger volumetric flow rates. It requires comparable mass flow rates to liquid nitrogen, but since gaseous helium has much lower density, the corresponding volumetric flow rates and the operating pressure drops are higher. The high flow rates result in increased pressure drop, and the changes in density with temperature are much larger than for liquid nitrogen.

There is a substantial literature on the minimization of the cryogenic load on conduction-cooled current leads, starting with the work of McFee [McFee]. Iwasa has systematically reviewed work on this field [Iwasa]. Recently, there has been work to try to minimize further the cryogenic load. Yamaguchi has proposed and tested the use of Peltier elements at the high temperature side of the current leads [Yamaguchi]. Bromberg has optimized the use of intermediate temperature stages as further means of decreasing the cryogenic load [Bromberg]. These studies indicate that it may be possible to decrease the cryogenic load by about half that of conventional systems.

In the case of current leads, the refrigeration requirement is about 0.1 W/A per current lead pair, for currents that go from room temperature to approximately liquid nitrogen

temperature Depending on the voltage of the transmission line, the cryogenic requirement for the primary feeder current leads could be as high as 2.5 kW (for 25 kA SC bus, 400 V), per set of power leads. A similar loss occurs in the secondary spurs (as the integrated current of the secondary spurs is the same as that of the primary feeders). The secondary spurs result in distributed losses along the distribution line. These large cryogenic loads represent a challenge. For one, it would be best if the superconductor temperature is as low as possible in order to minimize the amount and cost of superconductor required. Superconductor cost minimization is very important, especially in the near and middle term. The cost of the superconductor is a substantial fraction of the cost of the system, and thus its performance needs to be maximized.

In this document a few approaches that address the unique cooling needs of superconducting distribution systems are investigated. In particular, DC systems are investigated.

II. DC distribution system characteristics

Figure 1 shows a superconducting DC distribution system, such as those proposed for a data center [Furuse]. With respect to Figure 1, the power may come to the site through a high voltage transmission line, and then it is reduced to low voltage by an onsite transformer (not shown). The AC power output from the AC transformer is converted to DC by an AC/DC converter, followed by an uninterruptible power supply (UPS). The uninterruptible power supply can be a SMES, capacitors, ultracapacitors, battery, diesel generator set with AC/DC conversion, or other. A set of current leads, 8a and 8b are used to introduce the current to the superconductor through the cryostat. A large number of spurs 12 provide connectors to the superconducting distribution bus 9 (composed of elements 9a and 9b). Some of these spurs may be terminated by terminations 13, within the cryostat, that are not active in order to provide flexibility to the distribution bus. Most of the spurs are active and connected to current leads 10 that transfer the current from the superconductor to a normal conductor through the cryostat. These currents power the loads. The current is then returned by a similar superconducting electrical distribution bus.

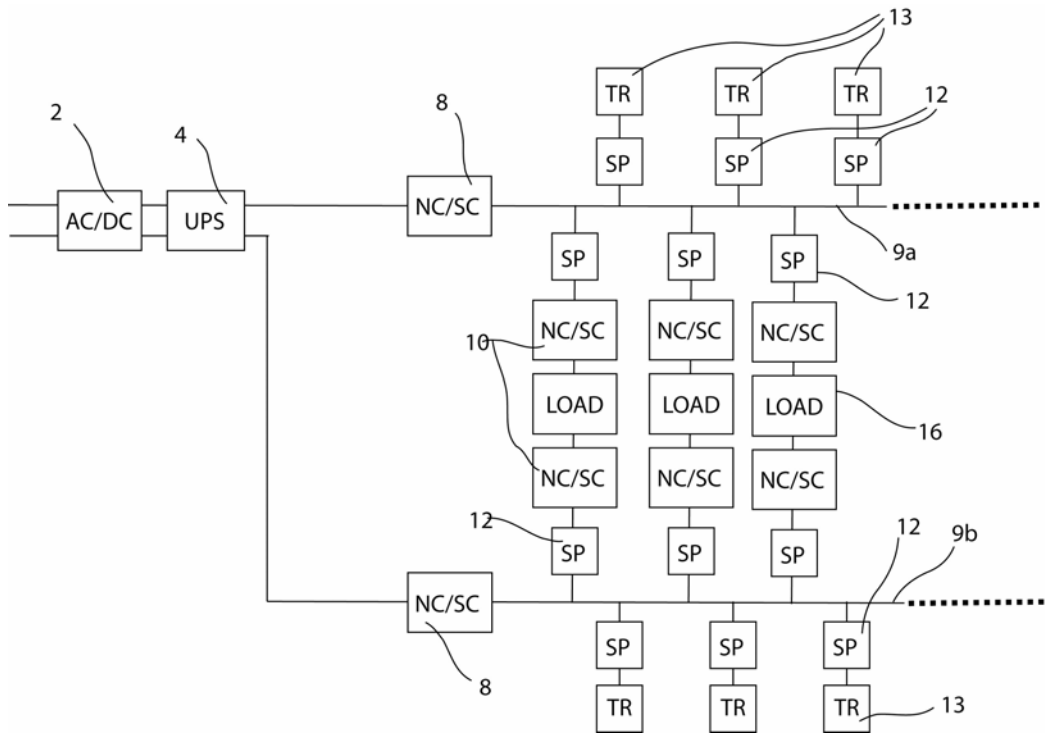


Figure 1. Schematic diagram of a circuit for a superconducting DC distribution system. Labels are defined in the text.

For DC distribution, it is desirable to have the current return also be at voltage, in order to maximize the transfer of power for a given amount of superconductor. If this arrangement is chosen, then the voltage polarity of bus 9a and 9b are opposite. In order to tolerate unbalanced loads, faults or transients, a small ground return is needed (not shown). This approach is attractive when the transmission is at high voltage, as the voltage is halved for constant power delivery capability.

Table 1 shows rough numbers for the cost of a nominal 10MW system for a data center [Pratt] with a topology as shown in Figure 1, with large power-density requirements. The numbers from the Navigant study [Navigant] have been used to scope near, middle and long term costs, assuming trends in cost reductions for the superconductor, the refrigeration units (cryocoolers) and the cryostat. It is not intended that Table 1 be precise, but rather to point out the items that dominate the cost. It is assumed that the distribution line operates at 400V and is 200 m long.

Table I. Costs of SC distribution system for data center

Power	MW	10	10	10
Length	m line	200	200	200
Voltage	V	400	400	400
Current	A	25000	25000	25000
YBCO cost	\$/kA m	\$400.00	\$50.00	\$10.00
Total cost		\$4,000,000	\$500,000	\$100,000
Cost of cryostat	\$/m	\$500	\$300	\$100
		\$200,000	\$120,000	\$40,000
Cost of cryocooler	\$/W	\$100	\$60	\$25
Heat leak	W/A	0.2	0.1	0.1
Total heat leak	W	5000	2500	2500
Refrigerator cost		\$500,000	\$150,000	\$62,500
Refrigerator power	W at RT	50000	25000	25000
Total cost		\$4,700,000	\$770,000	\$202,500

It is clear from Table 1 that in the near term the cost of the superconductor dominates by a wide margin. In the longer term, the cost of the cryogenic system is comparable to the cost of the superconductor. The reason for the relative change of the costs is that it is expected that the cost of the superconductor, a recent technology, will experience much faster cost reduction than either the cryostat or the cryocoolers, which are more mature technologies.

It is assumed that the cryogenic heat load is dominated by the current leads, a good assumption for short length cryostats. Means are being investigated in this report to decrease the thermal load due to the current leads and to investigate means to minimize the temperature rise in the superconductor coolant.

III. Topology options for cooling the superconductor and the current leads

The cooling process for a superconducting power distribution network requires special attention, different from superconducting power transmission lines where distributed losses along the cryostat dominate. In the case of short distribution networks the lumped losses due to the local heating by current leads dominate the refrigeration requirements.

This is especially true of the case when the superconducting distribution system has current leads for the primary and secondary feeders, and less of an issue for the case when there are not leads and the power transfer occurs via transformer action, which requires AC. Another difference between the superconducting distribution line and the superconducting transmission line is the use of many secondary feeders, although both lines utilize a single or a small number of primary feeders.

The topology of the cooling geometry need to address the following loads:

- Current lead
- Cryostat heat loads
- Superconductor losses

As mentioned above, it is ideal to have the superconductor as cold as possible. The cryostat and the current leads can have substantial temperature rise without major impact to the performance of the superconducting cable. Thus, it may be possible to cool the current leads separately from the superconducting cable, allowing the temperature of the cold end of the current lead to rise above the temperature of the superconductor. It may be necessary to decrease the current density in the transition from the normal current lead to the superconductor, and there will be heat conduction to the main superconducting cables. However, the temperature difference is expected to be small and thus the impact on the cryogenic losses is not large.

For DC application, the superconductor losses are negligible. Thus, only the cryostat losses and the current leads need to be addressed. For some of the best cryostats, it has been determined that the losses per unit length (due to radiation, conduction and convection) are around 1-2 W/m. For this system with 400 m of cryostat (for both polarities of a DC system 200 m long), the cryostat losses are small (see Table 1). It will be assumed that the approach from the accompanying paper [Bromberg1] will be used, minimizing the heat into the low temperature environment to 0.1 W/m.

Figure 2 shows a schematic of the conventional approach [Lee, Rostila, Maguire], with a single coolant that cools simultaneously the superconductor, the cryostat, and the current lead of a spur along the line.

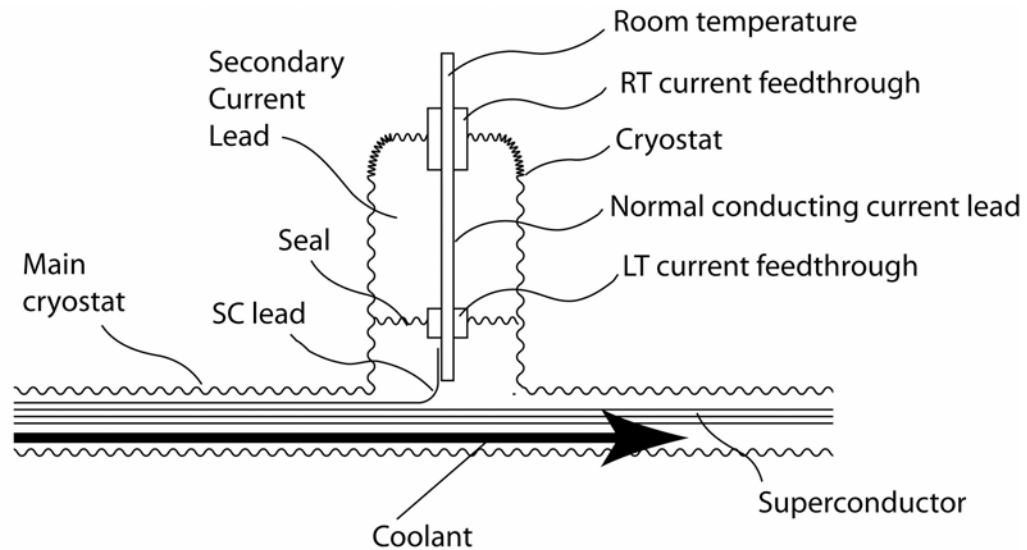


Figure 2 Conventional approach for cooling superconducting bus and current leads

In Figure 2, a current feedthrough and seal separates the coolant from the uncooled region of the current lead. The current lead consists of a cryostat that is shown in simplified form in Figure 2, a normal element and a superconducting element. A superconductor to normal conducting material joint is made between the normal conductor and superconductor lead in the cooled section of the cable. The normal conductor leaves the cryostat region through a current feedthrough. This geometry has the disadvantage that the heated coolant is remixed with the cold nitrogen. The superconductor downstream from the lead experiences increased temperature and thus decreased current carrying capability. High coolant speeds and large excess coolant capability can be provided to avoid this problem. In the case of excess coolant capability, the temperature differential between the cable inlet and the cable outlet are small, but there is increased pressure drop across the coolant loop with decreased pressure at the cable outlet (for a given inlet pressure).

With these constraints, it is possible to conceive multiple topologies that satisfy the requirements. The main constraint is that the superconductor has to be cooled with a separate fluid (or upstream using the same coolant) from the coolant that cools the current leads.

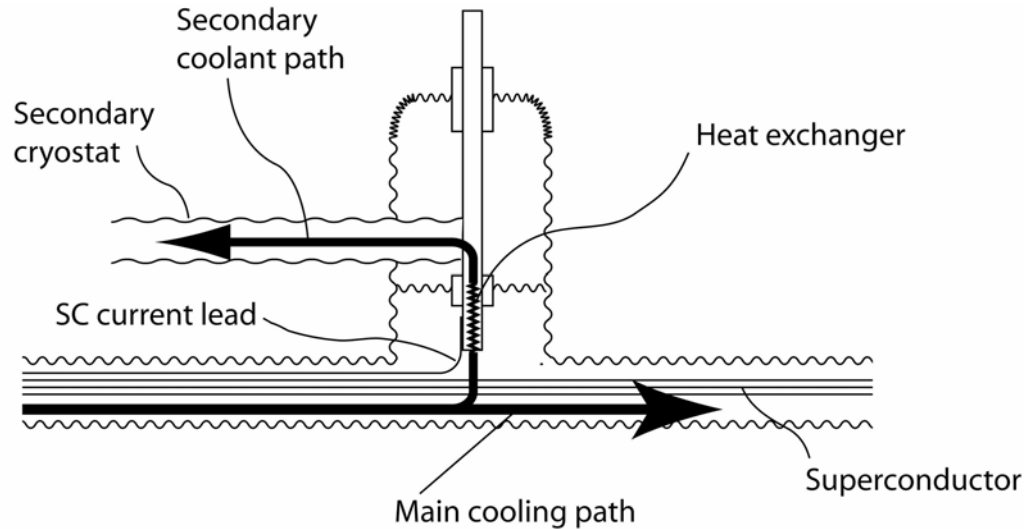


Figure 3 Cooling topology with segregation of the coolant fraction for cooling the secondary feeder current lead (a single spur is shown) away from the superconducting bus

Figure 3 shows a topology with the coolant that is used to cool the current lead extracted from the cold coolant stream, reducing the heat ingress into the superconductor coolant. A fraction of the main coolant is used to cool the current lead through a heat exchanger, and the warm coolant is removed from the cold cryostat and returned through a separate coolant channel. It should be noted that the two separate coolant paths can be within the same cryostat, to minimize the cost of the cryostat [Bromberg1]. Multiple current leads can be cooled in this manner, with the return path of the warm coolant returning through a single path towards the inlet of the cold coolant. One advantage of this geometry is that the coolant is returned to the inlet, where it can be re-cooled and reused for the inlet.

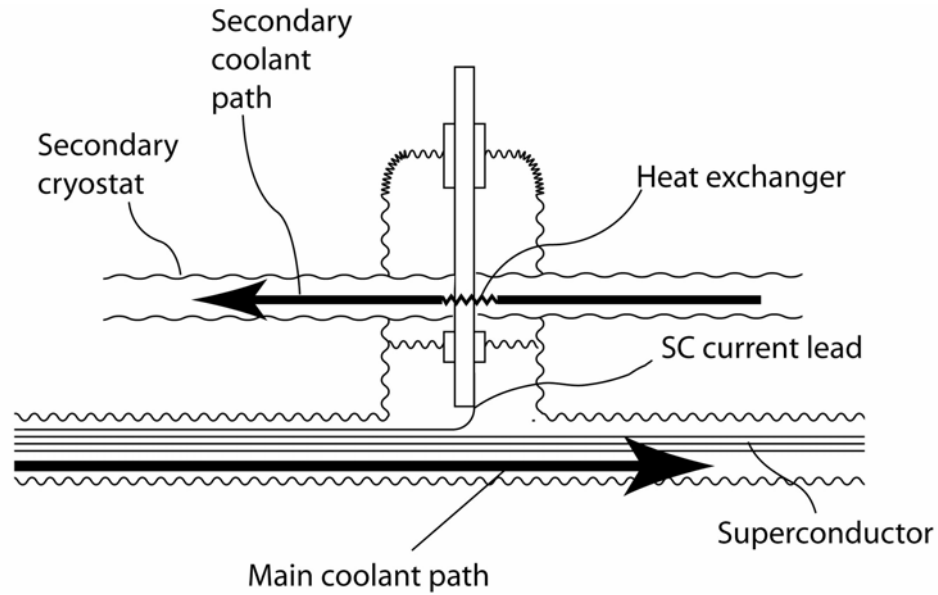


Figure 4. Cooling topology with separate cooling paths for the superconducting bus and for the secondary feeder (a single spur is shown) current leads

Figure 4 shows a variation of the topology shown in Figure 3, where there are two separate cooling paths that cool the arrangement, with the cold coolant path only cooling the superconductor bus, and the second, warmer coolant loop cooling the current lead. Note that there is distance along the normal conductor between the region cooled by the warm coolant and that by the cold coolant. The temperature difference between the two regions along the normal conductor results in heat transfer to the cold path, but because of ΔT is designed to be small, the heat input is small. Although shown in separate cryostats, it is possible for both paths to be in the same cryostat.

There is an operational difference between the topologies shown in Figure 3 and Figure 4. In Figure 3, the current leads of the spurs are all cooled with basically the same temperature coolant, as the heating of the superconductor is small. In Figure 4, the temperature of the coolant increases downstream from the current lead coolant, as there is substantial heating of this flow. However, there is simplicity in the manifolding of Figure 4 as there is only two main flows in the system, as opposed to multiple flow paths in the case of Figure 3.

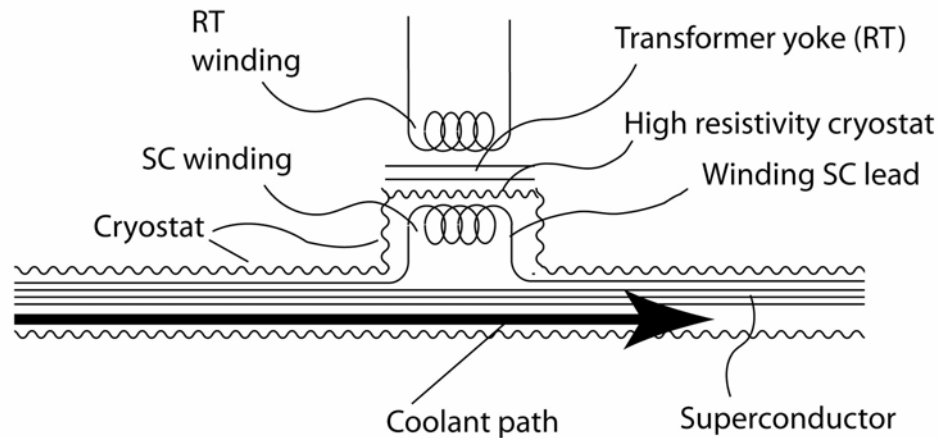


Figure 5. Coolant topology of contactless current transfer, with a single coolant path (for AC operation only).

One option that does not include current leads is shown in Figure 5, specifically for an AC system. In this case, the coupling between the room temperature circuit and the low temperature one is through inductive coupling. However, in this case the transformer yoke needs to be cooled. The superconductor bus and the primary superconducting transformer for a secondary current lead are cooled by the cold coolant. Shown in Figure 5 is a transformer core that could be at room temperature, which means that the primary winding needs to have a dielectric or high resistivity cryostat between the transformer core and the superconducting primary. Alternatively, the transformer core could be located on the cold side, in which case it needs to be cooled. Depending on the losses, a system such as described in Figure 2, 3 or 4 could be used.

The AC losses in the superconductor changes the distribution of the system losses. For the reported cases of AC systems, the AC losses correspond to numbers comparable to the cryostat losses, on the order of 1 W/m. Because there are no lead losses, the cryogenic load is dominated by the cryostat and the AC losses. This option will be discussed in a future report, as this report addresses DC systems.

So far, the discussions have considered only the secondary current leads (the spurs). It is possible to integrate both primary current leads (that feed the power to the system) for simplifying and optimizing the cooling manifolding.

IV. Fluid options for intermediate coolants

The use of intermediate coolants can be used to minimize the electrical refrigerator requirement. Bromberg [Bromberg] analyzed the effect on the current leads, while Miles investigated the effect for the cryostat [Miles].

There are several fluids that can be used as intermediate coolants. Some of the most promising fluids are shown in Table 2 which compares the properties of these fluids, including boiling temperatures at 1 bar and at 10 bar, the heat capacity, density and temperature excursion to the boiling phase between 10 bar and 1 bar and the heat capacity over that excursion. A figure of merit can be determined by dividing the rate of heat removal capability, $c \rho \Delta T A V$ (where c is the heat capacity, ρ the density, ΔT the allowable thermal excursion, A the cross sectional area of the channel, and V the velocity of the fluid), by the pressure drop per unit length, $f \rho V^2/2$ (where f is the friction factor). Although the figure of merit could have been the rate of heat removal divided by the pumping power, it is determined that the pumping power is not large, and thus not important, but the pressure drop limits the window of operation. Two assumptions for the friction factor were made in Table 2, one for laminar flow and the second one for turbulent flow. In laminar flow, $f \sim 1/Re$, where Re is the Reynolds number, and the figure of merit reduces to $c \rho \Delta T A D / \nu$, where D is the diameter of the cooling passage and ν is the viscosity. For the case of turbulent flow, f is only weakly dependent on Re , and the figure of merit is $(c \Delta T) A / V$. Table 2 shows the figures of merit for the different coolants considered, for constant A and constant V (for the case of turbulent flow).

The light hydrocarbons are about a factor of 2 better than liquid nitrogen. For the hydrocarbons, the boiling temperature is lowest for methane, and increases with molecular weight. Ammonia shows a high performance, but its temperature is rather elevated. However, the use of any of these coolants requires a more complex cryogenic system, with multiple coolants.

In this report, the possibility of using a second liquid nitrogen coolant path, operating at higher temperature is investigated. The implications for cooling the leads for distribution systems, as well as cryostat losses for transmission systems will be discussed in the following sections.

Table 2. Properties of potential cryogenic fluids

	Boiling 1 bar K	Boiling 10 bar K	ρ kg/m ³	ΔT K	c kJ/kg K	viscosity microPa s	visc average microPa s	$c \rho \Delta T / v$	$c \Delta T$
Nitrogen	77	105	750	30	2.2	130	130	381	66
Ammonia	240	300	650	60	4.3	500-150	300	559	258
NF3	170	220	1500	50	1	???	300	250	50
Methane	110	150	400	40	3.5	100-50	75	747	140
ethane	180	250	500	70	2.3	150-100	120	671	161
Propane	215	300	600	60	2	500-150	300	240	120
Argon	90	118	1300	30	1.2	120-200	150	312	36

V. Calculation of performance of cooling topologies for distribution systems

In this section, the performance of the several options discussed in Section III is assessed. It is not the goal of these calculations to fully optimize the system, as much more work needs to be done, including detailed investigation of the performance of the refrigerators. Instead, the goal is to provide insight into the potential advantages of the different options.

The calculations have been performed for a DC distribution grid, such as for a data center. For the purpose of the illustration, it is assumed that the total current is 25 kA and the length of the cables is 200 m. It is the goal of the design to limit the temperature excursion of the superconductor, since as shown in Table 1 it dominates cost in near term implementations. It is also desirable to minimize the power requirements for the refrigerators.

For the studies, a compressible, steady state code has been used (CCAN), developed at MIT by Gierszewski [CCAN]. CCAN calculates the temperature, pressure, power and other engineering quantities along the length of an actively cooled electrical conductor. The code was developed to perform engineering analysis of internally cooled conductors. The code assumed single phase flow and neglects axial conduction relative to heat transfer to the coolant. It is assumed that the refrigerators operate with 1/9 of Carnot efficiency, corresponding to near term expectations from the Navigant study [Navigant].

For this application, the cryogenic loads are dominated by the current leads. Table 3 shows the relevant parameters of the system. It is assumed the cryogenic load per each current lead is 0.05 W/A, a value that represents the state-of-the art. Bromberg has performed calculations to determine the optimization of current lead design using intermediate cooling, which could substantially decrease the cryogenic load to the cryogenic environment [Bromberg]. It is assumed that the system does not provide current path redundancy of the secondary system. If it does, the cryogenic load would increase by about a factor of 1.5 for a second set of current leads that are not carrying current, but result in increased cryogenic load. The cryogenic losses in the distribution system are indicated in Table 3, excluding those of the terminations (which could be cooled separately). In addition, only one of the polarity losses is described. Thus, only about 1/4 of the total cryogenic loads are included. However, these loads are distributed, and it is the purpose of the present report to investigate means of cooling them.

Table 3. Parameters for Superconducting DC distribution in data centers

Length	m	200
Current	A	25000
Cryogenic load	W/A	0.05
Total load, cable	W	1250
Cryostat load, Low T	W/m	0.1
Refrigerator efficiency		1/9 of Carnot

Figure 6 shows the temperature and pressure along the distribution system, for conventional current leads, assuming that the current leads in the secondary system are

distributed uniformly along the length of the cable. Because of the relatively short length (200 m), the pressure drop is not a problem, in sharp contrast with long-distance transmission systems (described in an accompanying report) [Bromberg1]. Substantial flow rates can be provided, 0.1 kg/s, in small cross sectional area (2 cm^2), with relatively small pressure drops. All of the heat is being removed at the low temperature.

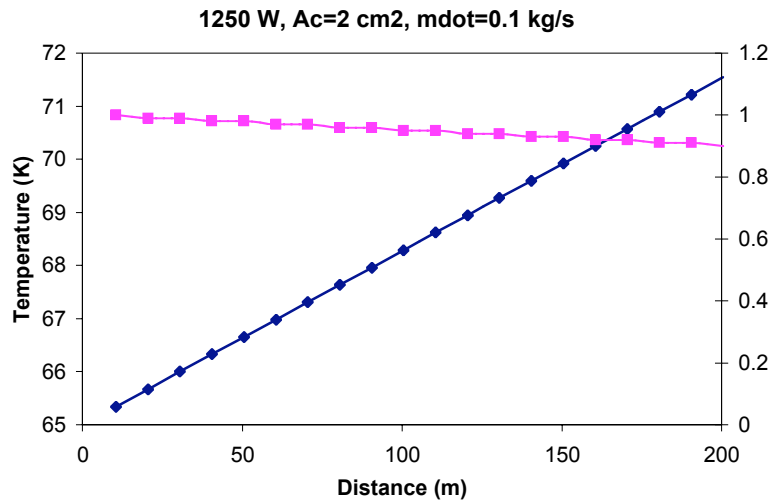


Figure 6. Temperature and pressure along the length of a conventional data center SC distribution system (as shown in Figure 2).

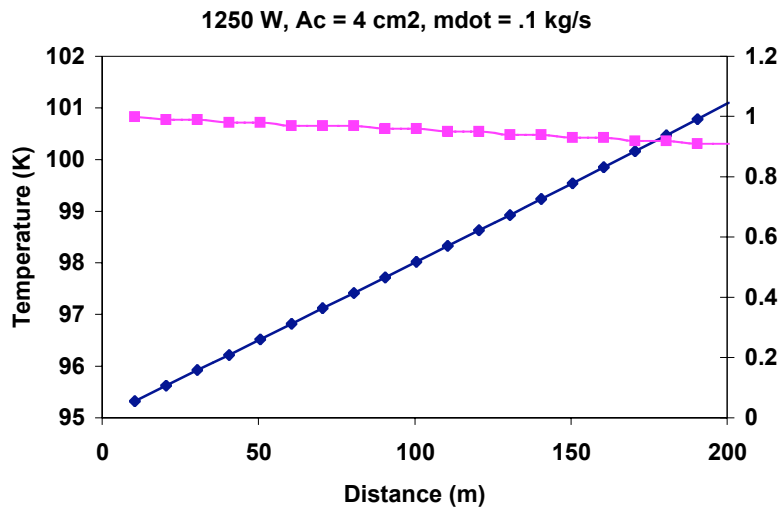


Figure 7. Temperature and pressure along the distribution system for the current lead cooling paths shown in Figure 4, operating near 100 K

Figure 7 shows the results for the case when the current leads are cooled separately, and the heat is intercepted at around 100 K. The result of this case is to minimize the cryogenic load to the low temperature environment.

Finally, the results of a system where the coolant first cools the superconductor and then the current leads, as in Figure 4, are shown in Figure 8. The total length of the coolant path in this case is now 400 m. The cross section of the coolant is decreased, as there is larger temperature drop allowed for the coolant in the return path since it is not affecting the superconductor. The coolant flow rate has also been decreased, to 0.02 kg/s, resulting in a much larger temperature rise in the coolant. The high temperature occurs in the return path when the coolant is used to cool the current leads, not the superconductor (as shown in Figure 4). The system has been sized so that the temperature at the outlet is near 100 K, near the boiling point. There is single phase fluid through the entire length. In this case, it is assumed that the cold environment experiences a heat loss of about 1/20 that of the case when the current leads are cooled by the cold coolant.

The comparison between the three approaches is shown in Table 4. Included in this table are the refrigeration loads. There is a substantial benefit from cooling the current leads at the higher temperature (intercepting the heat at higher temperature, resulting in substantial decrease of power requirement for the refrigerators). The savings in the coolant are about 35% for the case of separate coolant (Figure 4, with a return path cooling the current leads at a relative high initial temperature) and 15% for the go-and-return case (with a return at the initial temperature of the superconductor).

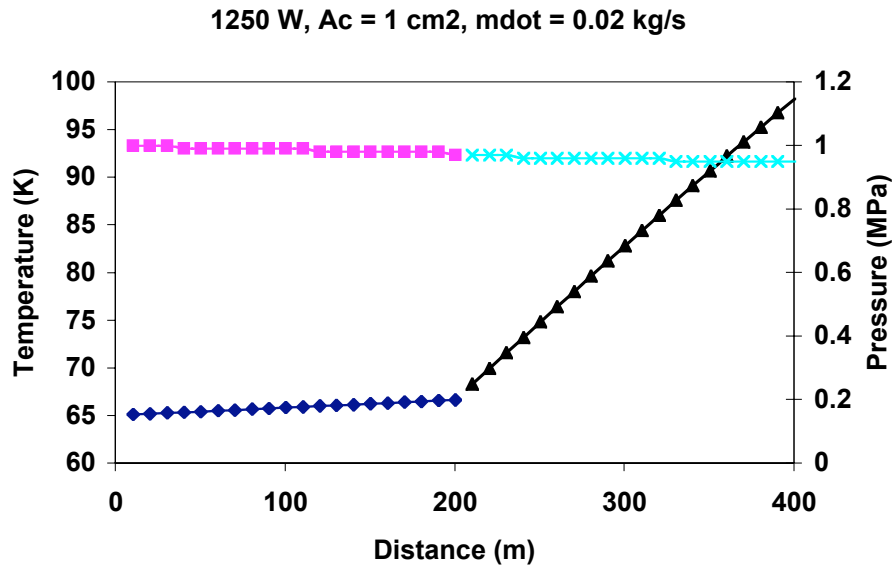


Figure 8. Temperature and pressure along the length of a SC distribution system, where the coolant first cools the superconductor, and the current leads.

Table 4. Comparison between base case (Figure 2), separate coolant (Figure 4) and go-

		Go and return			
		Base case	Only current lead	Low T	High T
Distributed load, total	W/m			6.26	6.26
\dot{m}	kg/s	0.1	0.1	0.02	0.02
A_c	cm^2	2	2	1	
T_{inlet}	K	65	95	66	67.7
T_{exit}	K	71.5	101	67.6	98.7
p_{exit}	MPa	0.9	0.91	0.97	0.94
Refrigerator power and-return	kW	21.5	13.1	1.1	17

VI. Heat exchanger considerations

Even in the case of liquid coolant, substantial cross sectional area may be required in order to transfer the heat from the current leads to the coolant. For the case of secondary feeders, areas on the order of 1000 cm^2 and coolant flow speeds of 0.10 m/s are

sufficient. For the primary feeder, carrying much more current, it is necessary to develop a heat exchanger that includes about the same area but much higher liquid nitrogen flow speed, on the order of meters per second. As the length of the heat exchanger is not large, the associated pressure drops are small. Thermal anchors at the cryogenic temperature with multiple holes or fins for increased cooling are desired. In both cases, the flow of the liquid nitrogen is in the direction from the superconductor to the copper in the current lead.

VII. Conclusions

In this report, several topologies for cooling superconducting distribution systems have been explored. The possibility of separating the cooling of the superconductor from that of the current leads has been explored.

It has been determined that the most attractive topologies include a separate cooling of the current leads, operating near the boiling temperature of the coolant, high pressure nitrogen. The superconductor is cooled through a separate path, using much colder coolant, with minimum temperature rise. The solution results not only in an attractive solution for cooling the superconductor and the current leads, but also in substantial reductions of the refrigerator power requirement and minimizing the use of expensive superconductor.

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