OPTIMUM OPERATING TEMPERATURE OF SUPERCONDUCTING CAVITIES

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Abstract

Superconducting radiofrequency (SCRF) cavities require cryogenic temperature to operate in the superconducting state where the RF power losses are extremely low. But this power has to be removed at very low temperatures using a refrigerator. While reducing the operating temperature results in lower losses for the cavities, it may severely impacts the cryogenic plant, drastically reducing its efficiency. On the other hand, the exponential dependence of the BCS surface resistance with temperature will ask for much higher refrigeration power at higher temperatures. Therefore, an optimum working temperature results, depending on frequency, accelerating field and cavity performance. This temperature should be determined by cost, performance, and risk minimization.

1 INTRODUCTION

While it is obvious that for frequencies over 1 Ghz, SCRF niobium cavities must operate in superfluid helium [1], the use of an intermediate frequency as 700 MHz for future proton linear accelerators requires a more thorough evaluation. For the sake of convenience, the APT (Accelerator Production of Tritium) high energy part [2] will be taken as an example. While reducing the operating temperature results in lower losses for the cavities, it severely impacts the cryogenic plant, reducing its efficiency (for example, going down from 2.0 K to 1.8 K will have a tremendous impact on the cryoplant's cold compressors, while achieving very little reduction of the cavity losses). On the other hand, a high operating temperature would require a very high-power refrigeration, due to the strong dependence of the BCS surface resistance with temperature (for example, operating at 4.5 K would require seven times more refrigeration power than for 2 K operation). Therefore, an optimal working temperature should exist in between these two limits.

2 COSTS ESTIMATION

2.1 Operation Cost

To properly optimize the operating temperature, all the items that may vary with this parameter should be taken into account. First, the two main items are the cryogenic plant and the electric power required to maintain the cryogenic temperature. The choice of the operating temperature will directly affect the total cryogenic power R required, which, in turn, will size the cryogenic plant. The AC electric power of the cryogenic plant can then be deduced using an overall efficiency η :

$$P_{AC} = \frac{R}{\eta} \qquad (1)$$

This will be the most important cost item in operation. The change in other operation costs of the cryoplant components (manpower, maintenance, etc.) will be assumed to be of second order when compared to AC power, and will be neglected here. Assuming a running time of 80% and an average price of (0.05 \$/kW$_e$h), the operating cost will amount to:

$$C_{op} = 0.35 \times P_{AC} \quad (\$/\text{year}) \qquad (2)$$

The total operating cost is obtained by multiplying C_{op} by the total lifetime of the accelerator.

2.2 Capital Cost

The change in capital cost C_{cap} with respect to operating temperature is assumed to be mostly due to the cryogenic plant. Green et al. [3] from Berkeley have estimated the capital costs of helium refrigerators and liquefiers based on a collection of existing systems, ranging from a few watts to 30 kW. They devised a simple formula[a] relating the cost C (in \$) to the refrigeration power R (in W)

$$C_{cap} = 12000 \left(\frac{\eta_{4.5K}}{\eta} R\right)^{0.7} \qquad (3)$$

$\eta_{4.5K}$ is the overall efficiency at 4.5 K.

These evaluations were mostly done for 4.5 K refrigerators of relatively small sizes. To take into account the additional needs for cold compressors while going to lower temperatures, a slightly modified formula will be used. The capital cost for one cryogenic system producing a refrigeration power R at temperature T will be taken as[b] :

$$C_{cap} = 3000 \left(3 + \frac{4.5}{T}\right) \left(\frac{\eta_{4.5K}}{\eta} R\right)^{0.7} \qquad (4)$$

If the accelerator requires an unusually large amount of refrigeration power, it will be assumed that the cryogenic plant is made of N identical cryogenic systems, each producing (1/N) of the total power.

$$C_{captotal}(R) = N \times C_{cap}(R/N) \qquad (5)$$

For APT, N = 3 will be taken. Although increasing the capital cost, this approach enables flexibility, enhances

[a] The factor has been adjusted to give the cryogenic power R in Watts.

[b] The temperature dependence should be theoretically already taken in account in the efficiency factor η. However, it will be assumed that the need for helium cold compressors will turn into additional costs higher than the efficiency ratios, taken here to increase linearly with (1/T). Whereas a lot of data points are available at 4.5 K, only a few are at 2 K (the most significant of these being CEBAF CHL).

availability, and relies on existing systems without requiring major technological developments.

2.3 Efficiency

The thermodynamic efficiency of the refrigerator system is roughly proportional to the ideal Carnot efficiency:

$$\eta_{Carnot} = \frac{T}{(T_a - T)} \qquad (6)$$

where T_a is the room temperature (generally taken as 310 K). Some systems can achieve up to 40% of Carnot efficiency. The efficiency goes up with size [3] and with temperature. If $\eta_r = \eta/\eta_{Carnot}$ is the ratio of the actual efficiency to the Carnot efficiency, the following approximate[c] formula will be used:

$$\eta_r = 0.035\ \mathrm{Ln}(R)\ \tanh(T/3) \qquad (7)$$

(In the case of a liquefaction mode, this efficiency is lower and has to be multiplied by a factor 75%±10%).
The overall efficiency will be:

$$\eta = \eta_r \cdot \eta_{Carnot} \qquad (8)$$

3 CRYOGENIC POWER REQUIREMENTS

The cryogenic power required is obtained by estimating the cryomodule heat loads which are the sum of the cavity losses plus a fixed heat flux amount (due to static losses, power couplers, transfer line losses, etc.). The latter losses (at the operating temperature T) are estimated for the time being to be around (10 W) per cavity in all cryomodules with an uncertainty of (± 5 W). Additional heat loads removed at the intercept temperature, assumed here to be 20 K, have to be added. Although these amount to roughly (80 W/cavity), they will play a minor role in the overall optimization and can be reasonably assumed to remain constant.

4 CAVITY LOSSES

Cavity losses will be the main item driving the optimization. The dissipated power in the cavity is :

$$P_d = \frac{V^2}{2R} = \frac{E_{acc}^2\, l^2\, R_s}{2(R/Q)\ G} \qquad (9)$$

where (R/Q) and G are both geometrical factors. E_{acc} is the accelerating field and l is the cavity accelerating length. Table I gives these numbers for the APT cavities. The surface resistance R_s can be calculated using the theoretical BCS value R_{BCS} (which increases exponentially with temperature) and adding a fixed residual resistance R_0 due to the residual static magnetic field, Q-disease, and surface impurities [4].

$$R_s = R_{BCS}(T) + R_0 \qquad (10)$$

[c] Ideally, this ratio should be almost constant. The variation with power is fitted from the curve given in [3]. The variation with temperature is extrapolated to other temperatures using a linear variation at low temperatures. The formula (7) used here is conservative.

The residual value is strongly dependent on the environment, as well as on the quality of the cavity niobium, fabrication, and preparation. An average value of (20 nΩ) will be taken with a uncertainty of ± (15 nΩ).

Table I - APT 5-cell Cavity Parameters

	E acc	l	(R/Q)	G
	(MeV/m)	(m)	(Ω)	(Ω)
β = 0.64	4,8	0,685	85,7	151
β = 0.82	5,5	0,878	134,0	208

5 TOTAL HEAT LOADS

Considering the above uncertainties, three different cases are labeled as "average," "best," and "worst." The "average" case will be most likely observed in the actual accelerator, if all the steps and procedures are properly followed. The "worst" case will give the maximum heat load that will drive the total refrigeration capacity, whereas the "best" case would be the minimum that could possibly be achieved. Table II summarizes the heat loads in each case, from which the required power for sizing the refrigerator and calculating the operating cost can be deduced.

Table II - Residual Resistance and Non-cavity Losses in the Three Cases Considered. (All powers are in Watts)

	AVERAGE	BEST	WORST
Residual resistance R_0(nΩ)	20	5	35
Cryomodule losses /cavity	10	5	15
Total Losses (excluding cavities)	4100	2050	6150

6 RESULTS

Cost results will be given for the three heat loads cases: worst, average, and best. Most of the conclusions will be given using data from the average case.

6.1 Capital Cost

First, the "worst" case will be used to size the needed refrigeration power R (including a 50% margin). That will determine the total capital cost C_{cap}, using equation (5). This cost, together with the refrigeration power R, is shown in Figure 1 for temperatures ranging between 1.8 K and 3.0 K.

Based exclusively on capital cost, the temperature giving the lowest cryogenic plant cost is 2.70 K. But that minimum is very broad (any temperature between 2.10 K and 3.40 K would be within 15% of that minimum cost, while the formula used should not be trusted to that accuracy). An operation at 2.0 K would result in adding 22% (13.2 M$) over the lower cost.

6.2 Operating Cost

As expected, the operating cost, shown in figure 2, strongly varies with the cavity losses. There is a significant cost difference between the "best" and the "worst" case (it more than doubles at 2.0 K). This reflects the importance of trying to increase the cavity quality factor Q. While the cost may widely change with cavity performance, there is no drastic variation of the optimum temperature. It increases from (2.00 K) in the best case to (2.50 K) in the worst, the average being (2.30 K). Again, this minimum is very broad and operating between (1.90 K) and (2.70 K) will only give less than 10% additional cost over the optimum.

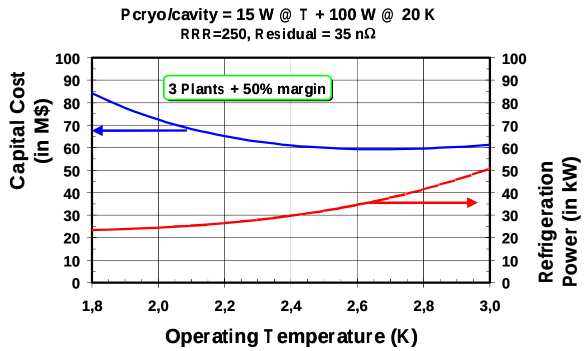

Figure 1 - Refrigeration power and capital cost as a function of the operating temperature.

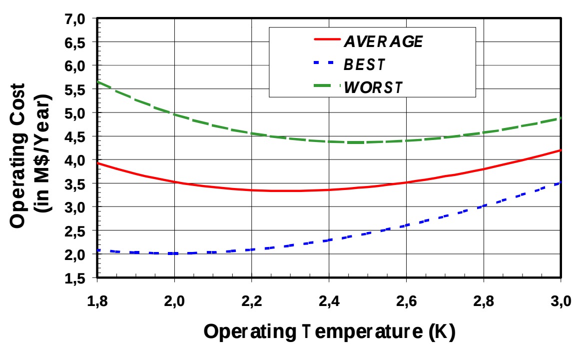

Figure 2 - Operating cost per year for the three cases considered.

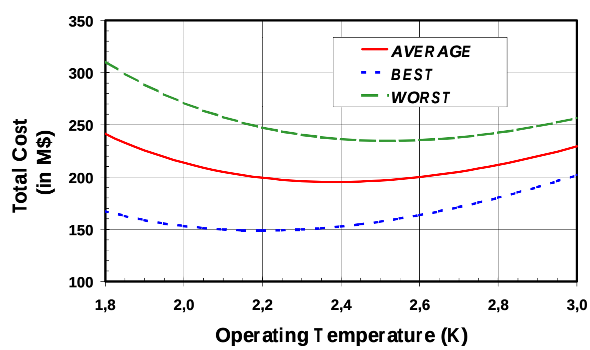

Figure 3 - Total cost for 40 years of operation.

7 TOTAL COST

The total cost is deduced by adding the capital to the operating cost integrated over the accelerator lifetime :

$$C_{Total} = C_{cap} + 40 \times C_{op} \qquad (11)$$

This total cost is plotted in Figure 3 as a function of temperature for the three cases. As expected, because the operation part amounts to 75% of the total cost, it will be driving the optimum temperature. The figures of the total cost (fig. 3) are very similar in shape to those shown in the preceding figure. The overall optimum temperature slightly shifts to higher values due to the lower capital cost. It moves from 2.20 K for the best case to 2.50 K for the worst, with a middle value of 2.40 K.

8 THE QUENCH FIELD

The above discussion implicitly assumes the cavities will reach the desired accelerating fields without any problem (no field emission, no quenches). But heat removal in a superfluid bath (He II at $T < T_{\lambda} = 2.17$ K) is much more effective than a normal liquid bath where nucleate boiling can occur that will limit the cavity performance at lower fields [5]. Boiling helium can also induce additional pressure vibrations that add to the microphonics induced in the SCRF cavities. This may result in a demand for additional RF input power which have to be carefully accounted for, as each additional 1% on the RF power is equivalent to adding 20% on the total cryogenic AC power. The expected quench field values in the normal fluid regime are around 50 mT as compared to more than 80 mT in superfluid helium. Therefore, superfluid operation can offer a much more comfortable margin in that respect. Moreover, the higher the helium temperature, the more heating one will have to extract from the RF surface, and the lower the quench field will be. This quench field issue is a very serious drawback that must be thoroughly addressed if operation above the λ point is decided.

9 CONCLUSION

The total cryoplant cost (including capital and operation) has been evaluated as a function of SCRF cavities temperature at a frequency of 700 MHz. The optimum operating temperature is found to be (2.4 ± 0.2) K. This optimum is broad and any operation between (2.0 K) and (2.8 K) would lead to less than a 10% excess cost. But operation in normal helium is risky, as performance may not even be achieved while gaining less than 3.5% on the total cost. Therefore, it is recommended that the operating temperature would be chosen in the superfluid helium regime (below 2.17 K).

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