CRYOGENIC OPTIMIZATION FOR CAVITY SYSTEMS

C. H. Rode
Continuous Electron Beam Accelerator Facility*
12000 Jefferson Avenue
Newport News, Virginia 23606

D. Proch
Deutsches Elektronen-Synchrotron
Notkestrasse 85
2000 Hamburg 52
Federal Republic of Germany

Introduction

Accelerator systems are being built with superconducting Nb cavities at 350, 500, 1500 and 2860 MHz; in addition cavities previously have been built at 1000 MHz. Cavity heat loads are a strong function of frequency and operating temperature, varying by more than an order of magnitude.

Heat Loads

The three primary sources of heat loads are static, temperature independent surface resistance (residual), and temperature dependent surface resistance (BCS). The main static components include bore tube, fundamental power coupler, and center anchor/tuners. The static heat load is typically 8 W/m at 500 MHz and varies approximately as the inverse of the square root of frequency.

The surface resistance is given by the equation

$$R_s = R_{bcs} + R_{res} = (Af^2/T)e^{(-17.67/T)} + R_{res}$$
$$\text{for } T < T_c/2 \text{ (4.6K)}$$

The first component, the BCS resistance (Bardeen, Cooper, Schrieffer), is due to the unbound Cooper Pairs of electrons. The second component is caused by localized resistive areas where defects, impurities, or surface dirt disturbs the superconducting properties. For f in MHz, we will use a value of $A = .000{,}028/(500)^2$ which neglects BCS surface resistance increases for high RRR material. Some of the predicted increases have not been observed, possibly due to surface work harding of the cavities.

The Q value is related to the surface resistance by a geometry factor G:

$$Q_0 = G/R_s \text{ and } 1/Q_0 = 1/Q_{bcs} + 1/Q_{res}$$

The geometry factor varies from 270 to 290 Ohms; we will assume an average value of 280. With the improved RRR material and clean room procedures we can achieve Q_{res} of better than 3×10^9.

The power dissipated per meter is given by the equation:

$$P = E^2/ZQ$$

P is power dissipated in W/m; E is average gradient in V/m; Z is shunt impedance in ohm/m; and Q is quality factor

The shunt impedance is typically 110 ohms per cell and drops off slightly with the frequency due to the non scaling of the bore tube diameter. A curve fit to existing cavities yields: $Z(\text{ohms/m}) = 380(f/500)^{.9}$.

We therefore get the approximate equation for total power in W/m: $P_t = P_{static} + P_{res} + P_{bcs}$.

$$P_t = \frac{8}{(f/500)^{.5}} + \frac{E^2}{380(f/500)^{.9}\, Q_{res}} + \frac{E^2\,(f/500)^{1.1}\,.000028\,e^{-(17.67/T)}}{380 \times 280T}$$

System Optimization

The compressor power P_w to produce refrigeration P_c is given by the equation:

$$P_w/P_c = ((300 - T)/T)/\text{efficiency}$$

As refrigerators become larger their efficiency increases and their unit capital costs decrease. The scaling factor for capital costs vary inversely with temperature and to the .7 power of heat load. For operating costs it varies inversely with temperature and to the .85 power of heat load; this is a doubling of efficiency for a factor of 100 in refrigeration.

If we assume $Q_{res} = 3 \times 10^9$ and operate at 5 MV/m, Figures 1 and 2 give us the scaling factors for refrigeration capital and operating costs as a function of temperature and frequency. The refrigeration costs at higher frequencies are noticeably less and we see much sharper minimums than at the lower ones.

Doubling the gradient has a minimal effect on the optimum temperature; lowering it by a tenth at the higher frequencies and a few tenths at the lower ones. If we assume a factor of two improvement in Q_{res} we see significant changes in the optimum temperatures (Figures 3 and 4). The optimum temperatures are 3.5 and 2.8 K for 350 and 500 MHz respectively.

Conclusions

350 MHz: For 5 MV/m the cavity is perfectly matched to standard refrigerators, 4.5 K output, both from a stand point of capital and operating costs. If we plan for future systems at higher gradients and Qs, the optimum is 3.5 K; but it may be worth the extra costs of 1 and 6% respectively to not run subatmospheric.

500 MHz: While at 5 MV/m, 4.5 K is way above the operating costs optimum; it is clearly the correct temperature since the cost penalty is only 3%. Figure 1 shows that it has

* Supported by the U. S. Department of Energy under contract DE-AC05-84ER40150

the same capital costs at 4.5 as the 350 MHz cavities. For future systems at higher gradients and Qs with penalities of 16 and 32% for capital and operating, one clearly will use a subatmospheric system. This would require a minimum of one stage of cold compression.

1000 MHz: At both 5 and 10 MV/m this is a good frequency choice if one wants to stay above the Lambda line (2.2 K). It requires either two or three stages of cold compression.

1500 MHz: At 5 MV/m one can operate on either side of the Lambda line; for future systems one must be below the line. CEBAF has chosen 2.0 K in order to be in a position to make use of higher gradients and Qs, and uses four stages of cold compression.

2860 MHz: This frequency is always pushing the lowest practical temperature, but it has the lowest costs.

Optimum gradient and frequency: Figures 5 and 6 represent the minimum value for ten year total cost for 1000 MV for Q_{res} of 3 and 6 10^9 at given gradient (and frequency) and optimum temperature. Total costs include accelerating structure, refrigerator capital costs, and refrigerator operating cost (power). We assume \$200 K/m for the accelerating structure, \$.05/kw-hr, and the CEBAF refrigerator cycle. We are neglecting tunnel and other related costs. Also we are not including fixed costs (e.g. operating labor, maintenance, RF power). At Q_{res} of 3 10^9, 7 MV/m is the optimum for lower frequencies and 10 MV/m is for high ones; these optimums increase roughly with the square root of Q_{res}.

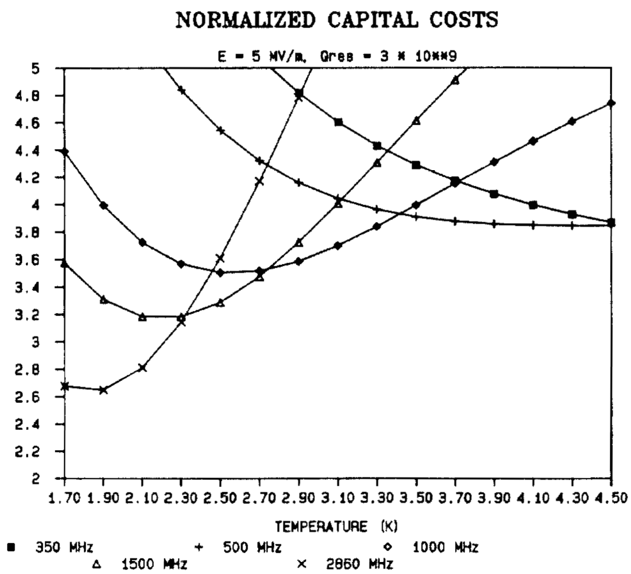

Figure 1: Scaling factor for refrigeration capital at 5 MV/m and $Q_{res} = 3 \times 10^9$.

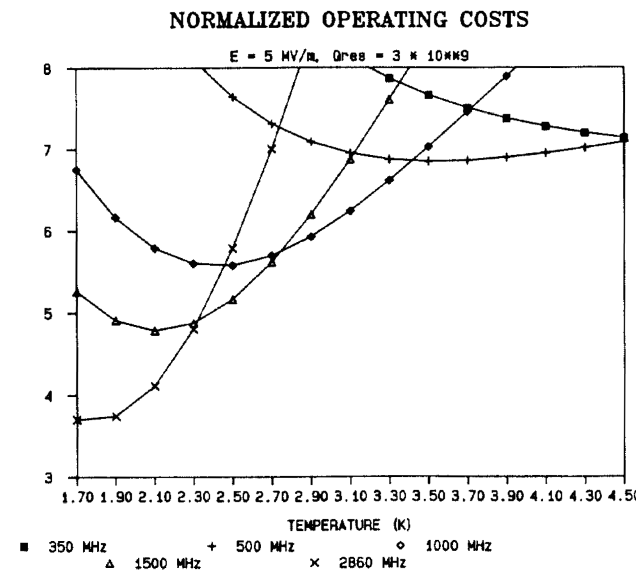

Figure 2: Scaling factor for refrigeration operating costs at 5 MV/m and $Q_{res} = 3 \times 10^9$.

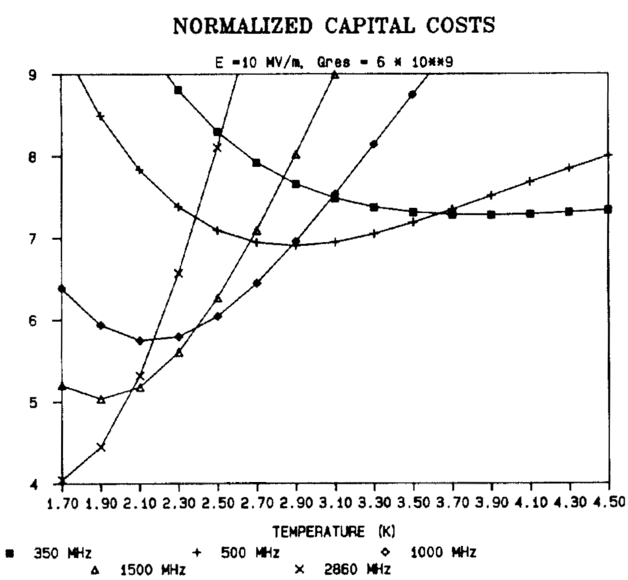

Figure 3: Scaling factor for refrigeration capital at 10 MV/m and $Q_{res} = 6 \times 10^9$.

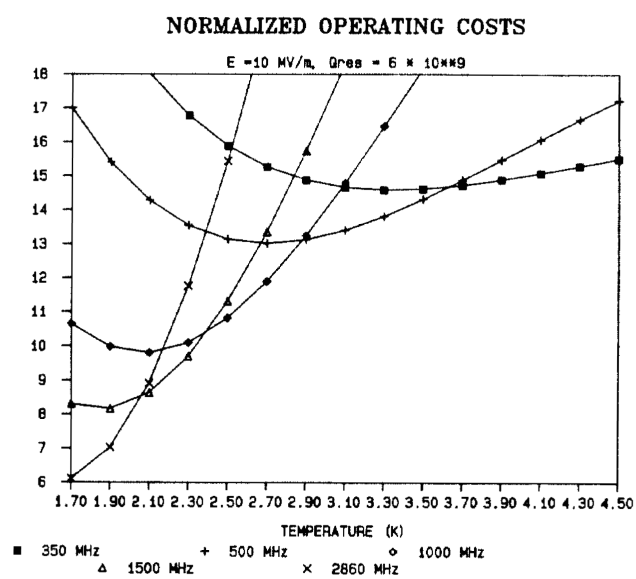

Figure 4: Scaling factor for refrigeration operating costs at 10 MV/m and $Q_{res} = 6 \times 10^9$.

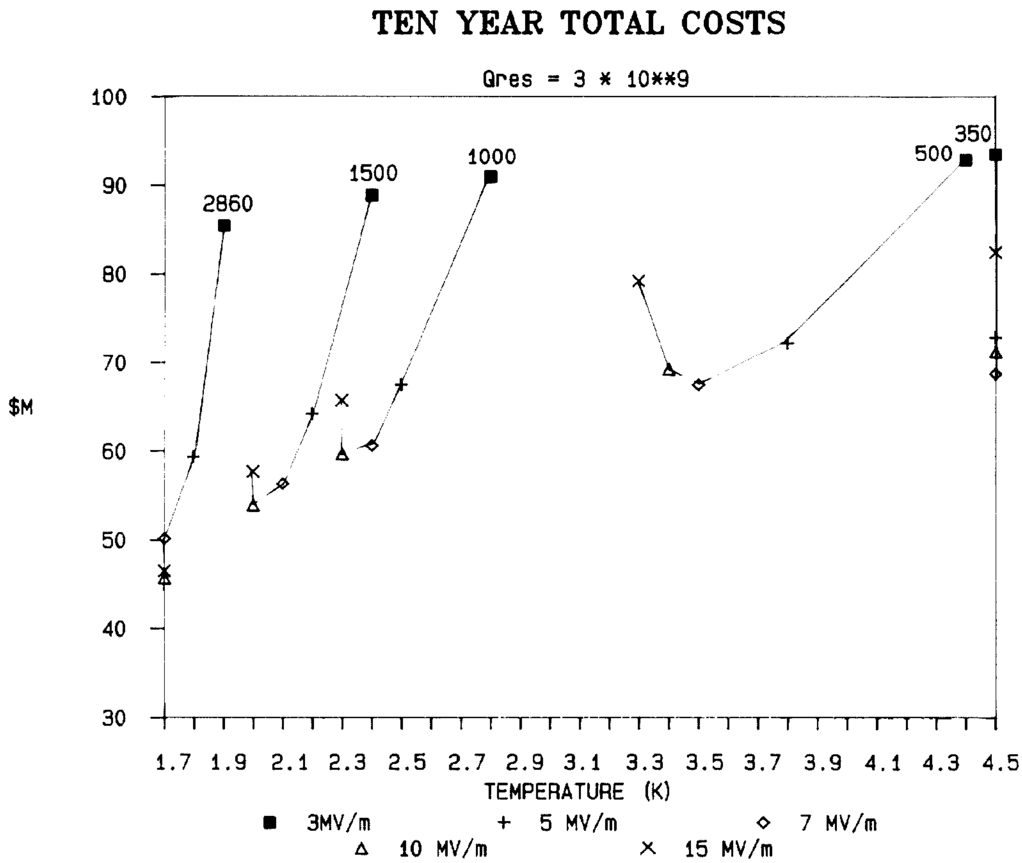

Figure 5: Minimum ten year total costs at $Q_{res} = 3 \times 10^9$ for 1000 MV.

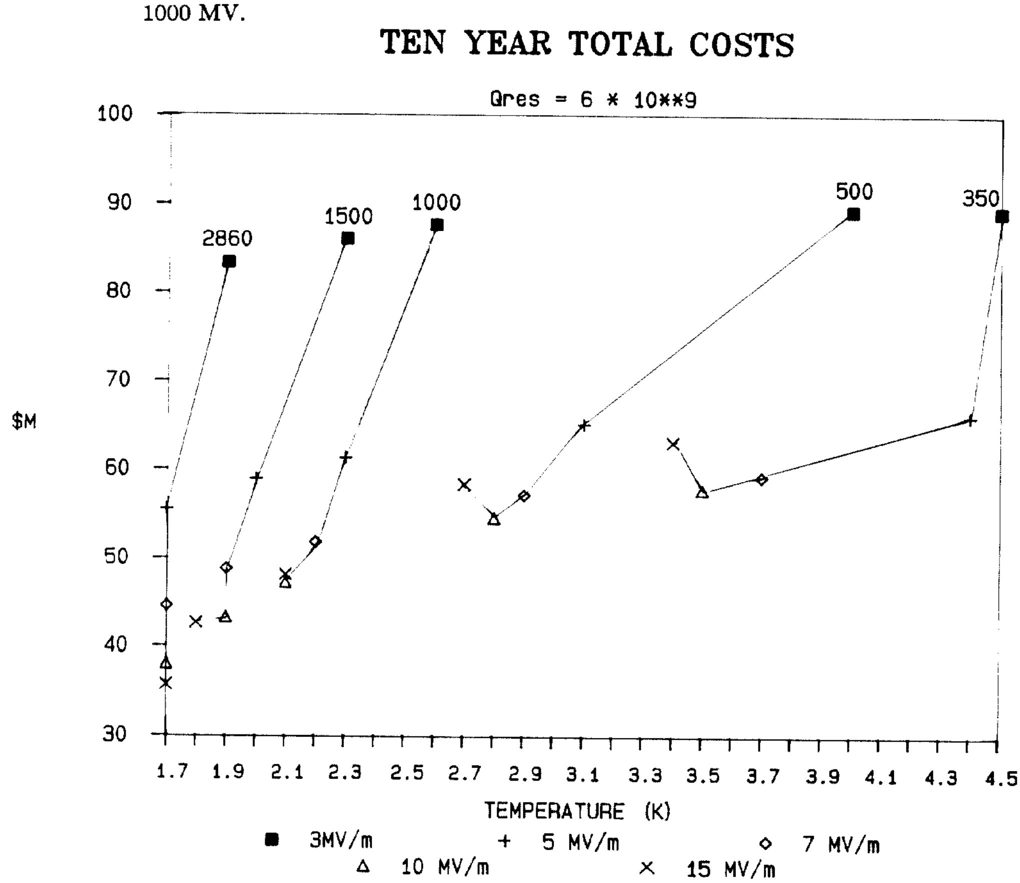

Figure 6: Minimum ten year total costs at $Q_{res} = 6 \times 10^9$ for 1000 MV.