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AN OPTIMIZED INPUT WAVEGUIDE FOR THE CEBAF SUPERCONDUCTING LINAC CAVITY

Paul Brindza, and George Biallas, CEBAF
L. Phillips, Cornell University
Continuous Electron Beam Accelerator Facility
12070 Jefferson Avenue
Newport News, VA 23606

Abstract

A thermally optimized input waveguide for the CEBAF Superconducting Linac Cavity, to operate at 2.0K, has been designed. Calculations leading to thermal optimization including conduction, specularly reflected radiation and RF power dissipation are presented. An economic comparison between a thermal intercept and continuous counter flow cooling has been made. Calculations and techniques for reducing specularly reflected radiation are discussed.

Introduction

The CEBAF superconducting linear accelerator[1] consists of 400 niobium cavities operating at a gradient of 5 MeV/meter. These cavities have an operating temperature of 2K which was chosen on the basis of overall economic optimization and operating heat loads.[2] The principle (75% of the total) heat loads are due to the RF and therefore techniques to reduce RF related heat loads are especially important. The CEBAF cavities[3,4] utilize a rectangular waveguide from ambient temperature to supply RF power at 1500 MHZ to excite the cavities. This waveguide is fabricated from thin walled stainless steel to minimize conduction with a 2μ thick copper plating to reduce RF dissipation. Thus the power dissipation is separated from the heat conduction and a more stable design obtained. The waveguide thus serves the same purpose as power leads for magnets and requires a proper design to achieve optimized performance. The waveguide heat load is due to conduction, direct and specularly reflected radiation and RF power dissipation. The effects due to conduction, RF dissipation and helium cooling have been analyzed in closed form and by numerical calculation, while the radiation has been analyzed for average ray "Monte Carlo" type technique. (Fig. 1)

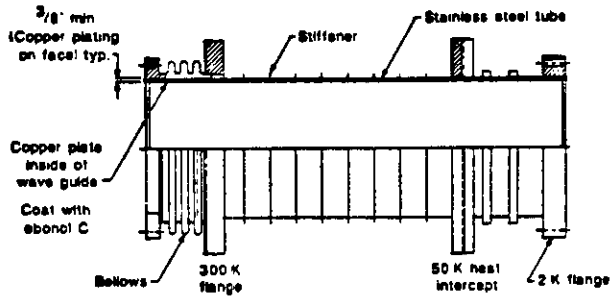

Figure 1 1500 MHz Input Waveguide for CEBAF

The case of single level thermal intercept style cooling has been compared to continuous counter-flow type cooling for the CEBAF waveguide. The results of an economic comparison lead to the selection of an intercept cooled design. A significant contribution to the loss from the waveguide is the funneling of 300K radiation by the relatively reflective walls. Calculation of this loss due to reflections from walls with emissivity characteristics of electroplated copper and for copper with an ebanol coating were performed. Measurement of the thermal performance of these waveguides with RF will be made to test the effectiveness of the ebonol coating to reduce the radiation losses. This waveguide design has been incorporated into the CEBAF production cavity-cryostat design.

Fundamental Coupler Cooling

The fundamental coupler waveguide has an internal power dissipation due to RF losses, which average to 0.2 W/cm for 2400W input power, typical for a full intensity beam. The variation in power dissipation vs temperature is very slight due to the anomolous skin depth effect and is thus ignored. The standing wave nature causes a small spatial variation on the order of 10% and this averages to 0.2 w/cm. The power input into the cavity cryostat at 2K in the absence of any other cooling is given by:

$$Q = \frac{kA}{L}(T_H - T_c) + \frac{1}{2} Q_2 \qquad (1)$$

$$Q = \frac{kA}{L}(T_H - T_c) - \frac{1}{2} \cdot Q_2 \qquad (2)$$

where $Q_2 = qL$. It can be seen that as Q_2 increases the cold end load increases and eventually one reaches a critical value where Q_{hot} is equal to zero. This means that the power dissipated in the waveguide is sufficient to supply all of the heat which leaves the cold end and thus Q_{hot} is zero. Increasing Q_2 beyond this point leads to a situation where the maximum temperature is somewhere along the length. There are two important conclusions here. First, the high temperature implies that one is closer to being unstable due to thermal runway. Second, it is clear that the length has not been chosen to the optimum value if the temperature exceeds 300K at some place other then the end. The optimal length can be derived by minimizing the power into the cold end resulting in

$$L = \sqrt{\frac{2Ak(T_H - Tc)}{q}} = 27.8 \text{ cm} \qquad (3)$$

$$Q_{cold} = 5.5W$$

where $K\ (T_H - T_c) = \int_{T_c}^{T_H} K dT = 30.6$ w/cm/k (4)

Table 1. Waveguide Characteristics

$q = (0.2)$ W/cm

$L = 35$ cm

$A = P \times Th = 2.53\ cm^2$

$P = 31.89$ cm

$Th = 0.079375$ cm (1/32 in)

$K = 0.1$ w/cm/k (304 st. stl.)

Coating = 2μ Copper

Waveguide With a Fixed Temperature Intercept

A popular method of reducing the heat load to devices with internal generation of power and conduction is to fix the temperature of an advantageously chosen position along the length. The resulting solution is just a pair of equations with appropriately chosen boundary conditions and lengths for the cold end temperature T_c and the warm end temperature T_w.

$$T_c = T_o + \frac{T_I - T_o}{l} + \frac{ql}{2K_c A} x - \frac{ql}{2K_c A} x^2 \quad (4)$$

$$T_w = T_I + \frac{T_H - T_I}{(L-l)} + \frac{q(L-l)}{2K_w A} \cdot (X-l) - \frac{q}{2K_w A} \cdot (X-l)^2 \quad (5)$$

$T_o = 2$ K, $T_I = 50$ K, $T_H = 300$ K (Fig.2)

$$K_c (T_I - T_o) = \int_{T_o}^{T_I} K dT = 1.3 \text{ w/cm}$$

$$K_w (T_H - T_I) = \int_{T_I}^{T_H} K dt = 29.3 \text{ w/cm}$$

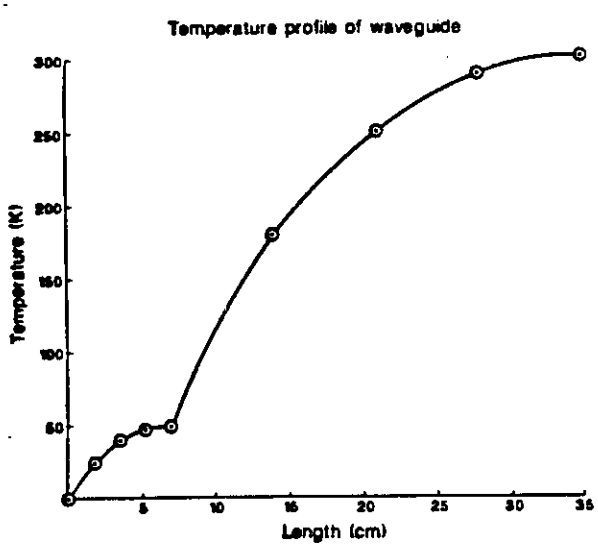

Figure 2

The power into 2K and 50K are as follows

$$Q_2 = K_c A \frac{dT_c}{dX}\Big|_o = \frac{AK_c}{l} (T_I - T_o) + \frac{ql}{2} \quad (6)$$

$$Q_{50} = Q_c(l) + Q_w(l) =$$

$$\frac{K_c A}{l} (T_I - T_o) - \frac{ql}{2} + \frac{K_w A}{(L-l)} (T_H - T_I) + \frac{q}{2}(L-l) \quad (7)$$

The lengths l and (L-l) are chosen to separately minimise the power dissipated at 2K and 50K respectively.

$$l = \sqrt{\frac{2A}{q} K_c (T_I - T_o)} = 5.84$$

$$(L-l) = \sqrt{\frac{2A}{q} K_w (T_H - T_I)} = 27.23 \text{ cm}$$

$Q = 1.168W$

$Q = 5.45W$

Helium Cooled Waveguide

The classic method of reducing heat loads in cryogenic systems for devices which bear both internal power dissipation as well as conduction is to bleed a small amount of helium to intercept the heat. This has the effect of adding a heat exchanger to the waveguide, and the overall power balance must now include the extra load on the refrigerator due to the effect of helium being returned at 300 K, which is a pure liquifier load.

Therefore, we have

$$Q = Q(\dot{m}) + Q(\dot{m})$$

Heat Leaks	Refrigeration Load
[decreases]	[increases]

with increasing $\dot{m}$

and one can find an optimum. This optimum should be compared with the economics of actually accomplishing the operating cost savings, if any.

The load factor from helium refrigerators is usually cited as 3W ≈ 1 l/hr. This means that at constant efficiency the same refrigerator can absorb either 3 Watts at its output temperature or produce 1 l/hr. The operating cost of liquifaction is slightly higher due to increased LN consumption and must be considered in the final economic analysis.

Equation (5) becomes:

$$\delta \left[kA \frac{dT}{dx} \right] + q\, \delta X - hp\, (T - T_{He})\, \delta x \quad (8)$$

with an auxiliary equation to describe the helium

$$hp\,(T - T_{He})\delta x = \dot{m}c\,dT_{He} \qquad (9)$$

Equations (8) and (9) may be combined and the dependent variables T and T_{He} decoupled without qualifying assumptions. This results in two equations which may be easily solved.

The waveguide equation is

$$KA\frac{d^2T}{dx^2} - \frac{hpkA}{\dot{m}c}\frac{d^2T}{dx^2} - \frac{hpdT}{dx} + \frac{hp}{\dot{m}c}\frac{Q_x}{L} = 0 \qquad (10)$$

Where solution is T(x) = (12)

$$\frac{Q_x X}{\dot{m}cL} + \left[\frac{300 - \frac{Q}{\dot{m}c} - 2e^{a_- L}}{e^{a_+ L} - e^{a_- L}}\right]\left(e^{a_+ x} - e^{a_- x}\right) + 2e^{a_- x}$$

Exponent $a_\pm$ = (13)

$$-\frac{hp}{2\dot{m}c} \pm \sqrt{\left(\frac{hp}{2\dot{m}c}\right)^2 + \frac{hp}{KA}}$$

Heat Leak Q = (14)

$$KA\frac{dT}{dx}\Big|_o = KA\left\{\frac{Q}{\dot{m}cL} + \left[\frac{300 - \frac{Q}{\dot{m}c} - 2e^{a_- L}}{e^{a_+ L} - e^{a_- L}}\right](a_+ - a_-) + 2a_-\right\}$$

The film coefficient for the mass flow range near .005 gm/sec may be evaluated from the following correlation due to McAdam's for Turbulent flow in a small (1/16") diameter tube.

$$h = \frac{.023K}{D}\,[NR]^{.8} \cdot [NPr]^{0.4} = .0027\,w/cm^2/K \qquad (15)$$

For $\dot{m}$ = .005 gm/sec

The total heat load including refrigeration load is

$$Q = \frac{KA}{L}(300-2)\left[\frac{\eta}{e^{\eta}-1}\right] + \qquad (16)$$

$$\frac{(qL)}{\eta}\left[1 - \frac{\eta}{(e^{\eta}-1)}\right] + \frac{\dot{m}}{\dot{m}_o}(.3724) \text{ Watts}$$

where

$$\eta = \frac{\dot{m}cL}{KA}, \quad \dot{m}_o = .005 \text{ gm/sec}$$

Figure (3) is a plot of equation (16) compared to the intercept value.

For all values of mass flow, the simple intercepted waveguide is the lower heat load choice and the best design solution.

Numerical Analysis

A numerical technique was employed to investigate the waveguide behavior and two cases were fully examined.

Case I: The incident power is 2400 watts with a reflected power of 400 watts. (High intensity beam)

Case II: The incident power is 1500 watts all of which is reflected. (Weak beam)

The stainless steel was taken as constant thermal conducting for the portion above 50K and modeled at $K=4.88 \times 10^{-4}\,T^{(1.23)}$ for T<50K. The heat flow was calculated into the 2K and 50K points for various combination of length until a minimum was found. Variations in the RF dissipation with length and temperature were ignored for this calculation due to their insignificance.

The calculational technique was an iterative one in which the waveguide is divided in N section.[5] A trial heat input at the warm end is chosen and the cold end temperature calculated by requiring net heat balance in each element. The trial heat input is varied until the descent temperature is reached. A minimum at about 7 cm in the heat dissipated is obtained for each case. (Fig. 4 & 5)

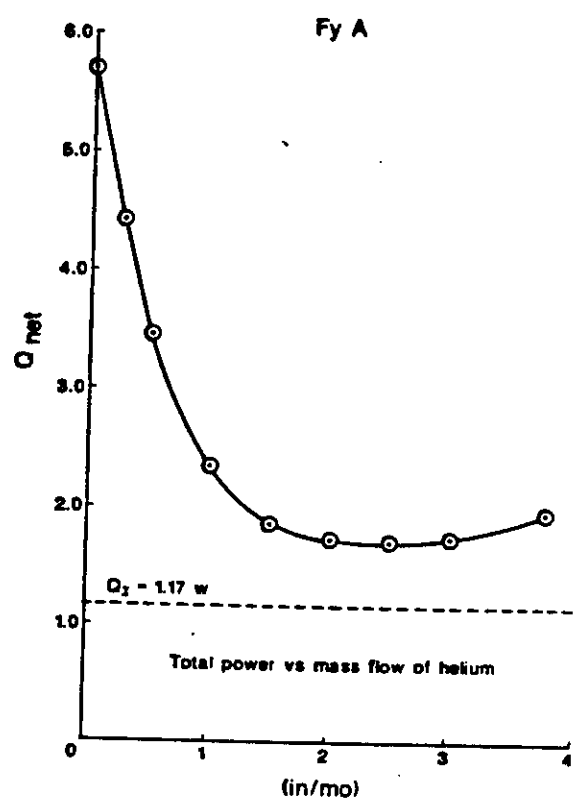

Figure 3 Power vs. Mass Flow of Helium

Black Body Radiation and Specular Reflection

The waveguide is an open rectangular duct with smooth, partially reflecting walls. Radiation entering from the 300K flange can propagate down by reflection and wall emissions to the 2K cryostat. Since the walls with a copper coating have an emissivity of 0.1 they are partially absorbing and the radiation is dissipated. The design calls for a thin "Ebanol" coating to further raise the emis sivity to 0.3. This coating is thin relative to the skin depth for the 1500 GHz input RF. A finite average ray "Monte Carlo" type calculation was performed to propagate rays down the waveguide and account for the power dissipated.

The average ray from a uniform hemispherical source is at 30° polar angle. Due to the rectangular nature of the waveguide four angles in the plane of the emitter were propagated. One each normal to the sides and 22 1/2° from each normal ray. A weighted average of 18 bounces was calculated. The total power leaving the 300K emitter was 1.34 watts and of this 0.023 watts was directly transmitted to 2K.

An additional 0.06 watts is emitted from the walls and propagated down to 2K while a totally negligible amount is absorbed below the 50K intercept and conducted down. The total additional power absorbed at 50K due to Black Body Radiation is 1.3W.

Conclusion

The CEBAF waveguide as designed appears to be a very stable well optimized solution. The final heat load into 2K is quite insensitive to variations in the intercept temperature and varies only slightly with changes in the power dissipated on a reasonable range.

Techniques to reduce the spectral radiation component have been incorporated into the final design. There are 8 waveguides of this design under construction and their performance will be measured along with the other properties of the CEBAF cavity and cryomodule.

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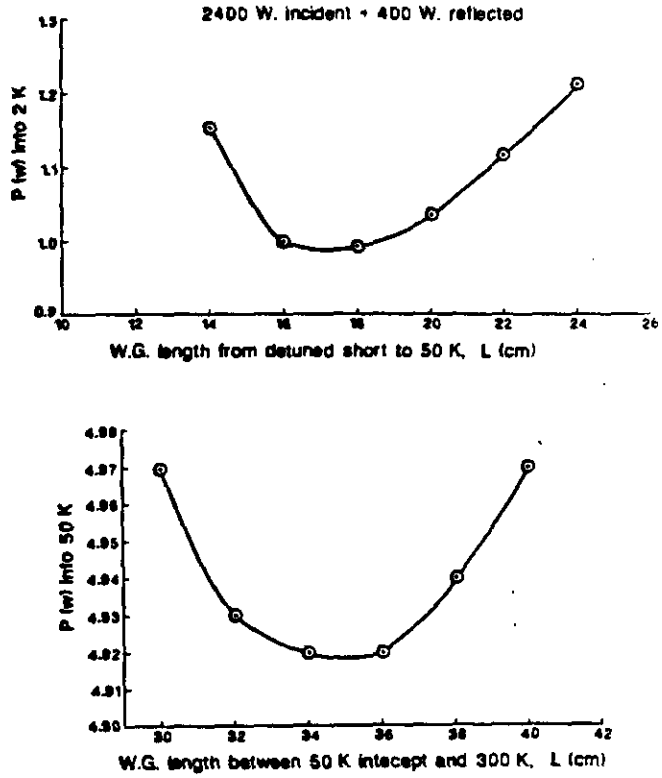

Figure 4

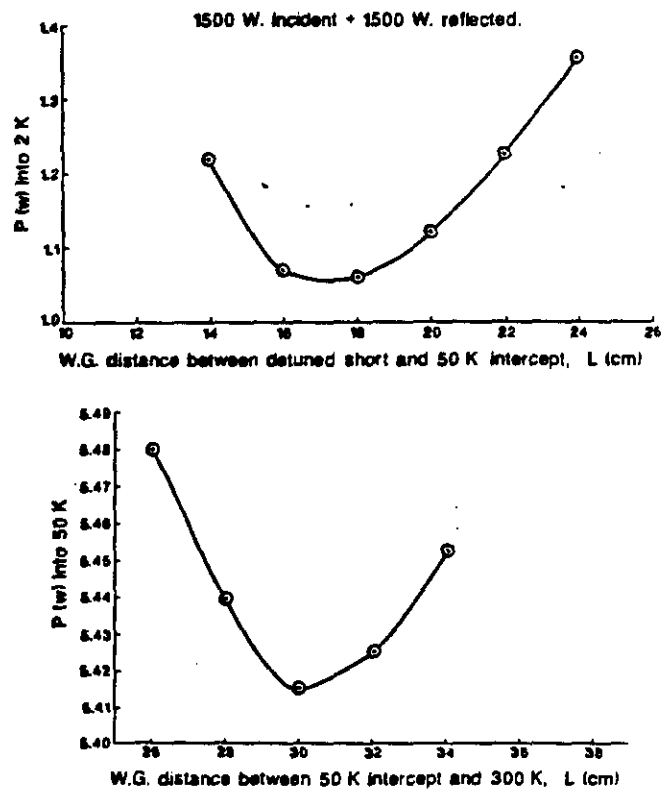

Figure 5