Superconducting Nb Accelerating Structure for a 50-MeV mm-wave Linac*

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Abstract

A planar doubled-sided muffin-tin structure is being studied as a possible candidate for a 120-GHz accelerator structure fabricated using the deep etched x-ray lithography and micromachining technique (LIGA). Thermal analysis has shown that a superconducting cavity using a thin Nb film on a copper structure will lower the power dissipation by several orders of magnitude. In this paper the various relevant parameters of the proposed superconducting cavity, such as the surface impedance, the shunt impedance, the unloaded quality factor, and the unloaded peak power, at very high frequencies, are discussed.

1. Introduction

The merits of superconducting Niobium cavities are considered for a 50--MeV mm-wave electron linac at the Advanced Photon Source (APS) [1]. A CW-operated accelerator has more to offer than those operated in pulsed modes, and the production of a low-energy continuous beam by the proposed micro-linac can be achieved by use of a superconducting accelerating structure.

The advantage of superconductors, compared with conventional conductors, resides in their lower surface resistance, even at very high frequencies [2].

Niobium is often used for accelerating structures because it has high transition temperatures, T_c=9.25°K, and a high critical field [3]. Structures can be made of copper, which is well suited for microfabrication techniques, and coated with a thin layer of niobium. Moreover, the high-purity of niobium treated with yttrium [3] is no longer limited by a defect-induced instability, but its field is limited by electron field emission.

2. Parameter Calculations

The rf parameters for a planar doubled-sided muffin-tin 120-GHz copper structure were calculated using the MAFIA code [4]. Table 1 compares these parameters for a copper cavity and a Nb-coated copper cavity operated in the $2\pi/3$ mode at 120 GHz.

The power lost in the walls of one cavity (P_c) can be evaluated from the accelerating gradient (E_{acc}) expected from the rf structure, its shunt impedance (R_{Sh}), and the length of one cavity (l):

$$P_c = E_{acc}^2 l / 2R_{Sh}.$$

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Table 1. Comparison of muffin-tin cavities operated in the $2\pi/3$ mode at 120 GHz, using normally conducting copper and superconducting niobium at 4.22°K

Parameter		Unit	Copper	Niobium at 4.22°K
Surface Resistance	R_s	Ω	9×10^{-2}	4.62×10^{-4}
Unloaded Q	Q_0		2160	4.21×10^{5}
Shunt Impedance	R_{Sh}	MΩ/m	312	6.08×10^{4}
Peak Power	P_0	W	29×10^{3}	146

The surface resistance (R_s) of the cavity and the corresponding power losses (P_c) at various Nb temperatures are shown in Figure 1. The straight line indicates the level of surface resistance and power losses in the case of room temperature copper cavities. These data show that the reduced temperature influences the surface resistance strongly. It is desirable to operate a superconducting accelerator at the lowest possible temperature.

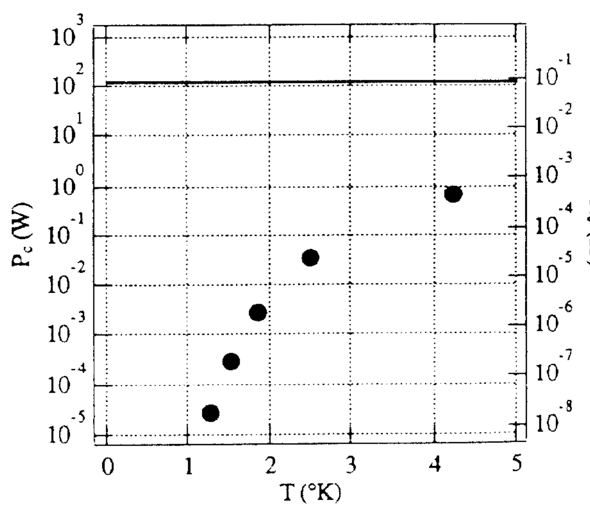

Figure 1. Surface resistance R_s of the cavity walls and the corresponding power losses P_c of one cavity, at various temperatures of superconducting niobium.

The shunt impedance of a copper cavity has been calculated numerically (Table 1). Assuming that we keep the same geometry of the cavity and the same fields, the shunt impedance (R_{Sh}) of the Nb-coated structure was extrapolated using different surface resistances at different temperatures:

$$R_{sh} = \left| \int_l E_z e^{-j\beta z} dz \right|^2 \Big/ \int_A |H|^2 R_s da,$$

where the numerator and the denominator represent, respectively, the square of the energy gain through a cavity and the power losses on its walls.

The unloaded Q, Q_0, has been calculated using MAFIA, for the copper structure [1]. If the same geometry is used with different conductors, the unloaded Q depends only on the surface resistance and $Q_0 = G/R_s$, where G is the geometry factor which remains constant. Knowing the surface resistance of the Nb structures for the various temperatures, yields the Q_0 values.

The unloaded quality factors and shunt impedances of the accelerating structures at various temperatures (4.22, 2.5, 1.85, 1.5, and 1.25°K) are shown in Figure 2.

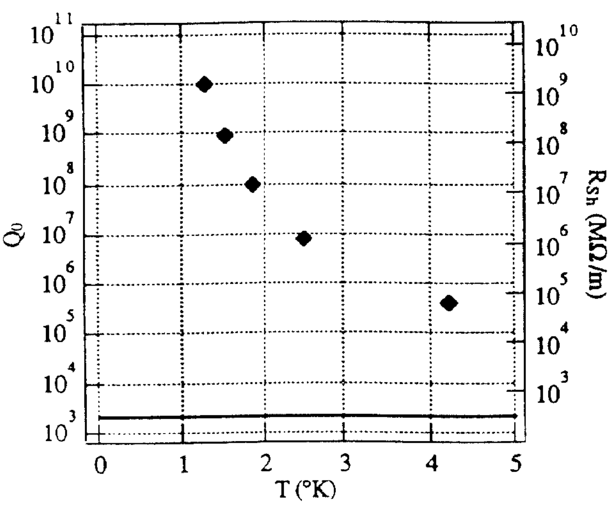

Figure 2 Unloaded quality factor Q_0 and shunt impedance R_{sh} of the accelerating structure, at various temperatures for superconducting niobium.

The straight line indicates the quality factor and the shunt impedance in the case of a conventional copper structure, and shows a considerable improvement in Q of superconducting cavities over that of a copper structure at room temperature. The shunt impedance for the acceleration is very high for superconducting niobium and so is the total efficiency (η) of rf-to-beam power conversion [5]:

$$\eta = \frac{1}{\left[1 + V/(2R_{sh}I_b)\right]}.$$

3. THERMAL ANALYSIS

For conventional linear accelerators, the problems caused by the thermal load due to rf power losses are minimal. For example, the linear accelerator in use at the Advanced Photon Source at Argonne has a thermal loading of approximately 0.4 W/cm^2 and can be efficiently cooled and stabilized using conventional techniques. Due to the smaller dimensions of the proposed mm-wave linear accelerator, thermal loading issues become important. Operated at room temperature in a traveling wave 2π/3 mode, the proposed device has an average heat flux of approximately 80 W/cm^2 when pulsed at only a 1% duty cycle. In order to efficiently cool the device to reasonable levels, more advanced cooling techniques such as microchannels are necessary.

Coating the proposed device with a thin layer of niobium and operating it in a superconducting mode considerably lowers the heat flux. This heat flux reduction, which is directly proportional to the decrease in surface resistance, significantly reduces the cooling requirements. However, the decreased heat flux is offset by the fact that the maximum allowable temperature rise is severely restricted due to the strong temperature dependence of the surface resistance. These conditions can lead to a thermal runaway effect where the device rapidly heats up and loses it superconducting properties.

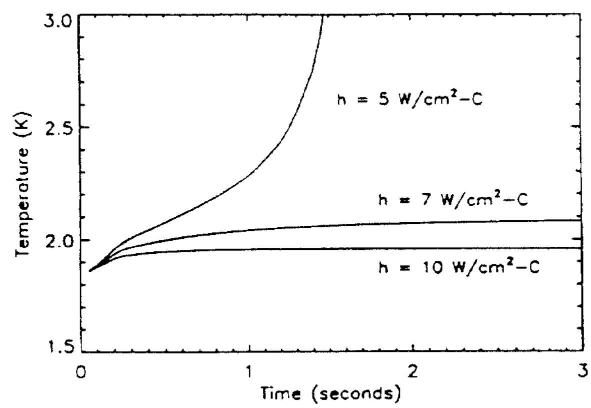

Figure 3. Typical increases of the maximum temperature, as a function of time for various effective film coefficients.

The thermal behavior of the structure was investigated using a finite element model. A 2π/3 standing wave structure operating at a 100% duty cycle was considered. The temperature dependent heat load was accounted for by using a transient analysis where the heat load was updated as a function of resistance after each time step. We used a surface resistance at 120 GHz as a function of temperature given by:

$$R_s = 2.52 \times 10^{-6} + 7.91 \times 10^{-2} e^{-2.01 T_c / T} \qquad (1)$$

where T_c is the critical temperature of niobium and T is the local temperature. The typical increases of the maximum temperature, as a function of time, for various effective film coefficients are shown in Figure 3.

In order to avoid thermal runaway problems, substantial cooling must still be used. However, when compared to the room temperature case, a much higher duty cycle may be used.

4. FUTURE DEVELOPMENTS

The power source for the continuous 50-MeV micro-linac with superconducting niobium cavities is being studied. It is a 120-GHz continuous traveling wave amplifier which will be micro-fabricated using the deep etched x-ray lithography and micromachining technique (LIGA). Since power requirements are lowered when using superconductivity, the proposed miniature tube is a possible candidate for the power source.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] A. Nassiri, R. L. Kustom, F. E. Mills, Y. W. Kang, A. D. Feinerman, H. Henke, P. J. Matthews, T. L. Willke, D. M. Grudzien, J. Song, and D. Horan, "A 50-MeV mm-wave Electron Linear Accelerator System for Production of Tunable Short Wavelength Synchrotron Radiation," IEDM, Washington DC, 1993.

[2] P. Wilson, "The Theoretical Surface Resistance for Superconducting Lead and Niobium at High Frequencies," SLAC-TN-70-35, December 1970.

[3] S. Turner, "Superconductivity in Particle Accelerators," CERN Accelerator School, Hamburg Germany, May 30- June 30 1988.

[4] Y. W. Kang, H. Henke, and R. L. Kustom, "A mm-wave Planar Microcavity Structure for Electron Linear Accelerator System," 1993 Particle Accelerator Conference, Washington DC, May 1993.

[5] W. Weingarten, "Superconducting Cavities," CERN/AT-RF 91-9, July 1991.