ENERGY GRADIENT LIMITS IN ROOM TEMPERATURE CW LINACS

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Summary

The average energy gradient is an important parameter in designing cw room temperature structures. This paper shows how to determine the power handling capability of room temperature structures using thermal stress and mechanical strain analysis. Energy gradient limits are shown to be related to the yield strength of OFHC copper. Results of the calculations are compared with measurements on S-band structures. In addition, scaling laws for designing high power room temperature structures are derived and discussed.

Introduction

Significant developments in the design of room temperature and superconducting linear accelerator structures have taken place. Much of the cw design effort has been directed towards increasing accelerating field gradients to reduce the length of beam recirculating systems. Average energy gradients of 2.0 MeV/m have been obtained in an S-band room temperature structure[1] and the MUSL-2 accelerator[2], using a superconducting linac, is routinely operated at an average energy gradient of 2.2 MeV/m. In parallel to these experimental achievements, design tools for rf cavities have evolved considerably: cavity surface temperature distributions and the resulting loss in shunt impedance can be predicted with computer codes such as PANT[3] or DOT[4]. Temperature distributions, thermal expansion and thermal stresses can be calculated with the computer code MARC[5]. In addition, the shift in operating frequency and the change in stopband frequency gap of a biperiodic structure as a function of rf power can be estimated accurately[6].

The design of high power cw structures is one of the accelerator development research programs undertaken at the Chalk River Nuclear Laboratories (CRNL). Different types of structures have been constructed and high power tested at CRNL. The experimental work has evolved simultaneously with a theoretical understanding of observed behaviour. This paper describes calculations of average energy gradient limits in room temperature cw linacs based on a thermal stress analysis using the finite element computer code MARC. The yield strength of annealed oxygen-free high-conductivity (OFHC) copper is used as the upper stress limit before a permanent cavity deformation occurs. A frequency scaling law for the onset of permanent deformations is derived based on the rf efficiency of cavities.

Thermal Stresses and Thermal Detuning

In a biperiodic system, a change in the stopband frequency gap results from a difference in the power distribution cavity to cavity and the relative sensitivity to dimensional changes of the accelerating and coupling cavities[6]. Measurements of the field distribution at high power[7] and calculations with the coupled RLC loop model computer code LOOPX[8] indicate that for well cooled structures, field differences cavity to cavity resulting from a change in the stopband frequency gap are usually smaller than the field variations associated with machining tolerances during fabrication and assembly of cavities.

Thermal stresses in a high power cavity result from a temperature gradient along the web between the beam aperture region and the outer wall. Such stresses are responsible for the deformation of the web in an on-axis coupled structure leading to detuning at high power[6]. When stresses exceed the yield strength, the material exhibits a permanent deformation and the low power resonant frequency is changed. Thus if a structure's cooling system eliminates temperature gradients, the structure's power handling capability is limited by coolant properties such as the boiling point, rather than the material's yield strength. Frequency shifts are inevitable and can be compensated by localized tuning of individual cavities.

Figure 1(a) and (b) illustrate the behaviour of biperiodic structures at overall uniform temperatures and with induced temperature gradients respectively. The π/2-mode and the average accelerating and coupling cavity frequencies as a function of structure temperature are shown in Fig. 1(a). A uniform temperature was obtained in an S-band on-axis coupled structure with water, at a regulated temperature, circulating through the cooling channels of the cavities. Using the measured dispersion curve, the average accelerating and coupling cavity frequencies were obtained from the computer code DISPER[9]. As expected, the observed normalized frequency shift of $15.6 \times 10^{-6}/°C$ agrees with $16.5 \times 10^{-6}/°C$, the thermal expansion coefficient of copper. The structure stopband frequency remained constant with water temperature indicating as expected an absence of temperature gradients and thermal stresses.

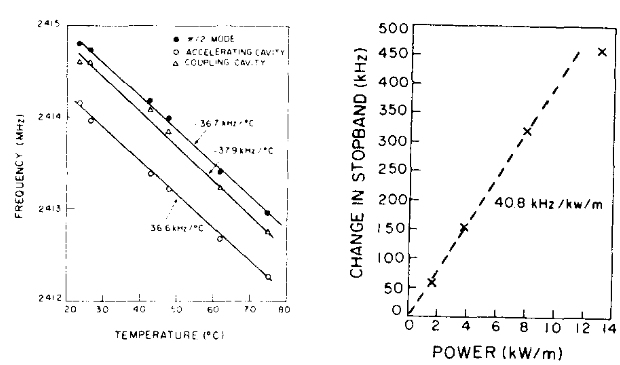

Fig. 1 (a) Frequency dependence of a S-band on-axis coupled structure versus uniform temperature.
(b) The change in the stopband frequency gap of a 2450 MHz on-axis coupled structure with rf power. Measurements performed at the Institut für Kernphysik der Johannes-Gutenberg-Universität, Mainz.

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The stopband frequency gap of a biperiodic system is defined as

$$\Delta \equiv \frac{\omega_1}{(1-k_2)^{1/2}} - \frac{\omega_2}{(1-k'_2)^{1/2}}$$

where ω_1 and k_2 are the average frequency and second neighbour coupling constant of the accelerating cavities and ω_2 and k'_2 are corresponding parameters for the coupling cavities. A temperature associated change in the stopband frequency gap is a measure of a structure's thermal detuning. Figure 1(b) shows the change in the stopband frequency gap as a function of power for a 2450 MHz on-axis coupled structure with circumferential cooling only. For these measurements, the inlet water temperature and flow were kept constant and resonance was maintained by reducing the drive frequency as drive power increased. A temperature increment of 1.1°C/kW/m above the bulk water temperature was measured at the nose cone region of the cavities. Thermal expansion of the nose cone region was limited by the cooler outer metal boundary leading to thermal stresses and a change in the stopband frequency gap of 40.8 kHz/kW/m. Below the yield point of the material, temperature distributions, thermal stresses and the change in the stopband frequency gap increase linearly with power.

Power Handling Capability of Room Temperature CW Linacs

Frequency shifts and change in stopband frequency gap of biperiodic structures at high power have been predicted[6] from thermal stress analysis. Table I shows the excellent agreement between calculations and measurements with S-band on-axis coupled structures. In the following discussion, the power handling capabilities of linac structures were determined for different cooling schemes and cavity web thickness. The reference structure was the 2450 MHz on-axis coupled linac constructed at the Institut für Kernphysik der Johannes-Gutenberg-Universität (Mainz) and operated in the second stage of their cw electron racetrack microtron (MAMI II). An effective shunt impedance of 67 MΩ/m was measured with beam at a rf power level of 13 kW/m.

Table I

Frequency Shifts and Change in Stopband for 2450 MHz On-Axis Coupled Structures*

	Frequency Shift kHz/kW/m	Change in Stopband kHz/kW/m
MAMI Section 1 (1.2 L/s)		
Measured	-21	40.8
Calculated	-22	40.3
MAMI Section 2 (0.92 L/s)		
Measured	-26.0	-
Calculated	-27.9	38.5

* Measurements performed at the Institut für Kernphysik der Johannes-Gutenberg-Universität, Mainz.

Circumferential Cooling

MAMI II structures were cooled by 29°C inlet water that flows through twelve equally spaced borings (6 mm diameter) on a constant 58 mm radius circle. The total water flow through each 1.775 m structure was 0.92 L/s. A maximum stress of 1 MPa/kW/m was computed for the region near the beam aperture using the calculated temperature gradient along the web. Hence, thermal stress reaches the yield strength of annealed OFHC copper[10] (69 MPa) at a structure power dissipation of 69 kW/m. At 69 kW/m, the average cooling water temperature was estimated to increase by 16°C with an average inner cavity surface temperature increase of 72°C. The change in copper surface resistivity associated with this temperature increase reduces the structure shunt impedance by 12%. Thus the maximum average energy gradient permissible before a permanent deformation of the structure occurs is about 2 MeV/m. Increasing the number of cooling channels or the circumferential water flow reduces the average cavity surface temperature, diminishing losses in shunt impedance. Such improvements do not have a significant effect on web temperature gradients and related thermal stresses. Hence improved circumferential cooling offers little benefit as far as reducing stress is concerned.

Web Cooling

Power handling capability of a structure is significantly improved by utilizing web cooling. A photograph of an S-band on-axis coupled segment constructed at CRNL with four 2 mm diameter borings through a 6 mm thick web is shown in Fig. 2(a). In this arrangement, a total flow rate of 0.1 L/s per segment was measured for a pressure drop of 400 kPa. Figure 2(b) shows calculated temperature gradients for different water flows. An increase in web water flow decreases the temperature gradient and reduces thermal stresses in the web. With an optimized cavity cooling design, the power handling capability of a structure is usually limited by the allowable temperature increase of the coolant. If, for example, water temperature increases were restricted to 70°C, web cooling of an on-axis coupled structure similar to the MAMI II cavities could achieve an average energy gradient of 2.9 MeV/m with an average inner cavity surface temperature of 120°C. The average energy gradient could be further increased to 3.7 MeV/m if a water manifold arrangement was employed for each meter of structure.

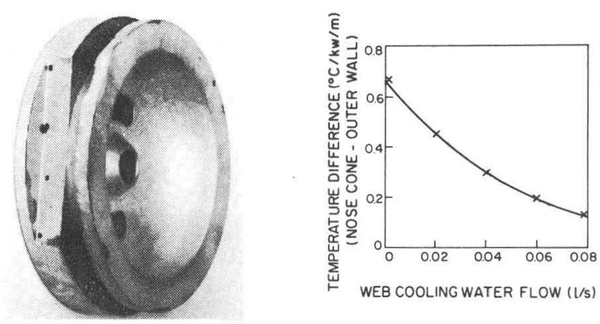

Fig. 2 (a) S-band on-axis coupled segment with web cooling. Four 2 mm diameter channels were bored through the web. This prototype was a test segment of a 10 segment structure.
(b) Incremental temperature difference between the beam aperture region and outer wall of a 2450 MHz on-axis coupled cavity with web cooling.

Cavity Web Thickness

Thermal conduction is improved by increasing the cavity web thickness. A thicker web allows for cooling channels in the nose cone region, hence providing for high power operation at the expense of a decrease in efficiency. Figure 3 summarizes results of calculations of normalized cavity efficiency from SUPERFISH[11] and average energy gradient at the onset of permanent cavity deformation for different web thickness based on a thermal stress analysis. The calculations were done for a 2450 MHz on-axis coupled structure with a MAMI II cavity profile that employed circumferential cooling only. Only the cavity web thickness parameter was modified. Calculated efficiencies were corrected for the loss in shunt impedance from cavity surface temperature increases and were normalized to the measured shunt impedance (67 MΩ/m) of the MAMI II cavities which have a web thickness of 6.19 mm. The temperature gradient at the onset of permanent cavity deformation was almost independent of the web thickness.

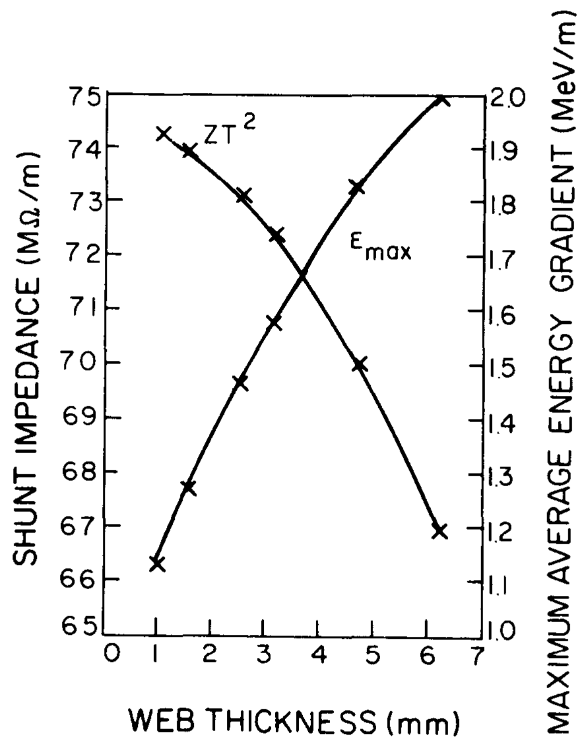

Fig. 3 Cavity efficiency and maximum permissible average energy gradient in a 2450 MHz on-axis coupled cavity. Circumferential cooling is assumed and the energy gradient limit is imposed by the predicted onset of a permanent deformation in the cavity geometry. Web cooling would increase the limit by a factor of at least 1.8. The web thickness does not include the on-axis coupling cavity.

Frequency Scaling

A direct scaling of the geometrical dimensions of a cavity with only circumferential cooling is used in Table II to obtain the frequency (f) dependence of the average energy gradient limit in room temperature cw linacs. Below the material's yield point, it is found that the average energy gradient at the onset of permanent deformations has a $f^{1/4}$ dependence. The $f^{1/4}$ dependence for the average energy gradient limit (based on thermal stresses) has been verified analytically for various cavity geometries with different assumed surface power densities in an attempt to approximate different mode excitations.

Discussion

Calculations indicate that average energy gradients as high as 3.7 MeV/m are attainable in room temperature cw linear accelerators with reasonable cooling flows. Such high energy gradients are comparable with results obtained with superconducting cw structures[12].

For a given length room temperature linac, the average energy gradient at the onset of permanent cavity deformation scales as the fourth root of the operating frequency. The corresponding rf power requirements are independent of frequency.

Fabrication tolerances, complexity of structure assembly, length of structure and power consumption are important parameters in designing linac structures. The technology of room temperature structures is well mastered and advances are being made to improve the reliability of superconducting cavities. At a given energy gradient, the rf power dissipated in a superconducting structure is about three orders of magnitude smaller than in room temperature cavities but refrigeration, necessary to obtain high rf efficiency in superconducting cavities, represents a significant portion of the overall system power requirements. In heavily beam loaded structures, a large fraction of the rf power is transferred to the beam and the attainable average energy gradient and structure reliability are as important parameters as the cavities' rf efficiency. The power deposited by beam losses in heavily beam loaded structures will determine the choice between room temperature and superconducting technologies.

Table II

Frequency Scaling of the Permissible Average Energy Gradient

Cavity Geometry (in mm)		
Radius	38.23	76.46
Length	50	100
Web Thickness	2.39	4.78
Beam Aperture	5.1	10.2
Ratio Gap to Length	0.6111	0.6111
SUPERFISH[11] Results		
Frequency	3000 MHz	1500 MHz
Effective Shunt Impedance	96.6 MΩ/m	68.3 MΩ/m
Power at 1 MeV/m	517.6 W/cavity	1464 W/cavity
MARC Results		
Maximum Thermal Stress	1.89 MPa/kW/m	1.89 MPa/kW/m
Maximum Permissible Average Energy Gradient	1.88 MeV/m	1.58 MeV/m
Cavity Parameters		**Frequency Scaling**
Shunt Impedance		$f^{1/2}$
Surface Area		f^{-2}
Power Dissipated/Unit Area*		$f^{1/2}$
Power Dissipated/Cavity*		$f^{-3/2}$
Thermal Stresses below Yield Point*		$f^{-1/2}$
Maximum Permissible Average Energy Gradient*		$f^{1/4}$

* At a given energy gradient.

References

1. L.M.Young and J.M. Potter, "CW Side-Coupled Linac for the Los Alamos/NBS Racetrack Microtron", IEEE Trans. Nucl. Sci., NS-30 (4), 3508 (1983).
2. P. Axel, L.S. Cardman, R.A. Daniel, A.O. Hanson, R.A. Hoffswell, R.M. Laszewski, W.C. Sellyey, N. Tone and A.M. Vetter, "The University of Illinois Nuclear Physics Laboratory, 1982", IEEE Trans. Nucl. Sci., NS-30 (2), 1112 (1983).
3. S.O. Schriber and R.F. Holsinger, "Additions and Improvements to the RF Cavity Code SUPERFISH", IEEE Trans. Nucl. Sci., NS-30 (4), 3545 (1983).
4. I. Wilson and H. Henke, "Thermal Analysis and Loss in Shunt Impedance of the LEP Accelerating Cell", ibid., 3590.
5. MARC, Marc Analysis Research Corporation, 260 Sheridan Ave., Palo Alto, CA 94306, USA.
6. J. McKeown and J.-P. Labrie, "Heat Transfer, Thermal Stress Analysis and the Dynamic Behaviour of High Power RF Structures", IEEE Trans. Nucl. Sci., NS-30 (4) 3593 (1983).
7. J. McKeown, R.T.F. Bird, K.C.D. Chan, S.H. Kidner and J.-P. Labrie, "High Power, On-Axis Coupled Linac Structure", Proc. of the 1981 Linear Accelerator Conference, Santa Fe, NM, LA-9234-C (1982) 332.
8. S.O. Schriber, LOOPX, A Coupled Loop-Circuit Model Computer Code, internal communication, Chalk River Nuclear Laboratories.
9. S.O. Schriber, "Fitting an Ordered Set of Mode Frequencies", Atomic Energy of Canada Limited, Report AECL-3669 (1970).
10. "OFHC-Brand Copper", AMCO Sales, 1961, Library of Congress Catalog Card No. 62-11986.
11. K.H. Halbach and R.F. Holsinger, "SUPERFISH - A Computer Program for Evaluation of RF Cavities with Cylindrical Symmetry", Particle Accelerators 7, 213 (1976).
12. M. Tigner, "Superconducting Microwave Cavities in Accelerators for Particle Physics, A Review", AIP Conf. Proc. of SLAC Summer Accelerator School (1982) 801.