HIGH POWER BEHAVIOUR OF K_a BAND LINAC STRUCTURES

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Abstract

Finite element thermal stress analysis has been used to optimize geometrical parameters of K_a band linac structures and obtain limits of steady state power dissipation in the structures. Computer simulation results are verified by scaling measurements of the power handling capability of an S-band structure.

Introduction

Linac structures operating at a wavelength of 9 mm are being developed for future high energy colliders[1-3] and may lead to a significant reduction in the size of these facilities. For a constant power dissipation per unit length, accelerating fields in K_a band structures are about 1.8 times greater than in more conventional S-band devices.

The size difference implies that frequency shifts from temperature variations are about 10 times greater, and absolute machining tolerances are about 3 times tighter, for K_a band structures than for S-band structures. The absolute bandwidth of K_a band structures is, however, about 30 times larger, making frequency control at high average power feasible.

The development of high power, high frequency rf sources such as gyroklystrons[4] and Lasertrons[5], and the compactness of K_a band structures could lead to new applications of linacs. This paper describes the results of computer simulations to determine the steady state characteristics of $2\pi/3$ travelling wave K_a band structures. Results of finite element thermal stress analysis are verified by scaling measurements of average power handling capability of a standing wave on-axis coupled structure.

Steady State Power Handling Capability

The operating power limit of a linac structure with steady state heat flux is determined by the material yield strength. A linac structure becomes unstable, and unpredictable changes in its rf characteristics take place, when thermal stresses exceeding the yield strength develop, because the beam aperture region is at a higher temperature than the outer cavity wall.

An on-axis coupled standing-wave structure, shown in Fig. 1, is a biperiodic system composed of accelerating and coupling cavities. The structure is characterized by its $\pi/2$ operating mode frequency, and its stopband frequency gap, defined by

$$\Delta \equiv \frac{\nu_c}{\sqrt{1-k_c}} - \frac{\nu_A}{\sqrt{1-k_A}} \qquad (1)$$

where ν_A, ν_c and k_A and k_c are average frequency and second neighbour coupling constants of accelerating and coupling cavities respectively.

Changes in the stopband frequency gap at high power are related to thermal stresses that have developed in the webs separating adjacent cavities.

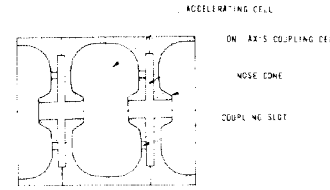

Fig. 1 Schematic representation of an on-axis coupled structure.

Since the volume of the on-axis coupling cavities is about 20 times smaller than the accelerating cavities, their resonant frequencies are much more sensitive to thermal effects. Changes in stopband frequency gap are therefore a sensitive method of detecting thermal strains. The power handling capability of a structure is exceeded when repeated cycles to the same power level cause permanent changes in the stopband frequency gap, indicating that cavity webs undergo plastic deformation every time the thermal cycle is applied.

Measurements of power handling capability have been made at the University of Mainz with a 2.45 GHz on-axis coupled linac structure[6]. Results indicated that without web cooling, the structure became unstable at average power levels above 70 kW/m. The 2.45 GHz structure used for these measurements had a web thickness of 6.19 mm and a beam aperture radius, a, of 7 mm. Circumferential water cooling was provided at the radius, b, 50 mm from the axis of symmetry.

The steady state power handling capability of other linac structures without web cooling can be scaled from these results using cavity geometrical parameters. Simple relationships between thermal stresses are obtained for a cavity web represented by a flat disk (such as in disk loaded structures). The maximum compressive thermal stress, σ, in the region of the beam apertures of a disk loaded structure is approximately given by

$$\sigma = \frac{\alpha E(T_a - T_b)}{\ln(\frac{b}{a})} \left[\frac{1}{2} - \frac{b^2}{b^2 - a^2} \ln(\frac{b}{a})\right] \qquad (2)$$

where α is the coefficient of thermal expansion of the cavity material, E is the modulus of elasticity, and T_a and T_b are the cavity web temperature at the beam aperture radius, a, and at the outer cavity radius, b, respectively.

The temperature difference, $T_a - T_b$, is a function of power distribution along the cavity web and of web thickness, t_w. For a uniform power distribution, the temperature difference is given by

$$T_a - T_b = \frac{P}{2\pi k t_w} \frac{b^2}{b^2 - a^2} \left[\frac{1}{2} - \frac{a^2}{2b^2} - \frac{a^2}{b^2} \ln(\frac{b}{a})\right] \qquad (3)$$

where P is the power dissipated at the surfaces of the webs and k is the thermal conductivity of the cavity material.

The expressions for maximum compressive thermal stress (eqn. (2)) and for temperature difference in cavity webs lead to the following observations:

(i) For the same power dissipation per unit length, maximum compressive thermal stress is independent of the cavity frequency, if all cavity dimensions scale with wavelength. Hence, the average power handling capability per unit length of linac structures without web cooling is, to the first order, independent of their operating frequency.

(ii) Power handling capability is proportional to cavity web thickness.

(iii) Power handling capability increases slowly with beam aperture diameter. As the beam aperture increases, the cavity diameter also increases to maintain the operating frequency if other cavity geometrical parameters are unchanged.

In a tuned on-axis coupled structure, power is dissipated on web surfaces in accelerating cavities and no power is dissipated in coupling cavities. For other types of linac structures, such as side coupled and travelling wave linacs, power handling capability is reduced by one half since power is dissipated on both sides of the cavity webs. For example, a side coupled structure with a web thickness of 6.19 mm at 2.45 GHz will become unstable at an average power level of about 35 kW/m. The rf efficiency of such structures is usually greater than on-axis coupled structures where the location of the coupling cavities make the effective web thickness significantly larger than in side-coupled structures.

Thermal Stress Analysis of K_a Band Structures

A useful K_a band linac requires minimization of fabrication complexity and maximization of heat transfer from the beam aperture to the water cooled cavity outer walls. Three $2\pi/3$ travelling wave cavity geometries, shown in Fig. 2, have been considered. Two of the 33.3 GHz cavities are based on the SLAC profile[7], with beam aperture diameters of 2.5 mm (Type A) and 3.0 mm (Type B). The third cavity is based on the LEP profile[8] with an enlarged cavity web at the junction with the outer wall and a beam aperture diameter of 2.5 mm (Type C). All web thicknesses are 0.5 mm and outer wall thickness are 2 mm.

Surface power densities obtained from standing wave field distributions calculated with SUPERFISH[9] are also given on Fig. 2. Neumann-Neumann and Dirichlet-Dirichlet boundary conditions were used to represent the travelling wave at two instants in time, at $\omega t=0$ and $\omega t=\pi/2$[10]. Steady state power distributions shown in Fig. 2 are obtained by averaging the surface powersobtained with the two boundary conditions.

RF properties of the three designs are summarized in Table I. An increase in beam aperture diameter of 20 percent reduces structure shunt impedance, r, by about 16 percent, and attenuation coefficient, α, (and consequently the fill time) by about one half. Adding a curved profile to the outer cavity wall can improve shunt impedance by about 11 percent.

Average accelerating gradient in a constant impedance structure with beam loading is given by[11]

$$\frac{V}{\ell} = (2\alpha Pr)^{1/2}\,\frac{1-e^{-\alpha\ell}}{\alpha\ell} - ir\left(1 - \frac{1-e^{-\alpha\ell}}{\alpha\ell}\right) \qquad (4)$$

where ℓ is structure length, i is beam current and P is rf power. For structures of equal length operating at the same energy gradient with low beam loading, rf power requirements are inversely proportional to αr. Hence, an increase of 20 percent in beam aperture diameter to improve heat transfer to the outer wall doubles rf power requirements. A widening of the cavity web at the junction with the outer wall has little effect on power requirements, although it modestly improves power handling capability.

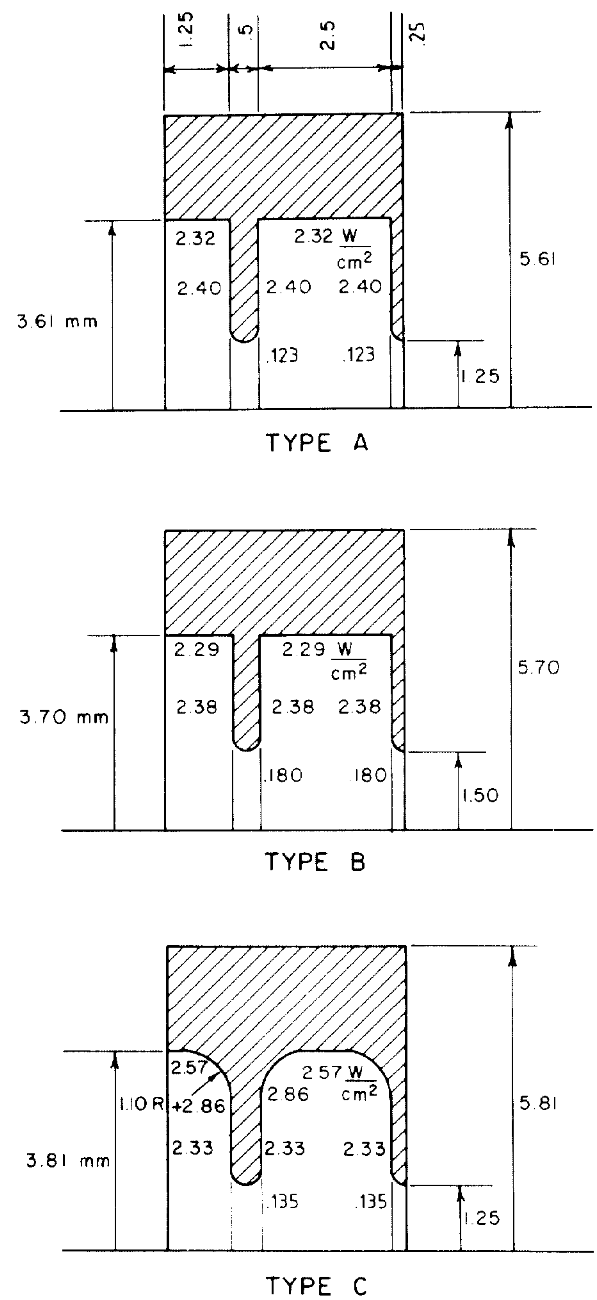

Fig. 2 Geometry of K_a band $2\pi/3$ travelling wave cavities. Surface power distributions are normalized to a power level of 1 kW/m. Cavity dimensions are in mm, surface power distributions are in W/cm^2.

Table I

RF Characteristics of K_a Band Constant-Impedance Structures

	Type A	Type B	Type C
Beam Aperture 2a (mm)	2.5	3.0	2.5
Cavity Diameter 2b (mm)	7.22	7.40	7.62
Shunt Impedance r (MΩ/m)	150.5	125.8	166.4
Q_0	4071	4094	4526
Group Velocity (v_g/c)	0.025	0.051	0.025
Attenuation (Np/m)	3.43	1.67	3.08

Results from thermal stress analysis with the MARC[12] computer code are shown in Fig. 3. Calculations assumed annealed OFHC copper structures and identical outer wall cooling conditions. The steady state power handling capability obtained from thermal stress analysis, and from scaling (eqn. (2) and (3)) the results of measurements with an S-band on-axis coupled structure[4], are given in Table II. The yield strength of annealed OFHC copper used in the calculations was 69 MPa[13]. Calculated power handling capabilities and scaled values agree within 10 percent.

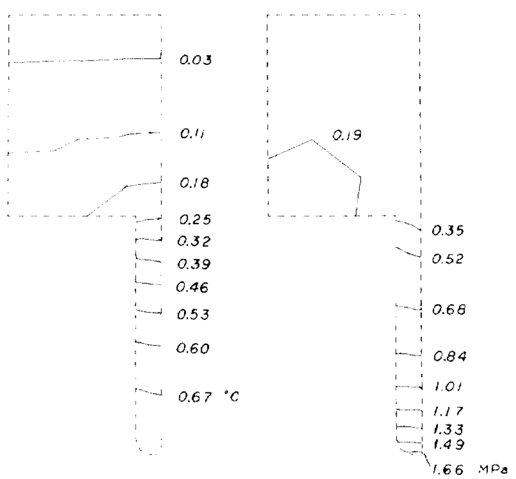

Fig. 3 Temperature and Von Mises thermal stress distributions in $2\pi/3$ (Type A) travelling wave cavities normalized to a power level of 1 kW/m. Similar results are obtained for cavities of Type B and C (see Table II).

Steady state power handling capability is proportional to web thickness, but does not depend as strongly on other cavity geometrical parameters. A 20 percent increase in beam aperture diameter decreases thermal stresses in the beam aperture region by about 10 percent. Increased rf power requirements overwhelm the small improvement in power handling capability.

An improvement to rf characteristics and average power handling capability is obtained by enlarging the cavity webs at the junction with the outer wall. The improvement is, however, modest: shunt impedance is increased by about 11 percent and steady state power handling capability by about 17 percent. The increase in fabrication cost is negligible.

Table II

Results from Thermal Stress Analysis

	Type A	Type B	Type C
Temperature Difference along Cavity Web (°C/kW/m)	0.632	0.587	0.534
Maximum Thermal Stress in Beam Aperture Region (MPa/kW/m)	1.680	1.526	1.432
Maximum Steady State Power Dissipation (kW/m)			
[from finite element analysis]	41	45	48
[scaled from measurements]	45	48	44

Summary

Finite element thermal stress analysis has been used to study heat transfer as a function of K_a band linac geometrical parameters. Results are in good agreement with scaling of measurements of average power handling capability made with an S-band linac. In K_a band linacs with a web thickness of 0.5 mm, where cooling cannot be readily provided, steady state power dissipation is limited to about 40 kW/m.

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