IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

EXPERIMENTAL AND CALCULATED RF PROPERTIES OF THE DISK-AND-WASHER STRUCTURE*

J. M. Potter, S. O. Schriber† and F. J. Humphry

Los Alamos Scientific Laboratory
Accelerator Technology Division, Los Alamos, New Mexico 87545

Abstract

A detailed study of the disk-and-washer structure using SUPERFISH has shown that the physical geometry can be optimized to make the structure more efficient than previously reported. The calculated ZT^2 is equal to that of an equivalent LAMPF cavity (neglecting any losses associated with the side-coupler slots) for $\beta = 0.6$ and is 30% higher for $\beta = 1.0$. Several techniques for supporting the washer were studied in addition to the conventional "L" supports. Two types of supports, the "TO" that supports two washers from every other disk with a T, and radial supports in the washer plane, improve left-right symmetry and reduce the tuning effort required to achieve a satisfactory field distribution. Effects of these supports on tuning procedures are discussed.

Introduction

The disk-and-washer structure, DAW, introduced by Andreev,[1] created a great deal of interest [2,3] because of a significant increase in group velocity - a factor of 10 improvement over the side-coupled structure used for LAMPF[4] at the Los Alamos Scientific Laboratory (LASL). Although the calculated rf efficiency of the DAW structure was slightly lower than an equivalent LASL cavity, benefits associated with a high group velocity made the structure attractive for proton and electron linacs. The only disadvantage of the structure was its larger overall radius when compared to an equivalent on-axis coupled structure.[5]

A further study of the DAW geometry using the computer program SUPERFISH[6] was necessary to investigate washer support effects, structure tolerances and mode behavior. This study showed that the DAW geometry could be further optimized resulting in rf efficiencies higher than reported earlier[3] - up to 85% higher for 1.0 beta cavities.

Experimental measurements using aluminum models were undertaken to determine suitable washer support techniques, assembly methods and rf properties not predictable by SUPERFISH. The most suitable washer support was a set of radial posts that connected the washer directly to the outer cylinder in the washer plane. This paper presents results of the calculations and measurements.

Calculations

Optimization calculations for the DAW geometry were made maintaining the $\pi/2$ accelerating mode frequency equal to the $\pi/2$ coupling mode frequency. Effective shunt impedance, ZT^2, at 1.35 GHz is shown in Fig. 1 as a function of the outer cylinder radius, R_C, for four betas, β, from 0.4 to 1.0. The 0.4, 0.6 and 0.8 geometries attained maximum values of 34, 59 and 81 MΩ/m, respectively. The $\beta = 1.0$ geometry has a maximum of 115 MΩ/m at a larger R_C than shown in the figure - much higher than 69 MΩ/m for an equivalent optimized LASL $\beta = 1.0$ cavity[7] at 1.35 GHz. Radii for the washer and the disk as a function of the outer cylinder radius are given in Fig. 2. Note that the radii overlap at $\backsim$16 cm for $\beta = 0.4$ and at $\backsim$12 cm for $\beta = 1.0$. The geometry without overlapping radii offers better vacuum conductance and more varied assembly techniques.

A schematic of the DAW geometry with different geometrical quantities defined is shown in Fig. 3. Optimum gap, g, and optimum disk width, t_D, as a function of beta can be determined from Fig. 4. The washer geometry for the calculations summarized in Figs. 1 and 2 did not have a bulb on its outer extremity, that is, $R_R = 0$ and $t_R = t_w$. Other parameters not given in the figures are $L = \beta\lambda/4$, $t_w = 0.35$ cm, $R_N = 0.25$ cm, $R_H = 1.1$ cm and $\Theta = 30^\circ$. Effects associated with a bulb on the washer extremity are presently being investigated.

Although high ZT^2 can be obtained with DAW geometries using large R_C, reasons other than mechanical ones limit the maximum radius selected for most applications. Studies of frequency dispersion curves as a function of R_C demonstrated that second neighbor coupling, k_2, increases considerably and this increase has a significant effect on the shape of the dispersion curves. For $R_C > 17$ cm at 1.35 GHz, the $\pi/2$ mode will experience mode overlapping and/or mode interference from modes between the $\pi/2$ and π modes. In addition, the $\pi/2$ mode group velocity begins to decrease. These effects appear at a similar R_C for all beta. For this reason, a maximum value of 17 cm was set for all 1.35 GHz DAW geometries. Under this constraint modes that normally (with $k_2 = 0$) wouldn't cause interference will be at least 0.15 GHz distant from the $\pi/2$ operating mode. Even with this restriction ZT^2 is 30% higher than that of an equivalent LASL cavity for $\beta = 1.0$.

PIGMI Geometry

The DAW geometry selected for PIGMI[8] had to meet specific mechanical constraints for an accelerator operating at 1.32 GHz. To avoid difficulties discussed above and to provide compatibility with available pipe size, R_C was fixed at 16.6 cm. A support knob or bulb was added at the outer extremity of the washer to provide a reasonable surface area for mounting radial supports, the web thickness, t_w, was increased to 0.4 cm to allow space for internal cooling channels, and a larger beam bore hole was required to mate with jigging that would be used during assembly brazing operations. Results of calculations normalized to 1 MV/m average on-axial electric field are listed in Table 1 for the PIGMI geometries.

A comparison of ZT^2 at 1.32 GHz as a function of beta is shown in Fig. 5 for the LASL cavity, the DAW with a support knob and the DAW without a support knob. The DAW geometry has a higher ZT^2 for beta greater than 0.6. Because calculations for the DAW geometry included losses in the coupling cavity, it is expected that experimental results will show a greater difference in favor of the DAW geometry.

Terminations and Washer Supports

Three different termination schemes, for a $\beta = 1.0$ DAW geometry, are illustrated in Fig. 6 - half cavity, full cavity and a full cavity attached to a coaxial coupler excited in a TEM-like mode. For the geometries studied, rf losses in the full cavity (full cavity with coaxial coupler) are 1.06 to 1.42 (1.08 to 1.51) times that of an equivalent full cavity without termination for betas from 0.4 to 1.0. Numerous schemes for coup-

*Work supported by the U. S. Department of Energy.
†Visitor from Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada K0J1J0

0018-9499/79/0600-3763$00.75 © 1979 IEEE

ling from an external rf source to the termination cavity can be employed.

Two locations for the washer support were determined. A radial support in the washer plane preserves symmetry about the washer and is the preferred support location. The support introduces a frequency perturbation that can be compensated by changing R_w. Ideal locations of a side washer support are shown by dashed lines in Fig. 7 for betas of 0.6 and 1.0. Electric field lines at one instant of time for the $\pi/2$ operating mode are shown to demonstrate the reason for choosing this location - fields are perpendicular to or zero at the washer support. Asymmetries in the rf fields on-axis from cavity to cavity related to asymmetrical supports can be compensated by changing t_D. A 44% change in t_D produces a 10% change in the on-axis fields for both the $\beta = 0.6$ and $\beta = 1.0$ geometries with the lower (higher) field occurring below the disk that had been shortened (increased).

More detailed information related to the calculations described above and to a DAW structure employed as a "harmonic accelerator" or as a graded-beta linac can be found in Ref. 9.

Experiments

Computer studies using SUPERFISH are limited to cavities with cylindrical symmetry. Because cylindrical symmetry of the DAW structure is broken by the necessity to support and cool the washer, details of washer support effects must be determined experimentally.

The initial washer support configuration was a set of three (later four) L-shaped conductors connecting each washer to an adjacent disk as illustrated schematically in Fig. 8a. This support scheme makes it possible to assemble a DAW tank from many identical units. Each unit consists of an outer wall section of length $\beta\lambda/2$, a disk, and the washer associated with that disk - a concept used in the original design of Andreev.[1]

Because L supports lie nearly in the intermediate minimum potential region of the $\pi/2$A accelerating mode, $\pi/2$A, they have little effect on its frequency. But, they do perturb the rest of the passband including the frequency of the $\pi/2$ coupling mode, $\pi/2$C. This perturbation must be determined experimentally to minimize accelerator tank tuning. Any type of support will introduce detuning that requires compensation.

The principal objection to L supports is the inherent fore-aft asymmetry in on-axis electric field, E, on either side of the washer. In the R-L-C coupled circuit model this asymmetry is equivalent to an imbalance in the nearest neighbor coupling constant, k. Figure 9a shows the on-axis distribution of E^2 in a structure with L supports as measured by bead pulls. The 19% change in electric field amplitude from gap to gap, corresponding to an error $\Delta k/k = 0.19$, was independent of the stop band ($\pi/2$A - $\pi/2$C).

Field asymmetry can be compensated by translating disks with respect to the washers along the axis until a flat distribution of field amplitudes is obtained. A slight error in correcting the imbalance can result in a large field distribution tilt because the effect of coupling constant errors is cumulative. For example, if $\Delta k/k = 10^{-3}$ for every cavity, 100 cavities would have a 10% field tilt. Therefore, another operation is added to the tuning procedure. Not only must the $\pi/2$A and $\pi/2$C mode frequencies be within acceptable tolerances, but individual coupling constants must be adjusted to achieve an untilted distribution of field amplitudes. Another problem of the fore-aft asymmetry is that cavity terminating planes are not reflecting planes of a periodic structure. The stop band is therefore a function of tank cavity number, making cavity pretuning more complicated.

These difficulties, coupled with a desire to keep fabrication costs low, led to a study of more symmetrical washer supports. The first alternative, the TT support, is similar to a set of four L supports attached to both sides of each washer. This scheme had the desired symmetry property but was rejected because of mechanical problems associated with overconstraining the washer position. In addition, the extra set of supports results in slightly increased rf losses.

Staggered TT supports were also considered. Two T's spaced 180° apart supported washers from each disk. Adjacent sets of T's were rotated by 90° relieving the over-constraint problem. Although support rf losses are similar to that of L supports, fabrication and assembly are more complicated.

Another washer support studied, the TO support illustrated in Fig. 8b, consists of four T supports connecting two washers to every other disk - intermediate disks support no washers. Figure 9b shows the measured on-axis distribution of E^2. Note the 19% step in E from gap to gap that alternates in sign. Correcting coupling constants is not as important because repetitive errors are no longer cumulative. The principal objections to the TO support are that the structure period is $\beta\lambda$ instead of $\beta\lambda/2$ and that higher order periodicity introduces stop bands at the $\pi/4$ and $3\pi/4$ modes. Because the $\pi/2$ mode group velocity is not appreciably affected by the extra stop bands, extra tuning procedures are unnecessary. Although this case has not been fully analyzed, it appears that structure stability is not greatly affected by the new stop bands.

The preferred washer support method uses radial supports in the center plane of the washer, as shown in Fig. 8c. Figure 9c illustrates the improved symmetry of the on-axis fields. Because radial supports are not on a zero potential surface, the $\pi/2$A mode frequency is perturbed; but the 0, $\pi/2$C and π modes are relatively unperturbed. Radial supports in β = 0.6 and 1.0 aluminum models increased the $\pi/2$A mode frequency by $\sim$4%. Support diameter had a minor effect on frequency.

Concerns that radial supports would have serious effects on the accelerating mode properties have proven unfounded. Preliminary measurements showed that the relative shunt impedance, Z/Q, was slightly higher for radial supports than for no supports. No evidence of a change in Q was noted. Copper brazed models are being fabricated so that accurate comparisons of Q's and Z's of DAW structures with TO and radial supports can be made.

Radial supports are mechanically more compatible with a new scheme for building DAW tanks. Tanks will be built in $\sim$1-m sections with solid copper washers, copper-plated stainless-steel outer cylinder and disks, and copper-plated stainless-steel radial supports. The large rf coupling constant should eliminate the need to fine tune each gap. The desired $\pi/2$A mode frequency could be obtained by tuning all the gaps collectively. Systematic errors in coupling constants can be accommodated by reversing alternate 1-m sections of a long tank.

Discussion and Conclusions

Further optimization of the DAW geometry has shown that higher ZT^2 can be obtained than reported earlier[3] - up to 85% higher. Reasons for limiting the outer cylinder radius for most applications have been given and these result in a $\beta = 1.0$ cavity that has a 30% higher ZT^2 than that of an equivalent LASL cavity.

Different termination and washer support methods have been studied. The radial washer support is the preferred method for supporting the washer and bringing cooling water to the washer. The full cavity termination with coaxial coupler appears to be the best method for bridging accelerating tanks together and for providing coupling from an external rf source into a region not directly exposed to the accelerated particle.

Some remaining uncertainties associated with non-axially symmetric modes, washer supports and one-point multipactor need to be resolved. A copper multicavity structure is being built using the PIGMI $\beta = 0.6$ geometry to determine Q's and Z's accurately and to investigate higher order modes.

References

1. V. G. Andreev et al., "Study of High-Energy Proton Linac Structures," Proc. of 1972 Proton Linac Conf., Los Alamos Scientific Laboratory Report No. LA-5115, 114 (1972).
2. J. J. Manca, E. A. Knapp and D. A. Swenson, "High Energy Accelerating Structures for High Gradient Proton Linac Applications," IEEE Trans. Nucl. Sci., NS-24, 1087 (1977).
3. J. J. Manca and E. A. Knapp, "Optimization of Disk and Washer Accelerating Cavities," Los Alamos Scientific Laboratory Report No. LA-7407 (1978).
4. E. A. Knapp and W. J. Shlaer, "Design and Initial Performance of a 20 MeV High Current Side Coupled Cavity Electron Accelerator," Proc. of 1968 Proton Linac Conf., Brookhaven National Laboratory Report No. BNL-50120, 635 (1968).
5. S. O. Schriber, L. W. Funk and R. M. Hutcheon, "Effective Shunt Impedance Comparison between S-Band Standing Wave Accelerators with On-Axis and Off-Axis Couplers," Proc. of 1976 Proton Linac Conf., Atomic Energy of Canada Limited Report No. AECL-5677, 338 (1976).
6. K. Halbach, R. F. Holsinger, W. E. Jule and D. A. Swenson, "Properties of the Cylindrical RF Cavity Evaluation Code SUPERFISH," ibid., 122 (1976).
7. J. J. Manca and E. A. Knapp, "TM_{01} Mode Accelerating Cavity Optimization," Los Alamos Scientific Laboratory Report No. LA-7323 (1978).
8. E. A. Knapp and D. A. Swenson, "The PIGMI Program at LASL," Proc. of 1976 Proton Linac Conf., Atomic Energy of Canada Limited Report No. AECL-5677, 230 (1976).
9. S. O. Schriber, "Room-Temperature Cavities for High-Beta Accelerating Structures", Proc. of Conf. on Future Poss. for Electron Accelerators, Charlottesville, VA (1979), to be published.

TABLE I

Parameters for the Disk and Washer (1.35 GHz) as a Function of Beta

[illegible]

Beta	R_D (cm)	R_W (cm)	$t_?$ (cm)	g/L	L (cm)	ZT^2 (MΩ/m)	T	Q	Emax on surface (MV/m)	% Power on Metal Walls Cylinder	Disk	Washer
0.4	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5.35	0.0012	0.70	99.3
0.5	12.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.862	23,215	[illegible]	0.0085	1.25	98.74
0.6	12.54	[illegible]	[illegible]	[illegible]	[illegible]	55.75	0.861	28,255	4.65	0.032	2.16	97.81
0.7	[illegible]	9.97	[illegible]	[illegible]	3.975	65.06	0.851	33,101	4.50	0.058	3.59	96.32
0.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	73.11	[illegible]	[illegible]	[illegible]	0.21	5.95	93.86
0.9	[illegible]	9.26	[illegible]	0.511	5.116	80.55	[illegible]	46,518	4.31	0.45	10.09	89.46
1.0	14.59	8.72	[illegible]	0.552	5.675	85.51	0.814	57,425	4.18	1.14	18.34	80.52

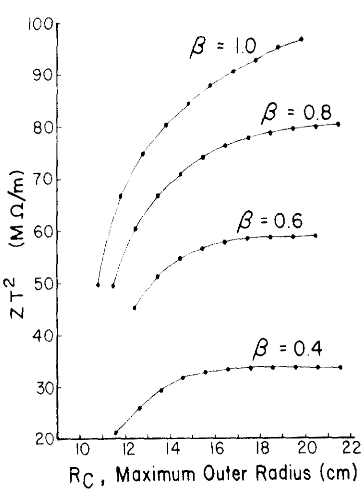

Fig. 1 Effective shunt impedance, ZT^2, of the 1.35 GHz disk-and-washer geometry as a function of the outer cylinder radius, R_C, for betas from 0.4 to 1.0.

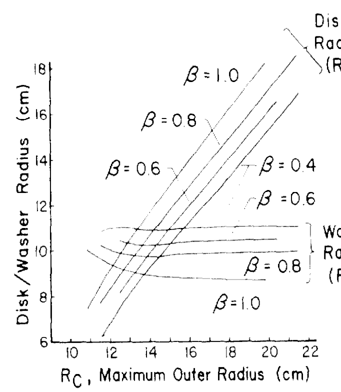

Fig. 2 Radii of the disk and the washer associated with Fig. 1 versus the outer cylinder radius, R_C, for betas from 0.4 to 1.0.

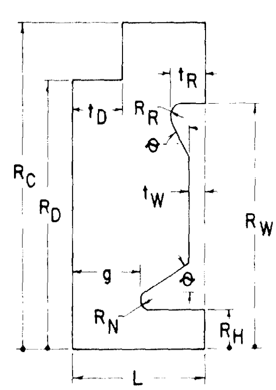

Fig. 3 Illustration of the disk-and-washer geometry showing the symbols used to define the various dimensions.

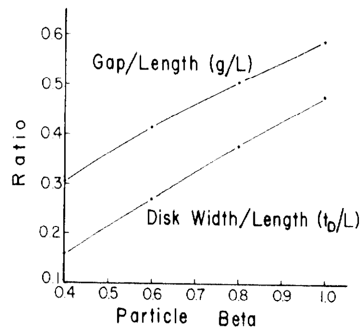

Fig. 4 Gap to length ratio and disk width to length ratio versus beta for the disk-and-washer geometry.

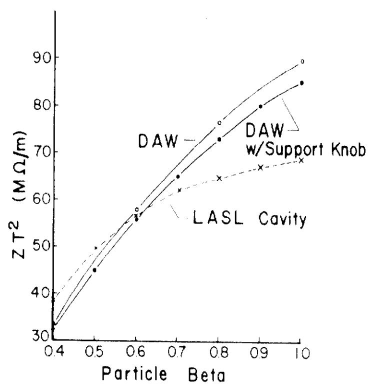

Fig. 5 Comparison of calculated effective shunt impedance, ZT^2, at 1.32 GHz for a LASL cavity and two disk-and-washer geometries as a function of particle beta.

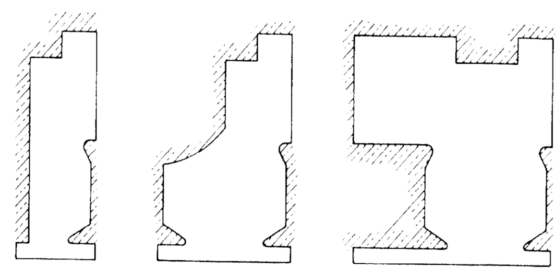

Fig. 6 Terminations for a β=1.0 disk-and-washer geometry in a) half cavity, b) full cavity and c) full cavity with co-axial coupler attached.

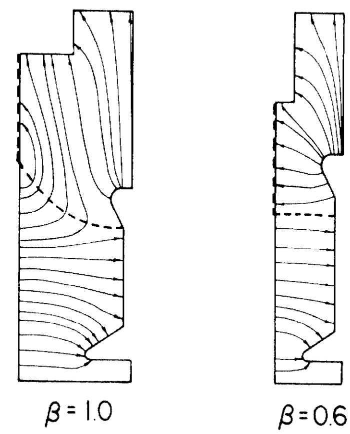

Fig. 7 Electric field distribution of the π/2 operating mode for β=0.6 and 1.0 cavities showing the ideal location for a side support by dashed lines.

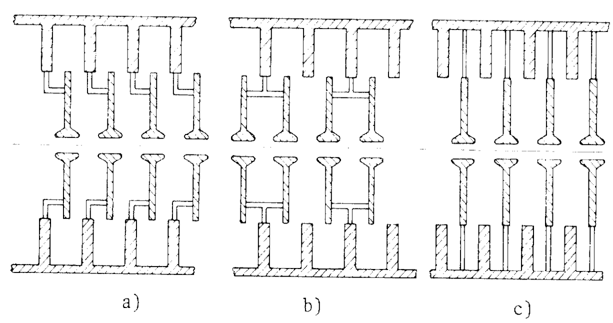

Fig. 8 Disk-and-washer structure with a) L supports, b) TO supports and c) radial supports.

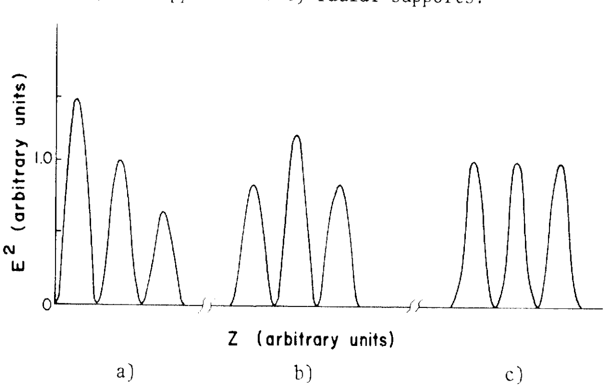

Fig. 9 Bead pull data giving the square of the on-axis electric fields corresponding with the a) L supports, b) TO supports and c) radial supports shown in Fig. 8.