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HIGH ENERGY ACCELERATING STRUCTURES FOR HIGH GRADIENT PROTON LINAC APPLICATIONS*

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Summary

The high-energy part of a proton linac, following a drift tube section, accelerates protons and H^- ions of energies above 150 MeV. High efficiency and high gradients in the accelerating structure considered for this part of a proton linac are the objectives of this study. Several known and improved structures working at 1350 MHz were optimized for maximum shunt impedance. The study was performed with the extensive use of a computer code -- SUPERFISH. The theoretical results of this study are presented.

Introduction

The efficiency of the drift tube linac structure drops dramatically for particle velocities in excess of half the velocity of light. In the region of β = 0.5 to β = 1.0, the coupled-cavity structures promise better efficiency for the acceleration of particles.

At the present time LAMPF is the only major facility to employ such a structure for the acceleration of protons. It uses the so-called "side-coupled linac" structure, invented by Knapp and Nagle at LASL for this application.[1] In the side-coupled structure, and other structures to be discussed in this paper, the main accelerating cavities are coupled together through a resonant coupling cavity to form a biperiodic chain of coupled cavities. In the side-coupled structure, the coupling cavity is off-axial and coupled to the two adjacent accelerating cavities through a pair of localized slots. A variation on this is the ring-coupled structure[2] where the coupling cavity is an annular ring surrounding the accelerating cavities, and coupled to them by a number of slots distributed around the circumference of the cavities. Because of the geometry, the ring-coupled structure lends itself to a more strongly coupled chain of cavities, and, as such, may represent an improvement over the side-coupled structure.

The efficiencies of the coupled structure are degraded from the basic single cavity efficiency by 5 to 15% due to the coupling slots and additional septum thickness. In these cases, the accelerating cavity is excited in the lowest TM mode. An exception to this, a structure which also operates in the $\pi/2$ mode, has been studied by V. G. Andreev[3,4], and employs a basic accelerating cavity operating in a higher TM mode (TM_{020}). This structure, called the disk and washer structure, can be thought of as a biperiodic chain of coupled cavities, operated in the $\pi/2$ mode, and terminated so that the coupling mode is essentially unexcited.

With the successful development of LAMPF, and the acceleration of intense beams of protons beyond the energy limits of the drift tube structure, numerous applications in medicine and industry are being recognized for intense, high energy proton beams.[5,6] The National Cancer Institute is supporting a program of accelerator development at LASL aimed at the extension of proton linac technologies to produce the most suitable Pion Generator for Medical Irradiations (PIGMI). A general description of this program was presented at the last proton linear accelerator conference in Chalk River.[7] The low energy part of that linac design was described in another paper at that conference.[8] In this paper we wish to describe the optimization work which has been done on the high energy portion of such a linac for pion production in a medical environment.

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Optimization of the Accelerating Cavities

In our search for a most efficient accelerating structure, we considered the LAMPF side-coupled structure as the reference design. However, several other variations of the side-coupled system have been proposed and in some cases developed into operating systems. We have considered these geometries in our considerations also. In our study we extensively used the new, and very powerful, computer code SUPERFISH.[9,10] SUPERFISH calculates the electromagnetic fields in an axially symmetric cavity for any mode with axial symmetry, using a block matrix inversion approach. Output includes all cavity parameters, field line plots, field on axis plots, and power distribution on the cavity walls. SUPERFISH can also calculate multicell cavity geometries. The calculation of the higher order modes is extremely important in a case when one of the higher order modes is used for the acceleration.

We scaled the 805 MHz LAMPF optimized accelerating cavity to the 1350 MHz frequency and recalculated all the parameters for different βs. The most important parameter, the effective shunt impedance, is shown in Fig. 1 as a function of $\beta = v/c$ for optimized gap factor $\alpha = g/L$, where g is gap and L is cavity length. The LAMPF side-coupled structure (LASC in our notation) using this cavity at the 805 MHz frequency has the coupling coefficient equal to $\sim$ 5%. The side-coupled cavity system loses about 5% in effective shunt impedance due to the presence of the coupling slot in the cavity wall. The so-called ring-coupled structure which uses the same accelerating cell with a coaxial cavity as a coupler between two adjacent cells, has approximately the same shunt impedance, but the coupling coefficient can be as high as 15%. The structures which use the modified LAMPF optimized cavity with the different on and off axis couplers usually have a slightly lower effective shunt impedance and we did not consider them for our purposes.

A recent development in coupled-cavity accelerator structures has been described by V. G. Andreev which provides an order of magnitude greater coupling than the LAMPF side-coupled structure. We will also take this structure into consideration for the PIGMI application. The cross section of this so-called disk and washer structure (DAW1) can be seen in Fig. 2. When the structure is terminated, as shown in Fig. 3a, it supports a standing wave mode with a strong longitudinal electric field on the axis to serve as the accelerating mode. When the structure is terminated, as shown in Fig. 3b, it supports a standing wave mode that serves as a coupling mode. The geometry can (and must) be chosen so that the frequency of these two modes are the same, which leads to the confluence of the dispersion curve in the $\pi/2$ mode. The change in dimensions of one region affects both frequencies. Indeed, the frequency change is different for the accelerating mode and coupling mode. Moreover, one frequency can be increased while the other one can be decreased with the same geometrical perturbation. There are also two additional frequencies corresponding to the zero and π modes. The field lines for all four frequencies as calculated by the SUPERFISH

program are shown in Fig. 4. One can see that the part of the cavity close to the axis is very similar to the LAMPF cavity, and we have found that geometrical perturbations in that part of the cavity have approximately the same affects on the cavity parameters as they have in the case of the LAMPF cavity. Therefore, we used the data from our previous optimization of the LAMPF cavity and applied them to the DAW1.

The next step was to optimize the outer part of the cavity. The disk thickness t_2 and the radii R and R_1 have an effect on the shunt impedance and mode frequency. These parameters were optimized consistent with certain mechanical constraints. Then we calculated the effective shunt impedance for different βs at optimum gap factors α. The results are shown in Fig. 1, and one can see that the effective shunt impedance (ZT^2) of DAW1 is slightly below the data for the LAMPF cavity. The practical value of ZT^2 may be 5% lower than this theoretical value due to the losses on the washer supports. The other calculated parameters and dimensions of the optimized cavities for different βs are summarized in Table I.

TABLE I

GEOMETRY AND CAVITY PARAMETERS FOR DAW1

β	0.4	0.6	0.8	1.0
f_0 [MHz]	700	735	751	750
$f_{\pi/2}$ [MHz]	1350	1350	1350	1350
f_π [MHz]	1556	1631	1666	1668
Z [MΩ/m]	46	74	87	95
Q	19850	29554	27990	30400
T	0.831	0.83	0.823	0.805
ZT^2 [MΩ/m]	31	51	59	60.6
α	0.4	0.5	0.55	0.6
R [cm]	16	15.2	14.8	14.3
R_1 [cm]	11.3	10.85	10.5	10.2
R_2 [cm]	11.5	11.05	10.7	10.4
r_B [cm]	1.1	1.1	1.1	1.1
r_N [cm]	0.25	0.25	0.25	0.25
t_1 [cm]	0.7	0.7	0.7	0.7
t_2 [cm]	0.8	0.8	0.8	0.8
g [cm]	1.8	3.33	4.88	6.66
L [cm]	4.44	6.66	8.88	11.11
Θ [°]	30	30	30	30

The advantages of the DAW1 structure are:

1. The high coupling coefficient (∿ 60%) makes the structure less sensitive to beam loading effects at high current operation.

2. The high coupling coefficient makes the structure significantly less sensitive to manufacturing tolerances.

3. Manufacturing of DAW1 may be easier than the side-coupled structure.

4. The vacuum conductance of DAW1 is higher, thus the vacuum system might be less complicated.

Among the disadvantages of DAW1 one has to mention that the rf power is dissipated almost entirely on the washer, which means that it has to be water-cooled, since the heat conductivity to the outside wall is very poor. One can use the washer supports for water flow; however, this requires vacuum-water joints, a delicate thing from vacuum leak considerations. Another disadvantage of DAW1 is a lack of convenient locations for high power drive points. RF drive is almost restricted to be at the end plates of the cavity system.

We have been attracted by the properties of the disc and washer structure, and in our optimization studies, we tried to improve its ZT^2 and some other parameters. We shaped the washer to make it thicker so that mechanically it is improved, and the cooling is easier. The shaped cavity is shown in Fig. 5. The effective shunt impedance for this shaped washer structure is approximately the same as that for DAW1, as can be seen in Fig. 1. Other calculated parameters and dimensions of the optimized cavities for different βs are shown in Table II.

TABLE II

GEOMETRY AND CAVITY PARAMETERS FOR DAW2

β	0.4	0.6	0.8	1.0
f_0 [MHz]	705	800	866	930
$f_{\pi/2}$ [MHz]	1350	1350	1350	1350
f_π [MHz]	1532	1655	1724	1900
Z [MΩ/m]	48	77	90.1	95.2
Q	18841	25900	27990	30400
T	0.831	0.83	0.823	0.807
ZT^2 [MΩ/m]	32.5	53	61	62
α	0.4	0.5	0.55	0.6
R [cm]	16	13.8	12.5	11.6
R_1 [cm]	11.2	10	9.4	8.5
R_2 [cm]	11.4	10.2	9.5	8.7
r_B [cm]	1.1	1.1	1.1	1.1
r_N [cm]	0.25	0.25	0.25	0.25
r_2 [cm]	1.0	1.0	1.0	1.0
t_1 [cm]	0.7	0.7	0.7	0.7
t_2 [cm]	0.8	0.8	0.8	0.8
g_1 [cm]	1.80	3.33	4.88	6.66
g_2 [cm]	1.1	1.5	2.44	3.33
L [cm]	4.44	6.66	8.88	11.11
Θ [°]	30	30	30	30

We found some other interesting features of this new configuration -- DAW2. It still has four mode frequencies (see Fig. 6), but one can see also the concentration of the field not only on the cavity axis but also around the second cone farther from the axis. The field separation became more pronounced in the π/2 mode which results in less perturbation due to the washer supports. The other improvement coming from the outer cone is that the accelerating and coupling mode frequencies are more independent; that is,

locations can be found where removing or adding material in the cavity affects either one mode or the other almost exclusively. This makes tuning much easier. Another effect is that the coupling mode becomes loaded by the cone's capacity; therefore, the cavity radius could be made smaller for the same resonant frequencies. Figure 7 shows the radii of all three structures as a function of β. The curve for the LASC corresponds to the radii of the main cell only, whereas the curves for the DAW structure corresponds to the entire structure.

We have calculated the rate of change of the two frequencies (e.g., "accelerating cell" frequency, $fr2$, and "coupling" frequency, $fr3$) due to perturbations of various physical dimensions in the range 1200 to 1500 MHz. The most important parameters for the tuning procedure for DAW2 with β = 0.6 are shown in Table III. One possible tuning strategy for the "coupling cavity" might be to trim a small amount of material from the corner of the "coupling cavity," represented by r_2 in Table II and in Fig. 5, which had purposefully been made a bit excessive during manufacture. This trimming can be done after the disk and washer are completed in a single unit. Thus, the best way to tune the coupling cell is to remove the material from the corner and/or from the outer cone. Either procedure has an almost negligible effect on the change of the "accelerating cell" frequency. The accelerating cell can be tuned by increasing its diameter or removing material from the cone on the cavity axis. Similarly, this has negligible effect on the frequency of the coupling cell.

TABLE III

TUNING EFFECTS OF PARAMETER CHANGES FOR DAW2

Parameter	$fr2$	Rate [MHz/cm]	$fr3$	Rate [MHz/cm]
$R_2\uparrow$	↓	120	-	-
$R\uparrow$	-	-	↓	210
$R_1\uparrow$	-	-	↑	190
$t_1\uparrow$	-	-	↓	240
$r_2\uparrow$	-	-	↓	80
$g_2\uparrow$	-	-	↑	240
$g_1\uparrow$	↑	210	-	-

We have calculated also the power dissipation on the segments of the cavity surface to see how it is distributed along the cavity. In both cases, DAW1 and DAW2, there is a little power dissipated in the disk and on the outer wall of the cavity (10%). Almost all power is lost in the washer (90%). Total power for the whole cavity is around 900 W at 1 MV/m acceleration rate, as calculated by SUPERFISH. It is obvious that the washer has to be cooled. We propose four washer supports which can be made hollow for water transfer into the washer.

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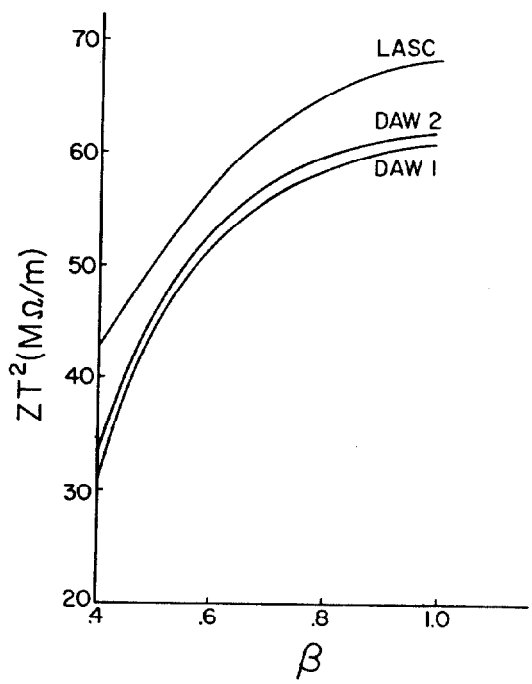

Fig. 1. Effective shunt impedance of three considered structures as a function of β.

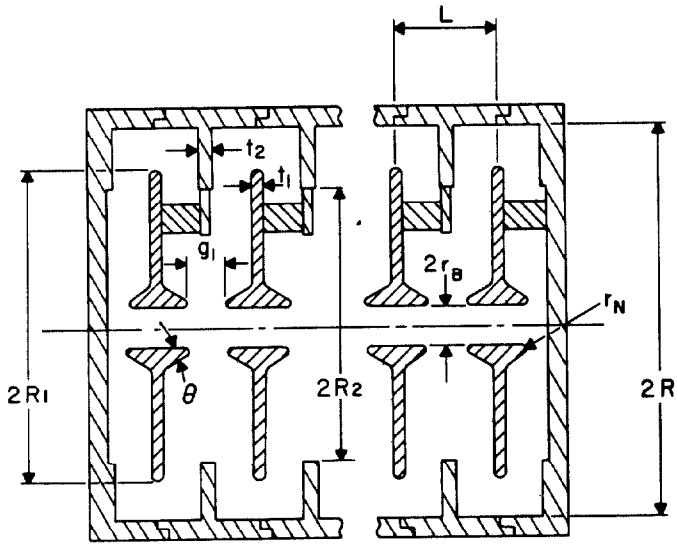

Fig. 2. Disk and washer structure -- DAW1.

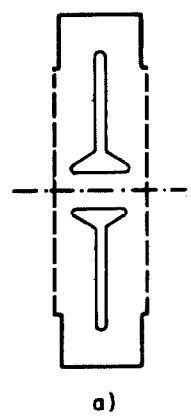

Fig. 3a. DAW1 segment with the accelerating mode.

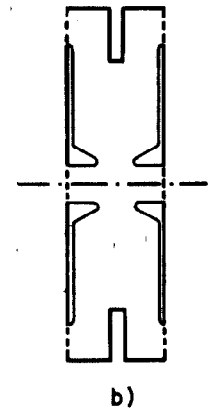

Fig. 3b. DAW1 segment with the coupling mode.

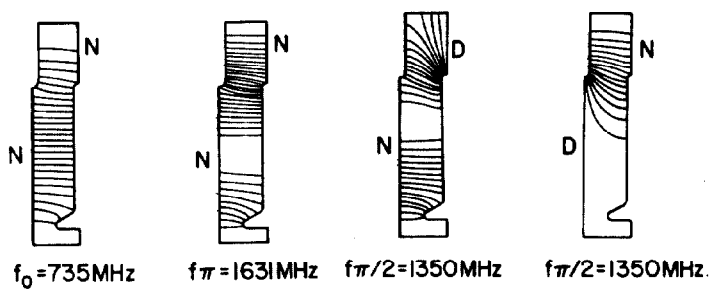

Fig. 4. Field patterns in a quadrant of the DAW1 cavity with the different boundaries. N marks the Neumann-type and D the Dirichlet-type boundaries (β = 0.6).

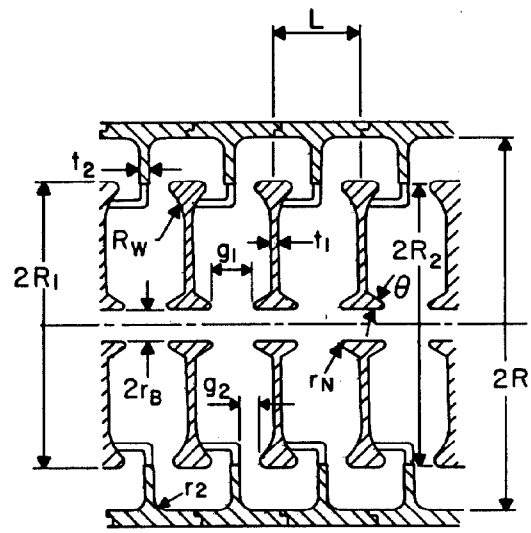

Fig. 5. Disk and washer structure, DAW2, with the shaped washer.

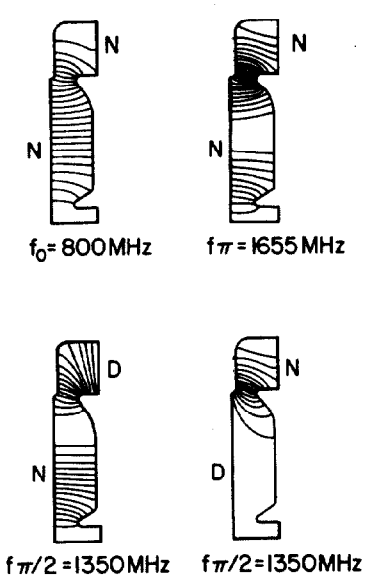

Fig. 6. Field patterns in a quadrant of the DAW2 cavity with Neumann (N) and Dirichlet (D) type boundaries (β = 0.6).

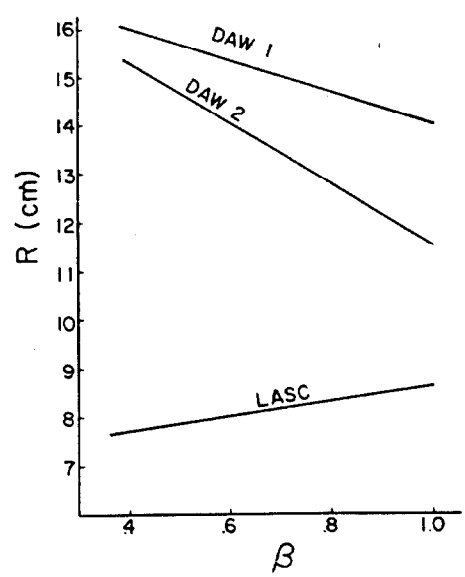

Fig. 7. Cavity radii for LASC, DAW1 and DAW2 versus β.