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ACCELERATING STRUCTURE RESEARCH AT LOS ALAMOS*

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Introduction

The design of a novel accelerating tank utilizing the electrical stability of the $\pi/2$ mode of operation, but having shunt impedances characteristic of the π-mode of operation has been described previously.[1-6] This side coupling principle, with some modifications, is now used in the accelerating system for the proposed L.A.M.P.F. Meson factory Linac. Several refinements in design have been made which raise the shunt impedance of this type system considerably above the values quoted in previous reports. In addition high power tests have been completed showing the design will withstand high gradient operation with no adverse characteristics. In prototype construction no fabricational problems have arisen.

Side Coupled Accelerator Tanks

Experimental studies[1,2] and an equivalent circuit analysis[2,4,6] have shown that $\pi/2$ mode operation of a long chain of accelerating cavities has many advantages over operation in the π-mode. Among these are: (a) the symmetry of close lying modes results in a first order cancellation of effects due to frequency errors in the cells comprising the chain. This results in very loose mechanical tolerances in the fabrication of the components in these tanks, (b) phase shifts due to energy transfer down the tank, while appreciable in π-mode structures, are negligible in $\pi/2$ mode standing wave operation, (c) electric field level and phase between cavities in the chain is unaffected in first order by heavy beam loading, (d) much longer tanks are possible than with π-mode systems. However, in an ordinary periodic system, such as a disk loaded waveguide, operation in the standing wave $\pi/2$ mode means a reduction in shunt impedance of approximately a factor of 2 over operation of a similar structure in the π-mode. The side coupled system avoids this loss, as well as opening up new possibilities for increasing the shunt impedance even further.

In the standing wave $\pi/2$ mode alternate cavities are not excited. By making use of this fact and placing alternate cavities off of the beam centerline, the high efficiencies realizable in π-mode weakly coupled systems may be realized in $\pi/2$ mode operation.[1,2] Coupling strengths of ~4% are adequate for systems with up to 100 cells, and may be easily attained with small slots placed in the high magnetic field region near the outer wall of the cavity.[6] By placing these coupling cavities outside the beam line it is possible to have several significant advantages over locating these cavities on the beam line.

1. It is possible to decouple the problem of achieving high shunt impedance from the problem of transferring energy from the feedpoint down the tank. This is possible because the coupling slots may be small and in the outer wall.
2. No interaction between the empty cavities and the beam is possible, reducing the possibility of transverse mode interaction and possible exitation of unwanted fields at the fundamental frequency in the empty cavities.
3. One may have access to the empty cavities (here called coupling cavities) for tuning, field measuring, and other operations necessary for proper alignment of the system.
4. The low field values in the side cavities make it possible to attach the vacuum equipment at this point without adversely effecting the electrical performance of the system.
5. A bridge cavity, storing energy but translated from the beam line, is easially incorporated into the accelerator tanks, allowing long tanks to be broken for focusing magnets without altering their electrical behavior. This allows each tank to use the full power output of the amplifiers without requiring power splitting, and thus attendant temperature control problems.

These points are all mentioned in the references quoted. Figure 1 shows a cutaway view of a side coupled accelerator structure. This particular model was made for $\beta = 0.4$ (about the lowest energy in LAMPF) and has shaped cavities for optimum shunt impedance. The coupling slots are formed by the intersection of a cylindrical cavity (the coupling cavity) and the toroidally shaped outer wall of the accelerating cavity. Small bosses are placed on the septa to increase the axial electric field slightly, and to raise the transit time factor through the cavity. The exact shape of the accelerating cavity has been optimized by using L.A.L.A.,[7] a digital computer mesh program which calculates the electric and magnetic field distributions, losses, frequencies and other derived parameters for cylindrically symmetric cavities with arbitrary boundaries. While this code does not include the effects of the coupling slots, they are small enough so that they provide a small perturbation on the final results obtained. Typically measured shunt impedances, for multi-cell tanks, are 80-85% that calculated by L.A.L.A. for equivalent geometrical dimensions. Table I shows several representative calculations by L.A.L.A. and the measured parameters for systems built to the L.A.L.A. derived dimensions. It appears that about half of the difference between L.A.L.A. calculations and model measurements are due to the copper surface finish and the remainder are due to the slot perturbations.

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Table I

Cavity	L.A.L.A. ZT^2	L.A.L.A. Q	L.A.L.A. T	Measured ZT^2	Measured Q	Measured T
Single cell shaped cavity, β = 0.65	45 MΩ/m	26,000	--	43.5 MΩ/m	24,500	--
5 cell β = 1 tank	52 MΩ/m	35,000	0.78	42 MΩ/m	28,500	0.775
39 cell β = 0.65 tank	34.5 MΩ/m	21,836	0.85	28.9 MΩ/m	17,800	0.83

Five Cell β = 1 Accelerator

A five cell accelerator tank with cells designed by the L.A.L.A. program to have optimum shunt impedance and cut to be synchronous for relativistic particles has been built. With this accelerator tank it has been possible to verify our shunt impedance calculations, test sparking characteristics at full gradient with accelerated beam present, work out tuning procedures for short tanks, study some rf window problems, and get data on outgas rates in the presence of strong rf fields. Figure 2 shows a cutaway drawing of this tank.

This accelerator tank, designated Model L, has performed exceptionally well in all tests made to date. The tank is composed of 5 full cells, and thus is not a periodic system in the true sense of the word. The gaps in the end cells are cut to give the proper frequency at the $\pi/2$ mode and this non-periodicity only affects modes other than the $\pi/2$ mode, the major effect being a small change in the dispersion curve near the 0 and π modes. The frequencies of the individual cells were adjusted before brazing to yield a continous dispersion curve through the $\pi/2$ mode. Power is introduced into the center cell through an iris cut in the outer wall. A ceramic disk in the plane of this iris provides a vacuum seal, and has caused no sparking problems as yet. During the matching of this iris to the waveguide the center cell frequency had to be adjusted to retain the proper overall frequency. The iris size is at present cut to provide unity coupling with no beam being accelerated, but may be enlarged in the future. 160 keV electrons have been injected into Model L and accelerated up to a maximum of 4 MeV over its one meter of length. The 4 MeV/m maximum energy gain gradient was imposed by considerations of personnel radiation safety, and this limit will be extended as soon as a shielded room is completed. No indication of sparking, other than a few normal cleanup sparks, has been observed at the gradients we have studied to date. Figure 3 is a graph of the observed output energy vs. input power for Model L. The measured shunt impedance of 41.7 MΩ/m is in agreement with the energy gained as a function of power to the accuracy of the experimental measurements. The curve shown in the figure is calculated by making a stepwise integration of the particle motion through the 5 cells of the tank. Experimentally determined field distributions were used in this calculation. The phase slip present due to the nonsynchronism of the electrons with the accelerating wave reduces the energy gain somewhat from what would be expected if phase synchronism were present throughout the length of the section. Energy gain was measured using a magnetic analyzer at the output of the section.

Tests remaining include operation in a heavily beam loaded condition. Currents accelerated to date have been severely limited by the shielding available. Tests with currents up to 20 mA peak are contemplated in the near future with this accelerator section.

Thirty-nine Cell β = 0.65 Prototype Tank

Designated Model F, this accelerator tank is not built using the optimized cavity shapes, but has accelerating cavities of cylindrical cross sections with heavy capacitive loading. Figure 4 shows a cross section of the accelerating cavity and associated coupling cavities for a section of this tank. Figure 5 shows Model F before the cooling jacket was installed, and Figure 6 shows Model F in place ready for rf testing. The mechanical fabrication of Model F is described in detail by H. G. Worstell in another paper at this conference.[8] Tuning procedures are also described in detail in a separate paper.[9] Discussion in this paper will be limited to tests performed on the tank with beam and at high rf power levels, and a brief discussion of final tank parameters.

Table II lists the parameters of the Model F accelerator tank, including final measurements of field level, amplitude, phase, etc.

Table II

Model F Parameters

ZT^2	28 MΩ/m	Number of cells	39
Q	17,800	Stop band	20 kc
$\Delta\phi$ cell to cell	<0.2°	Nearest neighbor coupling	4.7%
Input VSWR	1.075	Accelerator cell second nearest neighbor	-0.9%
$(\Delta E/E_{ave})$ max	= 1.2%	Coupling cell second nearest neighbor	0.5%
f	= 805 MHz		

The predicted tolerance to frequency errors[2,6] was verified during the tuning of this model. With ~500 kc errors $\Delta E/E$ was ~5%, which was reduced to ~1.2% by tuning the accelerating cells to minimize the field in the coupling cell toward the drive from the cell being tuned.[1,2,6] This tuning procedure worked very well, and the location of the side cavities makes this operation quite simple by making the coupling cells accessible for measurement. The residual tank unflatness appears to be associated with errors in slot length (e.g., coupling constant).

Figure 7 illustrates the dispersion curve obtained after the final tuning was completed. The parameters are listed on the curve.

High power operation has been very successful. This single tank has operated satisfactorially at 1 MW peak power and 3% duty factor, representing exitation to gradients double that expected in LAMPF and average power corresponding to 12% operation of LAMPF. No sustained sparking was encountered in raising the accelerating gradient to ~2.5 MV/m after a region of multipactoring at very low power levels was passed through. The heat dissipation characteristics of the tank are adequate to allow 12% duty factor at 1.25 MV/m gradient.

Electron beam measurements have been made verifying the measured shunt impedance to 2%, the accuracy of the measurements. The electron beam has also been used to drive transverse modes in the tank. However, no qualitative measure of the transverse mode shunt impedance has been obtained in this way. No non-harmonic mode exitation such as has been seen at SLAC has been observed in the tests we have done so far.

Measurements of single cell transverse mode shunt impedance have been made and are reported elsewhere at this conference.[10] It appears that by varying the outside diameter of the accelerating cavities keeping the fundamental mode frequency fixed (by varying G/L, the capacitive loading in the cavity), the transverse mode frequency may be made to vary from tank to tank and also be made to avoid any harmonic relationship to the 805 MHz (or 201.25 MHz) fundamental.

Future Plans

A 60 cell optimized shunt impedance accelerator tank is under construction and should be completed within two months. This will be a $\beta = 0.65$ tank, with additional provision to use a bridge coupler to connect two 25 cell sections together. Tests of sparking, vacuum, cooling, and alignment stability will be undertaken with this tank, as well as measurement of all of the electrical parameters associated with an accelerator tank of this type.

We plan to build a multi-tank high current electron accelerator to mockup as many of the accelerator tank problems as possible before settling on a final design for the LAMPF accelerator tanks. Some design parameters for this system are listed in Table III.

Table III

Accelerated Particles	electrons
Frequency	805 MHz
Injection Energy	100 keV
Tank No. 1 (pre accelerator)	
Number of cells	6
Cell length	Graded (β = 0.5 to 0.94)
RF power	<100 kW @ 12%
Output energy and current	1 MeV @ 25 mA peak
Tank No. 2	
Number of sections	4 coupled by bridge couplers
Number of cells	100
Synchronous β	1.0
RF power	1 MW @ 12%
Energy gain and current	20 MeV @ 25 mA peak
Beam loading	50%
Maximum average current	3 mA
Energy gain gradient	1.07 MeV/m
Unloaded energy gain	30 MeV

The accelerator is divided into two parts, an injector section which accelerates to 1 MeV and uses a separate power source whose phase may be varied with respect to the major portion of the accelerator tank, and the 100 cell accelerator proper. This allows the phase of the electron beam to be varied to allow checkout of the phase servo control systems to be incorporated in the high power rf amplifier systems. It also allows the graded phase velocity section to be built separately from the constant length cell section, separating these problems. The existing 1 MW rf test stand will be used to provide power for the prototype, requiring a modest waveguide run. The 100 cell tank is divided into 4 sections coupled by resonant bridge couplers. This is mostly to mockup conditions in LAMPF, but these bridge couplers should also effectively shorten the tank as far as transverse mode propagation within the tank is concerned. We expect to use the beam for studies of target heat dissipation problems for LAMPF.

While this small accelerator certainly does not mock-up exactly the conditions expected in LAMPF, it does allow studies to be made of many of the systems problems expected in the longer proton accelerator, and should also be a valuable test of the capabilities of the side coupled accelerator tanks as high duty factor electron linac components.

Acknowledgments

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References

1. E. A. Knapp "800 MHz RF Structures," Conf. on Proton Linear Accelerators, 4th, Midwestern Univ. Res. Assoc., July 20, 1964. p. 31-59 (MURA-ZA-4).
2. E. A. Knapp, IEEE Trans. Nucl. Sci. V. 12, No. 3, p. 118-127, 1965.
3. B. C. Knapp, et al, IEEE Trans., Nucl. Sci., V. 12, No. 3, p. 623 - 626, 1965.
4. D. E. Nagle "Coupled Resonator Model of Linear Accelerators," 4th, Midwestern Univ. Rex. Assoc., July 20, 24, 1964, p. 21-30 (MURA-LZ-4)

5. "A Proposal for a High Flux Meson Facility," Los Alamos Scientific Laboratory, Sept. 1964.
6. B. C. Knapp, et al, IEEE Trans. Nucl. Sci., V. 12, No. 3 p. 159-165.
7. H. Hoyt, et al, R.S.I., V. 37, No. 6, p. 755-762, June, 1966.
8. H. G. Worstell, "Design, Development, and Fabrication of Multicavity 805 MHz Accelerator Tanks," 1966 Linac Conf., Los Alamos, N.M., p.169.
9. L. N. Engel and E. A. Knapp, "Tuning and Field Measurement Techniques in a Resonantly Coupled Accelerator Tank," 1966 Linac Conf., Los Alamos, N.M., p. 132.
10. J. M. Potter, "Transverse Modes in Resonantly Coupled Accelerator," 1966 Linac Conf., Los Alamos, N.M., p. 109.

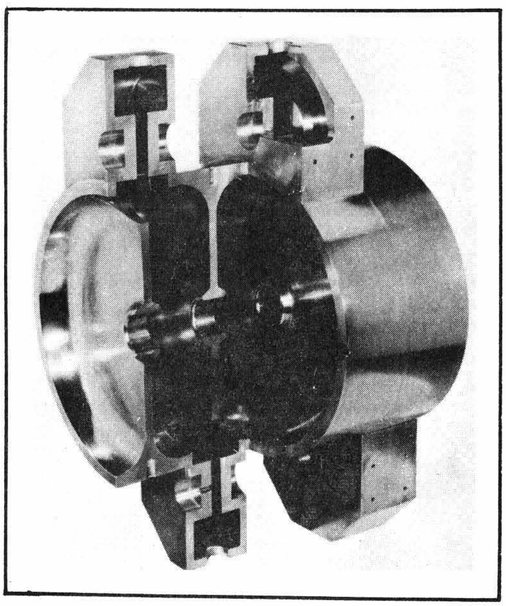

Fig. 1. Cutaway view of a side-coupled accelerator structure.

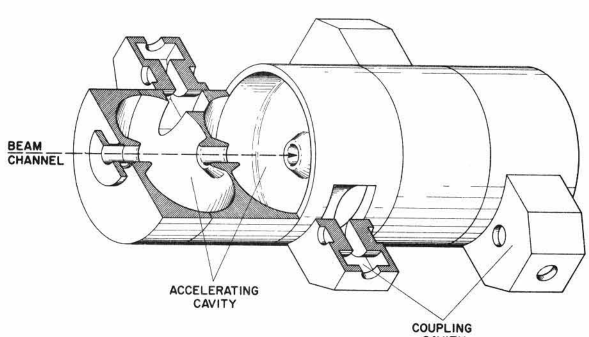

Fig. 2. Cutaway drawing of a side-coupled accelerator with $v_p/c = 1$.

DISCUSSION

E. A. KNAPP, LASL

FEATHERSTONE, Univ. of Minnesota: You referred to the tuning procedure, but you didn't say what you did when you tuned the tank. You said you excited one cell, but you didn't say what happened after that.

KNAPP: Yes, the tuning is done in the same way that the waveguide was tuned at SLAC: that is, in the beginning the tank is built several hundred kilocycles low in frequency, and then the outer walls are bent to make the frequency correct. We tune up to the frequency that we desire--you cannot overshoot.

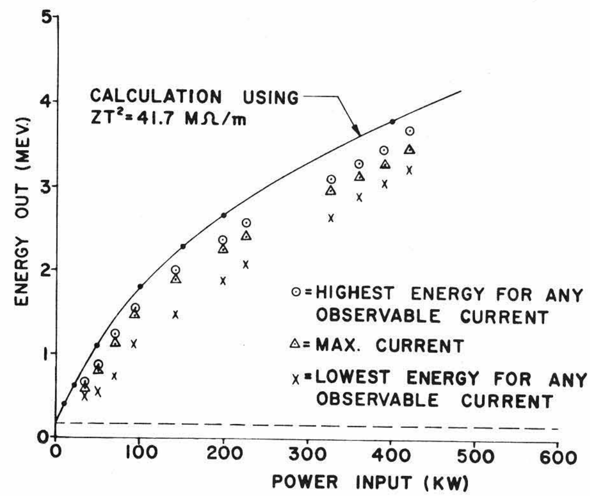

Fig. 3. Output energy of Model L vs drive power.

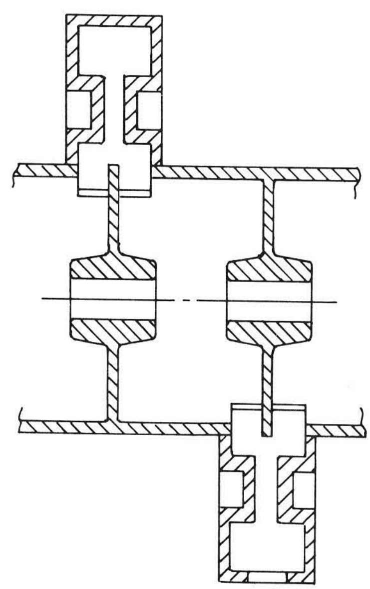

Fig. 4. Cross section of Model F accelerating cavity and associated coupling cells.

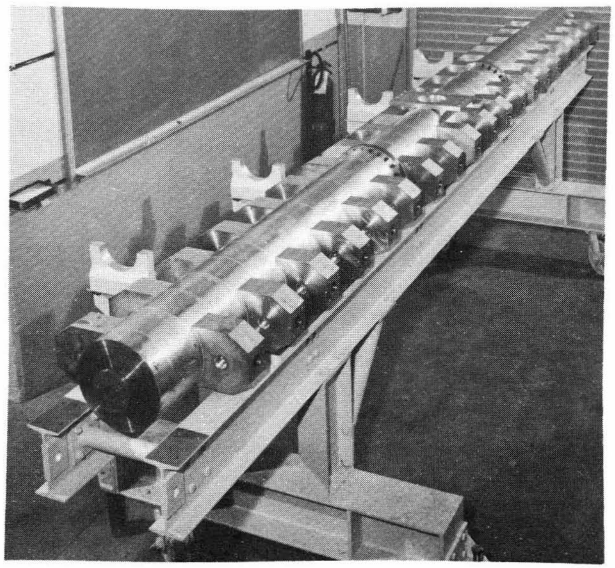

Fig. 5. Model F prior to installation of cooling tubes and vacuum manifold.

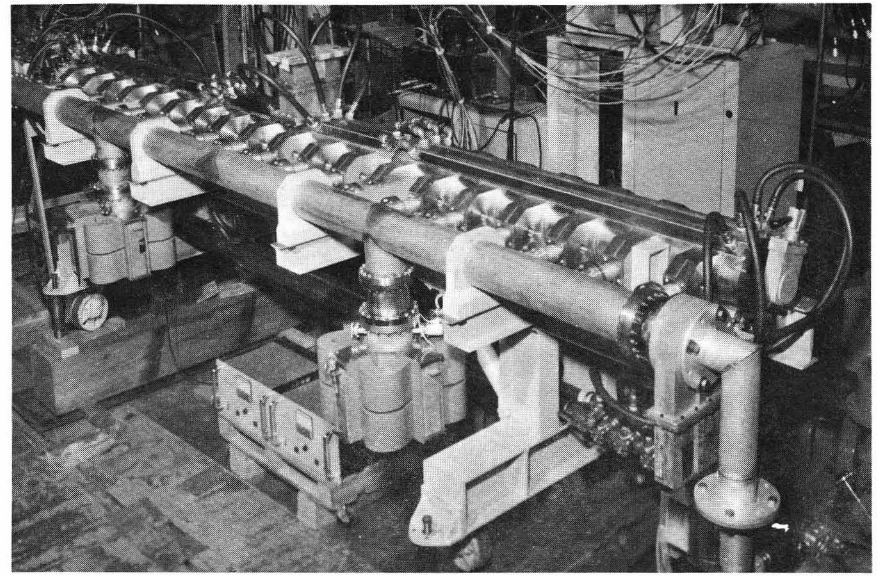

Fig. 6. Model F completed and under high power test.

SIDE COUPLED CAVITY DISPERSION RELATIONS

$$\omega^2 = \frac{\omega_1^2(A) + \omega_2^2 B \pm \sqrt{\left[\omega_1^2 A + \omega_2^2 B\right]^2 - 4\omega_1^2\omega_2^2\left[AB - K^2\cos^2\phi\right]}}{2\left[AB - K^2\cos^2\phi\right]}$$

K=CELL TO CELL COUPLING K′=① TO ① COUPLING K″=② TO ② COUPLING

$A = 1 + K''\cos 2\phi \qquad B = 1 + K'\cos 2\phi$

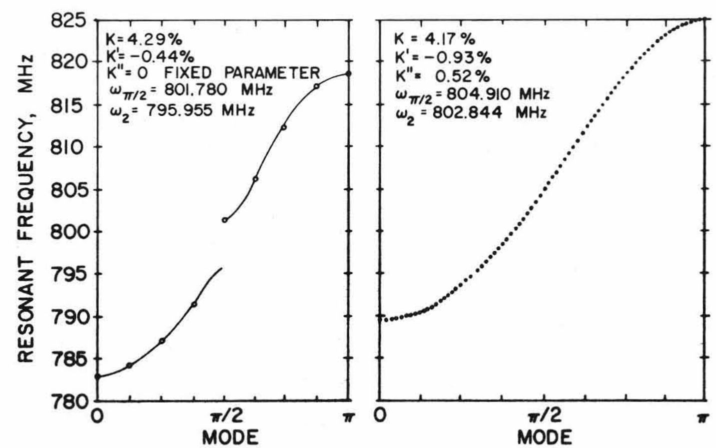

Fig. 7. Dispersion curve during initial prebraze tuning and after final tuning for Model F.