Development and Test of an Accelerating Cavity Shape for a Superconducting Linear Collider*

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INTRODUCTION

In order to use superconducting RF accelerating structures in the construction of a linear collider certain criteria must be addressed. Foremost of these criteria is the high accelerating gradient. This requirement might be more accurately expressed as the accelerating gradient per unit cost. We see therefore that cost/unit length is also a primary criteria. The cavity must be designed so that input power can be coupled in and higher order mode (HOM) power may be coupled out to the degree required by beam stability considerations.

At this time in the development of superconducting RF accelerating cavities, the accelerating gradient is limited by two phenomena, electron field emission and thermal breakdown. The first of these makes it imperative to choose a cell shape that minimizes E_{pk}/E_{acc} and the second phenomena to minimize H_{pk}/E_{acc} (the ratio of the peak surface fields to the accelerating gradient). As field emission is the dominant gradient limitation, there is considerable premium in lowering E_{pk}/E_{acc}. The cell to cell coupling (K) is also effected by the shape.This is true of the coupling of the HOM's as well as the fundamental TM_{010} mode. Because of this, the number of coupled cells comprising an accelerating unit is limited. A larger number of cells/module helps reduce the structure cost by reducing the number of couplers as well as by improving the filling factor for the machine. An effort is made here to increase the number of cells per module to 10.

Another consequence of the cell to cell coupling in the TM_{010} mode is the relative ease of tuning the structure to achieve uniform accelerating gradient along the length of the unit.

DESIGN OF THE STRUCTURE

In order to test our ability to produce an accelerating structure which best meets the requirements of a linear collider, a series of calculations were made in which we tried to design the shape of the structure which had the following properties:

- •Low E_{pk}/E_{acc}.
- •Tolerable cell to cell coupling (K) in the TM_{010} mode.
- •More than 5 cells/unit.
- •Low cost.
- •Tolerable Q_{ext} in all HOM's with couplers on the beam pipe.

Although it is straightforward to reduce E_{pk}/E_{acc} by reducing the beam pipe radius BT, this is undesirable because the transverse wakefields increase as BT^{-3} which makes it more difficult to control multibunch instabilities and meet alignment and vibration tolerances for the linac.

The family of cavity shapes that were considered are shown in figure 1.

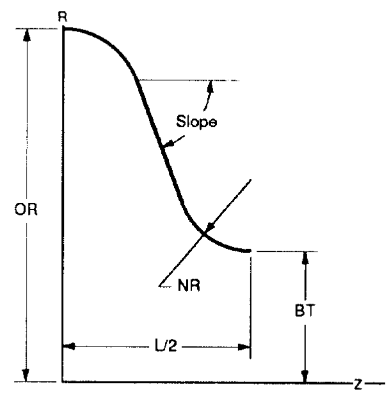

FIGURE 1.

Five independent variables describing the shape were explored:

OR, the outside radius.
BT, the beam tube radius.
L/2, the half length of the cell.
NR, the nose radius, and
Slope, the slope of the straight wall segment.

The OR which primarily determines the fundamental mode frequency is adjusted in all cases to obtain the desired value. The L/2 value is determined by the frequency as the particles to be accelerated must be kept in phase with the RF oscillations. Namely L/2 must be equal to 1/4 wavelength.

This leaves three parameters to explore. The functional relationships are shown in table 1.

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	K	E_{pk}/E_{acc}	R/Q
BT radius ⇑	⇑	⇑	⇓
NR radius ⇑	⇓	⇓	⇑
Slope ⇑	⇑	⇑	⇑

TABLE 1

Unfortunately, the coupling, K, tends to vary in the same direction as the E_{pk}/E_{acc} whereas we want K to be high and E_{pk}/E_{acc} to be low. The final list of parameters that were chosen are as shown in table 2.

Frequency	1500 MHz
OR (radius)	9.48 (9.43 ends) cm
NR (radius)	1.90 cm
BT (radius)	3.56 cm
Slope	70 degrees
L/2	4.93 cm
Coupling K	1.8%
E_{pk}/E_{acc}	2.1
R/Q	89 ohms/cell
H_{pk}/E_{acc}	57 gauss/MV/meter

TABLE 2.

Table 3 compares this TESLA shape to various other cavity shapes, all scaled to 3 GHz.

	LEP	Tristan	CEBAF	Wupp.	TESLA
# of cells	4	5	5	20	10
E_{pk}/E_{acc}	2.3	1.97	2.56	3.0	2.1
H_{pk}/E_{acc}	39	41	47	42	57
K	1.8%	1.5%	3.3%	4%	1.8%
BT dia. cm	2.82	2.83	3.3	3.5	3.56

TABLE 3

Consideration of the coupling (or damping) of all the HOM modes is very complex. An analytical technique[1] based on URMEL was used to predict the Q_{ext} of each of the HOM's. This value, along with the calculated value for R/Q of all the modes, gives us the shunt impedance, the pertinent parameter to be considered for beam stability. The dipole HOM modes, in particular, tend to be trapped in the center cells. It was determined that if the overlap of the pass-bands of the TM_{110} and the TE_{111} mode could be minimized, then the situation for damping all the pass-band members from the end cells was most favorable.[2] For a 10 cell cavity of the new shape, the calculated impedances ($R/Q*Q_{ext}$) for the monopoles and the dipoles up to 4 times the fundamental frequency are given in figure 2A and 2B. A comparison is made to the Cornell/CEBAF shape for the first few pass-bands.For the monopoles the R/Q is in Ω/cell and for the dipole the R/Q is given as longitudinal impedance in Ω/cell at 0.5 cm off the beam axis for a 3 GHz fundamental mode cavity. R/Q's are calculated using URMEL-T. The Q_{ext} values are calculated for both shapes using the method described in[1], which assumes a beam pipe coupler placed at both ends of the cavity. The highest Q_{ext} was about 10^6 for a family of monopole modes near f/f_0 =2.7, suggesting a trapped mode.[3] An improved program based on URMEL with a variable mesh showed that the highest Q_{ext} for monopoles in this region could rise to $5x10^6$.

Multibunch instability calculations are necessary to determine whether these impedances will be tolerable in a TeV linear collider.

In order to minimize the number of couplers required on the cavity module, the cells were polarized in a manner such that both polarizations of the dipole modes could be damped with one coupler.[4]

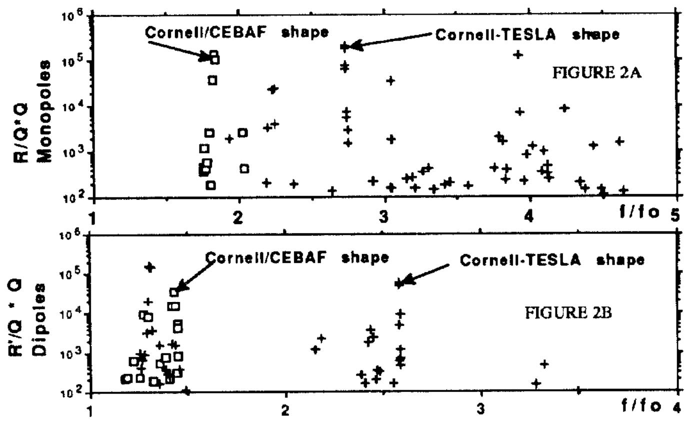

FIGURE 2.

CONSTRUCTION.

The plan was to focus our efforts on a ten cell structure. Calculations on cell to cell coupling indicated that this large number of cells should be satisfactory. This length of cavity, however, had two practical difficulties: 1) It would not fit into our available test stand, and 2) It would not fit into our furnace for final heat treating for field emission.[5]

In view of these restrictions, we manufactured a ten cell copper structure and a six cell niobium structure. These structures were made with no couplers.The parameters for this structure are shown in Table 2. With the rather low cell to cell coupling value (K), there was concern that the tuning for a level field profile would be difficult to achieve. This was one of the reasons that the ten cell copper structure was made. The tuning was, in fact, not difficult, even on the ten cell structure.

[1] W. Hartung et.al.,Proc. 1st International TESLA Workshop, Cornell Univ., 1990, p44

[2] D. Saraniti,Proc. 1st International TESLA Workshop, Cornell Univ., 1990, p466

[3] A. Mosnier,Proc. 1st International TESLA Workshop, Cornell Univ., 1990, p502

[4] J. Kirchgessner et.al.,Proc. 1989 PAC, Chicago, p479

[5] Q. S. Shu et.al.,Proc. 1989 PAC, Chicago, p491

Records were kept of the cost of construction including tuning and chemistry for the niobium six cell structure. These costs are shown in table 4.[6]

LTP6-1 Costs	Structure Cost	Cost/meter
Material	$1992	$3327
Deep Drawing	$456	$762
Welding	$720	$1202
Grinding	$35	$58
Beam Tubes	$293	$489
Flanges	$252	$421
Tuning	$512	$855
Chemistry	$1067	$1782
Total	$5327	$8896

TABLE 4.

These costs are considerably lower than previous structures because of the use of thinner material (1/16" instead of 1/8"), elimination of weld steps at the iris and equators, and the absence of couplers.

A special test stand, as shown in figure 3 was designed and constructed for this cavity. The stand provided adjustable RF input coupling and vacuum pumping, both at the bottom of the structure. This design provided good test results because of the minimization of contamination of the inside surface from above.

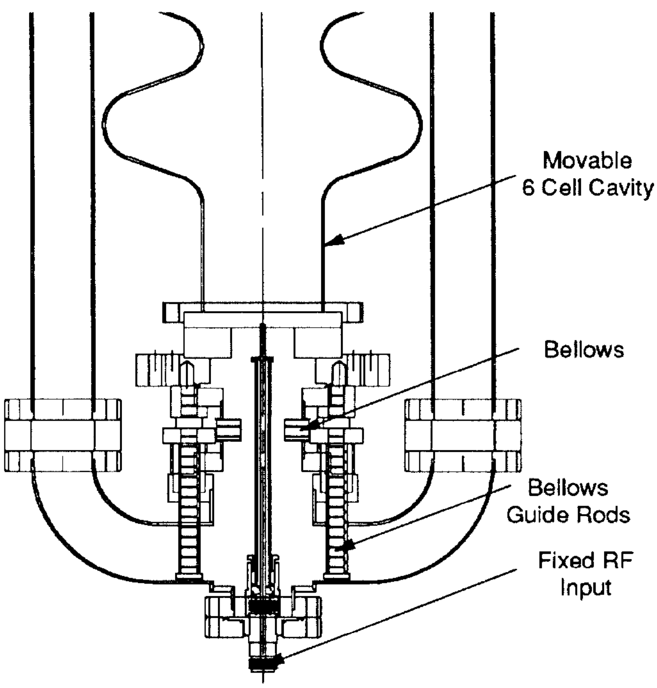

FIGURE 3.

[6] J. Kirchgessner,Proc. 1st International TESLA Workshop, Cornell Univ., 1990, p562

TEST OF CAVITY

This six cell niobium cavity (LTP6-1) was initially tested twice. In both tests the structure reached fields of E_{acc}=18 MV/meter with considerable field emission, but final thermal breakdown.

In order to reduce field emission we wished to vacuum fire the structure. Because the cell walls were only 1/16" thick, three longitudinal braces were welded to the equqtor of each of the cells to prevent distortion during firing and collapse during later tests.

In the process of welding on these braces, a gun arc in the EBW (electron beam welder) melted a 1/2" diameter hole in one of the cells. A very careful repair was made and when the cavity was remeasured at room temperature it was found to still retain adequate tune of all cells to give a level field profile.

The cavity was retested at this stage and the results were not very good. There was thermal breakdown at an E_{acc} level of 8-10 MV/meter.

After a heavy etch to hopefully remove the new defect, the cavity was fired for four hours at 1500 deg. C in a standard titanium lined niobium box.

After firing, the structure was rinsed but the titanium was not chemically removed from the outside of the structure. In this final test, the E_{acc} value achieved was 15.3 MV/meter. The results of these three test series are shown in figure 4. As can be seen in all cases, the Q of the structure was good. The field profile after heat treatment has not yet been measured. More heat treatment tests are planned.

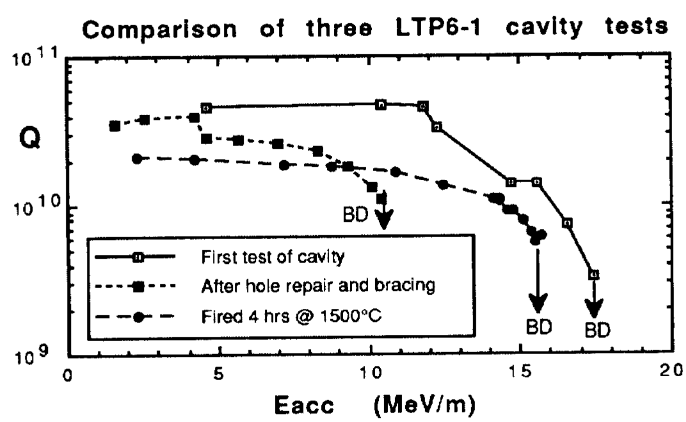

FIGURE 4.

CONCLUSIONS

The work on exploring new structures for a superconducting linear collider has only begun. The achievable accelerating gradient and the structure costs are of the utmost importance. The present values are within a factor of two of the desired values.

The question of operating frequency as well as other system parameters and HOM damping requirements need to be answered as soon as possible to allow research and development to proceed at a rapid pace.