INDUSTRIAL DEVELOPMENT OF CORNELL SUPERCONDUCTING CAVITIES FOR CEBAF

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ABSTRACT

Properties of the Cornell five-cell superconducting accelerating cavity and the suitability of this cavity for the CEBAF linac are discussed. The advanced technology required to produce these cavities was already known to some companies and is being transferred to others. The status of development of these cavities by industry, including test results on three of these cavities, is discussed.

CAVITY PROPERTIES AND REQUIREMENTS

The principal properties of the CEBAF/Cornell 5-cell elliptical superconducting cavity and the requirements of CEBAF are summarized in Table I. Some of the properties of this cavity have been described previously.[1]

High frequencies for superconducting cavities are favored by high geometrical shunt impedance (r/Q, proportional to the frequency, f), handling ease, reduced material usage ($\propto f^{-2}$ to f^{-3}), reduced susceptibility to microphonics, and by lower rf surface area and corresponding lower probability of a surface defect of a given size ($\propto f^{-2}$). Low frequencies are favored by fewer modules per unit length ($\propto f^{+1}$), lower temperature-dependent Bardeen-Cooper-Schreiffer (BCS) losses ($\propto f^2$), and lower transverse impedance ($\propto f^3$). The frequency of 1500 MHz was chosen by Cornell as an optimum compromise between these factors. CEBAF requires a frequency greater than 900 MHz. Since each successive bunch can be routed to a different one of the three end stations[2], the effective frequency at each end station is 1/3 of the rf frequency; a bunch repetition frequency of less than 300 MHz would be objectionable because the associated time interval between bunches would exceed the resolving time of the detectors.

After eliminating some initial design defects, a total of ten independent tests were conducted on the four 5-cell prototypes with complete input and higher-order-mode (HOM) output couplers built at Cornell. The average gradient reached in these ten tests was 8.2 MV/m; the highest value achieved was 15.3 MV/m. Fewer than 4 prototypes would be objectionable because design defects whose occurrence or severity fluctuated from one unit to another could easily go undetected. Fewer than ten independent tests would be objectionable because the fluctuations in performance from one surface preparation to another would not be adequately determined. Based on these results, a design specification of 5.0 MV/m was chosen for CEBAF. This gradient is sufficiently high to make a recirculating linear accelerator based on this technology economically feasible. Since each cavity in CEBAF is powered independently[3], any cavity whose gradient capability exceeds the specification can be used to full advantage.

TABLE I. CORNELL CAVITY PROPERTIES AND CEBAF REQUIREMENTS.

Property	Demonstrated, Cornell	Required, CEBAF
Frequency, MHz	1500	≥ 900
Accelerating gradient, MV/m	8.2 (Avg.)	≥ 5.0
Residual Q, × 10^{-9}	3.9 (Avg.)	≥ 3.0
Beam current transported, mA	22	0.8
Beam breakup threshold, mA	> 10 (in CEBAF)	≥ 0.2
Q_{ext}, input coupler, × 10^{-6}	0.007 - 100	2.2
Aperture diameter, cm	7.0	≥ 3.8
HOM power extracted, watts/m	>280	0.5
Power coupled into beam, kW/m	26	4

The average temperature-independent residual Q (Q_{res}) at high field achieved in the ten tests mentioned above was $3.9 \cdot 10^9$. Based on these results, the specification chosen for CEBAF is $3.0 \cdot 10^9$. This value is high enough to result in a reasonable refrigerator size and operating power.[4]

Two of the Cornell prototypes were tested with beam in CESR, Cornell's electron-positron storage ring. One of the quantities measured was the maximum current that could be passed through the cavity without driving the superconductor normal or inducing objectionable phenomena other than multi-bunch instabilities, which were suppressed with feedback during this measurement. The current obtained was 22 mA, compared to the 0.8 total mA required for CEBAF with four passes of the beam through the linac. The simultaneous operation of two superconducting cavities to store a beam in the CESR ring demonstrated that there is no problem associated with the use of multiple high Q cavities of this design.

The beam test of the cavities also served to verify the HOM impedances which were determined by bench measurements, SUPERFISH[5], and URMEL[6]. The instability threshold currents computed by a Monte-Carlo program[7] using the measured and computed cavity impedances agreed within a factor of two at all probability levels with the measured instability threshold currents[1] (the measured thresholds were generally greater than the computed ones). The mechanical tune of the cavities was stepped, and the instability threshold measured for each step; a threshold probability distribution was constructed from this information. A beam test is important to verify the higher order mode measurements for a number of reasons: the computer codes which are used compute the geometric impedance (r/Q), but cannot determine the external Q (Q_{ext}), which is controlled by the HOM extraction couplers; the couplers do not have cylindrical symmetry, and can disturb the mode patterns so that the computed r/Q values are inaccurate, and even the number of modes which exist can be affected: the density of modes is so high at several times the

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fundamental frequency that mode overlap makes accurate measurements of Q_{ext} values challenging; accurate measurement of the r/Q is difficult with the couplers present because the low resulting Q_{ext} makes perturbation measurements subject to instrumentation errors, and the couplers must be terminated in matched loads or the mode patterns will be altered; accurate measurements of the longitudinal impedances of modes which are hybridized transverse electric modes is difficult; and determination of the Q_{ext} values is made more difficult by the simultaneous propagation of several modes in the HOM or fundamental transmission lines. Using the r/Q and Q_{ext} values which were measured and computed, and which are supported by the beam test results, the beam breakup threshold computed for CEBAF using these cavities is in excess of 10 mA[8] of output current. Since the design output current of CEBAF is 200 µA, this provides a safety factor of 50. The principal longitudinal impedances are listed in Table 2, in order of decreasing impedance. The transverse impedances, r"/Q, are equal to the longitudinal impedance of a deflecting mode divided by the square of the distance of the beam from the mode axis (the beam is specified to be at the azimuth where the impedance is highest). The principal transverse impedances are listed in Table 3. T. a transverse impedances r"/Q of the quadrupole and sextupole modes are specified at a distance of 10 mm from the mode axis; their importance is reduced if the beam is centered to better than 5 mm.

The Q_{ext} value of the fundamental mode of the CEBAF/Cornell cavity can be varied between 7,000 and 10^8 by changing the location of the short on the input waveguide stub. The Q_{ext} value required for CEBAF is $2.2 \cdot 10^6$; this value represents overcoupling by a factor of 3 at full beam. This overcoupling is done to triple the bandwidth of the rf controls[3], to permit the cavity to be operated at full beam and a gradient as low as 0.83 MV/m, to permit the accelerator to be upgraded for operation in excess of its design current, and to reduce the sensitivity to microphonics. The disadvantage of overcoupling by this factor is a 20% power reflection at full beam.

The aperture of the CEBAF/Cornell cavity is 7.0 cm. The beam optics are such that, under normal conditions, the aperture occupied by the beam is over an order of magnitude smaller than this[9]. The aperture required under abnormal conditions to ensure that lost beam strikes room temperature surfaces and not helium temperature surfaces is 3.8 cm.

The power transferred to the beam in the Cornell beam test was 26 kW/m. This establishes the ability to transfer power into the cavity without being limited by problems at the vacuum windows or normal conducting to superconducting interface. The required power transferred to the beam in CEBAF is 4 kW/m. In the Cornell beam test, the Q_{ext} value of the fundamental mode was 150,000 and the rf dissipation in normal conducting surfaces with heat conducted into the liquid helium was equivalent to a Q of $5 \cdot 10^9$. With a Q_{ext} value for CEBAF of $2.2 \cdot 10^6$, the equivalent Q becomes $7.5 \cdot 10^{10}$.

The HOM power extracted in the Cornell beam test was 280 watts per meter. Due to the small charge per bunch and the comparatively low circulating current in CEBAF, less than 0.5 watts per meter of HOM power is generated in CEBAF; this power is small enough that it can be dissipated in the liquid helium. The ability of the CEBAF/Cornell cavity to extract ≥99.9% of the HOM power from the cryogenic region is not important in this case. However, rejection of the fundamental mode by the HOM extraction circuitry is important if the HOM coupler is to be terminated in the liquid helium. Arbitrarily high rejection of the fundamental can be obtained without tight mechanical tolerances by using the cut-off waveguide employed on the CEBAF/Cornell cavity; obtaining adequate rejection using a TEM-line with filters requires extremely tight tolerances or the use of two or more filters in series.

The CEBAF/Cornell cavity has been demonstrated to operate satisfactorily at temperatures between 1.8 and 2.35 K. A temperature of 2.0 K has been chosen for CEBAF as an economic optimum[4].

The CEBAF/Cornell cavity has an r/Q of 960 Ω/m, operates in the

TABLE 2. PRINCIPAL LONGITUDINAL IMPEDANCES

Order	Mode	f, MHz	r/Q, Ω/m	Q_{ext}	r, kΩ/m
1	$TM_{010}(\pi)$	1499.28	959.89	350000.	335962.
2	Coupler	1795.	66.6	66000.	4395.6
3	0-Theta	4413.	16.1	39000.	627.9
4	0-Theta	4435.	7.62	29500.	224.8
5	TM_{011}	2907.	246.	700.	172.2
6	$TM_{010}(3)$	1481.689	0.775	68800.	53.3
7	TM_{020}	3074.	7.8	6500.	50.7
8	TM_{020}	3002.	18.34	2100.	38.51
9	0-Theta	4417.	21.6	1700.	36.72
10	$TM_{010}(4)$	1494.074	0.121	145000.	17.49
11	TM_{011}	2769.	9.6	1600.	15.36
12	TM_{011}	2851.	13.7	800.	10.96
13	0-Theta	4407.	2.94	3300.	9.7
14	TM_{020}	2947.	6.9	1100.	7.59
15	TM_{020}	3044.	1.1	3400.	3.74
16	TM_{011}	2809.	3.2	1000.	3.2
17	$TM_{010}(2)$	1466.807	0.056	-37300.	-2.08
18	TM_{020}	3087.	0.1	11000.	1.1
19	$TM_{010}(1)$	1454.997	0.033	-27300.	-0.89
20	TM_{011}	2743.	0.078	8000.	0.624

TABLE 3. PRINCIPAL TRANSVERSE IMPEDANCES

Order	Mode	f, MHz	r"/Q, Ω/m^3	Q_{ext}	r", MΩ/m^3
1	2-Theta	3630.8	27000.	170000.	4590.
2	2-Theta	3622.7	2500.	1100000.	2750.
3	TE_{111}	1888.3	69500.	32000.	2224.
4	1-Theta	3507.8	2400.	780000.	1872.
5	1-Theta	3506.5	2500.	740000.	1850.
6	2-Theta	3640.6	12000.	150000.	1800.
7	1-Theta	3718.8	5700.	300000.	1710.
8	1-Theta	3509.2	11000.	150000.	1650.
9	2-Theta	3623.2	2500.	630000.	1575.
10	TM_{110}	2109.5	100000.	13000.	1300.
11	1-Theta	3510.7	9300.	130000.	1209.
12	TE_{111}	1888.1	69500.	16000.	1112.
13	2-Theta	3641.5	12000.	86000.	1032.
14	1-Theta	3699.8	2900.	330000.	957.
15	Coupler	1795.	14200.	66000.	937.2
16	2-Theta	3631.5	27000.	33000.	891.
17	TE_{211}	2570.4	9300.	90000.	837.
18	TE_{211}	2570.4	9300.	83000.	771.9
19	TE_{111}	1968.8	164000.	4000.	656.
20	TM_{110}	2085.9	50000.	10000.	500.
21	1-Theta	3525.0	5100.	98000.	499.8
22	TM_{110}	2121.8	11100.	40000.	444.

π mode, and has an active length of 0.5 m. Shorter lengths (i.e., fewer cells) would have the disadvantage of more modules per meter and a lower beamline filling fraction. Longer lengths have the problem that some of the HOM's exhibit objectionably small intercell coupling; this creates two problems: small dimensional errors in the cells can cause the HOM energy to be concentrated in cells where the HOM couplers cannot effectively extract it, and the intercell coupling can be so small that energy does not flow fast enough from the cells in which it is deposited by the beam to the cells from which it can be extracted. One might suspect that the relatively large aperture of 7 cm would prevent such problems. However, the calculation described below, performed in August 1983, demonstrates that this is not the case. The higher mode properties of a cavity having the same cell shape as the CEBAF/Cornell cavity was evaluated using SUPERFISH. In order to avoid effects associated with the different size of the full end cells, the case studied consisted of three full cells with a shorted half end cell at each end. Within each 7 cm diameter iris, an imaginary, very thin iris of adjustable diameter opening was inserted. The mode structures of the cavity for various openings in the thin iris were computed. Two HOM passbands, at approximately three times the fundamental frequency, exhibit particularly objectionable behavior, and are shown in Figure 1 as a function of the opening in the thin iris. Notice that the greatest frequency separation (lowest dimensional sensitivity) of the 4th and 5th members of the lower passband occurs at an opening of about 1.75 cm, and that this spacing decreases greatly as these modes approach the frequency of the lowest member of the upper passband (i.e., as the thin iris is removed). This clearly demonstrates that the largest iris opening does not necessarily correspond to the greatest intercell coupling for a particular mode.

Another design property exhibited by the CEBAF/Cornell cavity is referred to as "light cone symmetry." Although this property is not important at CEBAF's design bunch charge of $8.3 \cdot 10^5$ electrons, it could be important should much higher bunch charges be of interest at some time, and may be important for other applications. The concept of light cone symmetry is illustrated in Figure 2. For purposes of the illustration, an image charge is flowing on a wall at radius r_0 from the beam. The beam pipe is disrupted (for example, by a cavity), and then resumes at the same radius r_0. A first path length is defined as a straight line connecting the two beam pipes. A second path length is defined as a straight line segment from the end of the beam pipe to an hypothetical boundary, plus a second straight line segment from this point back to the continuing beam pipe. As long as the second path length minus the first path length exceeds the bunch length for all actual boundaries for which cylindrical symmetry is violated, light cone symmetry is said to be preserved, and the head of the bunch is unable to influence the tail of the bunch (on the same bunch passage) with a reflection from any surface for which cylindrical symmetry is not preserved. In view of the fact that the bunch must be centered in the SLC to better than 100 microns, it is clear that such symmetry can be important for high bunch charges.

The total voltage experienced by a speed-of-light particle passing parallel to the axis in a cylindrically symmetrical mode in a cylindrically symmetrical cavity is independent of the distance of the beam from the axis. However, the fields in the input coupler do not have cylindrical symmetry, and therefore cause a deflection of the beam. The deflection of the centroid of the beam can be compensated by static steering elements, but the difference in deflection of the head and the tail of the bunch cannot. Although this is an extremely small effect, the very low emittance of the bunch makes the effect objectionable[9]. There are eight cavities in a cryomodule between magnetic elements in the linac; by alternating the directions of the feed waveguides in a --++++-- pattern, the effect can be reduced to a negligible level (this is similar to what is done in the SLAC linac). Complete cancellation of the effect, although unnecessary, can be accomplished on all four passes through the linac by suitable variations in the gradients at which various cavities are operated. Such variations can be kept small if they exhibit the same periodicity along the linac as the betatron trajectory of a particle on the same pass.

INDUSTRIAL DEVELOPMENT

With the design of a superconducting cavity which is completely suitable for use in CEBAF in hand, the next required step is to develop the capability to produce these cavities at a rate suitable for construction of CEBAF. The production of 418 cavities plus 18 spares in a period of two years is required. Industrial involvement to achieve this rate is desirable.

In order to develop and demonstrate industrial capability to build these cavities, nine cavities are being built by four companies. Eight of these cavities will be installed as pairs in four cryostats to form what are referred to as "cryo-units". Cryo-units are the smallest individually usable components of the linac. Four cryo-units are joined together to form a cryomodule. The cryostats have been designed at CEBAF[10] with substantial input from outside experts.

The four companies building the nine industrial prototype cavities have all had representatives visit Cornell, and Cornell has made drawings, forming dies, computer numerically controlled milling machine information, and a fabrication procedures document available to these companies. In addition, personnel from Cornell have visited each of the companies to assist in solving any problems encountered in manufacturing the cavities.

The status of the prototype cavities is shown in Table 4. Note that the prior experience of the four companies in manufacturing superconducting cavities is quite diverse.

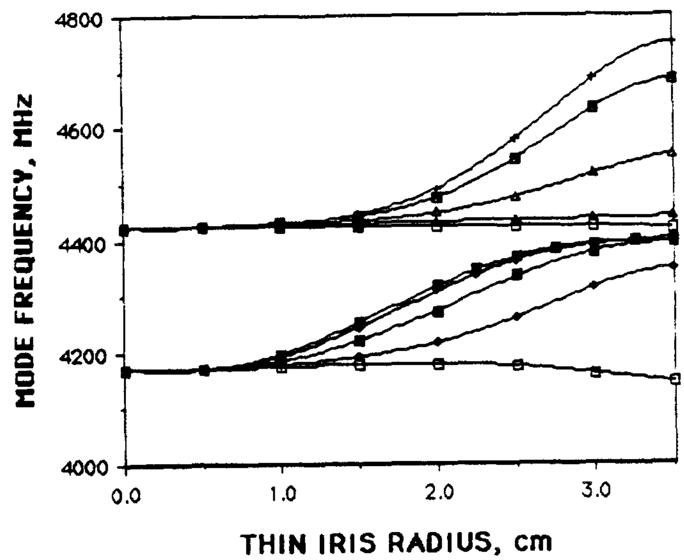

FIGURE 1. HOM PASSBANDS VS. IRIS RADIUS

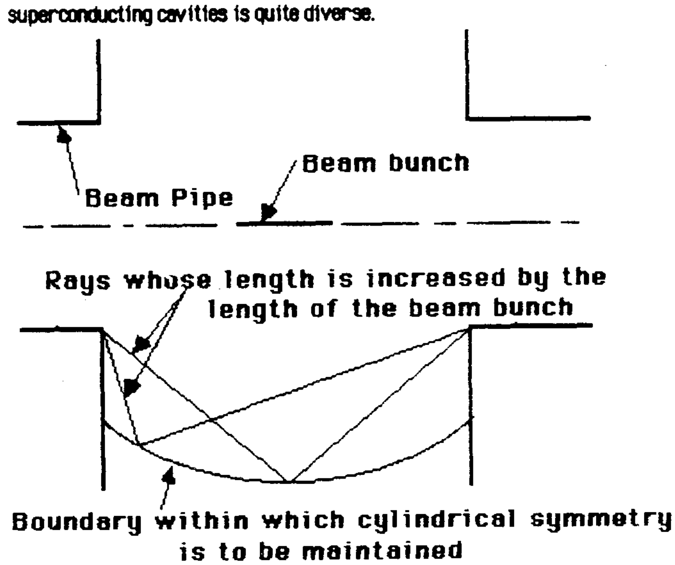

FIGURE 2. LIGHT CONE SYMMETRY.

INDUSTRIAL PROCESS IMPROVEMENTS

Each of the companies fabricating prototype cavities has introduced some modifications to the manufacturing technique which the respective company believes is better suited to their available manufacturing equipment, is less expensive, or involves lower risk.

Dornier eliminated the machined step at the equator of the cells, and used a separate fixture to maintain alignment of the cup halves during welding. This procedure eliminated the need to coat the machined steps with chemical resist during acid cleaning; this coating is normally required to preserve the precision of the fit of the machined steps.

Babcock and Wilcox has modified many of the weld geometries so that the number of welds requiring different sets of parameters is minimized.

TRW has used water soluble lubricant for deep drawing to simplify removal of the lubricant. Water soluble plastic spray has been used in lieu of tape to protect the parts during handling; this again simplifies removal. Non-toxic machining coolants have been used on the niobium in lieu of trichloroethane to avoid the need for ventilation systems and workcenter vapor fences. Solid aluminum mandrels were used in lieu of vacuum chucks for machining fixtures to minimize distortion during machining; similar mandrels were used during tack welding to minimize distortion. A lathe has been used in place of a milling machine to form the steps on the cup edges. The overall procedure used on the cups was modified as follows: with each cup held in the machining fixture, the iris edges are turned in the lathe. Two cups are then welded together, iris to iris. The grinding of the iris welds and the subsequent heavy chemistry is then performed. The machining fixures are reinstalled one at a time, and the pair of cups is held in the lathe using the fixture while the opposite equator edge is machined. This procedure avoids the need for the use of chemical resist to protect the machined edges from excessive dimensional changes.

TEST RESULTS ON INDUSTRIAL PROTOTYPE CAVITIES

Construction of four of the nine prototypes has been completed, and cryogenic tests have been performed on three of these cavities.

Cavities numbers 1 and 3 were manufactured by Interatom. Interatom, in collaboration with the University of Wuppertal, also designed and constructed the tuning, rf, vacuum, chemical, thermometry, and cryogenic apparatus necessary to tune, process, and test these cavities. Both of these cavities were tuned to have a flat field profile and to be at the correct frequency. The fundamental Q_{ext} has not yet been verified.

Cavity number 1 achieved an accelerating gradient of 6.1 MV/m, in excess of CEBAF's minimum specification of 5.0 MV/m. The Q_0 at 2.0 K was $3.3 \cdot 10^9$ at 5.0 MV/m. CEBAF's specification is $Q_{res} \geq 3.0 \cdot 10^9$; combining this with $Q_{BCS}(2.0\ K) = 1.14 \cdot 10^{10}$ yields $Q_0 \geq 2.37 \cdot 10^9$.

Cavity number 3 achieved an accelerating gradient of 6.8 MV/m in its acceptance test. The Q_0 was $7.0 \cdot 10^9$ at 5.0 MV/m. The Q_{res} at low field was $1.8 \cdot 10^{10}$. The breakdown location identified by thermometry in this acceptance test was subsequently ground using an internal grinder, and the cavity was retested. In this test, the cavity achieved 7.7 MV/m and a Q_0 of $7.5 \cdot 10^9$ at 7.5 MV/m. The Q_{res} at low field was $1.3 \cdot 10^{10}$.

A typical thermometry map, taken by the Interatom-Wuppertal collaboration, is shown in Figure 3.

Cavity number 2 was manufactured by Dornier. It was tuned, processed, and tested at Cornell[11]. This cavity was tuned to have a flat field profile, but its initial frequency was 13 MHz low, which was outside the range of tuning capability of the available tuner. The Q_{ext} value was low, primarily as a result of the low frequency.

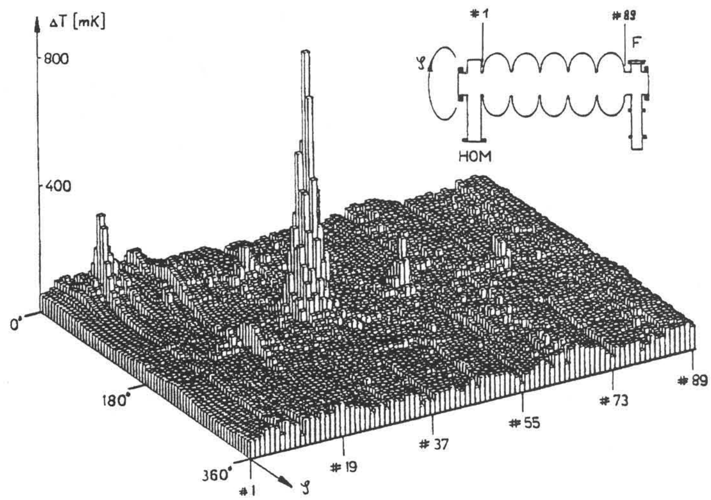

FIGURE 3. Temperature map of a superconducting CEBAF cavity at Eacc = 5.6 MV/m, taken with a thermometry system consisting of a rotating array of 89 temperature sensors. This system scans the cavity surface for enhanced losses and permits guided repair to be performed.[14]

TABLE 4. STATUS OF CAVITY MANUFACTURING AND TESTING

CAVITY NUMBER	MFR.	DATE ORDERED	DATE FABRICATION COMPLETED	DATE TESTING COMPLETED
1	Interatom	9/9/85	12/28/85	2/12/86
2	Dornier	11/8/85	2/1/86	2/12/86
3	Interatom	10/4/85	1/12/86	3/13/86
4	B & W	1/13/86	5/9/86	
5	TRW	1/13/86	(6/6/86)	
6	B & W	1/13/86	(6/28/86)	
7	TRW	1/13/86	(6/30/86)	
8	Interatom	4/23/86		
9	Interatom	4/23/86		

Cavity number 2 achieved an accelerating gradient of 7.9 MV/m on its first test. The Q_0 achieved was $6 \cdot 10^9$ at 7.9 MV/m, and the value of Q_{res} achieved was $2.75 \cdot 10^{10}$ at $\lesssim 5$ MV/m.

Cavity number 4 was manufactured by Babcock and Wilcox. This cavity has been tuned and will be processed and tested at Cornell. The field profile has been tuned to be flat, and an unusually small amount of tuning was necessary to bring the cavity to the correct frequency. The input coupling will be adjusted to the correct value after the first cryogenic test.

CONCLUSION

A well-proven cavity design which meets all of CEBAF's requirements is in hand. Industrial prototyping of cavities of this design has proceeded extremely well so far, with three of three industrially fabricated cavities tested exceeding CEBAF's specifications for gradient and Q_{res}.

Work remaining to be done to complete CEBAF's cavity and cryostat prototyping stage includes completion and testing of 6 additional industrially fabricated cavities. Following successful testing of these cavities individually, they will be tested in a vertical cryostat as pairs. The use of gate valves on the beam lines and Kapton windows on the input waveguides, combined with coupling of the input power into the cavities through the Kapton waveguide windows, permits the cavity pairs to be kept under vacuum during the pair test and permanently thereafter[12]. A test has already been performed on a single cell cavity to verify that there are no unexpected problems with this technique[13]. The pre-tested pair will then be installed in cryostats to form cryo-units, and these will be cryogenically tested.

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