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I. Introduction

High energy physics requires compact accelerators operating at extreme gradients, in excess of 100 MV/m. Scalings for trapping, pulsed-heating and other high-gradient phenomena favor miniature, short-wavelength structures to hold off the large electric fields required [1]. A critical problem in the practical study of such structures is the absence of a high-power, mm-wave source. Study of high-field phenomena at *conventional* wavelengths has required the development of high-power klystrons over several decades of research and engineering [2]. For mm-wave accelerators, we are approaching the corresponding learning curve for high-power handling by a different route, employing an existing accelerator to power mm-wave transfer structures, much as in a relativistic klystron. The benefit of such work is development of know-how in miniature structure fabrication, bench-test, and high-field studies in an accelerator beam environment, in parallel with mm-wave klystron development [3].

Here we report theory and measurements for a single miniature cavity with WR10 output, and 680-μm diameter beam tube, prepared for excitation by a relativistic electron beam. This work establishes that the 3.3-mm wavelength (91.4 GHz) scale is accessible to modern machining and measurement techniques, and provides the basis for understanding of cavity performance as a transfer structure.

II. Tolerances

To appreciate the machining and tuning tolerances involved it is helpful to consult the circuit-equivalent picture of the application, as seen in Fig. 1. A beam bunched at 11.424 GHz passes through the beam tube, exciting the cavity resonance at the 8th beam harmonic, 91.392 GHz. The beam pulse length of 100 ns is much longer than the loaded fill time of the cavity ($T_f \approx$1.5 ns), so that steady-state is reached early in the pulse. In steady-state, the cavity voltage $\tilde{V}_c$ may be may be expressed in terms of the beam current $\tilde{I}_b$ as [4],

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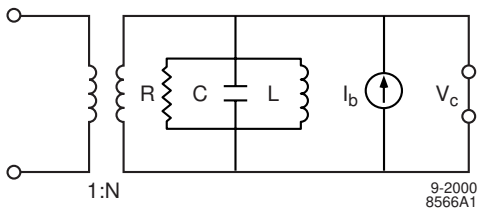

Fig. 1. Circuit equivalent for beam interaction with a single cavity with waveguide output. In the relativistic limit beam-loading admittance is negligible.

$$\tilde{V}_c = -\frac{1}{2}\cos\psi\, e^{j\psi}\, Q_L \left[\frac{R}{Q}\right] \tilde{I}_b, \tag{1}$$

where the beam-coupling parameter "R-over Q" is defined according to

$$\left[\frac{R}{Q}\right] = \frac{\left|\tilde{V}_c\right|^2}{\omega_0 U}, \tag{2}$$

in terms of stored energy U and resonance angular frequency ω_0. The tuning angle ψ is defined in terms of the loaded quality factor, Q_L, and the drive angular frequency ω, according to

$$\tan\psi = Q_L\left(\frac{\omega_0}{\omega} - \frac{\omega}{\omega_0}\right). \tag{3}$$

Power radiated by the cavity into the guide may then be determined according to

$$P_{out} = \frac{\left|\tilde{V}_c\right|^2}{Q_e\,[R/Q]}, \tag{4}$$

where Q_e is the external quality factor. From this one may show that a 10% reduction in power corresponds to a tuning angle of $\tan\psi = 1/3$, or cell detuning of $\delta\omega/\omega \approx 1/6Q_L$. For a loaded quality factor $Q_L \approx 415$,

III. Fabrication and Assembly

The completed geometry is indicated in Fig. 2. We describe next how this geometry was accomplished, with a set of four nominally identical cavities.

The oxygen-free electronic grade (OFE) copper cavity consists of three layers: a 2.44-mm thick plate with the cavity wire-EDM'd and two featureless plates comprising the cavity top and bottom. (The orientaion of the cavity "top" is at positive x in Fig. 2 and bottom is at negative x.) The three layers were diffusion bonded together employing a 1024^{o}C heat cycle at 25 psi for 10 minutes. The input waveguide coupling iris was then cut using sinker EDM. Ultrasonic acetone rinse had no measurable effect on wall

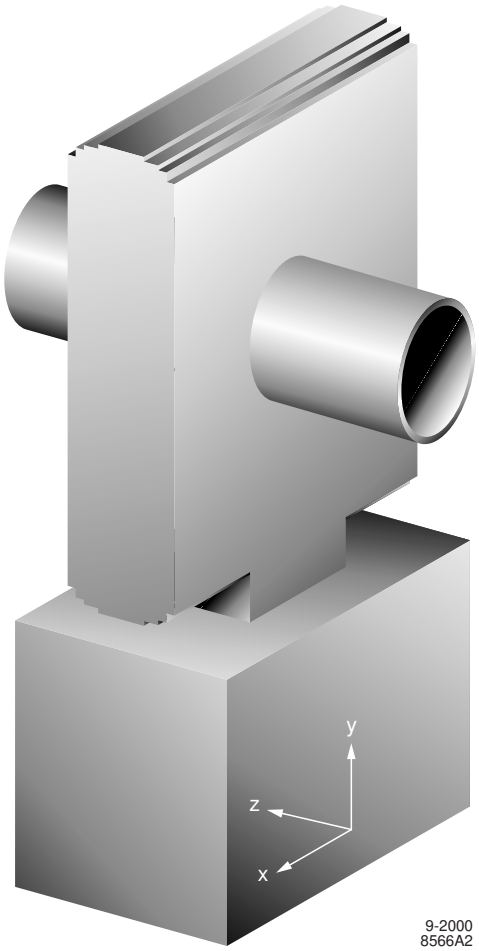

Fig. 2. Geometry of the interior conducting boundaries of the cavity, including coupling iris, beam-tube and WR10 output. The mesh shown is that employed for numerical simulations.

quality factor, and the cavity was subjected to chemical cleaning. This raised the wall Q (prior to cutting of the beam tube) from 1029 to 1252.

A threaded bolt circle conforming to WR10 0.75" flange was machined into the waveguide opening for each cavity. The width ("a" dimension) of the waveguide openings were intended to match the 0.1" wide dimension of WR10 guide, but were accidentally machined 0.1 mm narrower, resulting in a step on each side of the connecting waveguide. Analysis indicated that this would have negligible effect on the measurements.

To cut the beam-tubes, we used sinker EDM for the first, rough cut of the cavity. We then made a final cut of the 340 μm radius using wire EDM. To remove any debris created by the EDM process on the surfaces of the cavity walls, we etched the cavity by pumping an acid solution through the coupling port of the cavity.

IV. Measurements

To determine the state of the cavity, and as an aid in tuning, we employed a home-built W-band vector network analyzer (VNA) [5]. The VNA permits measurement of the steady-state complex reflection coefficient $\tilde{S}_{11}$ over a range

TABLE I
Measured and theoretical parameters for the single cell cavity with and without beam port.

	No Port	Beam Port
Q_w (analytic)	1574	—
Q_w (simulation)	1533	1540
Q_w (measured)	1252	1305
Q_e (simulation)	1400/1370	583
Q_e (measured)	1048	571
β	1.19	2.29
$[R/Q]$ (simulation)	134 Ω	110 Ω

of angular frequencies ω. This may be compared with the theoretical result for single-mode excitation of a resonator [4],

$$\tilde{S}_{11} = \frac{2\beta}{1+\beta}\cos\psi\, e^{j\psi} - 1. \tag{5}$$

The coupling parameter $\beta = Q_w/Q_e$ is the ratio of wall quality factor to external (or "diffractive") quality factor. Combining Eq. (5) with Slater's theorem, we may infer the electric field profile by means of a bead-pull. In this way have assessed the tune, and Q_e, Q_w, and β, as listed in Table I. Measured external quality factor was insensitive to the cleaning steps.

Also seen in Table I are the analytic results for a closed pillbox, and the numerical results for the cavity with beam ports obtained from the finite difference code *GdfidL* [6]. For the analytic comparison, we employed a rectangular pillbox of interior transverse dimensions $a \times b \approx 2.30$ mm$\times 2.44$ mm and transit length $L \approx 0.50$ mm. The corresponding resonance angular frequency is given by $\omega_0 = \beta_0 c$, where

$$\beta_0 = \sqrt{\frac{\pi^2}{a^2} + \frac{\pi^2}{b^2}}, \tag{6}$$

with $c \approx 2.9979 \times 10^8$m/s the speed of light. This gives a frequency of 89.6 GHz; accounting for the volume change due to the fillets from an 8-mil diameter EDM wire (about 0.8%), we calculate the resonance frequency to be 90.1 GHz. The measured frequency of the four cavities varied between 90.1 and 90.8 GHz, variation attributable to wire machining errors. Theoretical wall quality factor for the closed rectangular pillbox geometry may be expressed as

$$\frac{1}{Q_w} = 2\frac{R_s}{Z_0}\frac{1}{\beta_0 L}\left\{1 + \frac{2\pi^2 L}{\beta_0^2}\left(\frac{1}{a^3} + \frac{1}{b^3}\right)\right\}, \tag{7}$$

with $Z_0 \approx 377\Omega$ the impedance of free-space, and $R_s \approx$79 mΩ the theoretical surface resistance of a smooth OFE copper surface at the operating frequency. This corresponds to wall quality factor of 1.57×10^3.

The external quality factor, Q_e, may be calculated by two methods. One is a simple estimation from power transmission through the coupling iris, obtained from HFSS simulation [7]. With a rectangular iris of width 0.83 mm, height 0.5 mm and thickness 0.25 mm, we find $Q_e = 1400$.

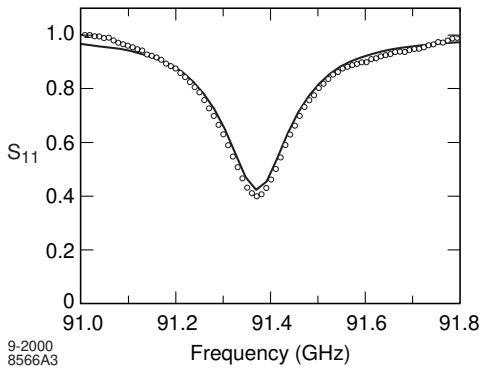

Fig. 3. Reflection coefficient versus frequency, from measurement, and numerical simulation.

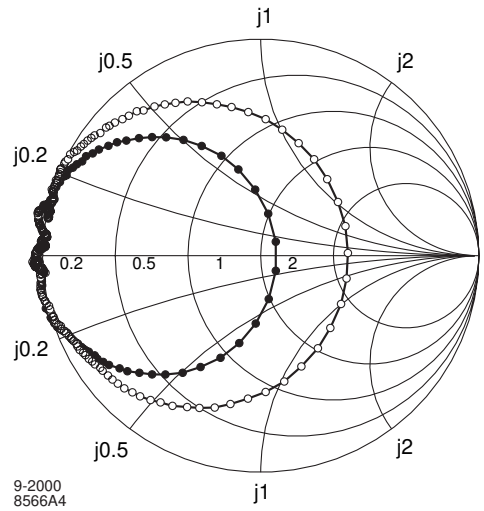

Fig. 4. Smith plot of measured S_{11} for the case of no beam port (black) and with a 680 μm beam port (white). For both cases, we see that the cavity is overcoupled.

A second method utilizes the frequency domain result of the closed cavity-waveguide system to find the complex resonance frequency of the waveguide loaded cavity [8]. This gives a Q_e of 1370 with no beam port. These dimensions correspond to the geometry prior to cutting of the beam tube and the second acid rinse.

The finished assembly, with beam port, had wider iris opening, of 0.92 mm. For this aperture the frequency-domain approach gives $Q_e \approx 583$, lowered due to the resulting stronger external coupling. The sensitivity of Q_e to the coupling iris width is noteworthy. A 20-μm wider iris lowers the Q_e by 200, while a 20-μm thinner iris reduces Q_e by 170.

The result for the scattering parameter S_{11} is indicated in Fig. 3, overlaid with the result computed with the time-domain module of *GdfidL*. The simulation employs a damping decrement based on the theoretical wall quality factor $Q_w \approx 1540$. The same result is seen in Smith-Chart form in Fig. 4. There one can also observe the effect of the chemical cleaning in decreasing the external quality factor. The original iris width was 0.87 mm, and this was widened to 0.92 mm in the course of chemical cleaning. A bead pull was also performed, with the measurement seen in Fig. 5, overlaid with the result computed with the frequency-domain module of *GdfidL*. The dielectric bead was formed by tieing a knot in a length of surgical fiber made of nylon.

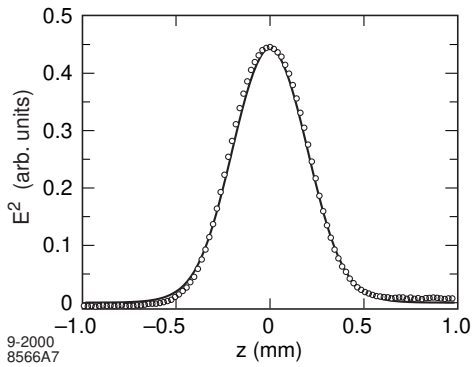

Fig. 5. Result for inferred axial electric field E_z from bead-pull measurement, overlaid with theory. The z coordinate is as shown in Fig. 2, with the bead pull along the beam axis.

The field profile data seen in Fig. 5 permit one to go on to infer peak electric field from cavity voltage, with the result $V_c/E_{pk} \approx 6.14\times10^{-4}$ m. Using Eq. (4) one may then infer peak field from power radiated. With $[R/Q] \approx 110\Omega$ from numerical simulation (*GdfidL*), and $Q_e \approx 571$ from measurement, a figure of $P_{out} \approx$1 kW corresponds to a cavity voltage of 7.9 kV, and a peak field of $E_{pk} \approx 12.9$ MV/m.

These bench measurements and simulations indicate that fabrication of, and bench measurement on a high-Q mm-wave waveguide-coupled resonator are quite feasible in practice. Results presented here provide the basis for understanding of the cavity interaction with a beam. This cavity has subsequently been installed on a 300 MeV, 0.5 A beamline at SLAC, producing peak power in the range of 1 kW, the subject of a later work.

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