Beam-Cavity Interaction Circuit at W-Band

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Abstract

We describe the design, fabrication and bench-study of a mm-wave cavity employed as a relativistic klystron output structure. The OFE copper cavity was prepared by electro-discharge machining and diffusion bonding, cleaned, and tuned to 91.4 GHz. Measured cavity characteristics are presented and compared with theory, including quality factor, $Q$, coupling parameter $\beta$, scattering matrix $S_{11}$, and axial electric field profile $E_z$. This work provides the basis for understanding of the cavity as a transfer structure.

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I. INTRODUCTION

High energy physics requires compact accelerators oper-
ating at extreme gradients, in excess of 100 MV/m. Scal-
ings 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 prob-
lem in the practical study of such structures is the absence
of a high-power, mm-wave source. Study of high-field phe-
nomena at conventional wavelengths has required the de-
velopment 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 de-
velopment of know-how in miniature structure fabrication,
bench-test, and high-field studies in an accelerator beam
environment, in parallel with mm-wave klystron develop-
ment [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 under-
standing of cavity performance as a transfer structure.

II. TOLERANCES

To appreciate the machining and tuning tolerances in-
volved 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 (Tj ≈ 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],

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

(1)

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

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

(2)
in terms of stored energy \( U \) and resonant angular fre-
quency \( \omega_0 \). The tuning angle \( \psi \) is defined in terms of the loaded
quality factor, \( Q_L \), and the drive angular frequency \( \omega \), ac-
cording to

\[
\tan \psi = Q_L \left( \frac{\omega_0}{\omega} - \frac{\omega}{\omega_0} \right).
\]

(3)

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

\[
P_{out} = \frac{|\tilde{V}_c|^2}{Q_x [R/Q]}.
\]

(4)

where \( Q_x \) 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 \( \delta \omega/\omega \approx 1/6 Q_L \).
For a loaded quality factor \( Q_L \approx 415 \), this is a detuning of
0.04% or 37 MHz.

III. FABRICATION AND ASSEMBLY

The completed geometry is indicated in Fig. 2. We de-
scribe 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 side plates com-
prising the cavity top and bottom. The three layers were
diffusion bonded together employing a 1024°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 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 of angular frequencies $\omega$. This may be compared with the theoretical result for single-mode excitation of a resonator [4],

$$\tilde{S}_{11} = \frac{2\beta}{1 + \beta} \cos \psi e^{j\nu} - 1. \quad (5)$$

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 $\beta$, 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 (GdidiL) results for the cavity with beam ports. For the analytic comparison, we employed a rectangular pillbox of interior transverse dimensions $a \times b \approx 2.30 \text{ mm} \times 2.44 \text{ mm}$ and transit length $L \approx 0.50 \text{ mm}$. The corresponding resonant angular frequency is given by $\omega_0 = \beta_0 c$, where

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

with $c \approx 2.9979 \times 10^8 \text{ m/s}$ the speed of light. This gives a frequency of 89.6 GHz; accounting for the volume change due to the fillets from an 8-nil diameter wire (about 0.8%), we calculate the resonant 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

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

with $Z_0 \approx 377 \Omega$ the impedance of free-space, and $R_s \approx 79 \text{ m}\Omega$ the theoretical surface resistance of a smooth OFE copper surface at the operating frequency. This corresponds to wall quality factor of $1.57 \times 10^8$.

#### TABLE I

<table>
<thead>
<tr>
<th></th>
<th>No Port</th>
<th>Beam Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_w$ (analytic)</td>
<td>1574</td>
<td>—</td>
</tr>
<tr>
<td>$Q_w$ (simulation)</td>
<td>1533</td>
<td>1540</td>
</tr>
<tr>
<td>$Q_w$ (measured)</td>
<td>1252</td>
<td>1305</td>
</tr>
<tr>
<td>$Q_e$ (simulation)</td>
<td>1400/1370</td>
<td>583</td>
</tr>
<tr>
<td>$Q_e$ (measured)</td>
<td>1048</td>
<td>571</td>
</tr>
<tr>
<td>$\beta$</td>
<td>1.19</td>
<td>2.29</td>
</tr>
<tr>
<td>$[R/Q]$ (simulation)</td>
<td>134 Ω</td>
<td>110 Ω</td>
</tr>
</tbody>
</table>
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 [6]. In a rectangular pillbox, the external $Q$ is given by

$$Q_e = \frac{4\pi}{|S_{21}|^2}.$$  

(8)

With a rectangular iris of width 0.83 mm, height 0.5 mm and thickness 0.25 mm, we find $Q_e = 1400$. A second method utilizes the frequency domain result of the closed cavity-waveguide system to find the complex resonant frequency of the waveguide loaded cavity [7]. 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 the code GdflDL [8]. 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**

A bead pull was also performed, with the measurement seen in Fig. 5, overlaid with the result computed with the frequency-domain module of the code GdflDL. The dielectric bead was formed by tying a knot in a length of surgical fiber made of nylon.

The field profile data seen in Fig. 5 permit one to go on to infer peak electric field from cavity voltage, with the result $V_c/E_{ph} \approx 6.14 \times 10^{-4}$ m. Using Eq. (4) one may then infer peak field from power radiated. With $|R/Q| \approx 110\Omega$ from numerical simulation (GdflDL), 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 $E_{ph} \approx 12.9$ 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 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.

**V. ACKNOWLEDGMENTS**

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**REFERENCES**


Fig. 5. Result for inferred axial electric field $E_z$ from bead-pull measurement, overlaid with theory.


