High Power Testing of the Prototype Accelerating Cavity (352 MHz) for the Advanced Photon Source (APS) *

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Abstract

Measurement of the higher order modes of a prototype single-cell 352 MHz cavity for the APS 7-Gev storage ring will be presented and discussed. A cavity made from solid copper was built according to dimensions derived from URMEL program runs. The longitudinal and transverse impedances of the first several higher order modes have been measured using various-shaped metal beads. High power (> 60 kW) testing of the cavity will be described along with design and operation of dampers for those modes with coupled-bunch instability threshold currents under 300 milliamperes, the maximum circulating positron current. Low power level rf circuitry for timing and synchronization of the various APS accelerators and storage ring will be described.

I. INTRODUCTION

The prototype all-copper cavity for the APS storage ring has been measured for higher-order modes (HOMs) and the data has been categorized by bead-pulling techniques. Those modes which may interfere with beam stability [1] have been damped with low-power devices.

The accelerating cavity shape is basically spherical with a rounded, slightly reentrant beam pipe (see Figure 1). This shape is derived from the program URMEL, and is optimized for highest shunt resistance or max voltage per unit power.

The cavity is made from three pieces of solid copper bolted together with an O-ring vacuum seal. To do rf testing, a vacuum of about 10^{-8} Torr is adequate. With this arrangement, the cavity can be taken apart and the inside shape can be modified for frequency tuning and/or shunt impedance adjustments. The APS cavities will be brazed or e-beam welded at these joints to have a vacuum of 10^{-10} for storing positrons.

We have lengthened the cavity by using shims of copper to learn how the HOMs shift in frequency. We intend to design the cavities with a spread in length along the beam axis by 0.3 mm per cavity or ±3 mm over the twenty cavities. This will spread the HOMs and thereby reduce cavity-bunch instabilities [1].

After the higher order modes (HOM) were measured using low power of about one milliwatt, the cavity was evacuated and high power was applied to vacuum condition the surfaces. The cavity was not baked in a vacuum oven.

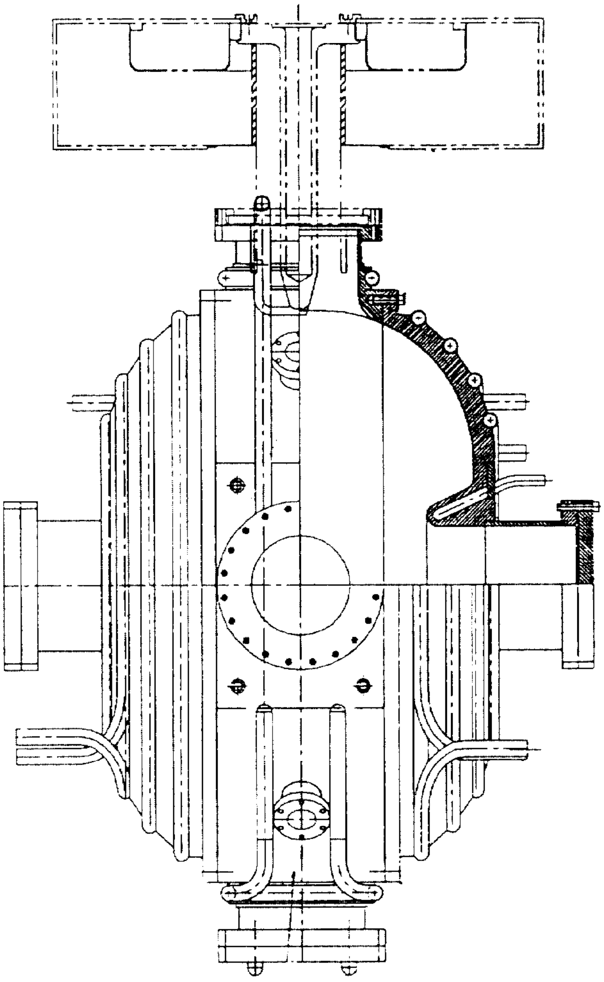

Figure 1. Prototype Storage Ring Cavity

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II. HOM MEASUREMENTS

We used standard bead perturbation techniques [2,3,4], primarily with metallic cylinders 25.4 mm long by .8 mm diameter, to measure the longitudinal E-field for monopole and dipole modes. Such needle-like objects do not significantly perturb the magnetic field or the transverse component of the electric field.

The perturbation of the longitudinal component $\vec{E}_\parallel$ of the electric field is related to the phase shift ϕ of the resonance by

$$-\tan\phi = \frac{Q}{W} 3\Delta V \varepsilon_0 F_1 |\vec{E}_\parallel|^2/2 \qquad (1)$$

(equation (18) on page 8 of [3]) where Q and W are the quality factor of and energy stored in the mode, and ΔV is the volume occupied by a prolate spheroidal perturber of high aspect ratio oriented parallel to $\vec{E}_\parallel$. Then

$$R_{shunt} = \frac{2|\int_0^L (-\tan\phi)^{\frac{1}{2}} e^{i\omega_0 z/c} dz|^2}{3\omega_0 \varepsilon_0 F_1 \Delta V}, \qquad (2)$$

is obtained by solving (1) for $\vec{E}_\parallel$ and substituting it into the general equation $R_{shunt} = |V|^2/P$ where $P = \omega_0 W/Q$ is the mean power dissipated and $V = \int_0^L \vec{E}_\parallel e^{i\omega_0 z/c} dz$ is the accumulated voltage difference experienced by a positron during its passage from $z = 0$ to $z = L$.

For dipole modes the longitudinal shunt resistance is zero along the axis of the cavity. By measuring two more longitudinal shunt resistances, off axis but close to and parallel to it, and noncollinear with it, we can get an approximation to the transverse gradient of the longitudinal shunt resistance at the axis. From this, by the Panofsky-Wenzel Theorem, we determine the transverse mode impedance as on page 6 of [3].

Ten modes were calculated to have impedances that will cause coupled-bunch instabilities near or below the 300 mA positron current which is the design goal of the APS [1]. These modes were measured and are listed in Table 1 along with the impedances calculated using URMEL [1].

Table 1.

Frequency (MHz)	R (Normal MΩ)	Threshold Current (mA)	Damping Ratio (dB)
536.7	1.67	80	23.
588.7	13.6	81	9.
761.1	25.6	43	30.
922.5	0.62	130	-
939.	0.23	340	40.
962.	6.1	180	-
1017.4	2.6	320	13.
1145.1	2.7	80	5.
1210.8	.49	80	-
1509.1	0.36	80	20.

III. HIGH POWER DAMPERS

We are now testing the HOM dampers on the prototype cavity for the rejection of the fundamental frequency power. Both coaxial probe coupled and aperture coupled dampers will be tested. A coaxial damper employs either an E- or a H-field probe. The probe is supported by an annular alumina window brazed to both inner and outer conductors for vacuum seal. The center conductor is water-cooled to remove heat generated by the fundamental mode. These dampers are on the equatorial plane of the cavity. In the E-field probe damper, the probe is directly terminated to a matched load. In the H-field probe damper, the loop is terminated to a matched load and a $\lambda/2$ shunt short stub through a $\lambda/2$ coaxial section. These form a short circuit for the fundamental mode frequency at the probe-cavity interface.

So far only the E-field dampers have undergone the high power tests; for several hours at 60 kW, for one hour at 80 kW, and for a short period of time at 100 kW.

Studies are being done to predict and control the damping property by adjusting the damper loading condition. At each HOM frequency, the input impedance of each damper is determined and then used to predict the damping ratios. The cavity with N dampers is treated as an N-terminal network. The scattering parameters are measured with a network analyzer. The reflection coefficient and then the damping ratio at each damper port is found for a certain loading condition. The computed and the measured damping ratios will be compared.

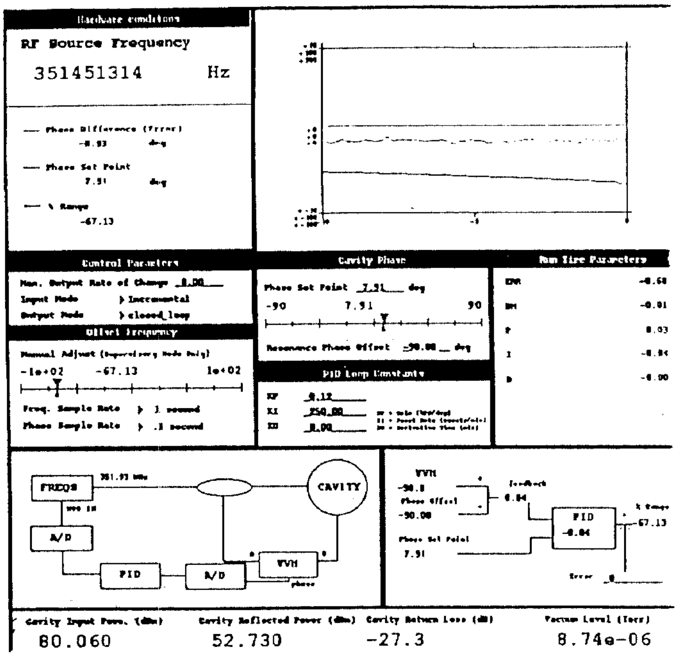
IV. HIGH POWER OPERATION

The cavity has been operated at up to 100 kW, which corresponds to 1 MV gap voltage, the engineering design goal. For 7 and 7.5 GeV operation of the storage ring, 37 and 58 kW, respectively are required.

Much outgassing occurred between 3 and 15 kW, but above 20 kW, mostly small glowing copper points and intermittent spark flashes were seen. The vacuum before applying rf power was about 3×10^{-7} T, but after several hours of running even at powers around 10 kW, it dropped into the 10^{-8} range. During rf conditioning, the vacuum was kept at about 5×10^{-7}, with excursions up to 10^{-6} each time the power level was increased. This would fall back to 5×10^{-7} in about a half-hour.

We are using a coupling loop developed at CERN and used in the 5-cell cavities at LEP. In Figure 1, the waveguide-to-post transition can be seen above the cavity. Three of the ceramic vacuum windows have broken; two at power levels below 20 kW and one at the 100 kW level. The first two we attribute to a combination of outgassing/arcing and mechanical stress from a misaligned waveguide flange. The third was used for several weeks at the 60 kW level and we concluded no more ceramic problems would be encountered. However, after powering the cavity at 80 kW (see Figure 2 for the computer control diagram) for about an hour and at 100 kW for 15 minutes, the ceramic did break.

Figure 2 Control Screen Showing 100 kW Power Into Cavity (80 dBm in lower left corner)



Hardware conditions

RF Source Frequency

351451314 Hz

Phase Difference (Error) -0.93 deg

Phase Set Point 7.91 deg

% Range -67.13

Control Parameters

Max. Output Rate of Change 0.00

Input Mode ▸ Incremental

Output Mode ▸ closed_loop

Offset Frequency

Manual Adjust (Supervisory Mode Only)

-1e+02 -67.13 1e+02

Freq. Sample Rate ▸ 1 second

Phase Sample Rate ▸ .1 second

Cavity Phase

Phase Set Point 7.91 deg

-90 7.91 90

Resonance Phase Offset -90.00 deg

PID Loop Constants

KP 0.12

KI 250.00

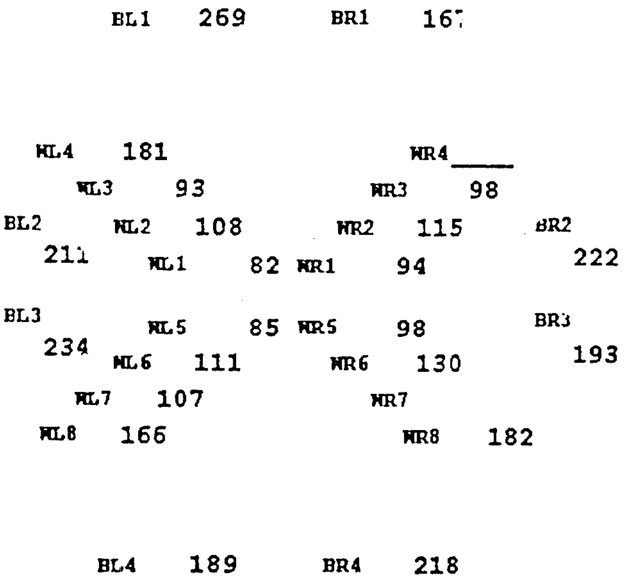
KD 0.00

Run Time Parameters

ERR	-0.68
DM	-0.01
P	0.03
I	-0.84
D	-0.00

Cavity Input Pow. (dBm)	Cavity Reflected Power (dBm)	Cavity Return Loss (dB)	Vacuum Level (Torr)
80.060	52.730	-27.3	8.74e-06

Figure 3 Cavity Temperatures (degrees F)



After consulting with both the designers and users [5] of these loop couplers, we conclude we conditioned the cavity too fast and at vacuum levels higher than appropriate. We are now using a fourth loop and running at around 2×10^{-7}, with the vacuum trip level set at 10^{-6}. Again, we emphasize that this prototype cavity was not vacuum baked at 150°C and are using the rf power for conditioning.

V. THERMAL STUDIES

Greater than expected temperatures, especially at the large ports of the perimeter, were evident. At 100 kW input, the maximum temperature of the copper was 181°F, at 75 kW, a maximum of 165°F. Thermocouples near the nose cone recorded the lowest temperatures (82°F and 81°F respectively) with a positive gradient radially outward to the high temperatures at the ports. (See Figure 3.) The 75 kW case has been studied analytically, with results indicating a maximum of 28°C ($\approx$ 82°F) above the cooling water temperature, or approximately 38°C ($\approx$ 100°F), can be expected. Variance is attributed to poor brazing of cooling tubes and port heating due to greater resistivity of stainless steel.

Though further studies are planned, it appears that nose cone cooling is sufficient, while port cooling must be improved. Production cavities will incorporate greater water cooling surface area, improved brazing techniques, and copper plating of inside surfaces of stainless steel. Provisions for supplemental cooling of vacuum flanges are planned.

VI. ACKNOWLEDGEMENTS

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References

[1] L. Emery, "Coupled-Bunch Instabilities in the APS Ring," in *Proceedings of the 1991 Particle Accelerator Conference*, San Francisco, CA, May 1991.

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[4] J. Bridges, J. Cook, R. Kustom, J. Song, "Measurements on Prototype Cavities (352 MHz) for the Advanced Photon Source (APS)," in *Proceedings of the 1991 IEEE Particle Accelerator Conference*, San Francisco, CA, May 1991, pp.693-695.

[5] Private communication with G. Geschonke of CERN and J. Jacob of ESRF.