High Power Operation of a Single-cell 352 MHz Cavity for the Advanced Photon Source (APS) *

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Abstract

The single-cell 352 MHz cavity for the APS 7-Gev positron storage ring has been tested up to one Mega-volt gap voltage at 100 kW. Thermal measurements were recorded to ensure adequate cooling. Higher Order Modes were damped using both voltage and current coupled dampers. The dampers have less than 2the fundemental mode. Stagger tuning of the higher modes has been done by slightly varying the length of each cavity to shift them apart in order to minimize their effect on multi-bunch instabilities.

I. INTRODUCTION

The prototype all-copper cavity for the APS storage ring has been powered to the nominal powers of 32 kW (7GeV), 50 kW (7.5 GeV) and the enginerring design goal of 100 kW. For the measured shunt resistance of 5 Megohms, 100 kW are required for one Mega.

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 maximum 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 wihout rf power is adequate. With this arrangement, the cavity could be taken apart and the inside shape modified for frequency tuning and/or shunt impedance adjustments. The APS cavities will be e-beam welded at these joints to have a vacuum of 10^{-10} for storing positrons.

The production cavities for the storage ring will be built 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 higher order modes and thereby reduce cavity-bunch instabilities [1]. The fundemental (accelerating) frequency is not shifted to first order since the increased magnetic feild stored in the longer volume is cancelled by the reduction in stored electric energy at accelerating gap. The fundemental mode is re-tuned by the piston tuner to the correct frequency. This tuner has less effect on the higher order modes.

After the higher order modes (HOM) were measured using low power of about one milliwatt [2], the cavity was evacuated and high power was applied to vacuum condition the surfaces. The cavity was not baked in a vacuum oven during fabrication as is the usual procedure.

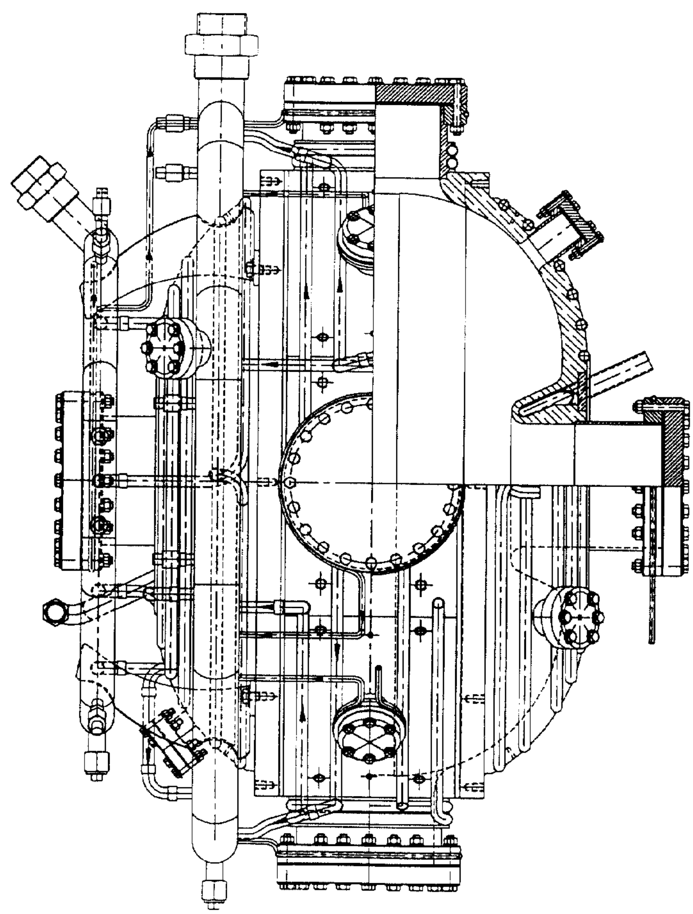

Figure 1. Storage Ring Cavity

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II. Initial High Power Operation

Since the cavity was bought as three machined copper pieces, we chemically cleaned the inside surfaces and stored them in dry nitrogen before assembly. We have no ovens for vacuum baking and so relied only on rf heating of the surfaces for outgassing.

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 ran the cavity intermittantly over a three-month period before reaching the 100 kW power goal. We had the usual occasional problems with various equipment comprising the test stand. But we did have an on-going problem during this time with breaking the ceramic vacuum seal located in the waveguide.

III. Drive Loop

We were using a coupling loop developed at CERN and used in the 5-cell cavities at LEP and also at ESRF. So this is a proven design, well tested at both labs. There is a cylindrical ceramic vacuum seal around the waveguide-to-post transition which is connected to a short length of coax, just long enough to reach to the inside wall of the cavity at which a copper bar forms a loop between the center and outer conductors.

During the conditioning, three of the ceramic vacuum windows broke; two at power levels below 20 kW and one at the 100 kW level. The first two we attributed to a combination of outgassing/arcing and mechanical stress from a misaligned waveguide flange which bolts to the loop. The third was used for several weeks (probably 20 to 30 hours total running time) at the 60 kW level and so 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 of typical operation) for about an hour and at 100 kW for 15 minutes, the ceramic did break.

Similar ceramic failures have occurred elsewhere (see, for example [3]). We were under a time constraint at that time, and knowingly were pushing to reach the design goal of one Megavolt on the accelerating gap. I estimate the total time the cavity was actually powered before it reached stable operation was over 100 hours. As a comparison, the 5-cell LEP cavities for the Booster Synchrotron take about 12 hours of conditioning to reach 20 kW, with only a few hours more to reach 100 kW operation. Presumably this fast rf conditioning is due to the 150 degree C vacuum treatment at the factory.

Figure 2. Control Screen Showing 90.4 kW Power Into Cavity (numbers at left margin)

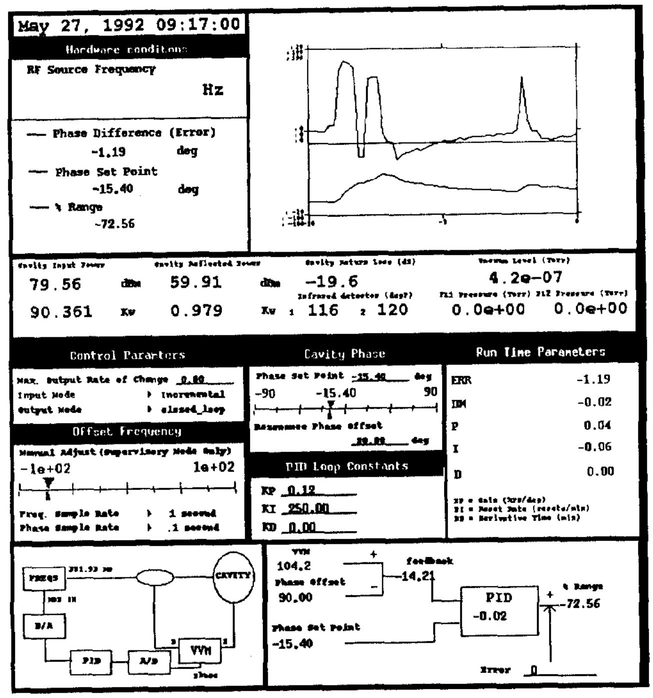
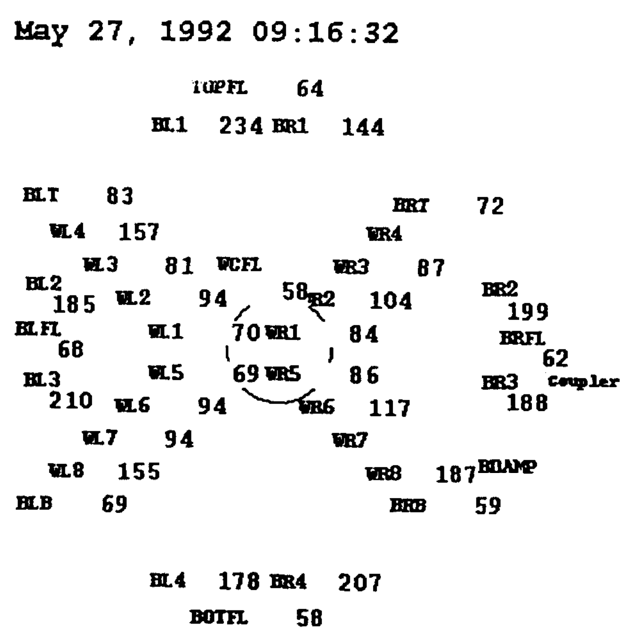


Figure 3. Cavity Temperatures (degrees F)



After consulting with both the designers and users [4] of these loop couplers, we concluded we conditioned the cavity too fast and at vacuum levels higher than appropriate. We then used a fourth loop and powered the cavity keeping the vacuum at 2×10^{-7}, with the vacuum trip level set at 10^{-6}. We also added more uniform air cooling for the ceramic and monitored the ceramic heating using two infra-red temperature meters, one on each side, to convince ourselves that the cooling was uniform. Again, we emphasize that this prototype cavity was not vacuum baked at 150°C and we used only rf power for conditioning the surfaces.

IV. Long-term High Power Operation

We then powered the cavity for about 1000 hours over the next few months, mostly between 80 and 100 kW power levels. As other components were added to or removed from the cavity, the re-conditioning time was typically 4 to 6 hours after vacuum pumping started. For starting with the vacuum intact, a half-hour was typical.

For storage ring operation, there will be four groups of four cavities, each group powered by one one-Megawatt klystron. For typical operation at 7 GeV (beam current of 300 mA) and 9.5 MV per turn, each cavity will operate at just under 600 kV/32 kW; for 7.5 Gev (but beam reduced to 200 mA) and 12 MV per turn, each cavity will run at 750 kV/50 kW. These are the two specified cavity operating points in the APS Design Specification.

If one group is not operational, only 3 MW will be available. In this case, by increasing the gap voltage to 1 MV, the 12 MV per turn and 200 mA beam current can still be maintained.

Figure 4. Beam Current vs. Cavities Available

Harmonic number	1296	
RF frequency	351.929	MHz
Peak voltage per turn	9.500	MV
Cavity parameters:		
Max voltage (estimated)	1.00	MV
Shunt resistance	5.60	MΩ
Max power	89.2	kW
Quality Factor, Q	48.6	10^3
Operating values:	7.5 GeV 200 mA	7.5 GeV 212 mA
Number of cavities	16	12
Voltage per turn	12.0	12.0
Voltage per cavity	750.0	1000.0
Power per cavity	50.2	89.2
Total power	804.0	1070.4
Beam power per cavity	113.7	159.3
Sum	163.9	248.5
Q (loaded)	16.0	15.37
Bandwidth (loaded)	22.1	23.0
Power lost (source to cavity)	17.4	18.0
Source power	2.90	3.00

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. These high temperatures were attributed to poor brazing of cooling tubes and port heating due to greater resistivity of stainless steel.

We decided that nose cone cooling was sufficient, but port cooling was not sufficient. Production cavities will incorporate greater water cooling surface area, improved brazing techniques, and copper plating of the inside surfaces of the stainless steel port flanges. Supplemental cooling of vacuum flanges was added. The final cooling scheme is shown in Figure 1.

VI. Future Plans

The first production cavity will be factory tested at Siemens for frequency in June, then will be assembled, baked, and leak-checked with delivery scheduled for mid-July. After full power testing at Argonne, we will decide if we want any modifications and then the full production run of twenty will start in the fall. The last cavities are to be delivered in June, 1994.

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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[3] Akemoto, "High-Power Input Coupler with a Cylindrical Alumina Window" in *Proc. 1991 IEEE PAC SF* May 91.

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