The APS Ceramic Chambers*

S. Milton and D. Warner
Advanced Photon Source, Argonne National Laboratory
9700 South Cass Avenue, Argonne IL 60439, U.S.A.

Abstract

Ceramics chambers are used in the Advanced Photon Source (APS) machines at the locations of the pulsed kicker and bumper magnets. The ceramic will be coated internally with a resistive paste. The resistance is chosen to allow the low frequency pulsed magnet field to penetrate but not the high frequency components of the circulating beam. Another design goal was to keep the power density experienced by the resistive coating to a minimum. These ceramics, their associated hardware, the coating process, and our recent experiences with them are described.

1. INTRODUCTION

There are nine pulsed kicker and bumper magnets used for injection and extraction in the APS machines. The rise and fall times of the magnetic pulse varies with the application. Table 1 lists the pulse parameters of the magnets in the APS machines.

Table 1: Pulsed Kicker and Bumper Magnet Parameters

	Peak Field [G]	Rise/Fall Times [nsec]
PAR inj./ext.	600/600	100
IS inj./ext.	308/690	150
SR inj.	700	1000

The eddy currents generated in a metallic vacuum chamber in response to the changing magnetic flux have very long time constants thus preventing the pulsed fields from penetrating to the beam. Instead, ceramic vacuum chambers are used for these applications. In order to provide a conductive path for the beam current and thus minimize the impedance seen by the beam, a thin conductive coating will be placed on the interior of these ceramic chambers. A second purpose for this coating is to provide a relatively low resistance route for charge to bleed off the ceramic in the event of a beam strike.

2. COATING CONSIDERATIONS

The choice of coating resistance is a balance of a number of factors. We chose to follow this recipe: 1) Determine the coating resistance which results in a minimum power density seen by the coating. 2) Check that this value for the surface resistance does not impact performance of the machine or the magnets. Unfortunately, with a uniform coating one does not have much maneuvering room regarding the impedance of the chamber as seen by the beam.

2.1 Power Density [1]

For simplicity assume a cylindrical tube of thickness d (not to be confused with the ceramic thickness) and diameter a. The skin depth at frequency ω in a nonferromagnetic conductor is

$$\delta = \sqrt{\frac{2\rho}{\mu_o\omega}} \quad , \tag{1}$$

where ρ is the material bulk resistivity, and μ_o is the permeability. If $\delta > d$ at the bunch characteristic frequency, $\omega = c/\sigma_z$, then the beam image currents flowing in the tube are roughly uniform and the surface power density due to beam image charges is

$$p_i = I_{tot}^2 R_\square \frac{1}{N_b}\frac{1}{(2\pi a)^2}\frac{C_r}{2\sigma_z\sqrt{\pi}} \qquad \text{or} \qquad p_i \propto R_\square \tag{2}$$

where I_{tot} is the total average beam current in amps, $R_\square = \rho/d$ is the tube surface resistance in ohms/square, N_b is the number of bunches in the machine, C_r is the machine circumference in meters, and σ_z is the bunch length, also in meters. The longest component of the eddy current decay times is [2]

$$\tau = \frac{\mu_o a}{2R_\square} \quad . \tag{3}$$

(For a rectangular tube of cross-section ***w (width)* x *h (height)*** this becomes $\tau = (\mu_o w)/(\pi R_\square)$ [3].) Assume this is short compared to the characteristic period of the magnetic pulse. A similar expression to (2) is then found for the power density within the tube due to the eddy currents induced by a 1/2 sine-wave pulse of characteristic frequency ω_k pulsing at a repetition frequency of f.

$$p_e = \frac{2fB_k^2a^2\omega_k\sin^2\theta}{R_\square} \qquad \text{or} \qquad p_e \propto \frac{1}{R_\square} \tag{4}$$

where B_k is the peak kicker field and θ is measured with respect to the applied magnetic field which is normal to the tube axis. Minimal total power density at $\theta = \pm\pi/2$ occurs when $p_i = p_e$. Solving for $R_\square$ one finds

$$R_\square = \frac{4\pi a^2 B_k}{I_{tot}}\left\{\frac{N_b\sigma_z f\omega_k\sqrt{\pi}}{C_r}\right\}^{1/2} \tag{5}$$

2.2 Field Distortions

The eddy currents distort the primary field, but the effect of this is minimized if the decay time of these currents is short compared to the $1/\omega_k$. We use a perturbative approach and assume the fields generated by the eddy currents are small compared to those of the magnet. Direct application of the oscillating field $B(t) = B_o\sin\omega_k t$ to the cylindrical tube results in a field inside given by

$$\frac{B(t)}{B_o} = \frac{1}{\sqrt{1+\omega_k^2\tau^2}}\sin(\omega_k t + \phi) \; ; \qquad \tan\phi = \omega_k\tau \; . \tag{6}$$

The eddy currents for more complex tube geometries produce more than just a dipole term. For example, the next highest multipole seen for a rectangular or elliptical tube is the sextupole. When calculated for the APS tube geometries they are

* Work supported by U.S. Department of Energy, Office of Basic Sciences, under Contract No. W-31-109-ENG-38.

smaller in size than the dipole term. The dipole term will thus be used as a scale for how serious the eddy currents are.

2.3 Tube Heating

Assuming equilibrium, the largest temperature rise across the ceramic tube thickness is

$$\Delta T = p_t \frac{t_c}{K} \qquad (7)$$

where t_c is the thickness of the ceramic, p_t is the total power density, at $\theta = \pi/2$, due to both the image charges and eddy currents, and K is the heat conductivity of alumina (≈ 0.2W/cm/°C at 25°C).

Table 2 provides a summary of equations as applied to the APS machines for the calculated optimal $R_{\square}$.

Table 2: Tabulated Results Summary

	PAR	IS	SR
$R_{\square}$ Opt. [Ω/□]	68	6	0.05
R_{tube} [Ω]	76	25	0.14
$p_i = p_e$ [W/m²]	248	23	427
P_{tot} [W]	55	7	67
τ [nsec]	0.5	3.2	350
δ [mm]	10	1.4	0.07
ΔT [°C]	8.7	0.8	15

Although optimal from the standpoint of power density, some improvement can be found. Because the circumference of the positron accumulator ring (PAR) is so small (30.7 m), the resistance of the vacuum chamber is dominated by that of the coatings on the ceramics. Reducing the resistance of the tubes helps; however, the power density due to eddy currents rises rapidly and limits how low one can go. We have chosen to reduce the surface resistance to something between 40 and 50 Ω/□. The problem in the SR lies in the high average current which demands a low resistance but results in unacceptably low pulsed field penetration to the beam. The resistance can only be raised to a point, however, since the temperature rise across the ceramic, due primarily to the beam image currents, becomes too high. We chose to use a value of ≈ 0.1 Ω/□. This keeps the temperature rise to within tolerance while improving the field penetration from 88% to 97%.

3. Tube Description

3.1 General Assembly

The ceramic tube assembly for the APS storage ring (SR) is shown in Figure 1. The tube assemblies for the injector synchrotron (IS) and PAR are similar in construction but have different cross-sections. The PAR tube is rectangular; where the IS is elliptical. The tube assembly consists of a 99.7% pure alumina ceramic tube, a Kovar flange brazed to the ceramic, and a bellows assembly with stainless steel Conflat vacuum flanges and an interior Be-Cu lining through the bellows section.

3.2 Coating Material

We chose to use a resistor material which is painted onto the tube and subsequently fired until fully sintered. The materials were obtained from Heraeus Cermalloy. These materials are widely used in the electronics industry and are relatively simple to apply and use. They are available over a very wide range of resistances ranging from 10 mΩ/□ to 100 MΩ/□.

We used these as opposed to sputtering since the method seemed to offer a broader range of resistance values and also opened up unique possibilities for the application of the paste. For instance one can easily envision painting strips, etc.

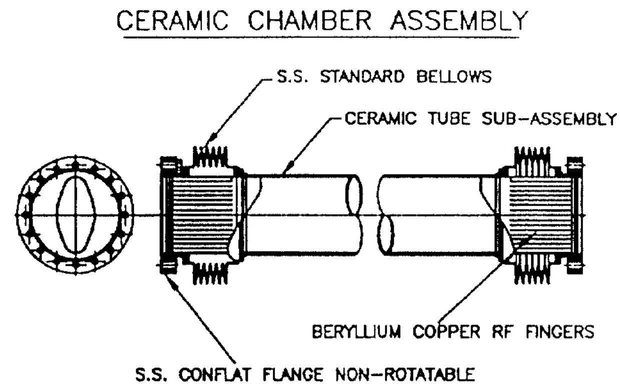

Figure 1: The SR Ceramic Tube Assembly

3.3 Coating Method

The paste is very viscous. In the electronics industry it is applied using the silk screening method, which allows for very accurate control of the final thickness. Since we must coat the inside of an odd-shaped tube, a different method was developed. With our method the paste must be thinned by 30% with the solvent Terpineol in order for it to flow freely through our system.

A custom coating station was built. The ceramic tubes are mounted vertically in the station and the coating nozzle, with brush, is inserted. The brush is a high density polyester open-cell sponge that is hot-wire cut to the shape of the tube plus approximately 5 mm and mounted on the end of a stainless steel tube through which the thinned paste flows.

The following method is the most successful in producing a uniform, consistent coating on our chambers. The chosen paste is pumped through the nozzle and allowed to accumulate into a uniform head on top of the brush. The brush is slowly pulled through the tube while continuing to maintain the head. Once it has reached the top of the tube most of the head is removed. The brush is then slowly pushed back down through the tube. It is pulled through the tube one last time and out the top while maintaining a small head at all times on the top of the brush. Typically streaks do not form using this method and the coating is very uniform in consistency. The tube is removed from the station and inserted into an oven at 150 °C for 10-15 min in order to remove all solvents. It is then fired in a programmable oven, using following firing cycle.

25°C $\xrightarrow{4\text{ hr}}$ 250°C $\xrightarrow{1\text{ hr}}$ 250°C $\xrightarrow{6.5\text{ hr}}$ 650°C $\xrightarrow{2\text{ hr}}$ 650°C $\xrightarrow{15\text{ hr}}$ 25°C

5 Torr, 10 l/min O_2 flow ⟷ Ambient Air

Heraeus calls for a different firing cycle with a peak temperature of 800 °C for 20 minutes. However, before coating, our tubes already have a Kovar flange brazed to them. The brazing joint melts at ≈ 680 °C thus we cannot heat the tubes to 800 °C. Nevertheless, we have found that many of the Heraeus pastes fully sinter at lower temperatures provided they are in the oven for a long enough period.

As a final step the bellows assembly is welded to the Kovar flange, and the tube is ready to install.

3.4 Epoxied Tubes

Brazing the Kovar flange to the ceramic was becoming a bottleneck with installation of both the PAR and IS. An interim solution was thus developed. The tube was coated and fired as before but without the end flange. Thick flanges with the bellows assembly already attached were then epoxied onto both ends of the tube. The epoxy used has a very high silver content and is thus highly conductive after curing.

Before installation the tubes are leak checked. The degassing rate of the sintered coatings is very low. Because of the limited surface area exposed to the vacuum, the net degassing rate of the epoxy has also been found to be acceptable.

4. MEASUREMENTS

Tests were done on sample ceramics to determine the effect of our firing cycle and coating methods on the final resistance of the fired paints. Multiple tests were performed on single samples to check for consistency of results. The pastes and their manufacturer-quoted resistances tested so far are: R8111, 10 Ω/□; R8105, 5 Ω/□; R410, 0.1 Ω/□.

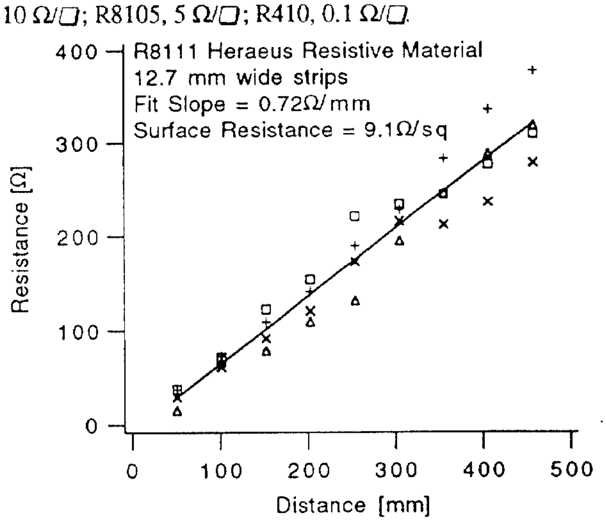

Figure 2: Measured resistance of four individual 12.7-mm-wide R8111 stripes on a painted and fired ceramic substrate.

4.1 Single Coating

Test samples were painted with stripes of various lengths and widths. These were fired and subsequently measured. Figure 2 shows an example of data for the R8111 paint after firing for two hours at 650 °C. The measured resistance is very close to that quoted by the manufacturer. Similar tests showed the R410 and R8105 pastes measured ≈ 0.2 Ω/□ and ≈ 8 Ω/□, respectively.

4.2 Multiple Coating and Firings

Because it is difficult to coat the interior of a tube consistently we checked the properties of the coatings after multiple firings. We also tested built-up layers of coatings between firings.

In the case of multiple firings of single coats, we found only small changes in the resistance of the coating. Usually the resistance dropped by 10% or so after the second firing.

We also coated several samples, fired these, measured them, applied a second coating, refired them, etc. to see if it was possible to incrementally and predictably reduce the resistance. Indeed this was found to be the case.

4.3 Tubes to Date

At present we have coated and assembled four PAR tubes, two IS injection tubes, and two IS extraction tubes all with the epoxy method. Three PAR and two IS tubes have been installed. In the case of the PAR, these tubes have been in place since the beginning of PAR commissioning (mid-Feb.) with only one problem to date. This tube was accidentally cracked due to mechanical stress caused during a maintenance period. There have been no failures of the coating or epoxy joints to date.

5. SUMMARY

Ceramic vacuum chamber tube assemblies have been constructed for the APS machines. Resistive coatings for these tubes have been specified primarily using the criteria of minimal power density as seen by the coating. However, adjustments to these "optimal" results have been made where deemed necessary.

Resistive pastes were used for the coating material. We have found that the use of these paints is quite simple, and we have adequate control over the final tube resistance. Although there is some variability in resistance from sample to sample, this can be corrected by building up the resistive layer with subsequent application of the paste and refiring of the tube.

6. ACKNOWLEDGEMENTS

We wish to thank F. Caspers for many useful conversations regarding the use of the resistive paste on ceramics tubes. We also express great thanks to S. Lockwood and D. Erikson for preparing and testing all tubes as well as C. Krieger for allowing us to tap his great wealth of technical experience.

7. REFERENCES

[1] J.M. Petersen, "Requirements for Resistive Coating on Ceramic Tubes in Kicker Magnets," Single Pass Collider Memo, CN-49, 4/81.

[2] W. Smythe, "Static and Dynamic Electricity: 2nd Edition," International Series in Pure and Applied Physics, McGraw-Hill, (1950).

[3] S. Kurennoy, "Using a Ceramic Chamber in Kicker Magnets," SSCL-Preprint-331, 5/93.