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BERYLLIUM WINDOWS FOR SYNCHROTRON RADIATION BEAM LINES

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Electron storage rings are today the most common sources of synchrotron radiation used for scientific research. The synchrotron radiation generated by the stored electron beam is led to the experimental area via a tangential exit pipe attached to the storage ring vacuum chamber. In some cases the experiment using the synchrotron radiation can be carried out in a clean, ultra-high vacuum environment, and the experimental chamber is connected directly to the beam line. There is no barrier between the experimental chamber and the storage ring vacuum chamber.

Frequently, however, the experiment must be isolated from the storage ring vacuum as, for example, when the experiment is performed in a gaseous environment. In this case, a window is needed to allow the synchrotron radiation to pass while serving as a barrier between the storage ring vacuum and the gas. In the visible and near ultraviolet spectrum quartz and sapphire windows are used. In the X-ray region, however, thin beryllium foils are used and the thinner the better. The low atomic number of beryllium makes it relatively transparent to X-rays, and the physical and mechanical properties of beryllium make it suitable for use in thin sections as a window material.

Beryllium is a silvery metal of low density (sp. gr. = 1.85). Its thermal conductivity is 1.8 watts/cm°C, about half that of copper, and its thermal coefficient of expansion is 10.8×10^{-6}/°C, about 2/3 that of copper. The mechanical properties of beryllium are interesting. Although it is a very light metal it is four times as stiff as aluminum ($E=40\times10^{6}$ psi), and the Poisson's ratio is extremely low (0.02). Beryllium has a hexagonal crystal lattice, and like many other hexagonal metals is fairly brittle, although ductility increases with increasing temperature up to about 250°C. Currently available thin (5-10 mil) beryllium foils have a yield strength of about 50,000 - 60,000 psi. This compares with high strength aluminum alloys and ordinary steel, but the brittleness of the beryllium must be viewed as a drawback, as it increases the likelihood of catastrophic failures. Another drawback is the grain growth that occurs when beryllium is heated above its recrystallization temperature (725-900°C depending on the processing of the metal).

Design and Fabrication of Beryllium Windows

Figure 1 shows the essential features of a beryllium window module. It consists of a water-cooled frame with a narrow window aperture. Covering the aperture is a beryllium foil. Flanges attached to the frame allow the window module to be attached to the beam line vacuum chamber. A small utility port is provided for pumping the space between tandem-mounted windows.

The history of beryllium window development at SSRL has consisted of attempts to build windows using thinner foils to reduce radiation absorption, particularly at the lower energies. The first beryllium windows made at SSRL used 10 mil foils high-temperature brazed to copper frames. These have been successful and are still in use. However, attempts to braze thinner foils have failed, primarily because of the grain growth problem mentioned above. Although there are braze alloys that melt at temperatures low enough to avoid grain growth in the beryllium, they are not suited for use in ultra high vacuum components because they contain constituents with high vapor pressure, e. g. cadmium. Beryllium window development at SSRL has, therefore, focused on methods of fastening the foil to the frame at lower temperatures, in order to avoid grain growth. One such effort was to bond the foil to the frame with a glass frit. Unfortunately the firing of the frit takes place in an atmosphere containing a small amount of oxygen, which causes an unacceptable oxidation of the copper frame.

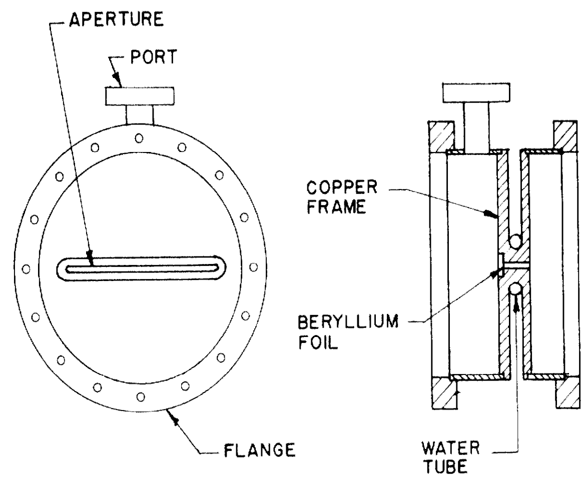

Figure 1. Beryllium window module.

Current work on Beryllium windows at SSRL is concentrating in two areas: mechanical seals, using an indium wire gasket, and diffusion bonding using a silver interlayer. A detail of a mechanical seal window is shown in Figure 2. The gasket is made of .070" diameter wire. The ends of the wire are melted together to form a continuous loop. The gasket is compressed between the beryllium foil and the copper frame by a stainless steeel clamp. A window of this type has been built and tested. It was found to be leak tight using a helium mass spectrometer leak detector and is currently installed on Beam Line II at SSRL. The mechanical seal window has the advantage of relative simplicity, and disadvantage that it cannot stand even moderately high temperature because of the low melting point of indium (157°C). Therefore the module cannot be baked with the beryllium foil in place. More mechanical seal windows are planned to replace the thicker brazed windows.

A diffusion bonding process for thin beryllium windows was developed at Lawrence Livermore Laboratories by John Truhan and others. It is a simple and straightforward process. The frame must be made of material with adequate strength at the bonding temperature (500°C). Other desireable qualities are good thermal conductivity and a thermal expansion coefficient similar to that of beryllium. The frame is coated with silver by vapor deposition or electroplating. The frame and the foil are placed in a chamber evacuated to 10^{-5} torr and heated to 500°C for one hour while the beryllium foil is mechanically pressed against the plated surface of the frame with a . pressure of 12,500 psi. The silver diffuses into the beryllium to give a strong leak-tight bond similar to a brazed joint. This promising technique has been used to produce very small (.5 mm × 20 mm) leak tight windows as thin as .0007 inch. A similar proprietary diffusion bonding process has been developed by Electrofusion Corporation. Compared to the Livermore technique it uses a higher temperature, lower mechanical pressure, and the diffusion bonding medium is a

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silver alloy rather than pure silver. Fabrication of the first diffusion-bonded 5-mil window has begun at SSRL. If it is successful, more windows will be made. The diffusion bonded window module is fully bakeable to 200°C.

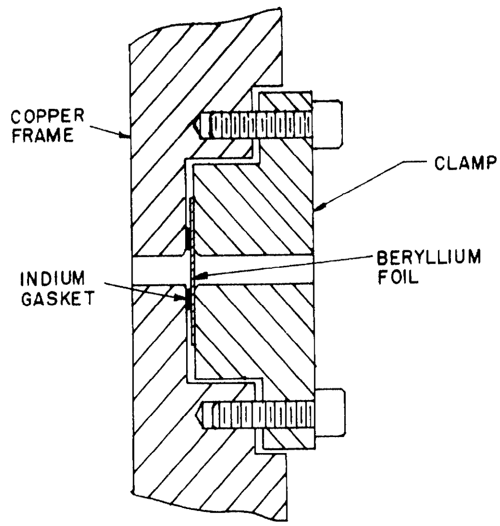

Figure 2. Detail of Mechanical Seal Window Module.

Thermal and Mechanical Aspects

Temperature gradients arise in the beryllium foil as heat is absorbed in a narrow strip along the horizontal center line of the foil and conducted away at the edges. The highest temperatures occur at the center of the window, where the heat conduction is essentially one dimensional to the top and bottom edges of the aperture. Figure 3 shows the temperature profile at the center of the window assuming negligible beam height. If the beam has significant height, the profile is rounded off in the center as shown.

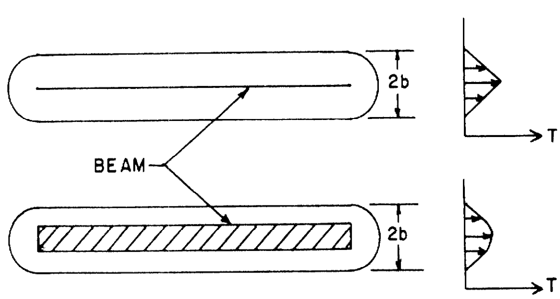

Figure 3. Temperature Profile in Beryllium Foil.

The analysis of the stresses arising from the temperature gradient is straightforward if the assumption is made that the temperature profile shown for the center of the window is assumed to be the same across the width of the window. Imagine that the window of height 2b is split along the horizontal midline into two pieces. The temperature distribution is a linear function in Cartesian coordinates, and a theorem of thermoelasticity states that in such cases the material is stress free in the absence of external tractions. The split foils will bend away from each other into curves of constant radius R given by

$$\frac{1}{R} = \alpha \frac{dT}{dy}$$

where α is the linear coefficient of thermal expansion. The hypothetical deformation is shown in Figure 4.

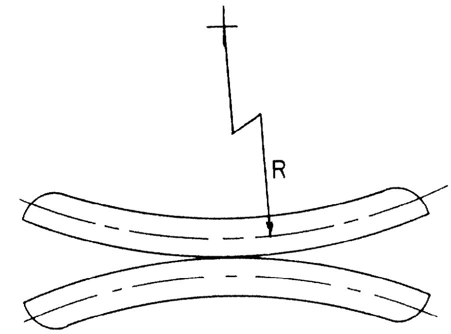

Figure 4. Thermal Deformation of Hypothetical Split Foils.

The foil is restrained from deforming in the manner shown since it is not split and is also fastened to a rigid frame. The resulting external tractions give rise to stresses in the foil. If the thermally deformed, hypothetically split foils are treated as beams, they can be straightened by the application of moments at each end given by

$$M = \frac{EI}{R} = \frac{Etb^3}{12R}$$

where t is the foil thickness which results in a maximum bending stress.

$$\sigma = \frac{Mb}{2I} = \frac{Eb}{2R}$$

Now this bending stress is compressive along the horizontal centerline of the unsplit foil and tensile at the top and bottom edges. We assume, however, that the frame resists the change in overall width of the foil due to the average temperature rise, leading to a superposition of a uniform compressive stress sufficient to cancel the tensile stress at the top and bottom edges of the foil. The compressive stress along the horizontal centerline is thereby doubled, giving

$$\sigma_{max} = \frac{Eb}{R} = \alpha Eb \frac{dT}{dy} = \alpha Eb \frac{\Delta T}{b} = \alpha E \Delta T$$

where ΔT is the difference in temperature between the centerline of the foil and the upper and lower edges.

In performing their function as barriers between a gaseous environment and the storage ring vacuum beryllium windows must withstand a pressure differential of the order of one atmosphere. The stress in the foil due to this atmospheric loading can be quite high given typical foil thickness and window apertures. For practical window dimensions the foil can be treated as a plate built in at the edges. Membrane stresses are ignored. With these assumptions the bending moment per unit width of foil is $\frac{pb}{3}$ on the top and bottom edges. On the horizontal center line the bending moment is $\frac{pb}{6}$, with curvature in the opposite direction. The maximum bending stress is $\frac{6M}{t^2}$ where M is the bending moment per unit lenghth, so that the maximum stress due to atmospheric loading is given by

$$\sigma_a = 2p\left(\frac{b}{t}\right)^2$$

At SSRL beryllium windows are mounted in tandem. The space between the windows is evacuated. In practice, this means that the upstream window has no stress due to atmospheric loading. However, the upstream window absorbs more of the incident radiation by a factor of four, so it has the greater temperature rise and the highest thermal stress. The downstream window bears the full atmospheric load, but the temperature rise is small, and the thermal stress is small compared to the stress due to atmospheric loading.

Examples

Calculations for two windows of 5 mil thickness are presented below for typical operating conditions at SSRL. The windows are assumed to be mounted 7 m from the radiation source in the SPEAR storage ring operating at 3.7 GeV and 75 kW total radiated power. The critical energy of the synchrotron radiation is 8.7 KeV. The upstream foil absorbs 17.25% of the incident radiation, and the downstream foil absorbs 4.38%. The incident power on the window is 17.05 watt/cm. Assume that the height of the window apertures is .25 inches (6 mm). The temperature rise is given by

$$\Delta T = \frac{\dot{q}b}{2kt}$$

where $\dot{q}$ is the absorbed power and k is the thermal conductivity of beryllium. The temperature rise of the upstream window is found to be 20.4°C and the rise in the downstream window is 5.18°C. The maximum thermal stress in the upstream window is 8800 psi. The maximum stress due to atmospheric loading on the downstream window is 18,400 psi.

Acknowledgment

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