APS STORAGE RING VACUUM SYSTEM PERFORMANCE

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Abstract

The Advanced Photon Source (APS) storage ring was designed to operated with 7-GeV, 100-mA positron beam with lifetimes > 20 hours. The lifetime is limited by residual gas scattering and Touschek scattering at this time. Photon-stimulated desorption and microwave power in the rf cavities are the main gas loads. Comparison of actual system gas loads and design calculations will be given. In addition, several special features of the storage ring vacuum system will be presented.

1 INTRODUCTION

The Advanced Photon Source (APS) is a high-intensity, hard x-ray synchrotron light source that is currently being commissioned and operated. The APS storage ring is designed to store up to 100 mA of 7-GeV positrons for up to 20 hours. In order to achieve the design goal for the stored beam lifetime, the accelerator vacuum system must achieve ~ 1-2 nanoTorr average pressure with the beam on. In fact, the storage ring has already achieved up to 37 hours lifetime for 100-mA beams of 7 GeV positrons.

The paper will discuss the design and fabrication of the storage ring chamber, absorbers, and special features. The storage ring chambers were fabricated from aluminum extrusions, then machined and welded to achieve the proper design. The photon absorbers presented special design and fabrication problems. The mechanical engineering group developed elegantly simple solutions to the high heat load problems associated with the absorbers.

Several problems encountered during the installation and operation of the storage ring vacuum system will also be discussed. Finally, the current performance and vacuum history will be presented.

2 VACUUM SYSTEM CONFIGURATION

The 1104-m circumference storage ring is divided into 40 sectors, each sector has six vacuum chambers. Each sector can be isolated with all-metal gate valves that have rf continuity through flexible stainless steel "fingers." The vacuum group was responsible for fabricating 235 of the 240 chambers. The five remaining sections were devoted to rf cavities (four sets of four cavities are used) and to the injection region. Thirty-five chambers will be replaced by insertion device vacuum chambers—to date 14 insertion devices have been installed.

Each sector has two bending magnet girder assemblies, three focusing magnet girder assemblies, and a drift chamber—some of the drift chambers have been replaced by rf cavities, an injection region, and insertion devices. The configuration provides two beam exit ports per sector, one for dipole radiation and one for insertion device radiation. The chamber and the photon absorbers were critical components to design and fabricate in order to achieve the design performance of the storage ring.

Each chamber has ports to install photon absorbers, vacuum pumps, vacuum diagnostics, and x-ray beam transmission. The pumping philosophy was to install non-evaporable getter (NEG) strips in the pumping antechamber along the chamber lengths and to install large capacity NEG cartridge pumps and ion pumps at locations near the photon absorbers. In the initial design the NEG material would act as the principal UHV pumps and the ion pumps would trap chemically unreactive gases. As will be discussed later, the NEG pumps are primarily used after bake-out and in early commissioning of a sector. The ion pumps can capture sufficiently the stimulated desorption gas load during beam operation.

3 CHAMBER FABRICATION

Fabrication of the storage ring vacuum chamber with aluminum (Al) and the use of Al Conflat flanges was an early design choice. Although there are many advantages of Al vacuum systems such as low cost extrusions, high thermal conductivity, low radiation activating, and low magnetic permeability, aluminum vacuum systems presented several technical challenges. Extruding the chamber to tolerances as demanding as the APS design had not been done before. Achieving reproducibility in machining, welding, forming, and cleaning the chambers presented a number of challenges. Finally, since an ultra-high vacuum system required bake-out to 150°C, bake-out procedures needed to be developed to maintain vacuum integrity of aluminum-to-stainless steel Conflat flange joints

The chamber extrusions were made of 6061 aluminum. A cross section of the extrusion is shown in Fig. 1. The elliptical area is the stored beam region, and the pentagonal area is the pumping antechamber. The connecting region allows the x-rays to pass through and across chambers. The slots in the antechamber are to capture carrier strips that hold the NEG strip, and the three holes are for water cooling channels.

The gap of the beam exit channel needs to be maintained very accurately. In addition, the distance from the beam chamber center to the antechamber wall is critical. After a number of die trials, extrusions were successfully made to hold the channel gap to 0.428 ± 0.010" and the cross chamber length to 11.05" ± 0.015".

The second major problem was reproducibly welding vacuum parts to the chamber. An extensive weld development program was established that devised self-aligning

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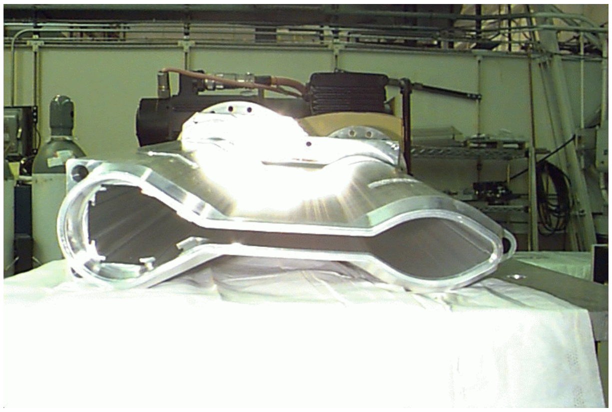

Figure 1: View of the APS storage ring Al extrusion used for vacuum chambers.

weld joints and used automatic welding systems to provide the repeatability. Over the production cycle reliability the vacuum-tight welds improved from 90% to better than 98%—and all weld leaks were repairable by manual welding. The major cause of leaks was oxide precipitation in the weld. A major breakthrough was the discovery that the Al feed wire introduced hydrogen to the weld. Subsequently, the Al wire was formed to thickness in an inert atmosphere.

Finally, cleaning the chamber presented yet more major problems. A KOH caustic wash was used in the initial development. However, the KOH was incompatible with 2219 Al used in the Al conflat flanges. Since 2219 Al is an alloy using 6% copper to harden the Al, KOH forced the copper to segregate to the surface where it then oxidized. It would be impossible to clean an assembled and welded vacuum chamber with KOH.

Use of an alkaline detergent and ultrasonic cleaning not only resolved the problem, but also provided a thinner oxide layer. The stimulated desorption rate from the detergent-cleaned chambers has been measured on a white light beamline at the NSLS x-ray ring at 2.5 GeV. The desorption coefficient curves for selected residual gases are shown as a function of photon flux in Fig. 2 [1]. The desorption coefficients are similar to Al surfaces with other surface treatments. As will be discussed later, gas load measurements from initial operation of the APS are poor because the storage ring vacuum system was unbaked during initial commissioning studies. The present system has a desorption rate of ~ 2-5 $\times$ 10^{-11} Torr per mA.

4 PHOTON ABSORBERS

The most demanding engineering problem for the storage ring vacuum system was the heat load on the photon absorbers, especially the absorbers at the bending magnet chamber. The x-ray power on these absorbers is greater than 5 kW, and the linear power density is greater than 100 W/mm. Engineers in the mechanical engineering group developed and fabricated an absorber that not only can withstand 12 kW, but is elegantly simple [2].

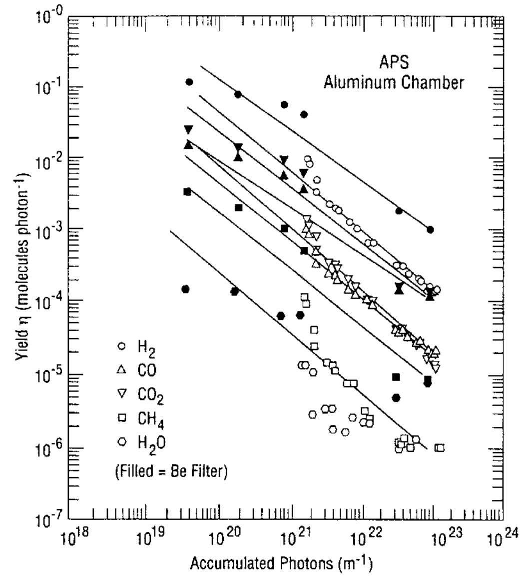

Figure 2: Simulated desorption coefficients for H_2, H_2O, CO, CO_2, and CH_4 as a function of integrated “white” x-ray beam from a 2.5-GeV electron beam [1].

The absorber is manufactured using GlidCop [3]—copper stabilized with 0.15% Al_2O_3. The internal water channels are cut using electric discharge machining (EDM), and a plug is brazed in to direct the inlet and outlet flow. The face is cut at an angle to disperse the power, and slots are machined to further spread the heat over the absorber surface. The absorber for the dipole chamber is shown in Fig. 3.

5 INITIAL PROBLEMS

During installation of the storage ring vacuum system, two problems developed that limited operation of the accelerator. Corrosion damaged the chamber water fittings and prevented bake-out of the sectors. A design flaw with the carriers for the NEG strip caused the strip to short to the chamber and prevented the NEG strip from being activated. This section details the problems and the redesign. These discussions are included for two reasons: to clarify misconceptions that have developed, and to highlight how seemingly minor changes can be disastrous in large vacuum systems.

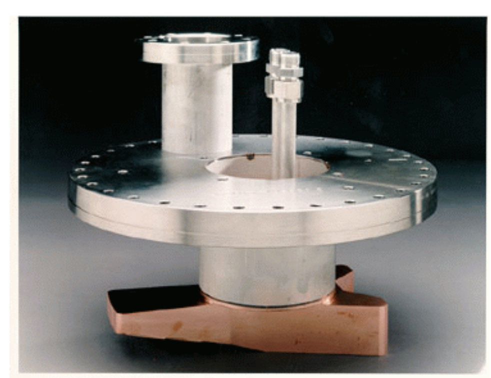

Figure 3: View of the APS absorber in chamber 2.

Soon after the problems of corrosion and NEG electrical shorts, the group learned that there were rumors in the accelerator community that the APS would have to replace its entire vacuum system. To illustrate how extravagant the rumors were, the problems were identified and the repairs completed in seven months. It would be a Herculean task to fabricate, install, and commission the complete vacuum system in seven months. The actual modifications undertaken by the vacuum group were daunting enough.

The first problem developed in a bi-metal joint between stainless steel and aluminum. The joint was welded to the chambers to connect the water headers to the chamber water channels. The water was deionized (DI) to 16 MΩ when the system was filled, but the conductivity fell to 500 kΩ. A galvanic cell developed across the bi-metal joint and the corrosion caused the joint to disintegrate. Without water circulating in the chambers, bake-outs could not be performed. This left the system base pressure in the low to mid 10^{-8} Torr range. Once it was determined that the principal failure was due to corrosion, the redesign was straightforward. A new chamber connector was made using 6061 aluminum, and the aluminum was connected to the stainless steel header system at a demountable flange. The flange used elastomer gaskets and jacket to electrically isolate the aluminum from the stainless steel at the joint. In addition, the water was continuously deionized and filtered to maintain a minimum resistivity of 3 MΩ. The major lesson learned from the failure analysis is that the water must be continuously deionized.

At the same time a second problem developed that also kept the system pressure high. The NEG strip that was installed in all of the chambers was to be activated by resistively heating the strip to 450^{o} C. In fact, the strip was activated in the individual chambers during testing and certification. However, when the strips were electrically connected in series so that the NEG strip in a full sector could be activated at one time, the strip shorted to ground.

The electrical problem was traced to subtle changes in the design of the NEG electrical circuit. In order to install the NEG strip in the chambers and be able to pass current through the strip, stainless steel carriers were riveted to the strip through a ceramic electrical break (see Fig. 4). The carriers were connected together by fitting a tab in a slot on the adjacent carrier. The carriers were then captured by the channels in the extrusion antechamber. Tests showed that the “railroad car” connections could be pushed into the chambers. Although the carriers worked and were tested, there was significant friction when installing the carriers over the length of the chamber—especially the curved (dipole) chambers. The carriers were “improved” by using a pin inserted into a hole instead of the tab-and-slot design. Unfortunately, this new design was not tested in a full sector assembly. Because of the friction, one carrier could be galled in the chamber channel. The adjacent carrier would flex due to thermal expansion during NEG activation, the pin would push through the hole and the carrier would move over the adjacent carrier. Now the distance between electrical breaks was shorter than the NEG strip at 450^{o} C, and the strip would buckle and short to the chamber.

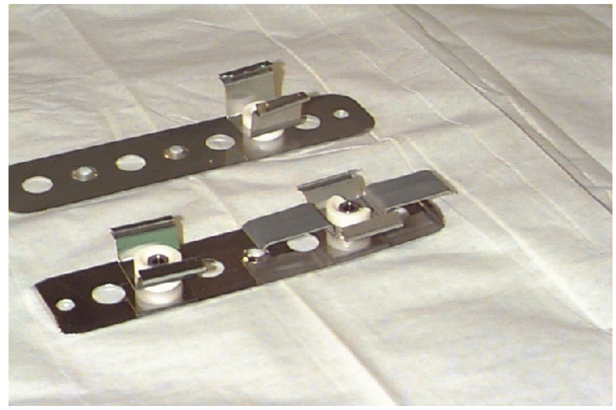

Figure 4: View of an old carrier for NEG strip (top); view of a new carrier for NEG strip (bottom).

The redesigned distributed NEG pump has layered protections. The new carriers were designed so that the carriers could not ride over adjacent carriers (Fig 4). The strip at temperature could not touch the chamber at the minimum span. In addition, a cantilevered plate coated with aluminum oxide blocked the strip from the carrier. The power supply was also rewired to have a ground fault circuit interrupt. If the strip somehow shorted out, the strip could not be overheated. Finally, new power supplies were built to activate individual chambers—also with ground fault indicators. So even in the event of a strip shorting to one chamber, the NEG pumps in a sector could still be activated. The new design is successful—the NEG strips have been installed around the ring, there are no shorted NEG strips in any chamber, and the strip can be activated in a full sector with one power supply.

6 ALUMINUM SYSTEM BAKE-OUT

The reinstallation of the water fittings and NEG strips created a third major problem that inhibited acceptable system base pressures. The bake-out of aluminum chambers with aluminum Conflat flanges mating with stainless steel flanges often opened a gasket seal. The problem was not significant when the individual chambers were being tested and certified; the failure rate was approximately one vacuum leak out of 30 or 40 flanges when baking the sector to 150°C. However, when an entire sector was being baked, the problem was significant because there are almost 50 flange seals in a sector. At least one gasket seal developed a leak in two out of three sector bake-outs.

Tests determined that gasket leaks could develop when the differential temperature was greater than 12°C. Obviously the larger the gradient, the more likely that the gasket seal would fail. Techniques were developed in which thermal insulation was wrapped around the aluminum-stainless steel flange assembly to minimize the temperature gradient. All but four flange assemblies could be protected with this passive temperature control. The two beam exit beam tubes and the two sector isolation valves required additional electrical heating to keep the flange temperatures within the 12°C range. The ion pumps were also electrically heated to at least 150°C.

7 SYSTEM PERFORMANCE

The new DI water system, NEG distributed pumps, and bake-out procedures have been successfully implemented. Since October 1995 the storage ring vacuum system has base pressures below 4×10^{-10} Torr. Today, 32 out of 40 sectors have base pressures below 1×10^{-10} Torr. With the new bake-out procedures, a gasket leak does not develop until after more than 10 sector bake-outs.

The dynamic system pressure is adequate at this time in commissioning/operation. The average ring pressure is below 2 nTorr at 100 mA. The beam lifetime at 100-mA stored current is more complex because the lifetime is a convolution of Touschek lifetime and residual gas scattering. In recent operating cycles with 100 mA in 200 bunches the lifetime was 37 hours. When 100 mA are stored in 60 bunches, the lifetime was only 14 hours. It is clear that the residual gas scattering lifetime and the Touschek lifetime are on the same order.

The high pressure regions of the storage ring are the rf cavities and the injection girders. The injection chamber is difficult to bake because it is surrounded by the magnet laminations and is potted in cement. Long bake-outs of the region are required in order to improve the base pressure. Plans to upgrade the vacuum system in the rf cavities are being finalized. Better system conditioning, and additional static and dynamic pumping will be added.

8 ACKNOWLEDGMENTS

As in any major project, the authors alone did not design, fabricate and install the accelerator vacuum systems. The mechanical engineering group under the supervision of Sushil Sharma was responsible for design, analysis, and fabrication of major components, such as the photon absorbers. The group technicians were essential to the successful system—especially the enormous work performed in a short time to re-install the water system, the NEG pumping, and perform sector bake-outs. Finally this work was supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

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