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Final Design and Status of the NSLS Vacuum System*

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At the 1978 AVS Symposium, we presented a design of the vacuum system for the National Synchrotron Light Source (NSLS),¹ which was to be built at Brookhaven National Laboratory. At this symposium we will describe the final system, as built, reasons for changes and the general status of the NSLS.

To briefly review, the NSLS is a dedicated facility for the purpose of producing synchrotron radiation. It consists of an electron linac-booster injector system, and two storage rings, one for UV research and the other for x-ray research. (Synchrotron radiation is produced by accelerating electrons in the storage rings.) The design current and energies are 1000 ma at 700 MeV for the VUV ring and 500 ma at 2.5 GeV for the X-ray ring. A total of 44 experimental beam ports are available for use. Since each beam port may be divided into two or more experimental beam lines, it is quite plausible to have upward of 100 simultaneously operating beam lines. See Fig. 1 for NSLS plan view.

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The current status of the machine is: the linac-booster is routinely operational, as required, to keep the storage rings charged. The VUV ring is operational 24 hours a day, five days a week. A stored beam of 170 ma at 700 MeV has been achieved. The pressure is in the $10^{-6}/10^{-7}$ Pa ($10^{-8}/10^{-9}$ Torr) range with stored beam. Seven experimental beam lines are operational and three more are under design or construction.

The X-ray ring has been commissioned to a point of storing and capturing an electron beam with a lifetime of a few minutes. Front ends for sixteen experimental beam lines have been installed, with construction of the balance of the beam line under way.

System Design

The vacuum system of a synchrotron radiation source is unique and differs from other vacuum systems in the following ways. First, sudden changes in the vacuum chamber cross sections can cause an energy transfer resulting in an energy loss to the electron beam and localized heating of the chamber. Second, only a portion of the synchrotron radiation passes through the experimental beam port, the remainder strikes the inside of the vacuum chamber wall liberating large quantities of sorbed gases. Third, the radiation striking the chamber requires water cooling to protect the chamber and maintain dimensional stability. Finally, but by no means least important, there should be no hydrocarbon contamination from pumps, elastomer seals, greases, etc., which could coat optical surfaces resulting in reduced beam fluxes.

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Beam Lifetime

Beam lifetime is another factor which influences the design of a synchrotron radiation source. A beam lifetime of ten hours, or greater, is a typical design value. An approximation for calculating beam lifetime, due to gas scattering (elastic and inelastic collisions with orbital electrons and nuclei of the residual gas), is given in Reference 2.

In this reference, it is shown that gas species having a high Z (atomic number) will have the strongest adverse affect on the beam lifetime and, therefore, must be minimized or eliminated. Hence, a clean oil-free all-metal system is desired. A 150° bakeout of such a system will result in residual gases consisting predominately of hydrogen, carbon monoxide, carbon dioxide, with traces of water vapor and methane, in that order.

For a 10 hour lifetime partial pressures of 10^{-9} Torr or less are required for all residual gases except hydrogen which can be a decade higher because of its low atomic number.

Gas Desorption

As mentioned earlier, synchrotron radiation produces a high dynamic gas load due to photoelectrons striking the inside chamber wall. This gas load far exceeds the thermal outgassing from the chamber.

Mathewson and Horikoshi³ gives an approximation for calculating the total number of photoelectrons per second per ma of beam $\frac{d^2N}{dt di}$ as:

$$\frac{d^2N}{dt dI} = 1.51 \times 10^{14} \frac{\rho \epsilon_c^{2/3}}{E^2} \left\{ (2.61) \int_{\epsilon=10}^{\epsilon=1.56 \times 10^3} \epsilon^{-2/3} \epsilon^{-0.94} d\epsilon \right. \\ \left. + (441.9) \int_{\epsilon=1.56 \times 10^3}^{\epsilon=\epsilon_c} \epsilon^{-2/3} \epsilon^{-1.13} d\epsilon \right\}$$

E = electron energy in GeV

ϵ = photon energy in eV

ϵ_c = critical energy = $\frac{2.2 \times 10^3 E^3 (\text{GeV})}{\rho(\text{m})}$

ρ = bending radius in meters

This is for normal incidence of the photons on the chamber wall.

However, for typical storage rings the angle of incidence (θ) is not normal and increases the photoelectric yield as $1/\sin\theta$.^{3,4}

The dynamic gas load (ΔQ) is calculated using the expression:

$$\Delta Q = \frac{dN}{dt dI} \frac{1}{\sin \theta} I (\eta)(2K) \text{ Torr } \ell \text{ sec}^{-1}$$

I = electron current in mA

where η is the desorption coefficient (number of molecules desorbed per electron)

2 required factor because the photoelectrons desorb when they are produced and again when they hit the chamber.

K = constant converting gas density to pressure.

The gas loads for the storage rings are $5.6 \eta \text{ Torr } \ell \text{ sec}^{-1}$ and $2.8 \eta \text{ Torr } \ell \text{ sec}^{-1}$ for the VUV and X-ray ring respectively.

Chamber Conditioning Time

Initially, the gas load during operation will be that due to thermal desorption, but as beam intensity increases this will quickly change to gas desorption from synchrotron radiation. The amount of gas desorbed is a function of the chamber cleanliness and conditioning. The desorption coefficient η , is the quantity used to describe the wall condition. It has been shown^{3,4} that for aluminum baked at 150°C for 24 hours, $\eta = 10^{-1}$ molecules per electron but for a beam lifetimes in excess of 10 hours η must be in the $10^{-6} - 10^{-7}$ range. This can be achieved either through self-cleaning or with an in-situ glow discharge. Both the VUV and the X-ray rings were designed for in-situ glow discharge conditioning, however, this technique has not yet been used.

Pumps

Roughing is done by cryosorption and 110 l sec^{-1} air bearing turbomolecular pumps. There is one roughing pump on the VUV ring and two on the X-ray. The high vacuum pumps are listed in Table 1.

<u>Table 1. High Vacuum Pumps</u>				
<u>Pump</u>	<u>Total Pump Speed*, l sec^{-1}</u>			
	<u>VUV Ring</u>		<u>X-ray Ring</u>	
Sputter Ion	(12 ea.)	1320	(24 ea.)	2640
Distributed Ion	(8 ea.)	1760	(16 ea.)	6240
Ti Sublimation	(20 ea.)	<u>7000</u>	(48 ea.)	<u>16800</u>
Total		10080		25680

*Nitrogen equivalent pumping speed, given at 10^{-7} Pa (10^{-9} Torr).

Residual Gas Analysis System

To guard against contaminating the storage rings from the experimental beam lines residual gas analyzers are used in each experimental line. A residual gas analysis of each beam line determines whether or not the vacuum valve separating the ring from the beam line is opened or continues to remain open.

A group of eight analyzer tubes with matching rf generators are multiplexed to a single controller which in turn communicates with a central computer via a microprocessor controlled programming unit. Three such systems each of eight analyzers and rf generators are being installed. They will be used to routinely monitor the beam lines.

When a gas phase (high pressure or obnoxious gases) experiment is being done, a dedicated analyzer, controller, and programming unit will be used to protect the ring in the event of a vacuum fault.

Distributed Ion Pumps

A distributed ion pump is built into each storage ring dipole magnet vacuum chamber. This pump makes use of the bending magnet dipole field (12.2 kgauss). It is of conventional diode design and is based on the work of Hartwig and Kouptsidis.⁵ It communicates with the main vacuum chamber, through which the electrons are circulating, via a series of punched slots 6 mm high by 25 mm long, see Fig. 2. The pumps are fabricated from type 304 stainless steel cells, 11 mm dia. x 0.25 mm wall x 22.2 mm high and spot welded to form the pump anode. The cathodes are machined from 1.57 mm thick titanium sheet, type 50A, commercially pure, aircraft quality.

Windows

Both storage rings are physically separated from the injection beam transport lines by 0.05 mm (.002") thick aluminum windows. These windows allow the electron beam to pass, but block any contamination into the UHV storage rings from the injection system. Figure 3 shows a typical window assembly. It is made the size of a conflat gasket and is used in a pair of standard flanges. The window is made from alloy 5052-H34 and the gasket from alloy 1100-0 temper. The gasket is made up of two rings half the standard gasket thickness. The gaskets and window are electron beam welded around the periphery to form an assembly. It is not important that the e-b well be vacuum tight, because the actual seal is made by the flange knife edges when bolted together. This window design has been used in the 1-1/3" and 2-3/4" O.D. flange sizes and has been successfully baked out to 250°C.⁵ Larger sizes are being developed for terminating the vacuum in the experimental beam lines.

Vacuum Chambers

The linac and booster, which make up the injector, are of conventional high vacuum design and operate at $10^{-5}/10^{-6}$ Pa ($10^{-7}/10^{-8}$ Torr).

The storage rings were fabricated from aluminum extrusions and are very similar in design except for overall size. The VUV ring is 51.7 meters in circumference and the X-ray ring 170.5 meters.

The extrusions were purchased from VAW Leichtmetall in Bonn, West Germany who also produced the extrusion for the PETRA facility at Hamburg, Germany which has a circumference of 2000 meters. The aluminum is a silicon magnesium alloy, similar to 6063-T5, but stress relieved to a yield strength of 16 kp mm⁻² (23,000 psi).

The machining and punching of the slots was done by Lansing Research Corp., Ithaca, NY. The chamber bending was done by Pacific Pipe, Oakland, CA (VUV) and Youngstown Welding and Engineering, Ohio (X-ray). Surprisingly, the VUV chambers, with a 1.91 meter radius, were easier to bend than the larger 6.875 meter radius for the X-ray ring. The VUV chambers were filled with sand and then bent in a large, but conventional tube bender. The X-ray chambers were not sand filled and were bent in a ram-shoe type bender.

Where possible, all cleaning of the vacuum components was done at BNL. A cleaning facility was designed and constructed for this project. The large chambers were cleaned off-site by BNL personnel.

When working with extrusions one must be very concerned with impurities in the melt, since they are difficult to detect in the final product. In addition to the fabricators manufacturing inspections and tests, our in-house tests consisted of dimensional check, leak check, and inspection of sample sections taken from the extrusion adjacent to either end of the piece which was to be used for the chamber. Of the one hundred sections taken, one showed an impurity of iron oxide. The length of the impurity was about 10 mm long. It is possible to detect this type of defect using radiography. However, from a practical standpoint, our experience using this technique was not good because of the different thicknesses in cross sections of the extrusion.

All flanges are of the stainless steel Conflat⁷ style. The flanges were purchased from Varian, Perkin-Elmer, MDC, and Huntington Mechanical Labs. They were purchased to a NSLS specification which essentially duplicated the Varian flange, both in geometry and material.

To join the stainless flanges to the aluminum extrusions, four types of aluminum-to-stainless transition joints were investigated; explosion bonded,⁸ roll bonded,⁹ inertia bonded,¹⁰ and DEPI¹¹ weld. Explosion bonded was ruled out because of cost and nonuniformity of joint, the DEPI weld technique not suited for the variety of sizes and shapes that we used. A total of 500 roll bonded joints were used with two leakers due to delamination during welding. A total 75 inertia welded joints of 19 mm and 38 mm dia tubes were used with no failures. However, one entire batch of approximately 20 pieces failed when they were initially machined. All 20 pieces broke apart at the joint. A few copper sealed flanges were machined from roll-bonded plate by BNL.

The storage ring chambers were assembled in a fixture, than TIG welded. The final test was an acceptable RGA scan after a 150°C bake. They were then assembled in the magnet ring and TIG welded by hand, three chambers together, to form 10 meter sections in the VUV ring and 17 meter sections in the X-ray ring. To remove a section of chamber, the particular section is hacksawed, by hand, using a saw guide to effect a straight cut.

Over 400 linear meters of aluminum weld were needed to assemble the chambers. A balanced-wave AC welding machine was generally used, except when DC welding was required for deep penetration.

The reliability of welding aluminum is directly related to the cleanliness of the parts. Leaks do occur more frequently than when welding stainless steel, at a ratio of approximately one and three quarters-to-one. The leaks are generally due to inclusion of foreign material or at the weld end-off. The first type of leak must be ground out before re-welding, the

latter is just rewelded and can be reduced by improving welding techniques. Alloy 4043 welding rod was used.

Wherever possible, internal welds were used. However, many of the joints had to be welded from the outside resulting in possible virtual leaks. The detrimental effects of virtual leaks were minimized by using an assembly procedure whereby all parts were cleaned prior to welding, with no further solution cleaning. The cleaned parts are wrapped in lint-free paper and aluminum foil until needed. When used, they were handled with white gloves through welding, leak test, bakeout, and installation. Figure 4 is a view of a VUV chamber before welding. Figure 5 is a view of an x-ray chamber assembled in a fixture for welding.

Areas not mentioned, but certainly in need of much development for this and future machines are: all metal valves, economical means of baking out large vacuum systems, and more available software for inexperienced machine operators to interpret RGA spectra.

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Fig. 1. NSLS Plan View

Fig. 2. NSLS Vacuum Chamber With Distributed Ion Pump

Fig. 3. Aluminum Window Assembly

Fig. 4. VUV Vacuum Chamber Before Welding

Fig. 5. X-ray Vacuum Chamber Assembled in Fixture for Welding

Fig. 5. X-ray Vacuum Chamber Assembled in Fixture for Welding