ULTRA-HIGH VACUUM SYSTEM OF THE BROOKHAVEN NATIONAL SYNCHROTRON LIGHT SOURCE

Conrad L. Foerster

Brookhaven National Laboratory, Upton, NY 11973.

ABSTRACT

The rings of the National Synchrotron Light Source (NSLS) have been supplying light to numerous users for approximately a decade and we recently enjoyed a fully conditioned machine vacuum at design currents. A brief description of the X-Ray storage ring, the VUV storage ring and their current supply is given along with some of their features. The ultra-high vacuum system employed for the storage rings and their advantages for the necessary stored beam environments are discussed including, a brief history of time. After several hundred amp hours of stored beam current operation, very little improvement in machine performance was seen due to conditioning. Sections of the rings were vented to dry nitrogen and replacement components were pre-baked and pre-argon glow conditioned prior to installation. Very little machine conditioning was needed to return to operation after recovering vacuum due to well established conditioning procedures. All straight sections in the X-Ray ring and the VUV ring have been filled with various insertion devices and most are fully operational. Each storage ring has a computer controlled total pressure and partial pressure monitoring system for the ring and its beam ports, to insure good vacuum.

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I. INTRODUCTION

The National Synchrotron Light Source (NSLS) has been supplying synchrotron radiation to numerous experimenters for a little over a decade now. The NSLS radiation sources are two storage rings known as the ultraviolet (UV) ring with a design energy of 750 MeV and the X-ray ring with 2.5 GeV. Design currents are presently 1 ampere for the UV and 0.5 ampere for the X-ray. Both rings have operated routinely at their design energies producing synchrotron radiation in a range from 1 to 1200 Å. Both storage rings have been fully conditioned for many years now and storage beam lifetimes are not limited by vacuum issues.

The NSLS vacuum system was described in Refs. [1] and [2]. Performance of the storage rings including life time consideration were discussed in Refs. [3], [4], [5]. This paper summarizes these references and some of the many other publications concerning the NSLS Vacuum. Major changes have been performed on both storage ring vacuum chambers following well established procedures without adverse effect to their operation and beam lifetime.

There are presently a total of 45 beam ports for experimenters and each port contains from one to four experimental beam lines. It is common to have upward of 100 beamlines operating simultaneously. The rings are operational 24 hours a day, seven days a week and are only shut down for maintenance periods. Beamline vacuum conditions are continuously monitored and lines not meeting requirements for ring operation are closed off until they do.
II. SYSTEM REQUIREMENTS

There are a number of special vacuum requirements for the NSLS vacuum system comprising the rings. First, the chamber walls must be smooth and offer a continuous path for the image current of the beam. There can be no sudden changes in the vacuum chamber cross sections which would cause an energy transfer resulting in an energy loss to the stored beam and localized heating in the chamber. Second, the radiation which does not go through the experimental beam port strikes the inner surfaces of the vacuum chamber resulting in higher pressure. Third, the radiation striking the wall requires water cooling for protection and to maintain dimensional stability. Fourth, hydrocarbon contamination must be minimized to protect optical surfaces, and finally the storage rings must be protected from experimental beamline accidents.

Beam lifetime is a major factor in the design of the synchrotron light source. A beam lifetime of 10 hours or more is a typical design value. Calculations for vacuum and lifetime in electron storage rings are given in Ref. [6]. It is shown that gas species having a high Z (atomic number) will have the strongest adverse affect on the beam lifetime and must be minimized or eliminated. Therefore, a clean, all-metal, oil free, and well conditioned vacuum system is needed. In a well pumped system the residual gases would be predominately hydrogen, carbon monoxide, carbon dioxide, with traces of water vapor and methane in that order. Partial pressures of $10^{-9}$ torr or less are required for all gases except hydrogen which may be a decade higher, due to its low Z.

Synchrotron radiation produces a high dynamic gas load due to photoelectrons striking
inside the vacuum chamber, primarily in the dipole bending sections. This gas load results in a pressure rise during operation which is proportional to beam current and it far exceeds the thermal outgassing from the chamber. The NSLS design utilizes water cooled Aluminum with water cooled absorbers in the areas most affected by photon stimulated desorption (PSD). PSD for vacuum chamber materials have been measured and some are given in Ref. [7,8,9]. The amount of gas desorbed is primarily a function of the internal vacuum chamber cleanliness, geometry, and conditioning. The desorption coefficient $\eta$ is used to describe the wall condition and it has been shown [9] that for 150°C vacuum baked aluminum it is initially $10^{-1}$ molecules photon$^{-1}$ and decreases to less than $10^{-4}$ molecules photon$^{-1}$ after exposure to 20 amp hours of operation.

In the NSLS storage rings the beam lifetime is governed by losses due to three mechanisms which depend on the interaction between residual gas molecules and the circulating beam in the vacuum chamber. The mechanisms are bremsstrahlung, coulomb scattering and trapped ions. Bremsstrahlung and coulomb losses can be calculated. Trapped ion effects are uncertainties and manifest themselves in several ways: they defocus the beam, they increase the transverse size of the beam, and they cause beam loss. An additional cause of shorter lifetime, independent of pressure, is known as the Touschek effect and is observed only in the VUV ring.

During operation the pressure in the machine improves due to synchrotron radiation cleaning. Self-cleaning permits more bunches to be stacked in the ring which lowers the electron density and increases Touschek lifetime. Insertion devices such as wigglers and undulators are good candidates for ion trapping due to their magnetic structure and abundant
photons. NEG pumps are used to insure low pressure in these devices.

III. VACUUM SYSTEM

The NSLS vacuum system consists of an electron gun, linac, a booster ring and the two electron storage rings along with beamlines (see Fig. 1 and Table I). 750 MeV electron bunches are supplied to either storage ring thru 0.05 mm thick aluminum isolation windows in injection beam transport lines from the booster ring. Rough pumping to $10^{-4}$ torr is performed by portable turbo molecular pumping (TMP) stations. We have approximately 12 TMP stations.

a. INJECTION, LINAC, AND BOOSTER

Electrons are produced from a 100 KeV electron gun and accelerated into a 100 MeV linac. The linac vacuum system consists of brazed copper and utilizes all metal seals. Valve seats are viton. Sputter ion pumps (SIP's) are used to achieve an operating pressure of $10^{-7}$ torr.

The booster ring consists of a stainless steel vacuum chamber with ceramic sections for electron bunch injection and ejection. The booster chamber cross-section is elliptical, 120 mm horizontally and 30 mm vertically. The vacuum chambers and components are welded in place to form one continuous ring. SIP's are used to achieve an operating pressure of $10^{-7}$ torr.

Beam transport lines, from the linac to booster, and from the booster to each storage ring are constructed from 60 mm diameter stainless steel tubing also welded in place. The transport lines are isolated from the storage ring vacuum using previously mentioned aluminum windows.
b. STORAGE RING VACUUM (See Fig. 2 & 3)

For a lifetime of more than ten hours a base pressure, without the electron beam, less than $10^{-10}$ torr is required. During stored beam operation the pressure will be a function of the beam and how much the ring has been conditioned. Conditioning is a result of vacuum system preparation (pumps and chambers), vacuum bake out, and self-cleaning with the electron beam. Self-cleaning is a lengthy process requiring a slow increase in the beam current. Argon glow conditioned replacement chambers and components have been installed in the rings without excessive loss in stored beam lifetimes.

The vacuum chambers are fabricated from Aluminum extrusion alloy 6063-T4. Aluminum to stainless steel transition material is used to join stainless steel flanges, bellows, and chambers to the aluminum chamber. The aluminum beam chambers are water cooled and bakeable. In the X-ray ring, water cooled copper absorbers are used at the crotch of each beam port as aluminum would melt during beam operation. These are stainless steel chambers in some of the straight sections which are used for insertion devices such as wigglers, undulators, and etc. The X-ray ring is 170 meter in circumference and the VUV is 51 meters.

A distributed ion pump (DIP) is built into each dipole magnet vacuum chamber (See Fig. 4). The original cylinder anode design DIP has been replaced in some diapole chambers with plate DIP’s which yield larger pumping speeds. The DIP communicates with the beam chamber vacuum through a series of punched slots (See Fig. 2). DIP cathodes are fabricated from type 50 A titanium sheet. The effective speed of the DIP is approximately 170 to 200 liter sec$^{-1}$ m$^{-1}$ for nitrogen at $10^{-9}$ torr.

Conventional SIP’s and Titanium sublimation pumps (TSP’s) are used in straight
sections, especially down stream of dipole bending magnets, to increase pumping speed (see Table II). These pumps also maintain vacuum when the ring magnets are turned off. Multifilament TSP's are used to minimize system venting.

Non-Evaporative Getter (NEG) pumps are used in some of the straight sections to pump insertion devices such as wigglers and undulators. We use the SAES type ST 707, in both strips and modules as they have proven best [12] for our needs. They are activated and later can be regenerated after use by heating to approximately 400°C for a short time. The NEG pumps are used to pump H₂, CO and CO₂.

Hot filament nude ion gauges (NIG's) are used to monitor vacuum in every super period of each ring and in every experimental beam line front end. The NIG's are dual filament and are calibrated before installation or replacement. In addition to reading the ultra high vacuum (UHV) condition the NIG's are used as sensors to automatically dump stored beam, close ring sector valves and beam line front end valves in case of vacuum accidents. All metal gate valves are used for the rings and front ends. Ring valves have RF shorting internally for the electron beam dynamics.

Two Residual Gas Analyzer (RGA) Systems are used on the NSLS [13] storage rings including their beamlines to protect them from contamination. There is a system on the VUV and one on the X-ray ring. Each has several analyzer heads with RF boxes distributed around the storage ring and an analyzer and RF box on each beam line front end. Each RGA system is run by a 386 PC computer which scans each head every few hours. Data is stored for later review and alarms are sent out for out of range readings. Each system reads the NIG for each head and normalizes RGA readings to its pressure reading. The systems read each front end's
gas composition and give warnings for excessive high Z gases or hydrocarbons. The systems are also used for leak detection.

C. EXPERIMENTAL BEAM LINES

There are 45 experimental beam ports on the storage rings. There are 16, plus an infrared port on the VUV ring and there are 28 ports on the X-ray ring. Generally each port is divided into from one to three experimental beam lines. There is a front end for each beam port which has the pressure monitoring, vacuum protection, and safety system. Beam line construction is the same as the ring except they are mostly stainless steel. Some beamlines are isolated from the front end using beryllium windows. Those beamlines common with the ring must be $10^{-9}$ torr or less and show no evidence of contamination.

IV NSLS VACUUM HISTORY

There were a lot of vacuum problems during the very early start-up and operation of the NSLS. Operation of the VUV was marginally acceptable in its early history but the X-ray ring needed work due to very poor vacuum and beam lifetime.

A. X-ray ring

After the initial NSLS commissioning through 1983, a number of tasks were performed in March 1984, to improve X-ray beam lifetime and ring vacuum. First, the X-ray ring was thoroughly leak tested and all leaks were eliminated. Sensitivity of detection was $1 \times 10^{-10}$ torr l/s. The entire vacuum system was then baked to approximately 120°C. Stainless steel chambers and components were baked to about 200°C. Several hot nitrogen (LN$_2$ Boil-off) purges of the entire ring were performed at the start of the bake. Next the rings was vacuum
baked for 30 hours. At the end of the bake all pumps and gauges were conditioned. SIP's with high leakage current were cleared with high voltage to the anode. Several calibrated NIG gauges were installed prior to the bake. Several days after the bake the average pressure was $10^{-10}$ torr range or less. The RGA's around the ring indicated the gas composition as ~95% Hydrogen and the rest CO, CO$_2$, and H$_2$O, in that order.

At the end of 1985 an additional RF cavity was added to the ring. By September 1986, 40 Ah of time integrated beam current was accumulated in the X-ray ring. During operation the average pressure was dominated by RF cavity pressures due to an air leak and to outgassing due to 40 kw of RF power needed in the cavities for stored beam.

In February 1987, the X-ray ring was shut down for major modification which included [4],

1. Installation of four insertion devices; three wigglers, and one undulator.
2. Installation of Laser-Electron-Gamma Spectroscopy (LEGS) facility.
3. Six new dipole chambers, which included plate DIP's, zero degree ports, and NEG pumps.
4. Reworking of RF cavities to minimize leaks and reduce multipactoring. Helicoflex seals were installed for the cavity cover and the cavities were titanium nitride coated.

Prior to this shutdown 627 amp-hours of beam operation was accumulated. All installed parts, components, and affected sections were baked and conditioned to established procedures. The X-ray ring was commissioned again in April, 1989 after a brief shut down. 1200 amp-hours were accumulated and the amp-hour clock was reset to zero. Operation of
the LEGS facility reduces the X-ray ring stored beam lifetime to approximately half of what it is with LEGS off.

B. VUV Ring

Prior to the August 1986 VUV ring shutdown, 2286 ampere-hours of time-integrated beam current were accumulated. The following modifications were made;

1. Four standard DIP's were replaced with new plate type DIP's.
2. A Transverse Optical Klystron (TOK) was installed in a straight section.
3. Clearing electrodes were installed.

Between the January 1987 start-up and March 1988, 2100 amp-hours were accumulated. The maximum beam current achieved was 1.3 A. The limit was imposed by heating of ceramic chambers and available RF power. In order to increase beam lifetime a harmonic RF cavity was added during the start of 1990. The cavity is used to increase bunch length thus allowing a greater number of electron bunch operation. By early in 1990 the VUV ring had accumulated over 8000 Amp-hours of beam operation.

V. PRESENT STATUS OF NSLS STORAGE RINGS, CONCLUSION.

Both the VUV and the X-ray storage ring have been operating with very good beam lifetime and with very little down time. The majority of maintenance work has been to upgrade the rings and insertion devices and to improve operations. As of November, 1994 the X-ray ring has accumulated 6400 amp-hours of beam operation and beam lifetimes have been the same since 1990 (see Fig. 6). Closing insertion device gaps and operation of LEGS reduce the beam lifetime. As of now the VUV ring has accumulated approximately 20,000 amp-hours of beam operation and its beam lifetimes have not changed since 1990 (see Fig. 5).
Beam life times in the VUV are also effected by undulator gap changes and are improved when the harmonic cavity is on.

Typical storage beam pressures around the rings shown are in Fig. 7 and Fig. 8, for when the stored beam life time is not affected by special devices. The lower pressure reading are generally in straight sections and the highest are from DIP's as expected. The pressures are derived from SIP and DIP pump currents and are relative to calibrated NIG's around the rings.

In order to preserve the stored beam lifetimes we have enjoyed for the past four to five years a great deal of preparation was performed on any new parts or assemblies installed in the rings. Parts and assemblies are vacuum baked and glow discharge conditioned prior to assembly. Aluminum chambers are vacuum baked to a maximum of 150°C and stainless steel to a maximum of 250°C. There are some exceptions. Aluminum and stainless steel are glow discharge conditioned to approximately $2 \times 10^{18}$ ions-cm$^2$ in Argon with 10% oxygen prior to installation. Copper and reactive metals are glow discharge conditioned to the same dose with 100% Argon. All backfilling to an atmosphere of ring section or parts and assemblies for the ring is accomplished using dry nitrogen boil-off. These techniques have been successful in recovering storage ring beam lifetimes in less than 20 amp-hours of operation.
References


**TABLE 1**

NSLS VACUUM SYSTEM PARAMETERS (1994)

<table>
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<th></th>
<th>Booster</th>
<th>VUV Ring</th>
<th>X-ray Ring</th>
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<tr>
<td>Circumference M</td>
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<td>51.7</td>
<td>170.5</td>
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<td>Cross Section mm x mm</td>
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<td>Dynamic Gas Load*</td>
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<tr>
<td>$T_0$/sec</td>
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<td>$5.6 \times 10^6$</td>
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<tr>
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<td>$10^{-7}$</td>
<td>$&lt;2 \times 10^{-10}$</td>
<td>$&lt;2 \times 10^{-10}$</td>
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<td>$2 \times 10^{-9}$</td>
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<td>Total Radiated Power, kW</td>
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<td>\ 252</td>
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<td>Power on chamber wall W/cm</td>
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<td>Bending Magnet Radius, m</td>
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<td>1.91</td>
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*After Argon glow discharge
TABLE 2

STORAGE RING UHV PUMPING AS OF DECEMBER 1994

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<tr>
<th>PUMP TYPE</th>
<th>SPEED (N$_2$) t s$^{-1}$</th>
<th>VUV Ea.</th>
<th>X-ray Ea.</th>
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<tr>
<td>DIP (Standard)</td>
<td>220</td>
<td>4</td>
<td>12</td>
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<td>DIP (Plate)</td>
<td>280</td>
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<td>TSP</td>
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<tr>
<td>STAR CELL</td>
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Fig. 2 Schematic of the UV Ring and Its Beam Lines (U1-U16).
Schematic of the X-ray Ring and Its Beamlines (X1-X29) Insertion Devices In Straight Sections Are Not Shown.
Fig. 4  Aluminum Vacuum Chamber Extrusion with Standard Distributed Ion Pump.
Fig. 5  VUV Ring Measured Beam Lifetime vs. Beam Current for Several Bunch Modes Up Till Present.
X-ray Ring Measured Beam Lifetime vs. Beam Current Up to Present.
VUV Pressure Reading In Torr, Around the Ring. Pump Numbers 1 thru 8 are DIP's. The Rest are SIP's from Super Period 1 to 4.