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National Synchrotron Light Source II
Energy & Photon Sciences Directorate

Brookhaven National Laboratory

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National Synchrotron Light Source II Storage Ring Vacuum Systems

Hsiao-Chaun Hseuh^{a)}, Charles Hetzel, Shuwei Leng, King Wilson,
Huijuan Xu, and Douglas. Zigrosser

National Synchrotron Light Source II

Brookhaven National Laboratory

Upton, NY 11973, USA

^{a)} Electronic mail: hseuh@bnl.gov

The National Synchrotron Light Source II (NSLS-II), completed in 2014, is a 3-GeV synchrotron radiation (SR) facility at Brookhaven National Laboratory (BNL), and has been in steady operation since. With a design electron current of 500 mA and sub nm.rad horizontal emittance, this 792-m circumference storage ring is providing the highest flux and brightness X-ray beam for SR users. The majority of the storage ring vacuum chambers are made of extruded aluminium. Chamber sections are interconnected using low-impedance RF shielded bellows. SR from the bending magnets is intercepted by water-cooled compact photon absorbers resided in the storage ring chambers. This paper presents the design of the storage ring vacuum system, the fabrication of vacuum chambers and other hardware, the installation, the commissioning and the continuing beam conditioning of the vacuum systems.

I. INTRODUCTION

The NSLS-II storage ring is a medium energy SR facility with the designed horizontal emittance of less than 1 nm.rad, one of the lowest among recent SR facilities,¹ thus providing the brightest X-ray beam to the users. It has replaced the aging NSLS² which was in operation for 32 years. The design and development of NSLS-II project was

started in 2006 and the construction started in early 2009. It consists of a 200-MeV Linac, a 3-GeV Booster synchrotron, the 3-GeV storage ring and seven project beam lines. The project was completed in early 2014 followed by beam commissioning. Stable operation of the machine was achieved in fall 2014 and has since provided high brightness X-rays for users. More insertion devices and beam lines are continually being built, installed and commissioned. Top-off injection mode³ has been implemented to provide constant current operation since summer of 2015.

With a circumference of 792 m, NSLS-II storage ring has 30 double-bend-achromatic (DBA) cells of ~19 m in length as shown in Figure 1(a). Each DBA cell consists of five magnet/chamber girders as shown in Figure 1(b) with two bending magnet (BM) girders and three multipole magnet girders. Between the cells are straight sections with alternating lengths of 6.6 m and 9.3 m, for insertion devices (ID), radiofrequency (RF) accelerating cavities and beam injection from the Booster ring. A schematic layout of the cell vacuum chambers without magnets is shown in Figure 1(c). It consists of two 3-m BM chambers with 6° curvature, three long multipole magnet chambers and a few short chambers, connected with RF-shielded bellows. There are two RF-shielded gate valves (GV) at the end of each cell to provide isolation during maintenance and for fault conditions.

Fig. 1. (Color Online) (a) Schematic layout of one superperiod (two DBA cells and straight sections) and front ends (FE) in the storage ring tunnel; (b) the side view of five magnet girders in one DBA cell showing two bending magnet girders and three multipole magnet (quadrupoles, sextupoles and correctors) girders; and (c) DBA cell chambers with magnets removed showing two dipole chambers (D), three multipole chambers (M), two short narrow chambers (S) and three fast corrector magnet chambers (F) interconnected with 4 RF shielded bellows (B), bracketed between two gate valves (GV).

The electron storage ring vacuum system and the chambers in particular are highly constrained by the lattice design and the magnet apertures. The vacuum chambers tend to be made as small as possible for magnet cost reason, resulted in very limited vacuum conductance. The vacuum chambers have to provide adequate and low impedance aperture for the circulating electron beam, low pressure to achieve reasonable beam lifetime and low bremsstrahlung radiation,⁴ while the cost, ease of fabrication and schedule have to be considered as well. For NSLS-II, low BM field of 0.4 Tesla with large bending radius of 25 m are used, which gives an advantage to the vacuum system design, such that the BM radiation has a small horizontal dispersion, therefore narrower

chambers made of aluminum extrusion are possible. The critical energy and power loss from BM radiation are at 2.39 keV, and 288 keV per turn, respectively, lower than those of some recent SR facilities. This makes interception of this narrow SR at normal incidence possible by using compact photon absorbers (ABS) resided inside the storage ring chambers.

The vacuum is required to be at 10^{-9} Torr (10^{-7} Pa) at the design beam current of 500 mA, which is somewhat relaxed as compared with that of other SR facilities. At this pressure, the beam-gas lifetime due to elastic and in-elastic scattering is 15-30 hours, depending on residual gas composition.⁵ However, the overall beam lifetime is dominated by Touschek (intra-bunch scattering) lifetime.⁵ The highly-charge electron bunch of ~1.5 nano-Coulomb per bunch coupled with very small bunch size of a few μm by a few mm long resulted in a very short Touschek lifetime of ~ 3 hours, much shorter than beam-gas lifetime. Nevertheless, vacuum less than 1×10^{-8} Torr is still required at straight sections to minimize bremsstrahlung radiation⁴ traveling toward front ends and beam lines.

II. VACUUM CHAMBER DESIGN AND FABRICATION

Aluminum 6063 was selected as the material for majority of NSLS-II storage ring vacuum chambers for its mechanical properties, thermal conductivity, low electrical resistivity (low impedance to the beam image current), low magnetic permeability and ease of machining. There is also vast experience in aluminum chamber fabrication at BNL and at Advanced Photon Source (APS) at Argonne National Laboratory (ANL), which participated in the fabrication of NSLS-II chambers.

The chamber cross sections are primarily driven by the lattice and the magnet geometry, but also need to meet the photon fan extraction requirements, minimum wall thickness while maximizing the pumping conductance. As described earlier, the large bending radius of 25 m produces a narrower horizontal fan at outboard side which can be fitted inside chambers with an ante-chamber of reasonable cross section, and allows the fabrication of these chambers out of aluminum extrusions with profiles shown in Figure 2. Two different but similar profiles are designed for BM chambers (D) and multipole magnet chambers (M) with elliptical beam channel of 76 mm horizontal by 25 mm vertical; connected to an ante-chamber via a narrow slot which allows photon extraction as well as linear pumping conductance. Three 13-mm Φ channels are included in the extrusion; two channels are used for cooling water loops to help maintain a stable chamber temperature. A long non-magnetic tubular resistive heater is inserted into the third channel, at outboard upper corner, to facilitate in-situ bakeouts.

Fig. 2. (a) Cross sections of multipole magnet chambers (M), as extruded, machined at magnet poles and at pump and stick ABS locations; (b) cross sections of BM chambers (D) as extruded, machined at magnet gap, and at pump and crotch ABS locations; (c) the tight fitting of M chambers at sextupole magnet pole location with ~ 1 mm clearance; (d) the extruded cross sections of short narrow aluminum chambers (S); and (e) the cross section of Inconel fast corrector chambers (F).

Approximately 200 long D and M aluminum chambers were required for the storage ring, including the day-one chambers for straight sections using M chamber cross section. The cost of extrusion was low as compared with machining and welding. However, there were only a few companies willing to take up the challenge of precision extrusion of large cross sections with relatively small quantities. It did take a few die trials and modifications over a three-year period to produce enough extrusions of correct geometries, with cross sectional accuracy of ± 1 mm over 5 m in length. The D extrusions were bent into the 6° curvature by capturing them in curved shims and spacers, while pressed by a large hydraulic press, as shown in Figures 3(a) and 3(b). After bending, the D extrusions were thermally cycled twice to 180°C to relieve the stress and to ensure the stability of the curvature in subsequent operations from machining to in-situ bakes. The D extrusions were then measured and selected for machining. The overall bending success rate was around 50%, due to over bend or twisting after thermal cycling. The M extrusions were only measured and selected prior to machining.

Fig. 3. (Color Online) (a) Bending of dipole extrusion with a hydraulic press; (b) while capturing the extrusion with curved shims and spacers to maintain the cross section; (c) precision machined pump port and chamber end for welding; (d) end adaptor between extrusion and bi-metallic flanges; (e) welding of the extrusion to end adaptors and bi-metallic flanges with automatic welder at APS; and (f) the welded chamber ends.

The selected extrusions were machined along the length to accommodate magnet pole tips with a clearance of > 1 mm between the chambers and some magnet poles, as shown in Figure 2 (c) for sextupole magnet poles. To have successful aluminum welding of these contoured openings, precision machining with very tight tolerances was required at these welding interfaces, as shown in Figure 3(c), for pumping ports, instrumentation, ABS, and most importantly for the end openings. Special end adaptor plates as shown in Figure 3(d) were needed for a smooth transition (low impedance path) inside the beam channel between the extrusion and the bi-metallic Conflat⁶ flanges. The joint between the

adaptor plates and extrusion was done through external welding without over beads or under beads. After machining, all individual chamber components were shipped to ANL where they were cleaned, inspected and welded together using APS automated welding facility, as shown in Figure 3(e). The final cleaning, leak checking and certification of the completed chambers were also performed by APS, prior to shipment to NSLS-II for integration.

Approximately 70 short narrow chambers (S) were fabricated using aluminum extrusion with same beam channel cross section as M chamber, but without the ante-chamber. The S chambers have two 13-mm Φ channels, one for cooling loop and one for the tubular resistive heater. The smaller cross section provides clearance for the ID photon exit pipes and accommodates the small gap three-pole wiggler (3PW) magnets located at 2nd bending magnets. Bi-metallic Conflat flanges are also used for the end flanges and for the pump ports. Ninety (90) fast corrector (F) chambers were fabricated from 1-mm wall Inconel 625 sheet, chosen for its low magnetic permeability, high strength and mostly high resistivity, thus minimizing eddy current and its effect from the fast pulsing corrector magnets. The two Inconel halves were seam-welded to form a hexagonal tube with the same inner cross section as the S extrusion. The Inconel tubes were then brazed to stainless steel Conflat flanges.

III. OTHER VACUUM COMPONENTS

A. *Photon Absorbers (ABS)*

The unused BM radiation is intercepted by discrete ABS to shield and protect downstream flanges, bellows and other components; preventing damage to un-cooled surfaces and potential vacuum leaks. There are three types of ABS used in storage ring,

stick ABS, crotch ABS and flange ABS, as shown in Figure 4, with 10-15 ABS per cell, depending on types of straight section devices. Other special ABS are also used inside ID chambers, at photon exit front ends (FE) and at beam lines (BL).

Fig. 4. (Color Online) Models of (a) crotch ABS with 19-mm horizontal opening; (b) crotch ABS without opening; (c) stick ABS; and (d) flange ABS.

Stick ABS is located at the end of M chambers to trim BM fan from the outboard side. Crotch ABS is located at the end of D chambers to block and absorb the majority of BM fan. In cells and straight sections with ID, a wide opening is provided in the crotch ABS to allow the high power ID photon fans through toward FE and BL. Crotch ABS without an opening are used when the straight sections are not yet populated with ID. This eliminates the need and the associated cost and effort to install FE photon exit pipes and other required components until an ID is installed. The flange ABS is installed along the electron beam channel, to protect critical components from wider ID fans or unexpected large beam orbit deviation. The insert of the flange ABS has tapered apertures from 76 to 64mm horizontally and 25 to 21mm vertically.

GlidCop⁷ is selected as material for all ABS for its high mechanical strength, stability after multiple-step brazing, and for its reliable service at elevated temperatures. The relatively weak BM field of 0.4 Tesla results in a BM photon fan with lower power density as compared with that of other SR facilities. This allows for compact and

simplified designs for stick ABS and crotch ABS. They are inserted horizontally from outboard side of the ante-chamber through a DN50 Conflat flange port into the edge of beam channel. The DN50 flange limits the transverse dimensions of the ABS to ~ 42 mm.

The stick ABS consists of an 8-mm outer diameter stainless steel tube bent into a U shape which supports the ABS and provides cooling water loop. A GlidCop shell is brazed onto the side of the tube that faces the beam to intercept the photon fan. The stainless tube is then welded to Conflat flange. This design allows the ABS tip to flange dimension be adjusted prior to welding, to accommodate different beam aperture requirements while using the same brazed assemblies.

A similar design is chosen for the zero opening crotch ABS. Copper tubing is used here to increase the heat transfer to the cooling water. Without the support of a stainless steel tube, the GlidCop shell is instead brazed to stainless steel flange to ensure the rigidity of the assembly. Au-Cu alloys of different eutectic temperatures are used in the multi-step brazing. Proper forming of the copper tubing is critical to ensure uniform gap between the GlidCop shell and the copper tubing for the braze alloy to flow properly, to achieve at least 75% contact, required to ensure adequate heat transfer to the cooling water. X-ray radiography imaging, as shown in Figure 5, is used, before and after the brazing, to ensure a good conformal fit between the pieces and the proper flow of the braze alloys, respectively.

Fig. 5. Radiographic images of the brazing zones for (a) stick ABS with poor alloy flow; (b) stick ABS with uniform Au alloy distribution; and (c) crotch ABS with uniform Au alloy distribution.

For crotch ABS with opening, GlidCop brazed to copper cooling tube approach is again used. Given that the cooling tubes cannot be placed on the mid-plane due to the SR exit opening, two cooling loops, one top and one bottom, are used. Opening of 75mm (H) x 18mm (V) is chosen for 1st BM crotch ABS to provide adequate apertures for ID fan exit, while crotch ABS for 2nd BM has 19-mm horizontal opening sufficient for useable BM and 3PW fans to exit to BM FE and BL.

B. RF Shielded Bellows

RF shielded bellows connects chambers between adjacent girder assemblies and compensates for chamber fabrication and alignment errors. The NSLS-II RF bellows are designed to accommodate a lateral offset of ± 2 mm, an angularity of ± 15 mrad and longitudinal compression of 15 mm for installation and for in-situ bakeouts. An outside RF finger design⁸ was chosen for its lower impedance even with extreme offsets.⁹ An exploded view of the internal structure of the RF bellows is shown in Figure 6. A stainless steel clamp plate is used to mount a pair of thin GlidCop fingers on to the left side flange. The GlidCop fingers are slotted to improve their flexibility and to provide multiple points of contact on the stainless sleeve. The stainless sleeve, inserted through right side flange opening, is silver plated to reduce sliding friction with GlidCop fingers. Silver plated Inconel 625 springs, which are inserted through left side flange opening and mounted on the inside of right side flange, prior to installing GlidCop fingers and stainless sleeve, are used to provide contact pressure between the sleeve and the GlidCop

fingers. The outer bellows weldments which include the hydro-formed convolutions, the end flanges and water cooling channels are purchased from a commercial supplier. The internal components are fabricated in house. The mechanical assembly of the bellows is done in a class 1000 clean room and takes less than 20 minutes to complete. Over 250 bellows have been installed and gone through multiple bakeout cycles with little temperature rise or any ill effect from the high intensity beam.⁸

Fig. 6. (Color Online) Exploded view of RF shielded bellows with bellows convolutions removed, showing GlidCop RF fingers mounted onto flange, Inconel springs, stainless sleeve; and also the side view of an assembled bellows.

C. Vacuum Pumps

The large gas load from SR induced desorption warrants the implementation of high UHV pumping speed in the storage ring. After initial rough down and in-situ bakeout of the vacuum sections, the system pumping is transferred from portable turbopumps stations (TMP) to UHV pumps, including sputter ion pumps (IP), titanium sublimation pumps (TSP), Non-Evaporable Getter (NEG) strips and NEG cartridges. Diode IP of 200 l/s and TSP of ~ 500 l/s are installed under each ABS to locally pump the desorbed gas load. NEG strips mounted in ante-chambers, as shown in Figure 7, provide linear pumping of the beam aperture through the narrow photon extraction channel, with a conductance of ~ 100 l/s/m. The NEG strips are activated at 450°C after initial bakeout

and will be activated again in a few years. The NEG cartridges are mostly used at in-vacuum undulators and at a few ABS with very high heat and gas loads. The effective UHV pumping speed in storage ring is around 100,000 l/sec (N_2 equivalent) in the beam channel, based on the conductances of the photon extraction channels and the pump manifolds at ABS. Both IP and TSP are remotely operated, controlled and monitored. The activation of NEG strips and cartridges is done locally and requires portable TMP to remove the desorbed hydrogen.

Fig. 7. (a) The riveted mounting of NEG strips with stainless post, carriers and ceramic insulators at 10-cm spacing; (b) the assembled NEG strip cartridge with two NEG strips; and (c) the cross sectional view of the NEG strips nested in the ante-chamber.

D. Vacuum Monitoring and Controls

There are 8 IP mounted under stick and crotch ABS in each 26-m cell and straight section, which provide a reasonable pressure profile through the pump current readings. Four cold cathode gauges (CCG) and two residual gas analysers (RGA) are mounted in each cell and straight section to provide additional monitoring of total and partial pressures in the storage ring. Due to their very small signals (down to pico-ampere level), CCG and RGA are mounted off the ante-chambers through a 50% baffle and two 90°

bends, to shield them from copious photoelectrons. In each cell and straight section, a dozen resistance temperature sensors (RTD) are mounted at selected locations on cell chambers to supplement the pressure measurement and protect the vacuum chambers and ABS from overheating when photons hit at abnormal locations. In sudden fault conditions, pressure excursion provides more sensitive and faster detection than RTD responses. Nevertheless, both will trip the safety interlocks through the cell programmable logic controller and dump the electron beam.

IV. VACUUM COMMISSIONING AND PERFORMANCE

A. Assembly, Installation and Commissioning

After arriving from APS, each cell chamber was measured for dimensional accuracy, and then moved into a Class 1000 clean room for assembly. An RF screen was installed at the photon extraction gap between beam channel and ante-chamber, to reduce the RF resonance amplitude and to shift the resonance frequency away from the 500 MHz accelerating cavity frequency. The NEG strip assembly was then installed into the ante-chamber, followed by mounting of pumps, gauges, beam position monitor buttons and tubular resistive heaters. The end flanges were then capped with blank-off flanges. The assembled chambers were baked at 150°C for 24 hrs, leak checked, and scanned with RGA for any sign of contamination. The chamber bakeout was carried out with the tubular resistive heaters, with no thermal insulation, which provides over 1 kW/m power. Conventional heating jackets were used on special components, such as the end flanges, IP, TSP, CCG and RGA. A few chambers were found with hydrocarbon contamination and were treated at 70°C for a few hours with a flow of ambient pressure oxygen gas

containing ~500 ppm ozone, which reduced the contamination by one to two orders of magnitude.

The assembled chambers were installed into the split magnets on the magnet girder, aligned, and baked to 130°C prior to installation into storage ring tunnel. After connecting the chambers with RF shielded bellows and with end gate valves, each vacuum section was baked to 130°C for 40 hours. Vacuum of mid 10^{-11} Torr was usually achieved after in-situ bakeout and pump activation, with no trace of hydrocarbon peaks in the RGA scans.

B. Vacuum Performance with Beam

With stored electron beam, the photon stimulated desorption (PSD) becomes the dominating source of gas, thus the proportional increase in pressure with beam current in the storage ring. The pressure distribution in a standard DBA cell was calculated during the early stage of the vacuum system design using Molflow+ code.^{10,11} Using PSD yield of 1×10^{-5} molecules per photon for copper¹² after 100 A·Hr accumulated beam dosage, average pressure of 2×10^{-9} Torr at 500 mA can be achieved¹³ with linear pumping from NEG strips and the lump pumps (IP and TSP) at ABS locations. As expected, the storage ring average pressure does increase linearly with the stored beam current, as shown in Figure 8 for 100 A·Hr and 300 A·Hr beam dosages. At same beam current, the average pressures at 300 A·Hr are ~ 20% lower than those at 100 A·Hr, indicating the beam conditioning effect, which lowers the PSD yields with increasing accumulated photon dosages. However the average pressure is a factor of 3 higher than that of our early simulation.¹³

Fig. 8. The storage ring average pressures (in nTorr) increase linearly with stored beam currents (in mA). At same beam currents, pressures at 300 A·Hr are ~ 20% lower than those at 100 A·Hr, showing a gradual decrease in desorption rate.

The decrease in PSD yield is best illustrated by plotting rate of pressure rise over current ($\Delta P/I$) versus the accumulated beam dosage ($\int I \cdot dt$), as shown in Figure 9. The ‘average’ bending magnet photon flux Γ in the storage ring can be calculated¹⁴ by:

$$\Gamma = 8.1 \times 10^{17} I \cdot E / C = 3.1 \times 10^{15} \text{ photons/m/mA/sec}$$

here I is current in mA, E energy in GeV and C circumference in meter. At a beam dosage of ~ 300 A·hr, $\Delta P/I$ is ~ 1.7×10^{-11} Torr/mA. Assuming an average pumping speed of 100 l/s/m, the ‘average’ PSD yield at 300 A·Hr is estimated to be ~ 2×10^{-5} molecules per photon, higher than 1×10^{-5} molecules per photon at 100 A·Hr for copper, used in our simulation.¹³

Fig. 9. The rate of pressure increase over beam current, $\Delta P/I$ (in nTorr/mA), plotted vs. accumulated beam dosage (in A·Hr) in log-log scales. The beam conditioning slope of this plot is approximately - 0.35.

The slope of this beam conditioning plot is around - 0.35, not as steep as the slopes of - 0.6 experienced at other similar SR facilities¹⁵, implying a slower beam conditioning rate. One possible cause of higher ‘average’ PSD yields and smaller conditioning slope is due to the scattered photons, from the primary photons hitting ABS at normal incidence, impinging on nearby less conditioned aluminium surfaces which would have much higher PSD yield than ABS copper surface.¹² Detailed study will be needed to distinguish and quantify the effect of the scattered photons from the primary photons. The other

possible cause is that many cells have been re-opened for the installation of new ID, ABS and FE, thus require re-conditioning by the beam to reduce PSD yield. The high PSD yield and slower conditioning rate are concerns when the storage ring operates at the design current of 500 mA, and the average pressure may reach high 10^{-9} Torr, resulting in excessive bremsstrahlung radiation toward front ends and beamlines.

V. SUMMARY

The NSLS-II storage ring vacuum system adopts ante-chamber design with smaller horizontal profiles and in-ring compact ABS, which ease the fabrication of the ABS and vacuum chambers through aluminum extrusion. The entire vacuum system was implemented in five years with limited resources. The storage ring vacuum system has been in operation with high reliability for beam commissioning and for user operation since 2014. After in-situ bakeouts, the average ring pressure is below 1×10^{-10} Torr. With increasing beam intensity and beam conditioning, the rate of pressure rise ($\Delta P/I$) due to PSD has dropped below 2×10^{-11} Torr/mA at > 300 A·Hr dosages. The beam conditioning rate, thus the PSD yield, is similar to that of other SR facilities,¹⁴ but slower than expected. Reduction of pressure rise to $\sim 1 \times 10^{-11}$ Torr/mA is necessary for 500-mA operation without excessive bremsstrahlung radiation toward FE and BL. These reductions in desorption rate and pressure rise should be reached around 1,000 A·Hr dosages, achievable in 2016 with steady operation at ~ 200 mA current.

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