NOVEL CHAMBER DESIGN FOR AN IN-VACUUM CRYO-COOLED MINI-GAP UNDULATOR

Jih-Perng Hu, Conrad L. Foerster, John R. Skaritka, David Waterman *

National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973-5000 U. S. A.
Phone: (631) 344-7113
Fax: (631) 344-3029
E-mail: hu1@bnl.gov

** Advanced Design Consulting USA, Inc.*
126 Ridge Road, PO Box 187
Lansing, NY 14882, U. S. A.
Phone: (607) 533-3531
Fax: (607) 533-3618
E-mail: dave_waterman@adc9001.com

ABSTRACT

A stainless steel, Ultra-High Vacuum (UHV) chamber, featuring a large vertical rectangular port (53”W by 16”H), has been fabricated to house the one-meter magnet assembly of a newly installed undulator insertion device for beamline X-25 at the National Synchrotron Light Source. To achieve UHV, the new chamber is equipped with a differential ion pump, NEG pump, nude ion gauge, residual gas analyzer, and an all metal roughing valve. Temperature of the magnet assembly is maintained below 90°C during vacuum bake.

The large rectangular port cover is sealed to the main flange of the chamber using a one-piece flat aluminum gasket and special sealing surfaces developed exclusively by Nor-Cal Products, Inc. The large flange provides easy access to the gap of the installed magnet girders for *in situ* magnetic measurements and shimming. Special window ports were designed into the cover and chamber for manipulation of optical micrometers external to the chamber to provide precise measurements of the in-vacuum magnet gap.

The vacuum chamber assembly features independently vacuum-isolated feedthroughs that can be used for either water-or-cryogenic refrigeration-cooling of the monolithic magnet girders. This would allow for cryogenic-cooled permanent magnet operation and has been successfully tested within temperature range of +100°C to -150°C. Details of the undulator assembly for beamline X-25 is described in the paper.

1. Introduction

At the National Synchrotron Light Source (NSLS) of Brookhaven National Laboratory (BNL), the X-ray beamline-25 (X-25) was commissioned in 1990 to allow experiments on multi-wavelength anomalous diffraction, utilizing the photon beam generated from a 27-pole hybrid-wiggler insertion device (3-28 keV, $2x10^{11}$ ph/s at 1Å). Beginning in 2004, programmatic focus of X-25 has shifted to monochromatic macromolecular crystallography (PXRR[1]), a U.S. NIH-DOE joint program on cell protein study. To improve beam intensity and quality for optimized structure-image collection from cells irradiated at >10-m downstream of the wiggler, upgrade of the X-25 and its radiation source began in early 2005. With intense effort attempted during very limited downtime in ring operation, the major tasks completed before 2006 has been replacement of front-end shutter with a water-cooled version, substitution of focusing mirrors in the beamline monochromator with nitrogen-cooled bendable crystals, and replacement of the hybrid-wiggler with a tunable, in-vacuum, cryo-ready, permanent magnet-based miniature-gap undulator (CPMU), as shown in Figures 1 and 2.

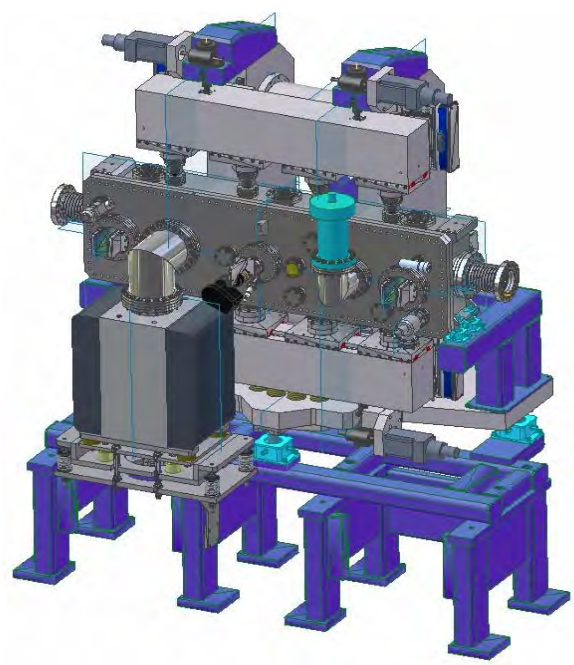

Figure 1. Front view of the 39-port chamber in the middle of CPMU assembly.

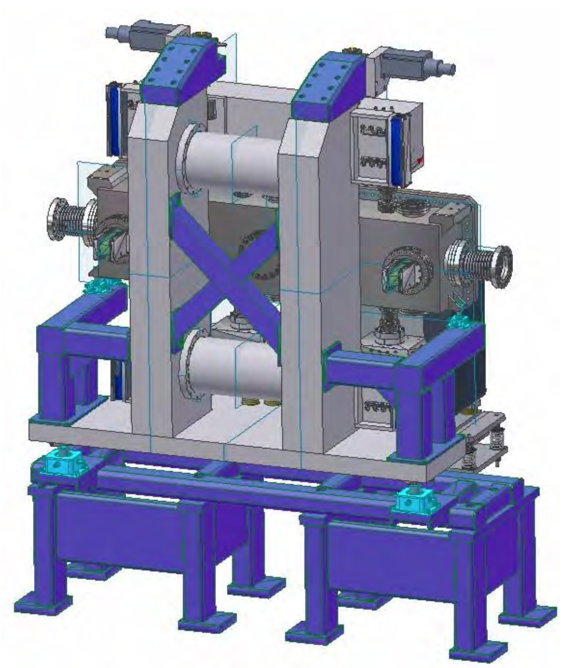

Figure 2. Reinforced chamber support at back of the CPMU assembly.

The custom-engineered CPMU, which is built on leading-edge technology of synchrotron insertion devices, has a rectangular UHV chamber (< $2x10^{-10}$ torr) fabricated to accommodate magnet arrays (Figure 3) and array-supporting girders (Figure 4) for a high-intensity photon beam produced in a miniature gap of magnets under optional cryogenic cooling. To fit the monolithic assembly of the undulator into a ring space (60") left behind by the removed wiggler, as displayed in Figure 5, geometrical configuration and structure dimensions (53" wide by 16" high by 10" deep) of the chamber were exclusively designed by the BNL/NSLS in cooperation with Advanced Design Consulting USA, Inc. Manufactured based on NC-machining (precision cut) followed by linear-friction stir welding[2] (to minimize distortion, porosity, and residual stress), the final product of the beam chamber after surface cleaning (ultrasonic bath, chemical wash) is a leak-tight and UHV-compatible unit, meeting all design criteria set up for the synchrotron insertion device.

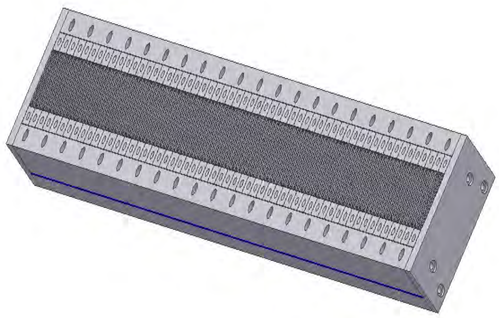

Figure 3. The BNL-built hybrid planar undulator magnet has 55 full-strength periods of 1.8-cm

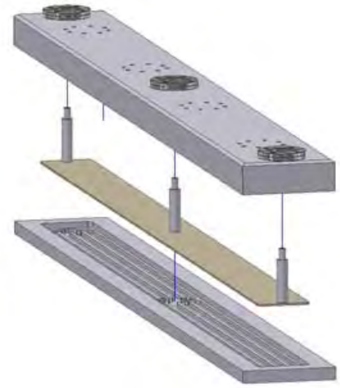

Figure 4. Aluminum girder that supports the magnet array has three cryo-cooling passages

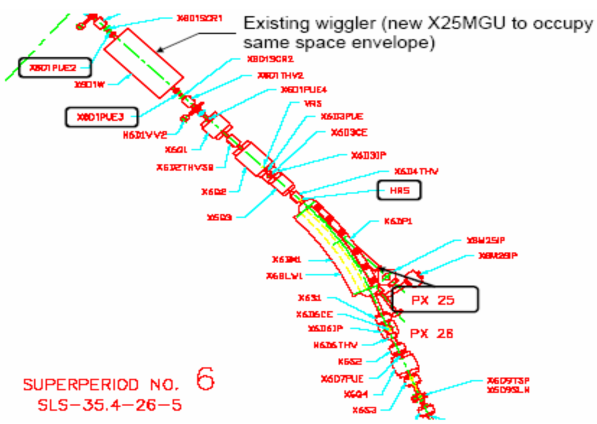

Figure 5. Superperiod-6 at X-ray ring showing the replacement location of old wiggler & new CPMU

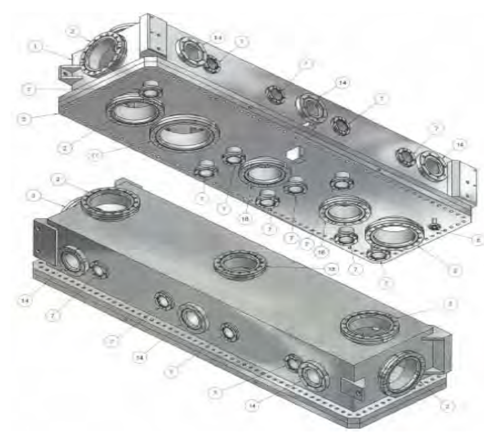

Figure 6. Chamber drawing shows a full-size removable front panel and multi build-in ports

Weighted at 300-lb, the undulator chamber as shown in Figure 6 comprises of a removable front panel (vertical port), which is sealed to the main flange of the chamber using Nor-Cal Company-fabricated one-piece, frame-type pure-aluminum gasket ($^{1}/_{64}$" thick by $1^{1}/_{2}$" wide). Unlike most off-the-shelf chambers available only in spherical or cylindrical geometry with small build-in viewing windows and end-ports for access during components changeover, the rectangular full-size port at the front of the CPMU chamber, as shown in Figure 7, permits easy and direct traverse access down the magnet gap and surrounding space for *in situ* magnetic measurements (Hall probe) and shimming (iron wires) when panel is removed during ring's downtime. Under normal situation when chamber is sealed with front cover in place, the gap control unit and surface cleanup device at chamber innards can still be maneuvered through a single or couple of the total 39 CF-flange sealed ports built at front panel and sidewall of the chamber. As shown in Figure 8, in addition to the two extended side-ports used for beam transport, the other window ports at size $^{1}/_{2}$" to 8" in diameter can be multi-functionally used to facilitate magnet-gap adjustment (motor-driven transducer), chamber vessel cleaning (glow discharge rod), cryogenic cooling (nitrogen or helium gas), beam profiling (CCD, BPM), RF-continuity check (window screen), array alignment (Keyence laser), residual gas analyzing (using RGA), pressure gauging (Convectron™, Cold Cathode) and system pumping (lumped TSP-Star Cell™ pump, NEG™ cartridge, turbo rough pumping). To prevent fatigue-induced leaking from occurring at sealing surfaces and welding joints due to long operating cycles (warm- or cold-start), enduring attraction force (at mini-gap), or repeated mechanical motion (girder-to-girder), 14 out of the 39 ports are shielded with bellows or tubes (vacuum guard). In preparation of bakeout (≤125°C), polyurethane-coated fiberglass tape and aluminum foil are used for wrapping of the entire chamber.

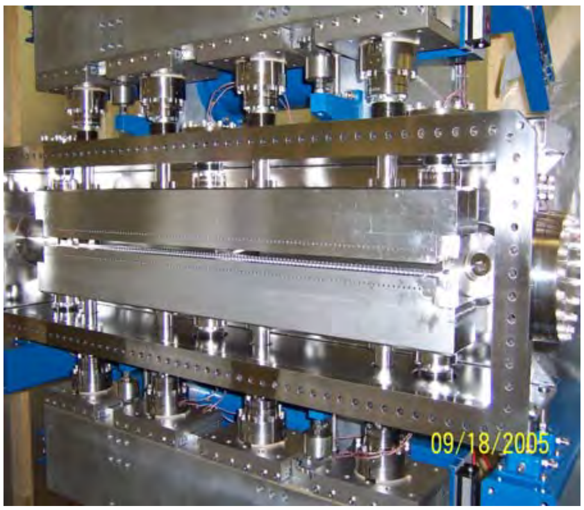

Figure 7. The fully opened jaw (19 mm) at chamber can ease the magnet for measurement and shimming

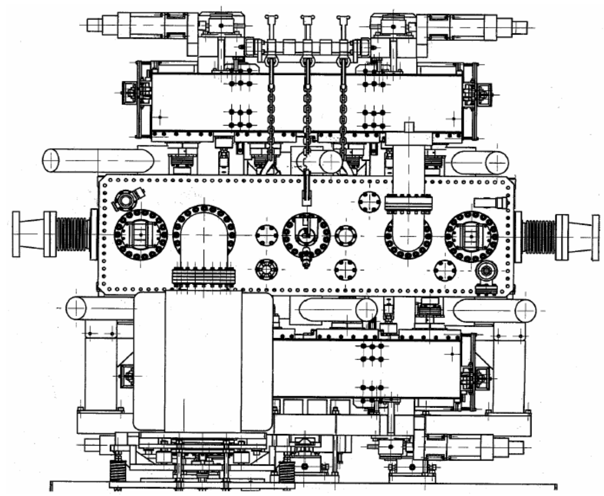

Figure 8. Front view of the CPMU showing outer girders, center chamber, ion pump, and multi-ports

2. In-Vacuum Chamber Design

To upgrade the radiation source of X-25, with primary goal aimed at brightness of the photon beam, a new permanent-magnet (NdFeB material) undulator designed with adjustable miniature gap (5.6-19 mm) for an easy tuning of the beam, as shown in Figure 9, is installed at the site of the removed hybrid wiggler. The small separation of magnet is achieved by using a large, yet stiff, chamber (16” high) to substitute for the fixed-size ring pipe (1” high) in magnet array and its associated control units. To orderly stack all the sensitive apparati atop an array of magnets and magnet-support girders within a single enclosure with undulated electron beam crossing at midplane, the chamber and its sealing surfaces must be made non-magnetic, radiation resistant, vacuum compatible, and structurally stable.

Chamber Wall and Sealing Gasket

Based on experience from previous beamline renovation and storage ring upgrade at NSLS, the material chosen for chamber fabrication is the low outgassing, high strength, low-carbon 304 stainless-steel plates, which are less magnetic than other graded carbon-steels or alloys. To ensure that the plate chosen is adequate in dimension, particularly the thickness, to withstand the magnetic force-induced bending, buckling, and shearing stresses (bounding cases), a concentrated load was assumed to act on weak spots of the chamber (welds, ports, corners) for conservative model calculation. Finite element method was employed to predict the thermal effect on chamber's sidewall, where there are peak power deposits due to characteristic emission of synchrotron radiation. Based on an additive effect from the gross weight (600-lb arrays), magnetic force (1776-lb attraction), system pressure (coolant injection), and thermal stress (350^{o}C for NEG^{TM} activation), the steel plate designed as chamber flange is $^{3}/_{8}$" thick, and that for the removable front cover where most of the window ports (CF-flanged) are built is of $^{7}/_{8}$" thick.

The gasket used for panel sealing, as shown in Figure 10, is constructed of a low outgassing, non-magnetic, electro-polished pure-aluminum sheet (AL-1100). The use of aluminum as gasket material takes into account protection for the steel chamber, since the soft gasket moderates much of the impact resulting from an abrupt change of temperature (-120^{o}C cooling, 125^{o}C bakeout), pressure (vacuum breach, magnetic force), or power (RF resonance, scattered radiation).. The normal stress on the $^{1}/_{64}$" thick and $1^{1}/_{2}$" wide gasket strip was calculated in terms of the compressive force from applied torque (14 ft-lb) on each fastener. Through iteration, the optimal number (126, $1^{1}/_{4}$" apart) and stem size ($^{1}/_{2}$") of the fastener used for chamber sealing were obtained.

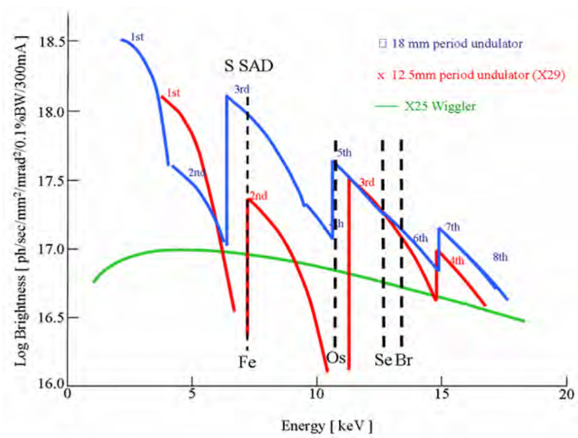

Figure 9. The harmonics and periods of undulator and wiggler are shown in the brightness vs. energy plot

Figure 10. A used AL-gasket on the working bench showing equally apart holes and dented sealing track

Window Ports at Chamber Walls

In addition to the removable front panel, which serves as a large vertical port for direct access of magnets and pole pieces, a total of 39 window-sized CF-flange sealed ports at chamber sidewall (Figure 4) were specifically incorporated for ease of magnet gap control and vessel cleaning. At top and bottom of the rectangular chamber, there are eight 4"-diameter bellow-shielded window ports used to locate the heavy-steel lead-screws (top four) and die-springs (bottom four), which connect the inner chamber girders with outer chamber girders (Figure 8). The two parallel outer girders each at dimension of $43^{1}/_{2}$" wide by $8^{1}/_{4}$" high by $6^{1}/_{2}$"deep are made from a chunk of solid 6061-aluminum (220-lb), designed to control the magnet gap between the two aluminum inner girders. Interspersed among the four equal-spaced screws (chamber top) and springs (chamber bottom) are three 5"-diameter vacuum-guarded window ports for coolant circulation use (Figure 4). The cryogenic refrigerant coming from an independent, Janis Company-made cooling unit will be pumped into the inner girder through a thermocouple-censored and tube-shielded center port. At inner girder below the magnet-support platen, the injected refrigerant (cold nitrogen or helium gas) will be equally distributed among multiple channels for uniform cooling of magnets before being discharged through two opposite side-ports. Along the electron beam path at chamber midplane, there are two in-line 6"-diameter ports at upstream and downstream locations, where BNL-approved flexible transition tubes, as shown in Figure 11, are attached to connect the vacuum chamber with ring pipe. The choice of a transition tube with its inside flexible sheet of Inconel-625 is based on a need to fulfill the RF electric continuity (image current flow) over the enlarged chamber section along the storage ring. Adjacent to the beam ports and at the edge of the chamber flange are two $^{1}/_{4}$"-diameter reamed holes built for magnet survey based on fiducial set points (pins) at gap. To measure the separation of magnet with high accuracy up to sub-micron range, LED-CCD coupled Keyence laser system was installed at four 4"-diameter ports that are symmetrically located near the edge at front and back of the vacuum chamber. For vessel pressure gauging and residual gas pumping *en route* to an ultra-high vacuum at $2x10^{-10}$ torr, the front panel has a ½"-port built for the Convectron gauge (Stinger^{TM}), a $1^{1}/_{2}$"-port for the Cold Cathode, a $1^{3}/_{8}$"-port for the turbo-station, a $1^{3}/_{4}$"-port for the RGA, a 2"-port for the manual switch of in-vacuum glow-discharge device (Figure 12), a 4"-port for the ZrFeV-based NEG^{TM} cartridge, a 6"-port for the 550 L/s ion pump (Star Cell^{TM} pump), and two $1^{3}/_{4}$"-diameter all-metal gate-valves (blanked ports) for required use by the leak detector (helium) and/or by the temperature censor (thermocouples). To ease the changeover of parts and devices, all ports built at front panel are CF-flanged.

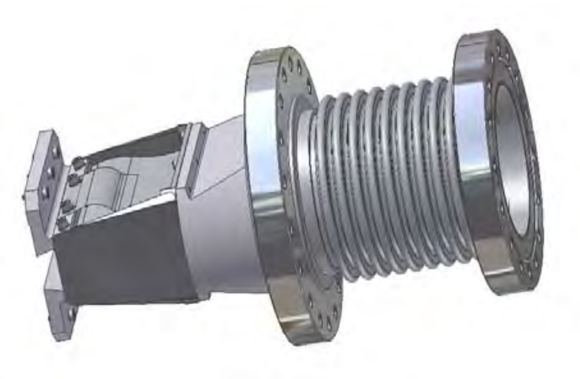

Figure 11. The BNL-approved flexible transition tube for image current transfer from chamber to ring pipe

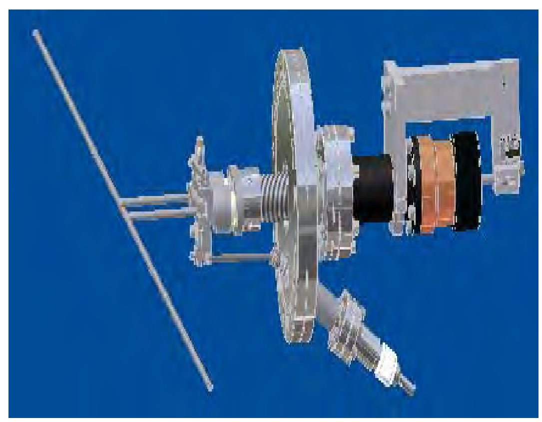

Figure 12. The glow discharge cleaning assembly in chamber vessel has a control bar at front panel

Permanent Magnet and Magnet Poles

Inside of the vacuum chamber and at the top of cryogenic-cooled aluminum girders, there are two parallel, face-to-face, 40"-wide magnets-and-pole sets in a 53-period array, where die-pressed NdFeB fabricated permanent magnets (2" by $1^{1}/_{8}$" by $^{3}/_{8}$") and TiN-coated FeCoV pole pieces ($1^{1}/_{2}$" by 1" by $^{1}/_{8}$") are inlaid side-by-side, as shown in Figure 13. The motor-driven array of magnets at an attainable gap of 5.6-19 mm, which correspondingly yields 1.0-0.3 Tesla on-axis field, was designed to produce a high-brightness photon beam (> 10^{21} ph/s/mm^{2}/mrad^{2}/0.1%BW) from highly-focused electrons (K ≈ 1.5

at T = -120^{o}C) through a periodic undulation. Unlike previous mini-gap insertion devices used at NSLS, the new undulator will be a tunable X-ray source over the photon range of 1.9-20 keV, with continuous coverage in overlapping bands, utilizing all harmonics from the fundamental up through the 9th mode. Specifically, there will be a significant and usable 2nd field harmonic on-axis due to a rather large emittance of the 2.8 GeV electron beam.

While actual performance of the undulator is under evaluation at the X-ray storage ring, pre-installation tests including integrated field measurements have been conducted at Magnetic Measurement Lab of the NSLS, using pulse-wiring scheme and calibrated Hall probe. A data plot[3] of three scans of the 2nd integral, respectively at horizontal midplane (0 mm) and two offset positions (+5 mm, -5 mm), under fixed 5.6-mm gap separation is shown in Figure 14.

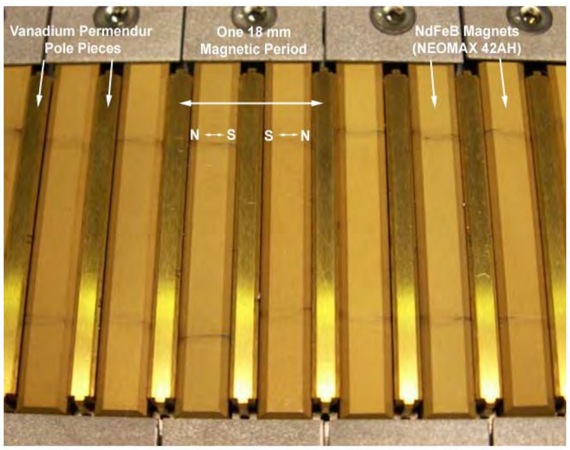

Figure 13. Array of permanent magnets and their pole pieces inlaid on a cryo-cooled inner chamber Al-girder

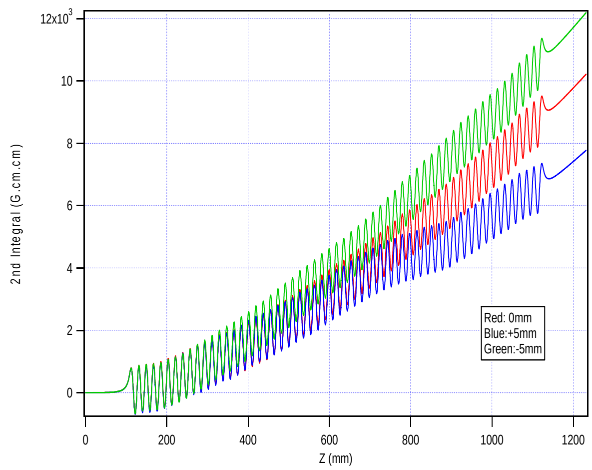

Figure 14. The 2nd integral for 3 scans with horizontal offset at 0 mm (red), +5 mm (blue), and -5 mm (green)

3. Conclusion

To pursue research in protein crystallography, which requires high resolution of structure image from irradiated cells, an in-vacuum cryogenic-cooled permanent-magnet undulator with an attainable miniature-gap of 5.6-19 mm was installed at NSLS' X-ray ring as a new radiation source to the beamline-25, at the location of the removed hybrid-wiggler. Based on a novel design, this undulator has a 53" wide by 16" high by 10" deep vacuum chamber featuring a large vertical rectangular port (a fully removable front panel) to house the 3-ft wide magnet assembly and its associated gap-control and vessel-cleaning systems. The large port cover is sealed to the main flange of the chamber, using a one-piece, flat, electro-polished aluminum gasket ($^{1}/_{64}$" thick by $1^{1}/_{2}$" wide). The gasket and sealing surface design is highly robust, proven by success in performing eight reseals with eight new gaskets. On sealing, the small scratches at steel surface of the chamber are tolerable since soft aluminum of gasket can perfectly fill them under 14 ft-lb applied torque to each of the 126, $1^{1}/_{4}$"-apart fasteners ($^{1}/_{2}$" bolts) along the chamber flange. The large flange facilitates direct access down the gap of installed magnet girders for *in situ* magnetic measurements and shimming. Special window ports of varying sizes were designed into the cover and chamber to admit optical micrometers (LED-CCD Keyence laser system) for precision measurements of the in-vacuum magnet gap from outside of the chamber. For radiationinduced heat removal (~10 watts during accelerator operation) and field-induced force counterbalance (1,770-lb at gap of 5.6-mm), special vacuum-guarded ports and isolated feedthroughs were built on the chamber's sidewall to provide cryogenic cooling (-120^{o}C) and energy absorbing (die-springs).

Model calculation has shown that, due to improved focusing of electron beam (K→1.5) through a miniature gap (1.0 Tesla on-axis at gap of 5.6 mm) in the UHV chamber (< $2x10^{-10}$ torr), the undulator will be able to generate a soft X-ray at ~15 times brighter than that from the replaced wiggler at energy of 6.3 keV, and ~6 times brighter at 10.5 keV.

Actual measurement of the photon flux, brightness, and scattering pattern as a function of magnet gap is ongoing, and all updates on beamline-25 will be posted at NSLS' website[1].

4. Acknowledgements

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5. References

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