“Micron Management“
Active Micron Level Gap Control of Undulator Magnets

J. Skaritka, S. Ramamoorthy, S. Chouhan, D. Harder, J. Hu, W. Rambo, T. Tanabe
NSLS, Brookhaven National Laboratory, Upton, NY, USA
W. Nolan, Biology Department, Brookhaven National Laboratory, Upton. N.Y., USA
J. Kulesza, D. Waterman, Advanced Design Consulting USA, Inc., Lansing, NY, USA

The authors gratefully acknowledge contributions by L. Berman, E. Johnson, G. Rakowsky, W. DeBoer, C. Nielson, and A. Borrelli of the NSLS.

This research is supported by the U. S. DOE under the contract DE - AC02 - 98CH10886.

Abstract
The X-25 Insertion device at the National Synchrotron Light Source is a newly installed 1M long, 18mm period, in-vacuum, Cryo-ready, Hybrid Undulator, replacing a 1.5M long wiggler magnet that had operated for the past 15 years. This Undulator requires extremely tight straightness, taper and gap control tolerances of the order of a several microns. First order Gap control is performed using 4 external stepper motors with a linear encoder feedback system that positions each magnet girder to a mean reproducibility of 1 micron. The one meter magnet length required multiple structural feed-thoughts in the vacuum envelope to assure continuity between rigid external structural girders and the in-vacuum magnet girders. However, magnetic and mechanical measurements indicated that gap dependent non-linear magnetic forces, environmental temperature gradients, and operational conditions caused deflections of the in-vacuum magnet girders that exceeded specification. The external linear encoders could not measure these affects and correction by the primary gap control system would be ineffective. The Undulator was designed to be used either as a water cooled Mini Gap Undulator “MGU” operating at 20C or a Cryogenic Permanent Magnet Undulator “CPMU” operating at -120C. During testing as a CPMU direct measurements of the magnet gap differed by greater then 1mm with respect to the gap as inferred by the external linear encoders. These measurements indicated that relying exclusively on a conventional external linear encoder based control system is insufficient under extreme conditions and a direct means of gap measurement and a secondary means of gap control are necessary to maintain micron control of the magnet girders over the full range of environmental and operational conditions. A system was devised to provide a secondary means of gap control to permit correction over the regime of these tertiary effects for up to 100 microns of non linear gap control. This paper shall describe the secondary gap control system and how it may be used to optimize Undulator performance

1.0 Introduction : “Brightness is Everything”

Many users of Third Generation Synchrotron Radiation Facilities continually search for ever brighter sources of X-rays to perform their experiment. To service these needs designers of radiation sources push the magnet performance envelop utilizing state-of-the art magnet and pole materials. Undulator designs are continually being optimized to provide the highest strength and quality magnetic fields to achieve the highest possible photon flux intensity and brightness. The undulator magnets are specifically designed to achieve extreme brightness but in doing so, stringent geometric requirements are imposed on the assembly and control systems of these advanced magnetic components. Further advancements in permanent magnet undulators are being limited by mechanical tolerances on the physical magnet gap that control the magnitude and quality of the undulator’s alternating magnetic field.

At the NSLS the recently installed Cryo-Ready In-Vacuum Undulator at the X-25 beamline is an advanced 18mm period hybrid design using Neodymium-Iron-Boron magnets and Vanadium-Permadore poles achieving peak fields of 0.95 Tesla at an operating gap of 5.6 mm[1]. The magnet gap of the X-25 undulator must be maintained to very demanding mechanical tolerances. Once shimmed each of the two magnet modules of the X-25 undulator must maintain straightness and parallelism to less than 4 microns over their 1 meter lengths. Below, Figures 1and 2 are photos of the X-25 undulator. Figure 1 shows the X-25 installation

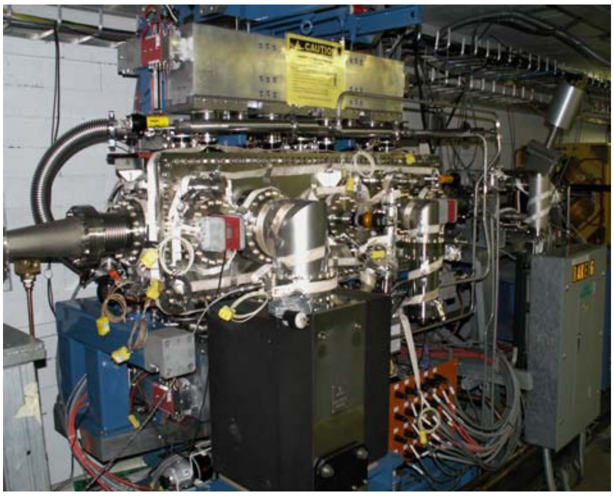


Figure 1

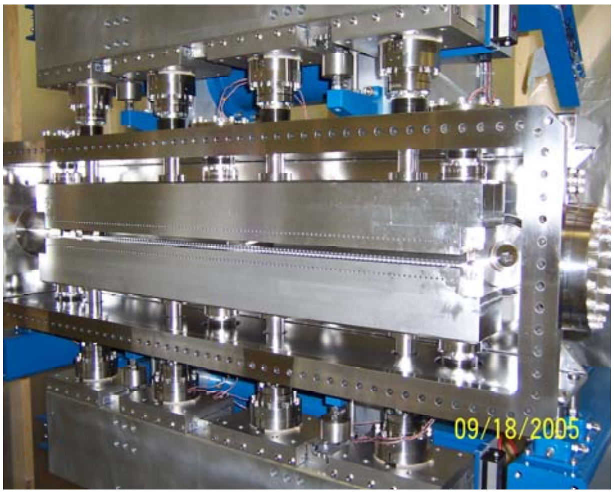


Figure 2

in the NSLS tunnel. Figure 2 shows the undulator’s magnet modules inside of the vacuum chamber with the large side flange removed.

The X-25 undulator is an ultra high vacuum device. The positioning of the magnet modules is controlled with the use of stainless steel posts that protrude through the vacuum envelope. These ports are attached to a Gap Separation Mechanism（GSM）composed primarily of aluminum structural elements. The in-vacuum magnet modules are themselves effectively isolated from the surrounding environment. But a temperature change across the over all magnet assembly of 0.2°C would distort the magnet gap beyond the required tolerances. Figure 3 shows measured temperatures at the undulator that are typical of normal operation. In the NSLS tunnel

the environment immediately surrounding of the undulator is routinely subjected to temperature swings of ± 1.5° C. When the beam is dumped, the tunnel temperature drops. After the fill, the temperature rises.

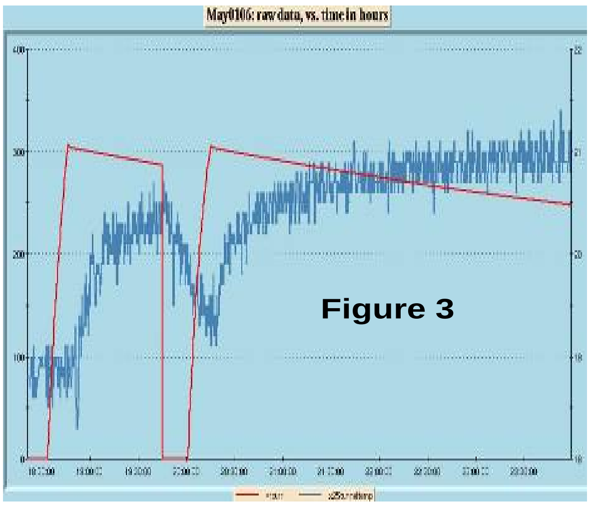


Figure 3

There were no practical means to control the local temperature at the undulator assembly to compensate variations in the NSLS tunnel temperature. This issue and other factors that could degrade the undulator performance lead the authors to develop a means to actively control the temperature of the stainless steel posts that in turn provides a secondary level of fine control for the positioning of the magnet modules.

This paper describes these developments and some of the potential ramifications of this work that can be applied to undulator designs for future machines such as the proposed NSLS-II project that is tentatively scheduled for completion in 2013, as well as a case study for a potentially lower cost means of upgrading equipment at older, less environmentally controlled facilities such as the NSLS.

2.0 Mechanical Necessity for a Local Temperature Induced Gap Control System

Temperature stability requirements for many of the recently constructed synchrotron radiation facilities specify a local temperature stability of ± 0.1°C. On conventional systems this requirement can be achieved locally using upgraded industrial temperature controllers[2], but for machines housed within buildings with a circumference on the order of a kilometer the demanding tolerance on environmental control may result in prohibitively high costs for the required HVAC system. In older less environmentally controlled operating facilities such as the NSLS changes to the current HVAC infrastructure were considered both technically unfeasibly and outside the project scope or budget for any specific insertion device.

The X-25 undulator and control system was designed and developed in close collaboration by engineers from both the National Synchrotron Light Source Department of the Brookhaven National Laboratory and the Advanced Design Consulting Company of Lancaster, New York, USA.

As will be described later in this report a change in project scope, an oversight of both parties late in the design process and certain fiscal and magnetic measurement requirements lead to a paradox, the only resolution of which necessitated the addition of secondary means of local Gap Control.

Figure 4 shows the typical measured effect of local tunnel temperature changes on the undulator gap. The Blue line is beam current. The purple line is local temperature and the Red stepped shaped incline is the actual magnet gap as measured by an optical micrometer integrated into the vacuum vessel. The linear encoders of the primary external control system for the Gap Separation Mechanism (GSM) measures no chance in the gap at all. This is due to the fact that all the components of the external GSM system is

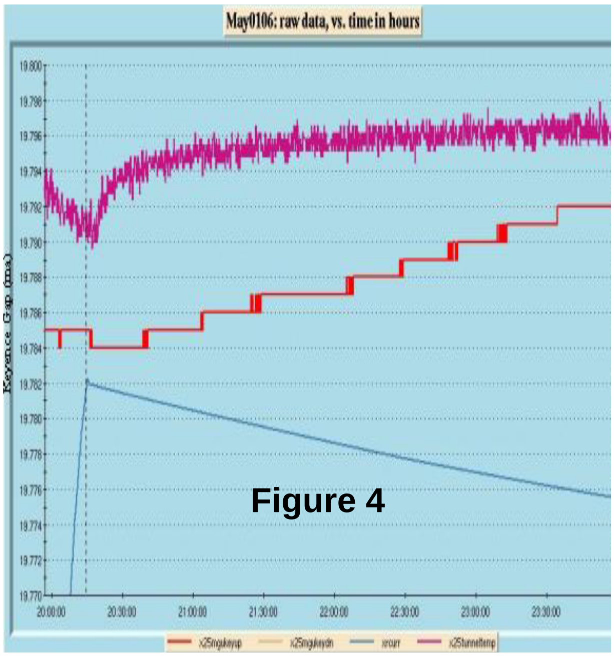


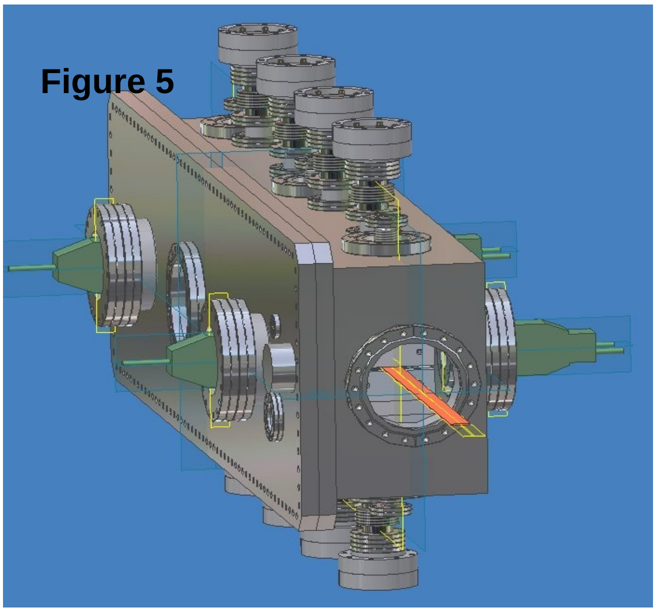
Figure 4

experiencing the same temperature change and as such do not experience differential motion. This motion is only observed in the worst possible place; The nearly inaccessible thermally isolated in-vacuum magnet gap! During the detailed design phase of the project it was found that conventional means to determine and maintain the gap of an in vacuum cryogenically capable undulator were inadequate to provide the necessary degree of control for the undulator magnet surface flatness and gap aperture.

Vacuum System Design and Magnetic Measurement Considerations

Figure 2 depicts the design of the overall mechanical system. In vacuum Girders with the required structural rigidity for the UHV magnet arrays required an impractically large vacuum vessel so it was decided to break up the magnet support girders in two parts. A system of two very rigid outer support girders each driven by two lead screws supported at the approximate quarter points and a second set of less massive in vacuum girders were devised. Between the out of vacuum and in vacuum girders is a system of 8 rigidly affixed stainless steel posts. This system provides an overall rigidity necessary to maintain the required straightness and flatness of the magnet modules over a range of magnet gaps and varying attractive magnetic forces. Temperature fluctuations in the environment surrounding the in vacuum magnet components, could result in unacceptable gap distortion. Further more, the distortions could not be detected using conventional means. The magnet gap in the current design of the CPMU is controlled using a pair of precision re-circulating ball nut lead screws driven by stepper motors. Position feed back is provided by precision linear encoders mounted to the outer girders. Environmentally induced changes that may occur between the outer girder and the magnet gap could not be detected by the externally mounted linear encoders.

A means to directly measure the magnet gap was necessary. Conventional mechanical methods to reliably measure the gap proved to be cost prohibitive. Optical micrometers were incorporated into the vacuum vessel of the X-25 undulator so to directly measure the magnet gap at either end of the magnet monoliths.[3] Figure 5 depicts the optical micrometers mounted into the X-25 undulator vacuum vessel. A further complexity of the X-25 undulator was its requirement to be refrigerated to a temperature of approximately -120° C (150K). The Remnant field of Neodymium-Iron Boron magnets can be significantly increased if operated at a



temperature of approximately 150K resulting in a magnetic field increase of approximately 19% in the magnet gap.

Cryogenic testing of the X25 undulator showed a discrepancy in magnet gap as measured by the external linear encoders of the GSM and the Gap as measured by the internal optical micrometers. The difference of up to 1.2mm at the maximum temperature excursion was recorded. This proved there could be no precision correlation between the internal and external measurement systems at these extreme thermal excursions and during cryogenic operation a means of direct feedback control must be provided using a device that can directly measure the magnet gap.

A further complexity is the necessity to measure the undulator magnet at its precise operating temperature. To assure that shimming to minimize phase and harmonic error content between the magnetic measurements laboratory and the tunnel, the magnet's operating temperature had to be maintained to a fraction of 1°C from the measurement lab temperature. It was planned that the initial operation of the X-25 undulator would take place at ambient temperature and water would be used to maintain the temperature of the magnet monoliths. For cryogenic operation the circulating gas pressure would be sub-atmospheric. The circulating cooling water however has a positive pressure of about 1/2 atmosphere to allow coolant to flow through the magnet monoliths. This pressure expresses itself as additional vertical loads at either end and in the center of the undulator. These loads were not considered during the initial phases of design. It was determined that the load resulting from the water pressure would flex the ends of the magnet monolith to a level that could be detrimental to magnet field quality. To correct this problem, the end stainless steel girder posts would have to be shortened by approximately 3 or 4 microns to induce as slight bending moment at the ends of the monolith to maintain gap straightness, but if the cooling medium were to be changed from pressurized water in the future to a low pressure gas, the post lengths would have to be changed again. The system does not provide for easy post adjustment and the effect of the pressure change would be invisible to the linear encoders of the GSM's control system. It was determined that by lowering the temperature of the four outer posts about 0.5°C with respect to the four inner posts would straighten the beam sufficiently to correct for the effect of the cooling water pressure on the magnet monolith.

Further applications of a system that could provide small local straightness control of the magnet monoliths could also provide correction of the external environmental conditions and to correct for thermal gradient induced flexure caused by cryogenic operation. A potential advantage of having an *insitu* means to fine tune the field quality of the undulator is to respond to user requirements for optimizing the quality of the harmonic content of the produced X-ray beam. Over time a look up table may be developed and implemented to optimize X-ray beam properties for each user. The magnet gap can thereby be controlled to a higher level of precision using thermal methods than by mechanical means alone. This provides the user in effect a control knob for minute adjustment of the magnetic field in the undulator gap.

Post Temperature Heater Controls

Heated Post Hardware Configuration

Figure 6

The temperature of each post is independently controlled by three heaters consisting of resistor pads (CADDOCK - 1%, 25 ohm, 50 watt high performance film resistor in a TO220 package, Allied part #5244115) installed around each post. An RTD probe (Omega 1PT100R624 platinum) mounted on each post monitors the temperature. A precise temperature control within 0.1 deg c is achieved by using Omega CNI-series controller (model number) that senses the RTD and adjusts the output current interval to the heaters to maintain the desired temperatures. Figure 6 is a photo of a heated post assembly.

The controller can be configured to operate in manual or ON/OFF or full auto tune PID control modes. The controller is equipped with a serial input for remote operations (temperature setting and temperature read-back). The serial input can be configured for RS-232 or RS-485 serial communication Using the front panel buttons and the LED displays, the controller can be configured for the desired input, outputs, control modes and serial communication protocol. Figure 7 shows the dramatic effect that happens when by suddenly dropping the post temperature the magnet gap increases.

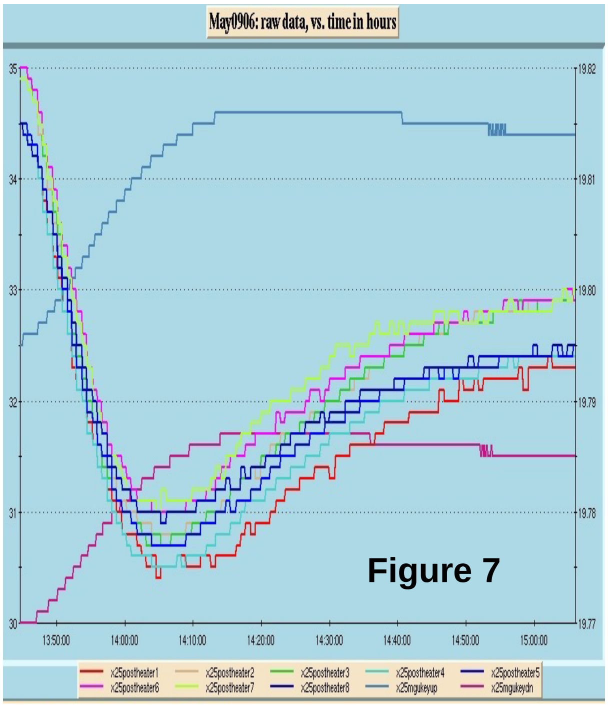


Figure 7

In the current application, the set-points (desired temperatures of the posts) are issued to the eight controllers through eight serial ports housed in a VME microprocessor system that is connected to the distributed NSLS control network. The VME system in addition controls the Mini Gap Undulator (MGU) and monitors the gap measured by linear encoders and Keyence optical scanner. This interface allows the operators to control the gap as well as set the temperatures of the posts and monitor the parameters via the distributed control network and save various data continuously in specified time interval.

Optimization of PID Loop Parameters

The temperature control of the posts is accomplished by PID loop control. To arrive at the optimum values for the PID loop parameters (Proportional Band, Integral/Reset time, Rate/derivative) the controller is initially configured for the Auto Tune mode and a temperature set-point (approximately 10 deg C above the current temperature) is issued to the controller. The cycle time (ON/OFF time within the Proportional Band) is chosen as 7 (recommended for Solid State relay). In the Auto-Tune mode, the controller will adjust the parameters (which may take several minutes). When the Auto Tune is complete, the PID loop parameters are stored in its memory, which can be retrieved from the controller. The plot of temperature versus time may indicate oscillations or over shoot or undershoot. The three parameters derived by the Auto-Tune were adjusted by trial and error until the oscillations disappear and the temperature is within 0.1 deg C from the set-point.

Multiple thermal cycling tests using the post heaters indicate the thermal to mechanical linkage has no back-lash and is reproducible to the level of measurement accuracy of less then 100 nm.

Figure 8 is a plot of the post temperature versus time after the parameters have been adjusted to simulate a simple control Loop. Studies are underway to find the appropriate transfer function that can be used to keep the gap constant by adjusting the temperatures of the posts. The Parker 6 K controller software algorithm used for the gap separation mechanism (GSM). guarantees a resolution of +/- 1 micron. By increasing the post temperatures, one can control the gap in sub-micron range. The minimum gap as measured by optical micrometer is ~5.4 mm because of the preset limits.By heating the posts, the gap can be decreased a few microns lower than 5.4 mm. This can influence the photon energy at which the spectral peaks occur.

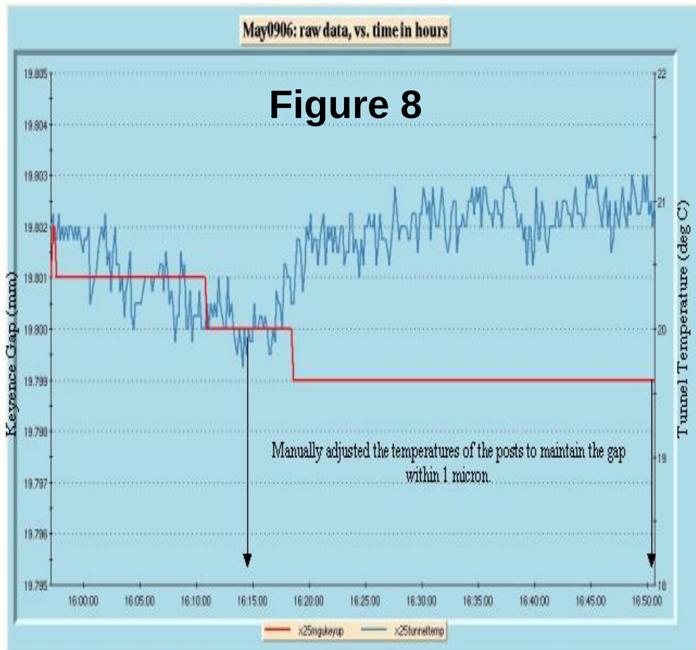
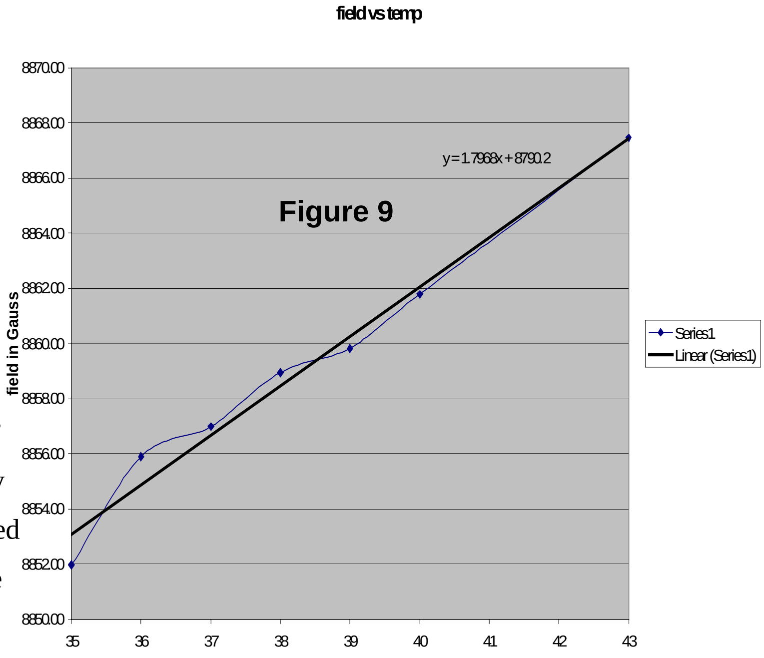


Figure 8

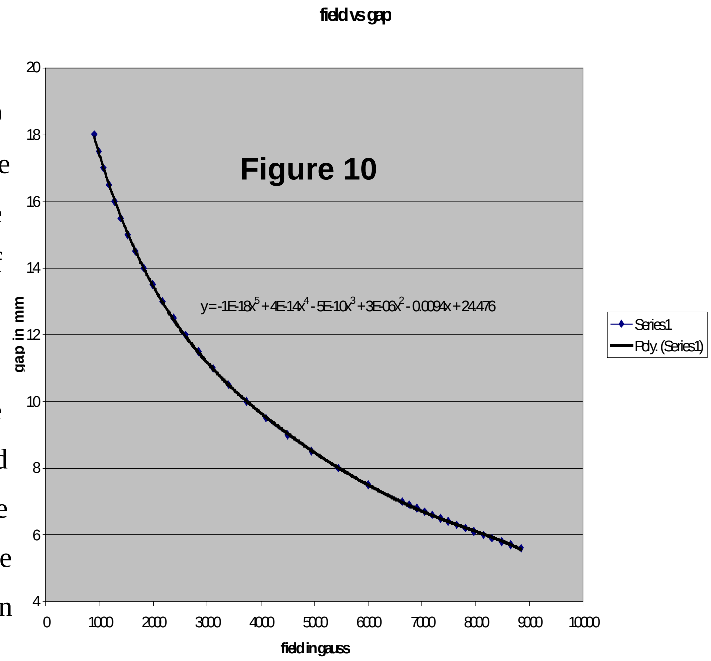
Correction of Temperature Variation and Optimization of the X-Ray Beam

Massive aluminum columns are used to form a strong back for the magnet monoliths and resist the bending moments induced by the magnetic fields. The aluminum columns and beams form the structural members of the Undulator's (GSM). Thermal couples continually monitor tunnel and GSM temperature. Electric heaters and thermal couples located the stainless steel support posts maintain their temperature at a nominal 30°C. The wattage and operating temperature of these heaters were chosen to maintain the post at a constant temperature, despite tunnel temperature fluctuations but not heat the post to a level where the post assembly



may become a high temperature safety hazard. Figure 9 demonstrates the measured effect of changing a single posts temperature and the resulting change in gap and magnetic field of the magnet pole immediately inline of the monolith support post.

The transfer function was measured as 2.7 microns of gap position control per degree C of change in post temperature. The posts can be controlled to within 0.1° C providing a potential level of control to approximately 0.3 microns. We have decided to utilize a layered approach to the control of the undulator gap. The primary means of gap control is using the stepper motor drives and external linear encoders to provide gap, aperture taper and elevation control. This system has demonstrated reproduce-ability to approximately 2 microns, as measured by the external linear encoders and confirmed by the in-vacuum optical micrometers. The thermal post control system is designed to be a layer of precision stability control on top of this conventional system with a control range of ± 50 microns with a reproduce ability of ± 0.3 microns.



During normal NSLS operations the undulator Gap will be opened and closed many times a day and over 100,000 times over the planed life of the undulator. Temperature fluctuations of several degrees C have been recorded by the GSM thermal couples. The massive aluminum columns of the GSM dampen the effects of rapid temperature swings, but provide the largest temperature effects. Aluminum was chosen due to its non-magnetic property so close to the magnet gap. Figure 10 Depicts the maximum measured field of the undulator as a function of magnet gap. As the column temperature rises in response to tunnel temperature cycles, gap increases to the order of 20 microns have been recorded by the in-vacuum optical micrometer.

Studies have been preformed to determine ways to use post temperature to optimize X-Ray beam performance. In one example the 7^{th} harmonic peak could be controlled to a repeatable energy of ±1 electron-volt. This **1 part in 10^5 X-ray Peak control** demonstrated the extreme reproducibility of this system and the overall achievement of X-25 Undulator project, the newest fully tunable X-ray source at the NSLS.

Figure 11 shows the measured spectrum of the X-25 Undulator and figure 12 shows the adjustability of the of the 7th harmonic peak by changing post temperatures.

Undulator Properties
Period ……………….18mm
Number of periods …..55
Overall Length ………990mm
Min. Operating Gap…5.6mm
Min. injection Gap ….18mm
maximum Gap ……...20mm
B max @20C ……….0.95 Tesla
K max @20C ……….1.59
E beam min. energy ...2.80 Gev
Min.E1 …………..….1.83kev
Min.E3 ……………. 5.49 kev
Min.E5 ……………. 9.15kev
Min.E7 ……………..12.81kev
Min.E9 …………….18.47kev

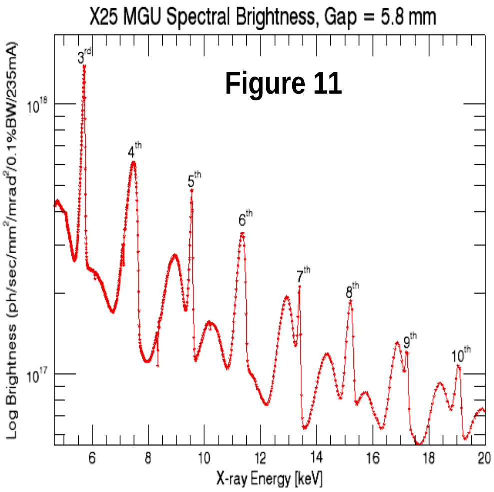


Figure 11

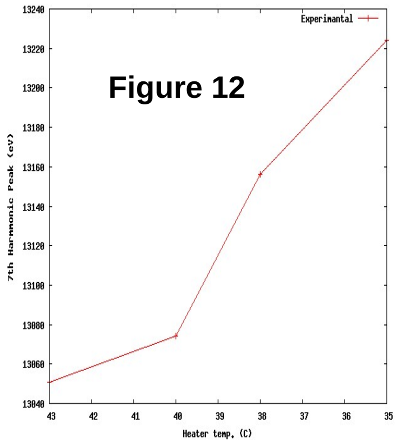


Figure 12

CPMU for NSLS II

This technique may prove to be very important to provide Ultra-precise control of long in-vacuum undulators gaps, such as the a 3 meter long CPMU depicted in Figure 13 that is being considered as the base line undulator design proposed for use at the NSLS II. Harmonic peak resolution of a few milli-EV and < 100 nano-meter gap control will be desired. UHV chambers over 2 meters in length have been made by industry and there are no impediments to extending any of the technologies discussed in this paper to a system up to 3.6 meters in length.

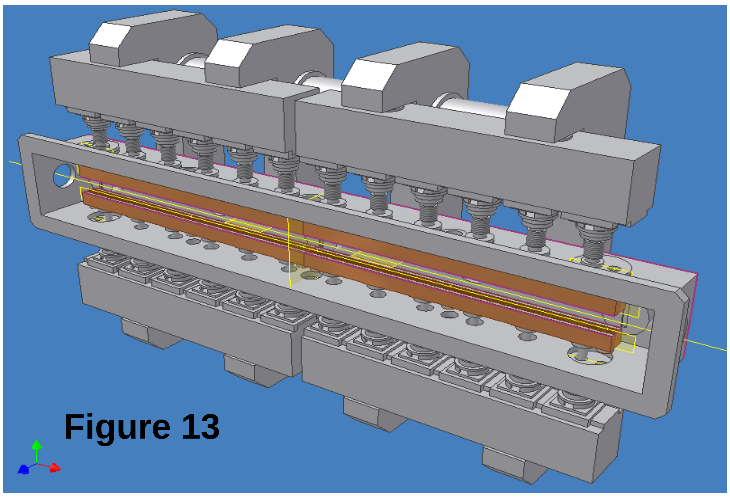


Figure 13

References:

1. **L.E. Berman, et. all, X-25 Up-Grade. NSLS Annual Users Meeting . May, 2006,** ***Brookhaven National Laboratory, Upton NY, USA***
2. **Sushil Sharma, April 2006, Private communications**
3. **Jih-Perng Hu**, Conrad L. Foerster, John R. Skaritka, David Waterman, **Novel Chamber Design for An In-Vacuum Cryogenic-Cooled Miniature-Gap Undulator,** ***4th International Workshop of the Mechanical Engineering Design for Synchrotron Radiation Equipment and Instrumentation, May 24-26, 2006, Egret Himeji, Japan***