Mechanical Design of NSLS Mini-gap Undulator (MGU)

D. Lynch, G. Rakowsky

National Synchrotron Light Source (NSLS),
Brookhaven National Laboratory (BNL), Upton, NY 11973, USA
Phone: 631-344-2253, FAX: 631-344-3238
E-mail: dlynch@bnl.gov

Abstract

The mechanical design considerations are discussed with respect to the currently installed X-13 and future X-29 MGU. Comparisons to the previous 2 generations of variable small-gap undulator evolution in the NSLS X-ray ring are made and design improvements noted. The design requirements and mechanical difficulties for holding, positioning and driving the magnetic arrays are explored. Structural, thermal and electrical considerations which influenced the design are then analyzed. The mechanical performance of the MGU currently installed at X-13 is examined and future installations and enhancements are presented.

Keywords: undulator, in-vacuum, small-gap, magnet-arrays

1. Introduction

Beginning with the Prototype Small Gap Undulator (PSGU), installed in the NSLS X-ray storage ring in 1994, and continuing to the present, the NSLS has developed a series of small gap undulator insertion devices for high brightness and high flux. The benefits of such devices have been well documented by Stefan [1]. The Mini-Gap Undulator (MGU) described in this report is the latest in this series of devices and builds on the successful mechanical design concepts proven in the earlier devices.

The X-13 PSGU was a pure-permanent magnet undulator with 1.6 cm period, equipped with a variable-gap vacuum chamber. Separate drive systems on the magnet arrays and the vacuum chamber gap permitted testing the beam dynamics and beam lifetime at reduced gap, independently of magnetic field effects. It demonstrated that at the midpoints of the long straight sections of the X-ray ring, where the vertical beam size is a minimum, the vertical aperture can be reduced to nearly 3.3 mm, provided that the device is not more than 35 cm long. It also demonstrated that a compact, short-period undulator can generate tunable, soft-X-ray photon beams with high brightness, previously available only at much higher energy machines.

The PSGU was retired in 1997 and replaced with the X-13 In-Vacuum UNdulator (IVUN), developed jointly with the Spring8 synchrotron light source in Japan. The IVUN utilized many of the drive and vacuum concepts developed for the PSGU, but now the magnet arrays were placed inside the vacuum envelope. While the minimum magnetic gap of the PSGU was limited to 6 mm by the intervening vacuum chamber, in the IVUN the magnetic arrays themselves could be closed down to the 3.3 mm limiting gap. As a result, the IVUN was able to attain the same peak magnetic field as the PSGU, but with a period of only 1.1 cm and 63% more periods in the same overall length. This resulted in even higher brightness at higher photon energies than with the PSGU.

The IVUN was upgraded in 2001 with a higher field, "hybrid" magnetic structure and renamed the X-13 Mini-Gap Undulator (MGU). The higher magnetic field gives a wider tuning range than was available with IVUN. The period and peak field were chosen to provide photons in the energy range 7-15 keV, requested by the user (utilizing the 2nd, 3rd and 5th harmonics). All of the drive and vacuum components from the IVUN were retained except for the magnet support structure which was redesigned to accommodate the greater attractive forces associated with the higher magnetic field. This design is currently being duplicated for a new MGU to be located in the RF straight section leading to X-29. Table 1 provides a comparison of the design and mechanical parameters for each of the 3 designs. Rakowsky [2] has compared the physics and magnetic parameters for the 3 devices.

This report will trace the process by which the MGU's performance requirements are transformed from specifications to a functioning apparatus (specifically the X-29 MGU). The X-29 MGU's dependence on the previous successful devices is described, the methodology utilized to meet the new challenges associated with the X-29 MGU are analyzed, including the design and/or modification of surrounding and downstream equipment to accommodate the output of the X-29 MGU. The current status of the X-29 MGU project is then discussed along with potential future advances in small gap devices.

Table 1: Comparative Parameters for NSLS Small Gap Undulators

	PSGU	**IVUN**	**MGU**
Period λ_u	16 mm	11 mm	12.5
Nom.Mag.Gap	6.0 mm	3.3 mm	3.3 mm
Peak Field B_u	0.62 T	0.68 T	1.0 T
Fund. Photon Energy	2.8 keV	5.4 keV	3.5 keV
e-beam Energy	2.8 GeV	2.8 GeV	2.8 GeV
Remote DOF	5	2	2
Manual DOF	22	22	22
Magnet Env.	In air	In vacuum	In vacuum
Magnet Type	Pure PM	Pure PM	PM Hybrid

2. Design Specifications

Design specifications for the MGU are evolved in a top-down approach is as follows:

The researcher specifies the required UV or x-ray spectral range, brightness, photon flux, etc., while the beam dynamics physicist determines minimum allowed vertical aperture profile in the proposed insertion device. The magnet scientist/engineer then determines the magnetic field parameters of the insertion device, the device type (wiggler or undulator), and, most importantly, its realizability and choice of technology (pure permanent magnet, PM-hybrid, or superconducting). From these the magnetic, tuning range, overall length, as well as the magnet and pole materials, their dimensions and the required field quality. As in most engineering problems, tradeoffs and compromise lead to a set of realizable magnetic parameters. These are then synthesized into a set of mechanical specifications for performance, environment, materials, limits and tolerances, etc. The MGU requirements are as indicated in the following subsections.

2.1 Performance

The MGU is required to position 2 identical magnet arrays of alternating field strengths with the magnetic parameters indicated in Table 1, above, such that arrays are oriented equidistant above and below, and with their magnetic flux direction perpendicular to the nominal horizontal plane of, the NSLS X-ray storage ring electron orbit. In addition, RF continuity must be maintained along the innermost face of the magnet arrays in order to accommodate the electron beam image current. The range of potential relative displacement of the inner most faces of the magnet arrays is to be from 3.3 to 10 mm while maintaining equal separation to the ring orbit plane.

2.2 Environment

The MGU must maintain x-ray ring ultra-high vacuum integrity (UHV) and must be capable of withstanding thermal effects of upstream dipole radiation. The physical envelope is limited to the available space between the RF cavities, which must also include isolation valves upstream and downstream of the MGU.

2.3 Materials

The selection of MGU fabrication materials, in general, must be in accordance with their suitability for the application. Strength, weight, thermal properties, electrical properties, magnetic properties, environmental health and safety factors and cost are some of the factors to be considered when making material selections. For the MGU, only the permanent magnet (Neodymium Iron Boron, NdFeB) and pole (Vanadium Permendur) materials were specified to mechanical engineering.

2.4 Accuracy, Limits, Tolerance

Most components of the MGU are to be built with accuracy, limits and tolerance based on prevailing practice at the NSLS. In addition, the accuracy and limits of the e-beam orbital path as set forth by Safranek [3], are to be utilized in ray tracing calculations to determine worst case conditions for thermal analyses. Magnetic engineering calculations also require that magnet positioning tolerances be as follows:

pole width	22 +/- 0.5 mm
pole length	2.54 +/- .025 mm

pole height	17 mm max, uniform to +/- .05 mm
magnetic gap (minimum, maximum)	3.3-10 mm repeatable to +/- .05 mm
overall undulator length	350 +/-10 mm
period	12.5 mm +/- .05 mm

Because the undulator is an array of nearly identical magnets, the uniformity of the magnets is more important to the magnetic field quality than the absolute dimensions.

2.5 Other Design Parameters

There are additional design parameters for the MGU which are not explicitly documented in the specifications provided by the beam physicist and magnet scientist. Mechanical specifications are thus inferred from NSLS standard practices, extracted from other NSLS documentation, or guided by “good practices” for mechanical engineering in general (e.g. specifications for design allowables, and analytical assumptions). In addition, the undulator output must be characterized in terms of peak energy flux and horizontal and vertical distribution of this flux for calculation of thermal exposure of downstream components. Finally, since the components downstream of the MGU are exposed also to dipole bend magnet radiation, these applicable specifications also need to be considered.

Total Undulator Power:	1048.3 Watts
Undulator peak power angular density:	6068.4 Watt/mrad^2
Undulator Power Dist., Gaussian, σ_X :	.25 mrad
Undulator Power Dist., Gaussian, σ_Y :	.1285 mrad
Bend Magnet Hor. Power Dist.:	40 w/mrad
Bend Magnet Vert. Opening Angle:	0.2 mrad

3. Design Concept

The design concept for the MGU, itself, is evolved from the PSGU and IVUN concepts with improvements to accommodate in-vacuum design and higher field magnets. The key features are as follows:

The base provides for manual rough positioning of the assembly with roll pitch and yaw adjustments on a 3 point support structure. Precision centering is accomplished by the relative motion of 2 inclined planes with linear bearings and rails. The actual base for the X-13 MGU is the original PSGU base, modified only slightly for the IVUN and reused without modification for the X-13 MGU. Minor modifications are required for the X-29 MGU to locate the assembly properly within the X-29 RF Cavity straight. Optical and mechanical limit switches and mechanical hard stops are common to all for remote control feedback and fail safe operation (Figure 1).

The external magnet drive system consists of an aluminum strongback, counter threaded drive screw shaft, stepper motor, 100-1 harmonic reducing drive and precision bearings. These control the magnet gap by driving the two large rigid boxes cantilevered off a linear bearing/rail drive system. This provides a relatively rigid and lightweight assembly to meet the tight positioning and repeatability requirements. The concept is similar from PSGU through MGU, although the strongback and upper and lower drive beams were considerably stiffened for IVUN from PSGU to deal with the increased attractive forces of the higher magnetic fields. In each case the drive system had a manual attitude adjustment (Figure 2).

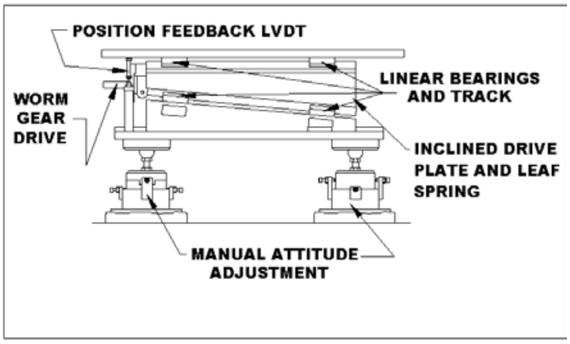

Fig. 1: MGU base.

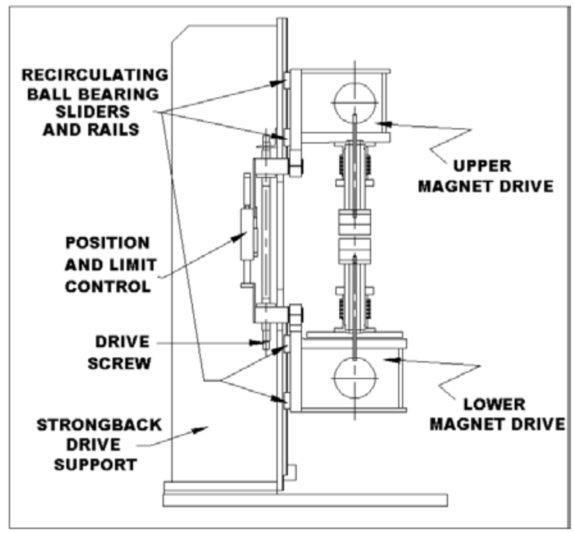

Fig. 2: MGU magnet drive.

The hardware between the drive beams differs for each of the 3 devices, due to both the differences in the nature of the magnet arrays they use and lessons learned from each preceding device. The PSGU had a separate well drive system for the vacuum portion with manual attitude adjustment and remote gap control. The magnet had separate manual attitude and remote gap adjustment systems and the individual magnets were clamped in place. The wells had integral cooling to absorb resistive heating due to image current and some bend magnet radiation. The IVUN used a double walled penetration to allow water cooling with an air guard and a vacuum jacket. The individual magnets were clamped and RF continuity attained with a 0.001" nickel foil. While the IVUN was successful in operation, problems during testing demonstrated (a) the double wall design became dimensionally unstable with gaps below 3.0 mm and (b) the magnet clamping design was questionable. The MGU is conceptually similar; changes to the magnet array and gap together with lessons learned from IVUN dictated design changes to both the double wall vacuum penetration (a stiffer support tube) and the magnet/pole clamping design (separate clamps for the magnets and integral threaded fastening for the poles) (Figure 3).

Vacuum integrity, RF continuity, longitudinal expansion/contraction compensation and integral downstream component thermal protection remains unchanged from the PSGU through the X-13 MGU, and the concept remains unchanged but the design implementation differs slightly for the X-29 MGU. Each use bellows connections, continuous flexible copper sheets attached to the magnet arrays (to the wells for the PSGU), an integral ion pump, a retractable glow discharge unit, a water cooled radiation absorber and a dedicated RGA diagnostic (Figure 4).

The X-13 downstream components including the dipole chamber and front end components have remained constant through all 3 devices. The X-29 dipole chamber and front end components, however, were originally designed for bend magnet radiation only. Consequently, the mechanical engineering requirements for the X-29 included completely new designs for the dipole chamber, and all front end components, particularly those used for thermal radiation control, the mask, the aperture and the safety shutter.

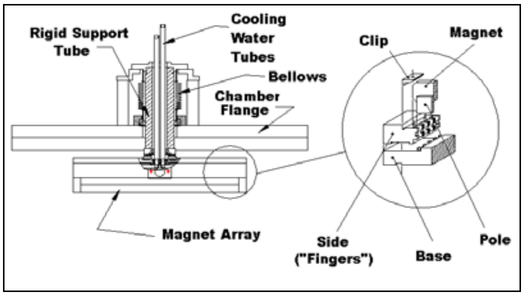

Fig. 3: MGU magnet holders.

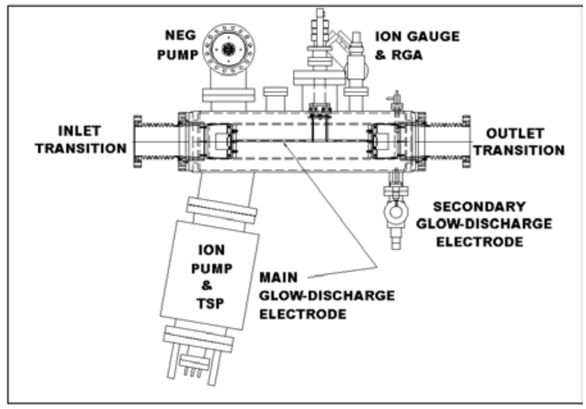

Fig. 4: MGU vacuum components.

4. Engineering Calculations

The engineering calculations required for this project include:

- deflection and stress calculations for the magnet positioning control system (strongback, drive beam, vacuum penetration) and a deflection budget to ensure gap control tuneability and repeatability
- vacuum calculations (pumping requirements, etc.)
- ray tracing calculations for both the MGU itself and downstream components
- cooling water flow calculations (cooling flow requirements, press. drop, temp. rise, and transport properties) for the MGU itself and downstream components
- thermal and thermal stress FEA calculations for illuminated surfaces within the MGU and downstream components.
- The details of these calculations are beyond the scope of this paper but are documented internally at the NSLS [4].

5. Fabrication, Assembly, Test, Installation, Operation

The mechanical engineering responsibilities for the NSLS MGU do not end with the approval of the Final Design Review Committee. They continue through all aspects of fabrication, assembly, test, installation and operation. The X-13 MGU required exceptional coordination, in that during a brief 3 week period, the existing X-13 IVUN was removed from the NSLS X-ray Ring, the IVUN specific components were removed and replaced with the MGU upgrade, the entire assembly was manually recalibrated, a series of magnet tests were performed, and the magnets were shimmed to optimize the field. The assembly was then returned to the ring, reinstalled, vacuum conditioned and has been operating successfully since January 2002.

The success of the X-13 MGU is attributable to careful planning and preparation all through the design and fabrication effort which included fabrication of prototype single pole and 10 pole magnet arrays (Figure 5). The prototypes were useful in proving out fabrication techniques to achieve required tolerances, heat treat technique and cycle for vanadium permendur, and the magnet and pole holding and positioning concept.

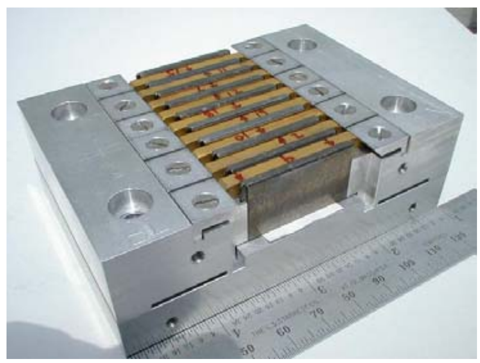

Fig. 5: 10 pole prototype MGU.

The X-29 MGU is currently underway with a high confidence of success based on the proven performance of the design at X-13. The X-29 MGU, however, requires a new dipole vacuum chamber and all new front end components. The X-29 dipole chamber all of its internal components are already in service and performing as predicted. The front end components are designed and currently being fabricated. The MGU and all of its supporting components are scheduled for installation during 2003. The new X-29 beamline will be operational shortly thereafter.

6. Conclusion

The NSLS X-ray ring has had a steady progression of successful small gap undulator insertion devices. Such small-gap devices can extend the NSLS 2^{nd}-generation machine's spectral range into the realm of hard X-ray energies, otherwise available only at the large, 3^{rd}-generation light sources. The process has been a series of smaller steps, each improving on its predecessor, and each extending the NSLS capabilities. The MGU represents the latest step and its initial deployment at X-13 has been an unqualified success.

The process continues with the current X-29 MGU project, and with similar devices currently in the proposal stages for a new device at X-9. Future improvements which are currently in the early stages of investigation include even smaller gap (~ 2 mm) devices and superconducting undulators.

7. Acknowledgements

The authors would like to acknowledge the efforts of Walter Stoeber, Richard Gambella, Mike Lehecka, Sal Pjerov, Mihai Radulescu and Chris Stelmach in the mechanical design of the MGU and its related components.

8. References

[1] P. M. Stefan, S. Krinsky, G. Rakowsky, L. Solomon, D. Lynch, T. Tanabe, H. Kitamura, "Small-Gap Research at the NSLS: Concepts and Results," BNL-65092
January, 1997.

[2] G. Rakowsky, D. Lynch, E. Blum, S. Krinsky, "NSLS In-Vacuum Undulators and Mini-Beta Straights," Proceedings of the 2001 Particle Accelerator Conference, Chicago, Illinois U.S.A. June, 2001, pp. 2453-2455 (2001).

[3] J. Safranek (NSLS), memo to D. Lynch, April 1, 1993, "Subject: Maximum orbit distortions in the NSLS x-ray ring without beam dump," [unpublished].

[4] D. Lynch, Engineering Design Analyses: Thermal Protection For Micro Gap Undulator Insertion Devices for Beamlines X9, X13 and X29, NSLS Design Report, February, 2001.