J. Synchrotron Rad. (1998). 5, 189–195

APS Insertion Devices: Recent Developments and Results

Efim Gluskin

Advanced Photon Source, Argonne National Laboratory, 9700 South Cass Avenue, APS-401, Argonne, IL 60439, USA. E-mail: gluskin@aps.anl.gov

(*Received 4 August 1997; accepted 15 October 1997*)

The Advanced Photon Source (APS) now has a total of 23 insertion devices (IDs). Over two-thirds of them are installed on the storage ring. The installed devices include 18, 27 and 55 mm-period undulators; an 85 mm-period wiggler; a 16 cm-period elliptical multipole wiggler; and many 33 mm-period undulators. Most of the IDs occupy storage-ring straight sections equipped with 8 mm vertical-aperture vacuum chambers. All of the IDs were measured magnetically at the APS and, in most cases, underwent a final magnetic tuning in order to minimize variation in the various integrals of the field through the ID over the full gap range. Special shimming techniques to correct magnetic field parameters in appropriate gap-dependent ways were developed and applied. Measurements of the closed-orbit distortion as a function of the ID gap variation have been completed, and results are in a good agreement with magnetic measurements. Spectral diagnostics of the ID radiation, including measurements of the absolute spectral flux, brilliance and polarization, show excellent agreement between calculated and measured results. Studies of the sensitivity of IDs to radiation exposure and measurements of the dose rate received by the IDs are in progress.

Keywords: insertion devices; undulators; magnetic performance; radiation diagnostics.

1. Introduction

In the early years of the Advanced Photon Source (APS) project, a strategy was conceived for the development of APS insertion devices (IDs): to develop and build a universal undulator that could provide radiation over a large energy range, 5–35 keV, without compromising the record high brilliance expected from a third-generation source (Shenoy *et al.*, 1988). In order to achieve this goal, state-of-the-art techniques and equipment needed to be developed. High brilliance could only be delivered if the magnetics of the ID were properly designed and built, with accurate tuning after fabrication. Precise magnetic tuning, in turn, required an advanced measurement system.

The wide energy range to be covered by the ID dictated a high peak magnetic field that could be varied in a precise and controllable manner. This led to the need for sophisticated controls and innovative vacuum systems with small vertical apertures.

Finally, experimental verification of the ID performance required not only the magnet measurement system but a set of diagnostic equipment capable of measuring the absolute spectral flux under the conditions of record high X-ray power density. The results of these measurements would need to be compared with theoretical calculations.

The status in realising these goals at the APS is presented in this paper.

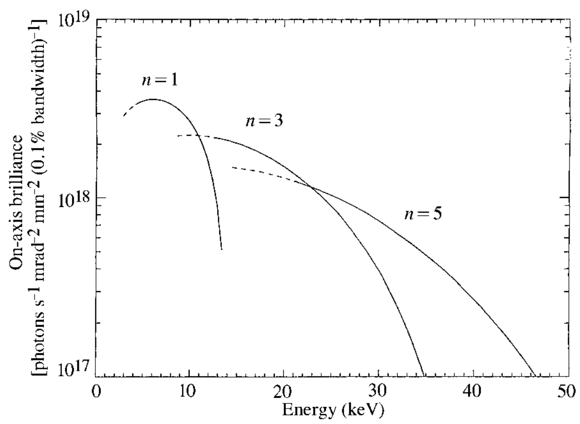

Figure 1
Calculated 33 mm-period undulator tuning curves for the first, third and fifth harmonics. Solid line: initial design; dashed line: final design. E = 7 GeV, I = 100 mA, 7.5 nm rad emittance and 4.3% coupling.

2. Magnetic performance of APS IDs

The magnetic performance of IDs should meet two major criteria: (i) continuous coverage over a wide energy range with record high brilliance, and (ii) small, if any, perturbation of the positron beam. In order to cover the 5–35 keV X-ray energy range using a single undulator on a 7 GeV storage ring, a 3.3 cm period and a 1.15 cm minimum gap were specified for the initial ID design (Savoy, 1992; Lai *et al.*, 1993). Fig. 1 shows the brilliance *versus* the X-ray energy – the tuning curve – of the APS undulator with its initial design parameters (solid lines).

ISSN 0909-0495 © 1998

Table 1
Statistics for 33 mm-period undulators (July 1997).

	Peak magnetic field (G)	First integral of horizontal field (G cm)	Second integral of horizontal field (kG cm^2)	First integral of vertical field (G cm)	Second integral of vertical field (kG cm^2)
Minimum	8952	11	4	16	8
Maximum	9138	41	18	62	88
Average	9047	24	11	44	43

The distinctive gap between the first and third harmonics in this energy range is easily seen. In order to close this gap, the undulator design was later enhanced and continuous coverage has been established (Dejus *et al.*, 1994). The overlapping of the harmonics was achieved by increasing the undulator peak magnetic field by two different means. One was the choice of a 'wedged pole' configuration for the hybrid magnetic undulator structure (Robinson *et al.*, 1990) instead of the traditional rectangular pole shape. The calculated values of the peak magnetic field for rectangular and 'wedged' pole configurations for the APS undulator at 1.15 cm magnetic gap are 6700 and 7200 G, respectively. The measured peak field value for a typical APS undulator is even higher and is equal to 8185 G at 1.15 cm magnetic gap. Another significant part of the increase is due to the innovative and successful ID vacuum chamber design developed at the APS, as well as to the high precision of fabrication of the IDs achieved by STI Optronics, the ID vendor. Both these factors brought the minimum magnetic gap down to 1.05 cm and the average peak magnetic field to 9047 G (averaged over 17 IDs). As a result, the undulator *A* tuning curve for the first, third and fifth harmonics covers the X-ray energy range between 4 and 40 keV continuously, as shown in Fig. 1 (dashed lines).

An important requirement for the magnetic performance of IDs is that there be minimal positron beam perturbation during ID gap change. In order to achieve this, the changes in field integrals through the ID should be minimized. The quantitative criteria for variation in the field integrals come from the requirement that the positron beam emittance must not be affected by more than 10% of its nominal value (Decker, 1992; Chae & Decker, 1996). These specifications for the APS IDs called for a very high quality magnetic field, and STI Optronics more than met these requirements. The requirements, however, were determined based on the assumption that there would be an active local feedback system to partly compensate for the remaining field errors. Further refining of the tuning of the IDs has been carried out in order to reduce or even eliminate the need for the active local feedback (Moog, Den Hartog *et al.*, 1997; Moog, Vasserman *et al.*, 1997). The results of the tuning of the field integrals for seventeen 33 mm-period undulators are summarized in Table 1.

An essential component of the ability to tune IDs is the ability to make accurate measurements of their magnetic field. The APS Magnetic Measurement Facility (Pflüger, 1992; Burkel *et al.*, 1993) now is equipped with two magnetic measurement benches, one with 3 m of travel and the other with 6 m of travel. There is also a high-quality laboratory electromagnet and a prototype APS dipole magnet for calibrating coils and Hall probes. A variety of probes can be mounted on either bench to map out the magnetic field in the gap of an ID. These probes include a number of coils of various lengths and orientations, as well as Hall probes. A recent addition to the probes is an axial Hall probe that is used to measure the transverse horizontal component of the magnetic field. Long stretched-wire-type rotating coils are also mounted on each bench so that integrals of the field through an ID can be measured more directly than with point-by-point measurements (Frachon, 1992). The reproducibility that is routinely attained for the first field integral measurements is better than 0.5 G cm. Using a Hall probe, the first field integral reproducibility is better than 5 G cm. That the reproducibility of the measurements also applies in the long term has been shown by Hall-probe measurements of an ID that repeated with an r.m.s. difference of 2 G cm after a period of one year.

In order to refine the magnetic field, tuning techniques have been developed (Vasserman, 1995; Gottschalk *et al.*, 1996). After the alignment of the magnetic structures has been checked and adjusted as necessary, the primary means of tuning the magnetic field is shimming. Different sizes, shapes and placements of small shims are used to adjust different aspects of the magnetic field. For most tuning techniques, the shims are placed on top of the magnets rather than on the poles because the magnetic structure was designed with the magnets recessed by a small amount compared with the poles. This allows shims to be placed on the magnets without affecting the achievable minimum gap. Shims can be placed along the ID as needed to straighten the trajectory and to decrease the phase error, thus helping to ensure a good undulator spectrum.

Once the trajectory through the ID is reasonably straight, first- and second-integral tuning is accomplished mainly by changing the configuration at the ends of the ID. A number of aspects of the end configuration are used in the tuning, including adjusting the strength of the end magnets, changing the height or shape of the last two poles (in ways that do not affect the vacuum chamber clearance at minimum gap!), or adding shim material to the gap faces of the magnets or between two magnets on the side of a pole. Each of these changes has its own effect on the magnetic field integrals and its own gap dependence. With some of the changes, the size of the effect varies even between nominally identical IDs, so it may be difficult to know *a priori* what will work best.

The measurements are used to tune the magnetic field, as described above, to minimize undesired effects on the stored beam. The real test of what has been achieved, however, is to install the ID in the storage ring and to measure the actual effect it has on the stored beam. The gap of the ID in these measurements is cycled between minimum gap and, typically, 45 mm. The global beam-position feedback in the storage ring is turned off for these experiments. The variation in the beam-position monitor (BPM) readings between the two different gaps is recorded for BPMs all around the ring. Calculations of the closed orbit are then performed in which a kick is added at the position of each end of the particular ID being tested, and the size of the kicks adjusted to fit the observed closed-orbit change. These kicks are then used to compute the first and second field integrals. The integrals determined in this way agree with the first and second integrals of the magnetic field through the ID as measured in the APS Magnetic Measurement Facility.

Also, measurements of the angular stability of the X-ray beam have been carried out. The gap on one ID was moved through its full range of travel while the position of the X-ray beam was observed in a different sector. No movement of the X-ray beam in the second sector was seen, to a sensitivity of 4 μrad. Work is in progress to repeat this measurement with an even higher sensitivity. Note that this is with no active local feedback correction on the particle beam orbit; only global feedback was in operation. The motion of the X-ray beam due to changes of the gap in the ID producing the beam has also been measured, using a zone plate to image the beam onto a position-sensitive detector. The position of the X-ray beam was found to be constant to within the 2 μrad sensitivity of that measurement, again with no local active feedback on the particle beam.

3. Spectral performance

The ultimate goal of tuning the magnetic field of an undulator is to achieve the high brilliance of an undulator source. The figure of merit for spectral performance is the r.m.s. phase error (Walker, 1993), which can be determined from magnetic measurements. The APS undulator specifications called for 8° phase error, and the undulator vendor more than met this demanding requirement. The phase error has been further refined at the APS so as to improve the spectral performance over a wider range of energies. Calculations show that there is a significant increase in intensity of the high harmonics when the phase error is decreased (Fig. 2). All undulators have been tuned to have r.m.s. phase errors less than 5°, and in some cases the phase error was between 1 and 2°.

In order to characterize the spectral performance of the undulator installed in the ring, absolute measurements of the undulator brightness as a function of angle and energy have been made (Ilinski *et al.*, 1995; Cai, Dejus *et al.*, 1996). The positron beam emittance has also been measured (Cai, Lai *et al.*, 1996; Cai *et al.*, 1997). This emittance can be combined with the measured spectral brightness to provide brilliance tuning curves. The quality of the undulator magnetic field may also be verified by observing the high-order harmonics of the undulator radiation.

The result of these measurements conducted under conditions of high incident power is shown in Fig. 3 and Fig. 4. As is clearly seen from the figures, the measurements are in remarkably good agreement with the calculation.

The quality of the undulator magnetic field was verified by observing the high-order harmonics of the undulator

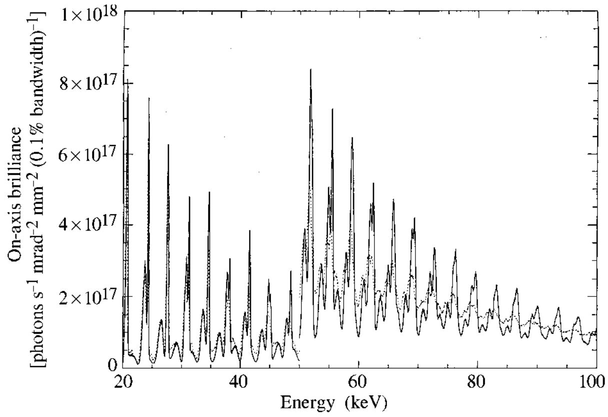

Figure 2
Calculated brilliance, beginning at the sixth harmonic, for (solid line) the 33 mm-period undulator with the 2.5° phase error and (dotted line) for an undulator with 4.6° phase error at 1.15 cm gap. The brilliance above 50 keV has been multiplied by a factor of four for clarity. While this difference in phase error has no effect at low harmonics, it would affect the brilliance at high harmonics.

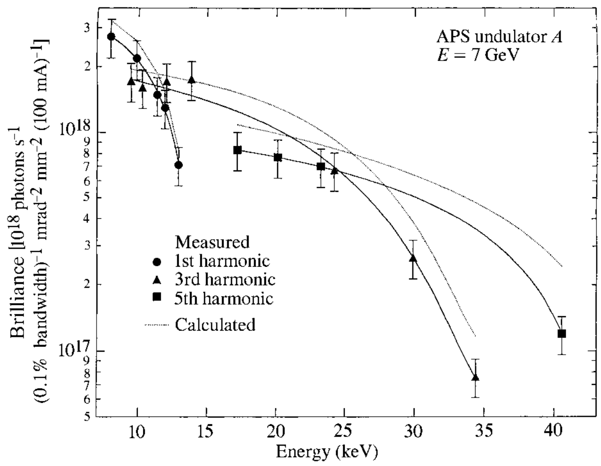

Figure 3
On-axis brilliance of X-rays from an undulator as a function of energy. The first, third and fifth harmonics are shown. The points are measured results; the lines are the results of calculations. There are two calculated curves for the third and fifth harmonics because the experimental measurements were made at two different times when the particle beam parameters were different.

radiation (Shastri *et al.*, 1996). More than thirty harmonics can be seen clearly in Fig. 5, where the measurements performed at an undulator gap of 11.1 mm are shown along with the results of calculations that used the measured magnetic field.

4. ID vacuum chambers

A number of considerations in the design of undulators drive the design of the vacuum chamber to small gaps. One of them is mentioned above: to produce a universal undulator that covers a wide energy range of emitted X-rays. On the other hand, particle beam transport considerations require the largest possible aperture. The competing requirements demand a vacuum chamber design with minimum chamber wall thickness, close tolerances for straightness and flatness to enable precision alignment, as well as mechanical and thermal stability. In addition, a low outgassing rate, ease of manufacturing, low maintenance and high reliability are also desirable.

During the past five years a new approach to the design and fabrication of extruded aluminium vacuum chambers for IDs has been developed at the APS (Trakhtenberg *et al.*, 1995; Den Hartog *et al.*, 1997). Versions of the vacuum chamber, with vertical apertures of 12, 8 and 5 mm and lengths of 2.5 and 5 m, were manufactured and tested. 20 chambers, 17 of which are 8 mm-aperture chambers, were installed in the storage ring and successfully integrated into the APS vacuum system. All have operated with full beam with the standard pressure below 10^{-9} Torr. Seventeen vacuum chambers have been coupled with IDs.

Alignment of the vacuum chamber on its support is routinely accomplished using optical techniques to a precision of ±75 μm over the entire surface. This allows minimum insertion-device pole gaps to be obtained. All of the installed undulators can achieve a minimum gap of 10.5 mm while maintaining clearance from the chamber.

Experience elsewhere with stainless steel chambers and ST707 NEG material suggested the possibility of levitating dust particles of ferromagnetic material into the beam aperture of the ID vacuum chamber during ID operations. The signature would be a sudden drop in the lifetime of stored beam due to collisions with the levitated particle. No evidence of this effect has been observed at the APS.

The standard 8 mm-aperture chamber with 1 mm wall thickness allows a minimum gap of 10.5 mm after allowing 0.250 mm on either side of the chamber for variations in straightness, flatness and ID pole height variations. Because the gap separation mechanism of undulator *A* is designed to be able to withstand the magnetic forces at a minimum gap of 8.5 mm, it is desirable to have a vacuum chamber that takes full advantage of the capabilities of the ID. A 5 mm-aperture extrusion was designed and fabricated and successfully machined to the same exacting tolerances as the standard 8 mm-aperture chamber. The chamber was completely assembled, certified for vacuum and prepared for installation into the storage ring. Current plans call for a test installation in the storage ring sometime during late 1997 or early 1998.

5. Special IDs for production of circularly polarized X-rays

In addition to the standard planar IDs, there is also an elliptical multipole wiggler (EMW) at the APS to provide circularly polarized X-rays. The very first device of this type, which served as a prototype for the APS EMW, was designed, built and successfully tested jointly by the APS, NSLS and the Budker Institute of Nuclear Physics (BINP, Novosibirsk) at the NSLS X-ray ring (Gluskin *et al.*, 1995; Singh *et al.*, 1996). The APS EMW was built jointly by the

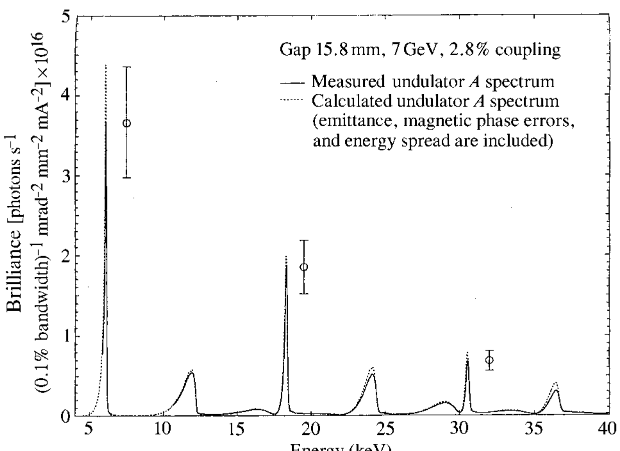

Figure 4
On-axis spectral brilliance is shown. The solid line was measured using the crystal spectrometer; the dotted line is from a calculation. The calculation included the measured field of the undulator, the measured electron beam emittance, and the design value for the energy spread.

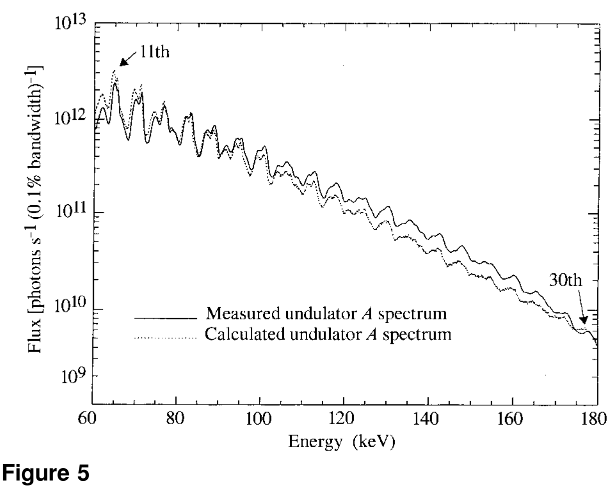

Figure 5
The harmonic structure of the undulator radiation at higher energies; harmonics as high as the 30th are clearly seen.

APS and BINP and is now operating at the APS. It has planar arrays of magnets and poles to produce the vertical magnetic field component and an electromagnet to generate the weaker horizontal field. The device has a 16 cm period. The total number of poles is 36 for the electromagnets and 37 for the permanent magnet array. 32 of the poles in each direction are full field. It is important to have an even number of full-field permanent-magnet poles so that the spatial distribution of radiation from the wiggler is, in principle, symmetric above and below the beam axis. An even number of full-field electromagnet poles was expected to simplify the tuning of the field because the demand for horizontal field quality is higher. The horizontal electromagnet field is designed to operate at a frequency of 10 Hz, at a peak current of 1 kA. This current produces a peak horizontal field of 997 G, or K_x = 1.5. The peak vertical field is 9826 G at the minimum gap of 24 mm, for K_y = 14.7.

The APS EMW has a special field integral compensation system, similar to the prototype, that operates at any frequency up to 10 Hz and for all values of K_y and K_x. This wiggler is now installed in the storage ring, and the first measurements of the degree of circular polarization using elastic and magnetic Compton scattering have been completed (Ilinski *et al.*, 1997). Results are in good agreement with calculations, and helicity switching was observed as expected.

While the EMW covers the high-energy spectrum of polarized X-rays, the novel circular-polarized undulator (CPU) at the APS would provide variably polarized X-rays in the intermediate energy range: from 0.5 to 3 keV. The tuning curve of the APS CPU is shown in Fig. 6. The Advanced Light Source (ALS) soft X-ray elliptical-polarized undulator (EPU) tuning curve is also plotted to demonstrate that the two devices are complementary to each other. The concept of the CPU was developed at the APS (Ivanov, 1995), and both symmetric and asymmetric electromagnetic structures have been presented (Gluskin, 1996*a*,*b*). The APS CPU was designed jointly by the APS and BINP. The device consists of two electromagnetic arrays: one provides the vertical magnetic field and the other the horizontal. The cross section of both arrays is shown in Fig. 7, and the main parameters are summarized in Table 2.

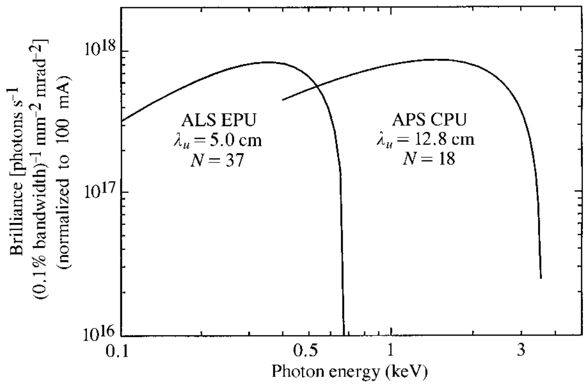

Figure 6
APS CPU tuning curve.

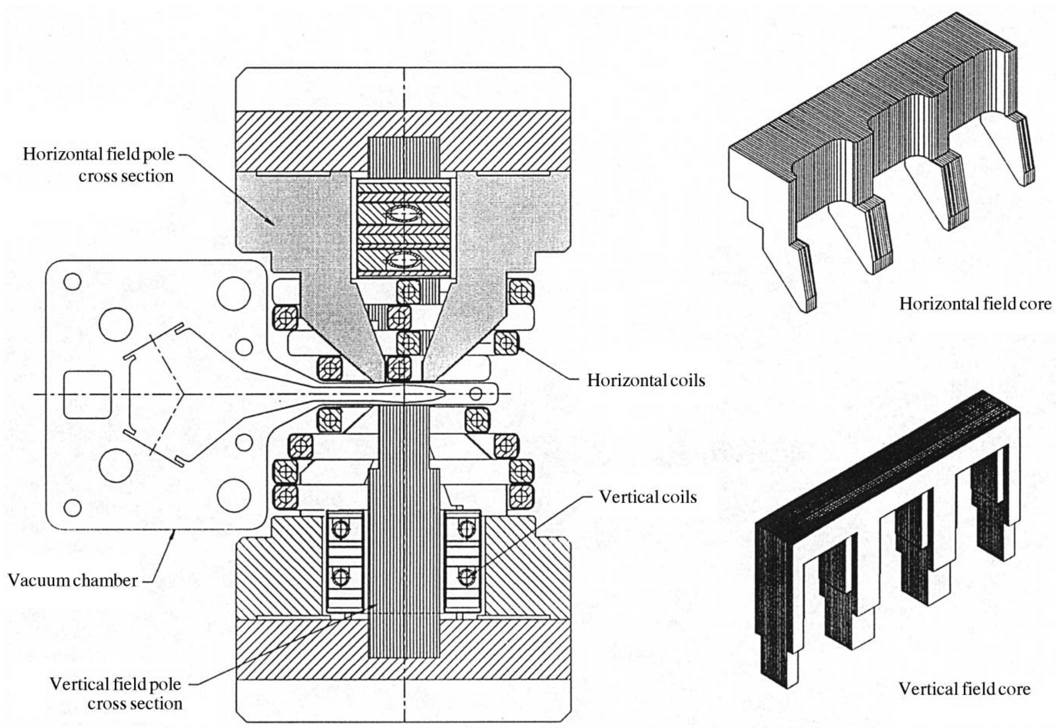

Figure 7
The cross section of the APS CPU electromagnets.

Table 2
Main technical parameters of the APS CPU.

Period	12.8 cm
Number of full-field vertical poles	35
Number of full-field horizontal poles	36
Overall length	2.4 m
Vertical pole gap	11 mm
Maximum magnetic field	0.24 T
Switching frequency	0–10 Hz
Switching rise time	<20 ms
Electromagnet DC stability	<1%
Maximum total power	800 W
Maximum power density	17 W mm^{-2}

The most important and unique feature of the CPU is the ability to vary the helicity of the circular polarization with a 10 Hz frequency, as well as to change by 90° the direction of the linear polarization (with the same frequency). The device is now being constructed at BINP and will be delivered to the APS in 1998. The magnetic measurements and tuning will be performed at the APS. A similar device is now being constructed for ELETTRA (Walker *et al.*, 1997).

6. Status of ID installation, the ID control system, and radiation exposure of IDs

There are 23 IDs currently at the APS, and 18 of them are installed around the ring (Table 3). The other five IDs will be installed in accordance with APS plans to bring new users on line.

In Table 3, note that there are two undulators installed in Sector 2. The straight sections are long enough to accommodate two of the standard-length (2.4 m) IDs. Some of the undulators are longer, however, and occupy the entire straight section, such as the EMW and the 18 mm-period undulator that is being used by the APS Diagnostics Group. The control of the IDs (Makarov *et al.*, 1997) installed in the storage ring is integrated into the APS EPICS (Experimental Physics and Industrial Control System) computer network with a dedicated input/output controller (IOC) for each straight section. Controlled parameters include upstream and downstream drive motors that allow parallel or tapered positioning of the magnetic structure, linear absolute encoders for position monitoring, absolute rotary encoders for redundancy, and protective limit switches and interlock circuitry. Operators and users can monitor status and initiate actions from the control room or from computers located in offices or on beamlines. Security is maintained by the use of a process variable server that allocates control according to predefined access tables. The control system has been designed to enable users to control the ID on their own beamline simply and easily without involving facility operators.

One of the important programs related to effective long-life ID operation is the monitoring and prevention of radiation damage to IDs (Moog, Den Hartog *et al.*, 1997). Monitoring of the radiation exposure is systematically carried out all around the ring. Thermoluminescent dosimeters and radiochromic film dosimeters are both used to cover the range up to 5 Mrad. Dosimeters are installed in all sectors where IDs are located. A few other sectors are also monitored. Special attention is paid to the location of each dosimeter in the straight section. Experiments to determine the spectrum of the radiation in the APS storage ring tunnel have been performed and found significant high-energy components of the radiation.

Table 3
IDs installed on the storage ring as of March 1997.

Sector	ID installed	Period length (mm)	Number of periods
1	Undulator	33	72
2	Undulator	33	72
2	Undulator	55	43
3	Undulator	27	88
5	Undulator	33	72
7	Undulator	33	72
8	Undulator	33	72
10	Undulator	33	72
11	Elliptical wiggler	160	18 horizontal, 18.5 vertical (32 full-field poles in each direction)
12	Undulator	33	72
13	Undulator	33	72
14	Wiggler	85	28
17	Undulator	33	72
18	Undulator	33	72
19	Undulator	33	72
20	Undulator	33	72
33	Undulator	33	72
35	Undulator	18	198

In order to minimize the radiation exposure, IDs are installed in the downstream part of the ID straight section whenever possible, and Pb shielding is installed in the open space upstream of the ID. The rate of radiation dose accumulation for the APS IDs has been, and will continue to be, measured. The highest accumulated dose by one ID so far is estimated to be around 5.4 Mrad. The magnetic quality of the devices that have received the highest doses has been rechecked. No radiation-induced demagnetization of the APS IDs has been observed to date.

7. Conclusions

The APS operates with state-of-the-art insertion devices that produce X-rays over a wide energy range. The high performance level of the APS IDs is due to the excellent quality of the magnetics, an innovative vacuum system, a reliable control system and is the result of many years of fruitful effort by the APS staff and STI Optronics. The performance of the IDs has been measured experimentally using special diagnostics tools and was found to be very close to the theoretical predictions.

In the near future, effort will continue to complete installation of the IDs and to maintain their high level of performance, which is especially important when the positron emittance and coupling are reduced. Also, preparations will be made for a 'top-off' mode of operations.

Long-term ID development at the APS will focus on the design of new undulators with smaller magnetic gaps and special IDs for fourth-generation synchrotron radiation sources.

The results described in this paper represent the highly fruitful efforts of a great many people. Invaluable contributions have come from people who joined the ID group for varying lengths of time (some as little as a few months) but who brought expertise developed at other institutions, such as DESY, ESRF, LBL or BINP, and then further developed and applied it to the APS. STI Optronics built and tuned insertion devices to exceed specifications that were already more demanding than those any vendor had previously been asked to meet. Last but not least are the contributions of the many ID group members and other APS staff who worked on the IDs and their controls, designed and built the vacuum chambers, or built and ran the diagnostics. The whole list of people is too long to enumerate here, but the author is privileged to present the results of all their efforts. The author thanks Dr E. R. Moog for careful reading of and suggestions about the manuscript. This work was supported by US Department of Energy, BES-Material Sciences, under contract No. W-31-109-Eng-38.

References

Burkel, L., Dejus, R., Maines, J., O'Brien, J., Pflüger, J. & Vasserman, I. (1993). Report ANL/APS/TB-12. Argonne National Laboratory, IL 60439, USA.

Cai, Z., Dejus, R. J., Den Hartog, P., Feng, Y., Gluskin, E., Haeffner, D., Ilinski, P., Lai, B., Legnini, D., Moog, E. R., Shastri, S., Trakhtenberg, E., Vasserman, I. & Yun, W. (1996). *Rev. Sci. Instrum.* **67**(9). (CD ROM.)

Cai, Z., Lai, B., Yun, W., Gluskin, E., Legnini, D., Ilinski, P. & Srajer, G. (1996). *Rev. Sci. Instrum.* **67**(9). (CD ROM.)

Cai, Z., Lai, B., Yun, W., Gluskin, E., Legnini, D., Ilinski, P., Trakhtenberg, E., Xu, S., Lee, H.-R. & Rodrigues, W. (1997). *Proc. SRI97*, Cornell University, USA, 17–20 June.

Chae, Y.-C. & Decker, G. (1996). *Proc. 1995 Part. Accel. Conf.* p. 3409. Piscataway, NJ: IEEE.

Decker, G. (1992). Unpublished.

Dejus, R., Lai, B., Moog, E. & Gluskin, E. (1994). Report ANL/APS/TB-17. Argonne National Laboratory, IL 60439, USA.

Den Hartog, P., Grimmer, J., Trakhtenberg, E., Wiemerslage, G. & Xu, S. (1997). *Proc. PAC97*, Canada, 12–16 May.

Frachon, D. (1992). PhD thesis, Université Joseph Fourier – Grenoble I, France.

Gluskin, E. (1996*a*). *Proc. 10th ICFA Beam Dyn. Panel Workshop*, ESRF, Grenoble, p. WG1-56.

Gluskin, E. (1996*b*). *Proc. Int. Workshop 30 m Long Straight Sections*, SPring-8, Japan, 17–19 April, pp. 106–113.

Gluskin, E., Frachon, D., Ivanov, P. M., Maines, J., Medvedko, E. A., Trakhtenberg, E., Turner, L. R., Vasserman, I., Erg, G. I., Evtushenko, Yu. A., Gavrilov, N. G., Kulipanov, G. N., Medvedko, A. S., Petrov, S. P., Popik, V. M., Vinokurov, N. A., Friedman, A., Krinsky, S., Rakowsky, G. & Singh, O. (1995). *Proc. PAC95*, Dallas, Texas, 1–5 May.

Gottschalk, S., Robinson, K., Vasserman, I., Dejus, R. & Moog, E. (1996). *Rev. Sci. Instrum.* **67**(9). (CD ROM.)

Ilinski, P., Venkataraman, C. T., Lang, J. C. & Srajer, G. (1997). *Proc. SRI97*, Cornell University, 17–20 June.

Ilinski, P., Yun, W., Lai, B., Gluskin, E. & Cai, Z. (1995). *Rev. Sci. Instrum.* **66**, 1907–1909.

Ivanov, P. M. (1995). Unpublished.

Lai, B., Khounsary, A., Savoy, R., Moog, E. & Gluskin, E. (1993). Report ANL/APS/TB-3. Argonne National Laboratory, IL 60439, USA.

Makarov, O. A., Den Hartog, P., Moog, E. R. & Smith, M. L. (1997). *Proc. SRI97*, Cornell University, USA, 17–20 June.

Moog, E. R., Den Hartog, P. K., Semones, E. J. & Job, P. K. (1997). *Proc. SRI97*, Cornell University, USA, 17–20 June.

Moog, E. R., Vasserman, I., Borland, M., Dejus, R., Den Hartog, P. K., Gluskin, E., Maines, J. & Trakhtenberg, E. (1997). *Proc. PAC97*, Vancouver, Canada, 12–16 May.

Pflüger, J. (1992). Unpublished.

Robinson, K. E., Gottschalk, S. C., Quimby, D. C., Slater, J. M. & Valla, A. S. (1990). *Nucl. Instrum. Methods*, A**291**, 394.

Savoy, R. (1992).Unpublished.

Shastri, S. D., Dejus, R. J., Haeffner, D. R. & Lang, J. C. (1996). *Rev. Sci. Instrum.* **67**(9). (CD ROM.)

Shenoy, G. K., Viccaro, P. J. & Mills, D. M. (1988). Report ANL-88–9. Argonne National Laboratory, IL 60439, USA.

Singh, O., Krinsky, S., Ivanov, P. M. & Medvedko, E. A. (1996). *Rev. Sci. Instrum.* **67**(9). (CD ROM.)

Trakhtenberg, E., Gluskin, E. & Xu, S. (1995). *Rev. Sci. Instrum.* **66**, 1809–1811.

Vasserman, I. (1995). Unpublished.

Walker, R. P. (1993). *Nucl. Instrum. Methods*, A**335**, 328.

Walker, R. P., Bulfone, D., Diviacco, B., Jark, W., Michelini, P., Tosi, L., Visintini, R., Ingold, G., Schafers, F., Scheer, M., Wustefeld, G., Eriksson, M. & Werin, S. (1997). *Proc. PAC97*, Vancouver, Canada, 12–16 May.