FAST-SWITCHING VARIABLY POLARIZING UNDULATOR*

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Abstract

Development of a new fast-switching electromagnetic variably polarizing undulator (EMVPU) is underway at the Advanced Photon Source (APS). The EMVPU can produce x-rays with left- and right-handed circular polarizations and horizontal and vertical linear polarizations in the energy range 400-2000 eV. The undulator will be able to switch between left- and right-handed circular polarizations at 10 Hz, fast enough to allow for magnetic circular dichroism studies that rely on lock-in amplifier techniques. The handedness switch will be accomplished by switching only the vertical component of the field while the horizontal component stays constant. Details of the EMVPU and its initial experimental test models are presented.

INTRODUCTION

The new EMVPU will join other all-electromagnetic undulators that are presently in use at APS—the CPU (circularly polarizing undulator) [1], with $E\gamma \geq 500$ eV and 1-Hz switching, that has been in operation since 2001; and the recently installed IEX undulator, a quasi-periodic variably polarizing undulator ($E\gamma \geq 250$ eV) that was designed and built at the APS [2] and commissioned successfully in 2012 [3]. The EMVPU, like those devices, will provide linear polarization (horizontal and vertical) and circular polarization (right- and left-handed) capabilities, but adds the capability of switching the circular polarization handedness at 10 Hz (with an 80% duty cycle), faster than previously available at APS. Fast-switching undulators are also in operation at ESRF [4] and SOLEIL [5] using a combination of electromagnets and permanent magnets.

The requirement for rapid handedness switching of the circular polarization is driven by the users' need to use lock-in detection for their magnetic scattering experiments. They require ample time between handedness switches—time when the photons produced are of the desired energy and polarization and when measurements can be made with a stable photon beam. Not only must the current in the coil stabilize to its new value rapidly, but any eddy currents and associated stray fields induced by the switching must be minimized.

In order to achieve fast switching in the EMVPU, the vertical (By) field coils are single-turn coils machined from a solid piece of copper. This minimizes the coil inductance to allow for the fastest possible switching speed. One-turn coils also provide right/left symmetry near the pole tips, reducing undesirable magnetic multipoles. Transient fields during the switching must also be minimized. Laminated cores minimize eddy currents in the By poles. Eddy currents in the vacuum chamber can significantly slow the switching speed so a vacuum chamber material with low electrical conductivity must be used. Any residual e-beam steering or multipole transients will be compensated during switching using corrector magnets on each end of the device.

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PARAMETERS

Table 1 lists selected parameters for the EMVPU.

Table 1: Selected Parameters

Parameter	Value	Unit
Period	12.5	cm
Gap	8.5	mm
Maximum effective field for linear polarization (horizontal or vertical)	3491	Gauss
Maximum effective field for circular polarization	2469	Gauss
Switching speed between right- and left-handed circular polarization	10	Hz

ONE-PERIOD TEST MODEL

General Concept

Figure 1 shows the general layout of the Bx and By coils, poles, and core for the lower jaw of the one-period test model. The upper jaw has similar geometry. The By coils are single-turn coils machined from oxygen-free copper. The By core is made from 0.64-mm-thick M-22 silicon steel laminations with a C5 coating. The laminations are laser-cut and epoxied together. The epoxy-impregnated Bx coils have 46 turns of square copper solid wire [6]. The Bx poles are made of heat-treated vanadium permendur, chosen because it gives 5% higher field than low-carbon steel. The Bx core is low-carbon steel with slots for stainless steel cooling-water tubes. These cooling-water tubes cool the Bx core, which cools the Bx poles; both in turn cool the Bx coils.

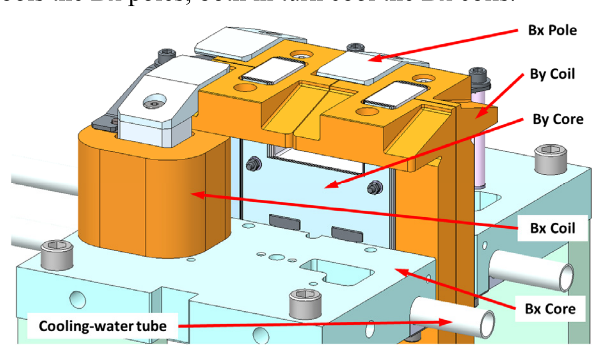

Figure 1: A 3-D CAD model of the one-period test model lower jaw (one Bx coil/pole assembly is hidden to show the By core).

Figure 2 shows a close-up of the one-period test model. The By coils are soldered to bus bars, after being tin plated to ease the soldering. The bus bars are water cooled

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with deionized cooling water and in turn cool the By coils.

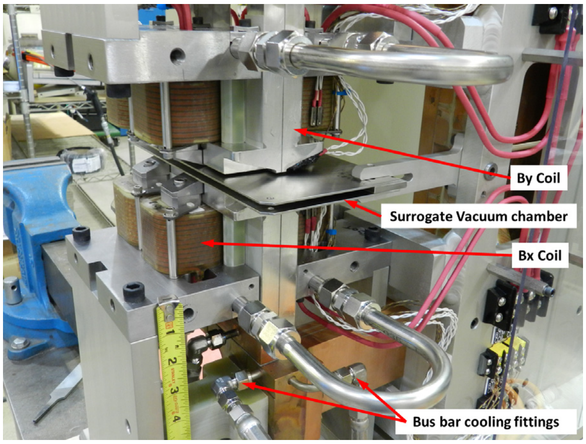

Figure 2: One-period test model.

Thorough testing of the switching speed of the one-period test model requires that the vacuum chamber be present so the eddy currents in the vacuum chamber can be properly taken into account. The final vacuum chamber will be made of stainless steel with a copper coating on the inside. For these tests, a surrogate vacuum chamber was used that would allow side insertion of a Hall probe for magnetic field measurement. The surrogate chamber, seen in Figure 2, is made from two pieces of 1.5-mm-thick 316 stainless separated by a 5-mm gap. The stainless steel pieces are plated with a 75-micron-thick copper strip on the inside.

Measured Field

The final power supply for the EMVPU is not yet available, so the original CPU power supply [7] was used for the testing. Switching rates as high as 10 Hz at 1400 amperes were achieved with the test model, as shown by the measured vertical peak field in Figure 3. The Hall probe was positioned inside the surrogate vacuum chamber. The rise time of the current was 16 ms; the rise time of the field was also 16 ms, showing that the limitation on rise time comes from this power supply rather than the device.

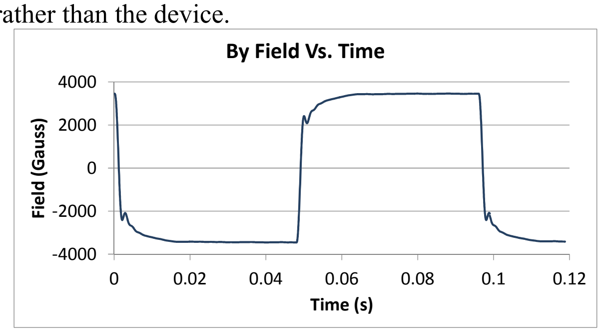

Figure 3: Time-dependence measurement of a one-period test model. The vertical field was ±3500 Gauss, switched at 10 Hz.

Solder Joint

The bus-bar solder joints are produced with a 50-micron-thick Sn60Pb40 (60/40) solder sheet, chosen because it has a melting temperature of 220°C as compared to over 500°C for silver solders. Because soldering needs to be done while the bus bars are assembled on the core, the lower temperature reduces the possibility of the core warping. All solder joints are assembled with a screw and spring washers. The spring washers take up the excess space produced as the solder melts. The joint screws are re-torqued after soldering to provide a full-contact solid joint. Figure 4 shows the solder joints of the By coils to the bus bars. The air gaps are filled with Nema Grade G-10 sheets after soldering.

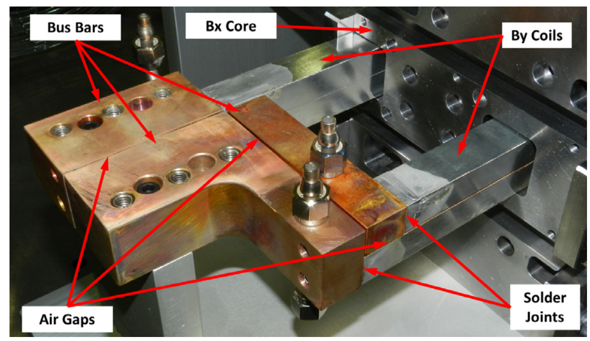

Figure 4: Solder joints of the By coils to the bus bars.

Simulated forces on the By coils and solder joints during switching are less than 1.8-kg force. A stress test was performed on the one-period test model to show how the coil supports and solder joints hold up. A nine-hour run with a current of 1400 amperes at 6 Hz was completed. There appeared to be no effect at all from the test.

FOUR-PERIOD TEST MODEL

A four-period test model is now under development at the APS. Figure 5 shows the model used for magnetic field analysis [8]. A new power supply is also under development at the APS. The new power supply will switch the current from -1400 to 1400 amperes within

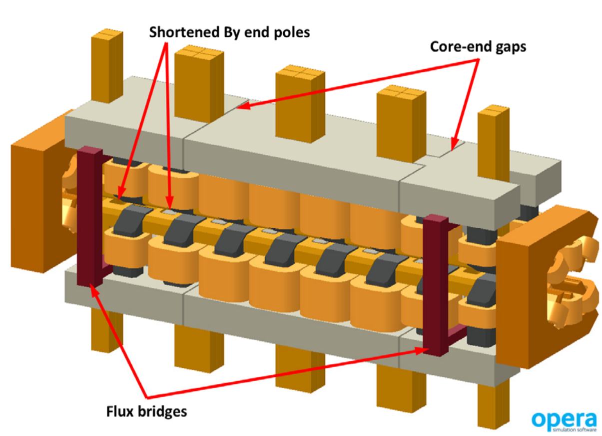

Figure 5: Magnetic field analysis model of the four-period test model.

6 ms. This will allow the field to fully switch within 10 ms (determined from simulations), giving the user 40 ms to take data between each switching event (80% duty cycle).

The two By end poles on each end are shortened vertically to produce the ¼-¾ full-field configuration on each end that minimizes the first and second integrals (i.e., keeps the horizontal beam steering straight and on axis). Simulations guided the addition of flux bridges and 2-mm-wide gaps in the core near the ends to reduce the large horizontal missteering during switching of the By field. An initial missteering of up to 180 micro-radians was reduced to less than 75 micro-radians. Fast end corrector magnets will correct the remaining missteering.

The ¼-¾ full-field configuration is achieved for the Bx field at each end by reducing the number of turns on the end Bx coils and also by shortening the Bx pole tips horizontally. Any further correction will be done with the end corrector magnets.

Figure 6 shows a 3-D CAD model of the four-period test model without the support frames. Corrector magnets with six laminated poles and separate power supplies for each coil are included at the upstream and downstream ends of the device. Table 2 gives the maximum integrated multipoles that each corrector magnet can produce. The horizontal dipole also comes with a skew sextupole component (66 G/cm). This additional skew sextupole component is used to correct the integrated skew sextupole component through the whole device, as was done for the electromagnetic variably polarizing quasi-periodic (IEX) undulator [2, 3].

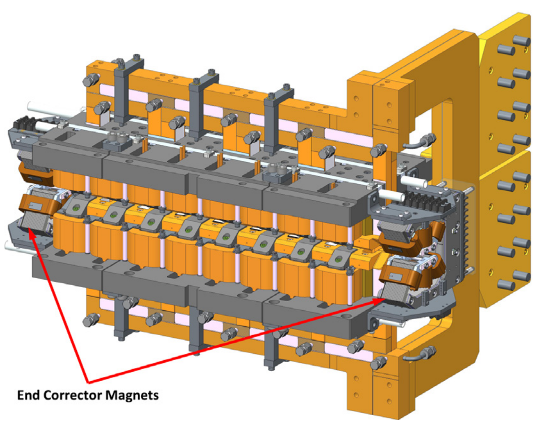

Figure 6: A 3-D CAD model of the four-period test model.

Table 2: Corrector Magnet Maximum Integrated Multipoles

Multipole	Value	Unit
Vertical dipole	958	G-cm
Normal quadrupole	469	G
Normal sextupole	569	G/cm
Horizontal dipole	653	G-cm
Skew quadrupole	69	G
Skew octupole	27	G/cm^2

VACUUM CHAMBER

APS typically uses aluminum insertion device vacuum chambers, but simulations show that the fastest possible switching through an aluminum vacuum chamber is 30 ms, due to the high electrical conductivity and resulting eddy currents in the Al. Figure 7 shows the simulated eddy currents in an aluminum vacuum chamber 130 microseconds after the start of switching.

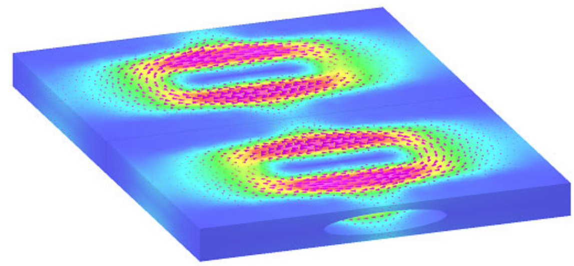

Figure 7: Simulated eddy currents in an aluminum vacuum chamber.

Stainless steel is much less electrically conductive than aluminum, reducing the switching time to 10 ms. The inside wall of the chamber must retain high conductivity, however, to minimize the resistive-wall impedance seen by the electron beam. Therefore, the inside wall will be coated with 75 microns of copper. Simulations show that a 75-micron Cu coating has a negligible effect on the switching speed. Further investigation into a stainless steel copper-coated insertion device vacuum chamber is ongoing at the APS.

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