THE INTERMEDIATE-ENERGY X-RAY (IEX) UNDULATOR COMMISSIONING RESULTS *

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Abstract

Strong beam perturbation from the intermediate-energy x-ray (IEX) undulator operation has been expected from the beginning. This paper describes our efforts including the initial magnet design, field measurements and compensation, special considerations of power supplies and the control system, and the final commissioning results with beam. Perturbations are well within the specified limits, and the IEX was made ready for user operation in less than six months.

INTRODUCTION

A 4.8-m electromagnetic undulator was designed, built, and installed at the APS to provide the Intermediate-Energy X-ray (IEX) beamline with variably polarized radiation. Details on the device itself are presented separately [1]. The main parameters of this device are listed in Table 1. Simulation results show that strong nonlinear fields are present in this device. To eliminate beam perturbations, 13 correction coils are included, which correct stray fields, orbit, tune, coupling, and some high-order perturbations. Together with four main coils (By, By-Quasi, Bx, Bx-Quasi), there are 17 power supplies for this single device. Besides the complexity of the device itself, special requirements from user operations are:

Table 1: IEX Main Parameters

Title	Description	Value	Unit
General	Length	4.8	m
	Period length	12.5	cm
Horizontal Linear	Energy	0.25-3	keV
	K Value	5.271-0.694	
Vertical Linear	Energy	0.44-3	keV
	K Value	3.863-0.694	
Circular Mode	Energy	0.44-3	keV
	K Value	3.863-0.694	

- Generates four polarization modes. Horizontal- and vertical-linear modes [H/V], clockwise and counter-clockwise circular modes [CW/CCW].
- In each mode, the quasi-periodic property can be switched on and off [1].
- Precise photon energy reproducibility.
- Polarization refinement at the sample location.

To satisfy requirements on energy reproducibility, the device is required to operate on a hysteresis loop. A special magnet degaussing and conditioning procedure also needs to be followed. The device provides radiation to two beamline branches in which, due to different properties of optical elements, different IEX settings are required for different branches to reach $> 99\%$ polarization purity at the sample location.

All facts added up together made IEX commissioning a difficult task. Commissioning started on May 2012 and by November 2012 all operational modes had been successfully commissioned with beam. This paper describes details of the commissioning efforts leading to eventual success.

MAGNET DESIGN AND MEASUREMENT

The magnet design and measurement were done in close coordination with simulation work. Simulation results [2] showed this device would be the strongest nonlinear perturbation source among all IDs that have been installed in the APS storage ring. Special measures were taken during the magnet design phase, including 2×6 correction coils added to each side of the device for making further corrections.

After magnet assembly, the field was measured over the entire excitation curve for each operational mode. Unlike other ID measurements, which measure B_y only in the xz plane (y=0) — i.e., 2D measurement—both B_x and B_y fields were measured in a 3D volume. One assembly fault (a magnet block was inadvertently made from a prototype part) was found through fitting the measured field map to the design model, and corrected. After fixing the fault, the IEX was re-measured and a full set of simulation work was done using the measured field map. For these simulations [3], field data were fitted to the wiggler field expansions while measured field error was represented by a kickmap element; other machine errors were also included. Simulation results showed that the magnet quality met our expections. The simulated dynamic aperture (see Figure 1) was only slightly reduced due to the strong nonlinear field errors. This reduction was expected based on design simulations and can be mitigated using the local correction coils based on later beam test.

POWER SUPPLY

As described in the previous section, the IEX has 17 individual power supplies (PSs) to provide field excitation and local beam perturbation corrections, making it one of the single most complicated powered elements in the ring. To reduce beam perturbations, all PSs are synchronized, and

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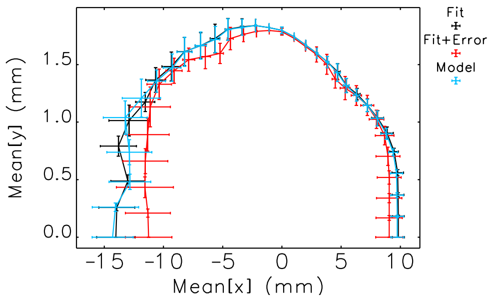
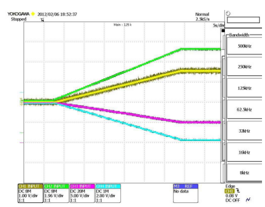
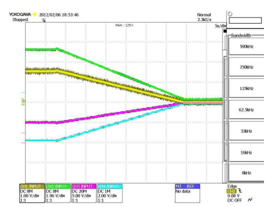
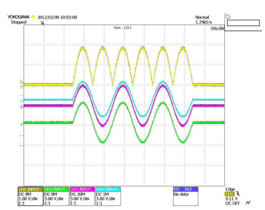


Figure 1: Dynamic aperture with machine errors. Black — field map from magnet measurement (fitted model); red — fitted model + measured field errors; blue — field map from IEX design.

a smooth linear ramp is made in between for each current change. This feature is built into the PSs local control system. Also, to simplify and standardize the required magnet conditioning and degaussing, these features are also built into the PSs local control system. Results are shown in Figure 2.


(a) Synchronized ramp


(b) Synchronized shutdown on interlock event


(c) Conditioning curve

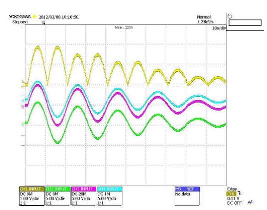

(d) Degaussing curve

Figure 2: Waveform of PSs on different events.

CONTROLS

As described in the introduction, the IEX can be operated in many ways. The total operational states comprise 3 (modes, combined CW/CCW to C mode) × 2 (quasi) × 2 (direction) × 2 (beamline) = 24. Each state could generate different beam perturbations and thus needs a separate correction table. We have used a 24-page SDDS file to include all the correction tables, where each page corresponds to one operational state. In each table, there are columns containing photon energies, plus main [H/V] and Earth coil settings. These values are from magnet measurements. There are another 12 columns—6 for upstream (US) and 6 for downstream (DS)—including correctors for horizontal and vertical dipole, normal and skew quad, normal sextupole, and skew octupole. These corrector settings are beam-based and tuned to remove orbit, tune, and coupling variations from IEX operation and restore injection efficiency using higher-order correctors. The IEX local correctors are made from different combinations of the extra windings on the end poles [1]. The correction moments contained in the correction table need to be converted inside the control system before being sent to the PSs.

In summary, besides many general control tasks, the IEX control system needs to accomplish many special requirements. They are contained in the state program code, as illustrated in Figure 3, and include:

- Determine current and future IEX status.
- Choose the proper correction table.
- Convert correction moments to power supply settings and send to power supply.
- Choose the proper way to do mode switch.
- Perform magnet conditioning and degaussing.

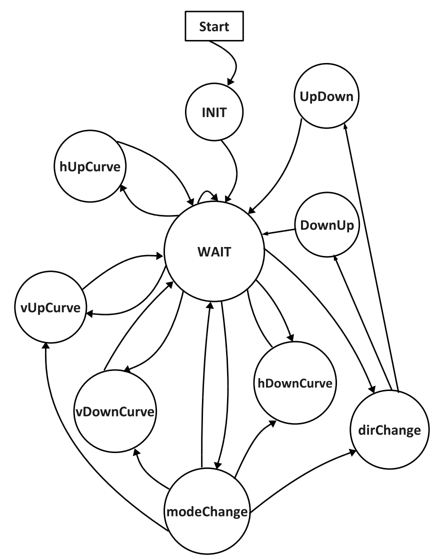


Figure 3: Diagram of IEX control state program.

COMMISSIONING WITH BEAM

The IEX was installed in the APS storage ring during the May 2012 shutdown. Thanks to thorough and careful work at every step (some of which is mentioned in the previous sections), in its first test with beam it was turned on and ramped to full strength step by step without beam loss. In this first beam test, there was no local correction—only regular APS orbit correction and feedback systems were employed. This clearly indicated that the device was working properly and that our assumptions and simulations had validity. Then we measured the tune shift and the dispersion perturbations with IEX on, and compared the results to our previous simulations, see Figure 4. We found very good agreement, which shows that the device is very close

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to the model and that various field errors were well controlled. After confirming that the device is well within our

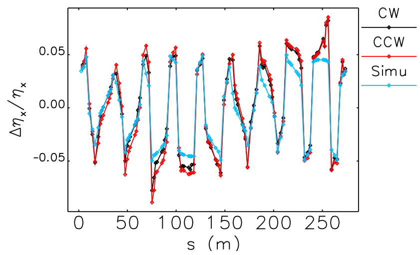
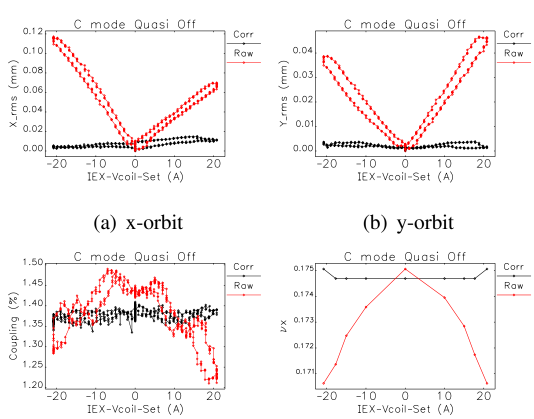


Figure 4: Dispersion error from IEX (quad ring): black/red - measurements made at CW and CCW mode; blue - simulation result.

expections and working properly, we started to debug our entire control program, simulate all possible user operation scenarios, and test the protection features with various simulated faults. At the same time, we started to build the local correction table (the 24-page SDDS file) for each operational state.

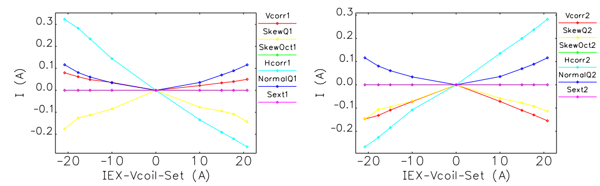
Techniques used for correction of similar APS devices [4, 5] have been adopted here with some adjustments. First, we measured beam response to the IEX local correction coils individually with IEX off. Then we measured beam perturbations while turning on the IEX. All corrector settings are then determined by multiplying beam perturbations with the inverse of the measured correction coil response. Normally, the tune and coupling variation is less sensitive to beam orbit going through the IEX magnet and had been corrected first, then the orbit perturbations are corrected. After several iterations (generally two is enough), most perturbations have been removed by the local correction coils. Some of the correction coil settings vs. the IEX main coil current and resulting orbit, tune, coupling variation with and without correction are shown in Figure 5 and 6. After about six months commissioning, the IEX was turned over for full user operation.



(a) x-orbit (b) y-orbit

(c) Coupling (d) Tune

Figure 5: Beam perturbations before (red) and after (black) local correction.



(a) Upstream correctors (b) Downstream correctors

Figure 6: IEX corrector settings (example of one page).

SUMMARY

IEX is the second circular polarized undulator to be installed in the APS. It has the strongest nonlinear field owing to its complex structure and high field. To eliminate its perturbation to the beam, we took great care in each step to ensure the device properties were within specifications and satisfied all user requirements. The device was able to run at full strength without losing beam immediately upon being turned on. Full correction table generation and debugging/troubleshooting of the control program took about six months (including a one-month shutdown in between). The device is now fully available for user operation with no restrictions.

ACKNOWLEDGMENTS

The successful IEX commissioning is the outcome of flawless work by many physicists, engineers, and technicians. We want to thank all of them sincerely for their great ideas and contributions. Methods developed from previous circular polarizing device commissioning, largely originated by L. Emery, also played a great role in the entire commissioning process. L. Emery's and V. Sajaev's rich experience on commissioning of new devices and their many suggestions helped us to avoid many mistakes.

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