FEEDFORWARD CORRECTION OF THE PULSED CIRCULARLY POLARIZING UNDULATOR AT THE ADVANCED PHOTON SOURCE*

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Abstract

A circularly polarizing undulator capabable of switching the polarization very rapidly was installed at the Advanced Photon Source. The net magnetic field perturbation is characterized in both planes by a transient orbit motion, which lasts about 30 ms, and a DC orbit shift. In addition, multipole magnetic moment errors are present. The correction system consists of small dipole and multipole correction magnets at the ends of the undulator, a multichannel arbitrary function generator (AFG) to program the corrector magnet current triggered on the polarization change event, low-level software to load and interpolate the AFG waveforms, and high-level software running on a workstation to determine the optimum AFG waveforms for the dipole correctors. We rely on the existing real-time feedback system to acquire the orbit transient and to automatically generate a close approximation of the required corrector wave forms. A choice of deterministic correction or trial-and-error manual adjustments of the wave forms is available in the high-level software.

INTRODUCTION

A circularly polarizing undulator (CPU), designed and built by the Budker Institute of Nuclear Physics, was installed at the Advanced Photon Source storage ring in May 2001. The 2.4-m long, 12.8-cm period, 34-pole electromagnet CPU has a set of vertical and horizontal coils that produce an internal helical trajectory in the electron beam for production of circularly polarized photons. A switching circuit in the vertical field coil power supply produces a trapezoidal-shaped current pattern with short transients (5-10 ms) and arbitrarily long DC parts, thus alternating the photon polarization between right-circular (RCP) and left-circular (LCP) with a small gap in the photon throughput, making this undulator a uniquely efficient device for polarization studies. The first stage of commissioning covered fixed polarization (DC modes) operation, which produced first light for users on August 1, 2001. In November 2001, we started commissioning of the more complex alternating polarization (AC mode) operation, which required the integration of several systems; this was completed in March 2003.

This paper will describe what needed to be done to commission the DC and AC modes, including some implementation details such as hardware designs, organization of data, use of existing storage ring systems, machine studies, and low-level and high-level software design.

The requirements for CPU operation are that the stored beam properties be minimally affected during operation. In general, insertion devices (IDs) cause small but measurable angular and position displacements of the beam orbit and some weak high-multipole moments. The field perturbations are dependent on the main coil current and the polarization mode. In addition, a short-lived transient in these fields occurs at the switching of polarization. Extensive magnetic measurement of the on-axis CPU field components were made at several main coil currents for the various modes. This data were used initially for the feedforward correcting channels. Since the CPU has very strong nonlinearities, especially during transients, and the fields are very sensitive to misalignment, we expected to have to make additional beam-based corrections after the CPU was installed in the storage ring. Though the slowly varying components of the angular and position displacements can be corrected by the real-time orbit feedback (RTFS) and the DC orbit correction (DC OC) systems at the APS, we strove to correct all measurable CPU perturbations.

MULTIPOLE CORRECTOR MAGNETS

The present correction system consists of four channels to compensate the first and second field integrals of both planes (two dipole magnets at the upstream end and two more at the downstream end). Additional channels were implemented for correcting higher-order multipole components: the normal quadrupole, skew quadrupole, and skew octupole field components [1].

The initial part of the commissioning plan called for making a complete magnetic characterization with no correction, then to repeat the bench measurement with correction turned on to confirm the tuning of the CPU.

The seven channels of corrector magnet currents are programmed by a multichannel arbitrary function generator (AFG) with a sampling rate of 1 kHz and a depth of 128 points. In the AC mode, the AFG produces alternating waveforms for each transition synchronized to a switching pulse (i.e., one waveform for RCP → LCP and a different waveform for LCP → RCP). On the last point of the AFG, the corrector current freezes until the next trigger. In DC modes, the AFGs produce a constant waveform and is updated when the CPU set point is changed. An EPICS IOC dedicated to the CPU handles the updating of AFG waveforms from stored tables of correction data specific to each operating mode. The tables are linearly interpolated at the CPU set point value and the resulting wave-

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forms are sent to the AFGs. The waveform data tables are loaded into the IOC from self-describing data set (SDDS) protocol-compliant [2] data files.

The use of SDDS files in managing the corrector waveform data was crucial. Briefly, SDDS datasets are files with headers that describe the structure and contents of the data in terms of names, units, and data type. The data itself is typically one or more instances of data pages, which are tables accompanied by parameters and multidimensional arrays. Access to data in SDDS files is *by name only*, which is the key feature for a robust protocol. A suite of data processing and display tools that work with SDDS files helps integrate data from various systems, which is the case here.

The data for configuring DC mode compensation is contained in a single file. Each data page of the file corresponds to a different polarization mode and contains a table of CPU main coil currents and the seven multipole corrector magnet currents. For AC mode configuration, one file for each corrector magnet is required because of the extra time dimension. Each data page corresponds to a particular CPU current set point with a table of time index and waveforms for the RCP and LCP states.

MEASUREMENT AND CORRECTION OF ORBIT PERTURBATION

It turns out that the dipole corrections based on the magnetic measurements did not correctly compensate the dipole perturbation for both DC operation and AC operation. We were not surprised by this since we knew of some CPU misalignments in the vertical plane (by 250 microns) due to inaccuracies in the manufacture of the poles. We proceeded to make beam-based measurements of the dipole perturbations to apply as feedforward correction. For the DC modes, the normal and skew quadrupole correction was confirmed with tune measurement and beam size measurements, respectively, while the skew octupolar correction was difficult to confirm. In any case, we found no effect on the beam lifetime from the octupole magnet operating at full range. For the AC modes, the latter three corrections would be difficult to confirm, so we left the correction from the initial magnet measurement as is.

DC Modes

The measurement and correction of the fields for DC mode operations required no extraordinary setup. We configured our existing system of DC orbit correction with the four CPU dipole correctors acting as the only correctors, while the CPU was ramping slowly between predetermined set points. The recorded values of the correctors were then written to the DC-mode operations compensation file. Occasionally one corrector reached its range limit at some CPU set point, in which case we continued orbit correction with the remaining corrector of that plane. Even though the compensation will not be perfect, the perturbation would be minimized, leaving the regular DC OC to make up the difference in user operations.

Figure 1 shows the difference between the initial correction based on the magnetic measurements and the final correction for the four dipoles in RCP mode. For the initial correction, the curves for the two vertical correctors were set the same because the magnetic measurement could not definitely detect a second integral perturbation. The final correction definitely displays a second integral correction for both planes.

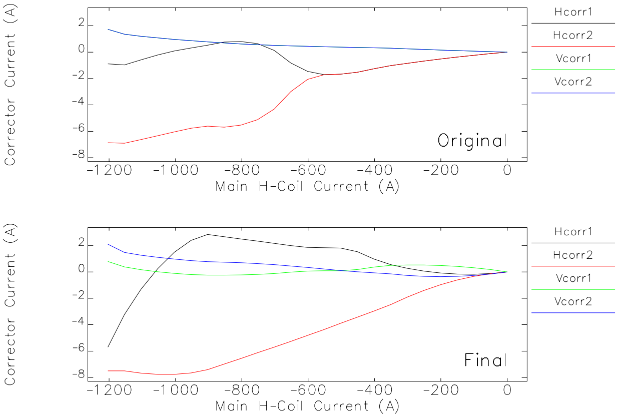

Figure 1: Original and final RCP mode correction of dipole fields.

AC Mode

The measurement and correction of the fields for AC mode operations required a more complicated setup because of the extra time dimension. Breifly, we use the transient orbit data to make changes to the dipole compensation waveforms. We needed to integrate several data sets, signals, and systems: the original waveforms from magnetic measurements, a timing signal, RTFS data acquisition system, a special RTFS correction matrix configuration, a GUI application for manual or automatic waveform feedback, a new Tcl/Tk widget for waveform display and tweaking, a SDDS data file structure to facilitate waveform operations, and the RTFS for rms orbit measurement.

The RTFS has access to almost all orbit data at a sampling rate of 1.5 kHz. The RTFS data acquisition can be triggered by the 2-Hz rate injection timing signal. To get synchronization between RTFS and CPU transition, the CPU switching circuit was connected to a trigger sequence derived from the same timing signal. The RTFS was set up for data acquisition with the loops open, otherwise the orbit would not truly reflect the magnetic filed perturbation.

It turned out that we could utilize the powerful RTFS to do some of the mathematical work. The data from the beam position monitor (BPM) system is actually transformed in real time into “corrector error” signals by multiplying the orbit data vector with rows of the RTFS correction matrix. The corrector error signals are the amount of current that would be commanded to the RTFS correctors (one per sector) to correct the global orbit for that time step, assuming unity gain. Even with the loops open, the matrix calculation goes on indefinitely. The correctors error signals from the upstream and downstream RTFS correctors (regular storage correctors) are the most relevant ones because they are the closest to the CPU. Since the RTFS correctors are not at the same location of the CPU dipoles, additional modification of the corrector error signals was sought. For a time, we ran the flexible RTFS with a correction matrix that had phantom RTFS correctors at the locations of the CPU dipoles. The corrector error signal would then correspond to exactly the required correction for the CPU correctors. In practise, however, the solutions were too noisy to use, mainly because the first and second integral correction components were solved simultaneously, the second integral solution being very sensitive to input error. Until we find a way to reduce the noise, we'll adopt the default correction matrix used for operations, which is less accurate but nevertheless permitted a convergence in tuning.

The next step was to make a change to the corrector waveform based on the orbit readback. We have the option of using the readback waveforms to calculate a change in the CPU dipole waveforms, or simply edit part of the CPU dipole waveforms in an attempt to change some visible features of the readback waveforms. At a given CPU current set point, there are eight waveforms to adjust, two waveforms for each of the four dipole magnets.

Finally, the data of the new waveforms for the given CPU set point were inserted into the four corrector SDDS files that had been loaded in the IOC. Tens of iterations were typically required for correcting perturbations for one CPU set point.

Graphical User Interface

A Tcl/Tk application was written to facilitate the control and processing steps for the AC mode correction described above. The application sets up the RTFS for acquiring the particular data required, collects the data over many CPU pulses, averages the data over several pulses, separates the orbit transients belonging to the RCP and LCP portions of cycle, and writes the data to a file in a selected working directory. The original version of the application did a deconvolution of the CPU corrector time response (7 ms) from the orbit transient and a transfer matrix multiplication to obtain the angle corrections required at the CPU correction locations. This method had the potential of converging to the right waveforms quickly, but had the noise problems mentioned earlier that the deconvolution itself worsened. In the later version of the application, the deterministic approach was replaced with a "manual" search approach. A waveform Tcl/Tk widget was designed specifically for displaying the orbit data and the corrector waveform data in adjacent frames. Each point of the corrector waveform can be selected by the mouse and moved vertically to change the value. After editing is completed, the waveform can be saved in an archival SDDS file, and uploaded to the IOC. Any archival waveform data can also be recalled and uploaded to the IOC. Preset plots of the RTFS and corrector waveform data are available.

Figure 2 shows an example of the orbit perturbation data before any correction, corresponding to a 250 μm orbit. After correction (not shown), the remaining perturbation is reduced to about 7 μm of orbit (0.1 A in the scale of Figure 2) and lasts about 15 ms.

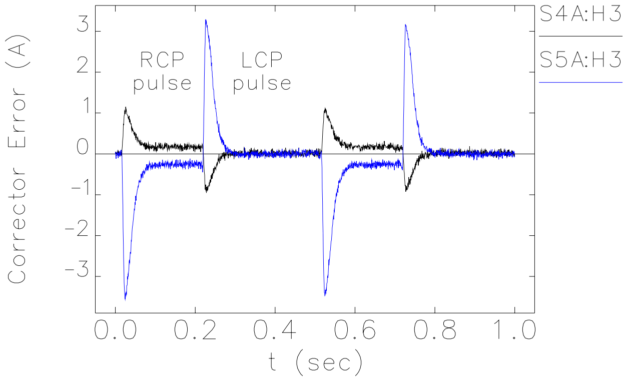

Figure 2: Orbit data for uncorrected CPU at 260 A.

USER OPERATION

We stop iterating the dipole corrector waveforms when the remaining orbit error doesn't appear to be correctable anymore. The remaining uncorrected errors occur just after the switch time, are short lived (5-15 ms), and are of small amplitude. The overall figure of merit for the quality of correction is the rms orbit calculated by the RTFS when the RTFS loops are closed. Because the RTFS correction bandwidth is about 50 Hz, we don't expect the remaining pulse-like errors to be corrected by the RTFS, though the DC-level error would be.

We decided arbitrarily that the acceptable increase in the rms orbit error (for 30 Hz BW) was to be 20% from its base level of 1.1 μm in the horizontal plane and 0.9 μm in the vertical plane. Because the rms error depends on the pulsing period, we have restricted the pulsing period to a minimum of 2 seconds. The measured rms orbit errors for the full operating range of the CPU varies from 1.1 μm to 1.3 μm in the horizontal plane and 0.9 μm to 1.3 μm in the vertical plane. The CPU set points most used by the user have rms orbit errors 1.2 μm and 0.9 μm in the horizontal and vertical planes, respectively.

REFERENCES

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