ANL/XFD/CP-94008

CONF-9706157--

Control System for Insertion Devices at the Advanced Photon Source

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Abstract. Eighteen insertion devices (IDs) are installed at the Advanced Photon Source (APS), and three more are scheduled for installation by the end of this year. A distributed control system for insertion devices at the APS storage ring was created with the Experimental Physics and Industrial Control System (EPICS). The basic components of this system are operator interfaces (OPIs), input output controllers (IOCs), and a local area network that allows the OPI and IOC to communicate. The IOC operates under the VxWorks OS with an EPICS database and a sequencer. The sequencer runs an ID control program written in State Notation Language. The OPI is built with the EPICS tool MEDM and provides display screens with input and output fields and buttons for gap control of the IDs. Global commands like "open all IDs" are C-shell scripts invoked from the display menu. The algorithms for control and protection of the ID and ID vacuum chamber and the accuracy of gap control are discussed.

INTRODUCTION

The Advanced Photon Source (APS) at Argonne National Laboratory is a national user facility designed to produce insertion-device- and bending-magnet-based synchrotron radiation to be used in forefront research in science and technology (Fig. 1). Of the 18 insertion devices (IDs) currently installed [1-5], 13 are 2.4-meter-long undulators with 3.3 cm periods, three are undulators with periods of 1.8 cm [4], 2.7 cm and 5.5 cm, respectively, one is an 8.5-cm-period wiggler, and one is an elliptical multipole wiggler (EMW) with a 16 cm period. The characteristics of X-rays produced by all of these IDs are adjusted by varying the gap between the upper and lower jaws - arrays of permanent magnets and poles. In addition to permanent magnets producing a vertical magnetic field, the EMW also has electromagnets that produce a horizontal magnetic field of alternating polarity at up to 10 Hz.
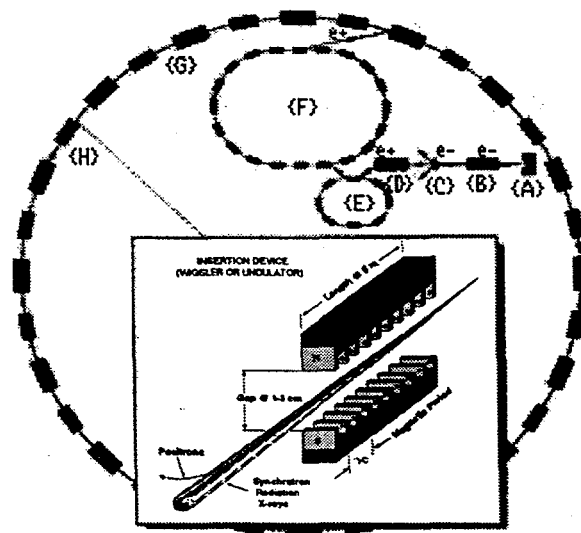

FIGURE 1. Schematic representation of the APS beam acceleration and storage complex: A - electron gun, B - electron linear accelerator (200 MeV), C - positron conversion target, D - positron linear accelerator (450 MeV), E - positron accumulator ring, F - booster/injector synchrotron (7 GeV), G - storage ring (7 GeV nominal energy), H - insertion device. Insert: an APS insertion device and X-ray beam.

HARDWARE DESCRIPTION

MASTER

On each ID, two stepper motors are used to change the gap between the upper and lower jaws. On all but the elliptical wiggler, one motor controls the gap at the upstream end, and another - the downstream end. On each end of the ID, one absolute linear and one absolute rotary encoder are installed. The control system includes power supplies, interlock electronics, encoder

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interfaces, drives for the stepper motors, and IOCs with an MVME-167 single-board computer connected to the local area network (LAN) via ethernet. The IOC is based on VME crate, it includes an Oregon Micro Systems' VME-8 controller, a VAROC interface, and an Acromag AVME9440 interface. The VME-8 board is capable of controlling eight stepper motors. The VAROC board, developed at the European Synchrotron Radiation Facility, interfaces up to 16 absolute encoders complying with the SSI (synchronous serial interface) protocol to the VMEbus. The AVME-9440 board provides 16 digital input and 16 digital output channels.

The EMW is a unique insertion device, which has been installed in sector 11 of the storage ring. It produces circularly polarized X-rays whose CW or CCW polarization is altered by switching the polarity of an electromagnet. A 1000 Amp electromagnet supply is controlled with an Allen-Bradley (AB) crate with binary and analog IO modules. The VME crate communicates with the AB crate through a 6008 SV scanner. The correcting coils of the EMW are controlled through an arbitrary function generator to reduce the magnetic field integrals for the electromagnet during transitions.

STRUCTURE OF THE CONTROL SYSTEM

The control system for insertion devices was created with EPICS [6]. It is a distributed control system with UNIX workstations as OPIs, VME crates as IOCs, and an ethernet-based LAN that allows the workstation and VME crate to communicate.

The IOC operates under the VxWorks OS [7], which is a high performance real-time operating system with a full range of UNIX-compatible networking facilities. The Motorola MVME 167-02B single-board microcomputer with a MC68040 processor is the heart of the IOC. The major part of the control software for an insertion device resides in the IOC. At boot time, after loading the operating system, a start-up script file is executed that contains commands to download the IOC database support programs, a sequencer program, a control program, EPICS databases, and data for magnetic field vs. ID gap. Almost all processing for insertion device control takes place in a *ctrl_ID* program executed by the sequencer. This program is written in State Notation Language [8] and consists of five state sets and an *exit* procedure.

State set *errlog_file* consists of three states: *start*, *init* and *update_file*. The *start* state opens the error logging file, the *init* state checks the connection with the ID database parameter variables, and the *update_file* state updates contents of the *errlog.idXX* file at the Unix file server every 5 minutes if the "errlog" file is open. Also this state terminates the *ctrl_ID* program if the "errlog" file exceeds a size of 500 kilobytes to prevent overbooking of the file storage. State set *speed* consists of two states: *speed_up* and *speed_down*. When the ID moves to a smaller gap (moves in the direction of the magnetic attractive force between the jaws) the *speed_up* state sets a high speed for the stepper motors, and when the ID gap opens (moves opposite to the direction of the magnetic force), the *speed_down* state sets a low speed for the stepper motors at small gaps where the magnetic force between the jaws is strong. State set *encoders* consists of two states: *init_enc* and *offset_enc*. The first one is used to initialize variables for encoder offsets, and the second state is used to write into the "errlog" file the change of each of these offsets or of the encoder selection. State set *buttons* consists of two states: *init_butt* and *butt*. The *init_butt* state is used to initialize the variables and to start the readout of the encoder values, then, after a 1/3 s delay, to initialize the variables in which the encoder values are used. The *butt* state is used for handling encoder and motor errors and events like *button is pressed* or *value is entered*, writing this information into the "errlog" file. State set *main_loop* consists of one state: *main_lp*, which is executed every 0.25 seconds. It checks gap values at the ID, calculates displacements and starts stepper motors, checks errors, and updates ID gap values and energies of X-ray photons. The procedure *exit* is used to close the *errlog.idXX* file and post the message *RESTART "ctrl_ID" PROGRAM* on the *ID Gap Control* display.

Operators and users can monitor status and initiate actions from the control room or from computers located in offices or at beamlines. Security is maintained by the use of a process variable server that allocates control according to predefined access tables. Global commands like *open all IDs* are C-shell scripts invoked from the display menu. During beam injection, users have no access to control the IDs.

OPERATOR INTERFACE

Control displays for IDs are available on UNIX workstations with the Motif Editor and Display Manager (MEDM) [9], which is an EPICS tool.

Basic control functions for the ID are provided by an *ID Gap Control* display, shown in Fig. 2. It allows the user to enter a value either for the desired gap or for the photon energy corresponding to the first harmonic of the undulator radiation.

Pressing the *Move* button starts the ID gap adjustment, and the *Stop* button, when pressed, stops the ID gap adjustment. The current state of the ID, average gap value in mm, and photon energy of the X-rays in keV are displayed above the input fields. Energy calculation uses the lookup table of magnetic field vs. gap for a particular device. Two strings show messages related to the status of the ID control program and to the conversion between the ID gap value and the photon energy of X-rays, for example: *desired position accepted, min gap value substituted, adjustment started, adjustment stopped, adjustment completed, conversion (Gap<-> Energy) OK, energy is too small*, etc. Also, the display contains information about ID type, serial number and its location in the storage ring. The *More* button opens a pull down menu that allows access to additional displays: *ID Taper Control, Call_in List* and *ID Commissioning Limit Control*.

The *ID Info* button invokes execution of a C-shell script that starts an *ID_online_info* program using interactive data language (IDL) and providing graphical and numerical information about IDs. Graphs of *Magnetic Field vs Gap, 1st Harmonic Energy vs Gap, Integrated Moments vs Gap (1st and 2nd integral), Integrated Multipole Moments vs Gap (quadrupole, sextupole, and octupole), RMS Phase Error vs Gap, RMS Peak Field Variation vs Gap, Trajectory Straightness vs Gap, Trajectory Angle vs Gap, Brilliance vs Energy,* as well as numerical data for any ID can be selected interactively. All of the data are collected during magnetic measurements before installation of the ID in the storage ring.
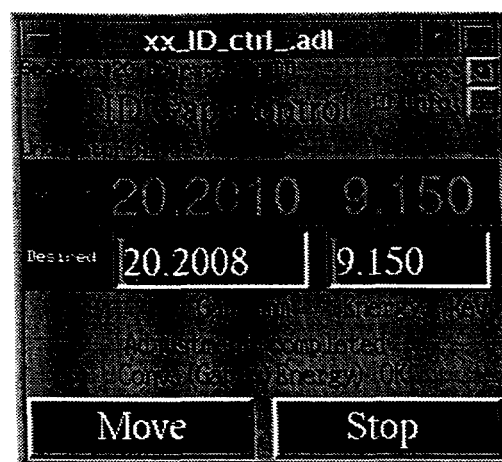

FIGURE 2. ID gap control display.

ALGORITHM FOR GAP ADJUSTMENT

Testing of entered gap values

Each time a new desired gap value (upstream, downstream or parallel) is entered, the *ctrl_ID* program checks that the value is within the range for ID gap and taper. When the entered value cannot be accepted, the program replaces it with the nearest acceptable value. In each case, an appropriate message appears on the *ID Gap Control* display.

Gap adjustment

Because the magnetic force between the ID jaws varies with gap and creates nonlinearity in the gap motion, multiple move commands are used to accomplish a single move request. Each move command is calculated to be 90% of the desired gap change, except when the discrepancy between desired and measured position becomes less than 10 μm. In this case, it moves only 30% of the remaining distance. Convergence to the desired position is usually obtained after several moves. It takes about 20 seconds for adjustment with 1 mm gap change, and about 5 minutes for change from minimal to maximal gap.

Movement of the extreme ends of the ID are coupled to the motion of the opposite end motor because of the placement of the mechanical pivot points. As a consequence, tapering of an ID must be carefully controlled to avoid damage to the storage ring vacuum chamber. The program will reduce the jaws' taper to 10% of the initial value if it exceeds the desired value by more than 50 μm. When the taper request exceeds the current taper by more then 50 μm, and both motors should move in the same direction, the jaws are leveled to the required average gap value before proceeding with the taper. Furthermore, if during adjustment the jaws' taper exceeds 200 μm, its value will appear on the control display. If the current taper exceeds the desired value by more than 400 μm or exceeds a value of 5.1 mm, then the taper will be reduced.

If the current gap value exceeds the maximum allowed gap value by more than 200 μm or becomes 50 μm smaller than the minimum allowed gap value during adjustment, then motion will be paused and new values will be loaded to the stepper motor controller.

Adjustment is considered as completed when both motors have finished motion and a difference between the desired gap value and one measured by linear encoders is less than 0.28 μm for both ends of the device. The resolution of the linear

encoders is 0.5 µm.

Encoder and motor errors

The noisy electromagnetic environment at the storage ring occasionally causes encoder errors. Readout of the encoders is executed each 0.25 seconds. Because the gap changes slowly, there are no conditions in which the value would differ from the previous one by more than 1 mm. Therefore, a change in encoder value of more than 1 mm is considered to be an encoder error. If the encoder error occurs during motion, a *Stop* command is issued, and an error message appears on the control display. Electrical noise may force the linear encoder counter to count up/down without motion. The program decides this error has occured when either linear encoder value changes more than 40 µm when there were no gap adjustments. In this case an error message, *reset US(DS)l, err. = <current_US(DS)_linear _encoder_drift>*, appears on the display.

To detect a motor error, the *ctrl_ID* program compares the displacement calculated for that motor from encoder data with the displacement obtained from the change of a step counter. This comparison is made each time the step counter change exceeds 0.5 mm. If the ratio of these two displacements (one based on the change of the step counter, and another based on the change of encoder data) is less than 0.6, this state is considered to be a motor error, a *Stop* command is issued, and an error message appears on the display. The program resets the step counter each time the motor position obtained from it differs from the value calculated with encoder data by more than 0.5 mm, and there is no adjustment. This action is not considered an error.

Monitoring of gap value, taper and limit switches

The upstream and downstream gap values are regularly compared with the software gap limits. When these values exceed the maximal gap limit by more than 0.2 mm, an *US = <value> over limit* or *DS = <value> over limit* message appears on the display. When these values are below the minimal gap limit by more than 0.05 mm, a *US = <value> under limit* or *DS = <value> under limit* message appears on the display.

During adjustment, a taper value (i.e., *US_gap_value - DS_gap_value*) is periodically calculated. If it exceeds 0.2 mm, an *US - DS = <value> mm* message appears on the display. If the taper value exceeds maximal taper + 0.1 mm (i.e., a 5.1 mm value), the *ctrl_ID* program places a *Taper = <value>, out of limit* message on the display.

The stepper motor driver monitors the limit switches. Should these limit switches be tripped, the *ctrl_ID* program would place the *Hard limit, US = <value>* and/or *Hard limit, DS = <value>* messages on the display, switch access to the device from *User* to *Operator* mode, and issue a *Stop* command.

DISCUSSION

The magnetic force between the ID jaws at the minimum gap is comparable with a gravity force for a 3-tonne mass. The storage ring aluminium vacuum chamber is 10 mm high between the jaws of the ID, with a wall thickness as small as 1 mm. The ID jaws cannot be allowed to damage the vacuum chamber. There are three levels of protection: mechanical level - hard stops are adjusted so as to stop motion at a gap of 10.4 mm and at full open gap; hardware level - limit switches that shut off the stepper motors at a gap of 10.7 mm and near maximum gap; software level - software limits (presently set at 11 mm and about 200 mm) that do not allow the jaws to hit the limit switches.

The accuracy of gap adjustments relies on the linear encoders having a 2.5 µm accuracy and a 0.5 µm resolution. At small gap values, the magnetic force between the jaws increases causing deformation
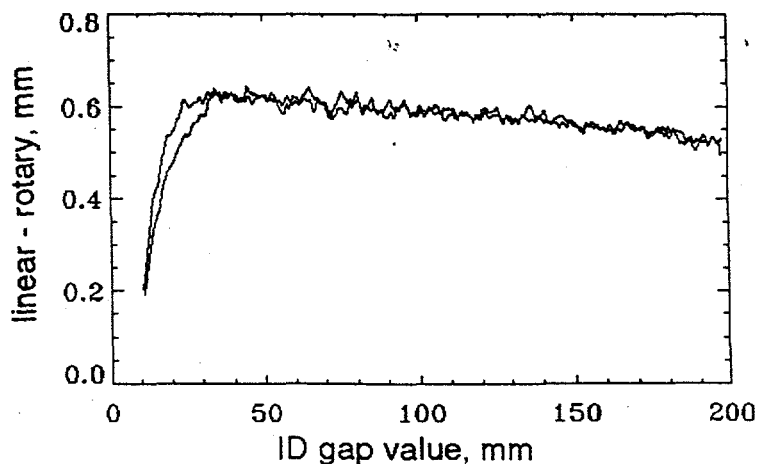

FIGURE 3. Difference between linear and rotary encoder values vs. gap for the Undulator A #4.

of the ID frame and main drive screws. The rotary encoders show values proportional to the drive screw rotation angle and so do not have a linear dependence on gap. The graph in Fig. 3 shows the difference between linear and rotary encoder values vs ID gap for the 3.3-cm-period Undulator A #4. As can be seen in the figure, the deformation exceeds 0.4 mm at minimum gap. Some additional errors in gap adjustment may arise from a jaw cant that appears in the figure as a hysteresis between the two data sets measured during opening and closing of the ID. Cant means a jaw rotation by a small angle around the axis parallel to the beam orbit. Because the linear encoders are not centered over the beam position, cant causes errors in gap measurements. According to our measurements, these errors can be as large as 20 - 40 μm. The rotary encoders have a 2.5 μm resolution, but about 20 μm variation is caused by the belt that connects them to the drive screws. However, they do operate more reliably in the electromagnetically noisy storage ring environment than do the linear encoders.

For further improvement of the reliability and the capabilities of the ID control system, we plan to enhance the control program with new features, such as scanning capabilities, more sophisticated conversion between the ID gap and the photon energy taking into account values of beam emittance and user's aperture, automatic resetting of linear encoders after beam injection into the storage ring, and the use of individual data of elastic deformation for ID frame and lead screws with data from rotary encoders for more precise comparison with gap measurement by linear encoders. To avoid cant-related errors in gap adjustment and to increase accuracy, we are considering installing another set of four linear encoders (with a 0.5 μm accuracy and a 10/256 μm resolution) in the plane of symmetry of the ID.

ACKNOWLEDGMENTS

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