STATUS OF THE CONTINUOUS MODE SCAN FOR UNDULATOR BEAMLINES AT BESSY II

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Abstract

At the synchrotron light source BESSY II monochromator (MONO) and insertion device (ID) scans can be done synchronized in two different modes. In step mode MONO and ID move independently to intermediate target positions of an energy scan. In continuous mode (CM) MONO and ID cover the whole range of the scan nonstop in a coupled motion. Data acquisition is done continuously at the speed provided by the CM scan and is available in regular user operation [1]. Currently CM is in operation at 11 undulator beamlines at BESSY II. 3 new beamlines requesting CM are under construction. During CM the MONO EPICS IOC acts as a controller forcing the MONO optics to follow the movement of the ID. A non-linear predictive control scheme is used to implement this dynamic coupling. The controller task utilizes polynomial regression to extrapolate the ID motion. Calculation of the trajectories for MONO grating and mirror is based on bijective gap to energy lookup tables and the grating equation. In this paper the technical implementation, limitations, recently developed diagnostic methods, and future plans for improvements are presented.

INTRODUCTION

The continuous mode is part of the monochromator control program (MCCP) and has been in operation since 2005 at a dipol beamline. The first employment at an undulator beamline was 2006 [2]. At the time of writing, 11 undulator beamlines (UE56/2 PGM1, UE56/2 PGM2, UE49/1 PGM1, UE52/1 SGM1, UE52/1 PGM1, UE46/1 PGM1, UE46/1 PGM2, UE56/1 PGM1, UE112 PGM1, U49/2 PGM1, U49/2 PGM2) and 6 dipol beamlines (PM1...4, HESGM, ISISS) support CM operation by the monochromator software. 3 beamlines (U125/2 PGM1, U411/1 PGM1 and EMIL-UE48/U17 PGM [3]) are under construction requiring CM. Dipol light sources provide a continuous spectra. Energy scanning can be done by solely moving the optical elements of the monochromator which makes the implementation of CM relatively easy. On undulator beamlines the motion has to be coupled with the undulator gap and shift axes that are controlled by the insertion device control program (IDCP). The mapping between energy and gap/shift is calculated using lookup tables and piecewise polynomial or splined interpolation. The tables are held by the MCCP, which sends the target positions for gap and shift via CAN bus to the IDCP and receives the gap/shift position feedback sent from the undulator (Fig. 1). Task synchronization for combined movements has to be done by the MCCP. As a result, the monochromator acts as slave and follows the movement of the undulator (master) .

Motivation

BESSY beamlines split up into branches with up to four experimental stations per undulator light source. Depending on the application, users can greatly benefit from the fact that CM scans are about five times faster than step scans [4]. In addition, exposure times of the samples are shorter and, in some cases, the measurements are even better [5].
A robust control loop with no maintenance effort, and without the need of manual interaction, is necessary in order to ensure accurate user operation with variable scan speeds. This requirement is even more challenging for the technical setups of the beamlines currently under construction [3]. Diagnostic methods are needed to locate possible disturbances from CAN/Ethernet-jitter, inaccurate lookup tables and vibrations.

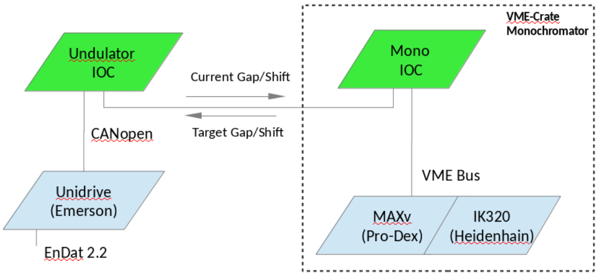


Figure 1: Interfaces used for CM from monochromator to motion controller (VME-Bus), encoder card (VME-Bus) and undulator IOC (CAN). VME based hardware for monochromator: MVME162 (Motorola), MAXv (Pro-Dex), or VME6, OMS58 (OMS), IK320 (Heidenhain).

TECHNICAL DESCRIPTION

The beamline control system is based on EPICS. Monochromator and undulator are controlled by EPICS IOCs (IDCP, MCCP). Both provide EPICS based operator interfaces. Additionally, the monochromator IOC provides connectivity over the BESSY extended monochromator control protocol (EMC) via RS232 or Ethernet. Users can control the beamline using EMC or EPICS. The communication via RS232 is slow but has proven to be reliable for CM operation when deterministic synchronization of data acquisition and monochromator energy feedback is critical. The CAN bus communication has been chosen between monochromator and undulator in order to reduce the jitter of the periodic position updates sent to the monochromator (Fig. 1).

Control Loop

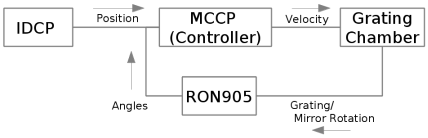


Figure 2: Feedback loop. Desired velocity profiles derived from the readback recieved from the undulator control program (IDCP). Monochromator position feedback from Heidenhain system (RON905).

A combination of the IK320 counter cards and a RON905 (Heidenhain) incremental angle encoder ensure an extremely high angular resolution of about 0.01 arcsec depending on noise and vibrations. The access time of the measured value of the IK320 is about 0.2 ms. This is relatively fast compared to the 10, 20 Hz position update from the undulator (Fig. 1). The MCCP receives the gap positions from the undulator and builds a list of undulator gaps and time stamps. The controller algorithm works at a variable rate from 2 to 4 Hz and forces the optical elements to follow the undulator by setting the proper velocities of grating and mirror. This is done by sending jog commands for linear blended moves to the motion controller (Fig. 1-3), causing the slow control loop update rate. Eventually, the result is a good approximation to the required non-linear velocity profile (Fig. 9).

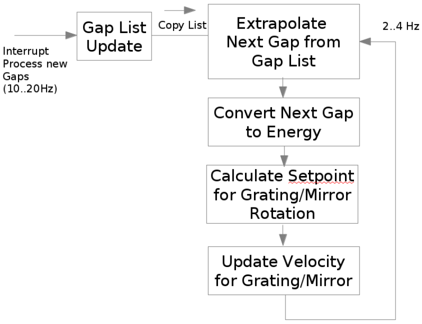


Figure 3: Feedback loop flow chart.

One-Step Ahead Prediction of Undulator Energy Due to the slow update rate of the control loop (e.g. 4 Hz) and the update rate of the current gap position (e.g. 20 Hz) it is essential for the accuracy of the CM to extrapolate the gap to the time of next control loop update (t_{N+1}).
Based on the observation of the last N gaps, two different extrapolation modes are implemented. First, obtaining the slope m via linear regression, the one-step ahead predicted Gap(t_{N+1}) is calculated as

$$\begin{aligned} Gap(t_N) &= m \cdot t_N + Gap(t_0) \\ Gap(t_{N+1}) &= Gap(t_N) + \frac{m}{f} \end{aligned}$$

, where f is the update rate of the control loop. Gap(t_0) is the first gap in the list and Gap(t_N) is the last one.

The second method is quadratic interpolation fitting better to the non-linear relationship of gap to energy as well as to the trajectories of the gap motion. Obtaining a,b,c after translation of the coordinate system and quadratic polynomial regression, the Gap(t_{N+1}) is calculated according to

$$Gap(t_{N+1}) = (a \cdot t_{N+1} + b) \cdot t_{N+1} + c + Gap(t_0)$$

The inverse mapping of energy to gap can be determined by the help of 3rd order polynomial interpolation or cubic splines using the undulator lookup table. The grating equation, monochromator type (PGM/SGM) and conditions (fix focus, fix beta, fix theta) are used to estimate the velocity necessary to force the monochromator to the same energy at the time t_{N+1}. Figure 3 shows the flow chart of the control loop.

Technical Requirements

The following error (FE) is the difference between monochromator energy and undulator energy. This error must be within the limits defined by the bandwidth of the undulator. One result of the FE are intensity modulations during the scan which should not exceed 2% of the maximum intensity for a given harmonic. The maximum tolerable FE significantly decreases with the bandwidth of higher undulator harmonics, given by

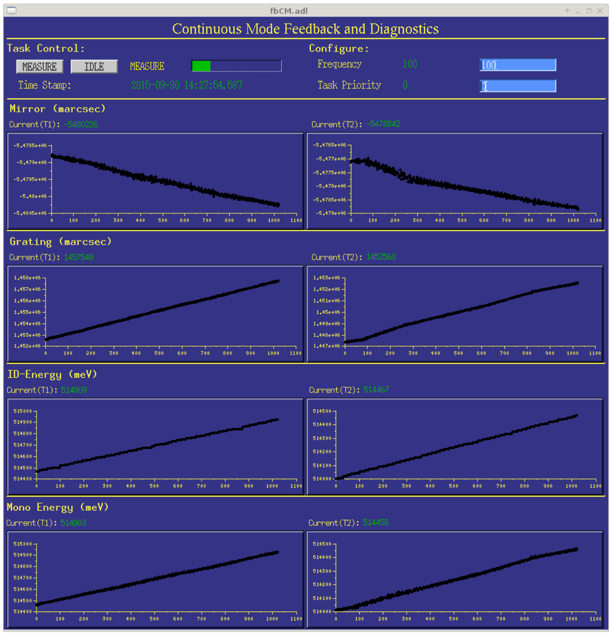
$$\frac{\Delta E_h}{E} \approx \frac{1}{hN}$$

, where N is the number of undulator periods and h is the undulator harmonic. For example at 435 eV on a beamline at U49/2 we have a maximum FE of about 0.67 eV (1st harmonic), 0.25 eV (3st harmonic) and 0.18 eV (5th harmonic). Hence, the gap position should be accurate in the range from 3 μm (5.th harmonic) to 50 μm (1st harmonic). Inaccurate lookup tables for the mapping from gap to shift could have a major impact on the maximum value of FE. The demanding control specifications in particular for higher scan speeds (dE/dt) have led to the development of diagnostic software.

Diagnostics

The diagnostic of the CM is not an easy task. Critical are the CAN bus communication, position measurement, lookup tables, the control loop and the actuators needed to move the monochromator and undulator.
The feedback module is a library for the EPICS framework written for real time feedback and data acquisition used for beamline diagnostics and optimization [6]. A recent software development at BESSY II is the implementation of a feedback module plugin for the MCCP in order to improve diagnostics and user feedback of the existing implementation of the CM. The interrupt triggered scheduling of the data processing, utilizing the VxWorks auxiliary clock (auxClock), allows data acquisition at rates of up to 4 kHz. This is a theoretical limit for the encoder data and can be generated for grating and mirror position by triggering the encoder cards after data processing. The readout starts then with the next feedback loop (Fig. 5). Reasonable feedback rates for

CM are in the range from 100 Hz to 1 kHz.
Monochromator energy, undulator energy and rotation of grating and mirror (Phi, Psi) are relevant parameters during CM. The gap position update rate via CAN bus can be analyzed and correlated to the higher frequency feedback of monochromator energy which is obtained via the grating equation and the encoder feedback for grating and mirror (Phi, Psi). Figure 4 shows the user interface of the plugin.


fbCM.adl

Continuous Mode Feedback and Diagnostics

Task Control:

MEASURE IDLE MEASURE

Time Stamp: 2015-09-30 14:27:54.587

Configure:

Frequency 100 100

Task Priority 0 0

Mirror (marcsec)

Current(T1): -5480226

Current(T2): -5478842

Grating (marcsec)

Current(T1): 1457549

Current(T2): 1452568

ID-Energy (meV)

Current(T1): 514909

Current(T2): 514467

Mono Energy (meV)

Current(T1): 514903

Current(T2): 514458

Figure 4: Continuous mode diagnostic panel for visualization during scan.

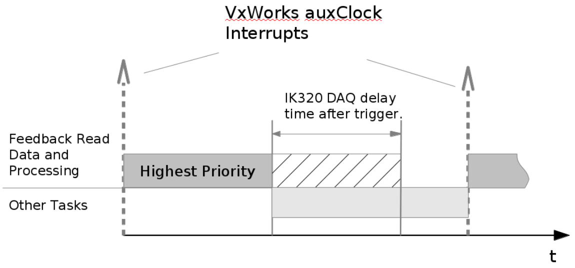
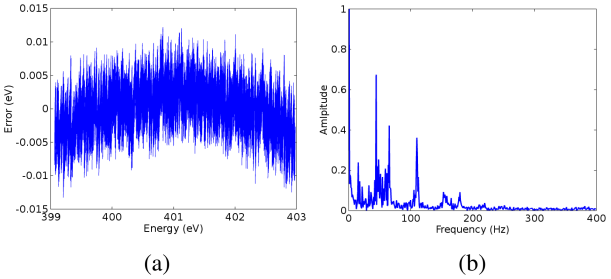


Figure 5: Real time position data acquisition and scheduling. The feedback task can be configured to run with highest priority 0. No polling or extra task switches are necessary to wait for encoder data to be ready.

Data Acquisition During data acquisition the user can read single data sets consisting of monochromator energy and data index. The waveform data can be received by monitoring two datasets (4 * 1024 values), which is undulator and monochromator energy, mirror and grating rotation. One set of arrays is filled by the feedback task while the other one is copied to the EPICS record layer (Fig. 4).
Figure 6 shows the divergence from constant energy velocity of a CM move at a high data rate. This could be used for post mortem correction of the energy scale by correlating the data acquisition of the experiment with the position data provided by the feedback plugin of the monochromator.



(a) (b)

Figure 6: Divergence of linear energy scale due to variance of dE/dt (a) and FFT of divergence signal (b).

Complex filters can be applied after the scan in order to remove disturbances like noise and vibrations from actuators.

Sample Frequency and Task Priority For such an application the feedback task has to be scheduled with highest priority so that the noise induced by the jitter of the data acquisition can be neglected (Fig. 5).
The waveform of Fig. 6a has no significant spectral contributions beyond 200 Hz. Hence, choosing a sample rate of 400 Hz, the waveform can be recovered with an error of the magnitude of the random noise level [7]. In the example of Fig. 6a it is in the range of meV and can, in principle be derived from the standard deviation of the position measurement of about $\sigma = 0.01$ arcsec and the grating equation.
Another application of the plugin would be during step mode. Closed loop positioning can by analyzed and any number of monochromator energy samples can be taken and precisely correlated to the measurement on the target position.

Position Update Jitter Distribution While gap position update jitter has no direct effect to the monochromator energy, it can have a big impact on the stability of the control loop causing intensity modulations. The jitter-distribution (Fig. 7) can be derived from the waveform data above.

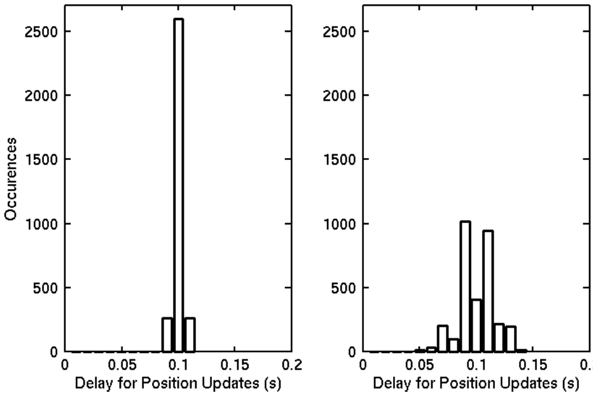


Figure 7: Jitter distribution for CAN bus communication diagnostics.

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EXPERIMENTAL VALIDATION

We verified the CM control loop and user feedback by taking a spectrum of molecular nitrogen. Figure 8 compares the conventional step mode with the continuous mode and the improved wavelength scale using data provided by the CM plugin of the feedback module. The scan time could be reduced by a factor of 5 improving the sampling rate at the same time.

A peculiar problem of incremental angular encoders, used for the positioning of the optical elements in monochroamtors, are interpolation errors that lead to a modulation of the wavelength scale of the monochromator. This is commonly encountered with the Heydemann correction [8] which is implemented in a fast and transparent way and also available in the continuous mode. The corrected data has been used to determine monochromator energy at a rate of 800 Hz. Disturbances like vibrations and noise can be filtered out of this energy trajectory profile for evaluation. This makes it in principle possible to improve the wavelength scale of the scan as demonstrated in Fig. 8.

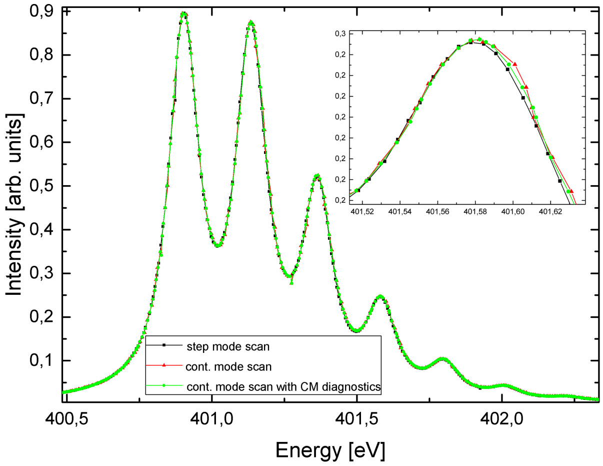

Figure 8: Nitrogen absorption spectra and comaparison of step mode ($C_{ff} = 2.25$), CM, and calibration of wavelength scale using the CM feedback plugin.

LIMITATIONS

At BESSY II there is a need for constant energy velocities. Unfortunately, the gap motion is limited to trapezoidal velocity profiles. Planar undulators would have to vary the velocity according to the non-linear mapping from gap to energy. An excessive example of this artifact is illustrated in Fig. 9. The energy rate dE/dt decreases significantly during the scan due to the non-linear mapping from energy to gap.

In order to obtain constant circular polarization, gap and shift would have to move on a complex path. This is very challenging with the existing motion control of the undulator (Unidrive, Emerson) and has not been implemented yet. Due to this limitation on the ID-controls, helical undulators cannot move the gap and shift synchronously. Energy scans have to be performed with fixed shift. As a result, scans are limited to only small ranges with a tolerable drop of elliptical polarization.

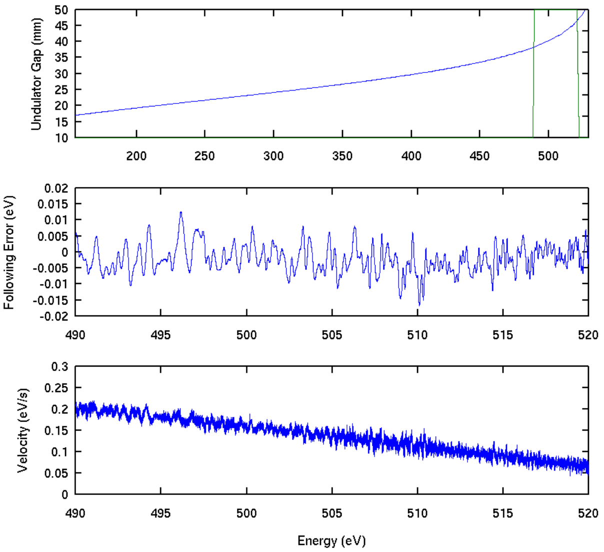

Figure 9: Energy vs. gap and the effect to dE/dt for moves with constant gap velocity.

PROCEEDING DEVELOPMENTS AND FUTURE PLANS

Considering the exceeding costs and manpower to replace the existing motion controllers, we prefer the extensive solution to implement the complex path of gap and shift axes, which are required for elliptical polarization scans with constant energy velocities, on the existing motion control of the undulator (Unidrive, Emerson). This can hopefully be done in near future.

For the new beamlines being build for the Energy Materials In-Situ Laboratory Berlin (EMIL [3]) a new motion control scheme for the monochromators has been chosen. The axes involved in CM are controlled by Geobrick IMS 2 (Delta Tau). As an result, we have a non deterministic Ethernet connection between monochromator IOC and the motion control (Fig. 10). Our investigation showed that jitter introduced by the network would not be acceptable. A possible solution would be to split the encoder signal of the undulator gap axis (EnDat 2.2, Heidenhain) as already proposed in SUMS [9] or to use the incremental quadrature encoder signal output from the Unidrive for gap position feedback with very low jitter at the rate of the servo update clock of the Geobricks (e.g. 5 kHz). Therefore, an accessory of the Geobricks using a fiber MACRO ring connection (Delta Tau) is located in the cabinet of the undulator. Data arrays representing the motion profile are distributed to the motion controls using EPICS waveform records. Tests have shown a smooth output in a cubic spline motion profile on the Geobricks.

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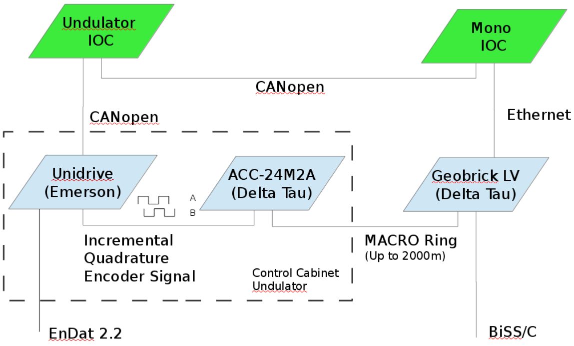

Figure 10: Interface used for CM from monochromator IOC to motion controller is non deterministic Ethernet. Direct encoder feedback from undulator gap to Geobrick.

CONCLUSIONS

An robust control scheme for CM is in operation at 11 undulator beamlines and 6 dipol beamlines. The monochromator successfully follows the undulator motion, intensity modulations can be avoided.

1 kHz real time energy feedback from the monochromator can be provided to the user by EPICS waveform records and time stamps. Diagnostic tools allow the detection of critical following errors, gap update jitter and other disturbances like vibrations and instabilities. Tests are ongoing for the undulator motion control to implement small segments of linear blended moves as approximation for the non-linear move profiles of gap and shift axes. For the new EMIL project the use of a new coordinated multi-axis motion solution has already been tested. A smooth motion control output for on the fly energy scans can be generated by programming splined moves in order to generate the complex path of grating and mirror.

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