A PROOF-OF-PRINCIPLE STUDY OF A SYNCHRONOUS MOVEMENT OF AN UNDULATOR ARRAY USING AN EtherCAT FIELDBUS AT European XFEL

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Abstract

The European XFEL project is a 4th generation X-ray light source. The undulator systems SASE 1, SASE 2 and SASE 3 are used to produce photon beams. Each undulator system consists of an array of undulator cells installed in a row along the electron beam. The motion control of an undulator system is carried out by means of industrial components using an EtherCAT fieldbus. One of its features is motion synchronization for undulator cells which belong to the same system. This paper describes the technical design and software implementation of the undulator system control providing that feature. It presents the results of an on-going proof-of-principle study of synchronous movement of four undulator cells as well as study of movement synchronization between undulator and phase shifter.

SYSTEM OVERVIEW

The European XFEL is using the principle of "self-amplified spontaneous emission" (SASE). The first beam will be delivered at the end of 2015 and will produce spatially coherent ≤80fs short photon pulses with a peak brilliance of 10^{32}-10^{34} photons/s/mm^2/mrad^2/0.1% BW in the energy range from 0.26 to 29.2 keV at electron beam energies of 10.5 GeV, 14 GeV, or 17.5 GeV [1, 2]. The startup configuration includes three undulator systems called SASE1, SASE2, and SASE3. SASE1 and SASE2 are optimized for the hard X-ray range from 4 to 29.2 keV. In order to do so, 35 cells are required. SASE3, which is using the spent beam from SASE1, is serving the soft X-ray range from 0.26 to about 2 keV and therefore needs only 21 cells.

An undulator system is a periodic array of undulator cells. A cell consists of a 5 m long undulator segment and a 1.1 m long intersection (see Fig. 1).

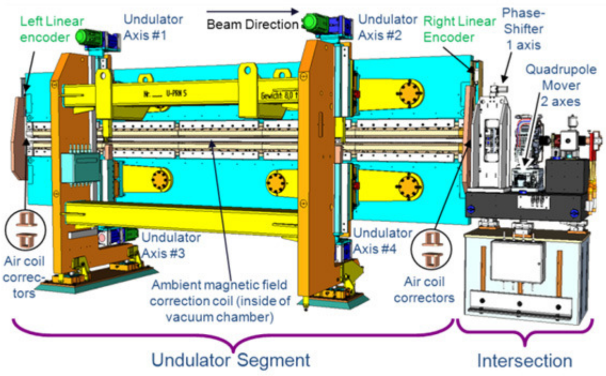

Figure 1: Undulator cell, showing undulator segment and intersection in array.

An undulator is controlled by four servo motors, which are used to set the gap between magnet structures. The intersections contain important elements that are necessary for free electron laser (FEL) operation: quadrupole magnets and movers for electron beam focusing and steering, beam position monitors, vacuum pumps, air coil correctors, which are necessary to compensate residual gap dependent steering errors of undulator segments and finally the phase shifters, which are needed to adjust the phase between electrons and photons field.

At fixed electron energy the photon wavelength of an FEL is only determined by the gap of the undulator system. This provides a possibility of fast tuning of the radiation wavelength and is highly desirable for many spectroscopic techniques requiring fast variation or scanning of the wavelength. From this point of view the synchronous movement of all undulator segments in one system as well as synchronization of the undulator gap change with a corresponding change of the phase shifter gap is of a great importance for user operation.

To control an undulator system consisting of 35 cells with more than 450 controlled elements is a challenging task. Such control system must fulfil the following main requirements:

- Possibility of building a complex control system with a large variety of components
- Using of high-speed fieldbus systems
- Synchronization of multiple axes.
- Cost-economic solutions

During the past decade industrial motion control technology has been developed to a high level of perfection. For the control of undulator systems, industrial components produced by Beckhoff Automation GmbH using the EtherCAT fieldbus and the TwinCAT software were selected [3].

FORMULATION OF THE PROBLEM

One of the important tasks for the control of the undulator system is a synchronized gap change of the undulator cells. The simplest way to achieve this is to issue a common start command for all undulator cells. The assumption is that if the start commands on all undulators will be synchronized, if there is no big difference in mechanical and magnetic properties of the undulators and all dynamic control parameters of undulators are the same, although the undulators are running freely, the gap change delay could stay in a reasonable small range of several milliseconds.

A more advanced technique uses a virtual master axis. This is already implemented in the Local Control Node

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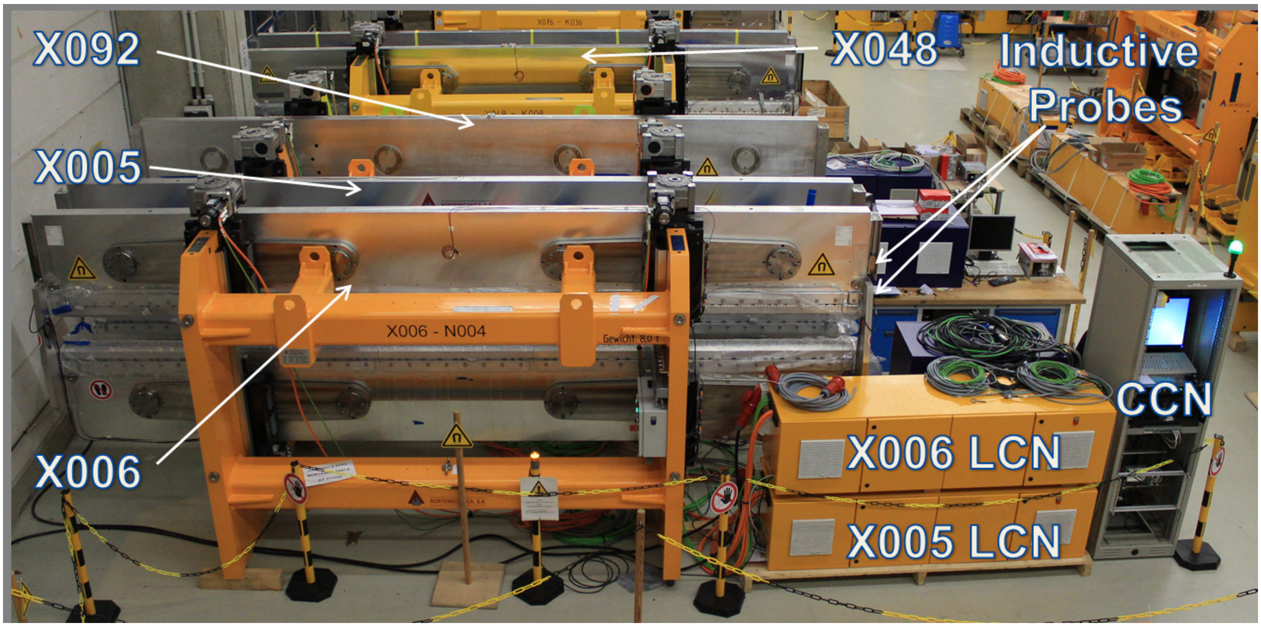


Figure 2: Test setup consisting of four undulator cells.

(LCN) where the axis that controls the phase shifter gap is cupped to the virtual undulator gap axis. Inside LCN, all axes and parameters depending on the magnetic field strength, i.e. on the undulator gap, are coupled to this one virtual axis [4]. Four undulator axes, one phase shifter axis, and four air coil correctors are the components that can be controlled locally and be coupled to the virtual axis. Two components of one undulator segment, undulator and phase shifter, belong to the numerical control (NC) and must run synchronously.

The purpose of this investigation is to prove the satisfactory synchronization level for an array of undulator cells as well as find the reachable level of synchronization between undulator and phase shifter. These results will help to plan the further software development strategy, namely the need to implement a virtual axis in the global control system and couple it with local virtual axes.

STUDY OF MOVEMENT SYNCHRONIZATION BETWEEN FOUR UNDULATORS

For these measurements a reduced model of one undulator system consisting of four undulator cells was assembled (see Fig. 2). The undulators X005, X006, X048 and X092 have been daisy chained over the EtherCAT and Ethernet network and connected to the Central Control Node (CCN). The EtherCAT network is used for real-time device and motion control, while the Ethernet is used for monitoring and remote access to the individual undulator PCs [4].

The NC dynamic parameters for all axes of undulators are the same: Acceleration / Deceleration is 12.84 mm/s^2; Acceleration / Deceleration Time is 0.5 s; Jerk is 77.04 mm/s^3, Kv factor for upper axes is 15 mm/s/mm and for lower ones is 20 mm/s/mm. Maximum gap change velocity is 8.56 mm/s.

The CCN is used to generate the start command and distribute it via EtherCAT fieldbus to all undulators at the same time, so that they change their gap simultaneously. After the start command has been received by the LCN, the PLC program computes new position set points of the axes and passes them to the NC. The axes then start to move to the new position.

In order to measure the delay of the gap changes between undulators the movements of undulators have been traced using two independent methods. The first was using the Beckhoff TwinCAT Scope View software. The Scope View was running on the CCN and collects the linear encoder position values from the TwinCAT System Manager of each LCN. These linear encoders are physically located on both sides of undulator and are measuring directly the gap size [3]. The second method was used as a cross check.

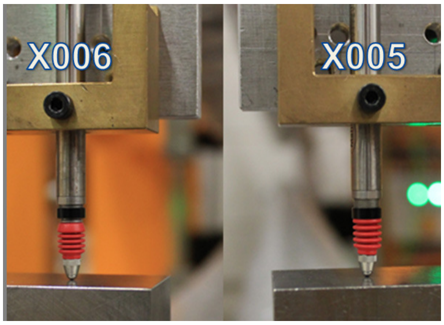


Figure 3: Two inductive probes installed on X006 and X005 undulators.

Two Millimar inductive probes P2004 have been fixed near the linear encoders of two undulators X005 and X006. They measured directly the gap size (see Fig. 3).

The probes were connected to the Millimar C1216 compact amplifier in the differential mode, so the output of the amplifier ΔG is equal to the difference between first gap G_1 and second gap G_2. The resolution of the measurement system is 0.01 µm. The accuracy of this measurement is limited by typical noise level. In our setup the accuracy was better than ±0.02 µm. That means, that, with a 8.56 mm/s gap change speed, the minimal time delay that could be detected is $4\cdot10^{-5}$ mm ÷ 8.56 mm/s = $4.7\cdot10^{-6}$ s.

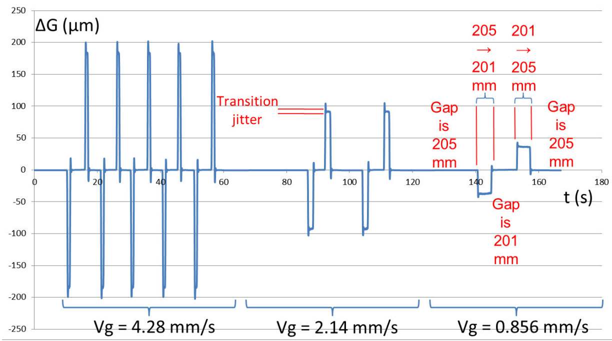
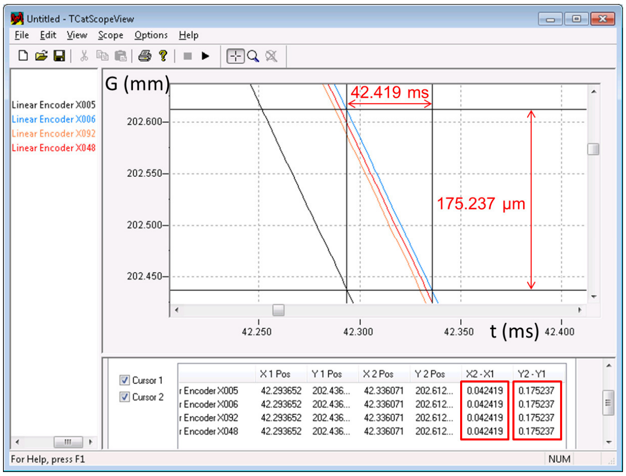


Figure 4: Difference between X005gap (G_1) and X 006 gap (G_2), measured by Millimar C1216 for three different velocities: 4.28 mm/s, 2.14 mm/s and 0.856 mm/s.

The system gap has been changed between 205 mm and 201 mm using 4.28 mm/s, 2.14 mm/s and 0.856 mm/s gap change velocities. The results presented in Figure 4 show that after issuing the start command, the value from inductive probe installed on X005 starts to change faster than value from inductive probe installed on X006. During the motion, the difference between both probes stays almost constant. As soon as the set value for both undulators is achieved, the difference gets back to zero.



☑ Cursor 1
☑ Cursor 2

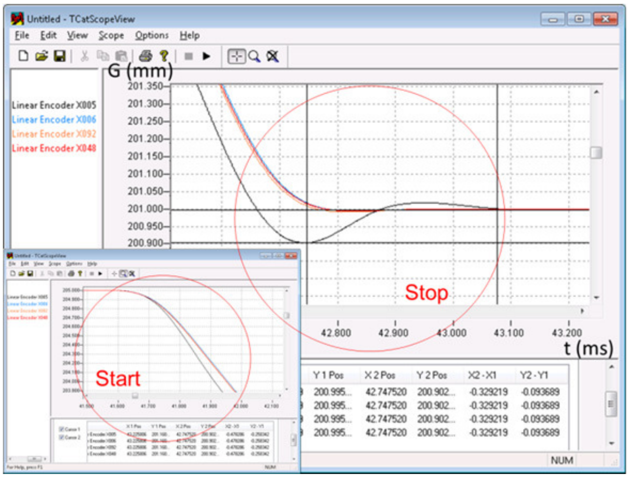
	X 1 Pos	Y 1 Pos	X 2 Pos	Y 2 Pos	X2 - X1	Y2 - Y1
r Encoder X005	42.293652	202.436...	42.336071	202.612...	0.042419	0.175237
r Encoder X006	42.293652	202.436...	42.336071	202.612...	0.042419	0.175237
r Encoder X092	42.293652	202.436...	42.336071	202.612...	0.042419	0.175237
r Encoder X048	42.293652	202.436...	42.336071	202.612...	0.042419	0.175237

Figure 5: Difference between X005gap (G_1) and X006 gap (G_2) at v_g = 4.28 mm/s, obtained by TwinCAT Scope View.

The measurement results for all three speeds show that the average time delay between X005 and X006 is 42.78±1.49 ms. To calculate this value the following formula is used: $\Delta t = (\Delta x/2 - \sigma/2) / v_g$, where Δx is the difference between maximal and minimal lag distance by closing and opening the gap, σ is the average value of jitter during the transition period (see Fig. 4) and v_g is the gap change velocity.

Simultaneously with the inductive probe measurements the TwinCAT Scope View traced the value of linear encoders for all four undulators. Comparison of two measurement methods shows very good agreement (see Fig. 5).

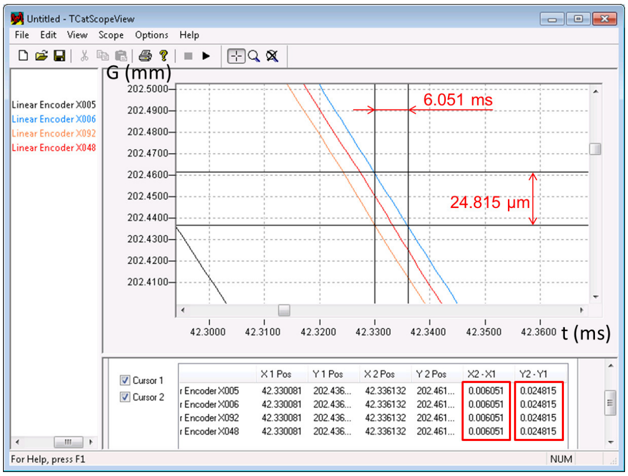
Analysis of the curves shows that dynamic control parameters of undulator X005 are not optimized. This is clearly observed at the start and at the end of the movement (see Fig. 6).



Y 1 Pos	X 2 Pos	Y 2 Pos	X2 - X1	Y2 - Y1
200.995...	42.747520	200.902...	-0.329219	-0.093689
200.995...	42.747520	200.902...	-0.329219	-0.093689
200.995...	42.747520	200.902...	-0.329219	-0.093689
200.995...	42.747520	200.902...	-0.329219	-0.093689

Figure 6: Dynamic behaviour of X005 undulator at the start and at the end of the movement in comparison with other three.

The synchronization of the gap change between the three other undulators is better than 10 ms (see Fig. 7). It provides a basis for the statement that by individual adjustments of undulator control parameters, the synchronization level of the whole system could be improved to approximately 10ms.



☑ Cursor 1
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	X 1 Pos	Y 1 Pos	X 2 Pos	Y 2 Pos	X2 - X1	Y2 - Y1
r Encoder X005	42.330081	202.436...	42.336132	202.461...	0.006051	0.024815
r Encoder X006	42.330081	202.436...	42.336132	202.461...	0.006051	0.024815
r Encoder X092	42.330081	202.436...	42.336132	202.461...	0.006051	0.024815
r Encoder X048	42.330081	202.436...	42.336132	202.461...	0.006051	0.024815

Figure 7: Difference between X006 X048 and X092 gap change at v_g = 4.28 mm/s.

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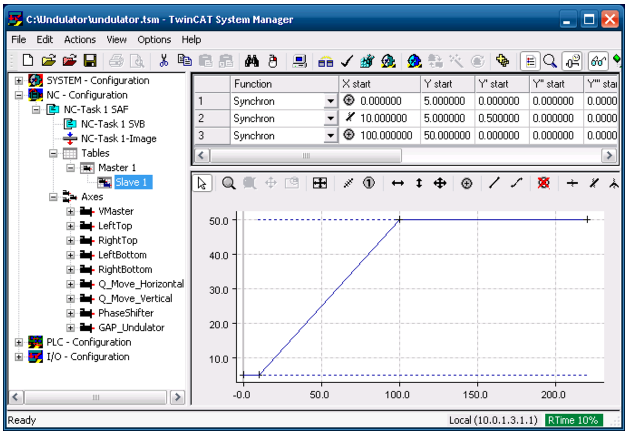
STUDY OF MOVEMENT SYNCHRONIZATION BETWEEN UNDULATOR AND PHASE SHIFTER

The other element of NC control of undulator system, which must follow the value of undulator gap, is the phase shifter. The phase shifter control is implemented inside the LCN in TwinCAT System Manager as a slave axis of the undulator gap. For these measurements the 1:1 camming table in the region from 10 mm to 100 mm was used (See Fig. 8). The phase shifter gap is controlled by a five-phase stepper motor, with right- and left-handed threads. The encoder is located on the upper magnet holder. Therefore, the actual gap is equal to the double of the value of the encoder



	Function	X start	Y start	Y' start	Y'' start	Y''' star
1	Synchron	0.000000	5.000000	0.000000	0.000000	0.0000
2	Synchron	10.000000	5.000000	0.500000	0.000000	0.0000
3	Synchron	100.000000	50.000000	0.000000	0.000000	0.0000

Figure 8: Camming table for phase shifter.

The movement of undulator and phase shifter has been traced using the same two independent methods: Millimar C1216 with inductive probes and Beckhoff TwinCAT Scope View. One Millimar inductive probe has been used to measure the undulator gap and the other one was used to measure the phase shifter gap. In the Scope View, the position of the undulator and phase shifter actual gaps were traced. The undulator gap was changed from 75 to 75.5 mm and back with 4.28 mm/s, 2.14 mm/s and 0.856 mm/s gap change velocities.

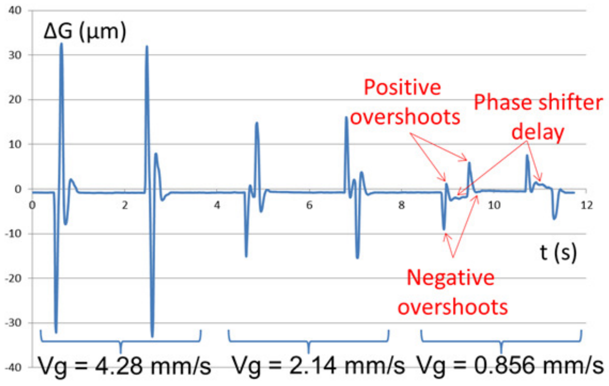


Figure 9: Difference between undulator and phase shifter gaps measured by Millimar C1216.

Figure 9 shows the results of measurements done using inductive probes, which are in a very good agreement with Scope View measurements. The differential measurements show that the phase shifter starts to move with some delay. Negative overshoot is ~ 7μm at 0.856 mm/s speed; later the control system tries to compensate this following error and the phase shifter overshoots the undulator gap by ~1μm. Afterwards, there is a small following error, which corresponds to ~ 1ms delay between undulator and phase shifter gaps. When the undulator stopped, the phase shifter again has ~7μm overshoot. The overall deviation between undulator and phase shifter gaps is in the range of ~±7ms. Anyhow it is important to mention that the requirement of the phase shifter gap control accuracy is ± 10 μm [3]. Therefore these overshoots at 0.856 mm/s gap change velocity are acceptable.

CONCLUSIONS

The results obtained by TwinCAT Scope View are in a very good agreement with independent measurements obtained by inductive probes.

The movement synchronization better than 10ms for undulators running freely can be achieved. Two prerequisites for this are individual adjustment of dynamic parameters of the undulator, which can neutralize dissimilarities of mechanical or magnetic properties, and synchronization of the start command to better than the local PLC cycle time. Better synchronization may be achieved by the implementation of one virtual axis in global control system and coupling it with all undulator cells in one system.

Coupling of phase shifter axis to undulator virtual axis results in a synchronization better than 15ms. Taking into account that both devices have completely different mechanical construction and control elements, this is an encouraging result which allows the assumption for further improvement.

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