Joint Undulator Development for PETRA III and the European XFEL Project

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Synergy between PETRA III and XFEL R&D activities

There are two large future projects at DESY, which depend heavily on the use of undulator technology and suggest common activities:

- PETRA III [1] requires 13 insertion devices by begin of 2008 of 2 and 5m length.

- The European XFEL project [2,3], which is presently in an extended R&D phase, requires 107 undulator segments, with a total length of 652m by 2012.

For both projects there are stringent requirements on the undulators with respect to performance and specifications. Aside from minor differences in the specifications of magnetic field properties they have a lot in common. The time schedules outlined above suggest that the construction effort for PETRA III and XFEL prototyping can be combined. Therefore, in order to make a synergetic approach a coordinated R&D activity has been started. Its main objective is a common development, which complies with the specifications for both projects resulting in time and cost savings by a reduction of design effort and more effective use of available resources at DESY. It is concentrated on:

1. Design of a standardized gap separation mechanical system, which is flexible in length and meets requirements for both projects.

2. R&D on requirements of motion control and overall control of undulator segments and distributed undulator systems.

3. Magnetic and hardware design of magnet structures for planar undulators but also for special devices, such as the helical APPLE II structures for PETRA III and SASE3 for the XFEL.

During the past 1½ years these points have been addressed in a R&D effort. A concept complying with the specifications of both projects has been developed. It concentrates on common properties for both projects such as precision mechanics and motion control. It is flexible with respect to total device length and can easily accommodate magnetic structures with different parameters. The majority of devices for PETRA III will be 2m long, while the XFEL will need 5m long segments only. In addition there are specific requirements for either PETRA III or XFEL. Examples are the quasi-periodic undulator for PETRA III and special components to be used in the intersections between XFEL undulator segments. This contributions gives an overview.

Undulator Segments
Tolerances

Vertical Alignment	± 100	μm
Gap	± 1	μm
Flatness	± 1	μm
Taper	± 1	mm

Table 1: Undulator tolerances

Mechanical tolerances were chosen on the basis of worst case assumptions. For stability and accuracy they are dominated by XFEL requirements for the line width to be smaller than the Pierce parameter ρ:

$$\frac{\Delta\lambda}{\lambda} \leq \rho \tag{1}$$

For the 1Å XFEL ρ amounts to 3×10^{-4} at1Å. In addition, a taper of ±1mm at both ends is possible, which is most important for PETRA III. Table 1 gives an overview of mechanical tolerances. They have a large impact on the design of the drive mechanics and the control system.

Mechanical Support Unit

A standard mechanical support unit has been designed. It uses standard off the shelf components such as guiding systems, spindles etc. which simplifies the design and minimizes machining need. Its length can be varied between 2 and 5m. Fig.1 gives an overview. There are several points, which deserve being mentioned:

1. The girders have a substantial rectangular cross section of 500 by 100mm. This cross section minimizes shear deformation, which in the μm range dominates over elastic deformation.
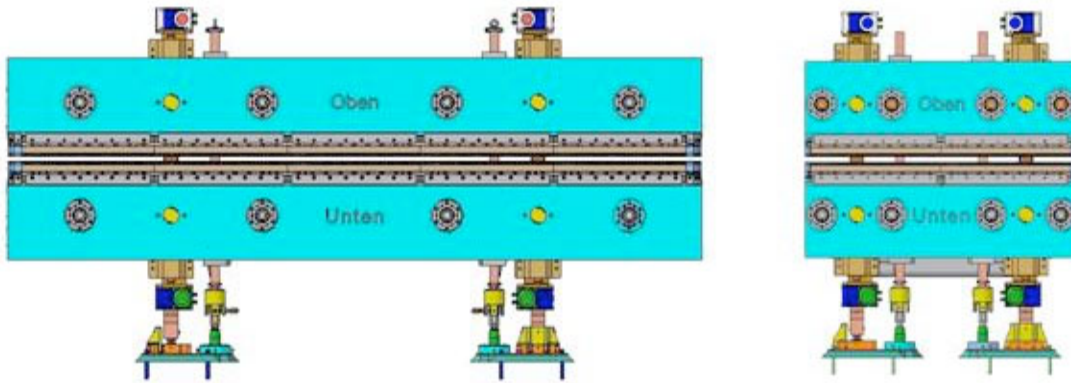

Fig. 1: Comparison of the 5m and 2m long undulator segments. They use standardized, identical components wherever it is possible.
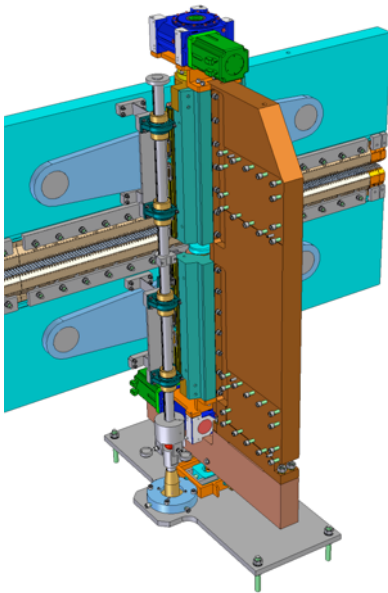

Fig. 2: Rear view showing one of the girder support columns, the auxiliary intermediate girder for the four point support and the guiding system for parallel girder alignment.

2. The materials for girders and support structures need to be identical in order to avoid any bimetallic bending as a function of temperature. Stainless steel will be taken for magnetic and stability reasons.

3. The girders are supported on four equidistant points. This reduces the deformation under magnetic load dramatically. Two auxiliary, intermediate girders are needed, which are shown in the rear view in Fig. 2.

4. The girders are connected to massive guideways and leadscrews integrated in the support columns using spherical supports. In this way the magnetic forces are transmitted and a rotational degree of freedom is provided. The exact parallel alignment of top and bottom girder is achieved through a separate individual guiding system also shown in Fig. 2. This system also integrates the encoders needed for the feedback of the motors. There are no forces on this guiding system. It provides the precision alignment only.

5. There are four motors, one for each spindle. They are electronically synchronized.

This design allows for all the flexibility, which is needed to cope with PETRA III as well as XFEL requirements.

Magnetic structures

The mechanical design of the magnetic structure is strongly influenced by the experience made with TTF1 [4]. It will be subdivided into 90cm long support segments for magnets and poles, which are clamped onto the girders. Stainless steel, the same as for the girders, will be used for the support structures in order to reduce bimetallic bending. The method of field fine tuning by pole height adjustment will be further refined and used to fine tune the field distribution [5,6]. It requires each pole to be height adjustable by about ±100μm.

Helical Undulator

The study of magnetic and biological materials which exhibit magnetic circular dichroism has created a demand for circularly polarized x-ray whose helicity may be switched between the right and left hand senses. Intense elliptically/circularly as well as linear polarized light under various angle can be generated using planar helical undulators. They are needed for the PETRA III [1] as
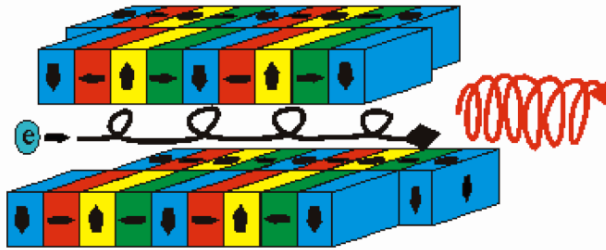

Figure 3: Sketch of an APPLE-II-type magnet design generating light with variable polarization via the longitudinal shift of magnet rows

well as the XFEL-project [2,3,7] and will be used at wavelengths > 4Å where no X-ray optical alternatives such as phase plates exist. We propose an APPLE-II-type (Advanced Planar Polarized Light Emitter, Fig. 3) structure [8,9] because it produces a higher field in the helical
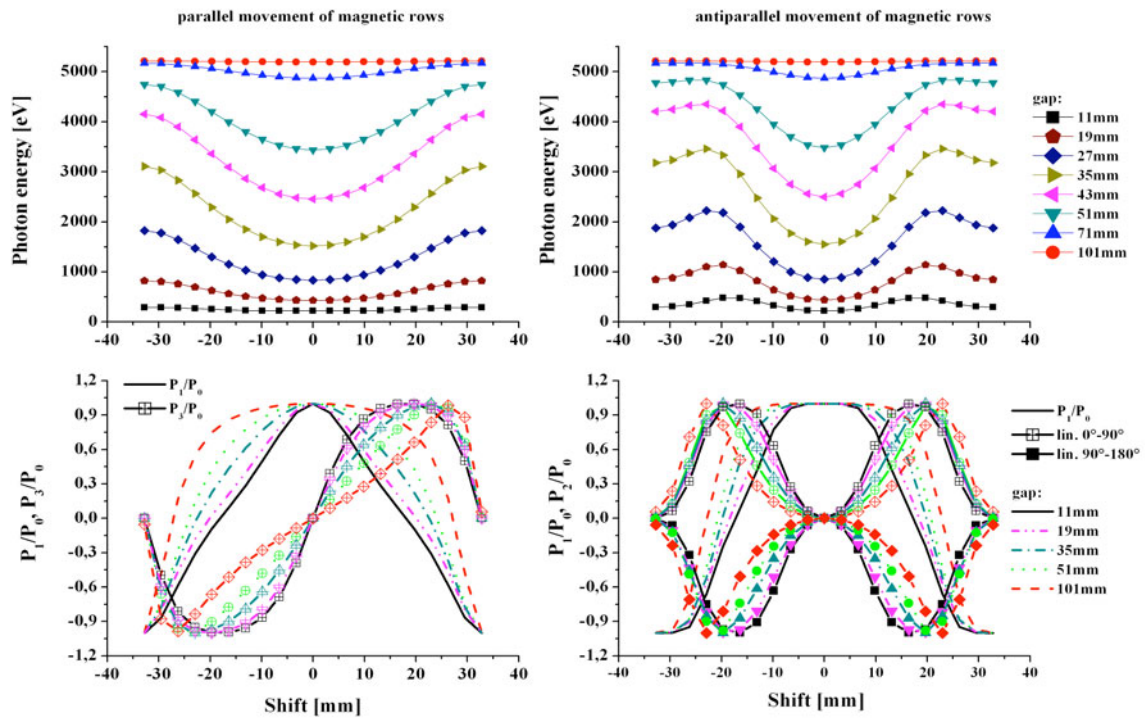

Figure 4: Shift and gap dependence of photon energy and various polarization states for parallel and anti-parallel movement of the magnetic rows

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mode. It is a planar magnetic structure and provides full control of polarization properties. Via the longitudinal movement of four separated magnet rows different polarization modes can be achieved. Parallel movement of two diagonally opposite rows leads to vertical linear and right/left circularly/ elliptically polarization. Anti-parallel movement of two diagonally opposite rows tilts the linear polarization vector from the horizontal to the vertical plane: 1. mode: 0°-90° and 2. mode: 90°-180°. For zero longitudinal shift, the APPLE-II device provides horizontal linear polarization and resembles a usual planar pure permanent undulator.

The period length of the device depends on the low photon energy limit for circularly polarized X-rays, for PETRA III it should be 250 eV [1]. Under this condition and assuming a minimum gap of 11mm the period length will be λ_u=65.6mm. Within a total length of 5m 74 periods can be realized, including the end structures and magic fingers. The magnet material will be NdFeB with a remanent field of 1.2 T. Using these parameters the magnetic field, K-values, energies etc. can be calculated with the RADIA code [10]. The results for a gap of 11mm are summarized in table 2.

Operation mode	Shift[mm]	B_{eff}[T]	K_{eff}[T]	E_1[eV]	Table 2:
Hor. Linear	00.00	1.10	6.74	219.70	Parameters of the soft X-ray undu-lator (APPLE_II-type) for lowest gap (11mm)
vert. Linear	32.80	0.96	5.85	287.89	
Circular	18.07	1.04	6.34	245.82	
45/135 ° linear	17.27	0.73	4.47	474.74	

Figure 4 shows the complex relationship between gap and shift variation to achieve the desired photon energy and polarization. Normally one has to adjust both parameters, gap and shift. The degree of polarization of light is characterized by the Stokes vectors. Circular polarization occurs, if the Stokes vector P_1/P_0=0 and P_3/P_0=±1. Horizontal linear polarized light has a polarization degree of P_1/P_0=1 and P_3/P_0=0 and vertical polarized light of P_1/P_0=-1 and P_3/P_0=0. The antiparallel movement of upper right and lower left or upper left and lower right row leads to linear polarized light under various angles characterized by P_2/P_0 and P_1/P_0. For 45°/135° linear polarized light P_2/P_0 is 1/-1 und P_1/P_0=0. Note that for circular and linear 45°/135° polarization the longitudinal shift of the rows varies with the gap. In PETRA III at 6 GeV the advantage of this device is the large tunability range of the 1st harmonic from 250eV to about 4keV (50 to 3.1Å). In the circular mode it provides 100% circular polarization over the whole energy range. Up to about 4keV the flux in the central cone in all polarization modes is ≥4*10^14 photons/s/0.1%BW. In the entire energy range up to 2.5keV, which can be covered by plane grating monochromators the flux will be nearly constant (Fig. 5).
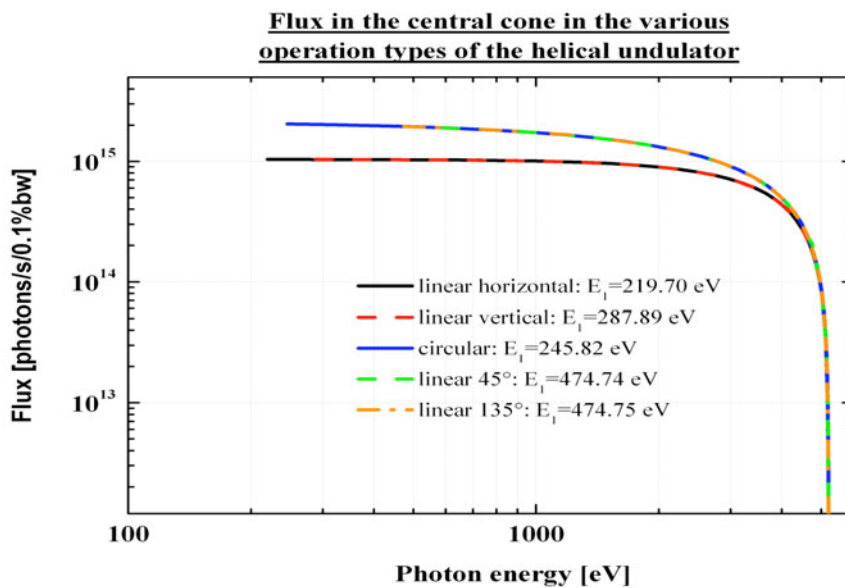
One critical aspect of this device are magnetic forces. Additional to usual planar devices the anti-parallel movement of the rows induces forces in transversal and longitudinal direction. Furthermore a load change occurs during a row shift. These aspects need to be considered in the mechanical design.

Figure 5: Flux in the central cone as a function of the photon energy

ID length	2 m	Deflection parameter K_{max}	2.7
Period length	31.4 mm	Deflection parameter $K_{max,reduced}$	2.2
Peak field	0.91 T	1st periodic harmonic E_1	2.4 keV
Reduced peak field	0.75 T	1st quasi-periodic harmonic E_1	2.6 keV

Table 3: Parameters of the PETRA III spectroscopy undulator with and without quasi-periodic modifications

Quasi-periodic Undulator For PETRA III

The photon spectrum of a conventional periodic planar undulator is dominated by the sharp peaks of equidistant harmonics. For experiments requiring monochromatic radiation, higher harmonics can be reduced either by total reflection at a mirror surface below a critical angle or by use of a detuned crystal monochromator taking advantage of the narrower Darwin curves at higher energies.

For even higher suppression of harmonics, an alternative approach is an insertion device emitting a spectrum with higher harmonics shifted to non-integer multiples of the energy of the first harmonic. With such devices the use of a crystal monochromator is advantageous because the shifted higher harmonics are not diffracted and thus eliminated. A possible approach is the design of a quasi-periodic undulator (QPU) as proposed by Sasaki et.al. [11,12] with higher harmonics shifted to irrational multiples. The electron path length (and thus the phase relation between electron and photon beam) in this type of undulator is varied by reducing the magnetic field for selected undulator half periods following a quasi-periodic pattern.

It has already been demonstrated at other facilities [13,14], that conventional Insertion Devices such as the standard PETRA III spectroscopy undulator can be converted into a QPU with only moderate modifications. By altering selected magnets or poles half period long sections are obtained with a reduced magnetic field (see parameters in Table 3).
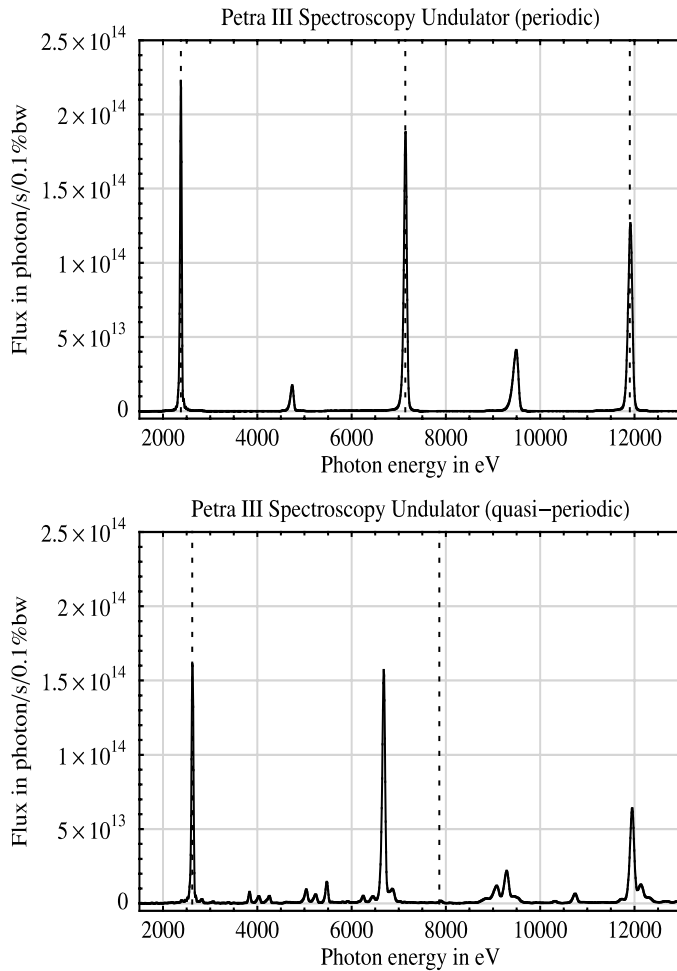
The spectra of the standard periodic and the quasi-periodic modified PETRA III spectroscopy undulator are shown in Fig. 6. The first harmonic of the QPU is shifted to a slightly higher photon energy of 2.6 keV compared to the periodic one with 2.4 keV. Clearly visibly is that the higher harmonics in the quasi-periodic spectrum are shifted away from integer multiples of the first harmonic as indicated by dotted lines. In this example the first harmonic intensity of the QPU is reduced only by ~28%, and the intensity at the regular third harmonic position (~7.8 keV) is reduced by ~99% with respect to the third harmonic of the periodic device. Further work will cover the investigation of additional undulator concepts with higher harmonics shifted to non-integer multiples of the energy of the first

Fig. 6: Flux spectrum through a 1x1mm2 aperture in a distance of 40m of a PETRA III standard undulator without (upper) and with quasiperiodic modifications (lower).
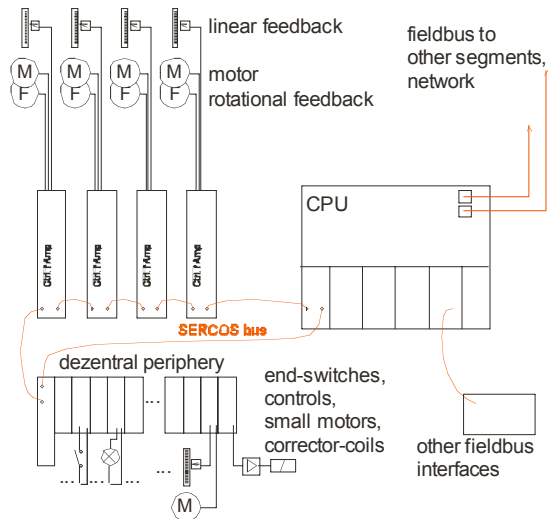
Fig. 7: Schematic of the prototype motion control system. There are four servo-motors and a CPU, for the control of an undulator segment.
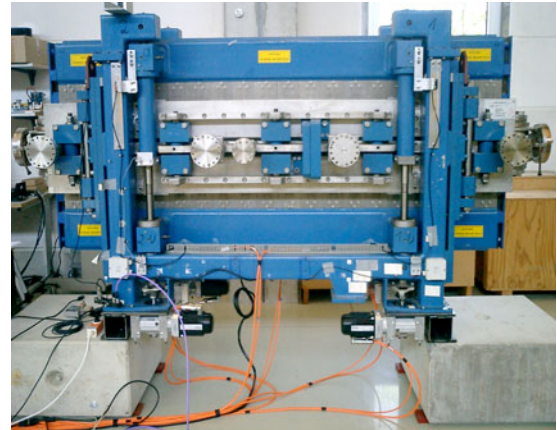Synchronization with other segments can be done via a fast fieldbus network.

Fig. 8: The reconstructed old HARWI Wiggler now equipped with 4 Servo-motors and linear encoders.

harmonic. Parameter studies will be performed to investigate the range of harmonic shifts and peak ratios that can be achieved by the different concepts. Following user requirements a QPU undulator will be designed by modifying the standard periodic PETRA III spectroscopy undulator.

Control System

Precision control of gap, synchronization of correctors and additional components such as phase shifters in XFEL systems or fast synchronization of correctors or external components such as monochromators with gap movement is of key importance for both the PETRA III project and the XFEL as well. The performance of a device critically depends on a good solution for the control system. Some key requirements are:

- Control of gap motion better than $1\mu m$

- Synchronization of the four motors (see above) with appropriate precision

- Reliable operation and system stability to highest standards

- Synchronization of additional components (i.e. corrector coils, phase shifters) with the gap

- Modularity and extendability, i.e. stand alone operation for a single segment as well as the capability to integrate them to systems consisting of 40 individual segments

- Expected life-time of > 15years and a correspondingly long term availability and reliability of components
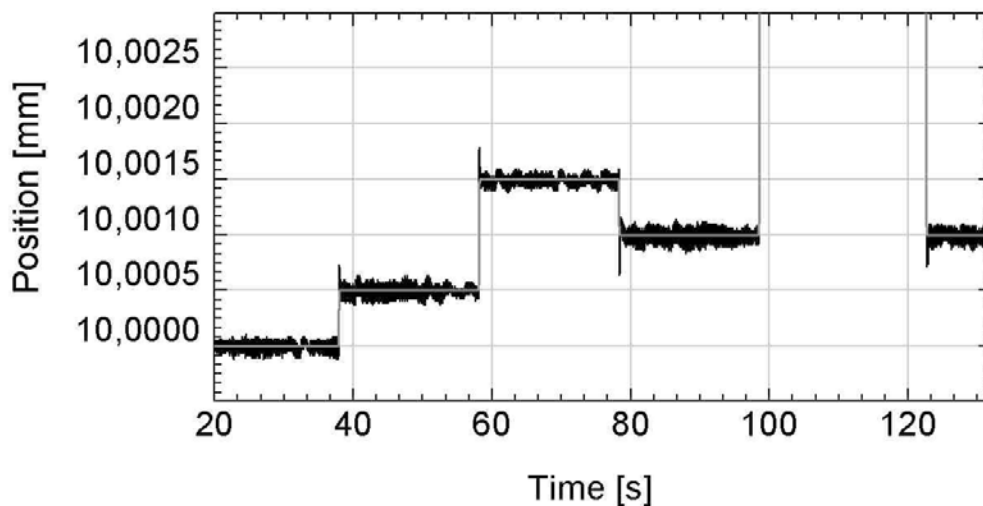
- Use of industrial standards and components

Figure9: Commanded (light gray) and measured (black) position for one axis. The vertical scale is 0.5µm/grid-line. The measured signal shows the typical jitter of an analog encoder signal. At t=98s the gap was closed and opened again to the old position (t>122s), demonstrating the achievable accuracy.

Over the past years there has been a tremendous development of control equipment and components for industrial applications such as automation, robotics, numerical machining, process- and motion control, printing machines, handling systems etc. Components are available as commercial off the shelf items and prices become more and more moderate. For these systems field-buses such as SERCOS, Profibus, CAN-bus, Ethernet or EtherCAT are used. Some of them are vendor independent. There are very fast solutions for triggering and synchronization of an arbitrary number of components in a system. To some extent even hardware compatibility between different manufacturers exists. Motion control and accuracy as well as safety, reliability and long-term requirements are fulfilled by these components. A market survey showed that such components are excellent for the motion control of Insertion Devices.

To gain first experience an old decommissioned wiggler used at HASYLAB for many years for coronary angiography (old HARWI) has been converted to a 'Motion Control Test Undulator' (MTU). Before conversion there was a central 3-phase motor and five gear boxes and drive shafts connected to the four spindles needed for gap change. Now there are four servo-motors with reduction gears directly flanged to the spindles and synchronized electronically via a central control unit produced by Beckhoff Industrie Elektronik, Germany. Figure 7 shows the schematic of the control system, which meanwhile serves as a template for the XFEL and PETRA III prototypes.

During extended tests no failures of the control-system where observed. In addition no problems especially with the synchronization occurred even during the delicate commissioning phase. Mechanical play and backlash could be observed in the measurements. However it was demonstrated that due to the direct measurement of the gap and the direct feedback loop it could be compensated by the control system. Figure 8 shows the devices after conversion to the MTU. In Figure 9 a sample measurement illustrating the accuracy is given. The commanded and measured actual positions of one axis (half gap values) are shown as a function of time. The origin is chosen at the maximum gap position. In the first 80sec the commanded position is changed three times in steps of 0.5 and 1µm. The picture shows clearly the ability of the system to reach a precision of about 0.1µm, while it was found that a single axis can have a mechanical play of 10µm and more.

Between t=98s and t=122s, the commanded position was changed by an amount way beyond the plotting range and then set back to the old value. Here the maximum speed of 30mm/s was used. It is seen that the target position was reached again with 0.1µm accuracy. The measured position

shows a jitter of some 0.01μm which is typical for the used linear encoder. It is due to the line width of 20μm and is still visible while the servo systems are not in the position-control mode.

Outlook

Presently (November 2005) a Call for Tender is performed for building first prototypes following the design ideas described in this contribution. Parameters for a PETRA III standard undulator with a period length of 29mm are assumed. The main objective is vendor qualification. The deliverables concentrate on mechanical aspects, manufacturing and assembly. In parallel, while the prototypes are under construction, at DESY work will be done on:

1. Development of robust and fast magnetic measurement techniques based on VUV-FEL experience for tuning these devices.

2. Set up of a magnetic lab dedicated to be used in an industrial environment as a prototype to be used for XFEL production.

3. Development and test of fast magnetic measurement and tuning techniques, which are to be used for an industrial serial production.

This development is heavily based on experience made on the VUV-FEL. In a first step the results are applied to the prototypes once they get delivered. The ultimate objective is to have certified, well proven manufacturing procedures available, which fulfill XFEL and PETRA III requirements and which can be used by qualified industrial partners. This is a prerequisite for a later industrial large scale production, which is required for the XFEL. A second generation of prototype to be launched in about two years will include the whole manufacturing done in industry.

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