UNDULATOR SYSTEMS AND PHOTON DIAGNOSTICS FOR THE EUROPEAN XFEL PROJECT

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Abstract

For the European XFEL project very long undulator systems are required. Due to the nature of the SASE process there are stringent requirements and tolerances on these systems. An extensive R&D phase toward solutions has been started. In this contribution an overview over this R&D work is given.

INTRODUCTION

Over the past years the design of the XFEL Laboratory has undergone several major changes. Initially it was linked to the TESLA Linear collider using a fraction of the 500 GeV e^- Linac in a time sharing fashion. This was the basis for the TDR, which is described in [1]. In 2002 the XFEL was proposed with a separate Linac [2], which is now the basis for the European XFEL project. Presently the project is in a defining stage. Despite of all these changes the intended scientific use and the wavelength range remain unchanged. The principle of self amplified spontaneous radiation (SASE) will be used for the European XFEL. It will predominantly operate in the hard X-ray regime around 1 Å, but also use soft X-rays at wavelengths >4 Å

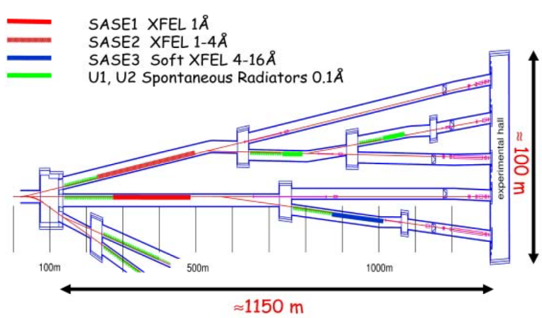

Fig. 1 Baseline layout of the beam distribution, the undulator systems, photon beam lines and

Undulator systems for SASE X-FELs differ quite a bit from those for Synchrotron Radiation sources or cavity FELs. They are much longer and have to meet different requirements and specifications. Design ideas and requirements for the undulator systems based on parameters found in [1] were already published [3]. This contribution focuses on recent upgrades and new design ideas not published before.

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UNDULATOR SYSTEM

Systems Overview

The whole XFEL will be built in underground tunnels. The total length of the accelerator, the FEL and the photon beam lines will be about 3.3km. Fig.1 shows a schematic overview of the beam distribution and the arrangement of the undulator systems of the Phase I of the European XFEL. In a later upgrade the number of beamlines can be doubled. The outgoing beamline in the bottom of Fig.1 belongs to beam distribution of Phase II, which will be built later. Table 1 shows parameters of the proposed undulator systems. Undulator and photon beam lines extend over a total length up to approximately 1150m. The beam is split in two beam lines, which serve SASE1 and SASE2. Both can be operated at 1Å. SASE1 is designed to operate at fixed wavelength while SASE 2 can be tuned from 1 to 4 Å. It therefore needs to be longer by about 25%.

After passing through the undulator the beam after SASE1 is still of sufficient quality to drive a second FEL called SASE3 which operates in the soft X-ray regime at wavelength > 4Å. An helical undulator of the APPLE 2 type is planned [4, 5] since in this wavelength range there is no alternative to generating circularly polarized X-rays.

The spend beam of SASE2 is used in two spontaneous radiators, which can generate hard x-rays at wavelength as short as 0.1 Å. In total there are five photon beamlines serving the experiments in the experimental hall with beam.

The undulator systems will be segmented in 5m long undulator segments and 1.1m long intersections (see also ref [3].)

In the tunnels there is free space left as can be seen in Fig.1. There are numerous upgrade options, which can be used to generate radiation for more beam lines ultrashort pulses, or ultra high resolution [6], which need additional space.

Undulator Segments

Tolerances

The linewidth of FEL radiation is of the order of the Pierce parameter ρ, which for the XFEL amounts to $3x10^{-4}$ at 1Å. For the undulator system this means that the first harmonic has to be tuned with an accuracy given by:

$$\frac{\Delta\lambda}{\lambda} \leq \rho \qquad (1)$$

The nature of the FEL process is such that in order to have an effect on the radiated power an error has to act over a power gain length, which for the XFEL is in the order of 10m. A conservative requirement would be to require eq.(1) for a 5m long undulator segment.

Table 1: Parameters for the proposed undulator systems

	λ_R [Å]	λ_0 [mm]	Gap [#] [mm]	B_0 [T]	K	β_0 [m]	L_{Sat} [+] [m]	N_{Tot} [++]	L_{Tot} [+++] [m]
SASE 1 *	1	35.6	10	1.0	3.3	32	133	33	201.3
SASE 2 *	1-4	48	19-10	0.63-1.37	2.8-6.1	46-15	174 -72	42	256.2
SASE 3 **	4-16	65	20-10	0.85-1.76	5.2-11	15	88-55	22	134.
U1, U2 ***	0.09-0.25	20.9	22-6	0.1-0.98	0.2-1.9	15	50	10	61.0
					Total		495	107	652.5

* Planar Hybrid Undulator
** Apple II Helical Undulator
*** Spontaneous Emitters operated on 1. Harmonic
\# Magnetic gap of SASE FELs is 10mm, that of Spontaneous emitters is 6mm
\+ Net saturation length with no contingency, spontaneous emitters are limited to 50m magnetic length
++ Number of 5m undulator segments plus 20% contingency
+++ Total system length includes 1.1m long intersection after each undulator segment

There are different error sources having an effect on the harmonic: Temperature via the temperature coefficient of the magnet material, vertical alignment via the hyperbolic cosine like field distribution, Gap and flatness errors via the exponential field dependence. If all error sources are equally weighted and using:

$$\Delta\lambda = \left|\frac{\partial\lambda}{\partial B}\right|\sqrt{\Delta B_{Temp}^2 + \Delta B_{Align}^2 + \Delta B_{Gap}^2 + \Delta B_{Flat}^2} \qquad (2)$$

the values reproduced in Table 2 result. These values are the basis for the designs shown in this contribution.

Table 2: Tolerances for the Undulator systems and 5m segments

Temperature	ΔT	± 0.08	K
Alignment	ΔY	± 100	µm
Gap	Δg	± 1	µm
Flatness	Δg	± 1	µm

Mechanic Support

Fig. 2 shows the design of the undulator segments for the XFEL. It is planned to have a standard drive system. Its design should meets the requirements for all XFEL undulator systems. There are several points, which deserve being mentioned:

1. The girders have a substantial rectangular cross section of 500 by 100mm. The reason for the rectangular cross section is to minimize shear deformation, which, in the µm range dominates over elastic deformation.
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 shown in Fig.3.
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 3. It also integrates the encoders needed for the feedback for the motors. There are no forces on this guiding system. It provides the precision alignment.
5. There are four motors, one for each spindle. They are electronically synchronized.

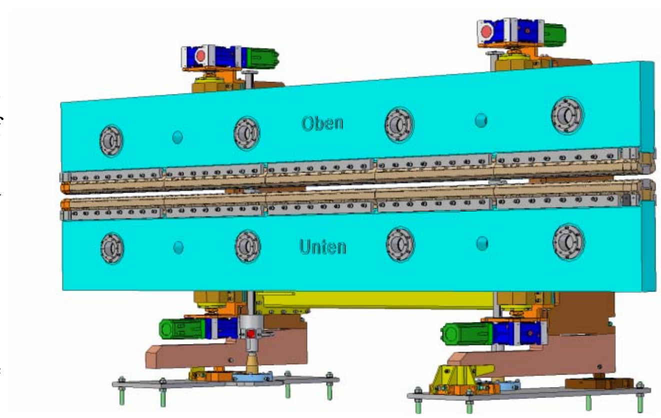

Fig.2 : View of a 5m long Undulator segment

Magnetic structures

The mechanical design of the magnetic structure is strongly influenced by the experience made with TTF1. 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 [7]. It requires each pole to be height adjustable by about ±100µm.

Intersections

Planar Permanent Magnet Quadrupoles (PPMQs)

The intersections were already described in [3]. It is currently investigated if electromagnetic (EM) components such as quadrupoles and phase shifters can be replaced by those using permanent magnets (PM).

These efforts are driven by the request to 1.) avoid any sources of heat in the undulator section, 2.) make components in the intersection as compact as possible and 3.) have sufficient accuracy for adjustments.

Fig 4 shows the principle of an adjustable PPMQ. It is an improvement of a proposal by Tatchyn [8]. A strong quadrupolar field is created in the center of the PM array, which consists of PM parallelepipeds separated by a gap. The top and bottom separation distance may be changed

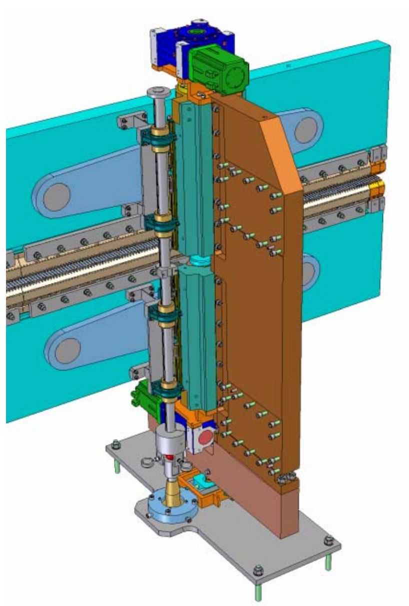

Fig. 3: Rear view showing the girder support column of one end, the auxiliary intermediate girder for the four point support and the guiding system, which integrates the position encoders for the top and bottom motor.

independently by moving the blocks along the z direction symmetrically to the Y-axis. In this way the gradient and the exact vertical center position can be adjusted. These relations are shown in the contour plots, Fig. 5. XFEL parameters were assumed: a gap of 12mm, a maximum integrated gradient of about 8T and a vertical center adjustability of ±1mm. Magnet dimensions are given in Fig. 5. It is seen that vertical center adjustment capability requires some compromise with the integrated gradient, which has to be smaller than the maximum achievable one: 12T are possible, but at almost no adjustability. As a compromise 8T were chosen, which allow for the required ±1mm. Horizontal adjustability is trivial: All four magnets may be moved by the desired amount along the Z-direction.

The good field area is about ± 1.5mm which is sufficient for an electron beam of a Linac with an RMS beam size of 25µm. Although looking exotic PPMQs were heavily and successfully used in the undulator for the VUV-FEL at the Tesla Test Facility Phase I (TTF1). Magnet arrays similar to that in Fig.4 were superimposed to the field of an PM undulator [9]. A total of 30 planar PM quadrupoles were integrated in the 15m long undulator section. They were forming a FODO lattice superimposed to the periodic field of the undulator and allowing for a beta function in the undulator of 1m only. Adjustment and alignment of the quadrupoles were done in a similar fashion as discussed above [9, 10].

A PPMQ may replace an EM quadrupole mounted on movable supports for beam steering.

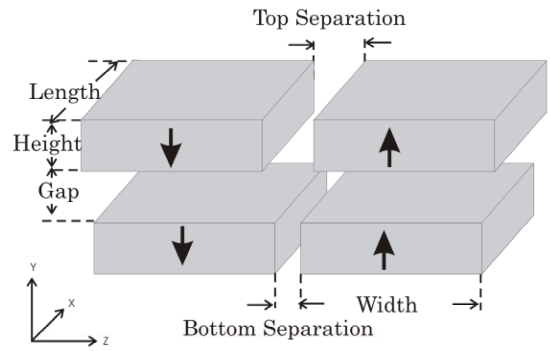

Fig. 4: Principle of a planar permanent magnet quadrupole

For the XFEL accurate control of the quadrupole center positions to 1-2 µm is desirable. The accuracy of the PPMQ principle depends on the stability and reproducibility of the PM material and on the accuracy of the mechanical components used to move the magnets. It also has to be compared with that of an EM quadrupole. This will be subject to investigations in the next future.

Phase shifter

In undulator systems with variable gaps a phase shifters are needed to exactly adjust the phase between segments so that constructive superposition occurs. The simplest way is to use a three magnet chicane using EM. This is described in [12]. Drawbacks of this solution systems are: 1.) Hysteresis in the magnets, 2.) Asymmetries in the magnets and 3) space requirements.

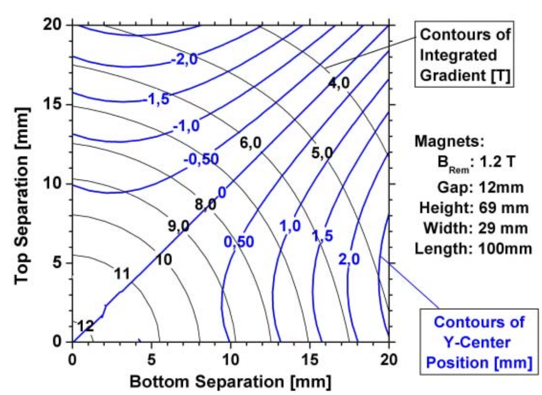

Fig. 5: Contour plot of the field gradient and the position of the vertical center as a function of Top and Bottom separation

Fig. 6 shows a sketch of a PM phase shifter. It uses a zero potential yoke made of soft iron, PMs and poles in a similar configuration as in the case of a hybrid undulator. The full center magnets excite flux in the poles next to them with the same strength but opposite sign. So the field integral is balanced. Additional magnets between poles and the zero potential yoke can be used to enhance

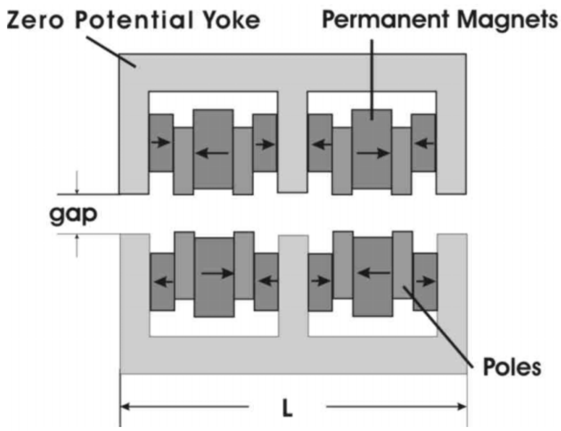

Fig. 6: Proposed PM phase shifter. The soft iron zero potential yoke avoids stray fields. The strength can be adjusted by changing the gap. The length L is about 200mm

the pole strength. Slight vertical movement of the short magnets can be used for error correction. In addition the zero potential yoke very effectively terminates outside fields. The strength of the phase shifter is controlled via the gap. First estimates indicate that the length can be shortened by a factor of 2 as compared to the EM version of [12]. A prototype is presently under construction.

CONTROL SYSTEM

There are several requirements on the control system:

- It has to control and synchronize the motion of the four motors of an undulator segment with high precision. The gap should be adjusted with an accuracy of $< 1\mu m$. In addition operational safety, i.e. proper failure recognition has to be guaranteed.
- It has to allow for synchronization of additional components, for example current settings of corrector coils, gap values for phase shifter settings etc. It should be possible to implement these corrections in a flexible manner.
- It must provide control of the whole undulator system i.e. synchronization of all individual undulator segments.
- It should be designed for a life of 15-20 years minimum.
- High reliability and availability of components is essential.
- Industrial Standards and components should be used.

Over the past years there has been a tremendous development of control systems and components for industrial applications such as automatation, robotics, numerical machining, process- and motion control, handling etc. Components are available off the shelf 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. The undulator control system will take advantage of these developments.

To gain first experience an old decommisioned wiggler used at HASYLAB for many years has been converted to a motion control test undulator. Before there was central 3-Phase motor and five gear boxes, which powered four spindles, which moved the girders. These component were replaced by four servo motors and one central control unit manufactured by Beckhoff Industrie Elektronik, Germany. Each motor has its own high resolution position encoder feedback with submicron resolution. First tests show that the gap can be controled with submicron resolution reproducibly back and forth: Mechanical play and backlash although detectable in the spindles is fully compensated by the encoder feedback. The 'In Position' gap with enabled feedback jitters by $0.2\mu m$. The synchronization works reliably and the hardware allows for the synchronization of external components. These results are encouraging and therefore the concept will be the basis for further developments.

UNDULATOR RELEVANT OPTICAL DIAGNOSTICS

An undulator system consisting of 42 segments like SASE2 (see table1) has an enormous number of parameters to adjust. The purpose of the photon beam diagnostic system is to check and verify the most important and critical ones. A diagnostic station for the XFEL has been proposed, which can be used to control settings of the undulator and the alignment of the e^- beam in the undulator section [13]. It uses the 5^{th} harmonic of the fundamental at a wavelength around 0.2Å. A single crystal monochromator in Laue geometry is used. Its design could be similar to the beam diagnostic system for PETRA [14]. The spontaneous radiation emitted either by a single segment or by groups of segments is analyzed. There are three basic measurements, which can be performed:

1. Position measurement of the photon beam
2. Exact measurement of the radiation wavelength or equivalently the K parameter
3. Measurement of the phasing between undulator segments

These measurements may be used to check settings of individual undulator segments, segment pairs or groups of segments. This will be facilitated by the possibility to open the gaps in all undulator segments to a 'switch off' position. Using the fast control system it is straightforward to implement automated procedures, which allow the following gap dependent measurement on any segment of an undulator system with high accuracy:

- Proper corrector setting to keep the beam position fixed
- In situ calibration of photon wavelength
- Phase shifter settings

Operational experience will show to what extend these measurements need to be repeated to allow for a safe routine operation of the undulator system.

The bunch charge may fluctuates by several percent and the bunch energy by 10^{-4}. This makes the precision measurements more difficult. Two alternative solutions were proposed by Yang [15]: Using his idea any two undulator segments of a system are compared. One of them, the last of the system is taken as 'reference undulator'. The same bunch passes through both undulators. A steerer magnet deflects the e^- beam before it entering the second. The radiation of both is now spacially separated and is passed through the same Laue monochromator, but intensities are analyzed individually. Differences in count rates are very sensitive to differences in the K parameter. A resolution of $\Delta K/K<10^{-5}$ has been reported, which is even more than required for an XFEL using eq. (1).

Alternatively charge and energy could be measured for each bunch and used for correction for the spectrum.

SUMMARY AND CONCLUSION

New design ideas for the undulator systems of the European XFEL project were presented. The specification requirements fully determine the design of the mechanical support system. In order to achieve stability on the µm level large cross section for the girders, four fold support and proper material pairing is needed. The control system has to support these accuracy requirements. Novel ideas for planar adjustable PM quadrupoles and phase shifters were presented. They are more compact then EM and avoid any heat dissipation.

These ideas are the basis for the first prototypes of undulator segments, phase shifters and PPMQs to be built in the near future.

ACKNOWLEDGEMENT

The help, discussions and support of my colleagues: M. Bräuer, P. Illinski, U. Hahn, H. Schulte-Schrepping, K. Tiedke, M. Tischer is gratefully acknowledged.

REFERENCES

[1] TESLA Technical Design Report Part V, The X-ray Free Electron Laser, G. Materlik, T. Tschentscher (Eds.) DESY 2001-011, ECFA 2001-209, TESLA-FEL2001-05, March 2001, http://tesla.desy.de/new_pages/0000_TESLA_Project.html

[2] TESLA XFEL Technical Design Report Supplement, R. Brinkmann, B. Faatz, K. Flöttmann, J. Rossbach, J. Schneider, H. Schulte-Schrepping D. Trines, T. Tschentscher, H. Weise, DESY 2002-167, TESLA-FEL2002-09, October 2002, http://tesla.desy.de/new_pages/0000_TESLA_Project.html

[3] J. Pflüger, M. Tischer, NIM A483, (2003), 388

[4] S. Sasaki, Nucl. Instr. and Methods A347, (1994), 83

[5] J. Bahrdt, A. Gaupp, U. Englisch, W. Frentrup, M. Scheer,TESLA-FEL2000-11, http://tesla.desy.de/new_pages/0000_TESLA_Project.html

[6] E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, "The Potential for the Development of the X-Ray Free Electron Laser", TESLA-FEL 2004-02, http://tesla.desy.de/new_pages/FEL_Reports/2004

[7] J. Pflüger, H. Lu, T. Teichmann, NIM A429, (1999), 368

[8] R. Tatchyn, NIM A341, (1994), 449

[9] J. Pflüger, Y. Nikitina, NIM A381, (1996), 554

[10] J. Pflüger, H. Lu, D. Köster, T. Teichmann, NIM A407, (1998), 386

[11] J. Pflüger, P. Gippner, A. Swiderski, T. Vielitz, "Magnetic Characterization of the Undulator for the VUV-FEL at the TESLA Test Facility", Proceedings of the FEL99, August 23-26, 1999, Hamburg, Germany

[12] J. Pflüger, M. Tischer, "A Prototype Phase Shifter for the Undulator Systems at the TESLA X-ray FEL", TESLA-FEL 2000-08 http://tesla.desy.de/new_pages/0000_TESLA_Project.html

[13] M. Tischer, P. Illinski, U. Hahn, J. Pflüger, H. Schulte-Schrepping, NIM A483, (2002), 418

[14] U. Hahn, H. Schulte-Schrepping, "Crystal Monochromator based Emittance Measurements at the PETRA Undulator Beamline", SRI 2003, AIP Conference Proc. Vol 705, 533-536

[15] BingXin Yang, "High resolution undulator measurements using angle-integrated spontaneous radiation", Proceedings of the PAC05, May 16-20, 2005, Knoxville, USA