# UNDULATORS FOR A SEEDED HGHG-FEL TEST BENCH AT MAX-LAB*

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## Abstract

Within the European FEL Design Study a seeded HGHG-FEL test bench will be set up at MAX-lab. In the modulator the 3rd harmonic of a Ti:Sapphire laser (267nm) interacts with the electron beam. In the following dispersive section the energy modulation is converted into a spatial modulation. The radiator emits at the third harmonic (89nm). The electron beam height at MAX-lab of 400mm requires a specific design of the undulator carriages. The magnetic and mechanical design of the HGHG stage will be presented.

## INTRODUCTION

As part of the European FEL Design Study a single stage seeded HGHG [1] test facility is set up at MAX-lab. The electron beam is produced in a new photocathode gun [2] and is accelerated in the injection linac of the MAX I-III rings. A bending magnet inside the MAX-II storage ring provides electrons alternatively for the storage ring or the new FEL experiment.

BESSY builds the undulators (modulator and radiator) and the chicane magnets for this setup and will take part in the installation and operation of the FEL. Furthermore, BESSY performs GENESIS [3] simulations to study the influence of various parameters on the FEL process. The results of the simulations will be crosschecked with experimental data.

The results of this project will be valuable for the planned BESSY Soft X-ray FEL [4]. The three seeded FELs of the BESSY facility are based on 2-4 cascaded HGHG stages and they cover the energy regime from 24eV to 1000eV. Currently, BESSY elaborates and tests experimental techniques, which are relevant for the FEL project. The femtosecond slicing facility at BESSY provides the possibility for ultra short pump probe experiments [5]. The synchronization of the laser and the electron beam as well as the optimization of the transverse overlap is an important issue at this setup. The experience gained in this experiment will be helpful for the commissioning of the HGHG-FEL at MAX-lab.

## GENESIS SIMULATIONS

Since the FEL process depends on the coupling of the transverse velocity component of the electrons to the electromagnetic radiation of the seed, a strong deflection of the electrons by the undulator field is needed. This is ensured when high undulator parameters (preferably K>1)

satisfy the resonance condition $\lambda_{res}=\lambda_u/(2\gamma^2)[1+K^2/2]$, where $\gamma$ denotes the beam energy and $\lambda_{res}$ and $\lambda_u$ are the radiation wavelength and the undulator period length, respectively. In order to account for the energy transfer from the electron beam to the radiation field during lasing, the resonance condition also suggests a taper of K as the beams progress along the undulator. Both the necessary K-parameters as well as the gradual taper of undulator field strength are provided by the undulator structures.

In order to predict FEL performance and stability, fully time-dependant FEL simulations were performed covering both the interaction of the electron beam and laser in the modulator as well as radiation from microbunching in the radiator. In the studies, the relevant electron beam parameters such as energy, energy-spread, slice emittance and peak current were derived from complete start-to-end simulations of the gun, injector and beam transport [6]. The numerical simulations show that lasing at 88nm can be expected with output powers in the MW-range while the beam energy spread and emittance emerge as critical parameters for FEL efficiency.

## PRINCIPAL LAYOUT

The HGHG FEL will be seeded with the third harmonic of a Ti:Sapphire laser (267nm). Flat top pulses with a length of 300fs and a peak power of 300MW are used. The electron beam energy is modulated in the first undulator. The overlap between the laser and the electron beam will be optimized using a THz signal as it is developed at the BESSY femtosecond slicing setup [3]. In the dispersive section consisting of four identical bending electromagnets the electron beam is spatially modulated. The bunched beam enters the radiator, which can be tuned to the harmonics 1-5 of the micro-bunched beam.
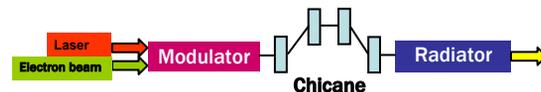


Figure 1: Principle layout of the seeded HGHG-FEL.

## THE UNDULATORS

Existing magnet structures will be used to build the undulators. A pure permanent magnet (PPM) structure has been loaned from the ESRF to be used in the modulator. The radiator will be equipped with the APPLE structure of the BESSY UE56-1. The parameters are summarized in table 1.

Figure 2 shows the achievable K-parameters for various undulator designs. The PPM curve refers to a gap of 10mm whereas the APPLE II curves have been evaluated for 12mm gap. The larger nominal gap of the radiator

provides space for pure permanent magnet shims to compensate for the magnet block inhomogeneities [7].

| Modulator | |
|---|---|
| Period length | 48 mm |
| Number of periods | 30 |
| Minimum gap | 10 mm |
| Maximum K-parameter | 4.3 |
| **Radiator** | |
| Period length | 56 mm |
| Number of periods | 30 |
| Minimum gap | 12 mm |
| Maximum K-parameter | 4.3 |
| **Chicane** | |
| Number of magnets | 4 |
| Type of magnet | H-frame, electromagnet |
| Gap | 15 mm |
| Pole dimensions (length x width) | 120 x 100 mm**2, including chamfer |
| Maximum current | 3A |
| Maximum field | 0.2 T |
| Distance between magnets | 400 mm |

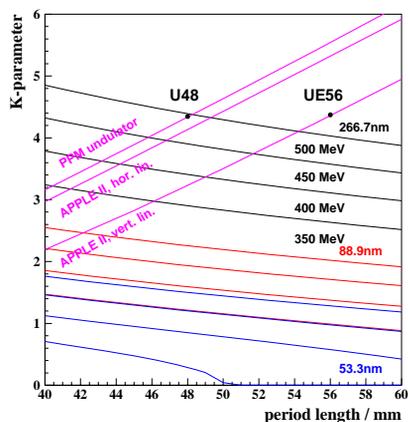Table1: Parameters of the undulators and the chicane



Figure 2: K-parameters for various undulator designs compared to K-parameters needed to generate 266.7 nm, 88.9nm and 53.3nm radiation for electron energies between 350-500MeV.

At an electron energy of 500MeV the modulator (period length = 48mm), operating at smallest gap, is resonant to the seeding radiation of the laser. As the target energy is 450MeV a sufficient safety margin in the undulator design is provided. The radiator reaches the 267nm even in the vertical linear mode. The radiator will be operated at this wavelength for tests related to the possible application of optical replica synthesis [8]. The project goal is the production of 88nm ($3^{rd}$ harmonic of the modulator). The production of even shorter wavelengths will also be studied.

Both undulators will have a motorized gap drive. The radiator provides also a motorized phase variation for polarization control. The modulator is moved only in case of an electron energy change whereas the radiator has to

be tuned also when the harmonic number of the radiation or the state of polarization is changed.

## THE CHICANE

The magnetic chicane converts the energy modulation of the electron beam into a spatial modulation. Optimum bunching is achieved if the energy modulation dominates the energy spread times the harmonic number $n$:

$$\Delta\gamma / \gamma \geq n \cdot \sigma_\gamma$$

With a relative energy spread of $\sigma_\gamma = 5 \cdot 10^{-4}$ an energy modulation of at least $\Delta\gamma / \gamma = 1.5(2.5) \cdot 10^{-3}$ is needed to operate on the third (fifth) harmonic. This defines the laser power.

The maximum bunching appears for a path length difference of $\Delta L = \lambda_{photon} / 4$ between modulated and non modulated electrons. The chicane is optimized such that $\Delta L = \lambda_{photon}^{1st} / 4 = 67nm$ can be reached with 500MeV electrons and an energy modulation of $\Delta\gamma / \gamma = 1.0 \cdot 10^{-3}$. For higher harmonics (shorter wavelengths) $\Delta L \geq \lambda_{photon} / 2$ can be produced and overbunchig effects can be studied.

The distance between the magnet centres is 400mm. This provides sufficient space for the installation of diagnostics.

In principle, the chicane can be realized either as a permanent magnet device or as an electromagnet. Both designs provide a tuneable delay. An electromagnetic design has been chosen due to the better field homogeneity (figure 3). Additionally, it can completely be switched off, which is of advantage when commissioning the undulator sections with beam.
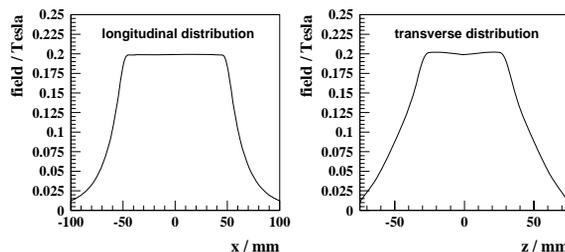


Figure 3: Longitudinal and transverse field distribution of one chicane magnet.

## MECHANICAL LAYOUT

The electron beam height at the HGHG-FEL is only 400mm and conventional undulator carriages cannot be used here. Elevating the beam height to 1.2m would require additional magnets and space and the beam quality, especially the beam emittance, would suffer from this extra deflections. Therefore, a new carriage has been developed which can cope with this geometry (figure 4). The same structure is used for both undulators. The accuracy is achieved with a stiff welded structure. Four sleds are driven with right and left threaded ball screws. The modulator is driven with one servo motor. The optional tapering requires two motors for the radiator. The

gap encoder is located in a line with the electron beam to avoid Abbe's comparator error [9].

The two undulators will be measured and shimmed at the existing measurement bench at BESSY. For this purpose the undulators have to be flipped into upright orientation (figure 5). At MAX-lab the final magnetic measurements will be performed in the operating position using a pulsed wire system.
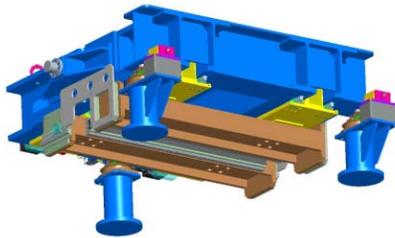


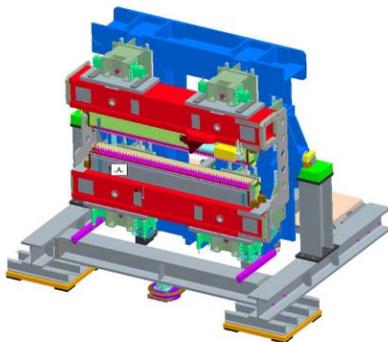Figure 4: Modulator in operating position.



Figure 5: Radiator in measurement position.

## RADIATION PROTECTION

Radiation damages of permanent undulator magnets have been reported and investigated by several authors [10-13], and a detailed study has been done for the TTF-FEL [14]. For the planned BESSY-FEL (2.25 GeV) we have estimated a beam loss of 300nC to cause an acceptable demagnetization of $dB/B = 1x10e-4$ of the NdFeB-magnets [1]. Scaled to the beam energy of 450 MeV, we expect a tolerable loss if not more than 1500 1-nC-bunches are dumped into the magnets. Therefore, a collimator and a monitor system with a fast interlock are necessary to protect the undulator magnets.

Various methods based on optical fibres can be used for beam loss monitoring. 1: A fast monitor system exploiting Cherenkov radiation has successfully been tested at FLASH [15]. It is fast and sensitive enough to detect losses of single bunches. 2: Fibres for optical time domain reflectometry have also been tested at the FLASH undulator [16]. The used fibres show a linear response for doses up to 1 kGy, which can be measured within a few minutes. Beam losses can be detected within a few milliseconds when the fibres are used as a power-meter. 3: Another method is based on fibre Bragg gratings as high dose radiation sensors [17]. This method is suitable for doses on the scale of many kGy. The system shows a

strong temperature sensitivity and it has to be studied whether it can be used also in the lower dose regime (<1kGy).

The systems 2 and 3 can be used to localize the regions of beam losses, which is essential for commissioning. It is planned to equip the undulators along the whole length with these fibres.

Most probably, Cherenkov fibres will be used as part of a beam loss monitor used in a fast interlock system. The signal will be used to shut off the gun laser, which can easily be accomplished between two shots.

It has still to be decided whether an OTDR or a fibre Bragg grating system will be used for integrated dose measurements

## REFERENCES

[1] L. H. Yu, J. Wu, Nucl. Instr. and Meth. in Nucl. Res. A 483 (2002) 493.

[2] S. Werin et al., these proceedings.

[3] S. Reiche, GENESIS, time dependent FEL code, http://pbpl.physics.ucla.edu/~reiche/.

[4] "The BESSY Soft X-Ray FEL". Technical Design Report, D. Kraemer et al., Berlin, 2004.

[5] S. Khan et al., Proceedings of the 2005 PAC, Knoxville, Tennessee, pp. 2309-2311.

[6] S. Thorin et al., these proceedings.

[7] J. Bahrdt et al., Ninth International Conference on Synchr. Rad. Instr., Daegu, Korea, 2006.

[8] E.L. Saldin et al., Proceedings of the 2004 FEL Conference, pp. 375-378.

[9] J. Bahrdt et al., Proceedings of the 2004 FEL conference, Trieste, Italy, pp 610-613.

[10] P. Colomp, T. Oddolaye, P. Elleaume, "Partial Demagnetization of ID6 and Dose Measurements on Certain Ids", Machine Technical Note 1-1996/ID, 1996.

[11] M. Petra et al., Nucl. Instr. and Meth. in Phys. Res. A, 507 (2003) pp. 422-425.

[12] P. Colomp, T. Oddolaye, P. Elleaume, "Demagnetization of Permanent Magnets to 180 MeV Electron Beam", Technical Report ESRF/MARCH-ID/93-09, European Synchrotron Radiation Facility, ESRF March 1993.

[13] T. Bizen, T. Tanaka, Y. Asano, D.E. Kim, J.S. Bak, H.S. Lee, H. Kitamaru, Nucl. Instr. and Meth. in Phys. Res. A 467-468 (2001) 185-189.

[14] H. Schlarb, "Collimation System for the VUV Free-Electron-Laser at the TESLA Test Facility", Thesis Work, Universität Hamburg, DESY-THESIS-2001-055, Nov. 2001.

[15] E. Janata, M. Körfer, H. Schlarb, Nucl. Instr. and Meth. in Phys. Res. A 253 (2004) 256-261.

[16] H. Henschel, J. Kuhnhenn, M. Körfer, F. Wulf, Nucl. Instr. and Meth. in Phys. Res. A 507 (2003) pp. 422-425.

[17] K. Krebber, H. Henschel, U. Weinhand, „Fibre Bragg Gratings as high dose radiation sensors", Meas. Sci. Technol. 17 (2006) pp. 1-8.