STATUS OF THE UNDULATOR SYSTEM OF THE SEEDED HGHG-FEL TEST BENCH AT MAX-LAB

J. Bahrdt, W. Frentrup, A. Gaupp, K. Goldammer, K. Holldack, M. Scheer, BESSY, Berlin, Germany
M. Brandin, F. Lindau, D. Pugachov, S. Thorin, S. Werin, Lund University, Lund, Sweden,
J. Kuhnhenn, Fraunhofer INT, Euskirchen, Germany

Abstract
Within the EUROFEL Design Study a seeded HGHG-FEL will be set up at the 450 MeV linac at MAX-lab. The undulators and the dispersive section have been installed. Two different glass fiber based radiation dose monitors have been integrated. We report on the performance of these components. The impact of electron losses on undulator magnets and the Cherenkov fibers have been simulated. The THz radiation as produced by the bunched electron beam in the dump magnet can be used as a measure of the longitudinal and transverse overlap of the electron beam and the laser beam which has been concluded from simulations.

INTRODUCTION

Within the European FEL Design Study a single stage seeded HGHG FEL [1] test bench is currently set up at MAX-lab [2]. The electrons will be accelerated in the injection linac of the MAX-I-III rings. The FEL experiment is located inside the MAX-II storage ring and the electron beam will be available between the injections into the MAX-lab rings. A new low emittance photocathode gun [3] will be installed at the end of 2007. The commissioning of the complete setup will start in September 2007 using an existing gun which provides a bunch charge of 0.08nC.

BESSY has built and installed the two permanent magnet undulators (modulator and radiator) and the electromagnetic chicane. Permanent magnets are sensitive to radiation damage and the deposited doses have to be monitored. For this purpose two glass fiber systems have been implemented: i) A Cherenkov system delivers fast signals which will be used for a laser interlock system in case of an electron beam missteering. ii) Absolute dose measurements are done with a powermeter system which is based on another type of glass fiber. A detailed study and comparison of both measurements systems in combination with numerical simulations will be very helpful for the design of future FEL sources.

The alignment of the electron beam with respect to the laser beam is crucial for a reliable operation of the seeded FEL and a robust diagnostic is required.

This work has been partially supported by the EU Commission in the Sixth Framework Program, Contract No. 011935 – EUROFEL.

Simulations show that the spectral distribution of the THz radiation as produced by the electron bunch in the dump magnet changes significantly if the seed laser interacts with the electron beam. Thus, the THz will be helpful in the commissioning phase and also later during normal operation as an input for feedback systems.

THE UNDULATORS

The parameters of the undulators and the chicane have been described in [4]. The electron beam height at the FEL location of 520mm requires a horizontal operation of the two undulators. The undulators have been measured and shimmed in the vertical position at the BESSY field measurement bench. After shimming the devices have been rotated by 90° and mounted onto three columns each. Fig. 1 shows the radiator in operating position at MAX-lab. In the final position the field integrals will be checked with a pulsed wire system and air coils at the undulator ends will be used to compensate residual field errors.

Figure 1: Radiator of the APPLE II type in operating position without vacuum chamber. Four power meter sensors (see below) at each undulator end (orange cable) are installed.

THE CHICANE

The chicane consists of four electromagnets (Fig. 2). Each magnet is made of two low carbon steel pieces (C < 0.01%) which are bolted together. The poles have been wire cut. The number of windings per coil is 432. The measured field integrals per Ampere for the four magnets are: 10.9, 10.9, 10.6, 10.7 Tmm / A.

The magnetic hysteresis of the four magnets as measured with a moving wire is ±0.25 Tmm (Fig. 3). Hall probe measurements show a reproducibility of the field setting below 5e-4 after two cycles (Fig. 3).

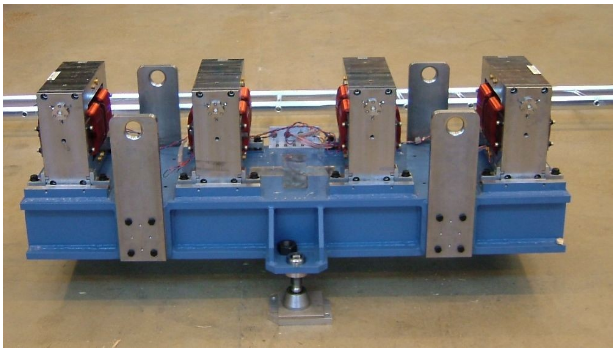

Figure 2: Electromagnetic Chicane.

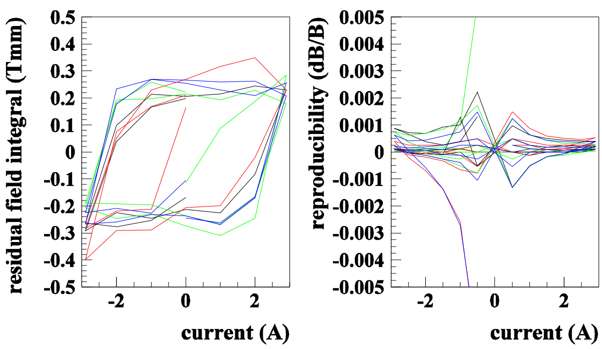

Figure 3: Left: Hysteresis of field integrals of the four magnets. The measurement noise is due to the presence of up to 30Tmm field integrals. Right: Reproducibility of field settings within a sequence of several current cycles of the magnets.

RADIATION PROTECTION OF THE MAGNETS

Significant demagnetization of undulator permanent magnets in storage rings have been reported in the literature [5-7]. The risk of demagnetization is even higher in single pass devices like linac based FELs. Extensive studies have been performed to get a quantitative understanding of demagnetization effects [8, 9]. Collimation systems have to be designed such that the radiation dose deposited into the magnets remains below an acceptable limit [10].

In the MAX-lab FEL a stainless steel capillary (length: 100mm, diameter 3mm, wall thickness: 12.5mm) is located in front of the modulator preventing the electron beam from hitting the circular beam pipe in case of a failure of the two vertical deflecting dipole magnets at the laser beam port (vertical beam displacement due to the dipole magnets: 20mm).

The electron losses will be monitored with two different systems, a Cherenkov system for fast beam loss detection and a powermeter system for absolute dose measurements. GEANT simulations have been performed to estimate the radiation doses in the magnets and to evaluate the corresponding number of produced Cherenkov photons. The experiences gained with these systems will be valuable for the BESSY Soft X-Ray FEL [11].

Cherenkov System

A Cherenkov fiber system [12] is fast and the signal can be used to switch off the electron beam in case of intolerable beam losses. During the commissioning phase the relative intensities of the individual fibers can be used to align the electron beam properly.

The system installed at the MAX-lab FEL consists of four radiation insensitive glass fibers (core: 300μm, cladding: 300 μm) mounted directly onto the circular undulator vacuum chamber which has a diameter of 10mm (Fig. 4). Thus, the fibers will provide detailed spatial information even for large undulator gaps. The sensitivity of the fibers is small as compared to large luminescence detectors. The small size, however, permits an installation close to the electron beam over many meters.

The GEANT [13] simulations are based on a 1nC bunch hitting the vacuum chamber wall of the modulator under zenith angles of 0.1 and 1mrad and azimuthal angles of 0, 45 and 90°, respectively. Four Cherenkov fibers and one Thermo Luminescence Detector (TLD) are included in the model (Fig. 4). The evaluated radiation doses induced in the TLD and the magnets and the produced Cherenkov photons are summarized in (Tab. 1). The given number of photons is the number detected by the photomultiplier (applying a numerical aperture of 0.22 inside the fiber and including the spectral characteristics of the multiplier).

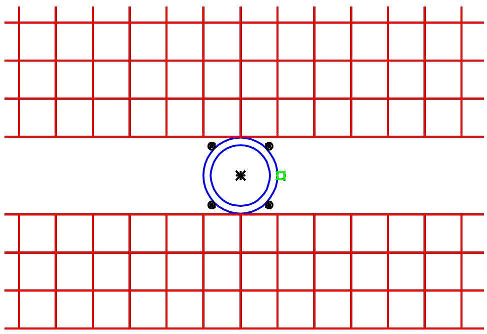

Figure 4: Cross section of the modulator including the permanent magnets (red), vacuum chamber (blue), Cherenkov monitors (black) and TLD monitor (green).

angles mrad / °	TLD mGy / nC	max. dose in magnet mGy / nC	Cherenkov photons/nC	
			forward direction	backward direction
0.1 / 0	1207	57	6.7e7	1.1e7
0.1 / 45	131	205	9.7e7	1.5e7

0.1 / 90	77	287	7.2e7	1.2e7
1.0 / 0	2730	188	1.2e8	2.1e7
1.0 / 45	412	487	1.6e8	2.7e7
1.0 / 90	279	588	1.3e8	2.3e7

Table 1: Results from GEANT simulations.

Maximum doses of 0.59 Gy/nC are detected for the 1mrad case (Fig. 5). It has been shown [14] that a maximum reduced dose (electron energy > 20MeV) of 70kGy can be tolerated in case of the BESSY Soft X-Ray FEL which represents a rather conservative number for the short MAX-lab FEL. Thus, the number of generated Cherenkov photons is sufficiently high to detect even small electron beam losses long before the magnets are damaged. The exact detection limit of the Cherenkov fibers will be subject to future combined numerical and experimental studies at the FEL.

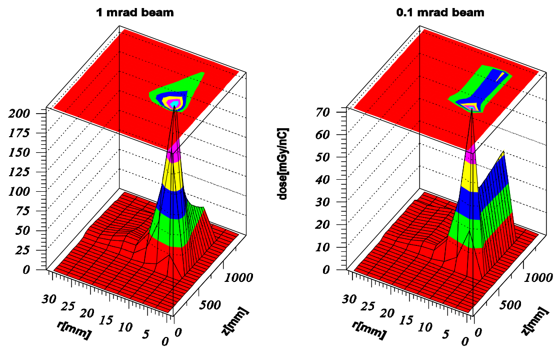

Figure 5: Radiation doses inside the magnets induced by a 1nC electron bunch hitting the vacuum chamber. The data are averaged over the 0°, 45° and 90° scenarios.

Powermeter System

Absolute radiation dose measurements can be done with calibrated glass fibers [15]. The fibers can be installed along the region of interest (e.g. the complete undulator system) providing spatial information of the beam losses (Optical Time Domain Reflectometer, OTDR). Another approach is a system of several local sensors which are multiplexed. The spatial resolution of the latter system is slightly lower (depending on the number of channels) but the complete dynamic range is available for each channel whereas in the OTDR system the dynamic range is available only for the whole system. A system with 16 local sensors has been installed at the MAX-lab FEL.

Glass fibers for telecommunication applications are not optimized for radiation dosimetry. Usually, the optical parameters which are relevant for dose measurements can vary by orders of magnitude. This requires a careful selection of the fibers. Four germanium and phosphorous doped polyimid coated 50/125/145 µm graded index fibers from different suppliers have been tested by the Fraunhofer INT, Euskirchen, Germany. A fiber fabricated by J-Fiber, Jena, Germany, has been selected for the MAX-lab FEL. The calibration of this fiber as determined with a Co-60 source is plotted in figure 6.

The figure of merit for the fiber selection is a combination of various parameters: i) high dynamic range; ii) radiation sensitivity; iii) annealing after irradiation; iv) linear response on total radiation dose; v) low sensitivity on dose per time.

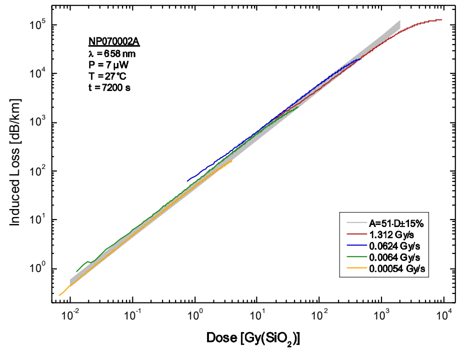

Figure 6: Calibration of the selected fiber.

The chosen fiber has the following performance (Fig. 6): i) in combination with the currently installed light source and the power meter the dynamic range is 30-40 dB ii) the attenuation is described by: (dB / km) = dose (Gy) * 51. For comparison: the sensitivity of conventional germanium doped 50/125/250 µm graded index fibers as used to connect the sensor modules to the light source and the analyzer is two orders of magnitude lower. iii) 24h after irradiation less than 10%. iv) The deviation from a linear curve within the range from 0.01-1000Gy is smaller than ±15%. v) A linear response has been demonstrated for dose rates between 0.0005 Gy/s up to 1.3 Gy/s.

The MAX-lab system consists of sixteen channels. One channel serves as a reference. The read out time for all 16 channels is less than 60s. The light source consists of an LED (658 nm) powered by a stable constant current power supply. 10% of the output power is measured directly (excluding the optical coupler, the optical switches and all fibers) with a power meter. In a temperature stabilized environment the source drifts are only 0.01dB / day. The influence of typical source drifts in a rough environment of 0.02-0.05dB / day can easily be compensated.

The reference fiber has no sensor module attached but is shortcut at the FEL location. It can be used to compensate for drifts of the support fibers.

The sensor fibers are wound to rectangular flat coils (50x50mm**2) and the radiation exposed length of one fiber is approximately 2m. The coils are mounted onto the magnet girders close to the upstream and downstream ends of the undulators. At smallest gap the distance to the electron beam is 7mm for the modulator and 28mm for the radiator. Radiation sensitive fibers are used only for the coils. The distance of 40m between the FEL and the electrical cabinet is bridged with radiation insensitive fibers.

The system has been installed in March 2007 and the drifts have been monitored since that time. The optical transparency of the 15 fibers has been corrected for fluctuations of the light source. The signals show a long term drift of ±0.03dB per day and a periodic structure superimposed to it (Fig.7, left). The drifts are dominated by temperature fluctuations which is concluded from a correlation diagram (Fig. 7, right). The various fibers show individual temperature dependencies. The data can be corrected using a specific temperature coefficient for each fiber. Two temperature sensors are installed at each undulator end. After correction the residual drifts are well below ±0.01dB for a period of several days. This guarantees a long term system sensitivity of better than 0.2Gy. The remaining differences between the fibers are due to the individual characteristics of the cascaded optical coupler behind the light source.

In case the fibers have reached the upper limit of the linear regime of 1000Gy they can be thermally annealed at a temperature of up to 350°C in order to recover the full transmission.

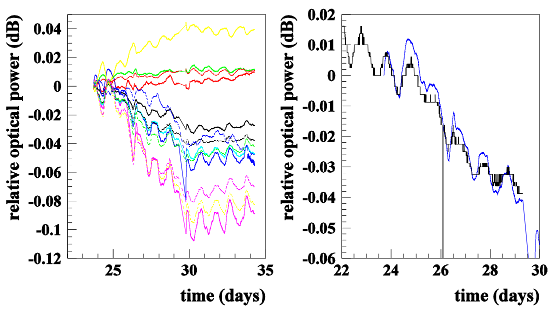

Figure 7: Left: Long term stability of the system consisting of 15 fibers. Right: The day by day fluctuations (blue) are closely correlated to the temperature variations (black).

THZ DIAGNOSTICS

The diagnostics of the FEL resonance in the modulator will be performed using a strong difference in coherent THZ emission [16,17] from the seeded and unseeded bunch after propagating through an additional bending magnet (dump magnet) behind the radiator. Since the electrons are gathering path length differences controlled by R56 along the magnet, the bunch shape in time domain is different for the seeded and unseeded case. This is caused by the change in energy spread due to the FEL resonance (Fig. 8 left).

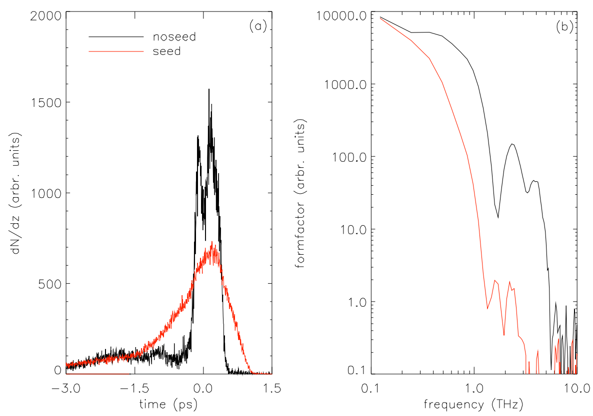

Figure 8: Left: Projection of the seeded and unseeded electron density in the bunch according to start-to-end simulations [2] after passing an R56 of 0.05 m. Right: Expected envelopes of THz spectra (formfactor) emitted by theses bunches for the seeded and unseeded case.

The THz power spectral density emitted there is ~ N(N+1)f, where f is the square of the Fourier transformation of the longitudinal electron density and N=0.6x10^9 (0.1 nC) is the number of electrons.

The calculated form factor f for the two cases (Fig. 8, right) demonstrates that the coherent far infrared emission in the range between 1 and 10 THz can be employed to detect the overlap between seed laser and bunch in the modulator. By setting an appropriate high pass filter the signal from a THz detector will almost completely drop to zero for a successful energy modulation of the electrons.

REFERENCES

[1] L. H. Yu, J. Wu, Nucl. Instr. and Meth. in Nucl. Res. A 483 (2002) 493.
[2] S. Werin, al., these proceedings.
[3] S. Werin et al., Proceedings of the EPAC 2006, Edinburgh, Scotland, 2006, pp 130-132.
[4] J. Bahrdt et al., Proceedings of the EPAC 2006, Edinburgh, Scotland, 2006, pp 59-61.
[5] P. Colomp, T. Oddolaye, P. Elleaume, "Partial Demagnetization of ID6 and Dose Measurements on Certain Ids", Machine Technical Note 1-1996/ID, 1996.
[6] M. Petra et al., Nucl. Instr. and Meth. in Phys. Res. A, 507 (2003) pp. 422-425.
[7] 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.
[8] 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.
[9] M. Marechal, T. Shintake, SRI2003, Conference Proceedings, AIP 705, (2004) pp 282-285.
[10] 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.
[11] "The BESSY Soft X-Ray FEL", Technical design Report, D. Kraemer et al., Berlin, 2004.
[12] M. Körfer, W. Göttmann, F. Wulf, J. Kuhnhenn, Proceedings of DIPAC 2005, Lyon, France, 2005, p301.
[13] GEANT 3.21, Detector Description and Simulation Tool, Computing and Networks Division, CERN, Geneva, Switzerland.
[14] J. Bahrdt et al., Proceedings of the FEL Conference 2006, Berlin, Germany, 2006, pp521-528.
[15] H. Henschel, M. Körfer, J. Kuhnhenn, U. Weinand, F. Wulf , Nucl. Instr. and Meth. in Phys. Res. A 526 (2004) pp. 537-550.
[16] Holldack et al. PRL 96, 054801 (2006).
[17] A. A. Zholents and K. Holldack, Proceedings FEL Conference 2006, Berlin, Germany, 2006, pp725-727.