FIRST EXPERIENCES WITH THE FIR-FEL AT ELBE

U. Lehnert, P. Michel, W. Seidel, G. Staats, J. Teichert, R. Wünsch
Forschungszentrum Dresden-Rossendorf e.V., 01314 Dresden, Germany

Abstract

We show the design and the parameters of operation of the long-wavelength (U100) FEL at ELBE. First lasing has been shown in August, 2006. Since then, the laser has undergone thorough commissioning and is available for user experiments since fall, 2006. Besides in-house users the IR beam is available to external users in the FELBE (FEL@ELBE) program witch is a part of the integrated activity on synchrotron and free electron laser science in the EU. At the beginning of 2007 lasing in the full designed wavelength range from 20 µm to 200 µm was demonstrated. The laser power typically reaches several Watts in cw operation but drops for very long wavelengths depending on the size of the used out-coupling hole. However, there exists a serious problem with small gaps in the wavelength spectrum. We attribute this behaviour to the transmission characteristics of the overmoded partial waveguide used from the undulator entrance to the first mirror.

INTRUDUCTION

At Forschungszentrum Dresden-Rossendorf, Germany, the radiation source ELBE (Electron Linac with high Brilliance and low Emittance) operates on the basis of a superconducting linear accelerator for electron energies up to 40 MeV with an average beam current of 1 mA in quasi continuous wave (cw) mode. The electron linac serves as a driver to generate several kinds of secondary radiation and particle beams. Two free-electron lasers generate radiation in the mid and far infrared for a very large field of applications reaching from semiconductor physics to biology. In addition, MeV Bremsstrahlung for nuclear (astro) physics, monochromatic hard-X-ray channelling radiation for radiobiological experiments, and in near future also neutrons and positrons for studies in nuclear reactor science and materials research are provided. The quality and range of the provided beams will be extended even further when the superconducting photo-electron gun [1] which is tested at present will become operational. The first FEL to become operational at ELBE was the mid-IR FEL [2] using two undulators with 27.3 mm period. With the available beam energies it covers a wavelength range from 3-24 µm. To extend the wavelength range into the far-IR a second FEL with a 100 mm period [3] undulator was installed. It now provides laser light from 20-200 µm. After first lasing in August, 2006 it is in routine user operation since fall, 2006. The relevant user facilities comprise 6 optical laboratories. Some of these are also used by in-house groups, mainly in the areas of semiconductor physics, and radiochemistry, and experiments there will require a certain level of collaboration with the in-house researchers. In particular noteworthy is the fact that a number of additional optical sources from the visible to the THz frequency range are available, e.g. for two-colour pump-probe experiments. These sources (Ti:sapphire laser and amplifier, OPO, OPA, broad-band THz generator) are all based on Ti:sapphire oscillators which are synchronized to the FEL with an accuracy better than a ps. Two laboratories are intended to provide users with utmost flexibility for their own experiments, also in scientific areas not covered by in-house groups (e.g., surface physics, molecular physics).

U100-FEL SETUP

The FIR-FEL at ELBE (see Fig. 1) uses a hybrid undulator with 100 mm period length. It consists of 38 periods equipped with SmCo magnets which were chosen due to their better radiation resistance with respect to NdFeB. With a minimum gap of 24 mm a maximum K_{rms} parameter of 2.7 is reached. The whole wavelength range from 20-200 µm is covered with electron beam energies from 20-35 MeV. To allow small undulator gaps a waveguide optical beam transport through the undulator is necessary. The ELBE FIR-FEL uses a partial waveguide spanning from the undulator entrance to the downstream mirror. The interior height was chosen to 10 mm. In horizontal direction the waveguide is wide enough to allow essentially free propagation. Thus, an overmoded parallel-plate waveguide is formed which shows low losses for the principal mode. The downstream mirror was placed as a cylindrical mirror inside the waveguide. On the upstream side the optical beam propagates freely through the focusing quadrupoles and the dipole to a toroidal mirror. To optimize the coupling between the waveguide mode and the free propagation the horizontal curvature of both mirrors was chosen to correspond to a Rayleigh range of 180 cm. The vertical curvature of the upstream mirror, however, equals its distance of 361 cm from the waveguide entrance. Round-trip optical losses inside the U100 resonator were computed using the GLAD [4] code. The mode conversion between waveguide and free propagation was approximated taking only the fundamental waveguide mode into account. The efficiency computed this way is above 94 % for all wavelengths yielding a reasonably high Q of the optical resonator. To allow for a near-optimum out-coupling over the whole wavelength range the upstream mirror chamber is equipped with three interchangeable mirrors of identical curvature but with 2.0, 4.0 and 7.0 mm out-coupling holes.

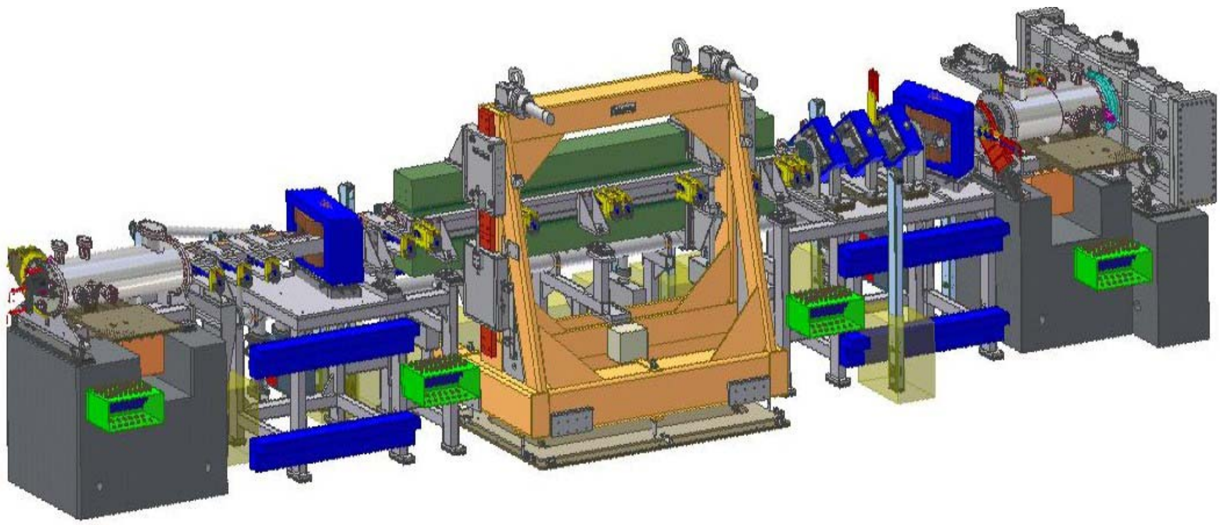

Figure 1: The setup of the FIR-FEL of ELBE. The electron beam enters from the right side through the blue bending magnet and quadrupole triplet. The upstream mirror chamber contains three interchangeable mirrors with different size out-coupling holes.

FEL OPERATION AND DIAGNOSTICS

Since the FEL gain is linearly proportional to the beam peak current it is highly desirable to minimize the electron bunch length in the vicinity of the undulator. Accordingly, calculations of the laser gain yield an optimum at minimum bunch length (see Fig. 2), even though this is bought at the expense of an increased energy spread of the electron beam. When tuning the electron beam the bunch length can be optimized by maximizing the signal of coherent optical transition radiation from a viewscreen. For the mid-IR FEL we have this way reached a minimum 1.5 ps bunch length for an optimized beam. It turns out, however, that for the startup of the FIR laser it is way more critical to minimize the energy spread of the beam even though adjusting the accelerator for energy spread drastically increases the bunch length at the undulator. The optical losses inside the U100 resonator do not exceed 6 % per pass (see Fig. 3), even when only the lowest order hybrid waveguide mode is considered. When out-coupling is included the losses rise by approximately twice the out-coupled fraction due to diffraction losses at the hole. These calculations are in good agreement with a recently measured value of 10 % loss per pass at 30 µm wavelength with the 2 mm out-coupling hole. The calculated average FEL output power reaches levels of 50 W for both maximum electron energy and undulator K parameter. In practise about 12 W were measured and delivered for user operation (see Fig. 4). To measure the energy spectrum at the exit of the FEL has proven an extremely versatile tool to start-up the lasing and to optimize the FEL operation. In the mid-IR FEL one typically can see the spontaneous emission and some spikes of increased intensity which one can use to

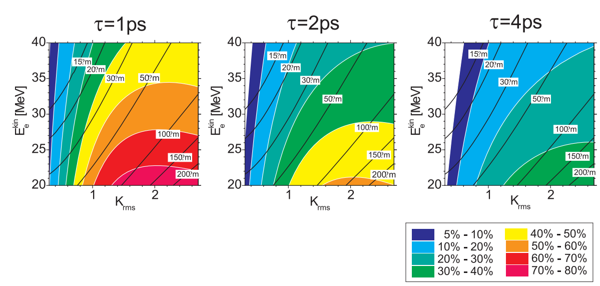

Figure 2: Computed small-signal gain in the low-gain approximation.

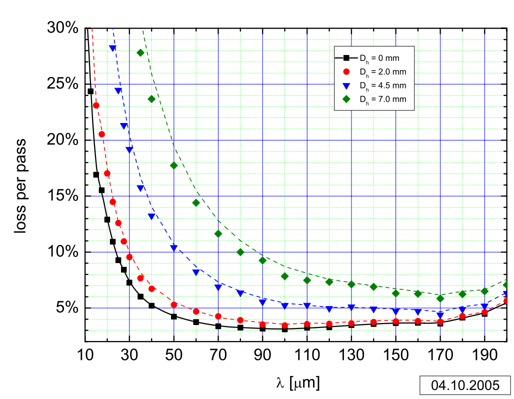

Figure 3: Round-trip losses of the optical beam in the U100 optical resonator. The black line shows the mode conversion losses only. The coloured data additionally include the out-coupling and diffraction losses at different out-coupling hole sizes. At 30 µm the 10 % loss per pass could be confirmed by cavity ring down measurements.

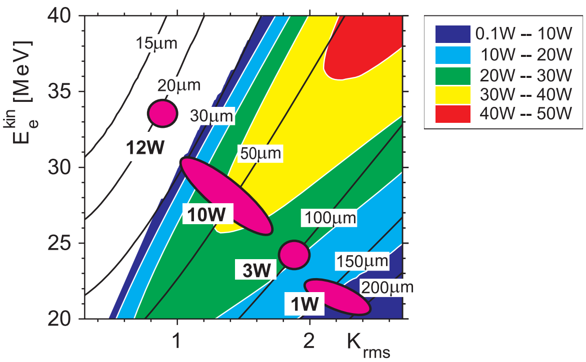

Figure 4: Typical output power of the FEL in CW operation. The best measured values are higher for most wavelengths but do not fully reach the predictions. For small wavelengths the computations show low power output due to high optical losses which was not seen this significantly in the experiment.

optimize the tuning until the laser starts. In the FIR-FEL the detection efficiency of our normally used reference detector is too low to see the spontaneous emission or small spikes of lasing startup. One, however, immediately notices the increase in energy spread on a viewscreen in the dispersive section after the FEL as soon as the FEL starts. It is even possible to use the energy spread as a measure for the amplitude of the optical field inside the resonator. Fig. 5 shows the energy spectrum when tuning the length of the optical resonator.

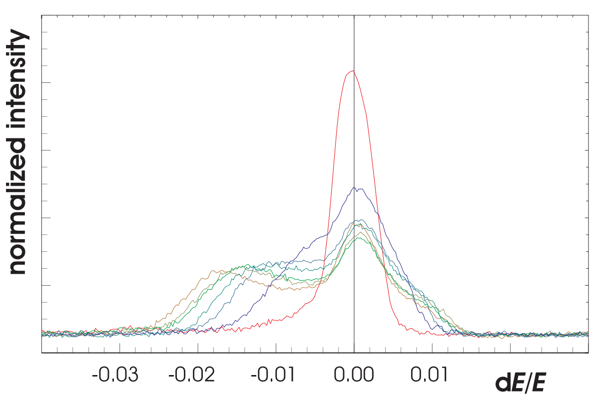

Figure 5: Energy spectra of the electron beam after passage through the FEL. The red trace shows the spectrum for a negative optical cavity detuning where the laser is off. Over green to blue the colours than indicate an increasing detuning with laser action. For minimum detuning (brown trace) the maximum power is out-coupled from the electron beam with some electrons loosing about 2 % of their initial energy. One notes that a certain fraction of the beam does not take part in the laser interaction and remains unchanged in energy.

INACCESSIBLE WAVELENGTH

While the combination of a partial waveguide in the undulator up to the downstream mirror with free optical propagation between the undulator entrance and the upstream mirror showed a reasonably high Q in theory there seam to be problems in practice. We made the observation that at some particular wavelengths it is impossible to start the laser. In addition, the optical spectra show well-defined suppressed wavelengths distributed over the whole range of operation. One example for this is shown in Fig. 6. At a fixed setting of the electron beam, the emission wavelength of the FEL was shifted by changing the undulator gap. For all recorded spectra the emission is suppressed at 30.3 µm wavelength with a marked drop in efficiency and output power when the nominal lasing wavelength just meets the dropout. An absorption line in the optical beam path to the diagnostic station can be excluded because the suppression effect is seen in the energy spread of the electron beam as well.

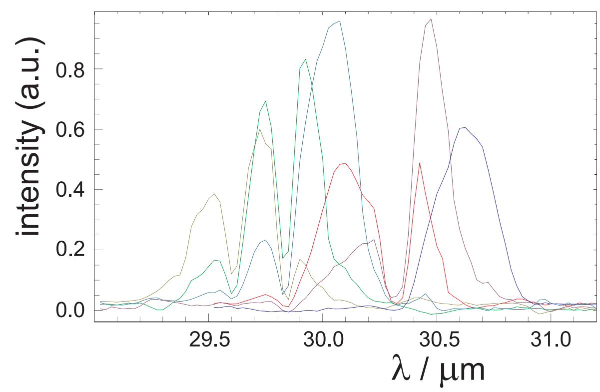

Figure 6: Optical spectra of the laser output shifting the nominal FEL wavelength over a wavelength gap at 30.3 µm.

We presently try to explain this effect with an interference of different optical waveguide modes. The re-circulated optical beam mainly couples into the fundamental transverse waveguide mode essentially spread over the whole waveguide gap. The light created by the laser interaction inside the undulator, however, is emitted in a localized area where the much smaller electron beam overlaps with the optical beam and therefore has a completely different mode structure. We have tried, to compute the phase of the emitted radiation with respect to the fundamental mode assuming a certain combination of modes which yields an angular emission pattern known for undulator radiation. This is propagated through the waveguide to the downstream mirror and back to the exit of the waveguide and yields the phase transfer function pictured in Fig. 7. It is obvious that for phase angles larger than $\pi/2$ the gain vanishes or even becomes negative due to destructive interference with the circulating fundamental mode. Fig. 8 compares the relative gain computed in this strongly simplified model to the wavelengths at which we have observed difficulties to start lasing or drop-outs in the measured wavelength spectra. Obviously, the match is not perfect and further detailed study of the phenomenon is required.

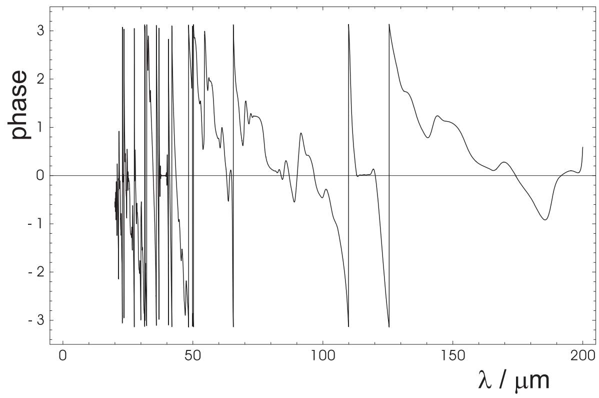

Figure 7: Transfer function of the waveguide for light generated with a gaussian profile at the interaction with the electron beam.

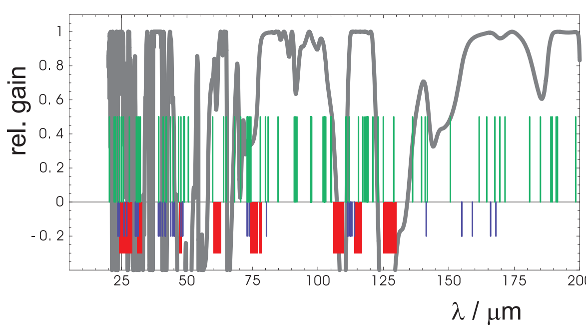

Figure 8: Computed relative FEL gain over the wavelength range. The green lines denote wavelengths at which the FEL was operated so far. The red stripes underline areas in which we had problems to start the lasing and blue lines show wavelengths at which the FEL showed prominent drop-outs in the optical spectrum.

OUTLOOK

Since first lasing in August, 2006, the FIR-FEL at ELBE was commissioned successfully and has since been put into full user operation. The full wavelength range has been demonstrated with the major beam parameters meeting specifications. With this, ELBE is established as a radiation source for the whole IR range from 3 to 200 µm. Both FELs are operated as a user facility, being open to users worldwide, provided their scientific proposals have been favourably evaluated by the panel responsible for distribution of beam time. Under the name ``FELBE" the facility is member of the EC funded ``Integrating Activity on Synchrotron and Free Electron Laser Science (IA-SFS)", which comprises most synchrotron and FEL facilities in Europe and provides financial support to users from EC and associated states. Instructions for beam time applications are available on the FELBE website (www.fzd.de/FELBE). A world novelty is the possibility to use the Elbe IR radiation for experiments in high magnetic fields. The beams of both FELs can be delivered into the new High Magnetic Field Lab Dresden (HLD) [5,6] which was built recently in immediate vicinity to the ELBE building. First experiments have been run this year and scientific results are soon to be expected.

REFERENCES

[1] C. A. Arnold, H. Büttig, D. Janssen, T. Kamps, G. Klemz, W.D. Lehmann, U. Lehnert, D. Lipka, F. Marhauser, P. Michel, K. Möller, P. Murcek, Ch. Schneider, R. Schurig, F. Staufenbiel, J. Stephan, J. Teichert, V. Volkov, I. Will and R. Xiang, Development of a superconducting radio frequency photoelectron injector, Nuclear Instruments and Methods in Physics Research A 577 (2007) 440-454

[2] P. Michel, P. Evtushenko, U. Lehnert, T. Dekorsy, F. Gabriel, E. Grosse, M. Helm, M. Krenz, W. Seidel, D. Wohlfarth, A. Wolf, R. Wünsch, First Lasing at the ELBE mid-IR FEL, 26th International Free Electron Laser Conference FEL 2004, Trieste, Italy

[3] E. Grosse, U. Lehnert, P. Michel, R. Schlenk, W. Seidel, A. Wolf, U. Willkommen, U. D. Wohlfarth, R. Wünsch, A Far-Infrared FEL for the Radiation Source ELBE, 27th Free Electron Laser Conference FEL 2005, Palo Alto, USA

[4] GLAD, Applied Optics Research, Woodland, WA 98674, USA

[5] F. Pobell, A.D. Bianchi, T. Herrmannsdörfer, H. Krug, S. Zherlitsyn, S. Zvyagin, J. Wosnitza, The New High Magnetic Field Laboratory at Dresden: a Pulsed-Field Laboratory at an IR Free-Electron-Laser Facility AIP Conference Proceedings 850 (2006) 1649

[6] J. Wosnitza, A.D. Bianchi, J. Freudenberger, J. Haase, T. Herrmannsdörfer, N. Kozlova, L. Schultz, S. Zherlitsyn, S.A. Zvyagin, Dresden Pulsed Magnetic Field Facility, J. Magn. Magn. Mat. 310 (2007) 2728