THREE YEARS OF CW-OPERATION AT FELBE - EXPERIENCES AND APPLICATIONS

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Abstract

This paper reviews the basic properties of the infrared free-electron laser FELBE at the Forschungszentrum Dresden-Rossendorf. A few highlight experiments using the cw-operation are discussed. Driven by a superconducting linear accelerator, FELBE continuously generates infrared pulses with a repetition rate of 13 MHz. In addition, operation in a macropulse modus (pulse duration $\geq 100\mu$s, repetition rate $\leq$ 25 Hz) is possible. At present FELBE delivers μJ pulses with typical duration of about 0.9-30 ps in the wavelength range 4-230 μm. Furthermore we give an outlook on experiments which will use the beam of FELBE in the High Magnetic Field Laboratory Dresden (HLD). The HLD currently provides pulsed magnetic fields up to 60 T. It operates as a user facility since 2007.

INTRODUCTION

The Radiation Source ELBE [1] at the Forschungszentrum Dresden-Rossendorf (FZD) is built around a superconducting electron linear accelerator, constructed to produce quasi cw electron beams (repetition rate 13 MHz) of up to 1 mA beam current at 12 - 34 MeV. The electron beam is used to generate various kinds of secondary radiations, but is used mainly to drive the two free-electron lasers U27 and U100 in the infrared region (4-230 μm). Starting in summer 2005 beam time is offered to external users in the frame of the EC funded ”Integrating Activity on Synchrotron and Free Electron Laser Science” (FELBE project [2]). FELBE is an acronym for the free-electron laser (FEL) at the Electron Linear accelerator with high Brilliance and Low Emittance (ELBE). Twice a year users are invited to submit proposals for experiments at ELBE. For the period January - June 2009 the deadline will be October 15, 2008. Access is free of charge for all non-proprietary research. Proposals are evaluated by the scientific advisory committee of ELBE. Based on their recommendations the final decision and allocation of beam time will be made by a local panel headed by the Scientific Director of the FZD.

In Fig. 1 the floor plan of the radiation source ELBE with the accelerator vault in the left is shown. Several beam lines lead to corresponding experimental stations. Although the main use is the FEL, we can further use very intense bremsstrahlung (up to 20 MeV) in the nuclear physics cave. Quasi-monochromatic X-rays are produced by channeling of relativistic electrons in single crystals. The energy of the X-rays is tunable between 10 keV and 100 keV. A cell-laboratory is located in direct neighbourhood of the ELBE facility. In addition a reference X-ray radiation source (up to 420 kV) is available on-site. The radiation physics cave is therefore well-suited for radiation biology experiments. The neutron beamline started operation in November 2007, providing neutrons of an energy up to 30 MeV. A source for mono-energetic positrons (1-30 keV) is under construction and will be available by the end of 2008. The FZD establishes a high-power laser laboratory planned to deliver the first 100 Terawatt laser pules to target in fall 2008 (see Fig. 1 down right). The most ambitious goal of this project is to develop a compact and reliable laser-ion accelerator.

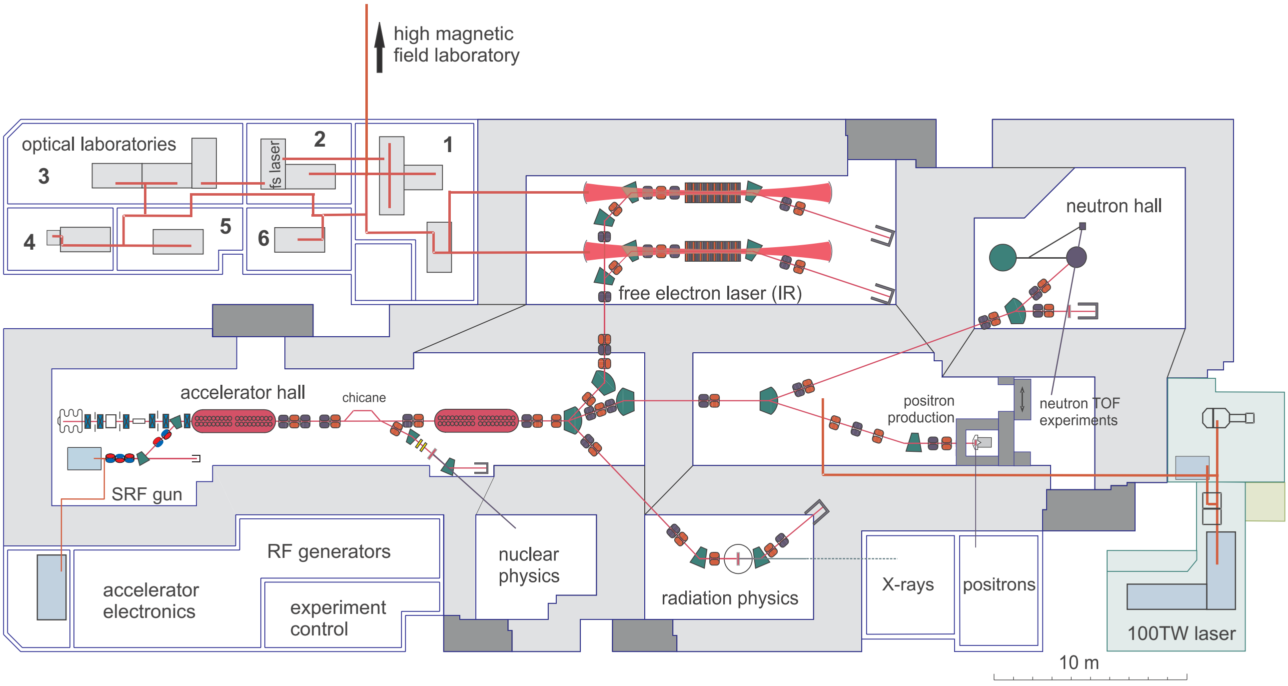
In the upper part of Fig. 1 the optical beam line from the outcoupling holes of U27 and U100 to the diagnostic station is shown. Behind the diagnostic table the IR light from the two FELs is transported to several laboratories in the same building and to the adjacent building (through a 27 m long tunnel) of the High Magnetic Field Laboratory (HLD) [3] as well (see Fig. 2), where the experimental setups are up to 70 m away from the FELs. Here, first self-designed magnets for fields up to 70 T for 100 ms in a bore of 24 mm have successfully been tested and first experiments with FELBE-IR beams have been carried out. The HLD is operated for in-house research and as a user facility as well.

Table 1: FEL specifications

Parameter	U27	U100
Undulator periode (cm)	2.73	10.0
Number of periods N$_u$	2x34	38
Undulator parameter K$_{rms}$	0.3-0.7	0.5-2.8
Wavelength (μm)	4-22	18-230
Extracted max. pulse energy (μJ)	2	5
Extracted max. aver. power (W) at certain wavelengths	30	65

FEL CHARACTERISTICS

Constructional peculiarities, the large wavelength range, the high average power in cw regime, and the beam property requirements of the users pose a challenge to the diagnostics [4] and beam line design [5]. In Table 1 the pa-



1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: Near-field IR experiment
5: Pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal deflection spectroscopy

Figure 1: Scheme of the ELBE facility. For explanation see text.

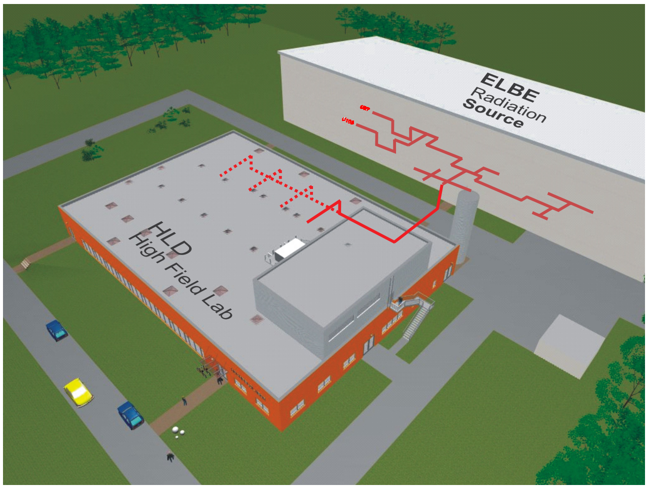


Figure 2: Arrangement of the ELBE building and the High Magnetic Field Laboratory with the IR beam transport system (red line) and the future extension (red dashed line).

rameters of both FELs are shown. The outcoupled laser power transported by the beam line strongly depends on the parameters of the electron beam and of the FEL undulator and resonator. To avoid the absorption of IR light, the pipes of the beam line are either evacuated or purged with dry nitrogen gas. To prevent damages at the beam line windows (KRS-5, ZnSe, Diamond, and Polymethylpentenfoil (TPX)), all windows are encoded with respect to the beam transmission. These numbers are integrated into the existing Programmable Logic Control (PLC) and Human-Machine-Interface (HMI) enviroment of ELBE. This ensures the appropriate window for the generated wavelength, whereas otherwise the beam will be blocked.

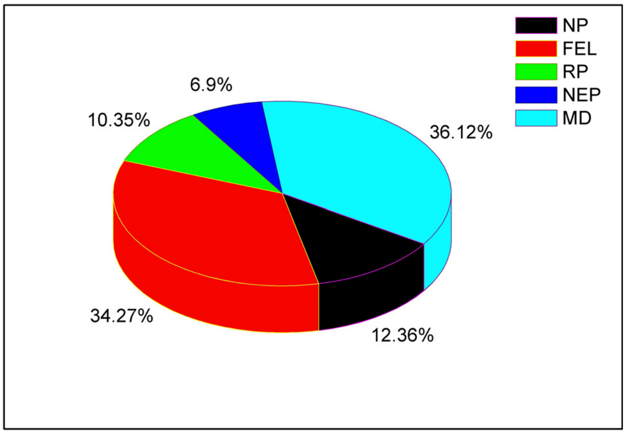


Figure 3: Allocation of ELBE beam time in the period July 2007 to August 2008.

Fig. 3 shows the allocation of ELBE beam time in the period July 2007 to August 2008 for NP (Nuclear Physics, Bremsstrahlung), FEL, RP (Radiation Physics, X-Rays), NEP (Neutron Physics, neutron time-of-flight) and MD (Machine Development). The FEL proposals required the

U27 with 49%; the U100 with 34% and both together with 17% of their used beam time. The fact that 95% of the FEL user beam time was delivered in cw mode can be considered as an impressive confirmation of the main ELBE concept which is based on a superconducting high average current accelerator as driver.

For successful operation of the FEL the beam stability in frequency and power is very important. FEL wavelength stability is extremely important for experiments using narrow bandwidth excitations or absorptions. Resonances in scanning near field optical microscopy (SNOM) [6] are smaller than 1% of the wavelength in some cases and require wavelength stability better than 0,5% over a few hours. Single-shot experiments like combined infrared high-pulsed magnetic field studies which can be done in the ELBE-HLD complex [3], requires FEL beam power stability during the 100 ms long magnet pulse of better than 1%. To improve the long and short term stability we developed and implemented active feed-back controls for electron energy and thus laser wavelength and out-coupled IR-beam power at FELBE [7].

FEL APPLICATIONS

The dynamic behavior of electrons in semiconductors and their heterostructures is of crucial importance for many of their optoelectronic applications. Most prominently, intersubband relaxation processes are directly incorporated into the design of quantum cascade lasers (QCLs) and quantum well infrared photodetectors. Along with further development of such devices, a detailed understanding of the intersubband relaxation in quantum well structures is important. The work in ref. [10] presents two-color pump-probe transmission measurements on doped GaAs/AlGaAs superlattices using the infrared free-electron laser FELBE in combination with a synchronized table-top broadband infrared light source. For minibands wider than the optical phonon energy of GaAs, fast relaxation, nearly constant for different excitation intensities is observed, whereas for narrow minibands, a strong temperature and intensity dependence of the relaxation is found (see Fig. 4).

Ferroelectric materials are named after ferromagnetic ones because they behave in a similar way. The main difference is that these materials are not magnetically, but permanently electrically polarized. They have great importance for data storage technology and novel piezoelectric devices. A group at the Technische Universität Dresden was able to produce microscopic images of ferroelectric domains with SNOM [6]. In the tiny regions of a ferroelectric material the electric polarization points in different directions. Scientists from TU Dresden aimed at getting an as clear as possible image of the domains in order to understand better how they function, and to specifically manipulate the electric charge of the domains for future devices. It turns out that the SNOM signal contains microscopic information about the sample, in fact with a resolution better than 200 nm, which is hundred times smaller than the wave-

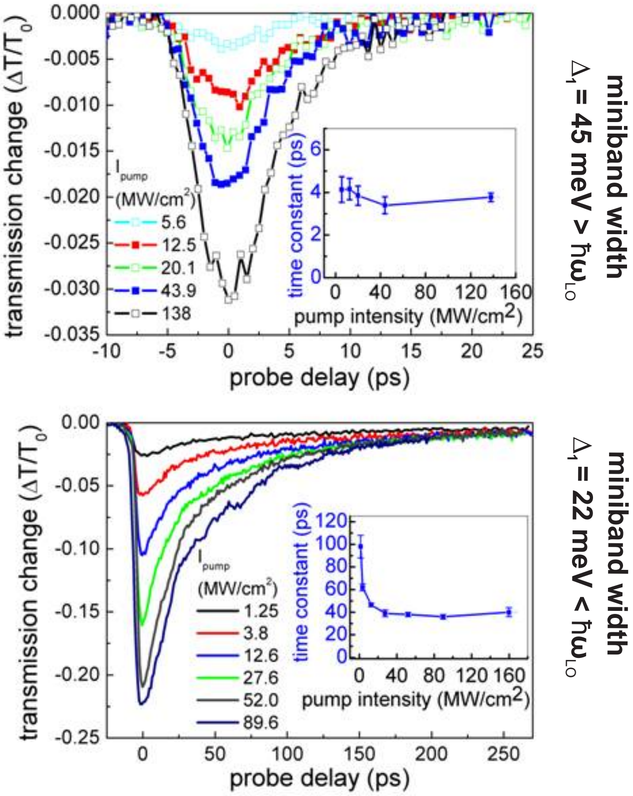


Figure 4: Transmission changes of two different samples (different miniband widths) at T= 4 K for several pump intensities. The insets show the recovery time extracted from an exponential fit to the data [10].

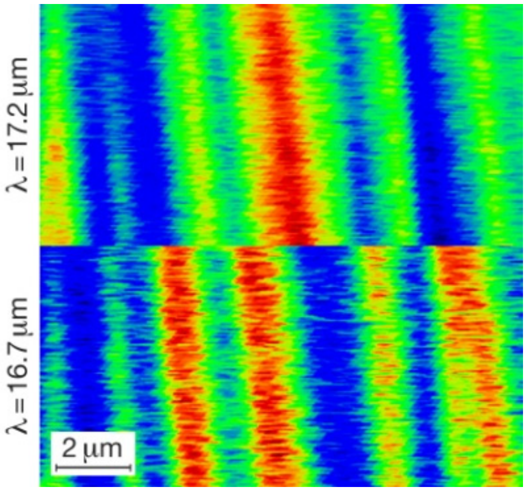


Figure 5: False-color image of the electric domains on the surface of a bariumtitanate crystal by using radiation with 17.2 and 16.7 μm. Strong signals are in red. The change of the colors from red to blue is clearly visible [6].

length of the light.

The domains of the ferroelectric material are shimmered in different colors (see Fig. 5). This is due to the fact that the interaction of the infrared light with the crystal via the tip is different for the two types of domains. The two types of domains have their individual resonance frequencies. This is the frequency at which the largest amount of infrared light is scattered. In the experiment, areas that appear bright in the image (red in false-color) at a wavelength of 16.7 μm, become dark (blue in false color), when the wavelength is tuned to 17.2 μm, and vice versa. The results show the huge potential the free-electron laser has when used for near-field microscopy. The large power and tunability are indispensable for this type of investigations. The group is presently extending its activities thanks to the funding by the German Science Foundation (DFG).

The High Magnetic Field Laboratory Dresden focuses on modern materials research in high magnetic fields. In particular, electronic properties of metallic, semiconducting, superconducting, and magnetic materials are invetigated. Unique in the world, the free-electron laser FELBE of the neighbouring superconducting electron accelerator ELBE can be used in combination with high-field magnets for magneto-optical experiments at low temperatures.

Highly-correlated electron systems have been a central issue of quantum physics for many years. Its was shown that quantum fluctuations are significantly enhanced in spin systems with reduced dimensionality. Apart from the fundamental quantum-mechanical concepts and theories, the problem of quantum effects in highly-correlated spin systems has tremendously high impact for numerous applications in modern technology. High-field/frequency electron spin resonance (ESR) is known for its remarkable resolution and the accessibility of large zero-field spin-level splitting in magnetic materials.

Recently, a new ESR spectrometer has been completed at the HLD at the FZD, which allows performing high-frequency ESR experiments in pulsed magnetic fields up to 60 T. The spectrometer operates in combination with free electron laser in the frequency range of about 1.3 - 70 THz. In Fig. 6 we show an example of an ESR spectrum in quasi-one-dimensional S=1/2 chain material (6MAP)CuCl3, obtained using pulsed-field FEL-ESR facilities in Rossendorf. Two very sharp absorption peaks, corresponding to the field-up and field-down sweeps of magnetic field, have been observed in the excitation spectrum. The resonance was detected at a frequency of 1.31 THz (228.6 μm) in a field of 44 T [8].

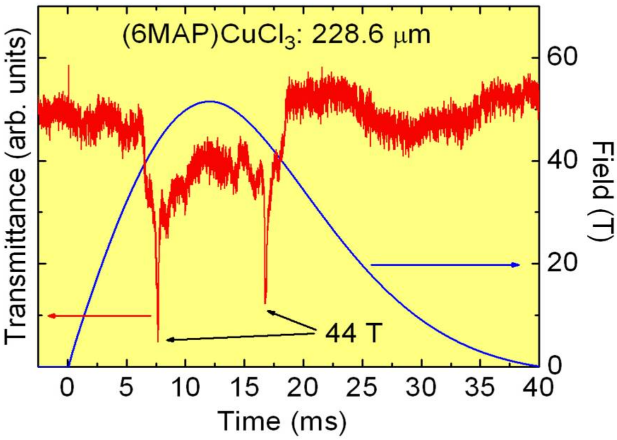


Figure 6: The absorption spectrum (in red) in quasi-one-dimensional S=1/2 chain material (6MAP)CuCl3, obtained at 80 K using pulsed-field FEL-ESR facilities in Rossendorf. Magnetic field is shown in blue (see text) [8].

Nowadays strained-layer InGaAs/GaAs heterostructures remain potentially interesting for many applications like high-frequency electronics, solar cells, and lasers. Experimentally, the effective mass of 2D holes in InGaAs/GaAs quantum wells (QW) was studied by many groups, however most of the measurements were limited to low magnetic fields. The cyclotron resonance absorption in p-type InGaAs/GaAs QWs was investigated at high magnetic fields up to 55 T [9]. The group traced the resonance position as a function of magnetic field when the excitation wavelength changes from 120 μm down to 65 μm. Obtained data were analyzed using a 4x4 Luttinger Hamiltonian that includes the quantum well potential profile as well as the strain potential. An excellent agreement with experimental data taking the usual Luttinger parameters from the literature, with no additional fit parameters, was found. On the other hand, the observed distribution of the spectral weight of cyclotron absorption lines contradicts the generally accepted behavior.

REFERENCES

[1] P. Michel et al., Proceedings of the 2004 FEL Conference, p. 8-13, Trieste, Italy

[2] www.fz-rossendorf.de/felbe

[3] J. Wosnitza et al., J. Phys.: Conf. Ser. 51, 619 (2006)

[4] W. Seidel et al., Proceedings of the 2006 FEL Conference, p. 341-344, Berlin, Germany

[5] W. Seidel et al., Proceedings of the 2007 FEL Conference, p. 171-174, Novosibirsk, Russia

[6] S.C. Kehr et al., Phys. Rev. Lett. **100**, 256403 (2008)

[7] M. Justus et al., Proceedings of the 2008 FEL Conference, FRAAU03, Gyeongju, Korea

[8] S. Zvyagin et al., in preparation

[9] O. Drachenko et al., submitted to Appl. Phys. Lett.

[10] D. Stehr et al., Appl. Phys. Lett. **92**, 051104 (2008)