THE ROSSENDORF IR-FEL ELBE

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Abstract

The radiation source ELBE is the central research facility in the Forschungszentrum Rossendorf. The machine is based on a 40 MeV superconducting RF Linac which can be operated up to 1 mA in cw mode. After commissioning the Bremsstrahlung and the X-ray facilities in 2002 and 2003, respectively, and the first lasing of the mid-IR FEL (3-22 µm) in 2004 about 7000 hours user beamtime have been provided. At present a second FEL for long IR waves (20-150 µm) using a partial waveguide is under commissioning. First lasing was demonstrated on August 21-st, 2006. Besides in-house users particularly the IR beam is available to external users in the FELBE (FEL@ELBE) program which is a part of the EU funded integrated activity on synchrotron and free electron laser science. In this contribution the fundamental features of the ELBE IR FEL's and the operational experiences which were collected during two years of FEL user operation are described. Future projects like the combination of the new High Magnetic Field lab with the ELBE-IR beams will open up unique experimental possibilities.

INTRODUCTION

In the Forschungszentrum Rossendorf in Dresden, Germany, the superconducting electron accelerator ELBE (Electron Linac with high Brilliance and low Emittance) has come into user operation in 2002. ELBE accelerates electrons to energies up to 40 MeV with an average beam current of 1 mA in quasi continuous wave (cw) mode. The electron linac [1] serves as a driver to generate several kinds of secondary radiation and particle beams, which are FEL-Infrared Radiation for a very large field of applications reaching from semiconductor physics to biology, 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. The kind and characteristics of the produced secondary beams at ELBE are in accordance with the scientific profile and the experimental requirements of the Forschungszentrum Rossendorf. For a layout of the ELBE building see Fig. 1.

ELECTRON LINAC

A driver for these different kinds of secondary radiation must be characterized by a high average beam current and a small transverse and longitudinal emittance. For this reason only a superconducting high frequency accelerator was taken into consideration. Low energy electron bunches are produced in a grid-pulsed thermionic gun operating at 250 keV DC voltage. It delivers pulses with a bunch charge up to 77 pC at 13 MHz repetition rate and about 450 ps length. The transverse emittance in this case is about 10 mm mrad caused by the electric-field deformation close to the grid [2]. To generate beams with smaller emittance values the grid can be pulsed with 260 MHz at drastically reduced bunch charge. In combination with phase space cutting using apertures, emittance values below 2 mm mrad can be achieved in this regime. For reduced average power, macro bunching is possible as well, yielding 100 µs or longer macro pulses at a < 25 Hz repetition rate. Pulse compression down to 10 ps which is necessary for injection into the 1.3 GHz RF accelerator is done by a two-stage RF bunch compressor operating at 260 MHz and 1.3 GHz, respectively.

The two main accelerator stages are based on two 9-cell RF cavities which were developed for the TESLA project at DESY [3] and are kept at 2 K using superfluid helium delivered by a commercial helium liquefier (Linde). The cavities are individually driven by 10 kW CPI klystron amplifiers. The RF couplers consist of a double-window arrangement and a door-knob shaped adapter for RF transmission from rectangular waveguides to co-axial cavity coupler antenna. The vacuum windows are rectangular plastic windows at room-temperature level and circular ceramic windows cooled by liquid nitrogen. The maximum acceleration field gradients of the cavities exceed 10 MV/m. In practice only 9-9.5 MV/m are accomplished limited by cavity heat loading and field emission. Taking into account that the total acceleration energy is reduced by nearly two MeV due to the capture of low-beta electrons in the first accelerator stage, the maximum total energy is about 36 MeV in practice. To achieve higher acceleration field the RF can be pulsed up to a duty cycle of 1:2. Maximum energy of about 50 MeV can be obtained at a duty cycle of 1:10. A magnetic bunch compressor with adjustable R_{56} < 500 mm is located between the acceleration modules and serves, together with the RF phase of the accelerator cavities, to modify the longitudinal phase space configuration. The electron beam parameters at ELBE will be considerably improved by replacing the thermionic DC gun by a superconducting RF photo gun [4] which is planned for 2007.

FREE ELECTRON LASERS

To cover the required wavelength range two FELs are required. The calculated ranges for both FELs are shown

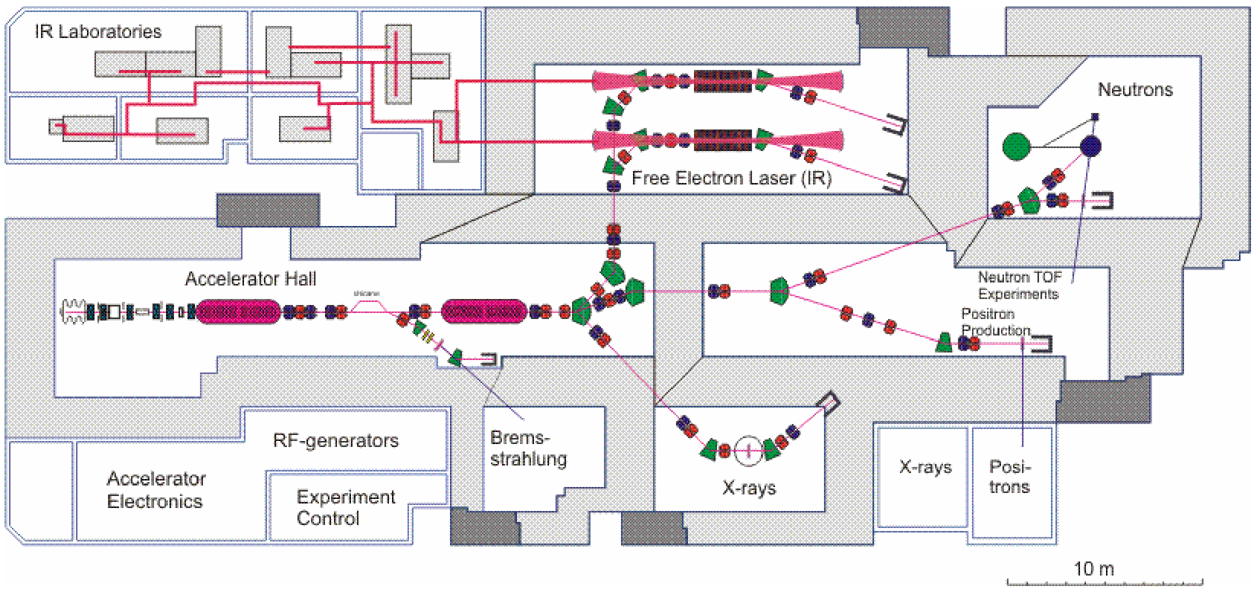

Figure 1: Layout of the Radiation Source ELBE

in Fig. 2. The U27 FEL consists of two 34-pole sections with individually adjustable gaps. The undulator period is 27.3 mm and the magnet material is NdFeB (hybrid type). The distance between the two sections is adjustable for phase matching. The gaps can be varied independently from 13.8 mm to 21 mm corresponding to K_{rms}= 0.7 to 0.3. To optimize the extraction ratio over the whole wavelength range mirrors with different outcoupling hole sizes (1.5, 2, 3, and 4 mm in diameter) are used. The mirrors are made of gold coated copper.

The U100 FEL for the far infrared range is based on a SmCo hybrid undulator which consists of 38 magnet periods each 100 mm long. The K_{rms} can be adjusted from

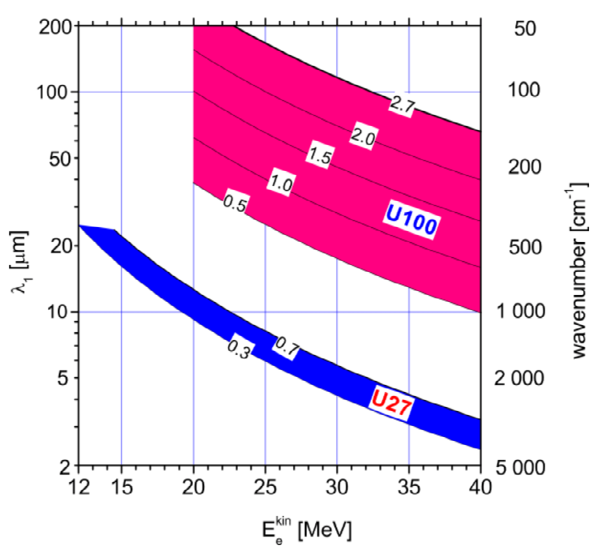

Fig.2: Wavelength ranges of the U27 and the U100 FELs at ELBE as a function of the electron kinetic energy calculated for the indicated values of the undulator parameter K_{rms}.

0.3 to 2.7 which corresponds to gaps of 85 to 24 mm. It is also equipped with interchangeable outcoupling mirrors (hole diameter 2, 4.5 and 7 mm). To obtain high enough magnetic fields in the undulator the gap and consequently the optical mode has to be sufficiently small. To fulfill this requirement the U100 FEL is equipped with a partial parallel-plate waveguide 10 mm wide. The horizontal size is wide enough to allow free propagation. The waveguide spans from the undulator entrance to the downstream mirror. In the remaining part of the optical cavity the optical mode propagates freely. Mirrors are toroidal on the free propagation side (6.33 m and 3.61 m curvature) and cylindrical (6.33 m curvature) on the waveguide side. They are also made of copper with gold coating.

OPTICAL USER LABS

Experiments are performed in the IR user labs, that are shown in the upper left corner of the sketch of Fig. 1. A lot of ancillary equipment is provided, most importantly a number of table-top optical sources like femtosecond Ti:sapphire lasers and a ps Nd:YAG laser which can be synchronized with the FEL to better than a picosecond. The labs are specially equipped for imaging of thin films on surfaces by polarization-modulation IR reflection-absorption spectroscopy and time resolved femtosecond (pump-probe) experiments. Scattering scanning-near-field optical microscopy (SNOM) has been performed as well, There is one user lab with permission for handling of radioactive substances which allows IR spectroscopy on radioactive samples.

The IR beams coming from U27 or U100 both enter a common beam path at the diagnostic station shown in Fig. 3. Most of its components are designed for remotely controlled operation. A scraper mirror is used to outcouple a certain fraction of the main beam for

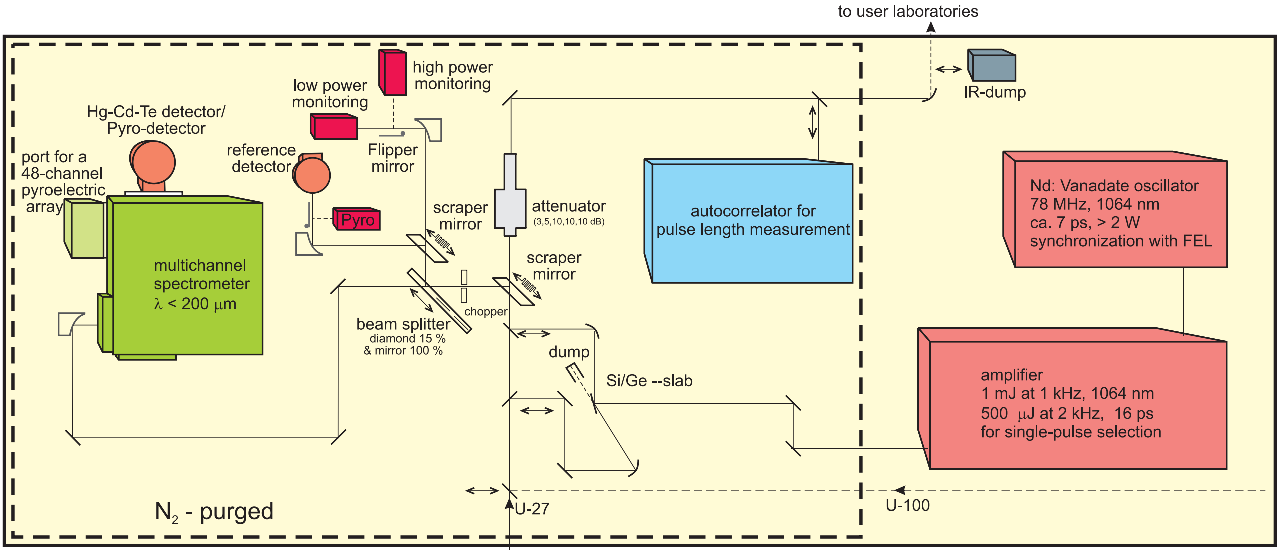

Fig 3. Layout of the diagnostic station for the IR beam.

diagnostic purposes. It can be directed either to an MCT detector which is used to monitor the start up of the laser and its temporal structure and which also acts as a reference detector for experiments or to one out of two power meters. Several MCT detectors are available with preamplifier bandwidth ranging up to 20 MHz enabling us to detect individual micro pulses. For very long wavelengths or measurements with extremely high sensitivity a Ge-Ga detector can be set up. Via a beam splitter part of the diagnostic beam can be sent through a wide-range spectrometer. To cope with CW operation of the FEL a chopper is included in the diagnostic beam path which is synchronized to the macro pulse in pulsed-mode operation. The main beam path to the user laboratories first contains a remotely controlled attenuator. A non-collinear background-free autocorrelator can be used to characterize the optical pulse duration. For experiments requiring lower repetition rates than the 13 MHz round-trip time of the optical resonators a semiconductor plasma switch driven by a Nd:YAG laser amplifier at 1 kHz rate can be used as pulse picker. The optical beamline to the

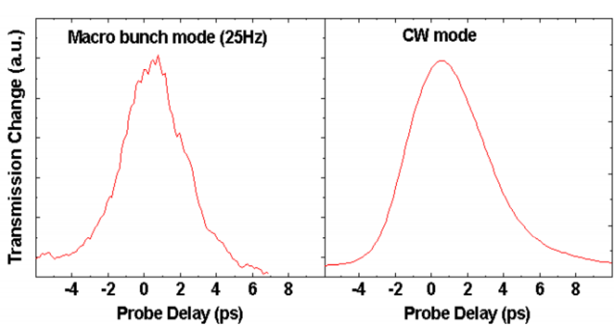

Fig 4. Transient transmission change measured with the pump-probe technique in accelerator macro pulsed mode (left) and in cw mode (right). Both pulses (15.8 µm) are generated by the FEL.

user laboratories is designed for less that 15% transmission loss between 3 and 150 µm wavelength. The typical horizontal polarization is conserved but can be switched if necessary.

Proposals for FEL experiments are evaluated and selected in a peer-review system. Under the name FELBE the facility is a 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 the EC and associated states. Up to now 12 experiments have been running at the ELBE FEL facility.

OPERATIONAL EXPERIENCES

First lasing of the U27 FEL was achieved in May 2004 [5]. Immediately after commissioning routine user operation was started. Up to now more than 1300 hours for user FEL experiments were delivered. The availability of the machine in 2006 has been higher than 90 %. The following parameters are achieved in practice: Laser radiation from 3.4 to 22 µm was generated. The outcoupled beam power depends strongly on the wavelength range. Low average power (<5 W) was observed in the ranges shorter than 5 and longer than 13 µm. In the range in between up to 25 W power could be extracted. In the region above 20 µm the outcoupled power is smaller than 1 W and finding stable conditions for lasing is difficult due to the high diffraction and aperture losses in the undulator vacuum chamber. The IR pulse duration can be varied by detuning the optical cavity. At 11 µm, which was an often required wavelength for user experiments, it could be adjusted from 0.9 to 3.4 ps. It could be shown by comparing autocorrelation traces with optical spectra that the pulses are bandwidth limited. By many of the FEL users high average power implying cw operation is required. Apart from the higher measuring rate and the associated better signal to noise ratio a clearly higher stability of the laser at cw operation was observed. Reasons for this observation are the continuous loading of the superconducting RF cavities and the continuous laser operation. Fluctuations due to build up of the laser into saturation can be avoided. Fig. 3 demonstrates the improved quality of the experimental data in cw mode. It shows a typical time resolved transmission traces measured by the pump-probe-technique in macro pulse mode (left) and cw mode (right). The measurements were done in the framework of an experiment to study electron dynamics in superlattices [6].

OUTLOOK

First lasing of the U100 FEL was demonstrated on August, 21-st, a few days before the FEL2006 conference. Now the actually available wavelength range and the parameters of the IR beam have to be determined. Then the extended wavelength range will immediately be made available to the user experiments.

In the near future the beams of the two FELs will be delivered into the new High Magnetic Field Lab Dresden (HLD) [7] which was built recently in immediate vicinity to the ELBE building. The HLD will provide magnetic-field pulses in the 60-100 Tesla range with 1000-10 ms pulse duration, thus opening the way for many new spectroscopic investigations, in particular in solid state and semiconductor physics. For these investigations also time resolved experiments are envisaged. The challenge here is to obtain a complete time-delay scan during the time of one magnetic field pulse. Recently we have demonstrated the measurement of an FEL interferometric autocorrelation trace within 25 ms [8]. In general, no synchronization of the FEL with magnetic field pulses is needed, since the FEL runs continuously at 13 MHz in cw mode which means that about 10^5 FEL pulses overlap with one 10 ms-magnetic field pulse. This should provide excellent measurement conditions.

ACKNOWLEDGEMENT

The authors thank Todd Smith from HEPL Stanford University and A.F.G. van der Meer from FELIX Nieuwegein for her useful help and advice. Furthermore we thank the engineering stuff of the Forschungszentrum Rossendorf for the successful cooperation.

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