AN ELECTROMAGNETIC UNDULATOR FOR THE FAR INFRARED AT ELBE

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Abstract

The first lasing in the mid infrared (IR) at the ELBE FEL [1, 2] allows us to specify the parameters of an additional undulator for longer wavelengths to complement the U27 undulator which is useful up to about 25 microns at most. In the longer wavelength range FELs constitute a unique radiation source with appealing properties. Radiation quanta in this range are appropriate for the low-energy spectroscopy of various interesting modes in solid-state quantum-structures as well as in complex biological systems (e. g. DNA molecules).

We envisage an electromagnetic undulator with a period of roughly 12 cm. Using the electron beam of ELBE, IR light from 15 to 150 microns and beyond can be produced. To keep the transverse beam extension small, the IR beam is to be guided by a partial waveguide. An appropriate bifocal resonator mirror minimizes the mode coupling losses at the exit of the waveguide. Detailed calculations and computer simulations predict an outcoupled laser power of roughly 15 W at 150 microns which will be transported to experimental stations. The maximum power is expected to be 35 W at wavelengths between 40 and 90 μm.

WHY ANOTHER UNDULATOR?

At present the U27 undulator at the radiation source ELBE is producing IR light between 16 and 22 μm at electron energies around 16 MeV. Soon a second cryostat with 18 more accelerator cells will be installed. The higher electron energy (up to 40 MeV) extends the range down to 3 μm. To extend the range to the far infrared ($\lambda \leq 150\,\mu\mathrm{m}$) another undulator with a larger period is envisaged.

In the far infrared a FEL constitutes a unique radiation source. Radiation quanta with this energy (10 - 100 meV, 2 - 20 THz) are appropriate for the spectroscopy of low-energy elementary and collective excitations. Such excitations are observed in solid-state quantum-structures and in complex biomolecules as well. Their study establishes the basis for understanding complex phenomena in solids and liquids and for elucidating processes in biological material. Technological and medical innovations are the long-term output of such investigation.

ITS PARAMETERS

To produce radiation in the THz region by means of the ELBE beam an undulator with a period λ_u of several centimeters is needed. To avoid the use of electron energies below 20 MeV, where the energy spread is larger than 0.3%, we propose an undulator period of λ_u= 12 cm which should preferably be made of electromagnets with an undulator gap of 18 mm. To get a sufficiently high single-pass gain 30-40 undulator periods are necessary resulting in a total undulator length of 4-5 m. The design of the electron beam line requires an asymmetric installation of this long undulator. Its middle is located roughly 1 m downstream from the resonator center. The maximum undulator parameter of $K_{\mathrm{rms}} \approx 2.5$ corresponds to a field amplitude of 0.3 T on the undulator axis.

Fig. 1 shows the wavelength range covered by such an FEL. It slightly overlaps the range of the U27 undulator [2] and allows to produce light up to 200 μm. Above 150 μm the diffraction losses in the presently designed IR beam line diminishes the power available in the user laboratories considerably.

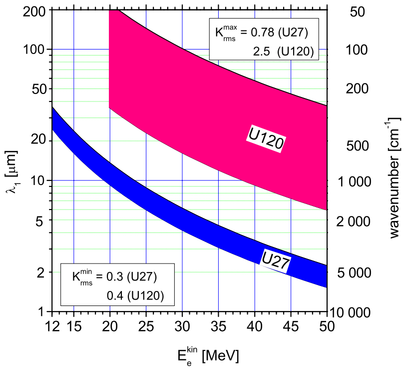

Figure 1: Wavelength ranges of the existing U27 and the planned U120 undulator of ELBE as a function of the kinetic electron energy E_e^{kin}. The colored areas indicate the wavelength λ_1 of the first (fundamental) harmonic.

Above roughly 50 μm the diffraction of the IR beam has seriously to be taken into account. It increases the beam radius in the resonator and the beam line and reduces the coupling with the electron beam in the undulator (filling factor). Big resonator mirrors, large diffraction losses and a small laser gain are the result. The long resonator (11.53 m) and the long undulator (4-5 m) make it even more difficult. That is why we propose a vertical beam compression by means of a rectangular waveguide spanning from the undulator entrance to the downstream resonator mirror (see Fig. 2). It should be 10 mm high. To avoid ohmic losses in the side walls the waveguide has to be broad enough to al-low a free beam propagation in the horizontal direction [4]. The free propagation on the upstream side of the resonator simplifies the passage through the dipole and quadrupole magnets and provides an approximately round beam profile at the outcoupling mirror (M1). The downstream mirror (M2) has to be cylindrical. The proposed setup is similar to that used at the FELIX facility [5]. Alternatively a complete waveguide without mode-coupling losses but with a rather asymmetric outcoupled beam profile can be used.

To minimize the optical beam cross section in the undulator we propose an asymmetric resonator with the horizontal beam waist located in the undulator center and a Rayleigh length of half the undulator length (≈ 2.5 m). The proposed height of the waveguide and the resulting pole gap are large enough for the electron beam and allows a sufficiently large magnetic field on the axis (0.3 T) at a reasonable current in the undulator coils.

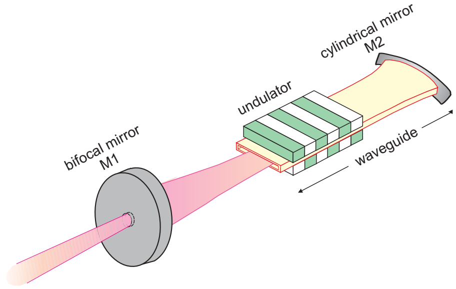

Figure 2: Optical mode compression by means of a resonator with partial waveguide.

While the horizontal radii of curvature are solely determined by the Rayleigh length and the waist position the vertical curvature of M1 can be used to minimize the mode conversion losses at the waveguide entrance. In general the optimum curvature depends on the wavelength (black line in Fig. 3).

Calculations using the code GLAD [6] have shown that a radius of curvature which is equal to the distance between resonator mirror and waveguide entrance (407 cm, far-field limit, red curve in Fig. 3) minimizes the mode conversion losses at $\lambda > 30\,\mu m$. Here, the losses per resonator pass do not exceed 7%. At shorter wavelengths the losses grow up to 12% per pass at 20 μm. For short electron pulses the gain exceeds this value. Using a larger radius of curvature (500 cm, blue curve) the losses can be reduced to 7%. But this mirror has an advantage only between 15 and 25 μm.

The parameters of electron beam, undulator and resonator are summarized in Table 1. The beam parameters are close to the actual beam parameters of ELBE. Putting into operation the superconducting RF-gun [3] the energy range can be extended to roughly 50 MeV.

EXPECTED GAIN AND POWER

Using the parameters of Table 1 we have calculated the single-pass gain (Fig. 4) and the outcoupled average laser

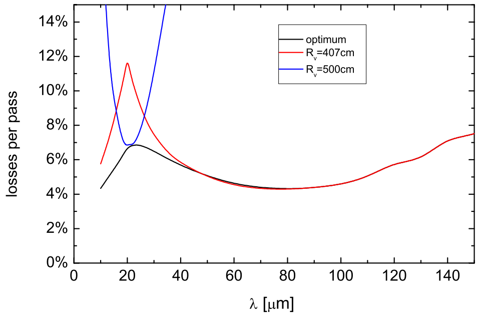

Figure 3: Resonator round-trip losses as a function of the wavelength λ calculated for various vertical radii of curvature R_v. The black line indicates the minimum losses while the red and blue lines stand for definite radii of curvature. Additionally to the mode conversion the absorption (2 x 0.7%) on the mirror surfaces has been taken into account.

Electron beam	
Kinetic energy	(10) 20-45 (50) MeV
Pulse charge	70 pC
Energy spread	60 keV
Norm. transv. emittance	15 mm mrad
Undulator	
Undulator period	12 cm
Number of periods	40
Magnetic field amplitude on axis	≤ 0.3 T
Undulator parameter ($K_{\rm rms}$)	≤ 2.5
Pole gap	18 mm
Resonator	
Length	1153 cm
Horizontal Rayleigh length	2.5 m
Horizontal radii of curvature	M1: 768.9 cm, M2: 607.7 cm
Vertical radii of curvature	M1: 407 cm M2: ∞
Waveguide height (internal)	10 mm
Waveguide length	746 cm

Table 1: Parameters of electron beam, undulator and resonator

power [7] (Fig. 5). Changing the rms pulse length from 1 to 4 ps the λ of maximum gain is shifted from 40 μm (45%) to 150 μm (30%). Notice that Fig. 4 displays the gain maximum with respect to resonator desynchronization. Maximum power is obtained at a smaller desynchronization where the gain is considerably smaller. That is why the maximum gain should clearly exceed the losses in the resonator. The maximum average outcoupled power is predicted to be approximately 35 W independently of the electron pulse length. The wavelength with the highest power varies from 12 μm at 1 ps to 70 μm at 4 ps. The pronounced drop of average power around 20 μm is caused by the large mode-coupling losses in this region (see Fig. 3).

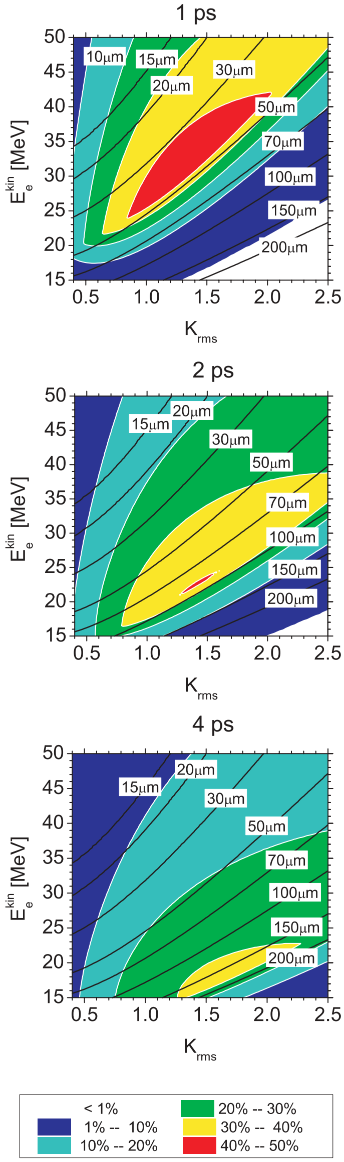

Figure 4: Laser gain predicted for 1, 2 and 4 ps (rms) electron pulses of ELBE as a function of undulator parameter $K_{\rm rms}$ and kinetic electron energy $E_{\rm e}^{\rm kin}$. Calculation for the parameters of Table 1 and optimum cavity desynchronization.

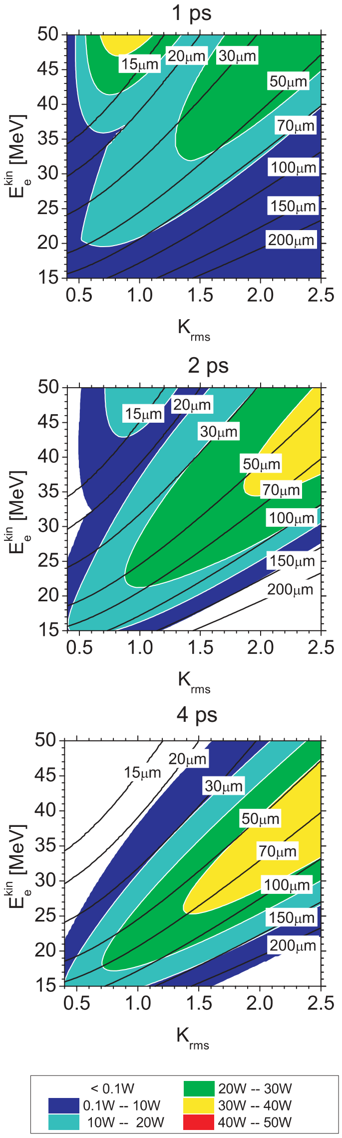

Figure 5: Maximum outcoupled average laser power predicted for 1, 2 and 4 ps (rms) electron pulses of ELBE as a function of undulator parameter $K_{\rm rms}$ and kinetic electron energy $E_{\rm e}^{\rm kin}$. Calculation for the parameters of Table 1.

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