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Investigation of short pulse effects in IR FELs and new simulation results

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Abstract

The Darmstadt IR FEL is designed to generate wavelengths between 3 and 10 μm and driven by the superconducting electron linear accelerator. The pulsed electron beam has a peak current of 2.7 A leading to a small signal gain of 5%. Currently, investigations of the energy transfer process inside the undulator are performed using the 1D time-dependent simulation code FAST1D-OSC. We present simulation results for the power vs. different desynchronization and tapering parameters as well as a comparison with experimental data from the S-DALINAC IR-FEL. Furthermore, a compact autocorrelation system assuring a background-free measurement of the optical pulse length is described. In a first test experiment at FELIX, the autocorrelator has been tested at wavelengths $5.7 \leqslant \lambda \leqslant 9.0$ μm. The frequency doubling in a 2 mm-long $ZnGeP_2$-crystal resulted in a time resolution of 300 fs and a conversion efficiency of 5%.

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Keywords: Free electron lasers; Tapering; Short optical pulses; Autocorrelator; Linac

1. Introduction

The Darmstadt FEL is driven by the superconducting Darmstadt recirculating linear electron accelerator S-DALINAC [1], that was designed to deliver a continuous wave (cw) electron beam and which has gone into operation in 1991. As a driver for the FEL, the accelerator provides electrons with an energy between 25 and 50 MeV, a peak beam current of 2.7 A at a micro-pulse repetition rate of 10 MHz and a pulse length of 2 ps. The laser pulses have the same temporal structure as the electron beam.

In Section 2, we introduce the code used for the numerical simulations of the interaction processes in the uniform and tapered undulator, present some results of the code verification and first results of numerical simulations of the Darmstadt FEL with a tapered undulator. In Section 3, the

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autocorrelator designed for further experimental studies of short-pulse effects at the S-DALINAC is presented and first results from a test experiment at FELIX are summarized.

2. Tapering

A method to increase the rather low FEL efficiency, proposed about two decades ago, is based on the tapering of the magnetic field of the undulator. Since the evolution of the macro pulse depends strongly on the applied cavity desynchronization, numerical simulations using the 1D time-dependent code FAST1D-OSC [2] for the parameters of our FEL were carried out. The core of the code is a module for the time-dependent simulation of the amplification process over one pass through the undulator [3]. The optical feed back is arranged in a way as described in Ref. [4]. The code allows to simulate time-dependent processes in an FEL oscillator with the variable undulator parameters. The FEL generation starts from the shot noise. The validity of the code was checked by comparing the results for various observables like macro-pulse evolution, spectral distributions and pulse shape with other codes and experiments. Fig. 1 shows the dependence of the FEL average macro-pulse power as a function of the cavity desynchronization. The solid line represents the results of the simulations and the solid circles the measured values. The measurements were carried out using a pulsed electron beam with a macro-pulse length of 4 ms, a

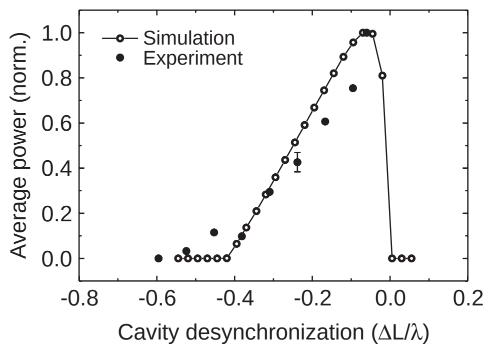

Fig. 1. Average macro-pulse power as a function of the cavity desynchronization for the Darmstadt IR FEL.

repetition rate of 31 Hz and an energy of 31 MeV, which together with the undulator K value of 1.106 result in a resonant wavelength of 7.036 μm. The simulation is in a good agreement with experiment.

In a next step, a numerical study of the processes which take place inside the tapered undulator was performed. The tapering strength is defined [4] as $\alpha = 4\pi N_u[K_{in}^2/(1+K_{in}^2/2)](1-K_{out}/K_{in})$, where N_u is the number of the undulator periods, and K_{in} and K_{out} are the dimensionless undulator parameters at the entrance and the exit of the undulator, respectively. A positive value of α corresponds to a decreasing magnetic field along the undulator.

The results of the simulations with respect to the saturated power are summarized in Fig. 2. For a positively tapered undulator (lower part), the saturation power of the FEL is always lower than in the case of an uniform undulator (solid line) independent of the applied cavity desynchronization. In the case of small inverse ($\alpha < 0$) tapering (Fig. 2, top) for certain desynchronizations, the power is predicted to reach the saturation at a level

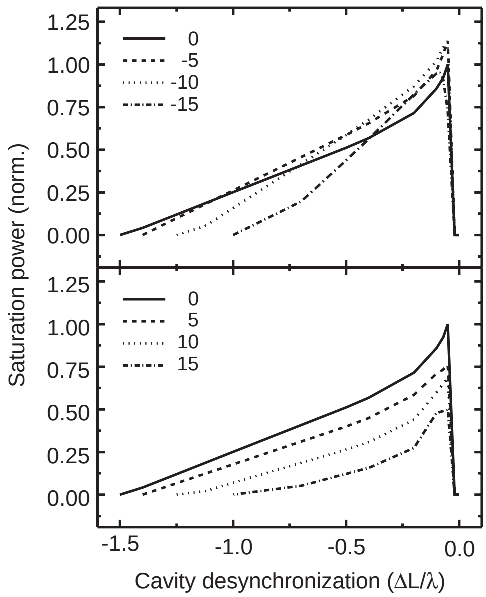

Fig. 2. Simulations of the saturation power vs. cavity desynchronization for negative (top) and positive (bottom) tapering parameters α listed in the inset of the figure.

that is up to about 15% higher than in the untapered case.

3. Autocorrelator and its test

In order to study the temporal structure of FEL pulses from the S-DALINAC, a device for the detection of short pulse and tapering effects had to operate at wavelengths between 4 and 10 μm with a time resolution <500 fs and pulse lengths up to 5 ps. A suppression of background and an easy and fast adjustment were required also. The comparison of different techniques resulted in the realization of a compact autocorrelator based on second harmonic generation (Fig. 3). The incoming laser pulse is split into two of equal intensities. One of them is delayed either by a retro reflector mounted on a motorized sledge giving the possibility of a measurement at a rate of 10 Hz or by a manually operated sledge. The other has a fixed path length. Both pulses, having a spatial distance of 12 mm perpendicular to the direction of travelling, are focused by a parabolic mirror with a focal length of 50 mm on a 2-mm-long $ZnGeP_2$ crystal. The crossed beam paths in the crystal ensure that frequency-doubled light is generated in the direction of the crystal only if both pulses have a temporal and spatial overlap. This results in a background-free measurement.

As a test of the autocorrelator, pulse lengths were measured for different wavelengths between 5.7 and 9.0 μm at FELIX [5]. The results are summarized in Fig. 4. A desynchronization of $\Delta L/\lambda = -0.54 \pm 0.09$ was chosen at 5.7 μm to generate shortest pulses. A pulse length of (305 $\pm$21) fs (fwhm) and a spectral width of (160 $\pm$15) nm (fwhm) resulting in a time-bandwidth product of (0.46$\pm$0.04) was measured in perfect agreement with the theoretical value of 0.44 for a Gaussian-shaped pulse. For the wavelengths between 6.2 and 9.0 μm the desynchronization was fixed at $\Delta L/\lambda = -1.15 \pm 0.05$. The measurement yielded pulse lengths around 1 ps and spectral widths from 60 to 110 nm.

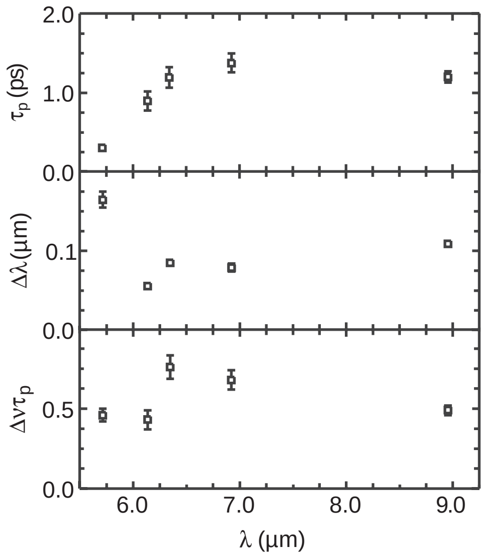

Fig. 4. Pulse length (top), spectral width (middle) and pulse length bandwidth product (bottom) at a fixed desynchronization of $\Delta L/\lambda = 0.57$ for different wavelengths of FEL light from FELIX.

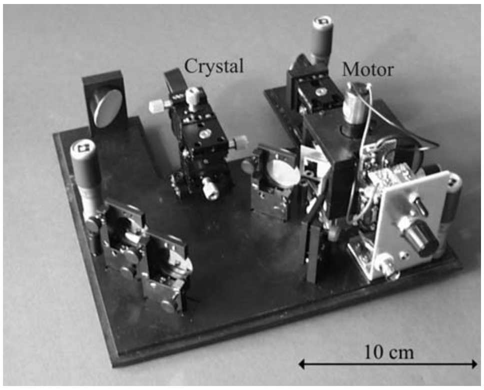

Fig. 3. Photo of the autocorrelator.

4. Conclusion

New results of numerical studies for the IR-FEL at the S-DALINAC predict for a small negative tapering of the undulator an increase of 15% in saturation power at a certain desynchronization parameter. Furthermore, to investigate short pulse effects as well as the energy transfer process between the electrons and the laser pulse experimentally, a compact and easy to adjust autocorrelator was developed and successfully tested at FELIX.

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