New Elements of the GPT Code to Simulate a Resonator Free-Electron Laser

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New elements of the computer code GPT[3] are being developed to simulate the energy transfer in a free-electron laser. In contrast to the single-frequency simulations applied so far the new elements allow us to study the spectral evolution of short laser pulses in a sufficiently large frequency range around the resonance frequency. For that reason we expand the electromagnetic field in a series of resonator eigenmodes with the frequency spacing $\Delta\nu = c/2L_R$ with the resonator length L_R. For the 11.53 m long ELBE resonator the spacing is $\Delta\nu = 13$ MHz. To study the evolution of a laser pulse one has to consider an interval in the order of 1 THz, i. e. roughly 80 000 eigenmodes.

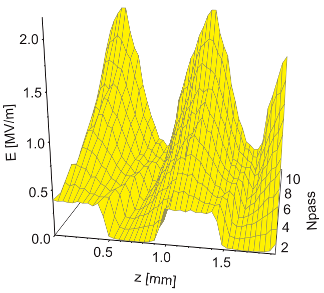

Fig. 1 *Amplification of a wavetrain during 20 passes in a* FEL. *The radiation is modeled with 20 ($N = 21922$) modes. The corresponding pulse repetition frequency is obviously too high; The radiation pulses overlap.*

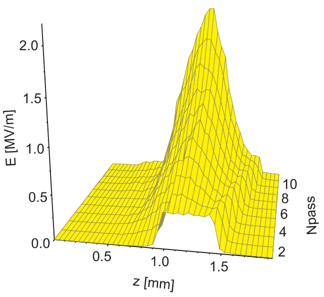

Fig. 2 *The same as in Fig. 1 but modeled with 200 ($N = 2296$) modes, a ten times lower* PRF. *The pulses do not overlap.*

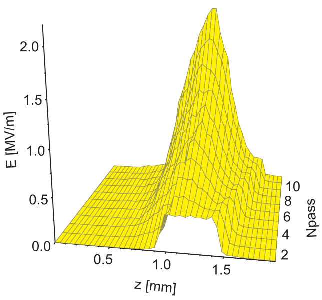

Fig. 3 *As Fig.,1 but with 2000 ($N = 230$) modes. The result is the same*

To reduce the number of modes to a manageable level we increase the frequency spacing by a factor N with the consequence that a single optical pulse in the resonator is replaced by a series of N pulses separated by a distance $D = 2L_R/N$ from each other. If D is much larger than the length of the pulses they do not overlap and we can consider any member of that pulse train as a representative of the actual pulse. Considering their interaction one has to take into account that a short electron pulse interacts with only one member of the optical pulse train.

The pulses produced by an IR FEL, driven by a RF accelerator, are not longer than a few millimeters. In this case, N can be chosen as large as 10000 with the reduction in CPU time by the same factor without overlapping of the various pulses. Figs. 1-3 show the evolution of a pulse, roughly 1 ps long, within different bases of frequency spacing.

The introduction of macro-particles, which are necessary to manage the large number of electrons in the pulse, distorts the ration between induced and spontaneous emission in favor of the latter. To get a realistic picture of the induced emission one has to reduce artificially the contribution of the spontaneous process. One way to do that is the introduction of copropagating positively charged macro-particles annihilating the spontaneous emission [2], or by copropagating identical bunches at the opposite side of the ponderomotive wave [3]. We have combined both methods to suppress the exaggerated spontaneous emission almost completely. To describe the start-up from noise where the spontaneous process is essential we introduce a seed electron without copropagating positive charge.

Fig. 4 shows the calculated gain of optical power for a very low initial field strength for our electron bunch modeled with 100 macro-particles accompanied by the corresponding positive charge and copropagating bunches. The data reproduce the expected behavior of induced emission without any visible contribution from spontaneous emission.

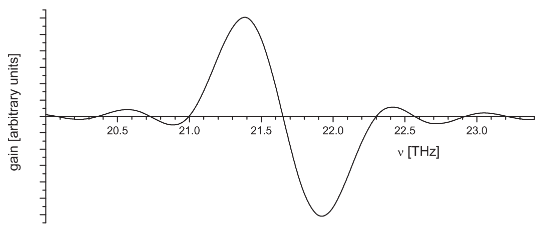

Fig. 4 *Single-pass gain versus frequency ν calculated for 0.1 V/m initial field strength and 100 macro-particles representing a monoenergetic electron bunch with a charge of $Q = 50$ pC and 20 MeV kinetic energy.*

The power of the optical pulse in the equilibrium after a few hundreds of passes through the resonator is an important quantity to be predicted. To accelerate the power build-up we use a seed particle as described above. This way the calculation time is remarkably reduced.

[1] M. J. de Loos, C. A. J. van der Geer, S. B. van der Geer,
3D Multi-Frequency FEL Simulations with the General Particle Tracer Code, EPAC 2002, Paris, France, pp.849;
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Start-Up Simulations of the Spectral and Spatial Evolution of the ELBE FEL

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We have used the new elements [1] of the GPT code [2] to simulate the temporal evolution of the optical beam in the ELBE FELs. The parameters of undulator and electron beam used in the calculation are displayed in table 1.

Undulator	
Number of periods	34
Period length	27.3 mm
Undulator parameter K_{rms}	1
Electron beam	
Energy	20 MeV
Energy spread	72 keV
Pulse charge	50 pC*
Pulse length	0.7 ps (210 μm)
Optical beam	
Resonance frequency	21.56 THz
Frequency range	19.8 .. 22.9 THz
Number of long. modes	200
Round trip loss	5%
Resonator length	11.53 m
Rayleigh range	1 m

Table 1 *Parameters of undulator, electron and optical beam as used in the calculations.*
**The 77 pC pulse charge of ELBE has been reduced to 50 pC. This is to simulate the gain degradation caused by the roughness of the undulator field.*

Fig. 1 shows the evolution of the total laser power without resonator detuning i. e. the round-trip time of the light corresponds exactly to the repetition rate of the electron bunches. The effect of a finite resonator detuning will be investigated in a separate paper [3]. The calculations have been performed with 200 longitudinal modes equidistantly distributed between 19.8 and 22.9 THz. The build-up time has artificially been reduced by means of a seed particle with the charge $Q = -1$ pC.

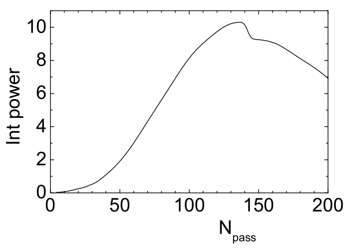

Fig. 1 *Evolution of the total intracavity radiation power (in arbitrary units) as a function of the number of passes N_{pass}.*

Figs. 2 and 3 display the spectral and spatial evolution of the first 200 passes.

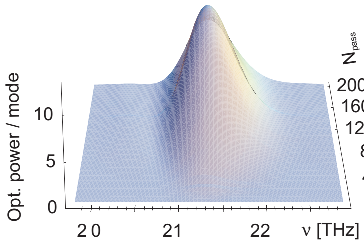

Fig. 2 *Internal laser power per mode as a function of frequency ν and number of passes N_{pass}*

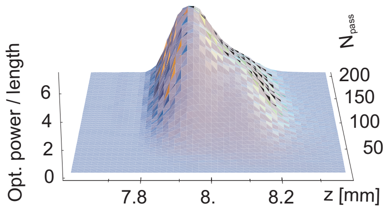

Fig. 3 *Internal laser power as a function of the longitudinal coordinate z and the number of passes N_{pass}*

The optical pulses evolve in quite a smooth manner, both in frequency and real space. When the power increases the spatial distribution narrows and the peak shifts towards the rear end of the pulse. This part of the optical pulse has been amplified at the rear part of the undulator where the gain is larger than in the front part due to the onset of microbunching. Consequently, the centroid of the light pulse is traveling slower than light in vacuum (c). The light pulse drifts away from the electron pulse, the gain reduces and falls below the loss in the resonator and the optical power begins to decay.

The effect described above is denotes as laser lethargy. It occurs if the electron pulses are shorter than the slippage length $\Delta = N_{\mathrm{u}}\lambda$. We have used $\mu_{\mathrm{c}} = \Delta/\sigma_z \approx 2.3 > 1$ in the calculation.

Laser lethargy can be compensated by reducing the resonator length L_{R} from the value synchronized with the repetition rate of the electron bunches, so that the smaller group velocity of the light pulse is compensated.

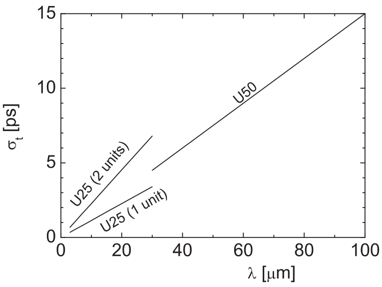

Fig. 4 *Electron pulse lengths σ_t corresponding to the condition $\mu_{\mathrm{c}} = 1$ is a function of the laser wavelength calculated for the undulators of ELBE.*

Fig. 4 displays the rms electron pulse lengths satisfying the condition $\mu_{\mathrm{c}} = 1$ (pulse length equals slippage length). Pulses around this value or shorter are expected to be affected by the lethargy problem.

[1] R. Wünsch,C. A. J. van der Geer, S. B. van der Geer, M. J. de Loos, this report,p. XXX
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Pulsar Physics, General Particle Tracer, http://*www.pulsar.nl*
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Simulation of Limit Cycle Oscillations in the U27 FEL

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Limit cycle oscillations in a short-pulse FEL, as a result of a periodic, self-replicating micropulse structure on successive cavity transits, were first predicted by Colson [1]. First experimental evidence was given in ref. [2]. To understand this phenomenon one has to remember the following features of the interaction in a FEL. Electrons slip back relative to an optical micropulse on their mutual travel through the undulator, due to the difference in forward velocity. As a consequence, the optical micropulse is stronger amplified at its trailing edge. In other words, its group velocity is somewhat smaller than the vacuum value. A micropulse stored in a perfectly synchronized resonator grows, narrows and retards on successive passes through the undulator, with the consequence that the laser gain is reduced (laser lethargy). In order to restore the gain, it is necessary to slightly desynchronize the resonator, which usually is done by reducing the cavity length. When the laser intensity approaches saturation the gain at the highest intensity is reduced first. As a result the center of power is shifted forward and the group velocity becomes larger than the value of optimum overlap between optical and electron pulse. The gain starts to decrease and the power falls below the saturation level. From now on another oscillation starts whereby the center of optical power performs an oscillation in the well of the ponderomotive potential. Limit cycle oscillations do only occur when the electron pulse is shorter than the slippage length $N_u\lambda$ (N_u: number of undulator periods, λ: radiation wavelength). Otherwise the oscillations are washed out.

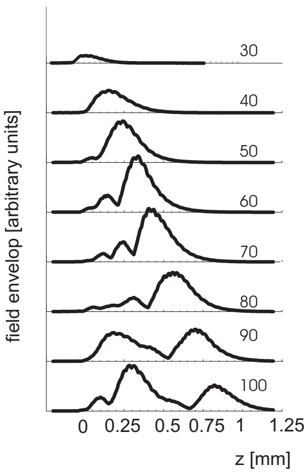

Fig. 1 *Envelope of the radiation field at the undulator exit after 30, 40, …, 100 passes calculated for one unit of the U27 undulator of ELBE (parameters see table 1 of ref. [4]). The resonator detuning is -0.5λ and 5% round-trip loss has been assumed.*

We have simulated such kind of oscillations for the ELBE FEL by means of the code GPT [3]. Fig. 1 shows the evolution of the envelope of the optical pulse. First, the optical pulse grows with the peak near to the trailing edge. Since the resonator is shorter than the value corresponding to the electron repetition rate the optical pulse moves forward from pass to pass. After 50 passes a second peak starts to grow at the trailing edge where the overlap with the electron pulse is large. This peak grows fast since the electron pulse has been prebunched by the strong field in the first part of the undulator. The leading edge of the pulse looses the overlap with the electron pulse and decays in dependence on the resonator loss. As a result the center of the optical peak moves forth and back in the ponderomotive well. This oscillation produces side lobes in the spectrum which emerge and vanish periodically (see Fig. 2).

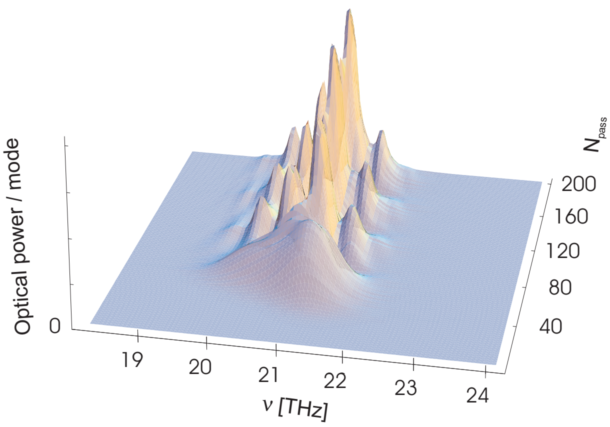

Fig. 2 *Evolution of the total radiation power as a function of frequency ν and number of passes N_{pass} calculated for the same parameters as in Fig. 1.*

Frequency and amplitude of the observed limit cycle oscillations depend on resonator detuning and round-trip loss. In Fig. 3, we vary the detuning from a value much smaller to a value much larger than the value giving optimum gain. At lower detuning the laser starts slowly but saturates at a higher power level which is characterized by remarkable oscillations. Detuning the resonator stronger than the value of optimum gain leads to both a small gain and a lower power level at saturation.

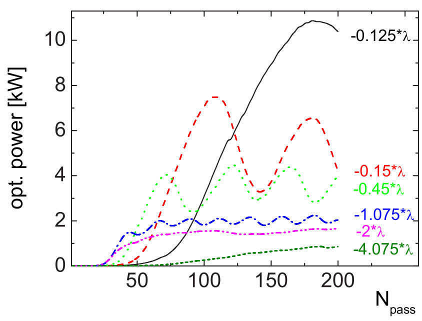

Fig. 3 *Evolution of the total laser power as a function of the number of passes N_{pass} calculated for the same parameters as in Fig. 1 and the indicated values of the resonator detuning.*

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Effects of Undulator-Field Irregularities

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In 2000 the magnetic fields of either section of the U27 undulator were scanned and analyzed at DESY using a hall-probe setup [1]. These measurements have been used to calculate the path of a reference electron (20 MeV) through the undulator (fig. 1a). After transporting the undulator to Rossendorf and installing the stainless steel vacuum chamber necessary for the electron beam the magnetic field has been rechecked by means of the pulsed wire method [2]. We found significant deviations from the field measured at DESY (fig. 1b). We suppose a displacement of certain magnets since inhomogeneities in the chamber material could not be detected by a low-μ permeability indicator. To remove the remarkable displacement of the average electron path we have shimmed some of the undulator magnets. The results are shown in figs. 1c and d for different gaps.

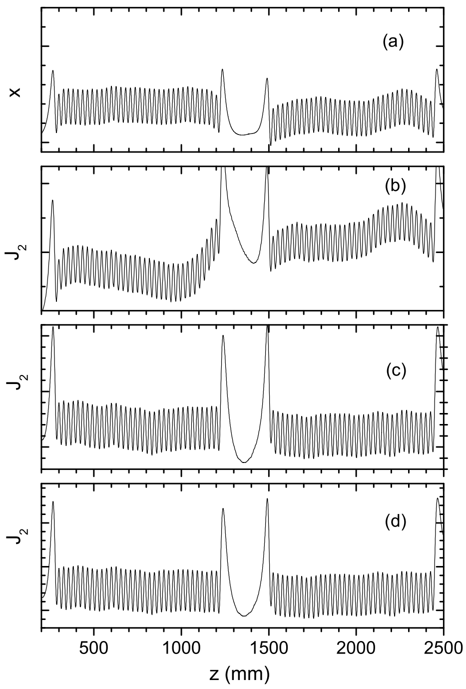

Fig. 1 *Path $x(z)$ of a 20 MeV reference electron through the two units of the U27 undulator (gap g=15 mm) calculated on the basis of a Hall-probe measurement (a) and second field integrals $J_2(z)$ determined by means of the pulsed-wire method before (b) and after (c) shimming several undulator magnets. Fig. (d) shows the field integral measured for the smaller gap g=13.5 mm with the same shimmed magnets.*

Irregularities in the electron path as seen in fig. 1 affect the lasing process. If the electrons are displaced from the optical axis on a part of their path through the undulator they experience a lower optical field and the laser gain is reduced. Moreover the resonance wavelength is shifted to longer values since an additional small fraction of kinetic energy is moved from the longitudinal to the transversal motion. Altogether the interaction of the electrons with the optical wave depends in a crucial way on their path and can not be described by a simple formula in the general case. That is why we have studied the influence of irregularities in the electron path on laser gain and wavelength by means of the 3-dimensional simulation code GPT [3]. Fig. 2 shows an example where one undulator unit has been studied and the field strength of 4 magnets has been manipulated such that a part of the electron oscillations is shifted away from the axis.

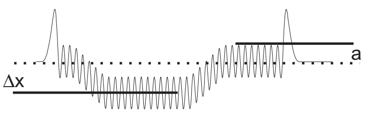

Fig. 2 *Electron path with irregularities*

The results of such a shift are illustrated in fig. 3. Independently of the electron energy we can conclude that a significant reduction of the gain or a shift in wavelength is only caused if the electron is displaced by more than twice the amplitude of the regular oscillation in the undulator. Irregularities as observed in fig. 1 can easily be tolerated by the FEL.

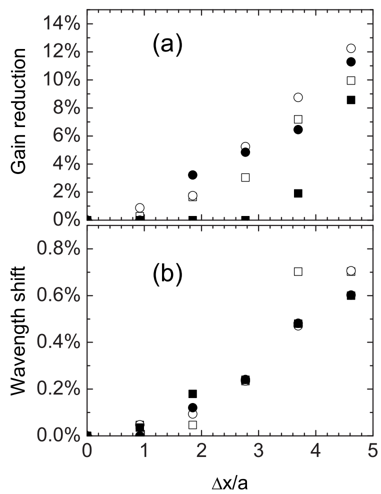

Fig. 3 *Gain reduction (a) and wavelength shift (b) as a function of the ratio $\Delta x/a$ (defined in fig. 2) calculated for a 20 MeV (open symbols) and 40 MeV (full symbols) electron pulse. The squares and spheres, respectively, represent a calculation without and with beam emittance (15 mm*mrad, 50 ps*keV) taking into account.*

[1] P. Gippner et al.; Proc. of the 23rd Int. Free Electron Laser Conference, II-55, Darmstadt, Germany, August 20-24, 2001; P. Gippner et al., Wiss.-Techn. Bericht, **FZR-319** (2001) 24; **FZR-341** (2002) 27

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