MACRO-PULSE GENERATION IN A STORAGE-RING FREE-ELECTRON LASER: A SINGLE-PARTICLE PLUS FEL NUMERICAL APPROACH

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Abstract

In a storage-ring free-electron laser (FEL), the onset and growth of intra-cavity power at the resonator wavelength can be naturally accompanied by coherent emission at higher harmonics. Contrary to what happens in single-pass linac-based devices, the electron beam is re-circulated in the storage ring and, while the microbunching becomes “thermalized” from turn to turn, the evolution of other bunch properties has to be considered. As a consequence, a correct theoretical understanding of the process requires a proper modeling of turn-by-turn evolution of the electron-beam phase-space, both inside the undulators, where the FEL interaction takes place, and along the ring. To simulate this process we have coupled a modified version of the 3D numerical code Ginger, which models the FEL interaction, together with a linear one-turn map, which propagates the electron beam along the ring. We present our results and a first benchmarking with experiments carried out using the Elettra storage-ring FEL.

INTRODUCTION

While the steady-state regime of a SRFEL can be properly simulated by means of simplified models, a realistic description of the light-electron interaction during the transient regime requires a more accurate theoretical framework. Existing 3D numerical codes are generally used for the simulation of single-pass configurations and require non-minor modifications in order to correctly reproduce the physics of a SRFEL. For this purpose, the GINGER [3] [4] FEL code was modified to follow multiple SR passes and in particular to allow individual macroparticles to change slice location form pass to pass. We developed simple additional programs to propagate the macroparticles around the ring and also to keep track of the radiation field evolution inside the optical cavity.

SIMULATION

The configuration under study is the Elettra storage-ring FEL, as shown in Figure 1. The simulation of the FEL interaction is performed by the modified version of Ginger, the optical cavity is modeled taking into account the losses of the cavity mirrors and the dimensions of the resonant Gaussian mode and the electron beam is propagated along the ring using a linear one-turn map.

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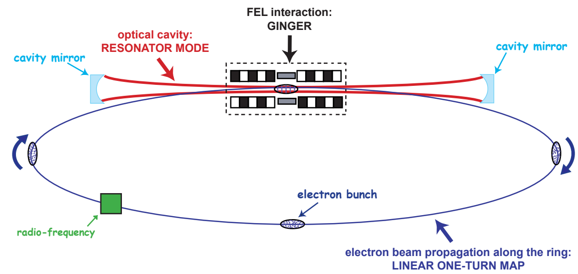

Figure 1: Experimental set-up of the Elettra storage-ring FEL.

The main storage-ring modification to Ginger

GINGER, like most “time-dependent” FEL simulation codes, normally uses a constant number of macroparticles per longitudinal slices, even in the case of a current strongly varying with time. For single-pass devices or for those devices in which there is no particle “memory” from pass to pass, this algorithm is acceptable. However, in the Elettra SRFEL, only some of the macroparticles interact with the FEL in a given pass, and, furthermore, during their revolution along the ring, the particles tend to $partially$ mix longitudinally on a length scale much longer than the slice-to-slice spacing but generally shorter than the full micropulse length. To permit proper simulation of these effects, GINGER was modified so that all macroparticles have the same equivalent charge and, consequently, the number of particles per slices is now allowed to vary. Each pass in the ring includes the following tasks: 1) a 6D macroparticle file ordered by time is read by GINGER and the particles are then appropriately assigned to different slices; 2) within each slice, each macroparticle is “cloned” N-times in 5D phase space to produce a quiet start; 3) the time-dependent radiation field (power, waist, timing) is read; in 4) a normal FEL simulation is done; 5) after random deleting a fraction (N-1)/N of existing macroparticles for each slice, the remainder are written to a disk file; 6) a SR tracking code read this file and advance the macroparticles on a 1-turn map around the ring; 7) the particles are reordered in time; 9) a separate code propagates the FEL radiation in the optical cavity; 10) start a new pass...

The linear one-turn map

Assuming decoupled longitudinal and transverse dynamics, the electron beam propagation at pass n in the longitudinal phase space can be described by [2]:

$$\tau_{n+1} = \tau_n - \alpha T_0 \epsilon_n \quad (1)$$

$$\epsilon_{n+1} = \epsilon_n + eV_{rf}/E_0 sin(\omega_{rf}\tau_{n+1} + \phi)$$
$$-U_{rad}E_0 - D(\epsilon_n, \tau_n) + R(\epsilon_n, \tau_n) \quad (2)$$

where τ_n is the relative position of the electron with respect to the synchronous electron, T_0 is the revolution period, ϵ_n is the electron normalized energy, ω_{rf} and V_{rf} the pulsation and the voltage of the radio-frequency cavity with phase ϕ, α is the momentum compaction, e the electron charge, E_0 the nominal electron energy, U_{rad} the energy radiated by synchrotron radiation, $D(\epsilon_n, \tau_n)$ the synchrotron damping term and $R(\epsilon_n, \tau_n)$ account for the stochastic process of photon emission. The parameters used are shown in Table 1 [5].

Table 1: Main Elettra storage ring parameters used for simulation.

Storage Ring	
Momentum compaction	$1.6\cdot10^{-3}$
Revolution period	$864\cdot10^{-9}$ s
Radio-frequency peak voltage	1.764 V
Radio-frequency peak pulsation	$4.6\cdot10^{8}$ Hz
Nominal normalized electron energy	$1.782\cdot10^{3}$
Bending curvature radius	5.5615 m
Normalized energy radiated	$1.094\cdot10^{-2}$

COMPARISON BETWEEN EXPERIMENT AND SIMULATION

Simulation has been performed using the parameter values reported in Table 1 and 2 [5] in order to reproduce the standard experimental condition for the Elettra storage ring FEL. Figure. 2 and Figure 3 show, respectively, the macropulse evolution obtained by a simulation and by an experiment at 660 nm. The rise-times and the widths of the pulses are comparable and also the asymmetrical shape is well modeled.

Table 2: Main electron beam parameters used for simulation.

Electron beam	
Energy	0.9 GeV
Peak current	105 A
RMS X emittance	$2.47\cdot10^{-6}$ m rad at 0.9 GeV
RMS Y emittance	$2.47\cdot10^{-7}$ m rad at 0.9 GeV
RMS energy-spread	0.12% at 0.9 GeV
RMS bunch-length	27 ps at 0.9 GeV

Figure 4 reports in a color scale plot the fast time (Horizontal) and the slow time (Vertical) evolution of the FEL pulse and electron bunch obtained from our simulations.

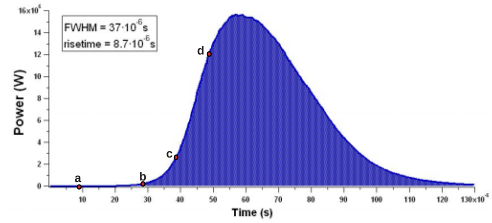

Figure 2: The FEL macropulse from simulation. The wavelength is 660nm.

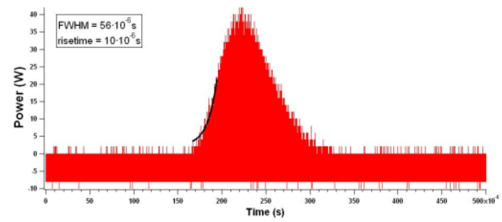

Figure 3: The experimental FEL macropulse obtained in Q-switch mode. The wavelength is 660nm.

These results, which are in a good agreement with similar experimental data obtained with streak-camera (Figure 5), show the relation between the FEL pulse and the bunch length.

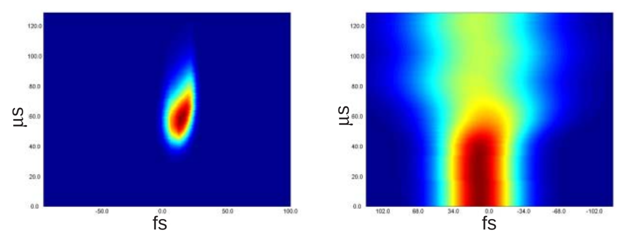

Figure 4: "Pseudo" streak-camera images obtained by simulation showing the effect of the FEL macropulse on the bunch dynamics.

A more accurate analysis of the electron bunch evolution during the FEL growth can be done by looking at the electron phase space. In Figure 6 we report phase space plots corresponding to some particular points of the FEL macropulse. The asymmetric growth of the energy spread has been already evidenced (see [6] and [7]).

CONCLUSIONS

Preliminary results for the macropulse generation in a SRFEL using a modified version of the FEL numerical code GINGER has been presented. Numerical results are in a good agreement with experimental data of the Elettra SRFEL in the Q-switching regime. Both the FEL pulse and the electron bunch dynamics are qualitatively reproduced. Further work is planed to improve the electron beam propagation along the ring and for an accurate analysis of the

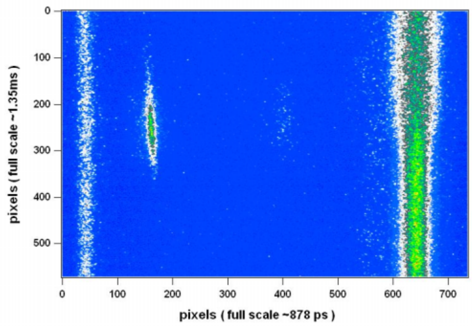

Figure 5: Streak-camera image of a macro FEL pulse (at left) plus the synchrotron radiation (at right).

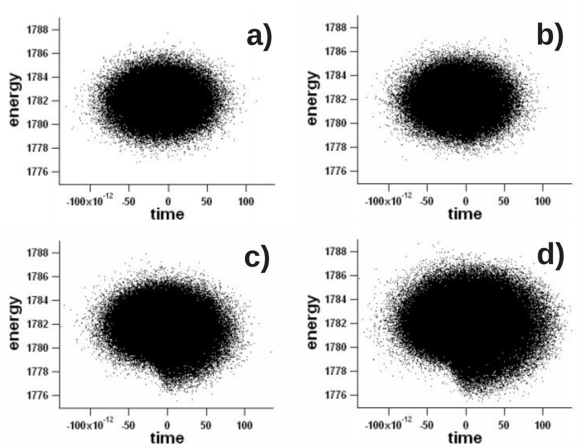

Figure 6: Evolution of the "Phase Space" along the macropulse growth. The labels refer to Figure 2.

fast time dynamics.

ACKNOWLEDGMENTS

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REFERENCES

[1] G. De Ninno $et al.$, Phys.Rev.E **64**, 026502 (2001).

[2] M. Sands, SLAC Report No. 121, 1970 (unpublished).

[3] W. M. Fawley, "A User Manual for GINGER and its Post-Processor XPLOTGIN." LBNL-49625-Rev. 1 (April 2004) (http://www-ssrl.slac.stanford.edu/lcls/technotes/lcls-tn-04-3.pdf).

[4] W. M. Fawley, LBNL CBP Tech Note-104 (1995).

[5] F. Iazzourene, private communication.

[6] V. N. Litvinenko $et al.$, NIM A **358**, 369 (1995).

[7] V. N. Litvinenko $et al.$, NIM A **375**, 46 (1996).