ELECTRON BEAM DYNAMICS UNDER COHERENT HARMONIC GENERATION OPERATION AT UVSOR-II

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Abstract

In the Coherent Harmonic Generation Free Electron Laser configuration, an external laser source is seeded inside a first undulator. The interaction between the electron beam and this seed induces energy modulation of the bunch, further converted into a density modulation, producing coherent radiation in a second undulator. The energy modulation enhances the energy spread of the electron bunch, converted by the machine optics into a modification of its longitudinal distribution. In the case of a storage ring FEL, the electrons are re-circulating: the same bunch keeps interacting with the seeded laser, and relaxation of the distribution is only allowed in between two laser injections. Such specific dynamics has been studied on the CHG FEL of UVSOR-II storage ring (Japan). The electron beam stored at 600 MeV is seeded using a 2.5 mJ, 1 kHz, 1.2 ps Ti:Sa laser at 800 nm wavelength, allowing radiation at 266 nm (third harmonic). A Streak Camera is used to record the evolution of the longitudinal profiles as a function of the repetition rate and average power of the seeding laser, leading to bunch lengthening and distortion dynamical analysis. It appeared that because the heating induced by the interaction remains local, the refreshment process of the electronic distribution is modified. The experimental results are compared to simulations.

INTRODUCTION

The combination of an intense fs laser with synchrotron electron beams now allows delivery of sub–ps light pulses in an extendend spectral domain: from TeraHertz [1] to X–rays [2]. The Coherent Harmonic Generation Free Electron Laser (CHG FEL) results from this assembly. In the CHG FEL [4, 5, 6], the electron beam is modulated in energy by the laser pulse, within the magnetic field of an undulator -so–called "modulator"-. Passing through a dispersive section converts this energy modulation into a density modulation, allowing in a second undulator -so–called radiator-, coherent emission at the seeding laser wavelength and its harmonics. Inversely to HGHG FEL configuration[7], the injected seed does not interact with a fresh bunch but a re–circulating synchrotron beam, which may drive degradation in time of the electronic distribution, and eventually of the output radiation properties. The effect of a ps laser pulse on an electronic distribution has already been studied in oscillator FELs physics (lasing results from the pass by pass amplification of the electrons spontaneous emission which is stored in an optical cavity). The light pulse increases the energy spread of the electron beam, the so–called bunch heating [8, 9], inducing bunch lengthening and shape distorsion [10, 11, 12, 13], until saturation is reached. Depending on the longitudinal overlap between the electrons circulating in the ring and the laser pulse in the optical cavity, the FEL can be operated in continuous or pulsed mode. In this last mode, the electron beam refreshes in between two pulses deliveries [14]. Q-switch operation of oscillator FELs gave similar results on heating dynamics and showed local effects on the electronic distribution [15, 16].

In this paper, we investigate the dynamical response of an electron bunch from a storage ring to the excitation of an external laser with shorter pulse duration (by one order of magnitude) and higher peak power, as it is the case for both Slicing and CHG schemes. A model is given for simulation of the electron-photon interaction inside the storage ring. It is then used, together with experimental results obtained on UVSOR-II CHG FEL, to understand the evolution towards saturation of the electronic distribution under the laser heating. Finally, local aspect of this interaction and its consequence on the dynamics are presented.

BEAM HEATING SIMULATION

The electron bunch distribution is simulated using a pass to pass model following the stored particles in the longitudinal phase space [18]. The initial code [13, 17] has been modified to include single pass interaction with an external laser. The evolution of the j^{th} particle at n^{th} pass is driven by:

$$\tau_{n+1,j} = \tau_{n,j} - \alpha T_0 \epsilon_{n,j} \quad (1)$$

$$\epsilon_{n+1,j} = \epsilon_{n,j} - U_0 + V_{RF,n,j} - D_{n,j} + R_{n,j} + SE + W_{mod,n,j} \quad (2)$$

with $\tau_{n,j}$ its relative longitudinal position and $\epsilon_{n,j}$ its relative normalized energy with respect to the synchronous particule. Energy variation is converted by the machine optics into a longitudinal displacement, which depends on the momentum compaction factor α and the revolution period T_0.

Along each revolution, the particule losses energy by synchrotron radiation (U_0), random emission (R) and spontaneous emission in the optical klystron (SE) [19]. D is the damping term. The interaction with the external laser induces a maximum energy exchange of [20]:

$$\Delta\gamma_{max} = \frac{2\pi K N \lambda_0}{\gamma \lambda_{Las}} \left(J_0(\xi) - J_0(\xi)\right) a_{Las} \quad (3)$$

where K is the deflexion parameter, N the number of undulator periods, λ_0 the undulator period, a_{Las} is the peak dimensionless potential vector of the laser electric field, $\lambda_{Las} = 2\pi c/\omega_{Las}$ its wavelength, γ the Lorentz factor, c the light speed, J the Bessel function and $\xi = \frac{K^2}{4(1+K^2/2)}$. Since the electric field experienced by the j^{th} electron depends on its relative position $\tau_{n,j}$ and phase Φ_j, the laser induced energy change is:

$$W_{mod,n,j} = \frac{\Delta\gamma_{max}}{\gamma}\, exp(-\frac{\tau_{n,j}^2}{2\sigma_{Las}^2})\, sin(\omega_{Las}\tau_{n,j} + \Phi_j) \quad (4)$$

with σ_{Las} the laser pulse duration. This term is set to zero if nT_0 is not a multiple of the laser period. Finally, the RF system provides an energy $V_{RF,n,j}$ to compensate the total losses and ensure equilibrium.

Thanks to this model, simulation of the electron bunch distribution evolution are performed, and compared to experimental results.

BEAM HEATING

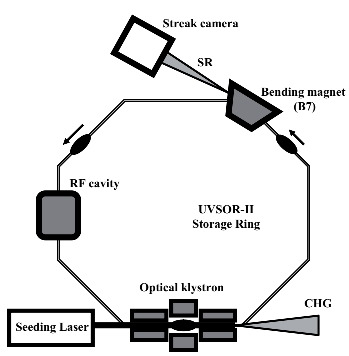

Figure 1: General scheme of the experimental setup for CHG experiment on UVSOR-II storage ring. A Ti:Sa laser is focussed inside the first part of the optical klystron. Coherent radiation (CHG) is collected at the output of the optical klystron and Synchrotron Radiation (SR) at the ouptut of B7 bending magnet for electron bunch profile measurements with a streak camera (Hamamatsu, C5680). Indeed, the distribution of the synchrotron radiation pulse is a replica of the electronic distribution.

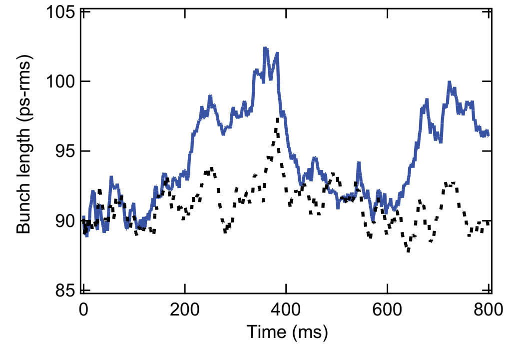

Figure 2: Bunch length measured with the streak camera. Continuous line: a mechanical light chopper at 2 Hz enables periodic laser injection (the laser is seeded during 250 ms at f_{rep} = 1 kHz, and then cut off during the following 250 ms). Dotted line: laser OFF. I = 4.8 mA. The natural bunch length at low current of this measurement is higher than expected because the RF cavity electric field was not optimised. Data are smoothed.

Table 1: Parameters for CHG operation at UVSOR-II.

	Symbol	Value
Electron beam		
Energy (MeV)	E	600
RF frequency (MHz)	f_{RF}	90.1
RF voltage (kV)	V_{RF}	94
Number of stored bunches	n_b	1
Period of revolution (ns)	T_0	178
Momentum compaction factor	α	0.028
Synchrotron frequency (kHz)	f_S	19.4
Damping time (ms)	τ_S	20
Natural energy spread (10^{-4})	σ_γ	3.4
Optical Klystron		
Number of periods	N	9
Spatial period (cm)	λ_0	11
Dispersive section length (cm)	L_d	33
Deflection parameter	K	6.06
Laser		
Average power (W)	P	1.5
Pulse duration (ps-fwhm)	σ_{Las}	1.2
Repetition rate (Hz)	f_{rep}	50 - 1000
Wavelength (nm)	λ_{Las}	800

The CHG experiments were performed on UVSOR-II [21] storage ring. A general scheme is given in Fig. 1, and the main parameters of the electron beam and laser are summarized in table 1. The intense Ti:Sa laser is focussed inside the modulator onto the electron beam. Using a mechanical light chopper, the laser is alternatively switched ON and OFF. The results are given in Fig. 2. This alternative injection drives clear oscillations of the bunch length at the laser injection frequency. Indeed, since bunch length can be assumed proportionnal to energy spread (operating at low current in potential well distorsion regime [22]), the bunch lengthening can be correlated to a heating of the distribution. When seeding is enabled (laser ON), the bunch length increases via laser heating (by 12 %); when seeding is disabled, the bunch length decreases back to the laser OFF value through the synchrotron damping process.

The longitudinal profile of the electron beam is then recorded with continuous seeding at 1 kHz, a standard CHG operation. At 1 mA, an increase by 12 % is measured (from 83 to 93 ps-rms), in agreement with the results of Fig. 2. The model reproduces the bunch length laser OFF at zero current, i.e. 80 ps-rms. In CHG operation (using P=1 W, f_{rep}=1 kHz and σ_{Las}=1.2 ps-fwhm), it leads to a bunch lengthening up to 107 ps-rms, a value slighlty higher than the experimental one probably because of non perfect synchronisation and alignment in the experiment.

Using 100 Hz repetition rate, still with 0.15 W seeding power, bunch lengthening could no longer be detected experimentally. Indeed, the simulated bunch length at 100 Hz repetition rate (and 0.1 W seeding power) only rises by 3.5 ps-rms, the limit of the experimental detection.

The simulations are found in good qualitative agreement with the experimental results, allowing further dynamical studies.

BEAM HEATING DYNAMICS

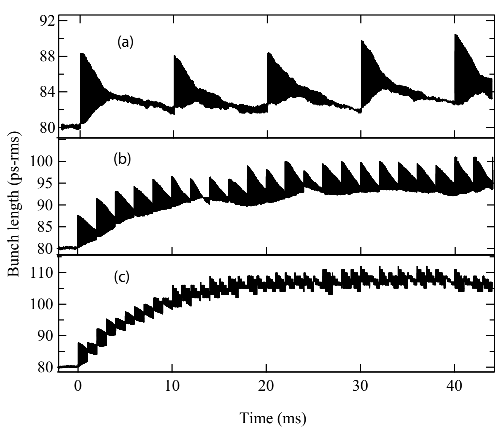

Figure 3: Bunch length evolution from laser OFF to stable CHG operation. (a) f_{rep}=100 Hz, $T_{90\%} \approx$ 20 ms, (b) f_{rep}=500 Hz, $T_{90\%}$ =18 ms, (c) f_{rep}=1 kHz, $T_{90\%}$ =14 ms. Simulation with 15000 particules and the parameters of table 1. $T_{90\%}$ is the time to reach 90% of the bunch length at saturation.

Simulation of Fig. 3 investigates the evolution of the electron beam from laser OFF initial state, to CHG operation state. When seeding is switched on, the average bunch length gradually increases, performing oscillations at the laser repetition rate, until a saturation is reached: the average bunch length becomes constant.

Whatever the simulated repetition rate, the rising time to saturation remains below 25 ms. An upper limit of the rising time of 100 ms is found using the mechanical chopper (see Fig. 2). A precise measurement would require a fast shutter (to be able to neglect rising of the seeding average power) synchronised with the streak camera acquisition. The simulated rising time decreases with f_{rep} (see Fig. 3): it is 20 ms at 100 Hz, 18 ms at 500 Hz and 14 ms at 1 kHz.

Once saturation is reached, the electronic distribution reveals a double oscillating time structure. After each laser injection, the bunch length suddenly increases, and then slowly decreases back to its value before previous injection: the bunch length oscillates at the laser repetition rate. In addition, all along CHG operation, synchrotron motion drives fast oscillations of the distribution at the synchrotron frequency.

Three levels of dynamics are found in the evolution of the electronic distribution. When the laser is injected, the electronic distribution responds to the laser periodic excitation by transiting to a pseudo equilibrium state. Once at saturation, the distribution oscillates at the laser repetition rate, refreshing in between two injections, and at the synchrotron frequency. The refreshment compensates the periodic bunch heating and allows to maintain equilibrium. In addition, the final heated state depends on the initial electron beam quality, but can also be tuned using, for instance, the seeding laser repetition rate. The bunch heating, i.e. energy spread can be controlled. This is of high interest since the coherent output power strongly depends on the energy spread at interaction [23, 24].

LOCAL BEAM HEATING

We now investigate on the local aspect of the electron-photon interaction, since the seeding laser pulse is shorter by nearly two orders of magnitude than the electron bunch. The profiles in CHG operation are simulated, and a typical example is given in fig. 4. Initially, laser is OFF and the distribution starts from Gaussian shape (a). The first injection of the laser causes a local distorsion in the center of the distribution (b): a hole appears one turn after injection and remains only for a few turns (few tens of μs). The edges of the distribution are not yet affected. Once saturation is reached (less than 25 ms later), each laser injection still induces a hole remaining just for a few turns (d), but the diffusion of the heated electrons causes a flattening of the whole distribution, and a density displacement towards the edges (c). The laser induces a local density defect in the profile, which vanishes in between two laser injections.

The electron beam phase space can be recontructed [25] in two dimensions given by the electronic density $N(\tau)$ and its derivative. In the phase space, a defect in the profile, as for instance a hole, will correspond to a large amplitude oscillation A_{hole}.

A_{hole} reduces with the repetition rate. The hole can no longer be detected at repetition rate higher than 5 kHz (and P=5W, σ_{Las}=1.2 ps-fwhm). The heated particules are diffused [13] over the whole bunch, causing strong bunch lengthening. A_{hole} increases with the pulse duration (at given repetition rate and peak power). The digged hole gets wider, still vanishing after a few turns, which eases the diffusion towards edges and causes bunch lengthening.

The laser induces a local distorsion in the distribution at

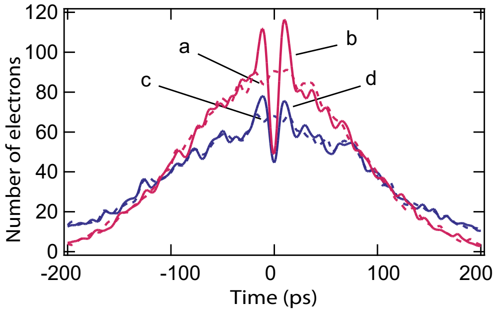

Figure 4: Simulated longitudinal profiles: (a) Laser OFF profile, (b) Profile two turns after first laser injection, (c) Profile in saturated regime 2 turns before a laser injection, (d) Profile in saturated regime two turns after a laser injection. Simulation parameters: f_{rep}=1 kHz, 4 W average power, 4.8 ps-fwhm pulse duration for the laser (optimised to produce a net hole in the distribution), 15000 particules, and other parameters of table 1

each injection which, thanks to a fast diffusion, disappears before next injection: even at saturation, the laser does not experience local density defect. On the other hand, this diffusion increases the bunch length and consequently reduces the electronic density all along the distribution. These local dynamics studies reveal that the tunability of the external laser parameters (f_{rep}, P and σ_{Las}) offers attractive perspectives of adjusting beam heating and consequently CHG ouptut power with possible optimisation between peak and average output power.

CONCLUSION

Electron dynamical response to an external short duration and intense laser has been investigated. Thanks to simulations found in agreement with experimental results obtained on UVSOR-II CHG FEL, we observed that the seeding of the laser causes -via bunch heating- a transition towards a saturated regime with double frequency oscillating structure (at the laser repetition rate and at the synchrotron frequencies). The bunch heating, and consequently the equilibrium state at saturation, can be adjusted using the laser parameters. This opens perpsectives to optimisation of the output radiation, especially in terms of peak or average power. While those results were obtained in CHG FEL configuration, they can be easily extended to any scheme involving interaction between intense electric field and stored electron beam.

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