PRELIMINARY STUDY OF SINGLE SPIKE SASE FEL OPERATION AT 0.26 NANOMETERS WAVELENGTH FOR THE EUROPEAN XFEL

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Abstract

The production of ultra-short (fs or sub-fs long), high power radiation pulses in the X-ray spectral region, showing a single spike spectrum, represents a challenge for many existent SASE- FELs [1] [2].

In order to realize single spike operation the length of the electron bunch after compression must be extremely small [3] (less than a micrometer) and the consequent degradation of its emittance has not to suppress the radiation production.

Several technical restrictions, such as limits of diagnostics for small charges, RF jitter and micro-bunching instabilities play an important role in the choice of the operation working point.

In this paper we are going to study the feasibility of single spike or few spikes lasing for bunches with a charge of tens of pC in the European XFEL facility [4] giving some preliminary results concerning the choice of the working point.

INTRODUCTION

Single Spike Condition

The radiation produced by Free Electron Lasers (FELs) working in the Self Amplified Spontaneous Emission (SASE) configuration is characterized by an energy spectrum constituted by many spikes. The number of the spikes depends on the longitudinal properties of the electron bunch. In fact, once the bunch is injected into the undulator, the radiation emitted by the electrons located in a certain longitudinal position can be amplified only by other electrons placed within a fixed longitudinal distance (in the forward direction) from them. This distance is proportional to the cooperation length, defined as a radiation slippage in one power gain length [3]. The cooperation length depends on the emitted radiation's wavelength λ, according to:

$$\mathrm{L_c} = L_{c1d}\left(1+\eta\right), \qquad (1)$$

where the parameter η, defined as in [5], takes into account transverse effects and beam energy spread, and L_{c1d} is the one-dimensional cooperation length, defined as:

$$\mathrm{L_{c1d}} = \frac{\lambda}{\sqrt{3}\cdot 4\pi\rho}, \qquad (2)$$

with ρ being the one dimensional FEL parameter.

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Every longitudinal slice in the bunch whose length is $2\pi L_c$ contributes to a different spike in the energy spectrum of the produced radiation, thus in order to have a single spike, the e-bunch must be shorter than $2\pi L_c$.

It is very difficult to satisfy this condition in X-rays FELs where, according to equations (1) and (2), $2\pi L_c$ becomes very small, typically a fraction of µm.

Single Spike at the European XFEL

Several methods have been proposed in order to achieve short e-bunch lengths and thus sub-fs radiation pulses (see for example [2] and its references).

In this paper we start from the very simple case of strong compression of electron bunches having a charge of tens of pC. We characterize different compression setups considering the most recent layout of the European XFEL. Our aim is to give a starting point for further optimization. The principal effects influencing the electron beam acceleration and transport, such as RF wakefields and coherent synchrotron radiation (CSR) effects inside magnetic compressors have been included. Space charge force has been fully included in the injector, while only longitudinal space charge force has been considered in the rest of the linear accelerator.

BUNCH COMPRESSION AT XFEL

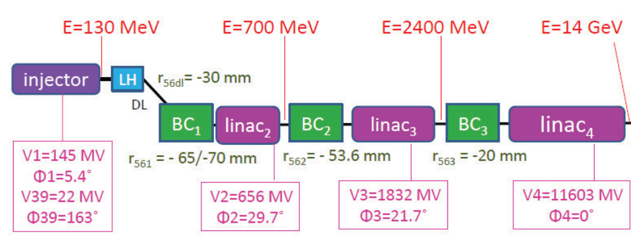

Figure 1: Scheme of the European XFEL layout including the parameters used in the following simulations. The three magnetic bunch compressors (BCs) have a variable curvature radius and thus a variable dispersion (R_{56}); in the work described in this paper the curvature radius in BC_1 has been changed in order to scan the bunch properties around the maximum compression point.

Layout Description

In Fig. 1 a scheme of the layout of the European XFEL is shown. Through the use of a third harmonic RF-cavity placed in the injector region, the correction of the non-linearity in the longitudinal phase space distribution of the e-bunch is possible. The laser heater (LH) can mitigate the effect of micro-bunching instability. The electron bunch compression starts in the dogleg and is completed in three magnetic stages.

The total compression factor can be optimized by either changing the RF chirp before entering the magnetic compressors or the curvature radius inside the compressors (i.e. the current of the dipoles in the chicanes).

The transport and compression of the e-bunch has been recently optimized for different charges, always considering a bunch produced by a 20 ps lasting flat-top laser pulse illuminating the photo-cathode [6] [9-10].

Since for the nominal injector laser pulse duration the strong compression applied with small charges to reach a short bunch appeared to be dominated by RF-tolerances, it has been chosen here to work with shorter laser flat-top length at the cathode.

Working at extremely low charges (1 pC or less) it is possible to obtain the single spike condition while keeping the beam peak current high, the emittance small and, consequently, L_c extremely short [1] [2]. In this way attosecond lasting radiation pulses are in principle reachable but the lack of diagnostics able to fully characterize electron bunches with charge smaller than few tens of pC makes the transport and the compression of the beam practically very difficult [11]. When using higher charges, the shortest achievable bunch length increases but we gain the possibility of diagnose the electron beam in order to match it with the undulator. In this case, it is relatively easy to obtain a few spikes SASE radiation spectrum having an integrated power of the order of 10 GW, but the single spike condition can eventually be reached only by optimizing the peak current of the central slice of the bunch and partially spoiling the beam emittance in order to increase the value of L_c. We will present simulations for 20 pC and 50 pC charged bunches.

Simulations: Input and Method

The nominal electron bunch at the XFEL has 1nC charge and is generated illuminating the cathode with a laser whose RMS transverse size and flat-top duration are respectively 0.4 mm and 20 ps. In this paper the laser parameters have been scaled with respect to the nominal setup in order to maintain constant the charge density and use the machine parameters defined for the nominal setup as a starting point. For the 20 pC case a laser shape having 0.11 mm RMS transverse size and 5.43 ps flat-top duration (FWHM) has been set, while for the 50 pC case the laser pulse duration is 7.4 ps FWHM and has a transverse RMS size of 0.15 mm. In all cases the rise and fall time of the flat-top are 2 ps.

The transport in the injector has been simulated using the tracking code ASTRA [7]. The RF-wakefields have been added analytically as described in [9]. The transport through the laser heater, the dogleg and the bunch compressors has been simulated using the code CSRtrack [8]. Finally the transport in the three linac-sections has been carried out by multiplying the particles coordinates times the correspondent linac transport matrix and adding analytically the wake caused by longitudinal space charge using formulas described in [9].

The electron bunch compression has been scanned around its maximum compression point by changing the curvature radius inside the first bunch compressor (BC_1 in Fig. 1).

The longitudinal phase space distributions correspondent to the electron bunches after compression have been used as input for Genesis [12] simulations in order to evaluate the power and the energy spectrum of the emitted radiation. At the moment, longitudinal wakefields occurring in the undulator has been not taken into account and no tapering has been applied. Both of these steps are foreseen in the future.

Results

Figure 2 summarizes the results of the simulations. It shows the normalized transverse emittance (N.E.) and the energy spread of the electron bunch as a function of the curvature radius r_1 of the first bunch compressor. The maximum compression point for the 20 pC bunch lies in the region of r_1~3.14 m while for 50 pC corresponds to r_1~3.13 m. Only for the 20 pC bunch the over-compression region has been explored.

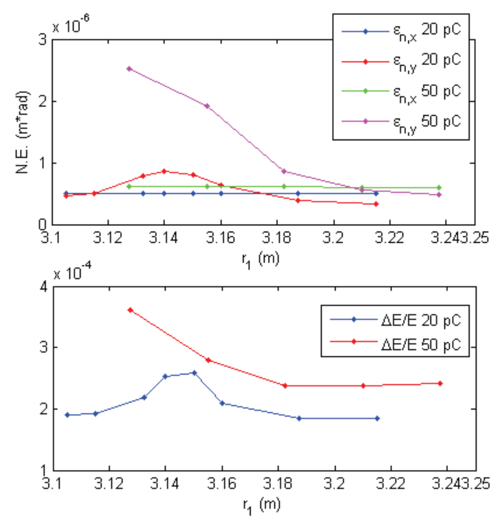

Figure 2: Summary of the compressed electron bunch characteristics as a function of the curvature radius (r_1) in BC_1. The normalized horizontal and vertical emittances ($\varepsilon_{n,x}$, $\varepsilon_{n,y}$) are plotted on the top and the total energy spread is plotted on the bottom figure.

The maximum compression point for the 20 pC bunch lies around r_1~3.14 m while for the 50 pC bunch corresponds to r_1~3.13 m.

In order to have an idea about the stability of the peak current with respect to the RF-jitter, all the simulation has been repeated changing the phase of the first accelerating cavity in the injector by ±0.005˚, which represents a very conservative estimation for the RF-jitter. The jitter in this cavity has been indeed found to be the dominant one for the compression [10]. Fig. 3 shows the result of this analysis: it presents the slice peak current and the normalized maximum deviation from its average value for each compression point. These quantities depend on the slice length that has been chosen to be close to $2\pi L_c$ at the maximum compression point, being about 0.28 μm for the 20 pC case and 0.35 μm for the 50 pC .

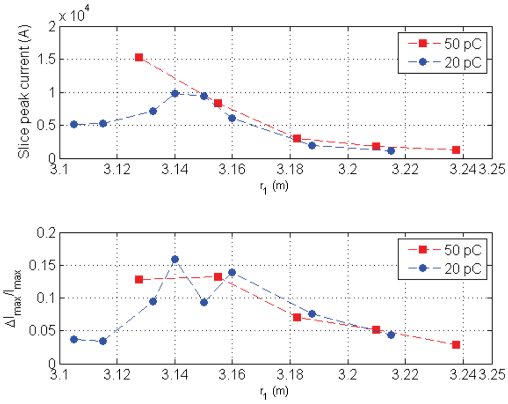

Figure 3: Slice peak current (on top) and normalized maximum deviation from its average value changing the phase of the first accelerating cavity in the injector by ±0.005° (on the bottom) as a function of the curvature radius (r_1) in BC_1. The slice peak current has been calculated considering a slice length of 0.35 μm for the 50 pC case and 0.28 μm for the 20 pC one.

SASE RADIATION

The electron bunch longitudinal phase space distributions have been used as input for Genesis simulations. In none of the simulated cases it has been possible to obtain a single spike in the spectrum nevertheless a few spikes SASE spectrum with power of ~10 GW and a radiation pulse length of the order of fs has been achieved. In Fig. 4 the longitudinal phase space corresponding to the 50 pC charge bunch compressed using r_1=3.1275 m in BC_1 at the entrance of the undulator is shown as an example. In the middle the longitudinal profile of the emitted power at saturation is plotted while on the bottom the spectrum of the emitted radiation at the saturation point is plotted.

CONCLUSIONS AND OUTLOOK

Preliminary start-to-end simulations have been performed for the optimization of single spike emission at the wavelength of 2.6 Å at the European XFEL.

Few spikes emission in the X-rays can be obtained relatively easily by compressing bunches with charges of tens of pC.

Further study is needed to decrease the number of spikes by increasing the peak current in the central slice of the bunch (tuning, for example, the energy chirp before the first magnetic compressors) and slightly spoiling the beam emittance.

The study of introducting a taper in the undulator is also foreseen.

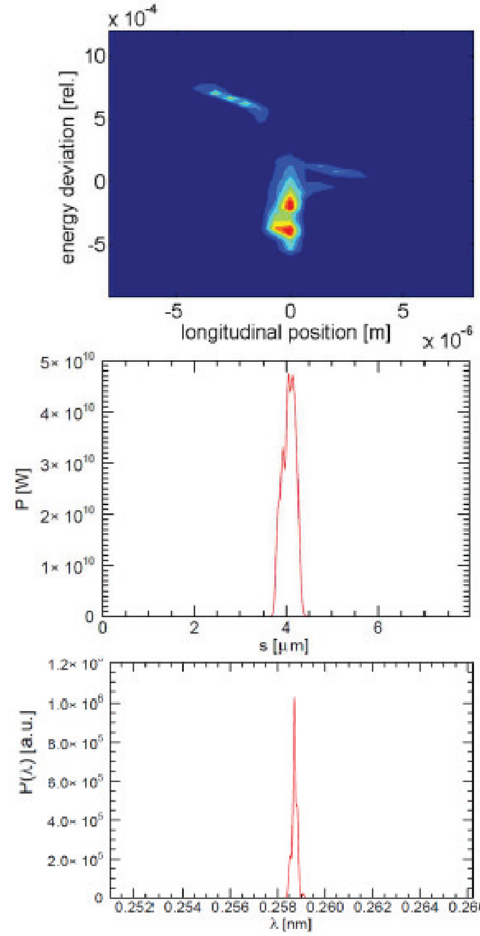

Figure 4: Longitudinal phase space distribution of the electron bunch at the entrance of the undulator, (on top), power of the emitted radiation as a function of the longitudinal coordinate within the electron bunch and spectrum of the emitted radiation at the saturation point.

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