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Compression of a 20 pC e-bunch at the European XFEL for Single Spike Operation

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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, represents a challenge for many existent SASE FELs.
In order to realize single spike lasing the length of the electron bunch must be extremely small (less than a micrometer) thus it is necessary to tune the linac and magnetic chicanes near to the maximum compression point. In this setup, the final length of the electron bunch strongly depends on the non-linearity of its longitudinal phase space. The use of a third harmonic RF cavity section placed right after the injector is foreseen at the European XFEL in order to correct the longitudinal phase space non-linearity up to the third order.
We describe a method for the optimization of the electron bunch compression presenting beam dynamics simulations for a 20 pC electron bunch.

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Keywords: SASE; longitudinal coherence; European XFEL; bunch compression; short x-ray pulses

1. Introduction

There is a considerable interest within the accelerator community in generating extremely short, fully longitudinally coherent x-ray pulses by Self Amplified Spontaneous Emission Free Electron Lasers (SASE FELs). The lower limit of the radiation pulse duration is mainly set by the shortest achievable length of the electron bunch at the entrance of the undulator, while the lack of longitudinal coherence comes from the fact that the final radiation pulse is obtained from the amplification of the spontaneous radiation. When the electron bunch enters the undulator many longitudinal modes are exited and spontaneous radiation at different wavelengths according to the electron energy is produced [Huang et al. 2007]. The SASE FEL process amplifies then all the frequency components within the acceptance bandwidth of the FEL. If we look at the longitudinal profile of the radiation pulse we observe that it is composed by many spikes (or modes) and the same number of spikes is present in the energy spectrum.

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Many methods have been proposed in order to produce fully coherent and/or extremely short x-ray radiation pulses using FELs, not necessarily in the conventional SASE configuration.

The use of a seed allows to obtain a better longitudinal coherence of the radiation pulse. The lack of good seeds for FELs in the x-ray region led to the invention of the self-seeding scheme [Amann et al. 2012], originally proposed at DESY [Feldhaus et al. 1997]. The tapering technique may allow to obtain both longitudinally coherent and extremely short radiation pulses. This technique already allowed single spike lasing at longer wavelengths at the SPARC facility [Giannessi et al. 2011] [Marcus et al. 2012]. For x-ray lasing, the required strong energy modulation within a short slice of the electron bunch can be produced by a few-cycle optical laser pulse in a short undulator, placed in front of the main undulator [Saldin et al 2006]. The recently proposed mode-locked x-ray SASE FEL technique [Thompson et al. 2008] allows to obtain trains of attosecond x-ray pulses by interposing properly set chicanes between the undulators. The enhanced SASE technique allows to obtain trains of few-cycle x-ray pulses from a FEL amplifier via a so called afterburner, i.e. several few periods undulator sections separated by chicanes [Dunning et al. 2013].

If we do not want to introduce any change in the machine layout, the easiest scheme to be applied remains the optimization of the compression of low charged bunches [Reiche at al. 2008] [Rosenzweig et al. 2008]. Due to the present lack of diagnostics for very low charges, some efforts both on the theoretical and experimental side has been spent at LCLS on the optimization of the compression of a 20 pC charged bunch [Wang et al. 2011] [Ding et al. 2009].

In this paper we would like to extend the optimization of the compression of a 20 pC electron bunch to the European XFEL layout including also the comparison of the performances delivered by different setups of the photo-cathode laser. The motivation for this study is supplied by the observation that the experimental characterization of a new working point for short pulses operation at the European XFEL is already feasible at the PITZ facility [Stephan et al. 2010] [Krasilnikov et al. 2012].

1.1. Single spike condition

The radiation produced by SASE FELs 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 [Bonifacio et al. 1994]. The cooperation length L_c depends on the emitted radiation's wavelength λ, according to:

$$L_c = L_{c1d}\,(1+\eta) \tag{1}$$

where the parameter η, defined as in [Boscolo et al. 2008], takes into account transverse effects and beam energy spread, and L_{c1d} is the one-dimensional cooperation length, defined as:

$$L_{c1d} = \frac{\lambda}{\sqrt{3}(4\pi\rho)} \tag{2}$$

with ρ being the one dimensional FEL parameter. 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 electron bunch must be shorter than $2\pi L_c$. It is very difficult to satisfy this condition in x-ray FELs where, according to equations 1 and 2, $2\pi L_c$ becomes very small, typically a fraction of μm.

1.2. Motivation and procedure

In order to fulfill the single spike condition (or get as close as possible to it) the charge of the electron bunch must be small (sub pC or few tens of pC) and it is necessary to work at the maximum compression point (or very close to it). These two requirements make the working point deeply different from the nominal XFEL working point that has been already extensively studied [Zagorodnov et al. 2011] and that has to fulfill mainly the ultra-high brilliance request. The optimization of the injector setup of the nominal European XFEL working points has been carried out by minimizing the transverse emittance of the electron bunch. In [Zagorodnov et al. 2010] has been underlined that the use of a similar approach for the ultra-short low charge operation ends up into strong stability requirements for the RF