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Energy phase correlation and pulse dynamics in short bunch high gain FELs

G. Dattoli [a,*], L. Giannessi [a], S. Pagnutti [b], P.L. Ottaviani [c]

[a] ENEA — Unità Tecnica Sviluppo di Applicazioni delle Radiazioni, Laboratorio di Modellistica Matematica, Centro Ricerche Frascati, Via E. Fermi 45-00044 Frascati, Roma, Italy
[b] ENEA — Unità Tecnica Metodi per la Sicurezza dei Reattori e del Ciclo del Combustibile, Laboratorio Sviluppo Metodi e Supporto Informatico, Via Martiri Monte Sole 4-40129 Bologna, Italy
[c] INFN Sezione di Bologna, Viale B. Pichat 6/2, 40127 Bologna, Italy

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ABSTRACT

We analyze the dynamics of Free Electron Laser (FEL) devices, operating with a bunched beam exhibiting a longitudinal phase space correlation. We show that the presence of an energy-position correlation term is responsible for very interesting effects like an enhancement of the peak output power, a shortening of the laser pulses and an increase of the non linearly generated harmonic intensities. We conjecture that the mechanism is due to a kind of energy tapering effect associated with the correlation. We discuss the difference of the dynamics with respect to an ordinary undulator tapering and the relative advantages.

1. Introduction

The FEL high gain dynamics is strongly affected by the characteristics of the electron beam phase space distribution. The effects of transverse phase space have been thoroughly investigated [1]. More recently, new concepts, associated with the slice phase space distribution, have emerged as a consequence of the peculiar properties of the FEL SASE dynamics [2], characterized by the so called coherence length, due to the slippage mechanism [3].

The FEL radiation, produced by a single electron bunch, slips, indeed, over the bunch itself, thus creating a kind of longitudinal mode-locking [4], responsible for a "local" coherence, due to the fact that radiation spans, during the interaction, over a small portion of the bunch only. Different, uncorrelated "local mode locked structures", distributed all over the bunch, may interfere destructively during the interaction, thus giving rise to the spiking behavior characterizing the SASE FEL radiation [5]. This is indeed one of the main problems, which may hamper the use of the FEL radiation, for applications requiring a good deal of coherence.

It is evident that an electron bunch, with a length comparable to the coherence length, would provide the natural solution to this problem.

In this paper we develop a systematic investigation of the characteristics of the FEL dynamics, with bunch length comparable to the coherence length and exhibiting also an energy position correlation [6].

We consider therefore a FEL driven by an electron bunch characterized by a longitudinal distribution of the type

$$f(z,\varepsilon)=\frac{1}{2\pi\sum_\varepsilon}\exp\left(-\frac{\gamma_\varepsilon z^2+2\alpha_\varepsilon z\varepsilon+\beta_\varepsilon\varepsilon^2}{2\sum_\varepsilon}\right)$$
$$\varepsilon=\frac{E-E_0}{E_0} \tag{1}$$

where ε is the relative energy and $\sum_\varepsilon$ is the longitudinal emittance, which, along with the Twiss parameters, define the bunch length and the relative energy spread as

$$\sigma_\varepsilon=\sqrt{\gamma_\varepsilon\sum\nolimits_\varepsilon},$$
$$\sigma_z=\sqrt{\beta_\varepsilon\sum\nolimits_\varepsilon}. \tag{2}$$

Furthermore the normalization of the distribution reported in Eq. (1) requires that

$$\beta_\varepsilon\gamma_\varepsilon-\alpha_\varepsilon^2=1. \tag{3}$$

The parameter α_ε accounts for the energy position correlation and the FEL operation, with an electron bunch having such a correlation, displays a very interesting dynamical behavior.

Before entering more specific aspects we note that electrons, exhibiting an energy correlation along the bunch, are characterized by an energy which depends on the position z_b inside the bunch specified by the relation

$$E(z_b)=E_0\left(1-\frac{\alpha_\varepsilon}{\beta_\varepsilon}z_b\right). \tag{4}$$

* Corresponding author.
E-mail address: dattoli@frascati.enea.it (G. Dattoli).

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If α_ε is negative the tail of the bunch will have less energy than the head. The electrons of the bunch are therefore radiating at different wavelengths, which becomes longer at the tail. The situation is reminiscent of a kind of energy tapering which may have consequence on the output radiation characteristics and in particular on the power, which should be larger than that obtained in the uncorrelated case.

This hypothesis is confirmed by the numerical computation, and in Fig. 1 we have reported the maximum power vs. α_ε for FEL parameters analogous to those presently employed at SPARC (undulator period $\lambda_u \cong 2.8$ cm, parameter strength $K \cong 2.06, E \cong 152$ MeV) but with bunch lengths corresponding to few (about 3 and 6) coherence lengths. The simulation shows a sharp dependence of the saturated power on α_ε which exhibits a maximum for negative value. This is just one aspect of a fairly interesting phenomenology, involving the FEL pulse dynamics and the relevant shape.

In this paper we discuss these effects and the relevant consequences on the harmonic generation and we will see how the energy correlation parameter may become a key quantity in the control of the FEL output beam quality.

2. Pulse shape and non linear harmonic generation

The FEL SASE operation with a beam exhibiting an energy phase correlation not only affects the maximum power, but also the laser pulse dynamics and shapes.

This is evident from Fig. 2 where we have reported the evolution of the pulses in the region around the saturation point (before and after) for the cases with negative, positive and without correlation.

In the region above saturation the laser pulses exhibit the so called super-radiant behavior [7]. They develop typical side bands in their rear part, because it interacts with the electron bunch, thus gaining more energy than the front part, which tends to escape outside the electron bunch. The presence of the side bands is a combination of slippage and finite length of the electron bunch.

The side band growth is smoothened by a non vanishing correlation parameter, which controls the side band growth in a fairly efficient way. For negative values the pulse remains significantly narrower than the other two cases with a significantly larger peak of the power.

The physical reasons underlying this behavior will be discussed later in section. Here we note that the control of the side-band growth is essentially due to the fact that the correlation parameter affects the slippage mechanism. For positive values, the lethargic effect, namely the slowing down of the laser pulse velocity due to the interaction and consequent gain, is enhanced. The electron and optical bunches overlaps for most of the time and therefore the rear and front part of the bunch experiences nearly equal gain factors. In absence of the correlation the slippage is not sufficiently counteracted by the lethargy and the side band grows. For negative values the center of mass moves faster, it is pulled outside abruptly and the side band has no sufficient time to grow.

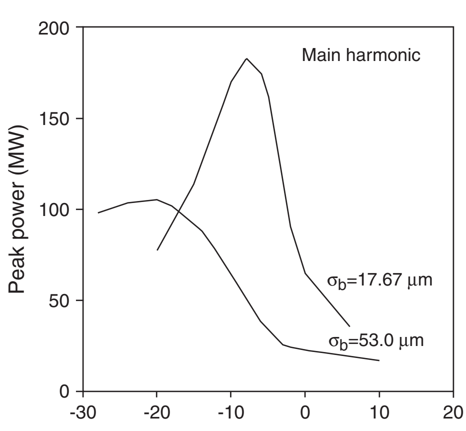

Fig. 1. Peak power vs. $\alpha_\varepsilon$for electron bunches with the same charge but different lengths a) $\sigma_z = 17.67$ μm, peak current $I_e = 159$ A, b) $\sigma_z = 53.0$ μm, peak current $I_e = 53$ A, $\Sigma = 10.60$ nm, $\sigma_\varepsilon \cong 6.10^{-4}$.

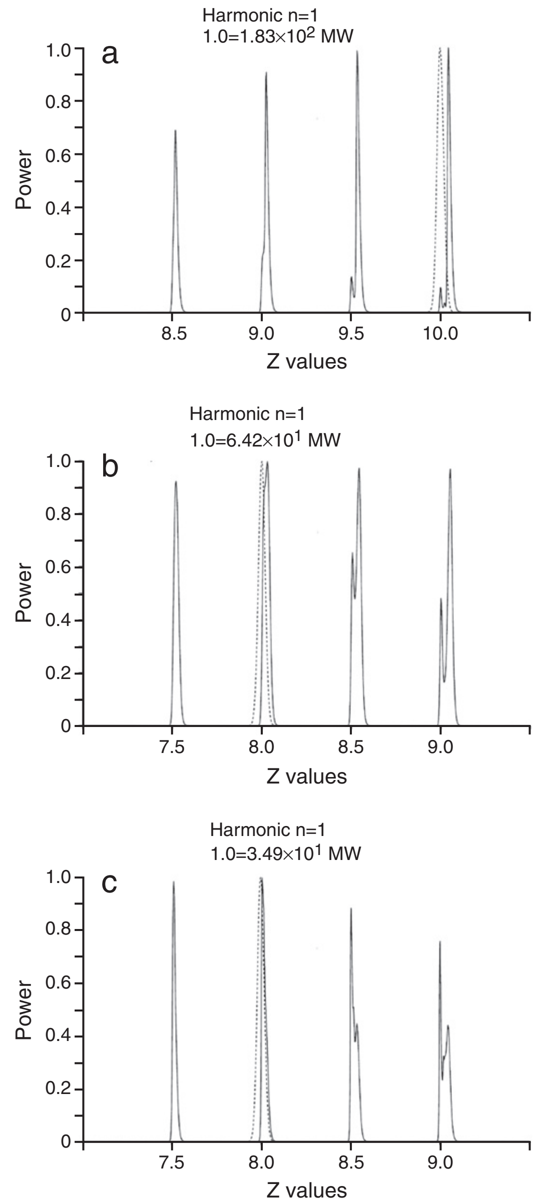

Fig. 2. Pulse shape evolution vs. the undulator longitudinal coordinate for the case $\sigma_z = 17.67$ μm, the dotted curve denotes the electron bunch distribution and specifies the position at which saturation (understood as the maximum power of the peak of the pulse) occurs. a) $\alpha_\varepsilon = -8$, b) $\alpha_\varepsilon = 0$, c) $\alpha_\varepsilon = 6$.

It is interesting to understand the consequence of the above dynamics on the non linear harmonic generation, which seems strongly enhanced for a beam with negative α_ε values (see Fig. 3).

The physical reasons determining this effect are just due to the fact that the shorter laser pulse emerging in the operation with negative correlation parameter determines a more efficient bunching, since a quite robust pulse interacts with almost fresh electrons, because the interaction occurs essentially on the border of the trailing edge of the electron bunch.

The effects we have pointed out appear quite remarkable and are peculiar of either the correlation factor and the shortness of the electron bunch. It is however interesting to consider the laser pulse shape evolution for larger values of the electron bunch length.