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Longitudinal Space Charge Driven Microbunching Instability in TTF2 linac

E.L. Saldin [a], E.A. Schneidmiller [a], M.V. Yurkov [b]

[a] *Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany*

[b] *Joint Institute for Nuclear Research, Dubna, 141980 Moscow Region, Russia*

Abstract

In this paper we study a possible microbunching instability (amplification of parasitic density modulations) in the TESLA Test Facility (Phase 2) linac. A longitudinal space charge field is found to be the main effect driving the instability. Analytical estimates show that initial perturbations of beam current in the range 0.5-1 mm will be amplified by a factor of a few hundred after the beam passed two bunch compressors. A method to suppress the instability is discussed.

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1 Introduction

Magnetic bunch compressors are designed to produce short electron bunches with a high peak current for linac-based short-wavelength free electron lasers (FELs) [1–7]. Microbunching instabilities of bright electron beams in linacs with bunch compressors are of serious concern and the subject of intense studies [8–17]. A simple physical picture of the instability [9,18,19] suggests that high-frequency components of the beam current spectrum (higher than typical inverse pulse duration) cause energy modulations at the same frequencies due to collective fields (longitudinal space charge, CSR, geometrical wakefields etc.). The energy modulation is converted into an induced density modulation while the beam is passing the bunch compressor. If the high-frequency self-fields are strong enough, the induced density modulation can be much larger than the initial one. In other words, the system can be treated as a high-gain klystron-like amplifier.

The main theoretical [10–12,15] and numerical [8,13,14,16] efforts were dedicated to coherent synchrotron radiation (CSR) driven instability. A contribution of geometrical wakefields to the total gain was recently studied in [17]. An amplification of parasitic modulations due to the longitudinal space charge (LSC) field was also considered [9,19] in the context of phase 1 of the TESLA Test Facility (TTF1) [2]. The aim of this paper is to study a possible LSC driven instability at TTF2 being under construction [4]. Since two bunch compressors are going to be used at TTF2, the total effect is expected to be much stronger. Our estimates, based on beam parameters taken from start-to-end simulations [20], predict that small initial density perturbations in the range 0.5-1 mm will be amplified by a factor of a few hundred. Generally speaking, our studies have led us to the conclusion that LSC could be the main source of instability (not only at TTF), dominating over contributions from CSR and other wakefields.

The paper is organized as follows. In Section 2 we present the gain formula for a single bunch compressor [9,19]. In Section 3 we discuss the LSC impedance in free space and limitations on use of this notion. In Section 4 we estimate the LSC induced gain for the case of a nominal design of TTF2. In Section 5 we consider a possible way to control local energy spread which seems to be the most effective cure for the instability. This is followed by a discussion on the importance of LSC for microbunching instabilities in Section 6.

2 Gain formula for a single bunch compressor

Let us assume that at some point of the beam line upstream of the bunch compressor there is a small current perturbation $\rho_{\rm i}$ at some wavenumber k (the modulation wavelength is $\lambda = 2\pi/k$):

$$I(z) = I_0 \left[1 + \rho_{\rm i} \cos(kz)\right] \ , \tag{1}$$

where z is coordinate along the beam. The amplitude of energy modulation $\Delta\gamma$ (in units of electron rest energy) due to collective self-fields can be described by longitudinal impedance $Z(k)$ [1]:

$$\Delta\gamma = \frac{|Z(k)|}{Z_0} \frac{I_0}{I_{\rm A}} \rho_{\rm i} \ , \tag{2}$$

where $Z_0 = 377 \ \Omega$ is the free-space impedance and $I_{\rm A} = 17$ kA is the Alfven current. If self-fields inside bunch compressor can be neglected, one can calculate the amplitude of the induced density modulation $\rho_{\rm ind}$ at the end of compressor. In general case, to find final density modulation $\rho_{\rm f}$ one should sum up induced modulation and (transformed to the end of compressor) initial one, taking care of phase relations. But in this paper we use approximation

$$\rho_{\rm i} \ll \rho_{\rm ind} \ll 1 \ .$$

In other words, $\rho_{\rm f} \simeq \rho_{\rm ind}$ and the gain in density modulation

$$G = \frac{\rho_{\rm f}}{\rho_{\rm i}} \simeq \frac{\rho_{\rm ind}}{\rho_{\rm i}}$$

is assumed to be high, $G \gg 1$ Under this approximation the gain depends neither on phase of $Z(k)$ nor on sign of momentum compaction factor R_{56} of the bunch compressor and is found to be [9,19]:

$$G = Ck|R_{56}| \frac{I_0}{\gamma_0 I_{\rm A}} \frac{|Z(k)|}{Z_0} \exp\left(-\frac{1}{2} C^2 k^2 R_{56}^2 \frac{\sigma_\gamma^2}{\gamma_0^2}\right) \tag{3}$$

[1] We use here the notion of integrated impedance, not the impedance per unit length

Here C is the compression factor, γ_0 is relativistic factor, and σ_γ is rms uncorrelated energy spread (in units of rest energy) before compression.

In the considered case the influence of beam emittance ϵ on longitudinal dynamics is a second order effect and is negligible when

$$Ck\epsilon S_c/\beta \ll 1 \ , \tag{4}$$

where S_c is the length of a path through compressor and β is the beta-function.

The formula (3) can be used when the effect of wakefields in front of compressor is much stronger than any collective effects inside the bunch compressor. In particular, CSR-related effects are strongly suppressed [10–12] when

$$k\sqrt{\epsilon\beta}\theta_d \gg 1 \ , \tag{5}$$

where θ_d is the bending angle in a dipole of the bunch compressor. The conditions (4) and (5) can easily be met simultaneously.

3 Longitudinal space charge impedance

Let us consider longitudinal space charge field of a modulated beam (1) propagating in free space. This field can easily be calculated in the rest frame of the beam (see, for instance, Refs. [21,22]). We analyze here the limit of "pencil" beam, when

$$p = \gamma/(k\sigma_\perp) \gg 1 \ . \tag{6}$$

Here $\sigma_\perp$ is the rms transverse size of the beam, and γ is relativistic factor. In this limit the field variation across the beam can be neglected, so that only on-axis field should be calculated. The impedance of a drift with the length L_d is then given by:

$$\frac{|Z(k)|}{Z_0} = \frac{2kL_d}{\gamma^2}(\ln p + const.) \ . \tag{7}$$

A numerical constant in the brackets depends on transverse shape of the beam and will be neglected in our estimates. The influence of vacuum chamber can be neglected when

$$\gamma/(kb) \ll 1 \ , \tag{8}$$

b being the transverse size of the vacuum chamber. In the opposite case the parameter p in (7) should be substituted by $b/\sigma_\perp$, so that the expression for the impedance takes a usual form (see, for instance, Ref. [23]). The density modulation in the drift does not change, i.e. a longitudinal motion can be neglected, under the condition:

$$(kL_d)^2 \frac{I_0 \ln p}{I_\mathrm{A} \gamma^5} \ll 1 \ . \tag{9}$$

Let us now estimate an effective LSC impedance for an accelerating structure with the length L_A and the average accelerating gradient $\mathrm{d}\gamma/\mathrm{d}s$. Considering γ in (7) as a function of s, neglecting change of $\ln p$ in the structure, and making integration, we can generalize (7) as follows:

$$\frac{|Z(k)|}{Z_0} \simeq \frac{2kL_\mathrm{A} \ln p}{\gamma_\mathrm{i} \gamma_\mathrm{f}} \ . \tag{10}$$

where γ_i and γ_f are relativistic factors before and after acceleration, respectively. When $\gamma_\mathrm{f} \gg \gamma_\mathrm{i}$, eq. (10) can be rewritten in the form:

$$\frac{|Z(k)|}{Z_0} \simeq \frac{2k \ln p}{\gamma_\mathrm{i} (\mathrm{d}\gamma/\mathrm{d}s)} \ . \tag{11}$$

4 Gain estimation for TTF2

The TESLA Test Facility Free Electron Laser (phase 2) is supposed to produce powerful coherent soft X-ray radiation [4]. A nominal design of TTF2 [20,24] assumes linearized compression of the electron beam in two bunch compressors. The laser driven RF gun produces low-emittance, flat-top electron bunch (total length is 7 mm) with the current about 40 A, which is accelerated off-crest in the TESLA module (ACC1). A third harmonic cavity is then used to linearize longitudinal phase space. At the energy of 120 MeV the beam is compressed by a factor of $C_1 = 8$ (the current increases up to 320 A) in the 4-bend

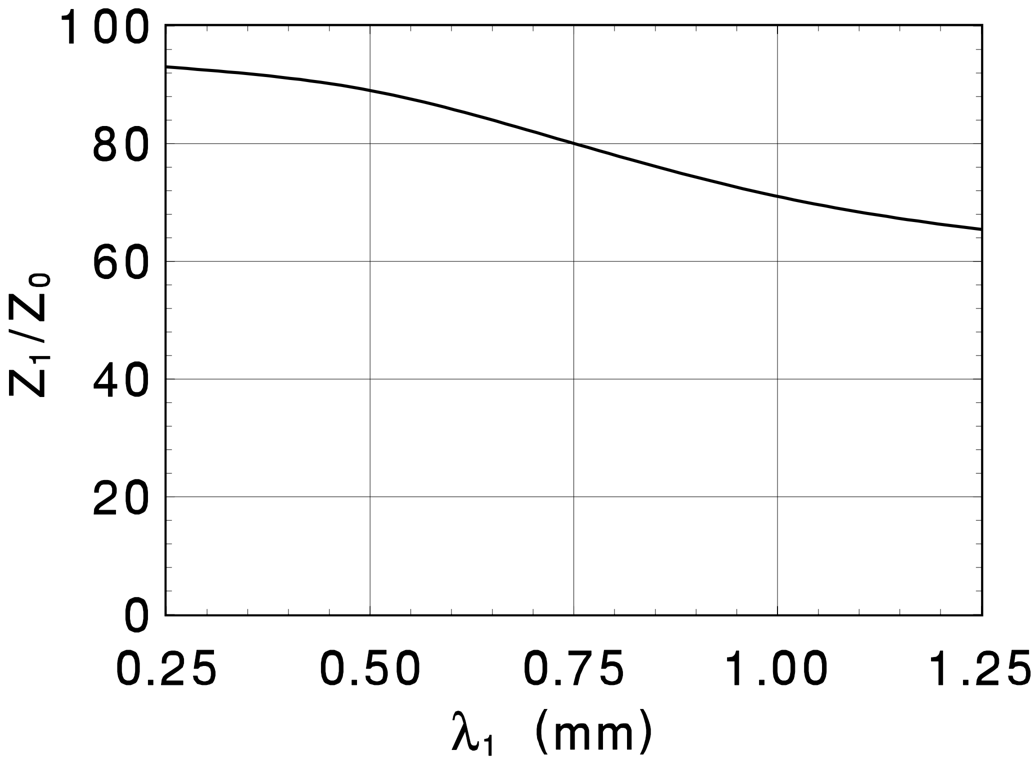

Fig. 1. The LSC impedance in ACC1 (numerical simulations)

chicane BC1 with the $R_{56} = 17$ cm. After that the beam passes a 14 m long drift, and is then accelerated off-crest in two TESLA modules (ACC2 and ACC3) up to 438 MeV. In an S-type chicane BC2 ($R_{56} = 4.9$ cm) the peak current increases by another factor of $C_2 = 8$, reaching the required level of about 2.5 kA. According to start-to-end simulations [20], the local energy spread after compression is below 200 keV, and the normalized slice emittance is 1-1.5 mm*mrad in the lasing area of the bunch.

Our estimates of the gain of LSC driven microbunching instability will be based on these parameters of the machine and of the electron beam. A very important parameter is the local energy spread before compression. If we divide final energy spread, about 200 keV, by a total compression factor, then we get about 3 keV. The simulations of the initial part of the machine show that, actually, the local energy spread before compression is visibly lower. Indeed, apart from the growth of this parameter due to compression itself, there is an additional growth due to CSR in the bunch compressors. However, for our estimates we assume that initial energy spread is 3 keV, thus possibly underestimating the total

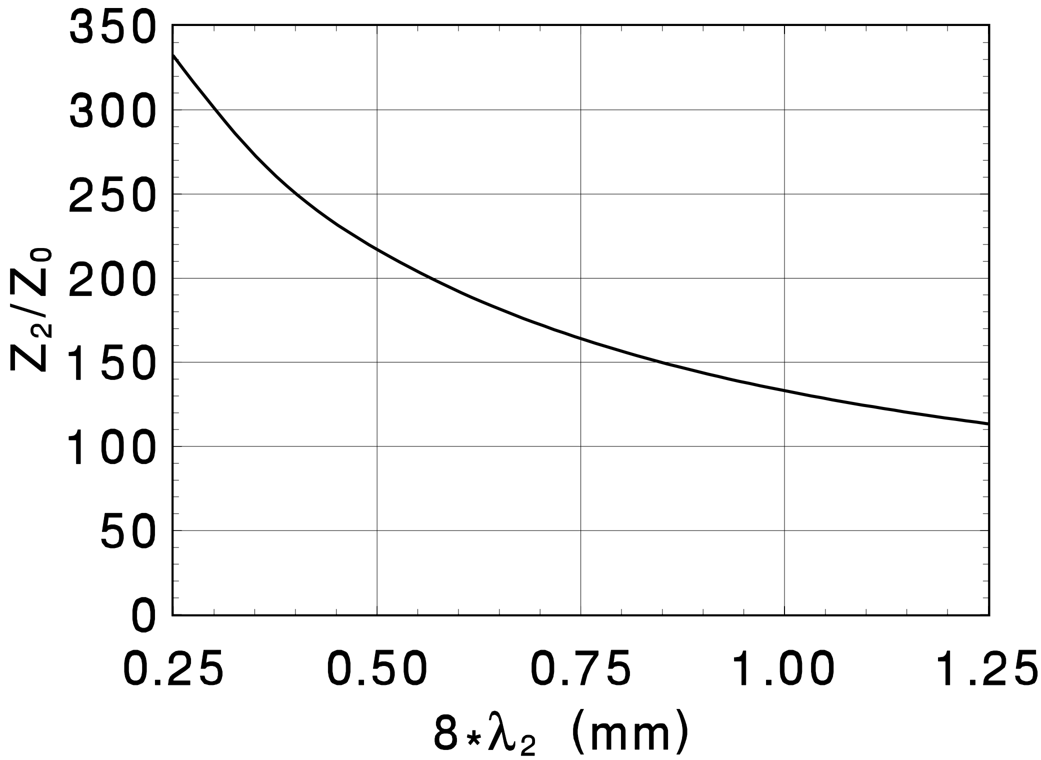

Fig. 2. The LSC impedance for the part of the machine between BC1 and BC2 (analytical calculations)

gain.

We perform the estimates using the following scheme. We do not analyze the processes in the gun and assume that the beam with some small amplitude of density modulation and a period λ_1 enters accelerating module ACC1. There the beam is quickly accelerated, the longitudinal motion gets frozen, and we can calculate the energy modulation (and, therefore, impedance in accordance with (2)). Then we compute the gain in BC1 using formula (3). A compressed beam (with the enhanced density modulation with a period $\lambda_2 = \lambda_1/C_1$) moves in the long drift and in the modules ACC2 and ACC3. We calculate impedance for this part of the machine and use again (3) to calculate the gain in BC2. The total gain is a product of partial gains in two compressors. We would like to study pure effect of the space charge and assume no wakefields inside bunch compressors [2].

[2] Estimates of CSR effects show that they do not play a dominant role in the considered range of parameters but can give corrections to the final result

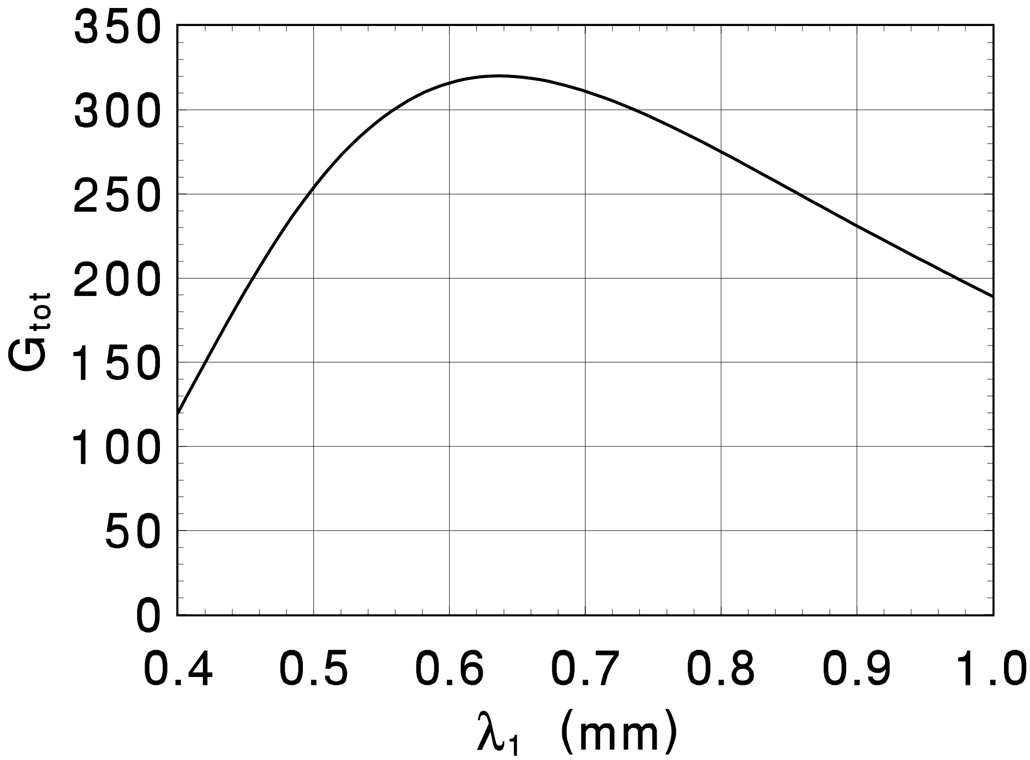

Fig. 3. Total gain versus initial modulation wavelength

Analyzing the above mentioned parameters, we come to the conclusion that the cut-off wavelength is defined by the smearing effect due to the energy spread in BC2. Corresponding initial modulation wavelength λ_1 is in the range 0.5-1 mm. Analytical calculations of the impedance in ACC1 would be difficult because the condition (6) is not well satisfied at the entrance to ACC1 (rms transverse size at this point is about 0.8 mm, and $\gamma_{\mathrm{i}} \simeq 9$). Besides, it is not clear a priori, whether or not the density modulation stays constant while the energy modulation is growing (taking into account low initial energy and reduced accelerating gradient in the first half of ACC1, $\mathrm{d}\gamma/\,\mathrm{ds} = 24\ \mathrm{m}^{-1}$). For these reasons we performed numerical simulations of this part of the machine with the help of the code Astra [25], introducing small density modulations at different wavelengths and getting corresponding energy modulations at the exit of ACC1. The impedance is then calculated using formula (2). The results of these calculations are presented in Fig. 1. Note that at the shortest wavelength on this plot the density modulation slightly decreases while beam is moving in ACC1.

As for the part of the machine between BC1 and BC2, the analytical approach is justified there. With the help of formulas (7) and (11) we calculate the total impedance, defining transverse size of the beam from the design optics and taking the nominal accelerating gradient in ACC2 and ACC3, $\mathrm{d}\gamma/\mathrm{ds} = 37\ \mathrm{m}^{-1}$. The resulting impedance is plotted in Fig. 2, where the wavelength is scaled to that before compression for comparison with Fig. 1. Note that the contribution of the long drift behind BC1 to the total impedance is about 70 %.

Finally, using formula (3) and Figs. 1 and 2, we calculate the total gain which is plotted in Fig. 3 versus initial modulation wavelength. In the given wavelength range the high-gain condition is well satisfied for each stage of compression. The maximum of the gain curve corresponds to the wavelength 10 μm after two-stage compression.

After compression the beam is accelerated up to 1 GeV (for the shortest FEL wavelength 6.4 nm) and then moves about 80 m to the undulator. The LSC impedance for the part of the machine between BC2 and the undulator at the wavelength 10 μm can be estimated at $|Z|/Z_0 \simeq 200$. According to formula (2), a 30 % density modulation at the exit of BC2 (which corresponds to the level of 10^{-3} at the entrance to ACC1 for the estimated gain of 300) would result in more than 4 MeV energy modulation at the undulator entrance. A reliable operation of the facility would require to keep the density modulation at the entrance to ACC1 well below the level of 10^{-3} (or to suppress the amplification mechanism).

5 How to cure the instability?

The estimates, presented in the previous section, show that LSC driven microbunching instability may be of serious concern at TTF2. The measures to cure this harmful effect can include suppression of the initial high-frequency density perturbations and of the amplification mechanism itself. As for the initial conditions, there can be different sources of noise in the gun in the considered spectral range, but it would be a difficult task to study them. On the other hand, the most important contribution to the density modulation may come from the ripples on the laser pulse. Numerical simulations [26] have shown that the modulations of the laser pulse in the range, considered in this paper, are not filtered out in the gun. They are efficiently converted (with the efficiency $30 - 50\%$) into the beam density modulations. Therefore, a special care should be taken in order to get a smooth laser pulse [3].

As for the amplification mechanism itself, an effective way to suppress the gain is to increase local energy spread since the gain critically depends on this parameter. For instance, increase of the energy spread at TTF2 up to 15-20 keV would eliminate the instability. At a high energy the use of superconducting wiggler, where the energy spread increases due to quantum fluctuations of synchrotron radiation, was suggested [6,28]. At TTF this method does not work because of the relatively low energy. A simple method to control the energy spread at low energy would be to use FEL type modulation of the beam in optical wavelength range by a laser pulse in an undulator. Then the beam goes through the bunch compressor where these coherent energy modulations are quickly dissipated, leading to the effective "heating" of the beam [4]. For illustration we present here a numerical example for TTF2. The undulator with ten periods, a period length 3 cm, and a peak field 0.49 T is located in front of BC1. A fraction of power in the second harmonic ($\lambda = 0.52\mu$m) of the Nd:YLF laser is outcoupled from the photoinjector laser system and is transported to the undulator. For a transverse size of the laser beam 0.5 mm (Rayleigh length is 1.5 m) and a power 300 kW, the amplitude of energy modulation will be about 20 keV (rms energy spread is smaller by $\sqrt{2}$). Of course, the required value of the modulation should be defined experimentally.

6 Discussion

Generally speaking, our studies have led us to the conclusion that LSC effect on microbunching instability is stronger than the effects of CSR and of geometrical wakefields for typical parameters of linacs with bunch compressors for FELs. Of course, CSR field is

[3] The nominal design of TTF2 assumes 20 ps flat-top laser pulse with a 2 ps rise/fall time [27]. One of the proposed methods for the pulse formation is a stacking of 2 ps pulses. It is worth mentioning that such way of preparing laser pulse can easily lead to significant distortions of the beam density in the potentially dangerous spectral range. The specified limitation on flat top inhomogeneity of the laser pulse $\pm 10\%$ does not seem to be tolerable.

[4] Similar mechanism takes place in storage ring FELs

much stronger at the energy of compression, but LSC effect is accumulated at much lower energies and over much longer distances. For example, as one can see from Fig. 2, the LSC impedance at the optimal wavelength ($\lambda_2 = 0.6/8 \simeq 0.08$ mm) is about 200, while CSR impedance in the first dipole of BC2 is 10. In addition, a suppression of CSR instability due to finite emittance effects does not play any role for LSC driven instability. The latter statement is, certainly, also valid for geometrical wakefields in the linac [17]. However, for a typical set of parameters the integrated LSC impedance is significantly larger than that of geometrical wakefields. Indeed, LSC is dominant as soon as $\gamma < kb$, where b is a typical transverse size of electrodynamic environment (like the radius of an iris of accelerating structure). Considering the gain calculations in Ref. [17] for Linac Coherent Light Source [6], we can observe that for high-frequency part of the gain curve this condition holds almost over the entire beam line. It means that the maximal total gain should be visibly larger than that obtained in Ref. [17] if one takes LSC into account. Even in the saturation example [17] with a multi-GeV beam after compression, the space charge effect would give an essential contribution to the final energy modulation. We would also like to point out that LSC may explain the amplification observed at the DUV facility [3], the effect which can not be explained by CSR [29]. Our conclusion is that for the studies of microbunching instabilities the space charge effect should be included into start-to-end simulations and analytical calculations.

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