ON THE REALISTIC GAIN ESTIMATION OF THE CSR MICROBUNCHING INSTABILITY IN BUNCH COMPRESSORS

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Abstract

For a realistic gain estimation of the CSR microbunching instability, we describe limitations of the current gain estimation methods in detail and several smearing effects which we do not consider yet.

INTRODUCTION

Unlike the normal CSR which may dilute the projected transverse emittances in a bunch compressor (BC), CSR may also be generated for a wavelength much shorter than the bunch length if the bunch has a periodic modulation in its current or energy profile before the bunch compressor [1]-[4]. In this case, the initial amplitude of the modulation can be amplified by CSR in the BC, and the slice emittances and the slice energy spread can be increased by the amplified microbunching [2], [5]. This is called the CSR microbunching instability in bunch compressors [2]-[5]. Since the slice emittances and the slice energy spread should be small enough for SASE FEL's, the CSR microbunching instability which dilutes the slice parameters is an important issue and is still under deep study [2]-[6]. The gain of the CSR microbunching instability is defined as the ratio of the final amplitude of the modulation after compression with respect to the initial amplitude of the modulation before compression [4]. Although new gain-increasing effects such as the short range wakefield in the linac and the longitudinal space charge force were recently reported, the estimated gain is still somewhat over-estimated [5], [6]. In this paper, we describe limitations of the current gain estimation methods in detail and the several smearing effects which we do not consider yet.

GAIN OF CSR INSTABILITY

According to Ref. [4], the gain G of the CSR microbunching instability due to the charge density or current modulation is given by

$$G = \left|\frac{b(k_f;f)}{b_0(k_0;0)}\right| \approx \left|\exp\left[-\frac{1}{2}\left(\frac{k_0 R_{56}\sigma_{\delta u}}{1+hR_{56}}\right)^2\right]\right.$$

$$+A\bar{I}_f\left\{\frac{\sqrt{\pi}\mathrm{erf}(\bar{\sigma}_x)}{2\bar{\sigma}_x}\exp\left[-\frac{1}{2}\left(\frac{k_0 R_{56}\sigma_{\delta u}}{1+hR_{56}}\right)^2\right]+\mathcal{F}_1\right\}$$

$$\left. + A^2\frac{(I_{pk}k_0^{4/3}R_{56}L_b)^2}{(\gamma I_A \rho_0^{2/3})^2}\mathcal{F}_0\mathcal{F}_2\right| , \qquad (1)$$

$$k_0 = \frac{2\pi}{\lambda} = (1+hR_{56})k_f , \quad A = 1.63i - 0.94 ,$$

$$\bar{I}_f = \frac{I_{pk}k_0^{4/3}R_{56}L_b}{\gamma I_A \rho_0^{2/3}} , \quad \bar{\sigma}_x = k_0 L_b \frac{\sqrt{\beta_0\epsilon_{nx}/\gamma}}{\rho_0} ,$$

where λ is the initial modulation wavelength before the BC, R_{56} is the momentum compaction factor of the BC, $h = d\delta/dz$ is the chirping constant where δ is the relative energy deviation dE/E, $\sigma_{\delta u}$ is the uncorrelated relative rms energy spread, ϵ_{nx} is the normalized horizontal rms emittance, I_{pk} is the peak current after compression, and γ is the Lorentz factor. Others are defined in Ref [4].

In order to estimate the gain of a single chicane which can generate a high peak current, we have applied Eq. (1) to a model chicane used at the CSR workshop [7]. In the case of a cold beam with $\epsilon_{nx} = 0$ and $\sigma_{\delta u} = 0$, its gain is high as shown in the red line of Fig. 1(left). But the gain can be damped at small λ if $\sigma_{\delta u}$ is increased to 2.0×10^{-6} as shown in the green line of Fig. 1(left) [8]. For the case $\epsilon_{nx} = 1.0$ μm and $\sigma_{\delta u} = 2.0 \times 10^{-6}$, the gain is significantly reduced as shown in the blue line of Fig. 1(left) [4].

Recently, it was found that the signs of R_{56} and h for the gain estimation were different with those for the CSR calculation [4]. After correcting the wrong signs of R_{56} and h, the gain becomes smaller than 7 as shown in the magenta line of Fig. 1(left) [4]. If $\sigma_{\delta u}$ is 9.5×10^{-6} which is close to the uncorrelated energy spread due to the intrabeam scattering in the linac $\sigma_{\delta u,IBS}$, the gain is about 5 as shown in Fig. 1(right) [9]. For the case $\sigma_{\delta u} = 5.0 \times 10^{-5}$, the gain is around 1 although I_{pk} is 6.0 kA. If $\sigma_{\delta u}$ is increased up to 1.0×10^{-4} which is close to the allowable maximum value for the SASE FEL saturation, the gain becomes smaller than 1. In the case of a single chicane, a nonzero $\sigma_{\delta u}$ and ϵ_{nx} can effectively suppress the CSR microbunching instability although the peak current is high enough [4], [8], [9]. Note that we have some margin in $\sigma_{\delta u}$ but the margin of ϵ_{nx} is small in suppressing the CSR microbunching instability [2].

LIMITATION AND SMEARING EFFECT

Originally, the microbunching instability due to CSR in the bunch compressor was found by ELEGANT during the

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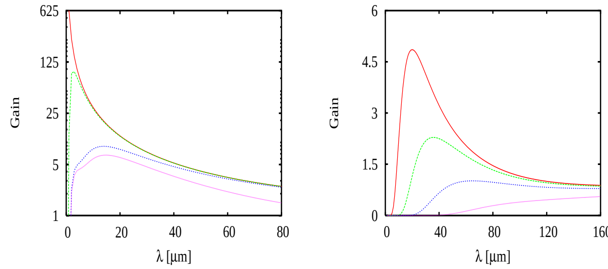

Figure 1: Gain of a model chicane as a function of the modulation wavelength λ. Here all used parameters are summarized in Table 1 where four numbers in a column are the parameters of red, green, blue, and magenta lines, respectively. More details can be found in Ref. [7].

Table 1: Parameters of model chicane used in Fig. 1.

Parameter	Unit	Fig. 1(left)	Fig. 1(right)
energy E	GeV	5.0	
I_{pk}	kA	6.0	
R_{56}	mm	-25, -25, -25, +25	+25, +25, +25, +25
h	m^{-1}	+36, +36, +36, -36	-36, -36, -36, -36
ϵ_{nx}	μm	0.0, 0.0, 1.0, 1.0	1.0, 1.0, 1.0, 1.0
$\sigma_{\delta u}$	10^{-6}	0.0, 2.0, 2.0, 2.0	9.5, 25, 50, 100

start-to-end simulation for the LCLS project [2]-[3]. Now ELEGANT as well as the analytical formulas are used in estimating the total gain of the CSR microbunching instability for the entire FEL driver linac. However a special attention is needed when we estimate the gain by the tracking code. If an initial distribution is generated by a random number generator, and the number of simulated macroparticles in a bunch is too low, the modulation can be amplified by a factor $\sqrt{N_b/N_m}$ where N_b is the actual number of electrons, and N_m is the number of simulated macroparticles in the bunch [8]. Although we use a quiet-start method based on Halton sequences to reduce the numerical noise in ELEGANT simulation, a modulation in the energy profile is artificially generated as shown in the upper two plots of Fig. 2. Here the bin number for the CSR calculation is 600 for the two cases [3]. TraFiC[4] also has a similar noise.

When the bunch length is compressed in the BC, the initial uncorrelated energy spread before the bunch compressor $\sigma_{\delta u,i}$ is increased by the compression factor $C = (1 + hR_{56})^{-1}$ due to the conservation of the longitudinal emittance. Generally, CSR induces a correlated energy spread along the bunch length during compression. However an uncorrelated energy spread may also be generated by quantum diffusion due to incoherent synchrotron radiation (ISR) and CSR. According to an ELEGANT simulation with consideration of ISR and CSR, the uncorrelated energy spread after the bunch compressor $\sigma_{\delta u,f}$ is much higher than $C \times \sigma_{\delta u,i}$ as shown in Fig. 3 and summarized in Table 2. In the case of the SCSS BC at the Phase-II stage,

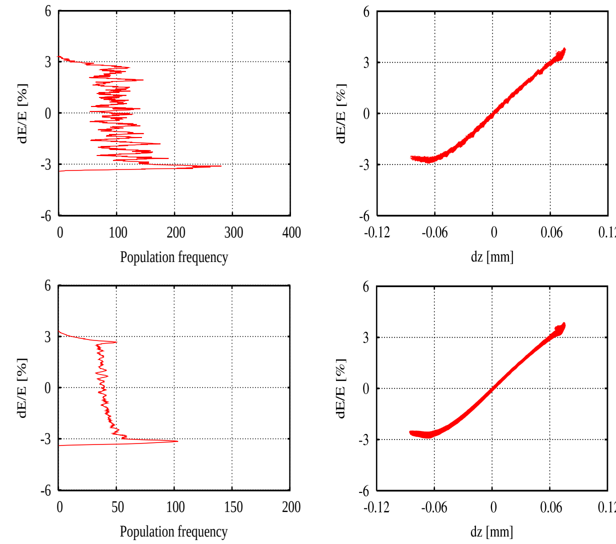

Figure 2: ELEGANT results of SCSS BC at the Phase-II stage with 5×10^4 macroparticles (upper row) and 2×10^6 macroparticles (lower row): (left column) population frequency versus the relative energy deviation after the BC (right column) longitudinal phase space after the BC. Here all initial conditions except the macroparticle number are the same for two cases. The main parameters are summarized in Table 2, and others are summarized in Ref. [1].

Table 2: Parameters of SCSS bunch compressor.

Parameter	Unit	Phase-I	Phase-II
E	MeV	230	218
single bunch charge Q	nC	1.0	1.0
I_{pk}	kA	0.5	2.0
compression factor C	·	4	8
ϵ_{nx}	μm	1.5	1.5
$\sigma_{\delta u,IBS}$	10^{-6}	9.5	9.7
$\sigma_{\delta u,i}$	10^{-5}	5.4	5.7
$\sigma_{\delta u,f}$	10^{-5}	25	58.4
$\sigma_{\delta u,SR}$	10^{-5}	3.4	12.8

the uncorrelated energy spread growth due to ISR and CSR $\sigma_{\delta u,SR} = \sigma_{\delta u,f} - C \times \sigma_{\delta u,i}$ is about 12.8×10^{-5}. In this paper, we used the sixth order polynomial fitting to remove the correlation, and the estimated $\sigma_{\delta u,f}$ is not changed significantly though we increase the fitting order up to ten. Note that only the $\sigma_{\delta u}$ growth due to compression is considered in the analytic gain estimation formula as shown in Eq. (1). If the peak current is not small, the uncorrelated energy spread growth due to ISR and CSR should be also considered in estimating the gain of the CSR instability with the analytic gain estimation formulas.

For the LCLS start-to-end simulation, PARMELA is used to consider the space charge (SC) force before the first bunch compressor. Then ELEGANT is used from the first bunch compressor without consideration of the SC force.

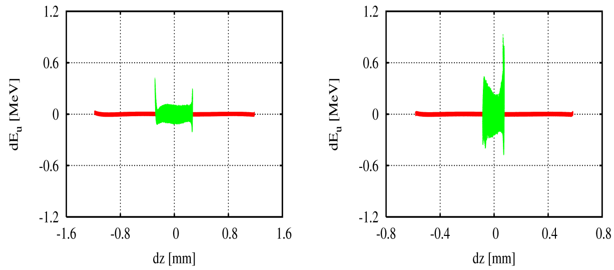

Figure 3: ELEGANT results with 2×10^6 macroparticles: change of the uncorrelated energy deviation dE_u in the SCSS BC Phase-I (left) and Phase-II (right). Here red and green dots are dE_u before and after the BC, respectively.

However according to the recent ASTRA trackings up to the TTF-2 second bunch compressor (BC3) without consideration of CSR, if the bunch length is compressed, the effects of the nonlinear space charge force is not ignorable though the beam energy is high [10]. Before the first bunch compressor, we consider the SC force, and the estimated uncorrelated rms energy deviation due to the SC force $(dE_{u,SC})_{\rm rms}$ is about 3.1 keV for $Q = 1.0$ nC as shown in Fig. 4(upper left) and summarized in Table 3. If we ignore the SC force from the first bunch compressor, $\sigma_{\delta u,SC}$ is not increased although the bunch length is compressed as shown in Fig. 4(upper right). Note that the uncorrelated energy spread growth due to compression by a factor $C = 8$ is already subtracted in Fig. 4, and $\sigma_{\delta u,SC}$ and $(dE_{u,SC})_{\rm rms}$ are only due to the SC force. When the SC force is considered after the bunch compressor, $\sigma_{\delta u,SC}$ is increased about 2.5 times as shown in Fig. 4(lower left). Although the beam energy is increased up to about 441 MeV where the second bunch compressor (BC3) will be located, $(dE_{u,SC})_{\rm rms}$ is still around 7.7 keV as shown in Fig. 4(lower right). In this case, $\sigma_{\delta u,SC}$ is decreased due to the increased beam energy or acceleration. Since the smearing effect due to the nonlinear space charge force in the linac is not considered in analytic formulas as well as in ELEGANT, their estimated gains are somewhat over-estimated in the linac. In the case of new gain-increasing effects such as the short range wakefield in the linac and the longitudinal SC force, it is also assumed that there is no uncorrelated energy spread growth in the linac [5], [6].

SUMMARY

In the case of a single chicane, the gain of the CSR microbunching instability is small for a beam with nonzero ϵ_{nx} and $\sigma_{\delta u}$. Although a modulation is amplified in the bunch compressor, it may be small or smeared out in the linac by various uncorrelated energy spread sources such as ISR and CSR in the BC and the intrabeam scattering and nonlinear space charge force in the linac. We expect that the total gain of the CSR microbunching instability for the entire FEL driver linac will not be high.

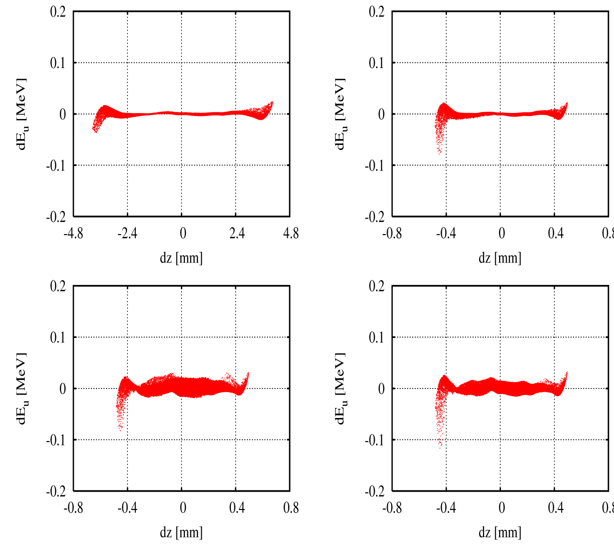

Figure 4: ASTRA trackings from the cathode with 5×10^5 macroparticles for dE_u estimation around the TTF-2 first bunch compressor (BC2) located at 20.88 m [10]: (upper left) before BC2 with the SC force, (upper right) before ACC2, with the SC force before BC2 then without the SC force from BC2 to ACC2, (lower left) before ACC2 with the SC force, (lower right) before BC3 with the SC force. The main parameters are summarized in Table 3 where four numbers in a column are the parameters of (upper left), (upper right), (lower left), and (lower right), respectively.

Table 3: Parameters of TTF-2 used in Fig. 4.

Parameter	Unit	Value
E	MeV	122, 122, 122, 441
bunch length σ_z	mm	1.9, 0.23, 0.23, 0.23
beam size σ_r	mm	0.2, 0.3, 0.3, 0.3
ϵ_{nx}	μm	1.87, 1.91, 1.98, 2.14
longitudinal position	m	20.8, 38.0, 38.0, 63.6
space charge force	·	on, on until 20.8 m then off, on, on
$(dE_{u,SC})_{\rm rms}$	keV	3.1, 3.2, 8.0, 7.7
$\sigma_{\delta u,SC}$	10^{-5}	2.5, 2.6, 6.4, 1.8

REFERENCES

[1] Y. Kim *et al.*, in *Proc. LINAC2002*, Gyeongju, Korea, 2002.

[2] LCLS Conceptual Design Report, SLAC-R-593, 2002.

[3] M. Borland, in *Proc. LINAC2002*, Gyeongju, Korea, 2002.

[4] Z. Huang *et al.*, in *Proc. FEL2002*, Argonne, USA, 2002.

[5] Z. Huang *et al.*, in these proceedings.

[6] E. L. Saldin *et al.*, DESY TESLA-FEL 2003-02, 2003.

[7] http://www.desy.de/csr/

[8] E. L. Saldin *et al.*, NIM A **490** (2002) 1.

[9] Z. Huang, SLAC Report No. LCLS-TN-02-8, 2002.

[10] The TTF FEL team, DESY TESLA-FEL 2002-01, 2002.