Nuclear Inst. and Methods in Physics Research, A 907 (2018) 182–187

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Control and application of beam microbunching in high brightness linac-driven free electron lasers

Z. Huang *, G. Stupakov *

SLAC National Accelerator Laboratory, Menlo Park, CA, USA

ARTICLE INFO

Keywords:
Microbunching
Instability
Free-electron laser

ABSTRACT

We review physical mechanisms and driving forces behind the microbunching instability in modern free-electron lasers. Laser heater and alternative methods to fight the instability are presented and evaluated. Advanced uses of the laser heater setup for temporal and spectral controls of the FEL and for intense THz production are discussed. A recent idea of using the microbunching instability for coherent generation of UV radiation is described. Noise suppression in relativistic beams is briefly reviewed.

1. Introduction

Modern free-electron lasers are playing an important role in development of new experimental techniques for studies of fundamental properties of matter in chemistry, biology, life sciences, complex materials, etc. [1]. Important parts of these FELs are high-brightness, high-current, relativistic electron beams which are typically generated in RF photo guns and compressed longitudinally in magnetic bunch compressors located at several locations in the linac [2]. When such a beam is sent though an undulator, an FEL instability develops driven by the electromagnetic interaction and leading to the longitudinal bunching in the beam at the undulator radiation wavelength. In optimal conditions, this induced bunching results in coherent undulator radiation which can be many orders more intense than the radiation of an un-bunched beam at the entrance to the undulator.

It turns out that transporting high-brightness electron beams through hundreds of meters of the accelerator and compressing it may lead to deterioration of its properties through a mechanism similar to the FEL instability but at much longer wavelengths. It is called the microbunching instability (MBI) and was first demonstrated in computer simulations in Ref. [3]. The existence of this instability is now well established in several FEL-driven accelerators (see, e.g., [4–6]). The instability creates both the energy and density modulations in the beam increasing the energy spread up to a level that can degrade the FEL gain process. An accompanying and undesired effect is a large coherent optical transition radiation signal at intercepting diagnostic screens, often limiting the utility of beam profile imaging systems [5,7–9].

In this paper we review the mechanism of the instability and various approaches to control it in modern FELs. We also discuss several beam dynamics aspects and radiation generation schemes that are related to the understanding of this instability.

2. Shot noise in a quiet beam

Before addressing the issue of beam instabilities it is important to understand statistical properties of a "quiet" beam—which is not subjected to such instabilities. In the absence of instabilities it is usually assumed that particles are randomly distributed in space without correlations between their positions.[1] Statistical properties of such a distribution are referred to as *shot noise*. While there are several techniques to describe shot noise, the most general one uses the language of the distribution functions and the formalism of the Vlasov equation. Below we will briefly characterize the distribution function of the shot noise.

We consider fluctuations in the beam in the laboratory frame of reference. The coordinate z marks the position of a particle inside the beam (with positive z in the direction of propagation), and $\eta = \Delta E/E_0$ is the relative energy deviation with the nominal energy of the beam $E_0 = \gamma mc^2$. The 1D distribution function is $f_0(z,\eta) = n_0 F(\eta) + \delta f(z,\eta)$ where $F(\eta)$ is the averaged distribution function normalized by $\int d\eta F(\eta) = 1$, and n_0 is the averaged line density of the beam. Note that we assume on average uniform distribution over z which is a reasonable local approximation for small-scale fluctuations. The fluctuational part

[1] More precisely, this is only true when one neglects the Coulomb interaction between the particles which establishes such correlations. This interaction however is typically small in relativistic beams. Correlations can also be imprinted on the beam in the process of electron emission in RF photo guns.

* Corresponding authors.
E-mail addresses: zrh@SLAC.Stanford.edu (Z. Huang), stupakov@slac.stanford.edu (G. Stupakov).

https://doi.org/10.1016/j.nima.2018.02.030
Received 3 January 2018; Received in revised form 5 February 2018; Accepted 5 February 2018
Available online 27 February 2018

$\delta f(z,\eta)$ can be Fourier expanded, $\delta \hat{f}_k(\eta) = \int_{-\infty}^{\infty} dz e^{-ikz} \delta f(z,\eta)$. For shot noise, according to the statistical physics of ideal gas [10],

$$\langle \delta f(z,\eta)\delta f(z',\eta')\rangle = n_0 F(\eta)\delta(z-z')\delta(\eta-\eta'), \tag{1}$$

which after the Fourier transformation gives

$$\langle \delta \hat{f}_k(\eta)\delta \hat{f}_{k'}(\eta')\rangle = 2\pi n_0 F(\eta)\delta(k+k')\delta(\eta-\eta'), \tag{2}$$

where the angular brackets denote ensemble averaging. Introducing the density fluctuation $\delta n(z) = \int d\eta\, \delta f(z,\eta)$ we find by integrating (1) over η and η'

$$\langle \delta n(z)\delta n(z')\rangle = n_0 \delta(z-z'). \tag{3}$$

This is a mathematical expression of the properties of the shot noise: density fluctuations in shot noise are uncorrelated in space.

3. Sources of impedance

According to the modern understanding there are two important sources of impedance that drive MBI. The first one is the longitudinal space charge (LSC) impedance (see, e.g., [11]). When a beam of small radius a propagates inside a round pipe of radius r_w with perfectly conducting walls it generates the longitudinal wakefield due to its space charge. Assuming $a \ll r_w$, the space charge impedance is given by the following expressions: for $k \equiv \omega/c \ll \gamma/r_w$,

$$Z_{\rm LSC}(k) \approx i\frac{Z_0 c}{4\pi}\frac{k}{\gamma^2}\left(1+2\ln\frac{r_w}{a}\right), \tag{4}$$

and for $\gamma/a \gg k \gg \gamma/r_w$,

$$Z_{\rm LSC}(k) \approx i\frac{Z_0 c}{4\pi}\frac{k}{\gamma^2}\left(1+2\ln\frac{\gamma}{ak}\right). \tag{5}$$

At even shorter wavelengths, for $k \gg \gamma/a$, the concept of impedance, strictly speaking, breaks down, because it is only valid if the induced field does not change much through the beam cross section. For analysis of the space charge forces at these short distances see [12,13]. As a numerical illustration of the region of applicability of Eq. (5) consider the following example: for $a = 100\,\mu$m, $\gamma = 500$, the condition $k \lesssim \gamma/a$ is satisfied for $\lambda = 2\pi/k \gtrsim 1\,\mu$m.

Another driver of the microbunching instability is the so called coherent synchrotron radiation (CSR) impedance. It arises when a relativistic particle is moving in free space in a circular orbit. The CSR wake is localized in front of the particle, $z > 0$. Assuming the orbit radius R and neglecting transition effects the CSR wake of a point charge per unit length of path for the distances $R \gg z \gg R/\gamma^3$ is given by the following equation[2] [14,15]:

$$w(z) \approx -\frac{E_\parallel}{e} = -\frac{2}{3^{4/3}R^{2/3}z^{4/3}}, \tag{6}$$

with the corresponding longitudinal CSR impedance

$$Z_{\rm CSR}(k) = \frac{Z_0}{4\pi}\frac{2}{3^{1/3}}\Gamma\left(\frac{2}{3}\right)e^{i\pi/6}\frac{k^{1/3}}{R^{2/3}}, \tag{7}$$

where Γ is the gamma-function. These formulas can be used if the transverse beam size $\sigma_\perp$ is not very large, $\sigma_\perp \ll (\lambda\!\!\!^{-2} R)^{1/3}$ (here $\lambda\!\!\!^- = 1/k$). Also the transient effects at the entrance to and exit from the magnet can be neglected it $l_{\rm magnet} \gtrsim (\lambda\!\!\!^- R^2)^{1/3}$.

4. Microbunching instability mechanism

Simulations and theories of MBI in bunch compressors were developed in 2001–2002 in Refs. [3,16–18] The mechanism for microbunching instability is similar to that in a klystron amplifier [16]. It is illustrated in Fig. 1. A high-brightness electron beam with a small amount of density modulation can create longitudinal self-fields that lead to beam energy modulation. Since a magnetic bunch compressor (usually a chicane) introduces path length dependence on energy, the induced energy modulation is then converted to additional density modulation that can be much larger than the initial density modulation. This amplification process (the gain in microbunching) is accompanied by a growth of energy modulation and a possible growth of emittance if significant energy modulation is induced in a dispersive region such as the chicane. Thus, the instability can be harmful to short-wavelength FEL performance by degrading the beam quality.

[2] An apparent divergence of the wake (6) is removed in calculation of the bunch wake through integration by parts.

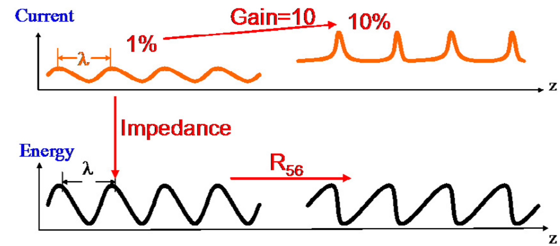

Fig. 1. Illustration of microbunching instability mechanism in linac-based FELs.

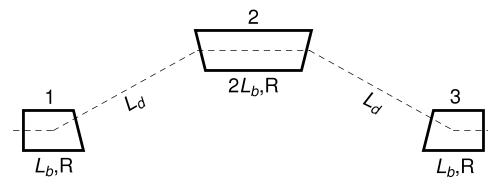

Fig. 2. A model of magnetic chicane consisting of three magnets with the middle one two times longer than the first and the last ones. The magnet lengths are L_b, $2L_b$ and L_b, the bending radius in the magnets is R, and the distance between the magnets is L_d.

It is typical to assume that modulation wavelengths are much shorter than the electron bunch length, and that density modulation amplitudes are much smaller than the average current. Under these assumptions, the amplitude of the density modulation at each wavelength grows independently and is characterized by a gain spectrum $G(k)$ of the accelerator system:

$$G(k) = \frac{n_f}{n_i}, \tag{8}$$

where n is the beam density modulation amplitude at the wavenumber k, and the initial density modulation can come from the non-uniformity of the drive laser for the photocathode electron sources, or more likely, the fundamental electron shot noise discussed in Section 2.

5. MBI gain in bunch compressor

In this section, we examine the microbunching gain due to effects of coherent synchrotron radiation and longitudinal space charge. Again, we consider a longitudinally uniform beam with an initial density modulation given by $\delta n(z) = n_i \sin k_i z$ with $\lambda_i = 2\pi/k_i$ the wavelength of the initial perturbation. The beam is sent through a chicane shown in Fig. 2. The beam has an energy chirp, and after the passage through the chicane the density becomes $\delta n(z) = n_f \sin k_f z$ where the final wavenumber is larger than the initial one due to the compression, $k_f = Ck_i$, with C the compression factor.

A relatively simple model for the calculation of the gain factor G was proposed in [16]. The model assumes the CSR wake in the magnets as a driving force of the instability, a cold beam and no compression, $C = 1$. Take an initial current perturbation $I = I_0 + I_1 \cos kz$ with $I_1 \ll I_0$. After passage through the first magnet the energy modulation in the beam is $\Delta E = eV = eL_b Z_{\rm CSR}(k) I_1$. Propagation from magnet 1 to 2 shifts the