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Theory and Observations of Microbunching Instability in Electron Machines*

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Abstract

For not very short bunches, the coherent synchrotron radiation (CSR) is usually suppressed by the shielding effect of the conducting walls of the vacuum chamber. However an initial density fluctuation in the beam with a characteristic length much shorter than the bunch length can radiate coherently. If the radiation-reaction force drives growth of the initial fluctuation, one can expect an instability which leads to micro-bunching of the beam and increased coherent radiation at short wavelengths.

It has recently been realized that such an instability can play an important role in electron/positron rings where it often manifests itself as a bursting of radiation in the range of hundreds of gigahertz or terahertz. This instability can also be a source of an undesirable emittance growth in bunch compressors used in the next generation short-wavelength FELs.

In this paper, we review progress in theoretical studies and numerical simulations of the microbunching instability and show connection of the theory to recent observations in electron machines.

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Theory and Observations of Microbunching Instability in Electron Machines

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INTRODUCTION

Over the last years there have been several reports of quasiperiodic bursts of coherent synchrotron radiation (CSR) in electron rings in the microwave and far-infrared range. The observations were made on synchrotron radiation light sources which include the Sinchrotron Ultraviolet Radiation Facility SURF II [1], VUV ring at the National Synchrotron Light Source at BNL [2,3], second generation light source MAX-I [4], BESSY II [5], and the Advanced Light Source at the Berkeley National Laboratory [6]. General features of those observations can be summarized as follows. Above a threshold current, there is a strongly increased radiation of the beam in the range of wavelengths shorter than the bunch length, $\lambda\!\!\!^{-} < \sigma_z$. At large currents, this radiation is observed as a sequence of random bursts. In the bursting regime, intensity of the radiation scales approximately as square of the number of particles in the bunch, indicating a coherent nature of the phenomenon.

It is generally accepted that the source of this radiation is related to the microbunching of the beam arising from development of a microwave instability. The impedance that causes the instability may be due to geometric wake fields from the vacuum chamber, especially in the rings with long bunches [1, 2]. However, according to diffraction model [7], the longitudinal impedance falls off with the frequency as $\omega^{-1/2}$ and cannot account for the instability at the wavelengths of order of a fraction of a millimeter. It has long been known that the synchrotron radiation itself generates a collective force [8] which, if the beam current is large enough, can alter the dynamics of the beam. The impedance associated with the synchrotron radiation increases with the frequency as $\omega^{1/3}$. A possible instability due to this force has been pointed out in Refs. [9, 10].

Typically in rings, the coherent synchrotron radiation at wavelengths of order of σ_z is suppressed due to the shielding effect of conducting walls of the vacuum chamber [11]. However, the wavelengths shorter than σ_z may not be shielded, and this allows to develop a simple theory of the CSR instability which assumes a coasting beam approximation and uses a CSR wake as the only source of the instability [12].

CSR – REVIEW OF THEORY

In application to the CSR instability, we are interested in the synchrotron radiation at wavelengths of the order of a size of microbunches, with a frequency ω typically well below the critical frequency for the synchrotron radiation. For an ultrarelativistic particle with the Lorentz factor $\gamma \gg 1$, in this range of frequencies, the spectrum of the radiation $dP/d\omega$ (per unit length of path) can be written as

$$\frac{dP}{d\omega} = \frac{3^{1/6}}{\pi}\Gamma\left(\frac{2}{3}\right)\left(\frac{\omega}{\omega_H}\right)^{1/3}\frac{e^2\omega_H}{c^2}\,, \qquad (1)$$

where $\omega_H = eB/\gamma mc$, with B the magnetic field, e the electron charge, m the electron mass, c the speed of light, and Γ the gamma-function. The characteristic angular spread θ of the radiation with reduced wavelength $\lambda\!\!\!^{-}$ (where $\lambda\!\!\!^{-} = c/\omega = 1/k$) is of order of $\theta \sim (\lambda\!\!\!^{-}/R)^{1/3}$, where R is the bending radius, $R = c/\omega_H$. Another important characteristic of the radiation is the formation length l_f: $l_f \sim \lambda\!\!\!^{-}/\theta^2 \sim (\lambda\!\!\!^{-} R^2)^{1/3}$—this is the length after which the electromagnetic field of the particle moving in a circular orbit "disconnects" from the source and freely propagates away. In a vacuum chamber with perfectly conducting walls, whether this "disconnection" actually occurs depends on another parameter, often called the "transverse coherence size", $l_\perp$. An estimate for $l_\perp$ is: $l_\perp \sim l_f\theta \sim \lambda\!\!\!^{-}/\theta \sim (\lambda\!\!\!^{-2} R)^{1/3}$. One of physical meanings of $l_\perp$ is that it is equal to the minimal spot size to which the radiation can be focused. Another meaning of this parameter is that it defines a scale for radiation coherence in the transverse direction. Electrons in a transverse cross section of a bunch of size $\sigma_\perp$ would radiate coherently only if $\sigma_\perp \lesssim l_\perp$. We emphasize here that both parameters, $l_\perp$ and l_f, are functions of frequency, with the scalings $l_\perp \propto \omega^{-3/2}$ and $l_f \propto \omega^{-1/2}$.

Closely related to the transverse coherence size is the shielding of the radiation by conducting walls: if the walls are closer than $l_\perp$ to the beam, the field lines during circular motion close onto the conducting walls, rather than disconnect from the charge. This means that the radiation at the frequencies where $l_\perp \gtrsim a$, where a is the pipe radius, is suppressed, or shielded.

For a bunch with N electrons, the radiation of each electron interferes with others. Assuming full transverse coherence (a one dimensional model of the beam), the total radiation of the bunch is [13]:

$$\left.\frac{dP}{d\omega}\right|_{\text{bunch}} = \frac{dP}{d\omega}N\left(1 + N|\hat{f}(\omega)|^2\right)\,, \qquad (2)$$

where $\hat{f}(\omega) = \int_{-\infty}^{\infty} dz f(z) e^{i\omega z/c}$ is the Fourier transform of the longitudinal distribution function of the beam $f(z)$ (normalized by $\int_{-\infty}^{\infty} f(z)dz = 1$). The first term on the right hand side of Eq. (2) is due to incoherent, and the second one – to coherent radiation. For a smooth distribution function (e.g., Gaussian, with rms bunch length σ_z), the Fourier image $\hat{f}(\omega)$ vanishes for $\lambdabar \lesssim \sigma_z$, and the radiation is incoherent. However, beam density modulation with $\lambdabar \lesssim \sigma_z$ would contribute to $\hat{f}(c/\lambdabar)$ and result in coherent radiation, if the amplitude of the perturbation is such that $|\hat{f}(c/\lambdabar)| \gtrsim N^{-1/2}$.

RADIATION REACTION FORCE—CSR WAKE FIELD

The collective force acting on the beam due to its coherent synchrotron radiation is described in terms of the so called CSR longitudinal wake [8, 14, 15]. For an ultra-relativistic particle, in one-dimensional approximation, this wake (per unit length of path) is given by the following formula:

$$w(z) = -\frac{2}{3^{4/3}R^{2/3}z^{4/3}} \,. \tag{3}$$

The wake is valid for distances z such that $R \gg z \gg R/\gamma^3$—a general behavior of the wake function including also distances $z \sim R/\gamma^3$ is shown in Fig. 1. The wake is

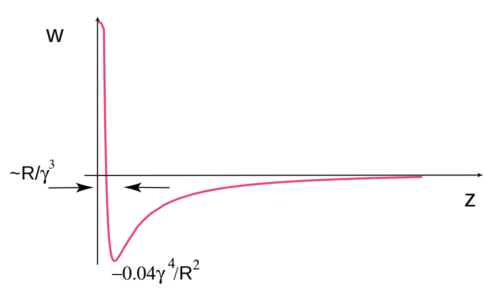

Figure 1: CSR wake as a function of distance. A simple formula (3) is applicable for not very short distances, to the right of the minimum of the wake. The wake reaches minimum at $z \sim R/\gamma^3$, with the minimum value of $-0.04\gamma^4/R^2$.

localized in front of the particle in contrast to "traditional" wakes in accelerator physics which trail the source charge [7]. This is explained by the fact that the charge follows a circular orbit and the radiation propagates along chords getting ahead of the source. The wake given by Eq. (3) has a strong singularity at $z \to 0$. In calculations, this singularity is eliminated by integration by parts and using the fact that the area under the curve $w(z)$ is equal to zero.

A simple wake Eq. (3) assumes a small transverse beam size [15], $\sigma_\perp \lesssim l_\perp \sim (\lambdabar^2 R)^{1/3}$, and neglects the shielding effect of the conducting walls. It is valid only for long enough magnets, $l_{\rm magnet} \gg l_f$, when transient effects at the entrance to and exit from the magnet can be neglected. A detailed study of transient effects in a short magnet can be found in Refs. [16, 17].

Using the wake field Eq. (3) one can calculate the CSR longitudinal impedance Z:

$$Z(k) = \frac{1}{c}\int_0^\infty dz w(z) e^{-ikz} = \frac{2}{3^{1/3}}\Gamma\left(\frac{2}{3}\right) e^{i\pi/6}\frac{k^{1/3}}{cR^{2/3}} \,. \tag{4}$$

The real part of this impedance is related to the spectrum of the energy loss of a charge due to radiation: $dP/d\omega = (e^2/\pi){\rm Re}Z$, see Eq. (1). Plots of a CSR wake for a Gaussian bunch can be found in Refs. [14, 15].

CSR INSTABILITY

Due to the CSR wake, an initial small density perturbation δn induces energy modulation in the beam δE. A finite momentum compaction factor of the ring converts δE into a density modulation. At the same time, the energy spread of the beam tends to smear out the initial density perturbation. Under certain conditions, which depend on the beam current, energy spread, and the wavelength of the modulation, the process can lead to an exponential growth of the perturbation.

A quantitative description of the instability can be obtained if we assume that the wavelength of the perturbation is much shorter than the bunch length, $\lambdabar \ll \sigma_z$, and use a coasting beam approximation. In this case, the dispersion relation for the frequency ω is given by the Keil-Schnell formula [18]:

$$\frac{inr_0c^2Z(k)}{\gamma}\int_{-\infty}^{\infty}\frac{d\delta\,(df/d\delta)}{\omega + ck\eta\delta} = 1 \,, \tag{5}$$

where n is the number of particles per unit length, η is the momentum compaction factor of the ring, $r_0 = e^2/mc^2$, $Z(k)$ is the CSR impedance given by Eq. (4), $f(\delta)$ is the energy distribution function normalized so that $\int f(\delta)d\delta = 1$. To take into account straight sections in the ring, where $R = \infty$ and there is no CSR wake, Z is replaced with a weighted impedance: $Z \to ZR/\langle R\rangle$, where $\langle R\rangle = C/2\pi$. The plot of ${\rm Re}\,\omega$ and ${\rm Im}\,\omega$ calculated from Eq. (5) for a Gaussian energy distribution with an rms relative energy spread δ_0, and $\eta > 0$ is shown in Fig. 2. It is convenient to introduce the dimensionless parameter Λ:

$$\Lambda = \frac{1}{|\eta|\gamma\delta_0^2}\frac{I}{I_A}\frac{R}{\langle R\rangle} \,, \tag{6}$$

where $I_A = mc^3/e = 17.5$ kA is the Alfven current. The maximum growth rate is reached at $kR = 0.68\Lambda^{3/2}$ and is equal to $({\rm Im}\,\omega)_{\rm max} = 0.43\Lambda^{3/2}c\eta\delta_0/R$.

Three colored areas in this plot refer to stability regions in the parameter space. In the green area 1, the beam is stable because ${\rm Im}\omega < 0$ due to Landau damping. This region corresponds to high frequencies, $kR > 2.0\Lambda^{3/2}$. In the yellow region 2, where $k \lesssim R^{1/2}/a^{3/2}$ (a is the transverse size of the vacuum chamber), the instability is suppressed by shielding of the radiation. Finally, at even lower

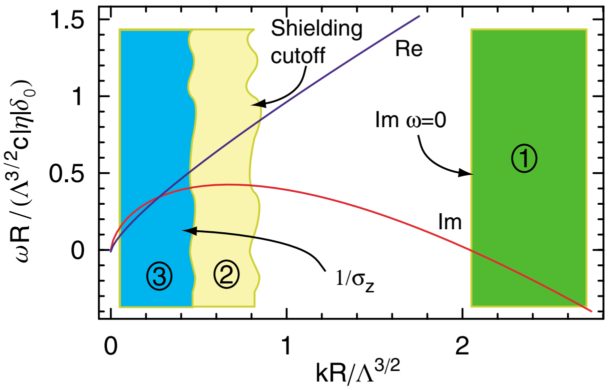

Figure 2: Plot of real (blue) and imaginary (red) parts of frequency ω as functions of k for positive η. Normalization of the frequency ω and the wavenumber k on the axes involves the parameter Λ defined by Eq. (6).

frequencies, in the blue area 3, the wavelength of the instability exceeds the bunch length and the coasting beam theory breaks down. The wavy lines between stability regions indicate fuzziness of the transition boundaries in our model.

In table 1, accelerator and beam parameters are presented for four existing rings, where the theory predicts CSR instability. The parameter I_b is the bunch current

Ring	ALS	VUV	LER KEKB
E (GeV)	1.5	0.81	3.4
η	$1.41 \cdot 10^{-3}$	$2.35 \cdot 10^{-2}$	$1 \cdot 10^{-4}$
δ_0	$7.1 \cdot 10^{-4}$	$5.0 \cdot 10^{-4}$	$7 \cdot 10^{-4}$
$\langle R \rangle$ (m)	31.3	8.11	480
R (m)	4	1.91	16.3
a (cm)	2	2.1	2.5
I_b (mA)	30	400	1
σ_z (cm)	0.7	4.7	1
$\lambda\!\!\!^{-}_{\rm sh}$ (cm)	0.14	0.2	0.1
$\lambda\!\!\!^{-}_{\rm th}$ (cm)	$4.7 \cdot 10^{-3}$	0.02	0.015

Table 1: Numerical Estimates for LER PEP-II, ALS, VUV and LER KEK-B rings

in the ring. Calculated in two last rows of the table are the reduced wavelength $\lambda\!\!\!^{-}_{\rm sh} = a^{3/2}R^{-1/2}$ for the shielding cutoff, and the instability threshold $\lambda\!\!\!^{-}_{\rm th} = 0.5R\Lambda^{-3/2}$. The beam is unstable for perturbations with the wavelengths between $2\pi\lambda\!\!\!^{-}_{\rm th}$ and $2\pi\lambda\!\!\!^{-}_{\rm sh}$.

There are several effects that are neglected in the simple theory described above. First, a zero transverse emittance of the beam was assumed. Second, the synchrotron damping γ_d due to incoherent radiation was neglected which makes the growth rate of the instability somewhat smaller, ${\rm Im}\,\omega \to {\rm Im}\,\omega - \gamma_d$ [19]. Finally, the retardation effects were neglected which is valid if the formation time for the radiation is smaller than the instability growth time, $t_f \sim l_f/c \ll 1/{\rm Im}\omega$. In most cases characteristic for modern rings, those effects are relatively minor.

NONLINEAR REGIME

After initial exponential growth, described by a linear theory, the instability comes into a nonlinear regime. Study of the nonlinear regime requires numerical simulation. Such simulations have been carried out in Ref. [20] where the authors numerically solved the Vlasov-Fokker-Planck equation, including CSR shielding with parallel plates, damping and quantum fluctuations due incoherent radiation.

The results of the numerical simulation can be described as follows. Initially, there are microstructures in the bunch of very small amplitude, giving small Fourier components with short wavelengths. Above a current threshold these Fourier components build up exponentially in agreement with linear theory described above. There is a corresponding burst of radiation, but it is limited in duration by a quick smoothing of the phase space distribution. Continued exponential growth is prevented by the intrinsic nonlinearity of self-consistent many-particle dynamics, which also contributes to phase space smoothing through quick generation of a relatively large spectrum of Fourier modes. Within one or two synchrotron periods the microstructures have almost disappeared, the overall bunch length has increased, and the burst of coherent radiation is finished. Next, radiation damping and diffusion from the usual incoherent radiation gradually reduce the bunch length and energy spread, restoring the conditions for instability and another burst, after a time somewhat smaller than the damping time. The computed bunch length shows fast oscillations typical of a quadrupole mode, while the envelope of those oscillations shows a sawtooth or relaxation pattern similar to the experimentally observed patterns.

COMPARISON WITH EXPERIMENT

A detailed comparison of the theory with observations has been carried out in the experiment at the Advanced Light Source (ALS), a 1.9 GeV electron storage ring [6]. The authors presented experimental evidence indicating that the instability thresholds predicted by the microbunching model correspond to the observed thresholds for the CSR bursts. For different electron beam energies and bunch lengths, the instability threshold was measured at 94 GHz by microwave detector, and by Si bolometer (up to $\lambda = 100$ μm).

It was observed that above a threshold single bunch current, bursts of signal appear. As the current increases, the burst signals increase in both amplitude and frequency. The polarization of the radiation was measured to be entirely in the plane of the electron beam orbit, consistent with the expected polarization level of greater than 99.5%. At the highest single bunch current, the bursts appear almost continuously. The plot of measured threshold current as a function of beam energy is shown in Fig. 3. A good agreement with the theory was found for two different wavelengths of the microbunching.

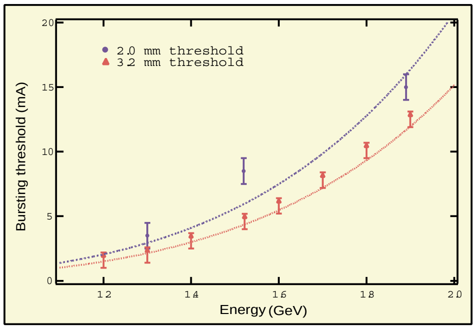

Figure 3: Plot of threshold current as a function of beam energy at two wavelengths: $\lambda = 2$ mm (blue dots), and $\lambda = 3.2$ mm (red triangles) [from Ref. [6]]. Solid lines are theoretical predictions for the thresholds obtained from Eq. (5).

RINGS WITH WIGGLERS

In the damping ring of the Next Linear Collider [21], there will be long magnetic wigglers which introduce an additional contribution to the radiation impedance. The analysis of the CSR instability in such a ring requires knowledge of the impedance of the synchrotron radiation in the wiggler. Based on the earlier study of the coherent radiation from a wiggler [22], in Ref. [23], a steady-state wake averaged over the wiggler period has be derived for the case $K^2/2 \gg 1$ (where K is the wiggler parameter) and $\gamma \gg 1$. The most interesting from the point of view of instability is a low-frequency part of the impedance, given by the following formula (per unit length of path):

$$Z_{\text{wiggler}}(\omega) \approx \frac{Z_0 \omega}{4c} \left[1 - \frac{2i}{\pi} \log \frac{\omega}{\omega_*} \right] , \qquad (7)$$

where $\omega_* = 4\gamma^2 c k_w / K^2$ and $Z_0 = 377$ Ohm. Eq. (7) is valid for $\omega \ll \omega_*$.

Results of the analysis of CSR instability in the NLC ring, taking into account the wiggler CSR impedance can be found in Ref. [24].

DISCRETE MODES NEAR SHIELDING THRESHOLD

There are several reasons why the simple theory of CSR microbunching instability developed in Ref. [12] is not applicable near that shielding threshold, $\lambda \sim a^{3/2}/R^{1/2}$. The most important one is that CSR does not have continuous spectrum here, and the modes that can interact with the beam, are discrete. The discreteness of the spectrum has been demonstrated in early papers [25, 26] for toroids of rectangular cross section. A more recent analysis of the shielded CSR impedance [27] extends the previous treatment of the problem and deals with arbitrary shapes of the toroid cross section.

Each synchronous mode in the toroid is characterized by frequency ω_n, a loss factor κ_n (per unit length), and a group velocity $v_{g,n}$. The wake associated with the n-th mode is

$$w_n(z) = 2\kappa_n \cos\left(\frac{\omega_n}{c} z\right) .$$

This wake, for lowest modes, propagates behind the particle. Calculation of ω_n, κ_n, and $v_{g,n}$, in the general case of arbitrary cross section requires numerical solution of two coupled partial differential equations [27]. For a toroid of round cross section of radius a, the lowest mode has been found to have the frequency $\omega_1 = 2.12 c R^{1/2} a^{-3/2}$, the loss factor $\kappa_1 = 2.11 a^{-2}$ and the group velocity $1 - v_{g,1}/c = 1.1 a/R$.

Near the shielding threshold, the CSR instability should be treated as an interaction of the beam with single modes, [28]. When the wavelength of the mode is smaller than the bunch length, one can still use the coasting beam approximation, but one cannot neglect retardation effects. Assuming an ideal toroidal chamber with a constant cross section (no straight sections in the ring), it turns out that the theory of single-mode instability [28] parallels that of SASE FEL (see, e.g., [29]). It gives the maximum growth rate of the instability for nth mode equal $\sqrt{3}\rho_n \omega_n/2$ where

$$\rho_n = \left[\frac{I}{I_A} \frac{c^2 \eta \kappa}{\omega_n^2 \gamma} \left(1 - \frac{v_{g,n}}{c} \right) \right]^{1/3} \qquad (8)$$

is an analog of the Pierce parameter in FELs.

Nonlinear regime of the instability in this approximations has been studied in Refs. [28, 30]

BUNCH COMPRESSOR

Microbunching due to CSR induced instability has been also identified in computer simulations as a potential danger in bunch compressors [31], where the energy spread in the beam is extremely small.

The basic mechanism of the instability is the same as in rings, with an additional complication due to the energy chirp in the beam [32–34]. As a result of the instability, an initial density perturbation in the beam with amplitude n_1 and a wavelength λ, after passage through the compressor, will be amplified to amplitude n_2. The ratio $G = n_2/n_1$ is called the gain factor; it is a function of λ. Note, that the wavelength of the perturbation after compression is smaller than the initial wavelength by a factor of compression ratio. Unstable wavelengths observed in simulations can be very short—of order of few microns. It was found that both the transverse emittance of the beam and its energy spread have a strong stabilizing effect at short wavelengths.

Calculation of the gain factor for combined effect of both LCLS bunch compressors was carried out in Ref. [35], and is shown in Fig. 4. The solid line corresponds to the rms energy spread $\delta_{\text{rms}} = 3 \cdot 10^{-6}$ and the dash line shows the case $\delta_{\text{rms}} = 3 \cdot 10^{-5}$. The lines are calculated from the theory, and squares and triangles are numerical simulations which show a good agreement between the two approaches. Note that with a small energy spread, the maximum amplification approaches 10, at wavelengths about 80 microns (after compression, this wavelength reduces to about 2 microns). Increase of the energy spread by ten times strongly suppresses the gain at short wavelength.

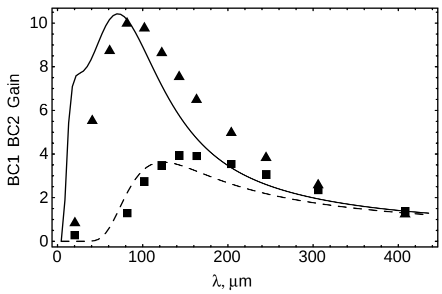

Figure 4: Gain factor for two LCLS bunch compressors as a function of wavelength λ of perturbations before compression (from Ref. [35]).

CONCLUSION

Coherent synchrotron radiation in electron and positron machines introduces a universal source of impedance which may become dominant source of the wake at high frequency where geometric and resistive wall impedances become small. Unless the wall shielding effect suppresses the CSR, its impedance remains even in a smooth vacuum chamber with perfectly conducting walls, and can drive a microwave instability of the beam.

Over the last several years, there has been a remarkable progress, both theoretically and experimentally, in our understanding of this microbunching instability and related coherent synchrotron radiation in rings. The existing theory predicts thresholds for the instability, and computer simulations show nonlinear evolution of the unstable state. These theoretical results are in good agreement with experimental observations.

Another practically important area of application of the CSR theory is bunch compressors, where amplification of an initial density perturbation can lead to the emittance growth of the compressed beam. Detailed studies and simulations of microbunching resulted in improved design of compressors, with a deleterious effect of CSR suppressed to a tolerable level.

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