MICROBUNCHING INSTABILITY STUDIES AT SOLEIL

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Abstract

Microbunching instability arises in storage rings when the number of electrons in a bunch exceeds a threshold value [1, 2, 3]. Its signature, i.e. a strong and irregular emission of Coherent Synchrotron Radiation (CSR) in the Terahertz (THz) domain, is studied at SOLEIL on the AILES infrared beamline [4], with the storage ring tuned in a low-alpha configuration (used to get shorter electron bunch) [5, 6]. The comparison of this observed THz CSR with numerical simulations of the longitudinal electron bunch dynamics permits to put in evidence that during the instability a modulation appears and drifts in the longitudinal profile of the electron bunch. The understanding of this instability is important as it limits some operation of the storage rings. Indeed the induced fluctuations prevent the use of THz on the far IR beamline at high current per bunch. In addition, in normal alpha operation this instability may spoil the electron/laser interaction effects required to get femtosecond and/or coherent pulse in storage rings (with slicing [7], Coherent Harmonic Generation or Echo-Enabled Harmonic Generation schemes on storage ring).

INTRODUCTION

Some characteristics of the experimental unstable THz CSR signals can be reproduced with numerical simulations, using either a macro-particle code [8], or Vlasov-Fokker-Planck equation [9]. The instability is due to collective effects, in particular the CSR wakefield plays an important role [10, 9] when radiations of electrons interact with other electrons in bending magnets [11, 12]. It has also been observed experimentally that THz CSR signals can have several times scale components [13, 14], indicating a complex dynamical behavior.
Electron bunch dynamics is investigated near the microbunching instability threshold, thanks to experimental THz signal analysis, combined to numerical macro-particle simulations. In particular, we shall demonstrate that it exists an experimental criterion indicating the presence of micro-bunching drifting along the longitudinal profile of the bunch.

SOLEIL PARAMETERS

Parameters of the SOLEIL storage ring are given in the table I [15, 16].

Table 1: SOLEIL storage ring parameters

Circumference (m)	354
Nominal energy E_0 (GeV)	2.75
Relative energy spread σ_E	1×10^{-3}
Radius R of the bending magnets (m)	5.39
Length L of the bending magnets (m)	1.05
Vacuum chamber height (mm)	12.5
Nominal momentum compression factor α_0	4.3×10^{-4}

EXPERIMENTAL TERAHERTZ SIGNAL NEAR THE INSTABILITY THRESHOLD

The THz signal, emitted in edge and constant field of a bending magnet, was recorded on the Terahertz and infrared beamline AILES [4]. In the experimental hutch, the THz signal is divided in two parts with a beamsplitter made of 6 μm thick Mylar film (Fig. 1). The first part is directly recorded by an InSb bolometer cooled at 4.2 K (from IR Labs) giving the temporal evolution of the THz signal. The second part is sent though a Michelson interferometer (Bruker IFS 125) before being recorded by a Si composite bolometer cooled at 4.2 K, giving the spectral information.

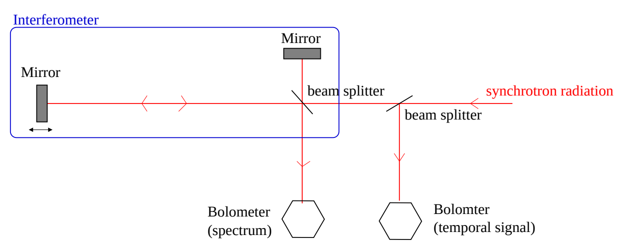

Figure 1: Layout of the experimental setup on the THz/IR beamline AILES.

Figure 2 shows typical temporal and spectral THz signals when the number of electrons (i.e. the current I) in the bunch is increased. Experiments were performed with a single bunch in a low-alpha mode, with $\alpha = \alpha_0/10$ (α_0 the nominal value) [6]. For a sufficiently small current ($I = 0.15$ mA), the temporal signal is stable (Fig. 2a) and the signal observed on the spectrum is very weak, signature of incoherent synchrotron radiation (Fig. 2d). For a higher current ($I = 0.20$ mA), the THz temporal does not present high fluctuations (Fig. 2b), while the increase of spectral components (between 9 and 20 cm^{-1}) indicates that a part of the radiation is coherent (Fig. 2d). Finally, for a higher current (I=0.35 mA), the temporal signal presents

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high fluctuations, the so-called ”bursts” [1, 2] (Fig. 2c) and the associated spectrum is very noisy (Fig. 2d).

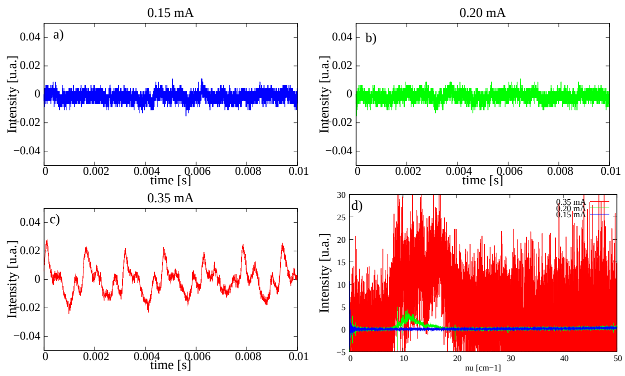

Figure 2: Experimental THz signals recorded in a low-alpha configuration ($\alpha = \alpha_0/10$). Temporal signals for a current of (a) 0.15 mA, (b) 0.20 mA and (c) 0.35 mA (resolution $\simeq$ 1 ms). d) associated spectrum (resolution: 0.004 cm^{-1}).

NUMERICAL AND EXPERIMENTAL CRITERION FOR THE PRESENCE OF MICRO-STRUCTURES

CSR signal is an important diagnostic to understand the micro-bunching instability since it indicates the presence of micro-structures in the longitudinal bunch profile. However, it gives indirect information about the electron bunch distribution, and in particular the longitudinal phase space is not observable experimentally. To understand more precisely the behavior of the electrons during the instability, numerical simulations have been performed.

Details of the numerical model

The electron dynamics is described by a macro-particle code, where each macro-particle represents several electrons. For the micro-bunching instability, the relevant direction is the longitudinal one [9, 10], and we limit the description of each macro-particle to two coordinates: its longitudinal position z and its associated relative energy p. The position (z, p) of each particle is calculated at each storage ring turn.

At each turn, a macro-particle loses some energy due to synchrotron radiation [17]. One part of theses losses is stochastic, due to quantum properties of the emission, inducing energy spread which reduces micro-structure amplitude. At each turn, the macro-particles are also accelerated by Radio-Frequency (RF) cavities to compensate the energy losses induced by the radiations. The longitudinal position of the macro-particle changes as a function of its energy since the bending radius of the electron trajectory depends on its energy. Taking only these elements into account, the behavior of the electron bunch is always ”stable” and the bunch composed by all the electrons has a Gaussian shape in the two longitudinal directions of the phase-space (z, p).

The instability comes from collective effects, in particular the interaction of the electrons with their own radiation (wakefield). For these simulations, following [9, 10], only the CSR wakefield is taken into account, describing interaction of electrons with their radiations in bending magnets, including also effects of the vacuum chamber. CSR wakefield is calculated from [11, 12].

Micro-structures in the bunch

Numerical simulations with a sufficiently high current (here I=0.55 mA) show that during the emission of THz CSR bursts, micro-structures appear and drift along the longitudinal profile as shown in Figure 3a). The simulations show that there is a signature of this behavior in the THz CSR signal, in the form of a modulation of the THz temporal signal (Fig. 3b). This modulation observed on numerical simulations at about 20 kHz (Fig. 3b) is confirmed on experimental THz signals, at about 35 kHz (Fig. 3c). The THz signals evolve also at a slower time scale due to the bursting behavior, with a typical time scale of one millisecond associated to the synchrotron radiation damping time [18] (on Fig. 3b,c only one burst is shown).

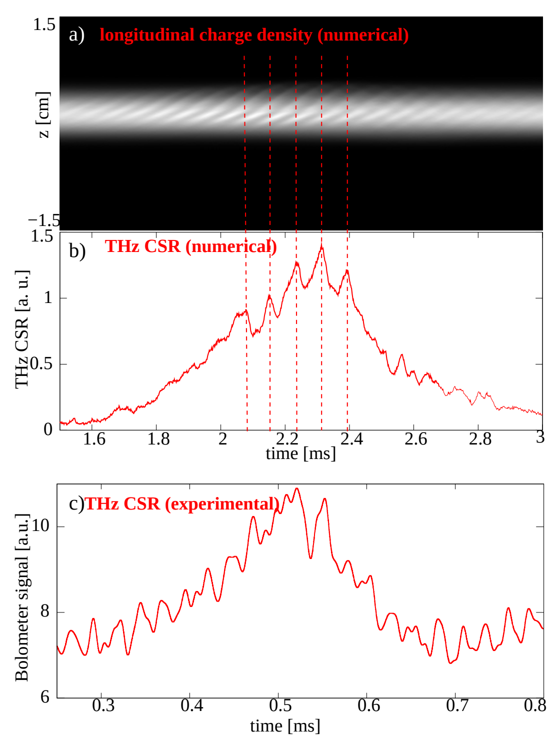

Figure 3: a) Longitudinal profile of the electron bunch as a function of time (from numerical simulation, with $\alpha_0/10$ and I=0.55 mA). b) Associated THz CSR signal between 5 cm^{-1} and 80 cm^{-1}. c) Experimental THz signal in $\alpha_0/10$ configuration with $I = 0.3$ mA (Frequencies higher than 100 kHz are removed, resolution $\simeq$1μs).

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Experimental observation of the micro-structure appearance

Finally, we have observed experimentally the appearance of this frequency around 35 kHz, signature of micro-structures drifting in the bunch profile. We have increased progressively the current of a single bunch in a low-alpha configuration ($\alpha = \alpha_0/10$), and recorded the THz temporal signal. At a current of I =0.14 mA, there is no significant component of the THz signal around 35 kHz (Fig. 4a), the system is stable. At $I = 0.227$ mA, frequency components around 35 kHz appear (Fig. 4b), indicating the presence of micro-structures drifting along the bunch. It is worth to noticing that at the apparition of the frequency around 35 kHz, there is no large component at lower frequency, i.e. there is no burst of THz CSR. Thus the micro-structures appears before the bursts. The micro-structures induce a bunch lengthening, which is next damped by synchrotron radiation, at a time scale of the synchrotron radiation damping. The repetition of this scenario leads to the bursting behavior [18].

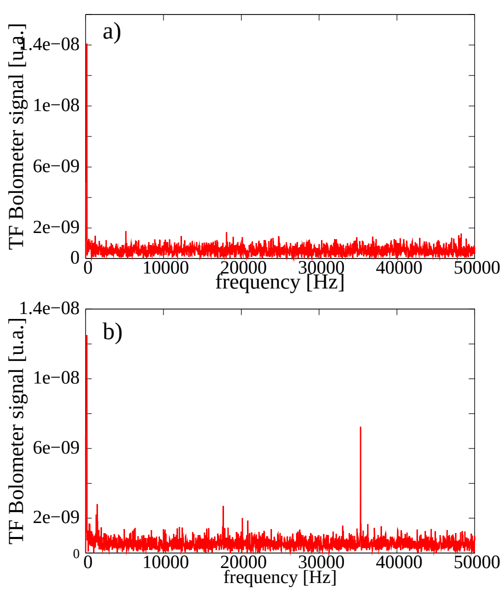

Figure 4: Absolute value of the Fourier transform of the experimental THz recorded at a current I of a) 0.14 mA and b) 0.227 mA in a low-alpha configuration ($\alpha = \alpha_0/10$).

CONCLUSION

In storage rings when the number of electron is increased, micro-bunching instability appears. We show that during this instability, in low-alpha mode, micro-structures drift in the longitudinal profile of the bunch. It induces a modulation of the THz CSR signal (at about 35 kHz at SOLEIL in $\alpha = \alpha_0/10$), which permits to observe experimentally the apparition of the micro-bunching instability. These observations are important in understanding the electron bunch dynamics and configure the storage ring in low-alpha mode, which is used to produced THz CSR and short bunches.

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