Laser Seeding of the Storage-Ring Microbunching Instability for High-Power Coherent Terahertz Radiation

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We report the first observation of laser seeding of the storage-ring microbunching instability. Above a threshold bunch current, the interaction of the beam and its radiation results in a coherent instability, observed as a series of stochastic bursts of coherent synchrotron radiation (CSR) at terahertz frequencies initiated by fluctuations in the beam density. We have observed that this effect can be seeded by imprinting an initial density modulation on the beam by means of laser "slicing." In such a situation, most of the bursts of CSR become synchronous with the pulses of the modulating laser and their average intensity scales exponentially with the current per bunch. We present detailed experimental observations of the seeding effect and a model of the phenomenon. This seeding mechanism also creates potential applications as a high-power source of CSR at terahertz frequencies.

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The interaction of a relativistic electron beam and its radiation creates a gain mechanism that is the basis for the emerging generation of free electron lasers (FEL) that promise high brightness photon pulses with sub-100 fsec duration. The FEL gain is used to generate intense photon pulses by amplifying either small fluctuations (i.e., noise) in the electron beam density or a small modulation in the density induced by the interaction with a laser beam. The second process is referred to as laser seeding. Although the next generation of FELs is based on linear accelerators, there is an analogous situation regarding the FEL gain mechanism in storage rings albeit at much longer wavelengths than the new FELs. Because of this gain, a modulation in the bunch distribution can be amplified resulting in an effect known as the microbunching instability (MBI) [1,2]. Normally, the MBI starts from noise and has been observed in many storage rings as stochastic bursts of coherent synchrotron radiation (CSR) at terahertz frequencies [3–9]. In this Letter, we report the first observation and characterization of the seeding of the MBI by laser inducing a modulation on the electron bunch. We also describe a model of the effect which accounts for the observations, and in the last part, we discuss the possibility of controlling this amplification process as a powerful source of THz CSR.

At the Advanced Light Source (ALS) electron storage ring, Lawrence Berkeley National Laboratory, a dedicated beam line is in operation since 1999 for the production of x-ray synchrotron radiation pulses with femtosecond duration [10]. A femtosecond laser pulse copropagates with the relativistic electron beam inside an undulator modulating the energy of the particles in a slice of the bunch with the same length of the laser pulse. Afterward, when the beam transits a dispersive region, the energy modulated electrons are transversely separated from the main bunch and used for the generation of the short x-ray synchrotron radiation pulses [11]. Because of the storage ring's nonzero momentum compaction (longitudinal dispersion), the energy modulation induces at the same time a temporary perturbation in the electron bunch's longitudinal distribution with the shape of a dip with two lateral bumps. The characteristic length of such a structure evolves from tens of femtosecond duration right after the undulator, quickly increasing up to the ps order and practically disappears in few ring turns [12–15].

It has been predicted [16] and experimentally verified [12–15] that such perturbations should radiate CSR pulses in the terahertz frequency range. These pulses are now routinely used as the main diagnostics for the tune-up of the femtoslicing x-ray experiments [12,17] and represent a potential source of terahertz radiation with appealing features such as synchronism with the modulating laser and x-ray pulses [18]. The observed laser seeding of the MBI described in this Letter could represent an opportunity for a further improvement in the performance of slicing based THz sources.

Before describing the data, we briefly review the main characteristics of the MBI, the single bunch instability induced by the field of the synchrotron radiation emitted by the bunch itself, hereafter referred as the CSR wake [1,2,8,9]. The intensity of these wakes increases with increasing current per bunch and in some cases can generate stable non-Gaussian bunches [19–22]. When a current threshold is exceeded, the CSR wake becomes strong enough to trigger an instability. Small fluctuations in the longitudinal distribution of the bunch are now amplified by the wake at the level of microstructures (microbunching) that can last for several turns and that are short enough to emit strong bursts of CSR in the terahertz frequency range. The MBI starting from noise is a stochastic process and the frequency of the bursts is generally random and their amplitudes show large fluctuations.

The top part of Fig. 1 shows an example of these high intensity THz CSR bursts associated with the MBI as

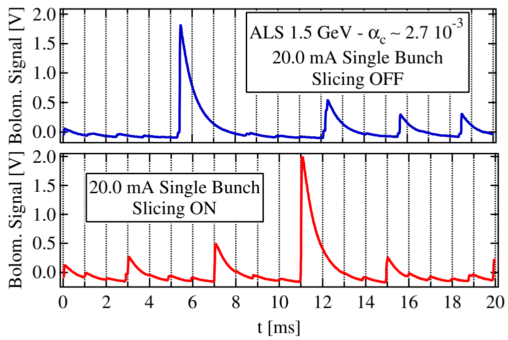

FIG. 1 (color online). Signal induced in a bolometer by the THz CSR bursts associated with the MBI. In the top part the 1 kHz repetition rate slicing laser is off while in the bottom one the laser is on.

measured at the ALS. The detector, a liquid-He cooled bolometer from Infrared Laboratories Inc., integrates any radiation component with frequency between ~0.05 and 5 THz. Its time response presents a fall time of several ms, much longer than the actual duration of the bursts, and thus completely defines the shape of the measured pulses. The bottom part of the figure shows what happens when the slicing laser is turned on at 1 kHz repetition rate. The overall scenario does not change much with the only remarkable exception that the bursts become now synchronous with the slicing laser (compare the bursts onset position with the 1 ms step vertical grid). In other words, above the current threshold for the MBI, the slicing process appears to seed the instability.

This hypothesis seems to be confirmed also by a frequency domain analysis of the data. Figure 2 shows a waterfall plot with the Fourier transform of the bolometer signals for different currents per bunch. Two things are evident from the figure, the onset of the instability at ~15 mA and the 1 kHz line and harmonics associated with the laser repetition frequency. The small inset in the figure shows two frequency spectra of the signal for currents above the MBI threshold and with the slicing laser on and off. The 1 kHz line and harmonics clearly disappear when the laser is switched off.

Figure 3 shows the total average CSR power (top part) and the part of it associated with the 1 KHz line (bottom part) versus the single bunch current. In both plots above the MBI threshold the curves grow exponentially with current. If the power at 1 kHz was due only to the particles in the bunch modulated in energy by the slicing laser then the dependence with current would be "just" quadratic. This case is shown in the bottom part of the figure by the blue dashed curve. We see that the dependence is quadratic only below the MBI threshold and then becomes exponential above it, where the power increases up to values of about 2 orders of magnitude larger than for the pure quadratic case.

We also measured the bursts using a faster THz detector, a ~800 kHz bandwidth "hot electron" bolometer by Infrared Laboratories Inc. An example of such data is shown in Fig. 4 where the detector signal, proportional to the CSR power, was observed at an oscilloscope triggered synchronously with the slicing laser. In the top part, the scope was in long persistence mode while in the bottom it was in average mode. In both the parts, the CSR pulse generated directly by the slicing (indicated as "CSR from slicing" in the figure) is well evident and shows high synchronism with the trigger and a very stable amplitude. The long persistence allows to see many THz CSR bursts with very large but variable amplitude. A significant part of them is synchronous with the slicing (as confirmed by the average mode measurement) forming a kind of broader pulse with a peak ~45 μs after the slicing induced pulse. A similar behavior was observed also at BESSY II indicating that the phenomenon could be quite general [23].

We now show that such observations can be explained in the framework of the MBI theory [1]. Heifets and Stupakov demonstrated that for a coasting beam and in the linear regime of the MBI, the modulation of the bunch distribu-

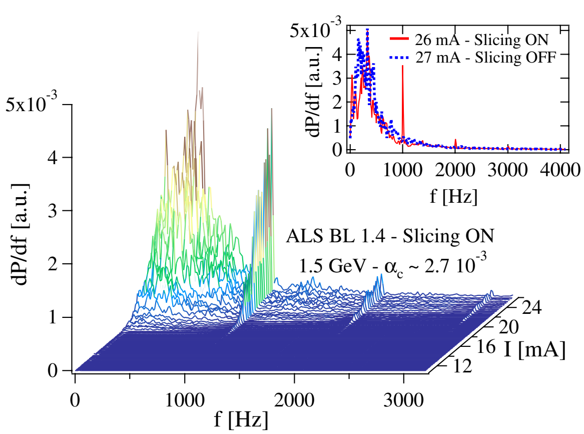

FIG. 2 (color online). Waterfall plot with the Fourier spectra of the bolometer signal for different currents per bunch. The small inset shows two spectra with slicing laser on and off.

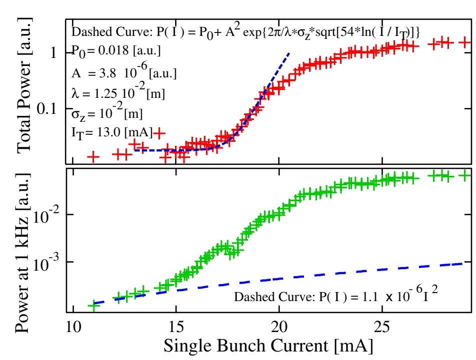

FIG. 3 (color online). Average THz CSR Power versus single bunch current. In the top panel, the measured total power is compared with theory (dashed blue line). In the bottom panel, the CSR power associated with the 1 kHz line of Fig. 2 is compared with the expected quadratic dependence (dashed blue) curve.

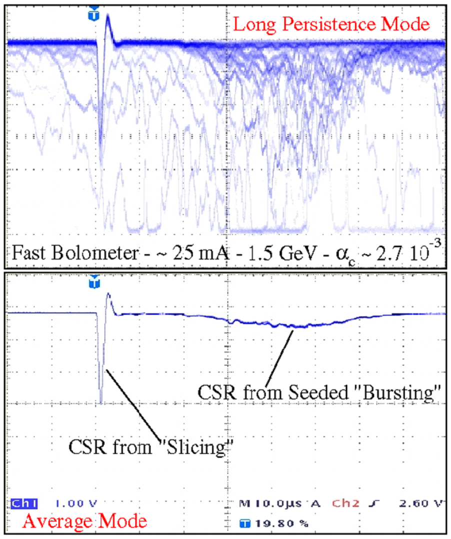

FIG. 4 (color online). The THz CSR signal as measured by a fast (800 kHz bandwidth) detector and an oscilloscope triggered with the 1 kHz slicing signal. In the top panel the oscilloscope is in long persistence mode and many individual laser slicing and burst events are observed. The lower panel shows the averaged detected THz CSR intensity.

tion induced by the CSR wake can be represented by a linear combination of modes of the kind:

$$\rho = \hat{\rho} e^{-i(\omega t - kz)}, \tag{1}$$

where ρ is the mode amplitude, $\hat{\rho}$ a constant, ω the complex frequency, $k = 2\pi/\lambda$ the wave number, and λ the wavelength. In the general case, the dispersion relation between ω and k for the case of the CSR wake must be calculated numerically, and the analysis of the MBI instability dynamics should be carried out by combining the effect of all the possible unstable modes, as done by the same authors in Ref. [24]. Nevertheless, assuming that a single unstable mode plays a dominant role, one can derive an approximate model by reducing the analysis to the investigation of this particular mode. We will try this approach for the simple case of a "cold" beam for which an analytical expression for the dispersion function has been derived [1]:

$$\omega = ck^{2/3}\sqrt{\frac{\Gamma(2/3)}{3^{1/3}}(\sqrt{3}i - 1)\frac{2\pi r_0 n_b \alpha_c R^{1/3}}{\gamma L}}. \tag{2}$$

Such an approximation can be used when:

$$k < \sim[(2\pi r_0 n_b R^{1/3})/(\alpha_c \gamma \delta_0^2 L)]^{3/2}. \tag{3}$$

In the last equations, Γ is the gamma function, r_0 the classical radius of the electron, R the dipole bending radius, α_c the momentum compaction, γ the beam energy in rest mass units, δ_0 the beam rms relative energy spread, L the ring circumference, c the speed of light, and n_b the linear particle density.

The CSR induces a modulation in the beam that, according to Eq. (1), starts moving along the bunch growing in amplitude exponentially. By using Eq. (2) we can estimate the group velocity v at which a mode propagates as well as its amplitude growth rate a:

$$v = \mathrm{Re}\left[\frac{d\omega}{dk}\right] \cong ck^{-1/3}\sqrt{\frac{2\Gamma(2/3)}{3^{7/3}}\frac{2\pi r_0 n_b \alpha_c R^{1/3}}{\gamma L}}, \tag{4}$$

$$a = \mathrm{Im}[\omega] \cong ck^{2/3}\sqrt{\frac{3^{2/3}\Gamma(2/3)}{2}\frac{2\pi r_0 n_b \alpha_c R^{1/3}}{\gamma L}}. \tag{5}$$

Expressions (2) and (3) have been derived for the case of a coasting beam. For a bunched beam, the linear particle density n_b depends on the position along the bunch z and because the MBI perturbation moves, its position z depends on t. If n_b at the perturbation position changes slowly with t, its amplitude [magnitude of Eq. (1)] can be obtained as the solution of the differential equation $d\rho/dt = a[z(t)]\rho$:

$$\rho(z) = \hat{\rho}\exp\left[\int_0^z \frac{a(\tilde{z})}{v(\tilde{z})}d\tilde{z}\right], \tag{6}$$

that combined with Eqs. (4) and (5) gives:

$$\rho(z) = \hat{\rho}\exp[\sqrt{27/4}kz], \tag{7}$$

showing that in this approximated model, the amplitude of the perturbation at a fixed z depends only on k.

The next step consists in accounting for the MBI threshold for n_b that we will indicate hereafter by n_b^T. For $n_b > n_b^T$ the CSR wake induces a density modulation (generally at the peak of the bunch where the particle density is the largest) that then starts to grow exponentially in amplitude while moving towards the bunch tails where n_b is smaller. When the modulation arrives at a bunch position where $n_b < n_b^T$ the CSR wake cannot sustain the amplitude growth anymore and the modulation starts to decrease and is gradually reabsorbed by the bunch. It is worth remarking that the described mechanism, which completely happens in the linear regime of the instability, describes the time evolution of a MBI burst in the general case, seeded and/or spontaneous.

For the case of a Gaussian bunch with N relativistic electrons, rms length σ_z, and particle density $n_b = (N/\sqrt{2\pi}\sigma_z)\exp(-z^2/2\sigma_z^2) = \hat{n}_b\exp(-z^2/2\sigma_z^2)$, the instability modulation starts to get reabsorbed when:

$$z = z_T = \sigma_z\sqrt{2\ln(\hat{n}_b/n_b^T)} = \sigma_z\sqrt{2\ln(I/I_T)}, \tag{8}$$

where I and I_T are the average current per bunch and its threshold for the MBI, respectively. By using this result in Eq. (7) and the fact that the CSR power P_{CSR} emitted by the modulation is proportional to the square of its amplitude we can finally write:

$$P_{\mathrm{CSR}} \propto \hat{\rho}^2\exp[k\sigma_z\sqrt{54\ln(I/I_T)}]. \tag{9}$$

Equation (9) can now be used for comparing the model with the ALS data. For the current-dependent quantities, we will use the "average" values $\sigma_z \sim 10$ mm, $\delta_0 \sim 0.8 \times 10^{-3}$, and $n_b = I/(\sqrt{2\pi} e \sigma_z f_0)$, with e the electron charge, $I \sim 20$ mA and $f_0 = 1.52$ MHz the revolution frequency. For the threshold I_T we can use the value of 13 mA derived from the bottom part of Fig. 3 at the point where the power growth stops to be quadratic and for $k = 2\pi/\lambda$ we use the value $2\pi/(1.25\sigma_z)$ exploiting the experimental observation that the first MBI unstable mode is the one with $\lambda \sim 1.25\sigma_z$ [22,25]. The other ALS parameters are $R = 4.957$ m, $\alpha_c = 2.7 \times 10^{-3}$, $\gamma = 2936.5$ (1.5 GeV beam energy), and $L = 197$ m. For such parameters, the cold beam criterion, Eq. (3), is respected. In the top part of Fig. 3, the blue dashed curve represents Eq. (9) calculated with the above values and with an offset and a scale factor adjusted for accounting for the background signal level and for the uncalibrated power of our measurements. The fit shows a good agreement with the data up to ~19 mA indicating that our approximated model is capable to account for the CSR power growth. Above this value, the experimental points show a saturation effect that we think is due to the fact that at high currents, the MBI goes in the nonlinear regime before the perturbation arrives at the point z_T.

The model can also explain the time structure shown by the CSR power signal in Fig. 4. As previously said, the slicing seeds the perturbation that starts on the average at the bunch peak, assumes its maximum amplitude at z_T, and after that is gradually reabsorbed. The CSR power radiated by the perturbation must show the same time structure, and Fig. 4 seems to really confirm this scenario. For a more quantitative comparison, we can use the fact that the distance in time between the peaks of the two pulses in the bottom part of the figure should coincides with the value $t_T = \int_0^{z_T} dz/v$ that takes for the perturbation for going from the bunch peak to the point z_T. By using Eqs. (4) and (8) and the parameter values for our case, we estimate $t_T \sim 31$ μs not far from the ~45 μs of the figure. Apart from the accuracy of the model, we think that the discrepancy is also due to the fact that the signal in the figure was taken with a current higher than the ~19 mA at which, according to Fig. 3 the linear regime breaks.

Equation (5) allows to estimate the growth rate for the MBI. Using our case numbers we obtain a value of few μs consistent with the sharp edges of the single burst signals visible in the top part of Fig. 4.

The described seeding phenomenon could find some interesting application as a THz source. Pump and probe and other experiments not requiring shot to shot intensity stability could benefit from the several orders of magnitude increase in power that the seeded MBI case offers. In a more speculative scenario, a fraction of the THz signal can be brought back into the ring to copropagate the bending magnet with a subsequent electron bunch, modulating its energy and seeding the MBI that generates a new burst that is then used in the loop for seeding a new fresh bunch. By this process, that continues involving all the bunches, one can in principle bring the CSR emission to a stable high-power saturation regime where all the bunches radiate coherently.

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