BROADBAND SELF-AMPLIFIED SPONTANEOUS COHERENT SYNCHROTRON RADIATION IN A STORAGE RING*

J. M. Byrd, A. Loftsdottir, W. Leemans, B. Marcelis, M. Martin, W. Mckinney, F. Sannibale, T. Scarvie, C. Steier,
LBNL, Berkeley, California, USA

Abstract

Bursts of coherent synchrotron radiation at far-infrared and millimeter wavelengths have been observed at several storage rings. A microbunching instability has been proposed as the source for the bursts but the mechanism has yet to be elucidated. We provide the first evidence that the bursts are due to a microbunching instability driven by the emission of synchrotron radiation in the bunch. Observations made at the Advanced Light Source are consistent with the values predicted by a model for the instability proposed by Heifets and Stupakov. These results demonstrate a new instability regime for high energy synchrotron radiation sources and will impact the design of future sources.

1 INTRODUCTION

Synchrotron radiation is generated by high energy electron beams accelerated by magnetic bending fields. Coherent synchrotron radiation (CSR) occurs when the emission of multiple electrons in a bunch is in phase, resulting in a quadratic dependence of the power emitted on the number of electrons participating. CSR is possible when the either the entire electron bunch or any longitudinal structure of the bunch is comparable to the radiation wavelength[1-2]. CSR has been a subject of great interest for some time to both the synchrotron radiation and accelerator design communities. The quadratic dependence of radiated power on the beam current promises a significant new source in the terahertz region. However, the effect of the coherent emission on the electron beam could result in a self-amplified instability, limiting the potential application of the CSR as a useful source.

In principle, CSR occurs at the radiation wavelength comparable to the bunch length. However, long wavelength synchrotron radiation is suppressed by a waveguide cutoff condition imposed by the vacuum chamber. For most modern electron rings, this cutoff occurs between a few millimeters to a few hundred microns. One of the difficulties in achieving steady CSR has been to reach bunch lengths shorter than these values.

There have been several reports of quasi-periodic bursts of CSR in the microwave and far-infrared range[3-8] . The mechanism for these bursts is not yet well understood. Recently a model to explain these effects has been proposed[9]. In this model, the interaction of the beam with its own synchrotron radiation creates microbunching within the electron bunch which then amplifies itself via coherent emission. We postulate that the subsequent growth and decay of the microbunching instability results in a series of bursts of CSR. This effect may have implications for the operations of present and future storage rings and may present an ultimate limit on the stable peak current density of a bunch that can be achieved.

In this paper, we present the first experimental evidence indicating that the instability thresholds predicted by the microbunching model correspond to the observed thresholds for the CSR bursts. We have measured the CSR bursts at the Advanced Light Source (ALS), a 1.5-1.9 GeV electron storage ring. The instability threshold was measured at several wavelengths for different electron beam energies and bunch lengths. These data show good agreement with the model.

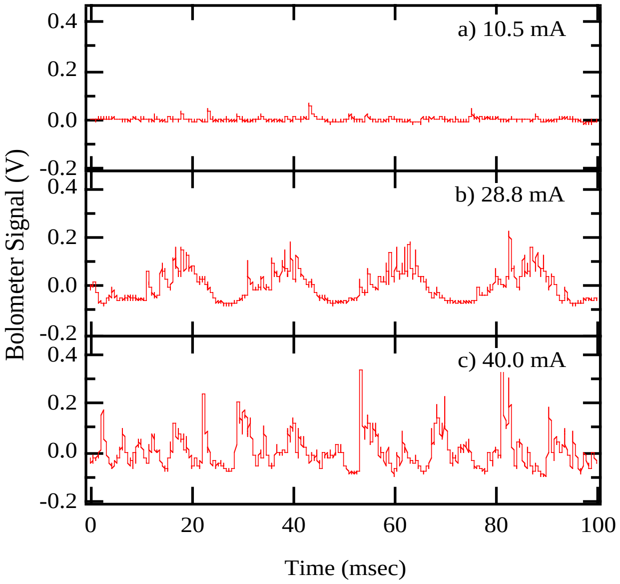

Figure 1: Bolometer signal measured demonstrating bursting above threshold at three current values. Between 27 and 31 mA the bursts develop a periodic behavior. Above this current they appear more chaotic.

2 SPONTANEOUS BURST OBSERVATIONS

Far-infrared measurements were carried out at the ALS IR beamline 1.4 [10-12]. This beamline collects 10-mrad vertical by 40-mrad horizontal of bend-magnet synchrotron radiation. The source is re-imaged by an off-axis ellipsoid with 3.5 m conjugate distances. The light is passed either through a CVD diamond window for FTIR spectral measurements, or a fused silica window for time-domain measurements with one of three far-IR detectors. FTIR spectra were acquired with a Bruker 66v/S spectrometer using a 26-micron Mylar beamsplitter and an Infrared Laboratories 4.2 K Si bolometer with a 100 cm^{-1} cut-on filter. Time-domain measurements of the far-IR emissions were made using the same 4.2 K bolometer, or a 1.6 K IR Labs Si bolometer with a 40 cm^{-1} Fluorogold cut-on filter. To measure at even longer wavelengths, a 94 GHz microwave detector system was used consisting of two RF diodes: an Impatt diode operating at 94 GHz and a Gunn diode that can be frequency tuned and locked at a specific frequency difference with the Impatt diode. This diode signal is mixed with the Impatt and incoming signal providing a signal at the difference frequency of ~500 MHz. The output signals of all three detector systems were monitored with an oscilloscope.

Examples of the signal observed on the 4.2 deg-K bolometer during bursting are shown in Figures 1a-c. Above a threshold single bunch current, bursts of signal appear. The time response of the burst signal is determined solely by the time response of the bolometer. As the current increases, the burst signals increase in both amplitude and frequency. At the highest single bunch current, the bursts appear almost continuously, often large enough to saturate the bolometer. At 27-31 mA, the bursts develop a periodic envelope as shown in Fig. 1b. The examples shown here are typical of the signals observed on all three detectors. A measurement of the average spectral content of the bursts using the 4.2 deg-K bolometer and Bruker 66v/S is shown in Fig. 2. All spectra are normalized to the thermal background signal (zero beam current) in order to minimize the response of the spectrometer, beamsplitter, and detector. The signal shows up to a hundredfold increase at wavenumbers below 30 cm-1 (λ>333 μm). The inset shows the integrated signal in the spectrum from 15-40 cm-1. A fit to a zero-offset quadratic is also shown, confirming that this signal is coherent.

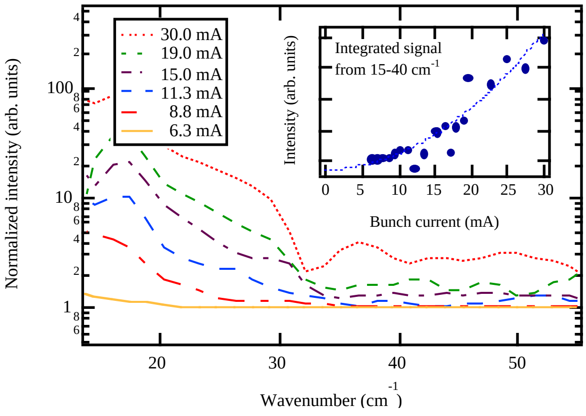

Figure 2: Average frequency spectrum of bursts as a function of current. Inset: the integrated signal shows a quadratic dependence of the signal on the bunch current.

The time-averaged signal on the 1.6 deg-K bolometer as a function of current for both single bunch and multibunch filling of the ring is shown in Fig. 3. The multibunch signal is expected to be incoherent and shows a linear dependence on current. Below the bursting threshold, the single bunch signal shows a dependence on current greater than linear and magnitude significantly higher than the multibunch signal at the same current. We believe this is an indication of stable CSR. At the threshold for observing bursts, the data shows an exponential increase which eventually shows some saturation at higher bunch currents.

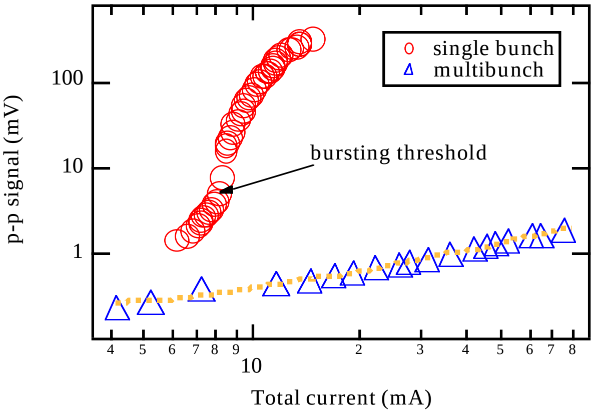

Figure 3: 1.6 deg-K bolometer signal as a function of total current for single and multibunch operation. The dashed is a linear fit to the multibunch signal.

3 MICROBUNCHING INSTABILITY MODEL

Heifeits and Stupakov have developed a model which predicts a microbunching instability excited by coherent synchrotron radiation in electron rings[9]. The model starts from the observation that fluctuations in the bunch longitudinal distribution with characteristic length much shorter than the bunch length can radiate coherently. Under proper conditions the CSR emission can increase the fluctuation triggering a chain effect leading to microbunching and instability. The possible wavelengths for CSR bursting are limited by vacuum chamber shielding that sets an upper limit and by the bunch energy spread which, for shorter wavelengths, generates a longitudinal “re-mixing" that opposes the growth of the microbunching. From the theory a criterion that gives a current threshold for the instability and the CSR bursting can be derived:

$$I_b > \frac{\pi^{1/6}}{\sqrt{2}}\frac{ec}{r_0}\frac{\gamma}{\rho^{1/3}}\alpha\delta_0^2\sigma\frac{1}{\lambda^{2/3}} \qquad (1)$$

where I is the average current per bunch, e the electron charge, c the speed of light, r_0 the electron classical radius, γ the beam energy in rest mass units, ρ the dipole bending radius, α the momentum compaction, δ the relative energy spread, the rms bunch length and λ the radiation wavelength. Equation 1 holds for $1/\gamma^2 << \alpha$, for

$\sigma >> \lambda/2\pi$, and for a gaussian longitudinal distribution. The wavelength λ can assume only values below the vacuum chamber cutoff.

The quantities δ and σ implicitly depend on γ, ρ, α and on other machine parameters. If a non-microwave instability regime is assumed than the expressions for the natural bunch length and energy spread can be used in (1) to obtain:

$$I > A \frac{1}{f_0 h^{1/2} V_{rf}^{1/2} \left(1-\left(\frac{U_0}{eV_{rf}}\right)^2\right)^{1/4}} \frac{\alpha^{3/2}}{\rho^{11/6} J_s^{3/2}} \frac{\gamma^9}{\lambda^2} \qquad (2)$$

where $A = (m_0 e c^6 C_q^3)^{1/2} / 2\pi^{1/3} r_0$, m_0 is the electron mass, h the harmonic number, f_0 the revolution frequency, V_{rf} the RF peak voltage, J_s the longitudinal partition number and C_q=3.8319 10^{-13} m.

In a recent upgrade of the ALS, superconductive bending magnets have replaced 3 of the 36 normal conductive ones. The new dipoles maintain the same bending angle but have different radius. In this situation, the instability theory can still be applied if in Eq. 2 ρ is replaced with an effective radius $\rho = \left(\rho_{sc}^{1/3} + 11\rho_n^{1/3}\right)^3/12$, with ρ_s and ρ_n being the radii of the super and normal conductive magnets respectively. Measurements of the current threshold as a function of the beam energy for three different wavelength values have been performed at the ALS. The results are showed in Fig. 4.

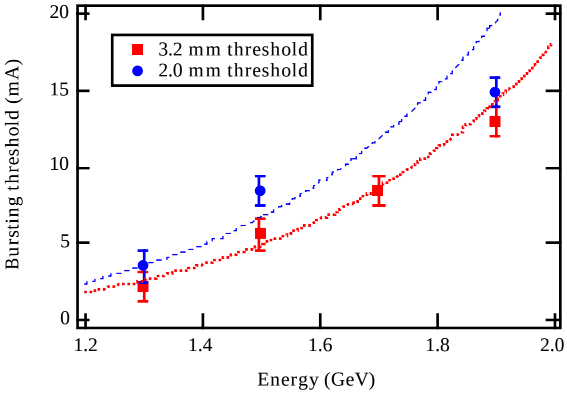

Figure 4: Bursting threshold measured vs. beam energy at 3.2 and 2 mm. Dashed lines show calculated threshold.

The points with error bars indicate the experimental data while the solid lines show the theoretical threshold calculated for the ALS parameters. The previously mentioned RF detector and the 1.6 K Si bolometer were used for the 2 different wavelength measurement sets. For the RF detector, which has a very narrowband response, the center value of λ=3.2 mm was used for calculating the theoretical curve in Fig. 4. For the bolometer, the lower limit (larger wavelength value) of its bandwidth, was used for the purpose. This assumption can be justified by the fact that the instability theory indicates that CSR bursting thresholds are smaller for larger wavelengths. Because of sensitivity, the RF detector was not able to detect any signal below threshold. This fact introduces some overestimate on the current threshold measured values. The asymmetric error bars in Fig. 4 on the RF detector data take into account for this effect. On the contrary, the very good sensitivity of the 1.6 K bolometer allowed a clear measurement also in the absence of CSR bursting. As the threshold for this case, it has been taken the current value where the measured curve starts to be non linear (appearance of the first coherent emission).

The agreement of the threshold at 3.2 mm with the theoretical curve good, especially considering that model is calculated using nominal machine parameters. We believe that the threshold at shorter wavelengths and higher bunch currents differs from the model due to increased energy spread and bunch length.

4 CONCLUSIONS

We have provided the first experimental evidence that synchrotron radiation can drive a microbunching instability in an electron storage ring resulting in periodic bursts of coherent synchrotron radiation. We believe that this mechanism is responsible for at least some of the unexplained observations of CSR bursts at several other electron rings.

5 REFERENCES

[1] J. S. Nodvick and D. S. Saxon, Phys. Rev. 96 (1954) 180.

[2] G. Williams, et. al., Phys. Rev. Lett. 2 (3)(1989) 261.

[3] U. Arp, et. al., Phys. Rev. ST Accel. Beams 4 054401 (2001)

[4] G. L. Carr, S. L. Kramer, J. B. Murphy, R. P. S. M. Lobo, D. B. Tanner, NIM A 463 387 (2001).

[5] A, Andersson, M. Johnson, B. Nelander, Optical Engineering, December 2000, Vol. 39(12).

[6] M. Abo-Bakr, J. Feikes, K. Holldack, D. Ponwitz, G. Wustefeld, EPAC2000, Vienna.

[7] B. Podobedov, G. L. Carr, S. L. Kramer, J. B. Murphy, Chicago, USA.

[8] M. Abo-Bakr, J. Feikes, K. Holldack, D. Ponwitz, G. Wustefeld, Phys. Rev. Lett., in press, May 2002.

[9] S. Heifets, G. Stupakov, Phys. Rev. ST Accel. Beams 5, 054402 (2002).

[10] W. R. McKinney, C. J. Hirschmugl, H. A. Padmore, et al., in SPIE, San Diego, CA, 1997), Vol. 3153, p. 59.

[11] W. R. McKinney, M.C. Martin, J. M. Byrd, et al. , in Accelerator-based Sources of Infrared and Spectroscopic Applications, edited by G. L. Carr and P. Dumas (SPIE Proceedings, Denver, CO, 1999), Vol. 3775, p. 37.

[12] M. C. Martin, W. R. McKinney, Ferroelectrics 249, 1 (2001).