

COHERENT SYNCHROTRON RADIATION EXPERIMENTS AT BESSY II *

K. Holldack, P. Kuske, G. Wüstefeld (BESSY, Berlin, Germany)
and H.-W. Hübers (DLR, Berlin, Germany)

Abstract

Coherent synchrotron radiation (CSR) in the steady state and bursting mode is generated. The emitted radiation is analysed in the time and frequency domain. A step mode Fourier transform (FT) spectrometer is applied to analyse bursting CSR.

a spectrum analyser and FT spectra. The emitted power of stable and bursting bunches is compared and finally high quality FT spectra measured from strongly bursting bunches are shown.

INTRODUCTION

Coherent synchrotron radiation in the sub-THz and THz range ($1\text{THz} \rightarrow \lambda = 0.3\text{mm} \rightarrow k = 30\text{cm}^{-1}$) has been detected at several electron storage rings [1]. The radiation is mostly emitted in irregular bursts, indicating a bunch instability. The BESSY II storage ring is presently the only place, where stable CSR can be produced [2]. The stable CSR is generated in a special mode of the ring optics, the 'low alpha' optics, where the momentum compaction factor α can be reduced by a factor of 100 and more to shorten the bunches. Our present understanding of the bursting and stable emission process is based on an interaction of the bunch with its own CSR wake field [3], [4], [5], [6]. At these short bunches the CSR impedance dominates the chamber impedance.

At currents below a threshold value, these wake fields lead to a static non-Gaussian, deformation of the bunches. The deformed bunches emit a CSR spectrum of much shorter wavelength than expected for purely Gaussian bunches. Increasing bunch current yields a larger bunch shape deformation and more CSR power and finally, above the current threshold, a bursting CSR emission. The stable CSR emission process is of large interest for application in THz spectroscopy. The application of this radiation for THz spectroscopy was recently shown in a dedicated experiment at BESSY [7]. As will be demonstrated in this note, in case of the bursting CSR emission good spectroscopic results can be achieved, if a FT spectrometer in the step mode is applied.

Moreover, the emitted bunch THz radiation opens new possibilities of beam diagnostics. For example, the power spectrum of the bunch can be measured by FT spectroscopy or unstable bunch oscillations can be detected in real time emitted CSR. This tool becomes the better, the shorter the bunches, were conventional methods such as strip line signal detection or streak camera measurements reach their limits.

In this note we present results from stable and bursting CSR emission. We firstly discuss the experimental set up, next we compare results from THz signals measured by

EXPERIMENTAL SET UP

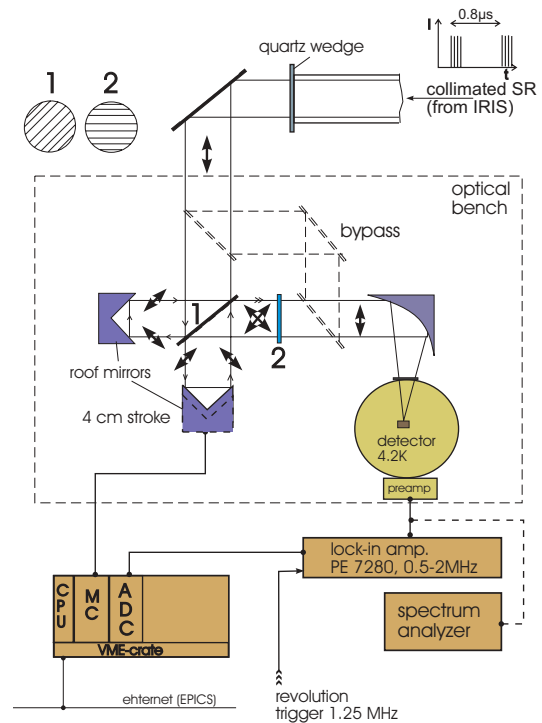


Figure 1: CSR detection system at the IRIS beam port.

Part of the CSR experiments were performed while the storage ring optics was tuned to the 'low alpha' optics with reduced bunch length. Starting from values which correspond to values of the regular user optics with $f_{s0} = 7.2\text{kHz}$, $\alpha_0 = 7.2 \cdot 10^{-4}$ and a zero current rms-bunch length of $\sigma_0 = 4\text{mm}$, $f_s (\sim \alpha^2)$ can be lowered to less than 1 kHz. The 'zero current' bunch length is reduced in proportion with f_s , however, already at rather low currents (10-100 $\mu\text{A}/\text{bunch}$) there will be a bunch lengthening by potential well deformation.

The THz radiation is emitted in dipoles where the vacuum chamber has a full height of 35mm, and a cutoff wavelength of about 4 mm. The CSR experiments were performed at the BESSY infrared experimental place IRIS [8]. It has an acceptance of $60 \times 40 \text{ mrad}^2$ and the photon beam is always kept in vacuum. The experimental set up is shown in Fig.1. The collimated THz-beam leaves the

*Work supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie and by the Land Berlin.

vacuum section by a quartz window, then passes through a Martin-Puplett FT spectrometer into a liquid He cooled InSb-detector. The pre-amplified signal is fed through a lock-in amplifier and then via an ADC into the EPICS control system. The beam revolution frequency of 1.25 MHz is used as the reference for the lock-in amplifier. The InSb-detector is sufficiently fast to resolve the beam revolution time of 800 ns. Typically 200 out of 400 rf-buckets were filled to get a strong signal modulation avoiding any base line drifts and low frequency noise. Typical current values are 10 to 100 μA (5 to 50 $\cdot 10^7$ electrons) per bunch. The equipment is sufficiently sensitive to measure the incoherent radiation spectrum down to current values of 1 μA per bunch.

TIME AND FREQUENCY CSR MEASUREMENTS

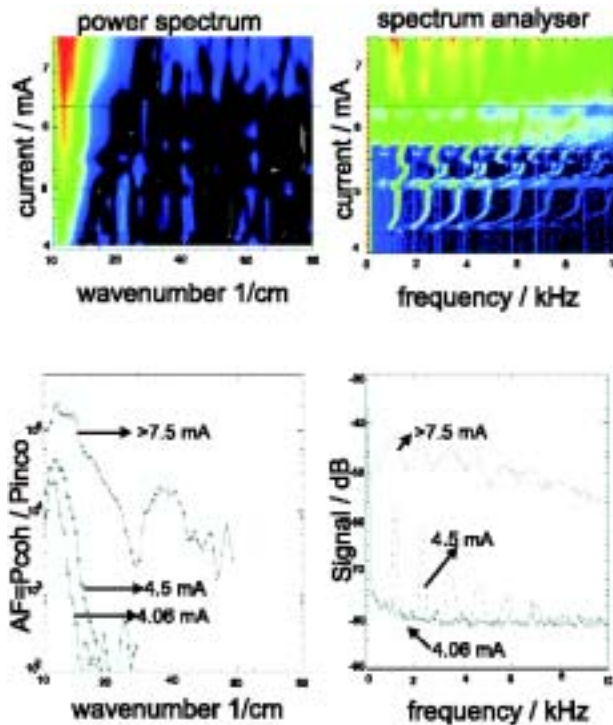


Figure 2: Current dependent scan of THz records from the FT spectrometer (left) and the spectrum analyser (right).

The temporal stability of the CSR signal can be well analysed by detecting sidebands of the revolution harmonics with a spectrum analyser. This is demonstrated with CSR signals analysed during the regular BESSY single bunch shift, where already CSR emission is visible at a low rate below 4 mA and with increasing power above 4 mA. In Fig. 2 a sequence of coherent THz-signals as a function of the bunch current is displayed, recorded during beam storage time with typical life times of few hours and varying from 7.5 to 4 mA. The left side shows the

THz-power spectrum from 2 cm^{-1} to 80 cm^{-1} ($\lambda = 5$ to 0.125 mm) normalised by the incoherent spectrum of the same current.

To describe the enhanced CSR compared to the incoherent power the amplification factor, A_F , is introduced. The radiated power P_λ at the wavelength λ is given by, $P_\lambda = p_\lambda N_e (1 + f_\lambda N_e)$, where N_e is the number of electrons, p_λ the emitted power by one electron and f_λ is the form factor. f_λ is calculated from the square of the longitudinal FT of the charge density. From this relation we define $A_F = P_\lambda / P_{incoh} = N f_\lambda$. The incoherent power spectra P_{incoh} used for normalisation were recorded with a low current, multi bunch filling. Below 5 cm^{-1} A_F is declining, indicating that there might be still some coherent content in the 'incoherent' spectra (see Fig. 2 bottom, left).

The right part of the figure shows spectrum analyser (Rohde & Schwarz FSEK30) data of the temporal oscillation frequencies in the 0 to 10 kHz range. These signals are very sensitive to bursting emission. At 4 mA bunch current, CSR is emitted by a stable process, no sideband signal is detected with the spectrum analyser. The corresponding FIR spectra show intensities at around and below 10 cm^{-1} . The CSR spectrum contains up to 10000 times more intensity than the incoherent one. At 4.3 mA a periodic signal is detected with the spectrum analyser, with frequencies of about 1.3 kHz and higher harmonics. This is just at the threshold of the bursting process. With increasing current the spectral power spectrum gains intensity and is increasing at higher wave numbers. There are some pronounced transitions in the oscillation structure visible, immediately at 4.3, 5.2, 5.3 and 5.6 mA, followed by a broad range between 5.7 and 6.3 mA and finally above 6.4 mA a broad, nearly constant band of more than 10 kHz appears with some distinct lines (Fig. 2 right side). Sometimes these transitions are combined with sudden intensity changes (see Fig. 3), the full range of signal power was found to be increased by 45 dB.

There are three cuts through the data to show better resolved details, at 4.06 mA just below the bursting threshold, at 4.5 mA when there is periodic bursting, and at 7.5 mA when the bursting shows an irregular temporal pattern with few distinct lines on it. The THz spectra at the first two cuts are quite similar, at 7.5 mA, within the bursting range, there is a broad line building up at around 40 cm^{-1} .

From single bunch streak camera measurements it is known, that the 4 mA bunches are 50 % longer than the 'zero current' value and at 7.5 mA the bunches are around 85 % longer. This lengthening does not reduce the emission process as one would expect from Gaussian bunches, it still becomes more powerful. The spectrum analyser delivers a tool, to clearly distinguish between steady state and bursting CSR and to define the thresholds with better than 10 μA precision.

BURSTING CSR

The power of the detector signal was recorded as a function of the bunch current at different α settings. To have a well defined bunch current, this was performed in a single bunch measurement with a corresponding low signal in the steady state. The records started at currents below the bursting threshold. The bursting threshold is very well localised, as demonstrated in Fig.3, starting at very low current already. At small f_s -frequencies corresponding to small α -values the recorded CSR power grows continuously with increasing beam current. In this case, all power of the side bands (see Fig.2 for comparison) are still within the 300 Hz bandwidth of the detection system. If $f_s > 5$ kHz the side bands could shift out of the accepted bandwidth range, leading to a strong modulations of the signal strength. The plots at $f_s=7.2$ kHz are measured with and without the two 7 Tesla wave length shifters (wls). The increased energy spread caused by the wls probably shifts the bursting threshold to larger values. In all 5 records the CSR stays stable only up to a power level of -85dB.

These data show, that the CSR power in the bursting case could be more than a factor 100 stronger (45dB), the upper limit was not yet tested. For further discussion of the bursting threshold see [6]. The power of the incoherent radiation into the acceptance of the IRIS beam line was estimated and scaled with the steady state radiation. An average value of 1 mW was found, whereas for the bursting emission 100 mW and more could be achieved.

The Martin-Puplett-FT spectrometer is operating in the step mode. At each position the spectrometer integrates the transmitted power for 200 ms. In case of bursting emission this leads to very reliable spectra, useful for spectroscopic applications. In Fig. 4 there are three successive runs demonstrating this. The life time of the beam was around 10 h and the synchrotron tune was $f_s = 1.85$ kHz. The 44.45 mA (resp. 43.91 mA, 43.28 mA) multi bunch current, distributed in 200 buckets, is about 5 times above the

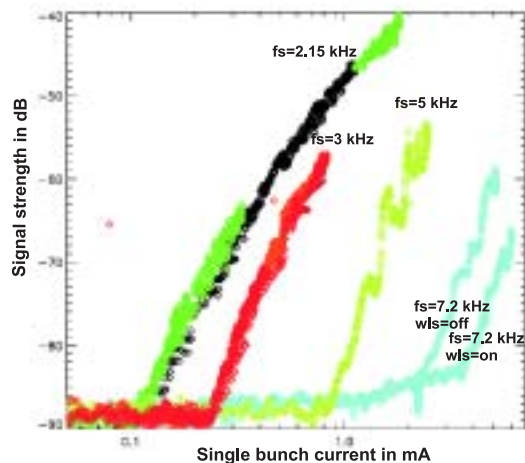


Figure 3: Bursting intensities at different α settings of the machine optics.

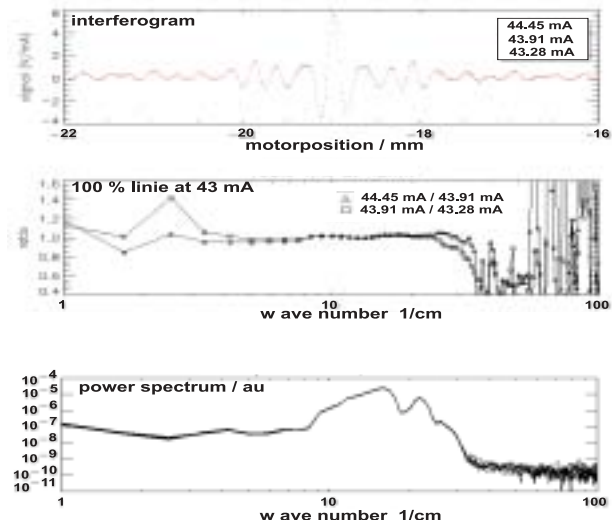


Figure 4: Interferogram and power spectra taken at strongly bursting CSR.

bursting threshold. In the range from 3 to 20 cm^{-1} the reproducibility is 2 % and better. The advantage for operating in the bursting range is the enhanced power output, such that strong absorbing or small samples can be probed in a range not accessible by other methods.

ACKNOWLEDGEMENTS

It is a pleasure to thank U. Schade for support at IRIS and our colleagues from BESSY for discussion and support.

REFERENCES

- [1] A.R. Hight-Walker, U. Arp, G.T. Fraser, T.B. Lucatorto, J. Wen, Proceedings of SPIE **3153**, 40 (1997).
Å. Andersson, M.S. Johnson, B. Nelander, Proceedings of SPIE **3775**, 77 (1999).
G.L. Carr, S.L. Kramer, J.B. Murphy, R.P.S.M. Lobo, D.B. Tanner, Nucl. Instr. and Meth. A **463**, 387 (2001).
J. M. Byrd, W. P. Leemans, A. Loftsdottir, B. Marcellis, M. C. Martin, W. R. McKinney, F. Sannibale, T. Scarvie, C. Steier, Phys. Rev. Lett. **89**, 224801 (2002).
- [2] M. Abo-Bakr, J. Feikes, K. Holldack, H.-W. Hübers, G. Wüstefeld, Phys. Rev. Lett. **88**, 254801 (2002).
M. Abo-Bakr, J. Feikes, K. Holldack, P. Kuske, W. B. Peatman, U. Schade, H.-W. Hübers, G. Wüstefeld, Phys. Rev. Lett. **90**, 094801 (2003).
- [3] K. Bane, S. Krinsky, J.B. Murphy, "Micro-Bunches Workshop", BNL, 1996, AIP Conf. Proc. **367**, 191 (1996).
- [4] G. Stupakov, S. Heifets, Phys. Rev. ST AB **5**, 054402.
- [5] M. Venturini, R. Warnock, Phys. Rev. Lett. **89**, 224802.
- [6] Coherent emission of synchrotron radiation and longitudinal instabilities, M. Abo-Bakr et al., see PAC2003 proceedings.
- [7] J. Singley et al., submitted to phys. Rev. Lett.
- [8] U. Schade, A. Röseler, E.H Korte, F. Bartl, K.P Hofmann, T. Noll and W.B. Peatman., Rev. Sci. Instr. **73**(3), 1568 (2002).