CSR AND THz EMISSION MEASUREMENTS AT THE DIAMOND LIGHT SOURCE

R. Bartolini[1,2], G. Cinque[1], I.P.S. Martin[1], G. Rehm[1], C. Thomas[1]
[1]Diamond Light Source, Oxfordshire, U.K.
[2]John Adams Institute, University of Oxford, U.K.

Abstract

After the successful implementation of the low alpha optics at Diamond we have started a characterisation of coherent THz emission with the aim of classifying the conditions for stable and bursting emission and to devise the best operational mode for potential THz users. CSR and THz emission have been characterised with the Diamond IR beamline B22, and with Schottky diode signals in the mm-wave region of the spectrum. These investigations confirmed the rich phenomenology associated to CSR emission under very different operating conditions and allowed assessing the possibility of using low alpha optics both in stable and bursting mode as a reliable source of THz radiation, with remarkable stability.

INTRODUCTION

Diamond is continuously striving to extend its operating capabilities to satisfy the increasing demands of the synchrotron users' community. In the last years, a considerable effort has been devoted to the generation of short (few ps) radiation pulse for both X-ray time resolved experiments and enhanced emission of coherent THz radiation.

Coherent emission of synchrotron radiation (CSR) in a storage ring occurs at wavelengths which are longer than the bunch length. The power of the radiation emitted in this wavelength range is increased by orders of magnitude and is quadratic with the charge in the bunch. CSR is normally suppressed at long wavelengths, by the shielding effect of the vacuum chamber, while at wavelengths comparable to or shorter than the bunch length, CSR is reduced due to the random phase structure of the particle distribution. However, bursts of CSR have been observed in rings where the stored bunch charge is above a threshold current, triggering a micro-bunching instability [1]. In such cases, local density modulation can occur in the bunch generating coherent emission at wavelengths which correspond to the longitudinal scale of these microstructures within the electron bunch. This radiation is very sensitive to the bunch charge, and can occur in a pseudo-periodic fashion or chaotically. Steady-state CSR can also be generated by reducing the length of the electron bunch below the radiation wavelength by operating the ring in a low-alpha configuration [2]. CSR has been observed at Diamond for both these modes of operation.

Previously, we have reported the results of mm-wave measurements using Schottky-barrier diodes [3]. More recently, the B22 Infra-Red (IR) micro-spectroscopy beamline at Diamond was used to provide detailed spectral characterisation of the CSR emission. This beamline accepts both dipole and edge radiation from the visible up to the THz region, (repetition)In order to identify the operational mode that best meets the users' requirements, extensive spectral measurements have been carried out in both stable and bursting modes. In addition, these measurements allow a deeper understanding of the complex beam dynamics that govern the radiation emission.

In this paper we present the results of recent measurements recorded on beamline B22 and further advances in the experimental characterisation of CSR using Schottky-barrier diode.

BEAMLINE B22 RESULTS

The B22 beamline has been in operation since December 2009 and is dedicated to InfraRed microspectrometry. Due to the wide Front End design (30x50 mrad^2 and about 32 mm vacuum vessel internal height) the IR beamline B22 operation range spans across the farIR/THz region, with effective performance tested up to 2 mm wavelength. The estimated cut-off of the front end is ~4mm. For our CSR experiments we used a Fourier Transform Infrared Spectroscopy (FTIR) end station Bruker Vertex V80 under vacuum, normally used for IR absorption spectroscopy. The FTIR is a Michelson type interferometer with the wavelength range selected by a suite of beam splitters. The beamline is equipped with several detector types and additional THz sources for references. For our experiments we used beamsplitters made of Mylar multilayers with thickness 50 μm and 125 μm. Spectra were acquired via Opus 6.5 software running on a dedicated PC to control the FTIR bench. Sixteen scans at a resolution 4 cm^{-1} were always merged over a spectral range going from 1 to 1000 cm^{-1} and a scanner velocity set to 1.6 kHz. In this way, the interferometer arm scans 1 cm in 1 second and one scan takes about 10 seconds. All measurements were taken with a far-IR DLaTGS detector at room temperature because of the high intensity of the signal available. A globar source at T=1500 K was also available for generating reference spectra.

In what follows we present three sets of experimental results corresponding to the standard operation of Diamond in users' mode and two cases for the low alpha optics: in the first one the THz emission occurs in a stable regime below the micro-bunching instability threshold, while in the second data were taken in the THz bursting regime.

Storage Ring Set-Up

The normal users' mode at the time when these experiment were made consisted of 200 mA equally distributed in either 900 bunches or 600 bunches. We report here the results obtained operating with 186 mA in 600 bunches.

The low alpha lattice used for these investigations is described in detail in [4]. For these investigations, the RF cavity voltage was set to 2.2 MV and the momentum compaction factor was -4.5×10^{-6}, giving a natural bunch length of 1.9 ps. Two ranges of bunch currents were investigated. In the first case the ring was filled with 800 bunches and current varied between 1 and 5 mA, corresponding to an average current per bunch between 1 and 6 μA. In the second case the ring was filled with 200 bunches and the current varied between 2 and 10 mA, corresponding to an average current per bunch between 10 and 50 μA. According to the theory developed in [1], the threshold for the micro-bunching instability is 10 μA for Diamond, i.e. the conditions described above were designed to cover both steady-state and bursting modes respectively.

Steady-State CSR Measurements

Spectra of the far-IR/THz radiation were acquired for each of the fill patterns described above using the FTIR interferometer. The results are shown in Fig. 1, in which a comparison is made to the emission of a black body and to the emission measured in standard user conditions.

From Fig. 1 it is clear the majority of the radiation is emitted within a peak around 11-12 cm^{-1} (0.9 mm wavelength) with a bandwidth of 7-8 cm^{-1} FWHM. Compared to the black body and standard user conditions modes, the CSR enhancement is most evident up to 30 cm^{-1}. The gain in observed intensity for 5 mA stored current is around 3 orders of magnitude compared to the measured intensity in standard user mode at 190 mA. The current ratio implies a further gain factor of 40 for the CSR emission. A systematic shift of the main peak toward shorter wavelengths is apparent with increasing bunch current. This can be attributed to a distortion of the longitudinal bunch shape due to interaction with the CSR radiation wakefield which in turn enhances the Fourier components at shorter wavelengths.

Approximating with a Gaussian distribution [5], steady-state CSR emission can be expected to occur for wavelengths

$$\frac{2\pi\sigma_z}{\sqrt{\ln \mathrm{N}}} \le \lambda \le \lambda_0 \qquad (1)$$

where λ_0 is the cut-off of the beam pipe, N is the number of electrons and σ_z is the r.m.s. bunch length. Since $\lambda_0=2h(h/\rho)^{1/2}$ where $\rho = 7.1$ m is the dipole radius and h = 34mm is the pipe height at the dipoles, the cut-off wavelength is $\lambda_0 = 4.7$ mm. However at long wavelength the emission is much reduced by the polyethylene window (tabulated T = 50% at 10 cm^{-1}) in front of the detector. At short wavelength the intensity of the radiation emission falls to its half maximum at ~14 cm^{-1} for the case of 4.9 mA stored current (equivalent to 0.7mm wavelength). According to (1) this corresponds to an electron bunch length of $\sigma_z < 0.48$mm. This value is slightly below the measured bunch length of 0.7 to 0.9mm taken with a streak camera; however, equation (1) does not take into account distortion in the longitudinal profile of the electron bunch.

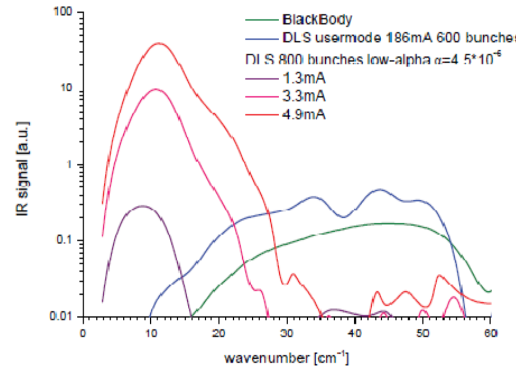

Figure 1: FTIR spectra acquired in low-alpha mode keeping the bunch current below the micro-bunching instability threshold (800 bunch fill pattern). Data for a black body and standard user mode are also shown. Beam splitter multilayer Mylar with 50 μm thickness.

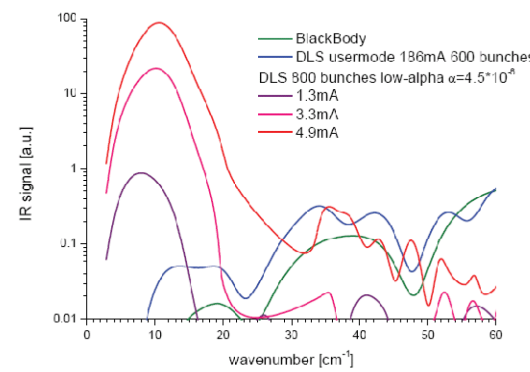

Figure 2: Same as Figure 1 with a beam splitter made of multilayer Mylar with 125 μm thickness.

Taking the integrated intensity within the main peak, the measured intensity is found to follow a more-than-quadratic dependency with bunch current. At first this appears to contradict the expected quadratic scaling with the number of electrons characteristic of CSR emission; however, this simple analysis fails to take account the changing bunch length and longitudinal bunch profile with bunch current and also neglects the frequency dependent filtering due to the pass-band of the beam splitters. Fig. 2 shows the spectra acquired in the same machine conditions as in Fig. 1 but with a different beam splitter (see captions for explanation). In fact, measurements with the Schottky diode at mm-wavelengths have demonstrated that a normalisation of the CSR intensity with the measured form factor can restore the anticipated quadratic scaling with bunch current [4]. More work is required to understand if this is also the case for the measured far IR/THz data.

Bursting Mode CSR Measurements

Following the steady-state measurements, spectra of the far-IR/THz emission were acquired for bunch currents above the micro-bunching instability current threshold. The results are shown in Fig. 3. Due to the higher intensity of CSR emission, measurements in bursting mode were attenuated by partially closing the horizontal collimator in the beamline. The attenuation was estimated to reduce the intensity by a factor of ~100.

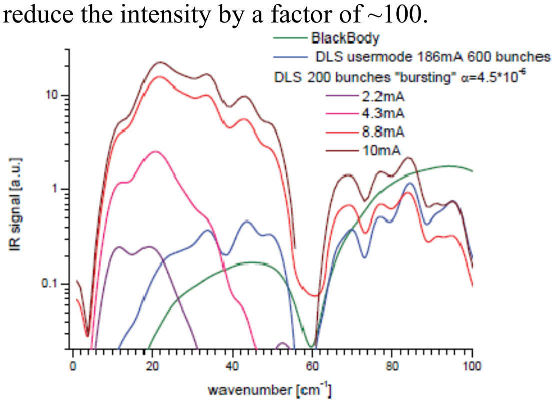

Figure 3: FTIR spectra acquired in low-alpha mode for bunch currents above the micro-bunching instability threshold (200 bunch fill pattern). Data for a black body and standard user mode are also shown.

Compared with the steady-state emission, the CSR spectra recorded in bursting mode extends to higher wavenumbers, with a gain over the black body and standard user mode measurements observed up to 70cm^{-1}. As before, the integral of the spectral intensity increases faster than quadratically as a function of the bunch current. The dip in the spectra at 60 cm^{-1} is due to interference of the light within the Mylar beam splitter. At 20cm^{-1}, the CSR gain factor is estimated to be ~10000.

This time, at 10mA stored current the drop to half maximum of the intensity occurs at around 40cm^{-1} (equivalent to 0.25mm wavelength), which from equation (1) gives a requirement on the electron bunch length of σ_z < 0.18mm, significantly different from the measured bunch length of 1.2mm. As such, the CSR emission can be ascribed to density modulations within the bunch itself. It cannot be excluded, however, that very skewed stable distributions might enhance the radiation emission up to 80 cm^{-1}. Regardless the actual mechanism, the CSR emission from the bunch appear to be remarkably stable when integrated over detector time of the order of tens of ms. This observation opens the possibility of using the low alpha lattice in bursting mode as a stable source of enhanced THz radiation for a class of experiment with long integration time (~tens of ms).

SCHOTTKY-BARRIER DIODE

Bursts of CSR have also been observed at Diamond in standard user mode whenever the bunch current exceeds a threshold value. The bursts are observed to occur initially with a pseudo-periodic nature, but as the bunch current is increased the emission exhibits a complicated, chaotic pattern. To investigate this effect in more detail, recent measurements were carried out using a Schottky barrier diode sensitive to the 60-90GHz bandwidth, for a variety of cavity voltages. The storage ring was filled to 4 mA single bunch current, and the ring collimators were partially closed in order to reduce the lifetime to 0.2 h. During the decay, spectra of the bursts were acquired as a function of bunch current (see Fig. 4 for a voltage of 2.0 MV and for a voltage of 2.5 MV). The intensity of the emission was observed to vary by 3 orders of magnitude.

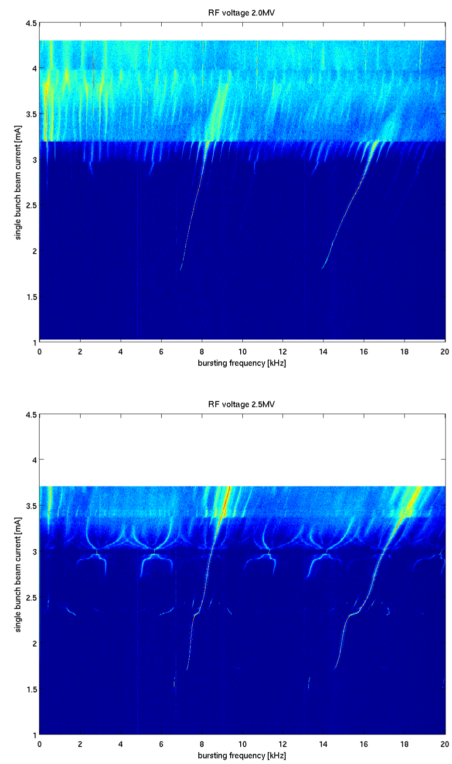

Figure 4: Spectral intensity of mm-wave emission as a function of bunch current. Data were measured using a Schottky barrier diode and a spectrum analyser. The main RF voltage was 2.0 MV and 2.5 MV (upper and lower plot respectively).

CONCLUSIONS

We have presented the results of the latest campaign of CSR and THz measurements performed at Diamond on the B22 IR beamline and also with a Schottky diode on a standard dipole port. We found that bursting emission in low alpha mode offers an interesting perspective for a stable THz source. Finally we would like to thank Mark Frogley for support during the measurements at the B22 IR beamline.

REFERENCES

[1] G. Stupakov, S. Heifets, PRST-AB **5**, 054402, (2002)
[2] M. Abo-Bakr et al., PRL **88**, 254801, (2002)
[3] G. Rehm et al., Proc DIPAC 2009, p. 369, (2009)
[4] I.P.S. Martin et al., PRST-AB **14**, 040705, (2011)
[5] F. Sannibale et al., PRL **93**, 094801, (2004)