Abstract. Diamond Light source is a third generation synchrotron facility dedicated to producing radiation of outstanding brightness, ranging from infra-red to x-rays. The short electron bunches that are accelerated around the storage ring are susceptible to the phenomenon of microbunching instabilities when the bunch charge exceeds a threshold. The primary feature of the microbunch instabilities is the onset of bursts of coherent synchrotron radiation (CSR) in the microwave range. The high frequencies involved in the emissions make detection and analysis challenging. A 60-90 GHz Schottky Barrier Diode detector was installed to investigate turn by turn evolution of the instabilities.

1. Introduction
The phenomenon of microbunch instabilities has been observed at many facilities around the world including Diamond Light Source [1, 2], UVSOR-II [3], ALS [4], BESSY-II [5, 6], the VUV ring at BNL [7], and many other facilities [8]. The key feature of the instability is the onset of bursts of coherent synchrotron radiation (CSR) in the microwave range. The wavelength of these radiation bursts is shorter than the bunch length, $\lambda < \sigma_z$. The onset of the bursts only occurs above a threshold current, where the bursts appear quasiperiodic. As the current increases, the bursting occurs in a random manner.

An exact explanation for the cause of the instability is an active research topic. The mechanism which drives the microbunching instability is not clear. Evidence has shown that they can be driven by a collective force which is self generated by the CSR [9, 10], or by broadband resonator wake fields [11]. We present the result of a series of measurements taken with a Schottky Barrier Diode detector at Diamond Light Source, investigating the onset and evolution of the CSR bursts as a function of bunch current. We were able to clearly detect the mm wave emissions and obtain a preliminary classification of the various emission patterns.

2. Theory
The frequency of radiation we are interested in is that of the order of the size of the microbunches. If we take a bunch of $N$ ultrarelativistic electrons with a Lorentz factor $\gamma \gg 1$, then the radiation spectrum from the bunch can be expressed as
\[
\left( \frac{dU}{d\lambda} \right)_{\text{Bunch}} = \left( \frac{dU}{d\lambda} \right)_{\text{e}} e^{(N + N(N - 1) |G(\lambda)|^2)}
\]

(1)

where \( \left( \frac{dU}{d\lambda} \right)_{\text{e}} \) is the emission from a single electron. The first term, proportional to \( N \), describes the incoherent emissions. The second term is the coherent part, which for \( N \gg 1 \) can be written as \( N(N - 1) \approx N^2 \), meaning the coherent part will dominate at those wavelengths where \( G(\lambda) \) is non zero. \( G(\lambda) \) is the longitudinal form factor, given by:

\[
G(\lambda) = \int_{-\infty}^{\infty} f(z)e^{2\pi iz/\lambda} dz
\]

(2)

where \( f(z) \) is the longitudinal particle distribution function and is normalised such that \( \int_{-\infty}^{\infty} f(z)dz = 1 \). The onset of the instability is determined by the number of electrons in the bunch being sufficiently high to pass the current threshold. The onset of the instability is characterised by the current threshold, and is given by:

\[
(\sigma_0 c)^{7/3} = \frac{c^2 Z_0}{2\pi F 3^{1/3}} \frac{I \rho^{1/3}}{V f_{rf} f_{rev}}
\]

(3)

where \( \sigma_0 \) is the zero current bunch length, \( I \) is the single bunch current, \( c \) is the speed of light, \( Z_0 = 377\Omega \) is the free space impedance, \( F = 7.456 \) [14], \( \rho \) is the dipole bending radius, \( V \) is the RF cavity voltage, \( f_{rf} \) is the RF frequency, and \( f_{rev} \) is the revolution frequency [14].

3. Experimental setup

Diamond Light Source is an electron synchrotron designed specifically to generate high intensity radiation. Basic parameters are shown in table 1. The primary source of the radiation is dipoles, however undulators and wigglers are also present in the Diamond lattice as insertion devices. Diamond’s design means that it can operate in numerous fill pattern modes, including a mode which consists of a single bunch. For this experiment, single bunch mode was chosen to ensure monitoring of the evolution of the same bunch. To record the signal appearance as a function of current, the beam current was manually ramped up to its highest value. A collimator was moved closer to the beam to introduce a rapid decay. To keep the decay rate quasi-linear, the collimator was moved closer to beam at numerous stages throughout the experiment.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| Energy                     | 3 GeV                  |
| Circumference              | 561.6 m                |
| RF Voltage                 | 2.4 MV                 |
| RF Frequency               | 499.7 MHz              |
| Bunch Length               | 3 mm rms (10 ps)       |
| Dipole bending radius      | 7.13m                  |
| Synchrotron frequency      | 1.7 kHz                |

The detector that was employed was a Schottky Barrier Diode (DXP-12) from Millitech, USA, along with a standard gain horn antenna (SGH-12). Figure 1 shows the experimental setup of the detector at the beam port. The detector is off centre due to a mirror inside the vacuum vessel reflecting light out of the port beneath the antenna [15] which is used in optical diagnostics. The antenna was aligned to receive horizontally polarised radiation. General properties of the
detector are shown in table 2. The detector was installed at the port at Diamond light source, which was then amplified by 40 dB by a Femto HSA-X-1-40 amplifier before being read by an Agilent N9020A Signal Analyser. The output from the analyser was displayed in the Diamond control room via remote desktop connection, using Agilent 89601B Vector Spectrum Analyser (VSA) software. The data was recorded separately in both the time and frequency domains.

**Table 2.** Properties of the Schottky Barrier Diode detector and Standard Gain Horn antenna.

| Element                  | Style                  |
|--------------------------|------------------------|
| Frequency Range          | 60 - 90 GHz            |
| Wavelength               | 3.33 - 5 mm            |
| Video Sensitivity        | 20 mV/mW               |
| Response Time            | 250 ps                 |
| Antenna Gain             | 24 dB                  |
| Input Aperture           | 30 × 23 mm             |

*Figure 1. Photo of the 60-90 GHz Schottky barrier diode detector and horn gain antenna.*

4. Microbunch Instability Observations

Four experiments were conducted to investigate the observations of the instability. Three of these were performed at different RF voltages of 2, 3, and 3.5 MV in order to establish the instability current threshold and also to observe the relative intensity of the detected frequencies. The quoted RF voltage values that were investigated are the sum of two RF cavities in the Diamond storage ring. The fourth trial was to investigate the bandwidth of the signal for an RF voltage of 3.5MV. The frequency domain data was recorded as a function of time, and the beam current was also recorded in a separate file in three second intervals, again as a function of time of day. As a result, the current data has to be interpolated to match the frequency data. The interpolated current function for the experiment conducted at 3.5MV RF voltage is shown in figure 2. As mentioned in section 3, the decay is near linear, and can easily be correlated with the frequency data.
Figure 2. Interpolated plot of beam current decay throughout the frequency detection experiment at 3.5MV RF voltage.

Figure 3 shows the time and frequency domain signals for several currents for an RF voltage of 3.5MV. The signal at 0 kHz in figures 3-6 corresponds to the revolution frequency to which our signal is modulated. The signal at 1.001 mA shows there are three frequencies present before the instability starts. These are presumed to be an artefact of a component in the RF system and remain present and unchanged throughout the experiment. The instability starts at 1.5mA and is characterised by the sudden appearance of several frequency components, with two prominent spectral features at 6.8 and 13.6 kHz. These two signals are multiples of the synchrotron frequency of 1.7 kHz, an effect which has previously been observed [6]. At higher currents, these two frequencies shift and develop sidebands, and a quasiperiodic structure appears in the time domain signal. The periodicity of this structure varies significantly with current, and at 3.150 mA, can be seen at a much higher peak voltage. As a result, there is an increase in overall power in the background. At the peak current of 4.210 mA, there is very little time domain structure and the bursts appear chaotic, as observed in previous experiments [1, 2]. Another noticeable effect throughout the current increase is the drifting of the prominent signals to higher frequencies.

Equation 3 can be used to predict a threshold for the onset of the instability. Using some of the parameters listed in table 1, an RF voltage of 3.5 MV, a revolution frequency of 534 kHz and a zero current bunch length of 3mm rms, the estimated threshold current is 1.26 mA. This is slightly smaller than our observed value of 1.5 mA. Figure 4 shows the signal at the instability threshold for the tests conducted for the lower RF voltages. The results also show that the threshold is higher for the lower RF voltages. At 3MV, the threshold current is similar to the value of 1.98 mA obtained in a previous experiment for the same RF voltage [1]. A higher threshold is unexpected as the threshold current is directly proportional to the RF voltage, shown in equation 3. The reason for these discrepancies is unknown, additional experiments would be required to deduce any further conclusions and provide an explanation.

The two tests also revealed that the two prominent frequencies that are produced at the threshold change with RF voltage. For 2 MV, the frequencies are at 6.9 and 13.8 kHz, and for 3 MV, the frequencies are at 7.2 and 14.4 kHz. This can be partially explained by the change in synchrotron frequency that results from an increase in RF voltage. Unfortunately, our results do
Figure 3. Frequency and time domain signals showing the onset and evolution of the instability for an RF voltage of 3.5 MV. The time domain graphs show the normalised amplitude modulation of the signal.

not match this relationship as the frequencies at 3.5 MV are lower than those at 3 MV. This is possibly due to the two RF cavities using different voltages, whereas the voltages were identical in the other two tests, however future research is necessary to provide an explanation for this phenomenon.

Figure 4. Frequency domain signals at instability threshold for RF voltages of 2 MV (a) and 3 MV (b).
Figure 5. Spectral displays of frequency domain signals as a function of single bunch current for varying RF voltages.

Figure 5 shows the spectral data across across the whole current range for all three trials. The colour applied to the plots represents the power of the signal at that frequency with blue being the background power without CSR signals. There are clear differences in the signals observed as expected due to the variations in bunch length. In all tests, we observed the fundamental and the first harmonic of the bursting signal at the onset of the instability. In the 2 MV test, these slowly increase in frequency until around 2.8 mA where the signals develop sidebands, however in the 3 MV test, the sidebands appear at a lower current of approximately 2.3 mA after a sudden jump of the prominent signals to higher frequencies. These sidebands also change frequency and are much more distinguished. In both these tests, there is a further jump at approximately 3.2 mA after which there is an increase in background signal over all frequencies. These features were also evident in the 3.5 MV test. Here, the sidebands around the two main signals are very prominent over a wide current range. There is also the unusual feature of a region above the threshold where the bursts are not observed. Another test was conducted at 3.5 MV where the CSR bursts were measured over a larger bandwidth, shown in figure 6. It is clear that there are additional harmonics of the synchrotron frequency where the CSR signal is observed, up to approximately 50 kHz.
5. Conclusions and Future Work
We have gathered further data on the microbunching instability using a 60-90 GHz Schottky barrier diode detector. The results have shown that there are significant levels of CSR bursts produced from a single bunch. There is a variation in observed signals from different RF voltages, with a higher voltage producing more prominent features and higher power bursts due to a shortened bunch length. The threshold for the instability also varies with RF voltage which can possibly be attributed to bunch length variations, however further experiments are planned to in which additional data on the instability thresholds will be obtained and firmer conclusions can be drawn. The evolution of the CSR bursts has also been observed. Strong signals are produced at harmonics of the synchrotron frequency which slowly increase in frequency with bunch current. Highly visible sidebands about these signals are also produced which exhibit unusual behaviour of larger changes of frequency. Furthermore, rapid frequency jumps in the signal are also seen, after which there is an increase in signal power over the whole 20 kHz bandwidth rather than the discrete signals at lower currents. There are no firm conclusions that can be drawn from our experiments about an explanation for the appearance of the instability and its evolution during changes in bunch current, resulting in the production of these CSR bursts. In the future, a dedicated port for experiments using mm-waves will be built where we plan to install additional detectors which operate at higher frequencies. We also intend to build a Michelson or Martin Puplett interferometer to measure the spectral content of the CSR bursts.

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