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LONGITUDINAL BEAM PROFILE MEASUREMENTS OF THE MICROBUNCHING INSTABILITY*

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Abstract

The microbunching instability is a phenomenon characterized by the onset of radiation bursts above a threshold bunch current. These bursts consist of coherent emissions with wavelengths comparable to the bunch length and shorter. The instability has recently been observed at Diamond Light Source, a 3rd generation synchrotron. The operating conditions for triggering the instability at Diamond Light Source are well known, however measuring the spectral content of the resulting emissions is a more challenging investigation. A Michelson interferometer has been installed with the aim of recording the coherent spectrum from the bunches, using ultra-fast response Schottky Barrier Diode detectors. The longitudinal profile of the bunches can be estimated with subsequent analysis.

INTRODUCTION

Previous studies in electron storage rings have shown experimental evidence of bursts of coherent synchrotron radiation above a threshold bunch current [1–3]. These bursts have wavelengths of the order of the bunch length and smaller, and are a result of a phenomenon known as the microbunching instability. At the onset of this instability, the bursting is quasi-periodic, however at higher currents, the bursts appears to be emitted randomly. In recent years, a study has been conducted at Diamond Light Source into the microbunching instability, including an investigation of the machine conditions necessary to produce the instability, as well as observing the onset and evolution of the bursting [4–6]. The instability is particularly prevalent during the operation of a low-alpha lattice [6, 7]. The low-alpha lattice can operate with a variable first-order momentum compaction factor [8], permitting the bunch length to be shortened to a sub-ps lengths. To further investigate the instability, a Michelson interferometer was installed for the express purpose of measuring the coherent spectral emissions [9]. In this paper, spectral measurements are shown and a preliminary form factor model fit are calculated over a range of bunch currents such that all evolutionary stages of the instability are measured.

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EXPERIMENTAL SETUP

The interferometer was installed at a mm-wave diagnostics viewport, located ∼ 4m from bending magnet B06. In the beam line, a cooled copper mirror absorbs incident x-ray radiation emitted from the bunch, whilst reflecting the mm wave emissions which are being investigated. A stainless steel mirror reflects the remaining radiation such that it is parallel to the beam pipe plane. The viewport is an 89mm diameter fused silica window. After the window, a variable rotational frequency chopper is installed to modulate the emitted beam, and a styrofoam sheet positioned to absorb the shorter wavelength infrared signals. Figure 1 shows the interferometer setup with the radiation direction of propagation shown by the yellow arrows. Spatial constraints have resulted in the inclusion of additional mirrors in the transfer line, mirror A is attached to a 3 dimensional linear stage setup and mirror B is actuator controlled, resulting in greater control of the position and entry angle of the incident radiation. Part C is the Michelson interferometer, which includes two fixed mirrors, a 150mm linearly translatable mirror, a $\sim 100\mu\mathrm{m}$ thick silicon wafer beamsplitter, and a 90° off-axis aluminium parabolic mirror. Although not shown in Fig. 1, the interferometer is enclosed in an aluminium box, which is covered both internally and externally with a pyramidal RF absorber for absorbing any unwanted reflections. The box has a 76mm diameter aperture through which the radiation enters the interferometer.

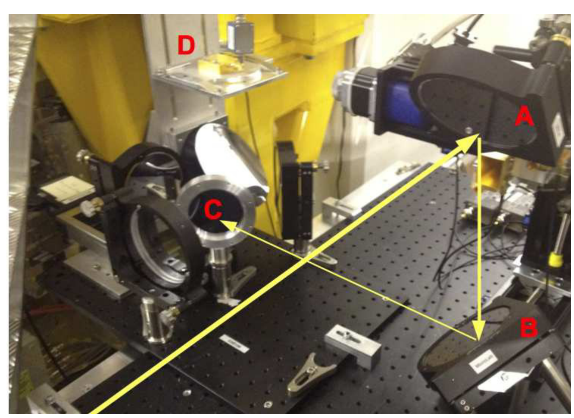

Figure 1: Interferometer Setup.

Component D is the detector, a quasi-optical, Schottky Barrier Diode detector, the specifications of which are given in Table 1. The quasi-optical detector was chosen due to its low noise and fast response time (∼250 ps). The

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Table 1: Detector Specifications

Parameter	Value
Frequency Range (GHz)	100 - 1000
Wavelength (mm)	3 - 0.3
Responsitivity (V/W)	500
Noise Equivalent Power ($\mathrm{pW}/\sqrt{\mathrm{Hz}}$)	10

detector output was connected to a lock-in amplifier, with the reference signal being provided by the chopper.

The interferometer was remotely operated by moving one arm continuously at 5mm/s between two absolute positions, and acquiring data at regular intervals. The bunch current was increased manually in discrete steps of $\sim 3\mu$A, with ten repeat interferometer scans being conducted for every current step. The decay lifetime of the bunches was sufficient for the interferometer to record the repeat measurements without any appreciable change in the instability's behaviour. The spectral content of the emissions were obtained by fast-fourier transform of the interferograms in post-experimental analysis.

The experiment was conducted with a low alpha lattice, with $\alpha_1 = -4.5 \times 10^{-6}$. Diamond uses two superconducting RF cavities operating at 500 MHz RF frequency, both of which were set to 1.7 MV. To achieve a good signal to noise ratio in our detected signal, the beam was comprised of 100 bunches of equal charge, thus the recorded data represents an average of all bunches.

COHERENT EMISSIONS MEASUREMENTS

The data recorded by the interferometer is shown in Fig. 2. Other than the clear changes in signal intensity, the displayed data appears to show little variation with increasing current, as displayed by the three example interferograms. More evident, albeit small changes are seen in the spectral content, shown in Fig. 3. The calculated spectra show that the signal is comprised primarily of frequencies between 100 and 350 GHz. Previous experiments estimate the threshold for the instability to be $\sim 15\mu$A for the quasi-periodical regime, and a bursting threshold of $\sim 30\mu$A [10]. In the spectra in Fig. 3 there is evidence of signal between 350 - 700 GHz above 30μA, suggesting the coherent emissions within the bursting regime contain these higher frequencies, however their relatively low power requires that further experimentation be conducted before any firm conclusions are drawn.

It is apparent that the calculated spectra are not smooth; there are unexpected dips in signal power, and a notable absence of signals from 0 to 150 GHz. The lack of power at these frequencies is due to a combination of diffraction within the system and detector response. The majority of the dips are due to the transmission coefficient of the fused silica viewport; the 6mm thick window causes regular drops in transmitted intensity that vary with wavelength.

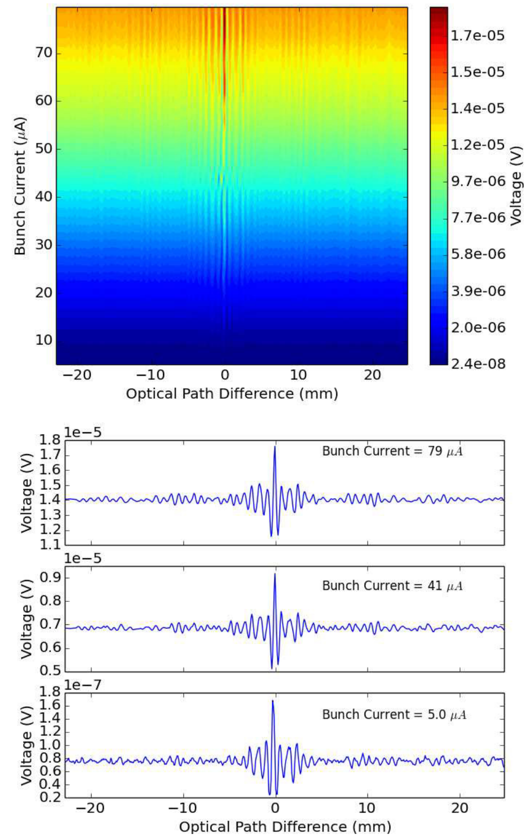

Figure 2: Measured interferograms over an 80 μA bunch current range, plus 3 examples of interferograms from the low, mid, and high current positions

Analysis has been conducted to eliminate the dips, however the spectral resolution of our data has prevented a complete removal. Additionally, the amorphous nature of fused silica has consequently inhibited the calculation of an absolute transmission spectra for the window in our setup. Further investigation is planned to improve the removal of the dips.

BEAM PROFILE CALCULATION

We can approximate the measured spectrum by fitting a model of longitudinal form factor. Due to the incomplete spectrum, only a preliminary model can be estimated at this stage. Ideally, the bunch would be expected to have a longitudinal form factor that would be purely gaussian, however the absence of low frequency signals suggests a modified gaussian. For our model, we applied a low frequency cut-off by using the analytical function in equation 1, where ω_0 is the cut-off frequency, C is an amplitude scaling parameter, and σ_z if the longitudinal bunch length [11].

$$F(\omega) = \left(1 - e^{-(\omega/\omega_0)^4}\right) C e^{-(\omega\sigma_z)^2} \quad (1)$$

A non-linear least-square fit was applied to the spectrum for each current step, with the fit parameters being ω_0, C, and σ_z. The three spectra shown in Fig. 3 additionally show the results of the fitted function, with the amplitude

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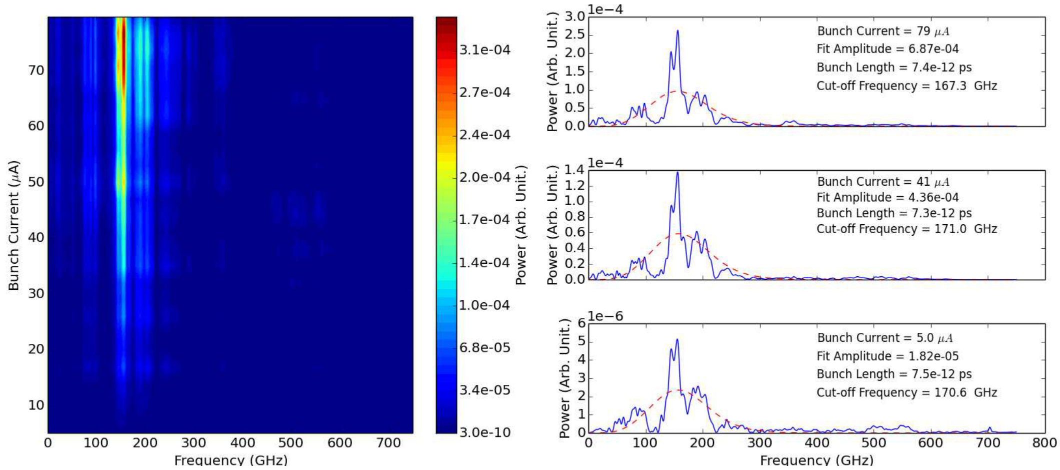

Figure 3: Calculated spectra from the measured interferograms, plus examples from the low, mid, and high current positions with fits of our form factor model

scaling parameter, bunch length, and cutoff frequency displayed. The fitted function shows some agreement with the spectral data, however any of the high frequency emissions above 30 μA do not appear to affect the fit. There is also consistency in the calculated cut-off frequency and bunch length. To provide a basis for comparison, streak camera measurements of the bunch length were recorded during the experiment. Unexpected behaviour from the streak camera prevented accurate recording of the bunch length for every current step, however one of the successful measurements is shown in Fig. 4. The FWHM bunch length was shown to be 10.0 ps, however to convert that to an rms value, we have to incorporate an unknown calibration factor from the streak camera, which is between 1.2 and 1.4. The calculated bunch length from the streak camera data is therefore approximately 3.3 ± 0.3 ps. From the data shown in Fig. 3, it is clear that the bunch length calculated from the form factor fit is over twice that of the measured value. The calculated values also do not conform to the expected increase with increasing bunch current, as displayed in [10]. The cause of the discrepancy is still under investigation, however the recorded spectra from our interferometer measurements is insufficient to calculate a suitable form factor an this stage of the project. The skewness of the streak camera image also suggests modifications to the model fit are necessary.

CONCLUSIONS AND FUTURE WORK

We have presented spectral measurements and calculated preliminary estimates of the form factor from bunches affected by the microbunching instability. The spectra, calculated from a Fourier transform of measurements by a Michelson interferometer, displayed unexpected absences in power due to optical properties within our setup. A gaussian fit with a low frequency cut-off was applied to provide an estimate of bunch length, however the incomplete spectra resulted in calculated values that did not match measurements taken with a streak camera. Future experiments are planned to alter the setup to reduce optical effects of the beam, and to conducted additional experiments improve both measurements and the analysis.

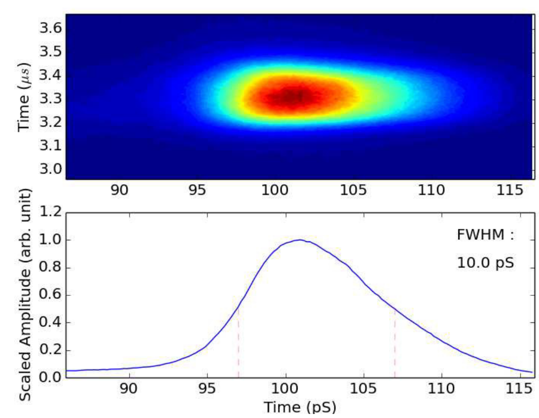

Figure 4: Streak camera image (top) and calculated FWHM bunch length (bottom) for an average bunch current of 38 μA

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