Microwave Emission Measurements from the Electron Beam in the VUV Ring

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The VUV storage ring has several large aperture beam ports for the collection of far-infrared (FIR) beams for research. As these beam lines were pushed to longer wavelengths, they were bothered by large bursts of radiation that saturated their detectors [1]. This was observed to be the result, predominantly, of radiation in the 42GHz region. The power in this band increased rapidly above a well-defined current threshold. Above this threshold it showed a quadratic dependence on bunch current, indicative of a coherent emission from the bunch. This threshold current for the onset of the coherent emission agrees with a model for instability of the electron bunch called the "microwave instability threshold". Above this current, the bunch length and the energy spread increase as the bunch current increases.

A program has begun to study the sources of this instability and its impact on the beam parameters of the VUV ring. The changes in the beam energy spread and bunch length have been studied at other accelerators and are being studied in the VUV ring using the diagnostic beam ports U5 and U3B. However, the high frequency impedance that drives this instability has not been directly measured. These impedances are usually modeled as individual components of the beam vacuum chamber, which works well at low frequencies (below the cut-off frequency of the beam vacuum chamber). At high frequencies, the fields from each component couple to the others, making modeling around the entire ring chamber a daunting, if not impossible, task. The availability of the large aperture FIR beamlines will permit direct measurements of the fields from these impedances stimulated by the beam itself, rather than indirect measurements by wires and antennae.

This article describes the ongoing series of microwave signal measurements, over a broad frequency range (3 to 75 GHz), that are being made on the VUV electron beam. These microwave signals were obtained using the readily available infrared beam port U12IR, that provided the first observations of these signals [1]. The first element of this port is a large flat mirror immediately after the beam exits the dipole. This mirror collects 90 X 90 mrads of the synchrotron radiation from the dipole with the source point 33.5° into the 45° dipole bend. The mirror bends the photon beam vertically and is followed by an elliptical focusing mirror that bends the beam horizontally and into an infrared optical beam pipe. This beam pipe directs the beam into one of several infrared instruments. The beam pipe cuts off the propagation of microwave wavelengths longer than 8mm, limiting the range measured in Ref.[1]. However, a movable metallic shutter upstream of this beam pipe was used to deflect microwave radiation through a glass view port, at right angles to the infrared beam. This port provides a large aperture exit window for long wavelength radiation. The vacuum pipe upstream of this window provides a $TE_{1,1}$ (first transverse E-field waveguide mode) cutoff wavelength of 34cm (f~0.88GHz). The microwave radiation exiting this window was collected in different bands (7 bands from 3 to 75 GHz) using standard pyramidal horn antennae and short sections of waveguide. The waveguide provides a low frequency cut-off filter and a high frequency cut-off was provided by a low pass filter. By limiting the fields in the waveguide to a single mode, $TE_{1,0}$, the output power from the waveguide is polarized as well as frequency-band-selected.

Measurement of the microwave power spectrum was performed using a microwave spectrum analyzer

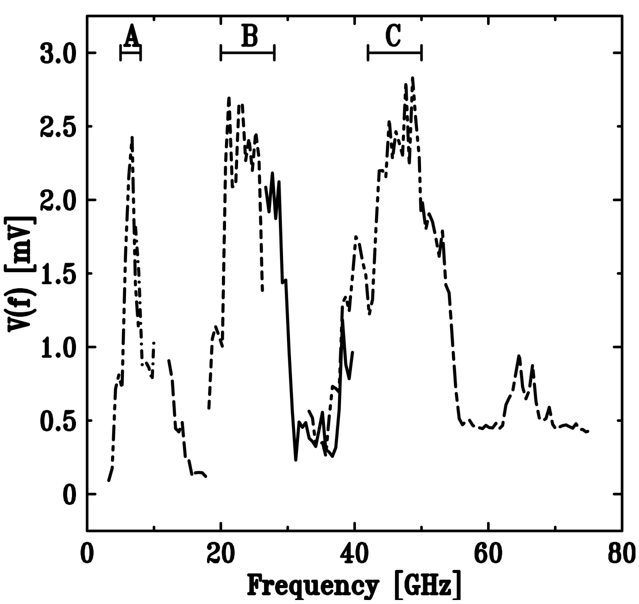

Figure 1. *Measured microwave frequency spectrum (voltage assuming a 50 Ohm input impedance) for a single electron bunch with current above* threshold*. Data from each of the seven waveguide collectors is shown by a different line dashing. The signal peaks labeled bands A, B, and C are marked and described in the text.*

(SA), rather than the Fourier Transform Infrared spectrometer used in [1]. Figure 1 shows the measured frequency spectrum of the detected microwave signal over the 3 to 75 GHz range, for beam currents (I~140mA) above the threshold current of $I_t \approx 100\ mA$, at a ring energy of E=737MeV. Three broad peaks (bands of signal) are observed in Fig.1: A (5-8GHz), B (20-28GHz) and C (42-50GHz). Only C agrees qualitatively with the peak observed in Ref.[1], since their spectrometer could not measure below ~30GHz. This peak and its higher order harmonics were found to agree with a two photon beam interference model, where the direct synchrotron radiation beam interferes with a reflected ray off the outer vacuum chamber wall [2]. This model would predict a destructive interference at 30 GHz and constructive peaks at 15 and 45GHz. The destructive interference valley is seen near 30 GHz and a constructive peak at 45GHz (C band). The B peak appears at 20GHz, somewhat higher in frequency than the 15GHz expected, but with a sharp fall-off below the 20GHz peak. This fall-off may result from the coherent synchrotron radiation being suppressed below 25.8GHz by shielding of the fields due to the metallic vacuum chamber. [3]. Although the B band signal is observed below this frequency, it is predicted that there should be an enhancement in the signal just above the frequency at which the shielding actually extinguishes the coherent synchrotron radiation signal [4].

The lowest band signal, the A band, seriously disagrees with the predicted cut-off frequency. To study this signal further, the time domain structure of the signals was detected using wide bandwidth RF diode detectors (RDD). Figure 2a shows the C band RDD signal (similar to B band) together with the A band signal on a fast time scale. The C band signal shows the single bunch radiating a prompt signal once per revolution. However, the A band signal is a broad peak, 60-80nsec wide and delayed at least 30nsec from the bunch passage. Although there may be a small prompt signal present, most of the power is delayed from the bunch. As described above, synchrotron radiation in this frequency range can be reflected off the vacuum chamber wall. However, it would have to undergo many reflections to account for the 30nsec delay, compared to the 30psec delay found to produce the B and C band signals. Consequently the possibility that the A band signal results from synchrotron radiation is highly unlikely. The most likely source of this signal is from the wakefield generated in a vacuum chamber impedance by the bunch current that propagates around the vacuum chamber (above the waveguide cut-off frequency of the vacuum chamber) and out the beam port.

Figure 2b shows the time structure of the burst of the A and C band signals on a longer time scale. The burst structure of the radiation mentioned above is clearly visible in both bands, with a time interval between peaks of 1 to 10 msec. The A signal always leads the C signal and sometimes is present without a corresponding C signal. The width of the A peak is wider and has a smaller peak to valley ratio than the C signal. The 1 msec time between bursts is surprising, since the damping times are expected to be longer. In order to generate such large peak signals, it is expected that a current density modulation should be induced on the beam bunch, which would yield coherent wakefield radiation. This was measured using a streak camera, borrowed from the SDL project, on the U3B beamline [5]. Figure 3 shows the measured current modulation on the bunch, obtained by triggering the streak camera on the peak of the A band burst, as compared to triggering in between bursts. When the A band signal is high, a 6.5GHz density modulation of the bunch current is observed, that isn't present when the A signal is low. Attempts to measure density modulation at the higher frequency bands (B and C) have not been successful at this time. This lack of observation is consistent with a model that coherent synchrotron radiation peaks B and C result from broadband coherent synchrotron radiation that is modified by a photon beam

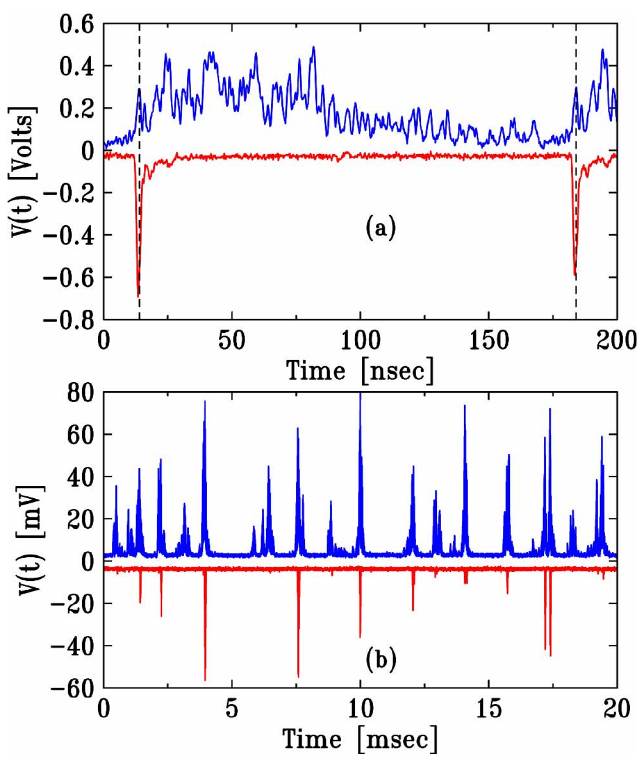

Figure 2. *(a) The fast time domain signal from the A (positive, inverted signal) and C band RDD's, showing the one bunch signal with the revolution time period (170nsec) marked. (vertical dashed lines) (b) Longer time scale measurement of the time period between bursts and their duration for A (positive, inverted signal) and C band.*

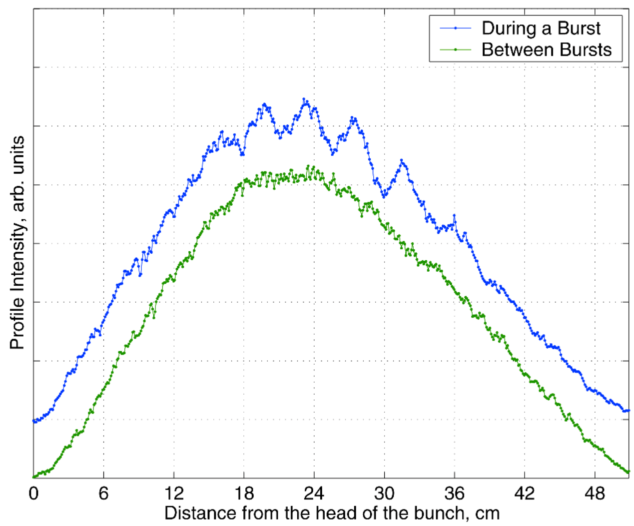

Figure 3. *Measured bunch current as a function of position in the bunch, measured by a streak camera detecting the synchrotron light at the U3B beamline. The upper curve was measured during the peak A band signal (during a burst) and the lower curve was measured when the A signal was low (between bursts).*

interference due to reflection off the chamber wall, rather than from a direct bunch density modulation. This model will be the focus of future studies.

Measuring the peak power of these signals with the RDD's is difficult, since their output has a nonlinear relation to the input power above a level of about 1 microwatt. Average power measurements using thermocouple sensors, which are linear devices, were used to measure the current dependence of the radiated power at the high power level. Figure 4 shows the average power versus beam current for the A and C bands at the VUV ring injection energy. The C band shows power increasing from a linear dependence on the bunch current at low current (up to ~100mA) and then rapidly increasing to a quadratic dependence, in agreement with the Ref.[1] measurements. The linear dependence agrees with incoherent synchrotron radiation, in that the total power possible per unit charge is greater than the measured power, allowing for collection losses. The A band doesn't show the clear threshold of the B and C bands. It also never shows a linear dependence on current and, above 10mA, the power emitted is greater than the total possible from synchrotron radiation. This supports the idea that the A band is not synchrotron radiation. In addition, measurements of the polarization of the radiation show a disagreement with the expected dominant horizontal polarization expected for synchrotron radiation and as measured in the B and C bands.

A search for a vacuum chamber component, which could be a source of the A band signal, led to consideration of the copper RF shields used to prevent heating of the vacuum chamber flexible bellows. Modeling the impedance for this structure showed several resonant peaks in the 5-7GHz region, in qualitative agreement with the measured high current frequency spectrum. However, at lower currents there is a shift of the peaks in the measured frequency spectra toward lower frequencies. Consequently, other impedances may be more important at the lower current levels.

Measurements of band A signal at very low currents requires a preamplifier. These measurements show that the pulsed nature of the radiation at low currents is similar to the high current behavior shown in Figure 2. This would indicate that RF phase noise might be a contributing source to the time structure of the bursts in the A band. Measurements of the A band signal have been used to monitor variations in this noise source during normal operations. Figure 5 shows the measured average power in band A for several fills, during normal stretched bunch operations of the VUV ring. Variations of the power level by factors of 2 to 3 are seen from fill to fill, as well as a non-smooth depen-

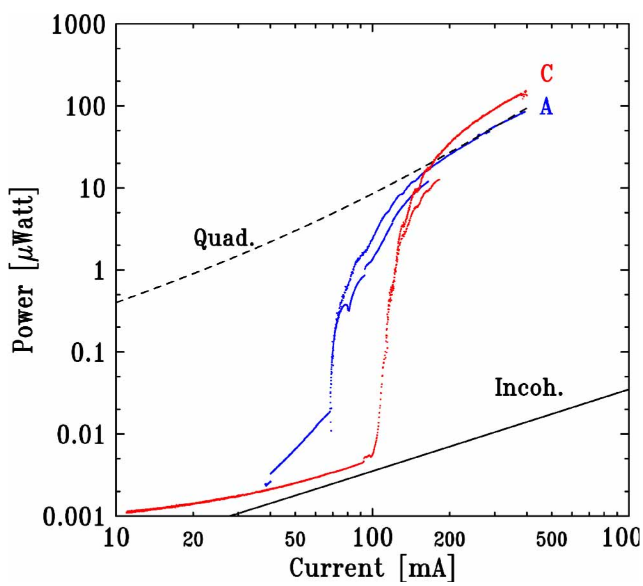

Figure 4. *Measurement of the average power radiated from the beam in bands A and C as a function of single bunch current. Measurements include thermo-couple sensors at power levels above 0.1 μW and RDD sensors below a level of 10 μW. At power levels above 1 μW , the RDD output is nonlinear, yielding lower values than the linear thermocouple sensors. The solid curve shows the maximum incoherent synchrotron radiation (unshielded) power for the A band. The dashed curve shows a quadratic current fit to the high current A band power.*

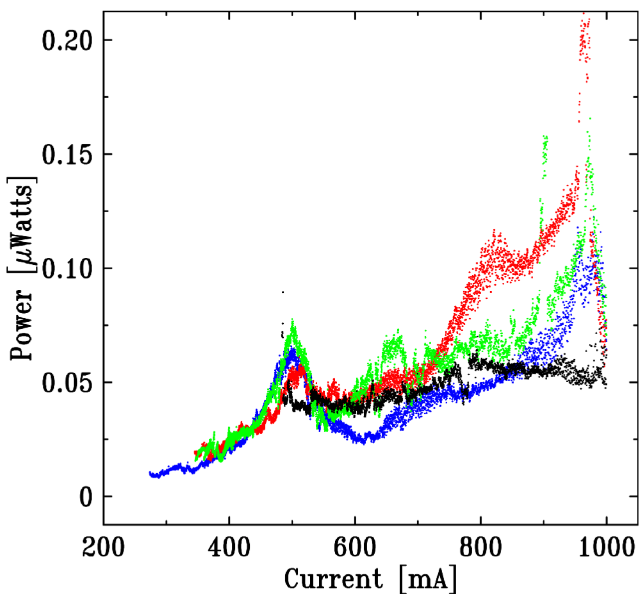

Figure 5. *Measurements of the A band power level versus total beam current for several 1Amp fills of the VUV ring. This data was taken during normal user operations, with 7 of 9 filled bunches and the bunches stretched to ~2nsec FWHM by the 4th harmonic RF system.*

dence on the total beam current. Some of the observed steps in this power correspond to steps in the measured average beam size and lifetime, which occur as the RF cavity tuner adjusts for the beam current-generated fields in the cavity. This microwave diagnostic will be useful in understanding this noise source and its impact on the beam properties.

Future studies will focus on understanding the relationship between the signals in these different bands. If the model of a low frequency current modulation being the source of the higher frequency coherent synchrotron radiation continues to be realistic, then it might be used to generate higher power FIR beams for research. This would require coupling real power into the beam, similar to the 4th harmonic RF system, but at higher frequencies. However, even if this research doesn't lead to new power levels for the FIR, it has already shown that microwave signals from the beam can provide new insight into stability of the beam bunches.

References

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