ORIGIN OF LONGITUDINAL DENSITY MODULATION OF UNSTABLE BUNCHES IN THE NSLS VUV RING*

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Abstract

We performed streak camera measurements of unstable bunches emitting bursts of coherent microwave and infrared radiation. Our goal was to understand the origin of the impedance which excites the instability, creating longitudinal beam density modulation during coherent bursts. The two possible candidates were the impedance from the corrugated bellow shields in the vacuum chamber or the coherent synchrotron radiation (CSR) impedance. To distinguish between the two we checked if the beam density modulation frequency depends on beam energy. Our data favor the impedance from the shields over CSR as the source of the measured modulation.

1 INTRODUCTION

Recently, quasi-periodic bursts of microwave radiation were observed coming from the NSLS VUV ring [1]. A typical burst lasted roughly 100 μs and the burst-to-burst separation was on the order of a ms. These emissions had a clear single bunch current threshold. The first observation was made on one of the infrared beamlines using an interferometer with a bolometric detector. Upstream apertures and other factors have limited the sensitivity of the system to 30-3000 GHz frequency range. With this system the frequency of emission bursts were reported to peak around 42 GHz. The signal power well above the threshold had quadratic dependence on beam current indicating coherent emission of radiation. Since the nominal bunch length in the VUV ring is $\sim$30 cm, coherent emission at 42 GHz from the bunch as a whole is exponentially small. This led to speculations that the observed emission bursts were due to longitudinal density modulation on a beam that was occurring during each burst.

This indeed has been proven in the streak camera experiment [2]. The longitudinal beam profiles recorded during coherent emission bursts have exhibited significant modulation, while the beam profiles taken between the bursts showed no modulation. A somewhat unexpected result was that the strongest modulation occurred at 6.5 GHz while no measurable modulation was found at 42 GHz or higher frequencies. Another surprise was that microwave radiation bursts coming from the beamline, which were used to derive a trigger for the streak camera, had a significant power in the 5-8 GHz range. Unlike the emissions at 42 GHz, the bursts at frequencies this low could not have been CSR due to the shielding effect of the vacuum chamber [11].

This has stimulated more detailed studies of temporal, spectral and polarization properties of emissions coming from the infrared beamlines the results of which are reported elsewhere [3, 4, 5]. Important points for this paper are:

- The emission spectrum has many bands.
- Emissions in the lowest, 5-8 GHz, band are not CSR but rather propagating wake fields of the beam (TM and TE modes excited by the image currents in the vacuum chamber).
- Emissions in all the higher bands are predominantly CSR.
- Emission bursts in different bands occur simultaneously, indicating a common mechanism of excitation.

Separately, to understand the cause of a quasi-periodic appearance of beam density modulation, a series of coherent emission power measurements have been performed with varying momentum compaction [1] and beam energy [9]. They have shown that the coherent emission threshold scales in agreement with the Boussard/Keil-Schnell bunched beam criterion for microwave instability [14]. Therefore a microwave instability was conjectured to cause these density perturbations. Admittedly the picture is still incomplete, since, for example, we are not sure what causes the bursting structure of the instability with the fall time being significantly faster than the radiation damping time.

A simpler question, which we address in this paper, is what impedance may cause this microwave instability. The two possible candidates are the impedance of the corrugated bellow shields in the vacuum chamber or the CSR impedance. The first one, being fairly narrow-band, is expected to cause modulation of the same frequency independent of the beam energy or other parameters. On the contrary, for the case of the CSR impedance, the frequency of the beam density modulation due to microwave instability scales very strongly with beam energy [6, 7]. Therefore, we have realized that repeating the experiment [2] at different energies and measuring the modulation frequency should give some clues to the source impedance for the instability.

2 IMPEDANCES

2.1 Shielded bellow impedance

The VUV ring is equipped with eight convoluted RF shields made from copper which are installed inside the vacuum chamber bellows to reduce beam-induced heating.

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Each shield has ten 1 cm deep rounded convolutions spaced 7.1 mm apart from each other. The wake field due to this shield was calculated by two different time domain EM codes [5, 10]. In the frequency domain these calculations show that the impedance has a well defined peak around 6.5 GHz, which was also confirmed in recent bench measurements on a spare bellow shield [5]. While the total impedance budget for the VUV ring has never been computed we expect the impedance of the shields be the dominant contribution at the 4-7 GHz frequency range. Consequently, if a microwave instability is excited due to this impedance, we expect the structure of the collective modes of the beam to reflect the impedance peak, i.e. unstable mode(s) should result in a 6.5 GHz modulation of the beam density. Furthermore, since the shields are static, we don't expect this modulation frequency to depend on beam parameters such as energy, current, bunch length, etc.

2.2 CSR impedance

It has been realized that the action of coherent synchrotron radiation back on a bunch could be conveniently described in terms of the wake field or impedance [12, 13]. The latter is fairly broad-band and, neglecting the screening effect of the vacuum chamber, scales with frequency as $\omega^{1/3}/R^{2/3}$, where R is the bending radius.

Recently Heifets and Stupakov have performed a linearized Vlasov equation analysis of longitudinal dynamics of coasting beam subject to the CSR impedance [6, 7]. They have shown that a modulation of beam density with frequency f_{mod} is unstable provided $f_{mod}R < \lambda^{3/2}c/\pi$. Here λ is the beam intensity parameter $\lambda \equiv \frac{n_b r_0}{\alpha\gamma\delta_0^2}$, where n_b is the number of particles in a bunch, r_0 is the classical electron radius, α is the momentum compaction, γ is the beam energy in units of electron rest mass, and δ_0 is the zero current rms energy spread. Another result is that the wave-number of the most unstable mode is $0.68\lambda^{3/2}/R$. Assuming the usual linear dependence of energy spread on beam energy, this means that the beam density modulation frequency scales with energy as $f_{mod} \sim \gamma^{-9/2}$.

It is worth emphasizing that in the NSLS VUV ring the observed modulation frequency of 6.5 GHz is significantly below the shielded CSR cutoff frequency of about 24 GHz, and therefore the CSR impedance is unlikely to cause this modulation directly. However, since the CSR bursts (at frequencies above the shielded CSR cutoff) occur simultaneously with the 6.5 GHz modulation, one could in principle have the CSR impedance to be the dominant cause of the instability creating some high frequency modulation on the bunch, and then have some (unknown) mechanism leading to sub-harmonic of this modulation amplified at 6.5 GHz. In such a scenario, however, this modulation frequency should scale as stated above, which is what we have attempted to check experimentally.

3 EXPERIMENT AND RESULTS

3.1 Setup

With the exception of a different streak camera model used (Hamamatsu 6860 instead of Hamamatsu 5680) the experimental setup was almost identical to that described in [2]. A brief overview is given below.

We ran the camera in a synchroscan mode, locked to the ring RF. Visible synchrotron light from a dipole was brought to the streak camera by a series of mirrors. The camera was running in a single sweep mode and, to get the longitudinal beam profile, the CCD was integrating the image along the input slit. Since we wanted to study the bunch during coherent emission bursts the streak camera was externally triggered on a signal derived from the coherent burst.

Briefly, a logic pulse was derived from detected microwave power bursts in the 3-15 GHz range. The duration of the pulse was set to 3 μs corresponding to 18 passages of an electron bunch. This setting was a trade-off between the increase in streak camera noise for shorter averaging times vs. trying not to average out any fast beam dynamics. Note that the trigger duration set to this value was much shorter than 100 μs observed emission burst duration and the synchrotron period [8]. Also, microwave power bursts in different frequency ranges have occurred simultaneously but were outside the bandwidth of our receiver.

An alternative method to run the streak camera for this experiment is to use a dual sweep mode (with the input slit replaced by a pinhole and the slow sweep initiated by the same trigger as above), so that the CCD shows the bunch on several successive turns. The resulting beam profile is obtained by averaging over the desired number of turns. In this method the averaging time is controlled by the slow sweep speed of the streak tube rather then by the external trigger. We have tried this mode and, for corresponding settings, the results were quite similar to the first method.

3.2 Measurements, data analysis, and results

Similar to [2] our measurements were done with a single bunch stored in the ring and harmonic RF turned off. Bunches with the current above the instability threshold were injected in the ring and a series of beam profiles were recorded. Most beam profiles we were getting, such as the one shown in Fig. 1 taken at 800 MeV, contained significant density modulation. In spite of different beam energy this profile looks quite similar to the one shown in Fig. 3 of reference [2].

The experiment was repeated for several stored beam energies in the range of 600-800 MeV, where data sets, typically containing several hundred profiles each, were recorded at each energy setting. To analyze the data we have applied an FFT to each individual profile and then averaged the FFT amplitude over each set. Some of the resulting averages are plotted in Fig. 2.

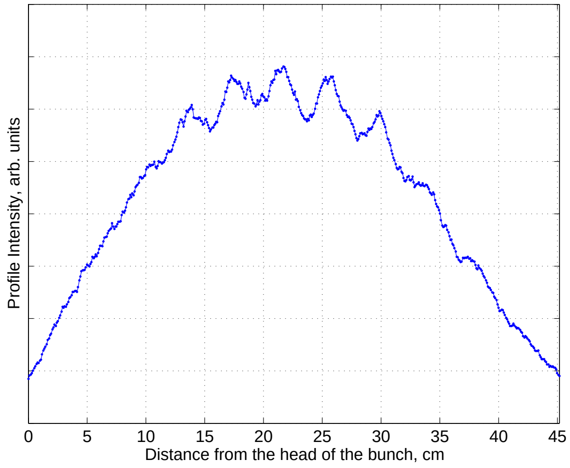

Figure 1: Typical beam profile during an emission burst.

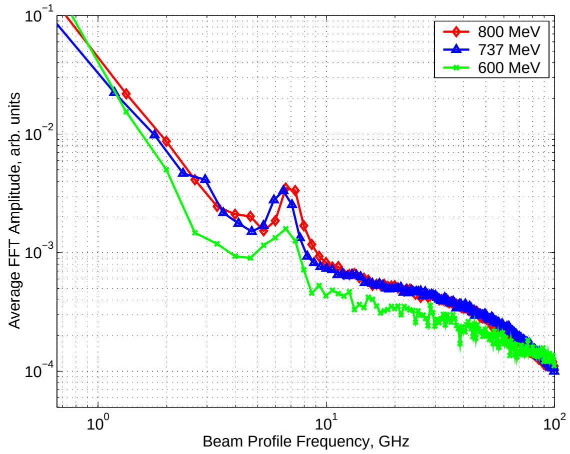

Figure 2: Average FFT amplitudes of beam profiles.

It shows the maximum of the density modulation to occur at $f_{mod} \approx 6.5$ GHz independently of the beam energy. Given the sizes of our data sets and the width of the peaks, we estimate the measurement error to be around 10%. Therefore, we conclude from our experiments that in the energy range of 600-800 MeV the beam profile modulation frequency is consistent with a constant, specifically f_{mod} = 6.5 GHz ± 10%.

In addition, we should point out that at any given energy we have not observed any significant variation in modulation frequency as a function of beam current. The modulation amplitude, however, did decrease with decaying beam current, and the modulation disappeared completely below the threshold of coherent emissions.

4 SUMMARY AND CONCLUSIONS

We have studied the density modulation of a VUV ring electron bunch, which it possesses when emitting a burst of coherent microwave power. We have shown that in the 600-800 MeV stored bunch energy range the modulation frequency is consistent with a constant. In spite of a relatively narrow energy range the data definitely excludes $\gamma^{-9/2}$ dependence expected for the case of the CSR impedance. Therefore, our result favors the impedance from the corrugated bellow shields over the CSR as the source of measured modulation at 6.5 GHz. Furthermore, as we suggest in a separate paper [4], this impedance, through the modulation it creates on a bunch, may also be responsible for the CSR emissions observed at higher frequencies.

Finally, we note that the scaling of modulation frequency could also be checked by varying the momentum compaction rather than the beam energy. While for the case of the CSR impedance the expected dependence is weaker, $f_{mod} \sim \alpha^{-3/2}$, in the VUV ring this is easily compensated due to extremely wide range of α supported by the lattice. However, the setup for this experiment as well as the absolute measurements of α are somewhat more involved, and so far we have not made a systematic study of this. Nevertheless, on several occasions, we did run this experiment with low α lattices that resulted in synchrotron tune reduced by as much as a factor of six from the nominal case. We have never observed the 6.5 GHz modulation peak to move in frequency, however, it did tend to flatten out and disappear for smaller values of α. This, again, favors the impedance from the corrugated bellow shields as the source of measured modulation.

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