OBSERVATION OF FREQUENCY LOCKED COHERENT TRANSITION RADIATION*

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Abstract

Measurements of frequency locked, coherent transition radiation (CTR) were performed at the 17 GHz high-gradient accelerator facility built by Haimson Research Corporation (HRC) at the Massachusetts Institute of Technology Plasma Science and Fusion Center. CTR produced from a metallic foil placed in the beam path was extracted through a window, and measured with a variety of detectors, including: WR6 diode detector, and double heterodyne receiver system. The angular energy distribution measured by the diode agrees with calculations for a 15 MeV, 150 mA, 110 ns beam of 1 ps bunches. Heterodyne receiver and frequency meter measurements were able to show frequency locking, namely inter-bunch coherence at integer multiples of the accelerator RF frequency of 17.14 GHz. At the locked frequencies the power levels are enhanced by the number of bunches in a single beam pulse. The CTR was measured as a comb of locked frequencies up to 377 GHz, with a bandwidth of 50 MHz.

INTRODUCTION

Transition radiation (TR) is produced when a charge travels from one medium into another [1]. When more than a single charge is emitting radiation, especially for the case of bunched beams, coherence is possible. For wavelengths longer than the bunch-length of the electrons comprising the bunch, TR produced by each individual charge is radiated in phase, leading to an N_e^2 enhancement in the power, where N_e is the number of electrons in a single bunch. Another similar effect can be observed when a train of electron bunches impinges on the foil. When the radiated frequency is an integer multiple of the spacing between the bunches, the radiation from each subsequent bunch is radiated in phase. For N_b bunches, there will be an enhancement of N_b to the total power radiated for frequencies that satisfy $f = n f_{rf.}$, for integer n.

Theory

For the case of transition from vacuum to conductor, the radiation can be calculated by examining the fields induced on the conducting medium. This can be done analytically [2], or with an electric-field integral equation (EFIE) method [3-5].

Analytic considerations illuminate a number of properties for CTR, as can be seen in the following expression:

$$\frac{dI_{TR}}{d\omega d\Omega} = \frac{e^2\beta^2}{\pi^2 c}\left(\frac{\sin\theta - \beta\cos\varphi}{(1-\beta\sin\theta\cos\varphi)^2 - \beta^2\cos^2\theta}\right)^2 \quad (1)$$

Where the differential TR power is expressed as a function of $\beta = v/c$, the observation angle θ, and the angle between the incident charge and foil φ. The radiation produced is emitted backwards, into the vacuum region, and peaked at an angle of $\sim 1/\gamma$, with a comparable angular width, as shown in Figure 1. TR is emitted in a continuous range, up to $\omega \sim \gamma\omega_p$, where ω_p is the plasma frequency of the metallic foil [2]. Coherence adds a single N_e enhancement, and an additional form factor dependent N_e, but for wavelengths longer than the bunch length this factor is ~1, giving an overall N_e^2, as previously noted.

Frequency Locking

For a train of bunches the previous results are modified in the following manner. For one bunch, the longitudinal bunch distribution, f(t) gives a continuous Fourier transform, $F(\omega)$. For a train of bunches, or any periodic function $f_P(t)$ with periodicity $T = 1/f_{RF}$, the continuous Fourier transform is made up of discrete Fourier components $A_n\ \delta(\omega-2\pi n f_{RF})$. For a finite train of N_b bunches the δ-functions have a width $\sim 1/N_b$ and the A_n carry an N_b^2 enhancement. Because a single factor of N_b is already expected for a non-periodic train, a net N_b enhancement is present for any coherent detection system capable of resolving the $\sim 1/N_b$ width of the frequency-locking. For our beam we expect a train of ~500 bunches spaced at 17.14 GHz, giving excellent enhancement of the power at these frequencies, and a very narrow bandwidth.

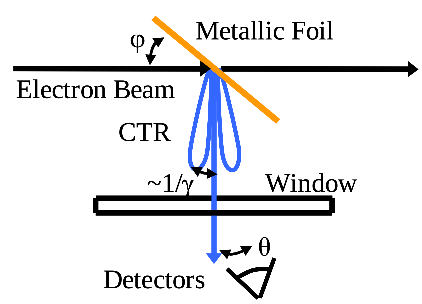

Figure 1: Schematic of experimental setup, φ is the orientation angle of the foil with respect to the beam, θ is the observation angle.

EXPERIMENTAL SETUP

The experiment was carried out on the 17.14 GHz MIT HRC linac. The electron beam consisted of a train of ~500 15 MeV, 1ps bunches, with an average current of 150 mA.

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A 5 cm square, 25 μm thick, Titanium foil was placed at $\varphi = 45°$ so that CTR generated could be extracted through a quartz window perpendicular to the beam path. The foil was mounted on a stepper-motor driven feed-through, so that it could be centered in the beam path. A WR6 diode video detector, frequency meter and double heterodyne receiver were used to detect and analyze the CTR.

Detectors

The video diode detector used was a Pacific Millimeter Products DD Broadband Detector, containing a single zero bias GaAs diode. The diode was attached to a Custom Microwave HO6R horn antenna. The diode was calibrated at 140 GHz using an impatt diode continuous wave source, a variable attenuator, and power meter. The diode with the horn were mounted one meter from the foil on a translation stage with pitch/yaw control to optimize the direction of the horn. The frequency response range of the diode was 110-170 GHz.

The diode was also used in conjunction with a frequency meter as an independent means to verify the Heterodyne measurements, and to estimate how much power was emitted at various frequencies. The frequency meter used was a Hughes adjustable notch filter, which can be tuned to frequencies from 110-166 GHz. As the filter was adjusted, we received a signal that corresponds to the power radiated with any power emitted at the filter frequency absorbed. Normal CTR from a single bunch, without the frequency locking effect would show no structure, and little change as the dial was adjusted. Frequency Locked CTR would show dramatic dips when the meter is tuned to precisely $n\, f_{rf}$.

To further examine frequency locking, a double heterodyne receiver system was used to mix down the radiation frequencies to lower, directly measurable ones [6]. This is accomplished by mixing the incoming CTR with a known frequency local oscillator (LO1), filtering and amplifying the signal, and then again mixing with another known frequency local oscillator (LO2). We used a backward wave oscillator with variable frequency 110-170 GHz for LO1, and a solid state 2GHz oscillator for LO2. As the LO1 frequency was slowly scanned, the resulting incoming signal was then Fast Fourier Transformed (FFT) into 4 peaks, corresponding to:

$$f_{CTR} = n\, f_{LO1} \pm f_{LO2} \pm \Delta \qquad (2)$$

The LO1 order can be calculated by observing how quickly the FFT peaks moved as the LO1 frequency was changed. By identifying the 4 FFT peaks that are associated with each n and averaging their frequencies, we can calculate the singular frequencies of CTR, and eliminate the dependence on the LO2 frequency and Δ .

EXPERIMENTAL RESULTS

The diode was scanned across the window at a distance of 1m. For each diode position, the direction of the horn was optimized for maximal signal. A central minimum was observed at $\theta = 0$. This agrees with the form predicted by (1). The horn was then rotated 90°, and scanned vertically, in 1cm steps to again center on $\theta = 0$. With the diode centered, scans were made horizontally on the translation stage, the results of which are shown in Figure 2. EFIE code [4-5] calculations were made, and show much better qualitative agreement with the observations of the angular power distribution than (1), which predicts a maximum at $\theta \sim 2°$.

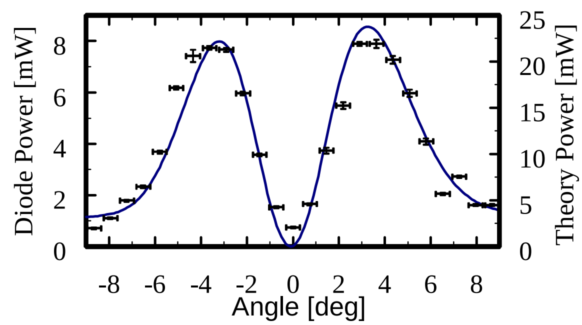

Figure 2: Angular distribution of CTR power measured by the diode, points, and theory calculations made with EFIE code, shown by the blue line.

Coherence was verified by placing the diode at a maximum, $\theta \sim 3°$, and varying the beam current. As predicted by theory, the power shows a linear dependence on the beam current squared, as demonstrated by the excellent agreement with the linear fit shown in Figure 3.

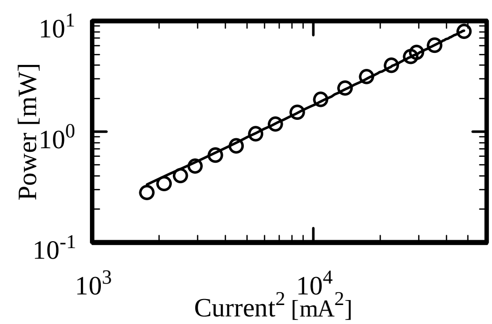

Figure 3: CTR power measured by the diode as a function of the beam current squared. Solid lines is linear fit to circular data points.

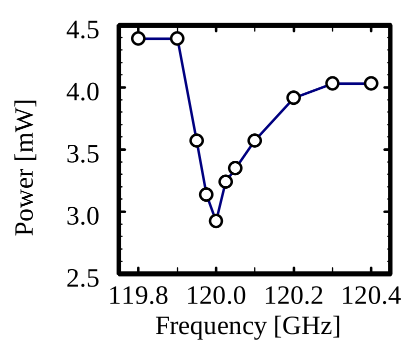

Figure 4: Power measured by the diode attached to frequency meter. Dip at 120.0 ± .025 GHz consistent with

7th harmonic of RF frequency. Similar dips obtained at 137.1 ± 0.5 and 154.3 ± 0.1 GHz are also consistent.

The diode and horn were then attached to the frequency meter. As discussed in the experimental setup, as the meter was adjusted in the vicinity of n f_{rf}, dips were observed, as shown in Figure 4, at the frequencies of 119.98, 137.12 and 154.26 GHz, which correspond to the n = 7, 8, 9 harmonics of the RF frequency. This technique is powerful for the limited range of the meter, unless you compare the frequency meter bandwidth of 100 MHz to the bandwidth of the train ~$1/N_b$ ~ 1/500 ~ 50 MHz.

Heterodyne measurements were made as described in the experimental setup section. The BWO used as LO1 was remotely controlled, and the frequency was varied in the range 117-156 GHz. All FFT peaks observed were recorded, and then matched in sets of four, each set corresponding to a single f_{CTR}, by (2). Figure 5 provides a summary of all orders of f_{RF} observed, and the frequencies measured by the heterodyne system. Figure 6 shows a typical FFT, showing a narrow bandwidth of 28 MHz. An additional property (2) is that when the RF frequency is changed, the peaks on the FFT shift. This was directly observed as the RF frequency was varied in the range 17.136-17.142 GHz.

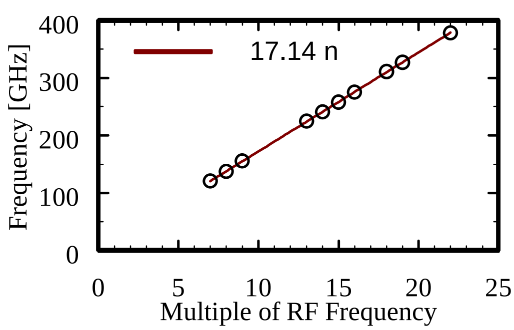

Figure 5: CTR Spectrum measured with double heterodyne receiver, plotted against the multiple of the RF frequency of 17.14 GHz.

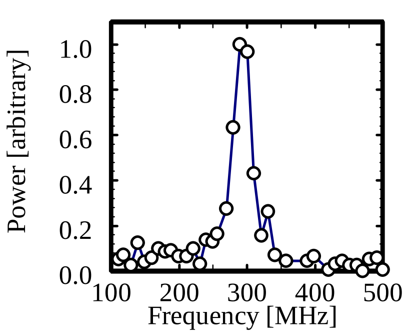

Figure 6: FFT at 240 GHz showing 28 MHz FWHM.

DISCUSSION

The observed CTR angular distribution, coherence, and frequency locking were in agreement with expectations. Angular shape fits theory well, though power levels are ~3 time less than expected. Possible explanations include more extensive window losses than expected, less gain in the diode horn, and EFIE limitations. The EFIE code assumed a foil of infinite extent into the page in Figure 1. A finite foil may decrease the radiated power. Frequency-locking was verified by two independent measurements: one made with a frequency meter, and another using a heterodyne receiver system. The heterodyne system was able to resolve frequency content with very narrow bandwidth, up to a frequency of 377.08 GHz.

Previous observations of bunch to bunch coherence, or frequency locking have been of two types. There are interferometer measurements, which confirm that when the path length difference in the two interference arms used is equal to the spacing between bunches, another signal is observed [7]. This effect would also be observable in high resolution spectra of CTR. These spectra are limited by their frequency resolution, which is typically only on the order of the RF frequency. With the techniques described here we have been able to observe frequency locking with very high resolution, due to the sensitivity of the heterodyne system and the high operating RF frequency. CTR is an important topic of current research for both radiation production, and beam diagnostics.

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