COHERENT RADIATION MEASUREMENTS AT THE NSLS SOURCE DEVELOPMENT LAB*

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Abstract

The far-infrared coherent emission from short electron bunches has been detected and partially characterized for two source locations at the NSLS Source Development Lab (SDL) accelerator system. One location is designed to extract dipole edge radiation while the other extracts transition radiation produced a short distance downstream of the SDL linac. The coherently radiated energy per pulse is 10's of nJ, and depends quadratically on bunch charge. The spectral content agrees with the longitudinal bunch density as determined from other measurements.

1 INTRODUCTION

1.1 Coherent emission

The radiated power spectrum for N relativistic charged particles moving in the z-direction and experiencing a common acceleration is

$$P_N(\omega) = [N + N(N-1) f(\omega)] P_0(\omega) \qquad (1)$$

where $P_0(\omega)$ is the radiated power spectrum for a single particle and $f(\omega)$ is related to the longitudinal bunch density $S(z)$ through [1]

$$f(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega\hat{n}\cdot\bar{z}/c} S(z) dz \right|^2 \qquad (2).$$

For large N and $f(\omega) \neq 0$ (e.g. at low frequencies where the wavelength is greater than the bunch length), the radiated power is dominated by the coherent term, i.e. $P_N(\omega) \sim N^2 f(\omega) P_0(\omega)$. Thus the coherent spectral power contains information on the longitudinal bunch density [2,3].

1.2 Radiation sources

Electromagnetic (synchrotron) radiation is produced at various structures within a typical accelerator system. Transition radiation is produced where the beampipe impedance changes suddenly. In addition to well-known dipole radiation, bending magnets produce radiation where the beam crosses the edges of the dipole's magnetic field. Interest in this so-called "edge radiation" has grown in recent years due to its usefulness as a source for mid-infrared spectroscopy [4], but the long wavelength behavior is not well known. Edge radiation has qualities similar to transition radiation (e.g., radial polarization) and approaches its far-field limiting form only at a distance $R \gg \lambda\gamma^2$, which can easily exceed the dimensions of most beamlines. A typical edge beamline views the straight section between two dipoles, resulting in two interfering sources and further complications.

The intent of our study is to confirm the presence of long wavelength coherent synchrotron radiation at two source locations (one being a dipole edge source) and compare the spectral properties with other measurements of the bunch density profile. Much of our study follows the work done previously at the TESLA test facility [3]

2 INSTRUMENTATION

2.1 Bunch compression in the SDL LINAC

The SDL is based on an S-band linac, comprised of four SLAC-type accelerator sections, with a dipole chicane between the 2nd and 3rd sections. Short electron bunches with a charge of up to 1 nC are produced by a photocathode electron gun. An energy chirp, produced in the upstream linac sections, leads to bunch compression in the chicane. Bunch lengths of ~500 fs have been produced in this manner. From here, the approximately 200 MeV compressed electron bunches pass through a small undulator, followed by two dipole bends and the beam dump. Further details of the SDL and bunch compression are given elsewhere [5].

2.2 Synchrotron radiation ports

Two ports were developed for extracting synchrotron radiation. Each has a crystalline quartz vacuum window that limits the useful far-infrared spectral range to wavelengths greater than 40 microns. One port extracts dipole edge radiation and the other is designed to extract undulator radiation.

The edge port views the short straight section between the two dipoles preceding the beam dump. Thus it collects edge radiation produced as the beam exits an upstream dipole, and again as it enters a second dipole downstream. The two edges are 107.4 cm apart and interference between the two sources is expected to complicate the emitted radiation pattern. Light is extracted through a 2 cm high by 4 cm wide pipe that

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starts at the downstream edge and leads to a 2.5 cm diameter aperture after a distance of 85 cm. This gives a vertical opening angle (half angle) of 12 mr and a horizontal angle of 15 mr for the near edge, and less than half this for the far edge source. A system of 3 mirrors collects and relays the light to a detector located about 1 m distant (outside the lead shielding). The bunch shapes through this region are not known to great accuracy due to dispersion in the upstream dipole.

The undulator port is located immediately downstream of the linac, where the bunches are shortest and well-characterized. This beamport also uses a 3-mirror collection system, with the radiation focused into an infrared detector, or coupled into 12.7 mm I.D. copper pipe for transporting to a far-infrared spectrometer located outside the accelerator vault. We found that far-infrared radiation was produced at this location even with the undulator removed, suggesting that transition radiation was the dominant source due to the proximity of the extraction mirror to the beam.

2.3 Far-infrared spectrometry

The spectral content of the coherent emission from the undulator port was measured using a step-scan Michelson interferometer (in vacuum) equipped with 15 cm diameter optics[A] and a liquid helium cooled bolometric detector. The detector has a responsivity of about 10^5 V/W for slowly varying signals (below a few hundred Hz). The detector's internal optics limit the long wavelength response to about 2 mm. We used an oscilloscope to view the signal, and a lock-in amplifier for the spectroscopy. The linac's 5 Hz trigger was used for the reference signal.

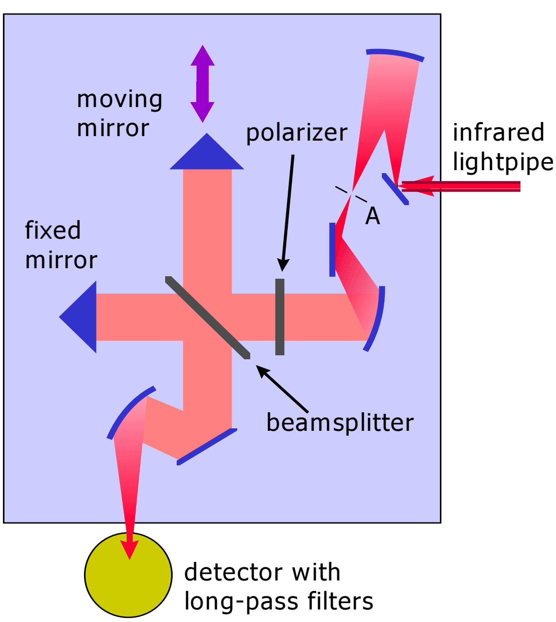

Figure 1. Schematic of the far-infrared polarizing interferometer.

As noted above, the far-infrared radiation was brought to the spectrometer through 12.7 mm ID copper pipe, allowing the spectrometer to be operated outside of the accelerator vault. The effect of this pipe on the spectral content is not known with great accuracy.

3 RESULTS

3.1 Detected signal

Individual pulses of long wavelength radiation were observed for both the edge and undulator beamports. A typical detector pulse is shown in Fig. 2. Since the pulses are significantly shorter than the detector's thermal relaxation time (about 300µs), the signal is proportional to the energy in the pulse rather than the instantaneous power. The energy in this pulse, found by integrating the transient response signal, is 5 nJ. For the shortest bunches, energies exceeding the detector's saturation limit of 20 nJ were observed.

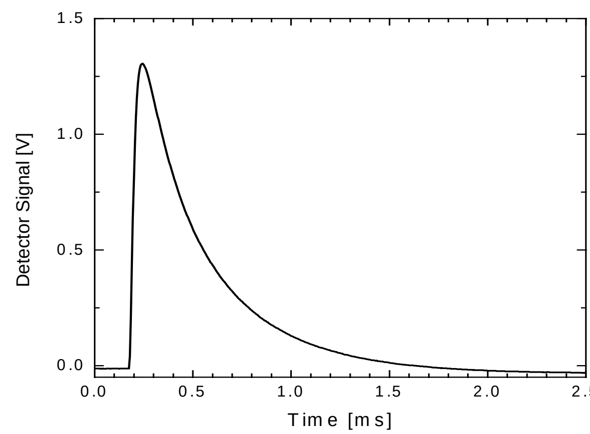

Figure 2. Detector response to a single coherent far-infrared pulse.

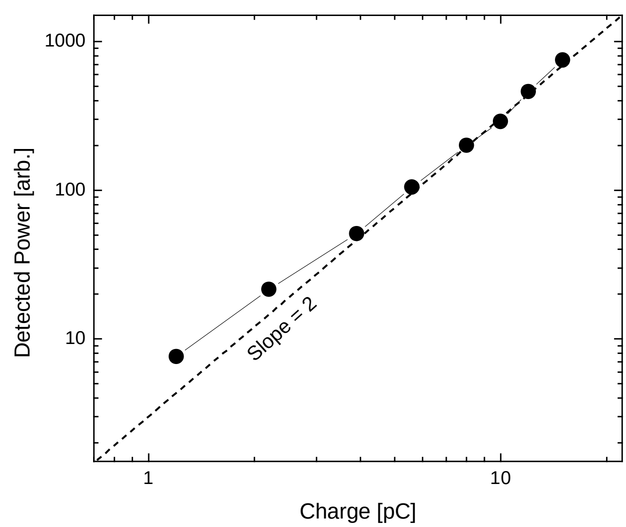

Figure 3: Log-log plot of the radiated far-infrared energy as a function of charge.

We measured the strength of the far-infrared emission as a function of charge. A long-pass filter ($\lambda > \lambda_c$ = 0.5 mm) minimized the sensitivity to any changes in the bunch shape. The results are shown in Fig. 3 as a log-log plot. The quadratic dependence confirms the coherent emission mechanism.

3.2 Polarization

The approximate polarization of the emitted light was checked using a wire grid polarizer. No linearly polarized component was observed at the undulator location, consistent with transition radiation (which has a radial polarization). Partially polarized light was found at the edge location, with a horizontal component about 3 times the vertical component. Though this is the polarization expected for long wavelength dipole radiation, beamline apertures and waveguide effects complicate the situation. The properties of edge radiation have been described by Chubar[ref]. Bosch[refs] has detailed the properties at long wavelengths. When the distance to the source R is less than $\lambda\gamma^2$, the fields have not reached their far-field limiting forms and the full expression for the EM fields must be used (including the velocity terms). In this near-field regime, the emitted field pattern forms a hollow cone with maximum intensity at an angle $\theta \sim (\lambda/R)^{1/2}$. Thus the majority of radiation at 10 cm^{-1} (λ = 1 mm) intercepts the beampipe after a distance of about 30 cm., and a portion of the light is either obscured or propagates in a guided mode of the metal pipe. Either of these will affect the apparent polarization content at the end of the beamline.

3.3 Bunch profile and spectral content

Measurements of the beam energy spread are obtained from a profile monitor at a dispersive location. Setting the final accelerator section to zero phase gives the electrons a linear energy "chirp", making this monitor sensitive to the longitudinal bunch profile. Bunch lengths ranging from several ps down to 500 fs are achieved depending on the degree of compression. An example of a bunch profile for conditions of moderate compression is shown in Fig. 4. In addition to the overall bunch length (about 1 ps), a density modulation within the bunch has appeared. The ~ 170 fs (50 µm) density modulation increases to nearly 100% at maximum compression.

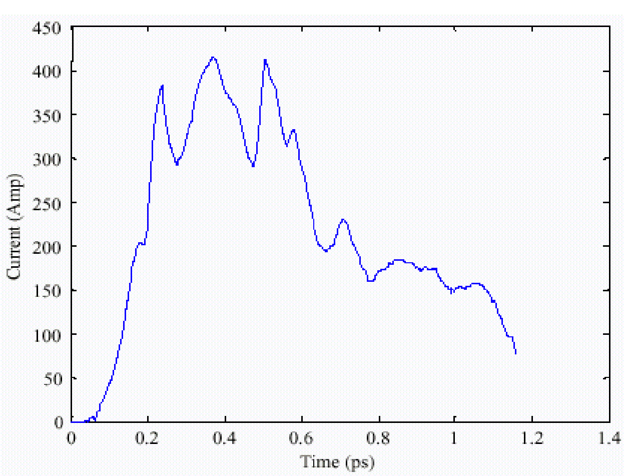

Figure 4. Longitudinal density for a moderately compressed bunch

Eq. 2 shows than an electron bunch will coherently emit for frequencies (in wavenumber) below $\nu \sim 1/L$ where L is the bunch length in cm. Examples of coherent spectra are shown in Fig. 5 for bunch lengths ranging from several ps down to about 500 fs. Note that the spectral content for a smooth 5 ps (0.15 cm) long bunch is mostly below 5 cm^{-1}, but reducing the bunch length a factor of ten extends the spectral range up to 50 cm^{-1}. Additionally, emission in the 200 cm^{-1} range is observed for highly compressed bunches, consistent with the microbunching observed using the profile monitor.

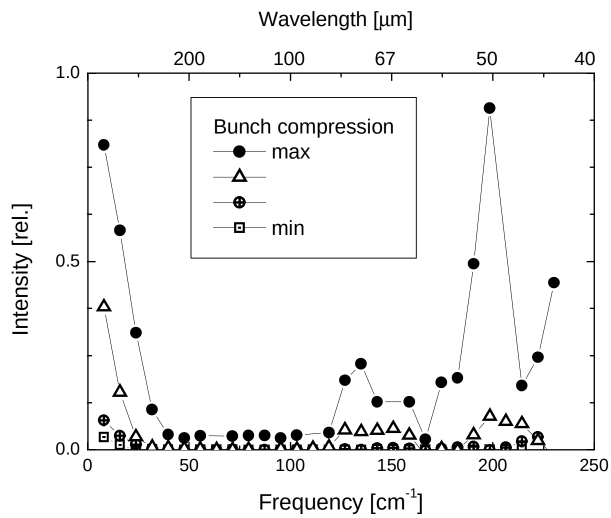

Fig. 5. Coherent spectral intensity for four levels of bunch compression.

4 CONCLUSIONS

We have observed coherent synchrotron radiation emission from two port locations on the SDL linac. The geometry of the edge port prevents us from differentiating edge and dipole radiation, so the particular source mechanism is unclear. The largest amount of radiation occurs where the bunches are shortest, immediately downstream of the linac. That emission is consistent with transition radiation.

We have also measured the coherent spectral content and found reasonable agreement with longitudinal density profiles as determined using a beam profile monitor.

5 REFERENCES

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