ELECTRON BEAM INSTRUMENTATION TECHNIQUES USING COHERENT RADIATION

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Abstract

Much progress has been made on coherent radiation research since coherent synchrotron radiation was first observed in 1989. The use of coherent radiation as a bunch length diagnostic tool has been studied by several groups. In this paper, brief introductions to coherent radiation and far-infrared measurement are given, the progress and status of their beam diagnostic application are reviewed, different techniques are described, and their advantages and limitations are discussed.

1 INTRODUCTION

In recent years, there has been increasing interest in short electron bunches for different applications such as short wavelength FELs, linear colliders, advanced accelerators, e.g. laser or plasma wakefield accelerators, and Compton backscattering X-ray sources [1-3]. Meanwhile, much progress has been made on photoinjectors and different magnetic and RF bunching schemes to produce very short bunches [4-7]. Measuring short bunches becomes essential for developing, characterizing, and operating such machines.

Conventionally, the longitudinal distribution and bunch duration of short electron bunches can be measured by streak cameras or transverse RF deflecting cavities [6, 8]. However, with such devices it becomes very challenging to measure bunch lengths down to a few hundred femtoseconds. Another technique is the RF zero-phasing method with the use of RF cavities and a spectrometer [9-12]. Using such a technique, bunch lengths as short as 84 fs (rms) have been measured and the longitudinal distribution function has been retrieved. However, the measurement is destructive. Recently, frequency domain techniques have been developed, based on a relation between the bunch profile and the coherent radiation spectrum. This paper will focus on the progress and status of such frequency domain measurements.

2 COHERENT RADIATION

Coherent synchrotron radiation was theoretically studied by Nodvick and Saxon in 1954 and later by Michel in 1982 [13-14]. It was first observed by Nakazato and his colleagues at Tohoku University in 1989 [15]. Since then, extensive experimental studies have been carried out by several groups to characterize the coherent radiation of various radiation mechanisms and to explore their applications [16-19]. If a single electron radiates under certain conditions, the total radiated electromagnetic field from an electron bunch is the superposition of that of each individual electron with phase factors. Therefore, the radiation power at a measurement point can expressed as [20]

$$P_{\text{total}}(\lambda) = P_{\text{ind}}(\lambda)\left|\sum_{i=1}^{N} e^{j2\pi z\cos\theta/\lambda}\right|^2$$
$$= P_{\text{ind}}(\lambda)[N + N(N-1)F(\lambda)] \qquad (1)$$

where $P_{\text{ind}}(\lambda)$ and $P_{\text{total}}(\lambda)$ are the radiation power of individual electron and all electrons in the bunch, respectively, N is the number of electrons in the bunch, λ is the radiation wavelength, z is the longitudinal position of electrons, θ is the angle between the longitudinal direction and the observation direction, and $F(\lambda)$ is the so-called form factor given by

$$F(\lambda) = \left|\int_{-\infty}^{+\infty} dz S(z) e^{j2\pi z\cos\theta/\lambda}\right|^2 \qquad (2)$$

where $S(z)$ is the normalized longitudinal distribution function. The first term on the right side of Eq. (1) is the incoherent part proportional to N. The second term is the coherent part proportional to the square of N. $P_{\text{ind}}(\lambda)$ is usually well characterized and N can be known from current measurement. The form factor is of real interest from the beam diagnostic point of view. When the radiation wavelength is much shorter than the bunch size, electrons radiate out of phase, the form factor becomes zero, and the coherent effect diminishes. When the wavelength is much longer than the bunch length, the electrons radiate in phase, the form factor approaches one, and the radiation power is enhanced coherently by a factor of N, which is typically in the range of 10^6 to 10^{10} for most accelerators. In between, there is a transition regime where the wavelength is comparable to the bunch size. The shape of the form factor and the location of the transition region are completely determined by the distribution function, i.e. both the bunch shape and size. A plot of the numerical calculation of Eq. (1) is shown in Fig. 1, where the solid curves are the coherent synchrotron radiation power versus wavelength for different bunch lengths of Gaussian profile bunches, while the dashed curve is the incoherent part.

It is very important to bear in mind that the form factor is derived from the power spectrum, i.e. it is a real and positive quantity. All the phase information of the Fourier transformation of the distribution function is lost, as shown in Eq. (2). It is unfortunate that in general, the distribution function can not be uniquely determined by the measured form factor.

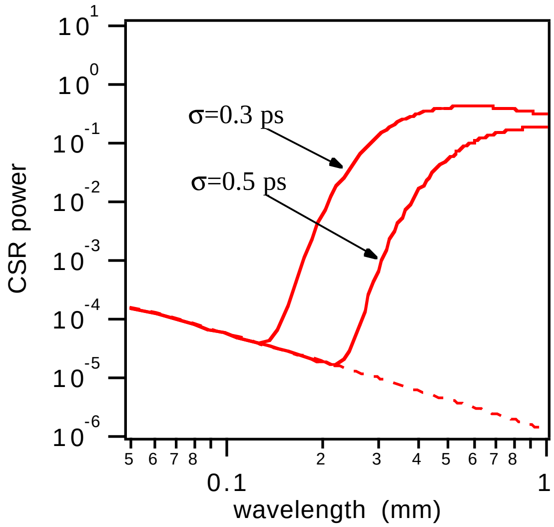

Fig. 1 Calculated CSR power spectrum with 20% flat bandwidth for Gaussian beams with different bunch length.

The above equations are derived for the one dimensional case, i.e. all the phase differences between electrons are due to their longitudinal position differences. In practice, when bunches are short, their application to certain experimental conditions needs to be evaluated. They may become inaccurate if the phase differences due to the transverse beam size or the finite acceptance angle are not negligibly small, compared to the phase differences due to the longitudinal position. It is also assumed that the longitudinal distribution function remains unchanged during radiation formation. This may not be a good approximation for synchrotron radiation if the path length difference introduced by the bending magnetic field is significant compared to the bunch length, particularly for very short bunches.

Since coherent radiation is a result of the superposition of electromagnetic waves, coherent enhancement exists for all electromagnetic radiation mechanisms such as synchrotron radiation, transition radiation, diffraction radiation, Cherenkov radiation, Smith-Purcell radiation, and even wakefield effects. However, the radiation at long wavelengths may be suppressed by boundary conditions, noting the equations are valid only for free space. Coherent synchrotron radiation has been widely used for beam diagnostic purposes due to its noninvasive nature, while transition radiation has been favored for the flatness of its emission spectrum. Recent studies on diffraction radiation make it another potential noninvasive alternative, especially for high energy beams [18].

3 FAR-INFRARED RADIATION MEASUREMENT

Most broadband spectrum measurements are performed with thermal detectors because of their flat frequency response [21]. The radiation is absorbed by the bulk of the material, which changes its physical properties due to the temperature change. Helium-cooled bolometers are the most sensitive thermal detectors. Their superb performance comes at the expense of higher cost and complicated operations. The Golay cell is one of the most widely used room temperature far-infrared detectors. It has flat frequency response well into the millimeter region. Even though its detectivity is much less than that of helium-cooled bolometers, it is adequate for most high charge, short bunch applications. Unfortunately, reliable vendors are becoming difficult to find. Another room temperature detector is the pyroelectric detector. Its responsitivity can be comparable to the Golay cell and its time response is faster than other thermal detectors. It is commercially available and relatively inexpensive. However, its frequency response, especially at long wavelengths, is not readily available from the vendor.

Another type of far-infrared bandpass detector is the Schottky whisker diode, which has been used in bandpass measurement of coherent synchrotron radiation [22-25]. It has adequate sensitivity for most short bunch applications and is also relatively inexpensive. Although it is quite fragile to electrical and mechanical shocks, it has been used in a typical accelerator environment.

To obtain spectral information, either a grating monochromator or an interferometer is needed [21]. The typical example of the former is the conventional echelette grating type. The radiation power at a specific wavelength is enhanced by the diffraction effect and collected at a corresponding angle of the grating plane. The radiation power spectrum is measured by scanning the angle. To avoid higher diffraction orders, prefiltering of the radiation is required. An interferometer uses the interference between two beams split from the incident radiation beam. The radiation power is measured versus the path differences, yielding a so-called interferogram. The radiation spectrum can be computed from the Fourier transform of the interferogram. Another wavelength selecting device is the bandpass mesh filter with a typical bandwidth of 20%. Such a filter combined with a broadband thermal detector is also suitable for the bandpass measurement [26].

Mirrors, focusing parabolic reflectors, and cone shaped light pipes are the most widely used optical components. One of the difficulties for the spectral measurement is that the absorption and refractive indexes of many non-metal materials are strongly frequency dependent. The frequency properties of the vacuum windows, beam splitter, and the effect of water absorption need to be evaluated at the design stage for the wavelength region of interest.

4 COHERENT RADIATION SPECTRAL MEASUREMENT

It is clear that in order to obtain the longitudinal distribution, namely the bunch shape and length, the spectrum of the coherent radiation needs to be measured over the wavelength span of the transition region. Many spectrum measurements of coherent radiation have been successfully performed. Only a few representative examples are discussed here to illustrate the principles.

In 1991, Ishi and his colleagues at Tohoku University reported their spectral measurement results of coherent synchrotron radiation in the far-infrared region [27]. The spectrum was measured by a far-infrared spectrometer consisting of a Helium-cooled bolometer, five echelette gratings, and long-wavelength-pass and short-wavelength-pass filters. All optical components were enclosed in vacuum to eliminate water absorption. Radiation intensity was monitored by another detector during the grating rotation scan to correct beam induced fluctuations. The system was calibrated with a blackbody radiator to within a factor of 1.5. The coherent enhancement was comparable with the number of electrons in the bunch, 3.6×10^6. A spectrum from wavelengths of 0.16 to 3.5 mm was obtained with a resolution of 0.1 cm^{-1} at wavelength of 1 mm, and the bunch form factor was derived accordingly.

A cosine transformation of the square root of the form factor was applied to estimate the distribution function. Though such an approximation ensured the resulting distribution function to be real and positive, it also artificially forced the resulting distribution function to be symmetric and peaked at the center. The result shows a Gaussian like shape with a full width at half maximum of 0.25 mm, which is much shorter than the 2 mm length estimated. One of the simulated results indicated that the bunch shape is about 1.3 mm with three spikes of about 0.1 mm in width at the ends. It was then believed that these spikes might contribute to the measured fall-off at short wavelength, resulting in the computed narrow bunch length.

In 1991, using a polarizing interferometer with a resolution of 0.09 cm^{-1}, Shibata and the Tohoku group observed a bunch-to-bunch interference pattern, i.e. RF sidebands on the coherent synchrotron radiation spectrum derived from a measured interferogram [28]. In 1994, the first cross-comparison was made by the same group between a streak camera measurement of the bunch shape and a spectrum measurement of the coherent transition radiation [29]. Instead of using a cosine transformation, a triangular distribution function with a width of 8.5 mm was found. The measured form factor matched the envelope of its calculated oscillatory closely. A streak camera measurement revealed that the bunch shape could be fitted very well by a Gaussian function with a width of 7.2 mm. Though these two distributions are rather close in the time domain, but clearly distinguishable, the corresponding form factors differed significantly in the frequency domain.

In 1994, another interferogram measurement of the coherent transition radiation was reported by Kung of Stanford University, and later the refined results were given by Lihn [5, 31]. Such a measurement was proposed by Barry of CEBAF in 1991 [32]. A pyroelectric detector and a Michelson interferometer with a resolution of 0.5 cm^{-1} were used to obtain the interferogram. The spectrum computed from the interferogram was contaminated by water vapor absorption and the interference pattern of the beam-splitter. Based on the assumption of uniform charge distribution, the bunch length was estimated to be 50 fs (rms) using a thin mylar beam-splitter of 12.7 μm. This value was later revised to 142 fs (rms) still based on the uniform distribution assumption, after a careful analysis of the effect of the thickness of the beam-splitter on the width of the measured interferogram. The difficulties of obtaining the distribution function were discussed. Similar measurements were also performed by other group [33]. No longitudinal distribution function was reconstructed due to the bandwidth limitation of the measurement.

Using the Kramers-Kronig relation was first proposed by Lai of Cornell University in 1994, to compute phase information from the measured spectrum under a minimal phase condition [34]. The method is able to generate asymmetric distribution functions from an inverse Fourier transform. The technique was applied to spectral measurement results of both coherent synchrotron and transition radiation [35]. Artificial asymptotic attachment to both ends of the measured spectrum was discussed, given that the bandwidth of the measurement is limited in practice. Unfortunately, due to practical limitations, the results were not verified by an independent bunch distribution measurement. Numerical studies with distributions which are a superposition of three Gaussian components revealed that the sequential order of the Gaussian peaks could not be uniquely determined [36]. In some cases, the calculated minimal phase significantly differed from the actual phase. Therefore, the minimal phase assumption is not always valid. In practice, the minimal phase assumption is difficult to validate because the bunch distribution is generally unknown.

5 COHERENT RADIATION BANDPASS MEASUREMENT

Despite the difficulties of reconstructing the distribution function, the strong dependence of radiation power on bunch distribution and bunch length were observed in experiments. As can be seen in Fig. 1, the radiation power within a certain bandwidth in the transition region changes rapidly as bunch length varies. Therefore, an appropriate bandpass detector can be employed as a bunch length monitor to detect relative bunch length and shape changes.

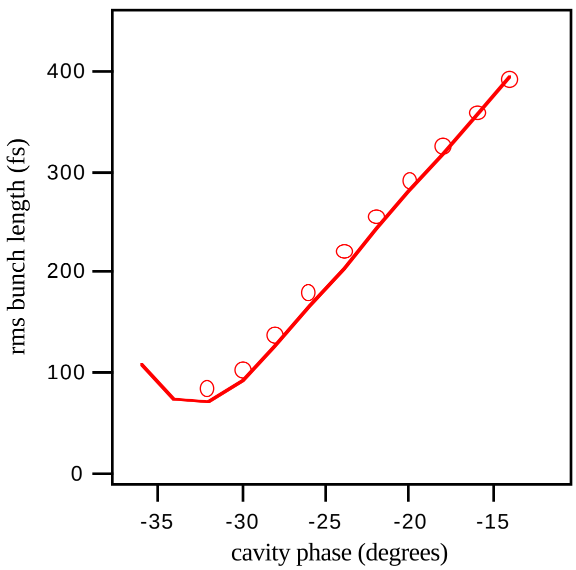

Fig. 2 Bunch lengths versus phase change of the bunching cavity, where the circles are from measurement while the solid curve is from simulation.

A very stringent demand on final energy spread, with a design goal of 2.5×10^{-5} (rms), requires short bunches at the Continuous Electron Beam Accelerator Facility (CEBAF) of Jefferson Lab. CEBAF is routinely operated within its bunch length specification of 0.5 ps (rms). A different approach was taken. Instead of trying to obtain absolute longitudinal distributions by measuring the spectrum of the coherent radiation, relative distribution changes were measured by detecting integrated coherent radiation power within the transition region. Such a noninvasive coherent synchrotron radiation bunch length monitor has been developed at Jefferson Lab to detect bunch length changes resulting from RF phase drifts in the bunch forming region during CW beam delivery [25]. Schottky whisker diodes were used as far infrared detectors. The bunching process, and bunch shape and length were systematically studied by measurement using an RF zero-phasing technique and by numerical simulation [37, 12]. Bunch lengths were varied as the RF phase of a bunching cavity was changed. The measurements are in excellent agreement with simulation, as shown in Fig. 2 where the circles are from measurement while the solid curve is from simulation. The monitor was calibrated by an RF zero-phasing measurement. The results are shown in Fig. 3. The minimum bunch length of 84 fs (rms) was actually found by maximizing the output signal from the diode, which is proportional to the detected radiation power, as shown in Fig. 4. The monitor was able to detect a few femtosecond bunch length change for a 0.5 ps (rms) Gaussian bunch containing 3×10^{5} electrons, and still better for shorter bunches. An optical chopper was installed to enable the monitor to operate for both pulsed and CW beam delivery. It is worth mentioning that since the bandpass measurement is a relative measurement of only the changes, it is much less sensitive to errors introduced by finite transverse beam size, radiation acceptance angle of the detector, and path difference due to dispersion. The monitor signal changes result from not only the bunch length changes but also the bunch shape in general.

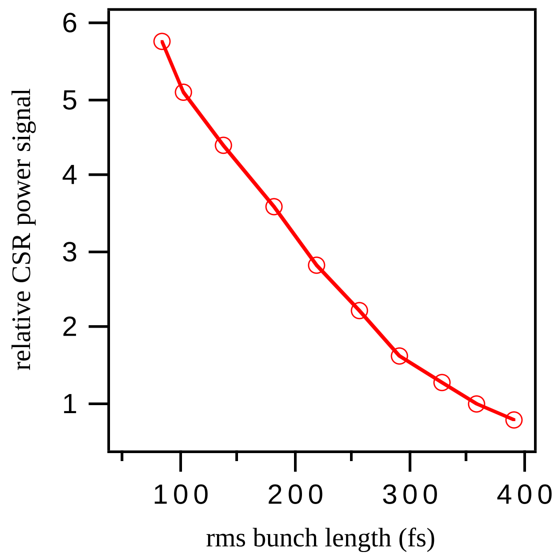

Fig. 3 Experiment result of CSR power versus rms bunch length where CSR power was measured by the Schottky diode and bunch lengths were measured by the zero-phasing technique.

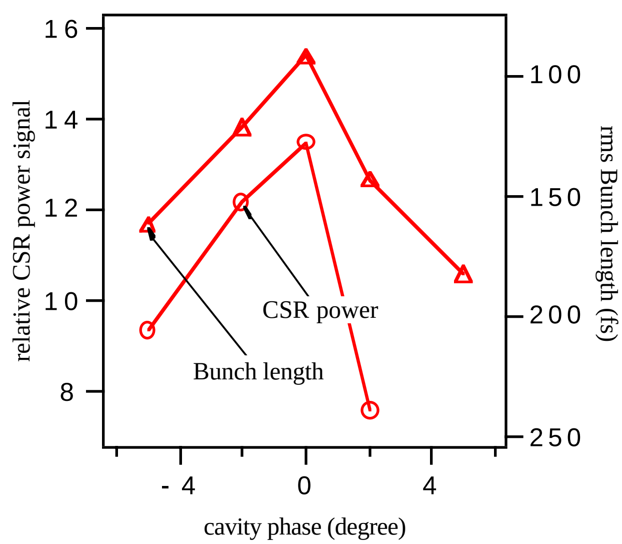

Fig. 4 Measurement results of CSR power and bunch lengths versus relative SRF phase changes. The maximum CSR power signal yields the shortest bunch length

The strategy for bunch length control at Jefferson Lab is: (1) use zero-phasing measurements as the primary standard to characterize the longitudinal beam dynamics and to calibrate the coherent synchrotron radiation monitor, assisted by PARMELA simulations as cross-checks; (2) use noninvasive monitoring to detect bunch length change during beam delivery, and when the monitor signal varies outside of acceptable bounds indicating the bunch length has changed; (3) use a phase transfer function measurement to correct the RF phase drifts that have occurred [38].

From a single monitor signal, it is difficult to determine which RF phase has drifted among multiple RF bunching phases. However, a multi-frequency monitor, such as the one developed at Tohoku University, may be able to provide patterns or signatures to identify certain phase drifts [39]. One can also use either a multiple bandpass detector or a broadband detector plus rotation filters or gratings.

5 SUMMARY

Extensive work has been done to use coherent radiation as a tool to diagnose bunch shape and length. Many spectrum measurements have been carried out by various groups. Different techniques have been employed to derive the bunch distribution function from the measured spectrum, such as using cosine transformations, envelope matching, and the Kramers-Kronig relation. Due to the lack of phase information, a general procedure has not yet been established to obtain the actual bunch distribution and length. In order to advance the technique and to verify measurement results, it is essential and invaluable to employ an independent method, such as RF zero-phasing or a streak camera, just like every development of a new diagnostic technique. A well-tested particle simulation code can also provide very helpful insights on the bunching process and parameter dependence.

Despite difficulties in obtaining bunch shapes and lengths, bunch length monitors have been developed. They can be built with either bandpass detectors or broadband detectors plus frequency selection devices such as bandpass filters or gratings. These monitors are very sensitive to bunch length and longitudinal distribution variations. They are primarily used as diagnostic tools during beam delivery, rather than for beam characterization. To be useful, they need to be calibrated.

In short, the coherent radiation technique has not yet reached a stage at which it can be employed as the sole means of characterizing longitudinal distributions of short electron bunches. Therefore, it is essential to use an accurate longitudinal distribution measurement with the verification of simulations for characterizing bunching processes. Then, both bandpass and spectral measurements can be highly valuable in routine optimization of machine performance, in a noninvasive fashion if desired.

6 ACKNOWLEDGMENT

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REFERENCES

[1] H. Winick, et al., NIM, A**347** (1994), 199.
[2] R. H. Siemann, Proc. of 1993 PAC Conf., 532.
[3] W. B. Mori, et at., AIP Conf. Proc. **335**, 112 (1994).
[4] T. Raubenheimer, et al., Proc. of 1993 PAC Conf., 635.
[5] P. Kung, et al., Phys. Rev. Lett. **73**, 967 (1994).
[6] B. Carlsten, AIP Conf. Proc. **367**, 21 (1995).
[7] G. A. Krafft, AIP Conf. Proc. **367**, 46 (1995).
[8] A. H. Lumpkin, AIP Conf. **367**, 327 (1995).
[9] L. Rivkin et al., Proc. of 1st EPAC (1988), 634.
[10] J. Seeman et al., Proc. of 1988 LINAC Conf., 441.
[11] K. Bane et al., Proc. of 2nd EPAC (1990), 1762.
[12] D. X. Wang, et al. "Measuring Longitudinal Distribution and Bunch Length of Femtosecond Bunches with RF Zero-phasing Method", these proceedings.
[13] J. S. Nodvick, et al., Phys. Rev. **96**, 180 (1954).
[14] F. C. Michel, Phys. Rev. Lett. **48**, 580 (1982).
[15] T. Nakazato, et al.., Phys. Rev. Lett. **63**, 1245 (1989).
[16] U. Happek, et al., Phys. Rev. Lett., **67**, 2962 (1991).
[17] Y. Shibata, et al., Phys. Rev. **A44**, R3449 (1991).
[18] Y. Shibata, et al., Phys. Rev. E52, 6787 (1995).
[19] Y. Shibata, et al., AIP Conf. **367**, 473 (1995).
[20] C. J. Hirschmugl, et al., Phys. Rev. **A 44**, 1316 (1991).
[21] M. F. Kimmitt, Far-Infrared Techniques, (Pion Limited, London, 1970).
[22] T. W. Crowe, et al., Proc. IEEE, **80**, 11 (1992).
[23] W. Peatman, et al., Int. J. of Infrared and Millimeter Waves, **11** (3), 355 (1990).
[24] P. Wood, PhD Thesis, University of Virginia (1994).
[25] D. X. Wang, et al., Appl. Phys. Lett. **70** (4), 529 (1997).
[26] D. Porterfield, et al., Appl. Optics, **33** (25), 6046 (1994).
[27] K. Ishi, et al., Phys. Rev. A**43**, 5597 (1991).
[28] Y. Shibata, et al., Phys. Rev. **A44**, R3445 (1991).
[29] Y. Shibata, et al., Phys. Rev. **A44**, R3445 (1991).
[30] Y. Shibata, et al., Phys. Rev. **E50**, 1479 (1994).
[31] H. C. Lihn, et al., Phys. Rev. **E53**, 6413 (1996).
[32] W. Barry, et al., Proc. of Workshop on Advanced Beam Instrumentation, KEK, Tsukuba, Japan (1991).
[33] V. Schlott, et al., Particle Accelerators, **52**, 45 (1996).
[34] R. Lai, et al., Phys. Rev. E **50**, 3342 (1994).
[35] R. Lai, et al., Phys. Rev. E **50**, 4294 (1994).
[36] R. Lai, et al., Phys. Rev. E **52**, 6787 (1995).
[37] D. X. Wang, Proc. of 1996 LINAC Conf., 303.
[38] G. A. Krafft, et al., Proc. of 1995 PAC Conf., 2601.
[39] T. Nakazato, et al., Proc. of 1994 LINAC Conf., 890.