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A noninvasive bunch length monitor for femtosecond electron bunches

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A bunch length monitor for ultrashort (90 fs to 1 ps) electron bunches using a coherent synchrotron radiation detection techniques has been developed in a collaboration between the Thomas Jefferson National accelerator Facility (Jefferson Lab) and the University of Virginia. The noninvasive, high-resolution, high-sensitivity, low-noise monitor employs a state-of-the-art "bandpass" GaAs Schottky whisker diode operated at room temperature. This letter presents the monitor's performance. © *1997 American Institute of Physics.* [S0003-6951(97)00604-9]

With the advance of accelerator technologies, many accelerators are being designed and operated with very short bunch lengths, typically in the few-picosecond to subpicosecond range. Future linear colliders and short-wavelength (FEL)s are examples. Consequently, there has been an increasing interest in producing very short electron bunches and studying interactions between electromagnetic radiation and short bunches.[1] Jefferson Lab's continuous electron beam accelerator (CEBA)[2] routinely operates with an rms bunch length of 0.5 ps to meet a stringent requirement for final momentum spread. An operationally reliable, inexpensive bunch length monitor that is noninvasive of beam is highly desirable for commissioning and operating such a short-bunch machine.

An electron radiates with a wide spectrum when it is bent through a dipole, the so-called synchrotron radiation (SR). When the bunch length of the radiating electron beam is short compared to the SR wavelength, the individual electrons radiate in phase and the SR power becomes proportional to the square of the number of electrons per bunch (typically 10^6 to 10^{10}), the so-called coherent synchrotron radiation (CSR). The CSR power also depends on longitudinal distribution of charge. The sensitive dependence of the CSR power on the bunch length can serve as the basis for a bunch length monitor that is both useful and desirable for the subpicosecond regime, where very few alternative techniques are available.

The CSR power can be expressed as[3-5]

$$P_{csr}(\lambda)=P_{inc}(\lambda)[1+(N-1)F(\lambda)], \quad (1)$$

where P_{csr} and P_{inc} are the coherent and the incoherent synchrotron radiation power, respectively; N is the number electrons per bunch; and F is a bunch form factor given by

$$F(\lambda)=\left|\int S(z)e^{-\frac{2\pi i z}{\lambda}}dz\right|^2, \quad (2)$$

where $S(z)$ is the normalized longitudinal density distribution, and the integral is over a single bunch. Here the bunch length is defined as the rms value. Equation (1) is plotted for a Gaussian distribution in Fig. 1. Comparison of two CSR power spectrum curves in Fig. 1—say $\sigma=0.3$ and 0.5 ps—shows that the spectrum for the shorter bunch length covers the spectrum for the longer bunch length at long wavelengths but has extra power at short wavelengths. Therefore, the output signal from a CSR power detector with an arbitrary "bandpass" characteristic will always increase as the bunch length becomes shorter, until such power changes take place at wavelengths outside the range of the detector.

The critical component of this CSR detector is a state-of-the-art whisker-contacted GaAs Schottky diode developed and fabricated at the Semiconductor Device Laboratory of the University of Virginia (UVA). Its design and fabrication are described in the literature.[6-8] Figure 2 is a photograph of the quite compact diode assembly. The diode is connected to a dc current supply. Due to its nonlinear properties, the diode

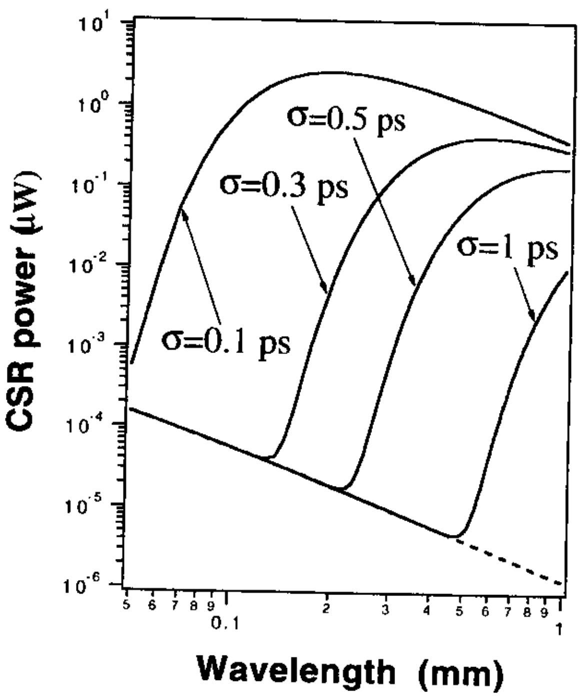

FIG. 1. Each curve shows the CSR power as a function of wavelength for a different bunch length, as measured by a detector with a flat 20% bandwidth.

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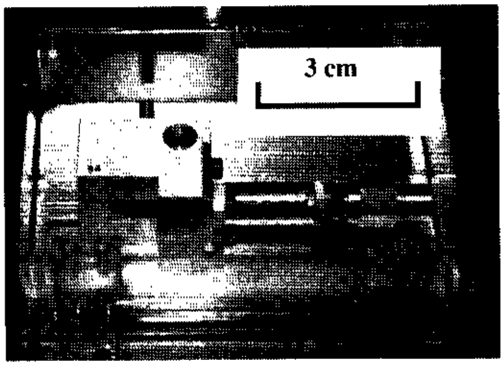

FIG. 2. A GaAs Schottky whisker diode assembly.

generates a voltage change that is proportional to the radiation power incident on it. Such a detector was installed directly after a dipole at the end of the CEBA injector. The CSR propagates through a vacuum window and is focused on the diode by a parabolic reflector. Tests were conducted with a 45 MeV bunch train of 100 μs duration where individual bunches were separated by 2 ns. The beam pulse repeated at 60 Hz.

One of the important characteristics of CSR power is its quadratic dependence on beam current. In the experiment, the beam current was carefully varied without changing the bunch length. The measurement results showed the quadratic dependence expected from the coherent nature of the detected radiation.[9] The bending magnet was turned off to verify that the detected radiation is directly related to the magnetic field. The beam-related signal was a factor of 24 down.

The bunch length was independently measured by a zero-phasing technique. A time-correlated momentum spread is introduced to the bunch by adjusting the last eight accelerating cavities in the injector to the zero-crossing rf phase. A dipole spectrometer magnet translates this longitudinal momentum spread into a position spread. Therefore, the bunch length can be simply determined by

$$\sigma = 1.86 \frac{180}{\pi} \frac{\sqrt{x_{\rm rms}^2 - x_{0\rm rms}^2}}{D} \frac{E}{\Delta E}, \tag{3}$$

where σ is the rms bunch length in picoseconds, 1.86 is the unit conversion factor between rf degrees and picoseconds, D is the dispersion of the spectrometer, E is the beam energy with the zero-crossing cavities off, ΔE is the energy gain at crest of the zero-crossing cavities, and $x_{\rm rms}$ and $x_{0\rm rms}$ are horizontal rms widths with the zero-crossing cavities on and off, respectively, measured by a wire beam profile scanner following the spectrometer magnet.

To determine the monitor performance and resolution, the bunch length was systematically changed by individually varying the phases of the rf cavities that affect the bunching process. Two typical horizontal profiles from the wire scanner are shown in Fig. 3. The phase of the first superconducting rf (Srf) cavity of the injects is varied to change the bunch length. The horizontal traces can be fit very well to Gaussian curves; the rms bunch length is obtained using Eq. (3). The CSR power increased as the bunch length became shorter, as shown in Fig. 4. With continued shifting of the phase of the

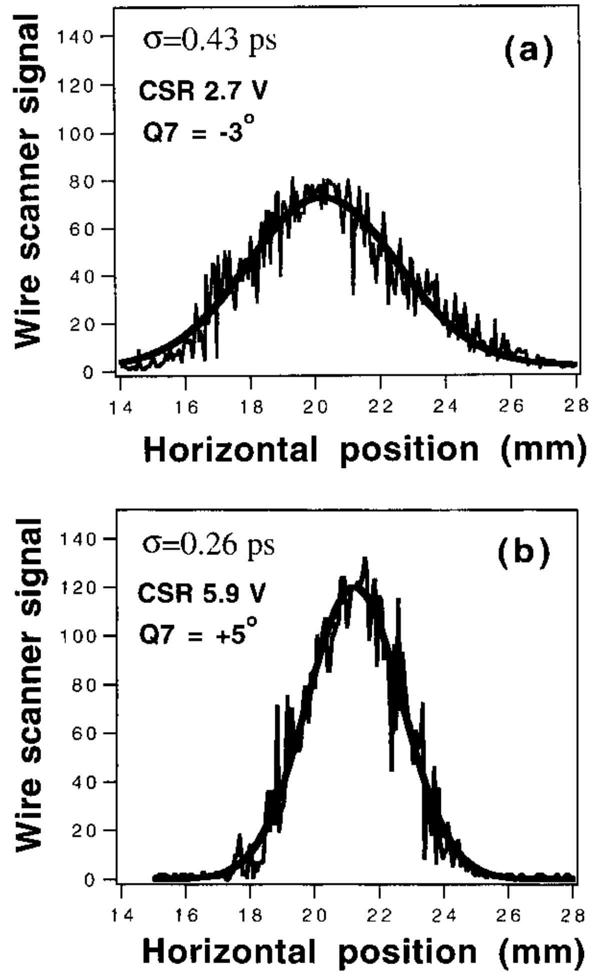

FIG. 3. Horizontal profiles at the 45 MeV spectrometer, where the noisy signals are from the wire scanner, the smooth curves are Gaussian fit, σ represents the rms bunch length, CSR represents CSR power signal, and $Q7$ is the phase change of the first Srf cavity.

cavity, the CSR power signal finally peaked at conditions yielding the shortest bunch length, as demonstrated in Fig. 5, where both the CSR power and bunch length are plotted against the phase changes. The shortest bunch length reached was 91 fs, or 27 μm.

With bunches containing 3×10^5electrons, 200 signal averages gave signal-to-noise ratios of 450 at 91 fs bunch length and 100 at 600 fs for the CSR signal after amplification. The main limitation on the resolution in our experiment is due to a slow signal fluctuation of about 30 mV with a few-minute time scale. At typical operating conditions, the CSR signal changed from 4 to 2 V as the bunch length increased from 0.45 to 0.6 ps, so a bunch length change of a few femtoseconds may be resolved for Gaussian bunches. The CSR signal can be easily seen for a bunch length around 0.5 ps with 6×10^4 electrons per bunch. The power level of the radiation detected was on the order of several nW during the bunch train. The signal level may be improved by opening up the acceptance of the vacuum window, by focusing the CSR spot more tightly at the detector, and possibly by improving the present electronics. The diode assemblies are very compact (about 3 cm in size) and are relatively inexpensive (a few thousand U.S. dollars).

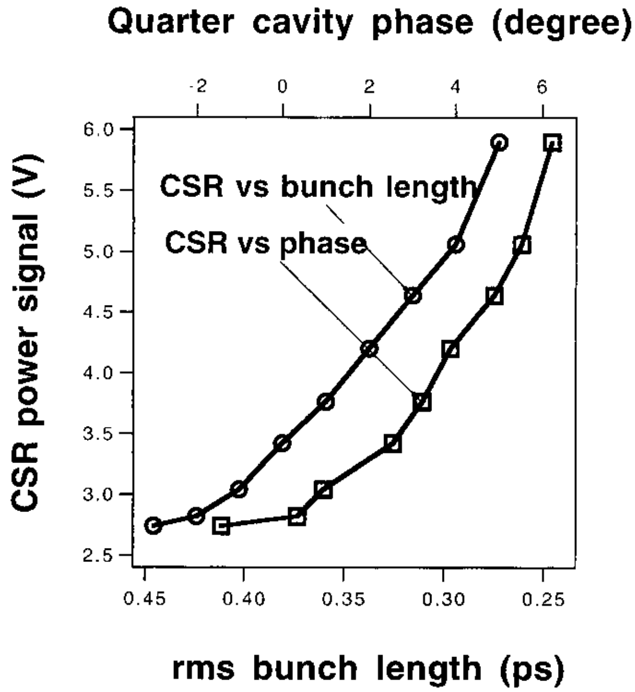

FIG. 4. CSR power signal vs bunch length and phase change of the first Srf cavity, where the circles and the squares are measuremtn data points.

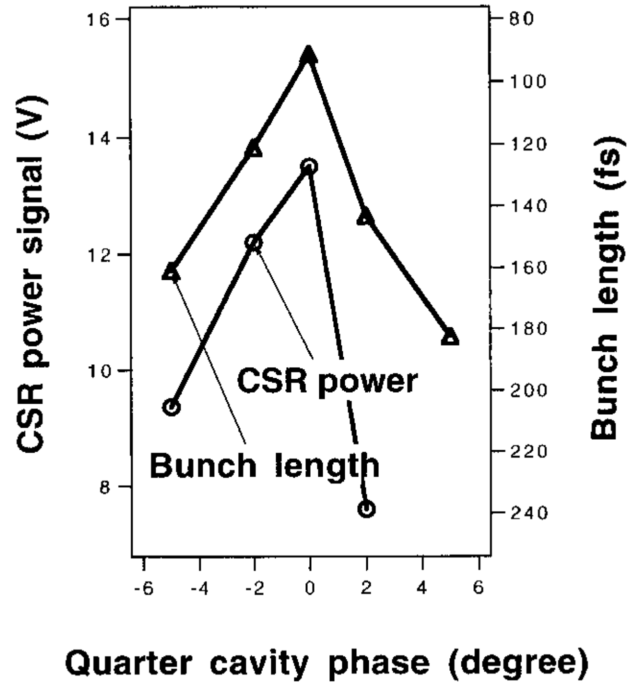

FIG. 5. Both CSR power signal and bunch length vs phase change of first Srf cavity where the circles and the triangles are measuremtn data points.

Potentially such detectors may be integrated into an accelerator control system to lock the operating bunch length. The main shortcoming of such detectors is that they cannot measure the longitudinal profile directly. Therefore, in practice, the monitor needs to be calibrated against a precise measurement, which could be a destructive method such as the zero-phasing method used here.

To summarize, a noninvasive bunch length monitor based on the detection of CSR power has been developed for very short electron bunches. This compact device has fast rise time, low noise, wide dynamic range, and high resolution and sensitivity, and it operates at room temperature. To the best of our knowledge, there is no alternative device to monitor such very short bunches at such low bunch charge.

The 513 μm diode used in these measurements had good response and sensitivity for bunch lengths between 0.1 and 0.5 ps. The resolution of the detector is a few femtoseconds for a half-picosecond Gaussian bunch containing 3×10^5 electrons, and much better for shorter bunches. The diode was able to detect CSR signals for bunch lengths of 0.5 ps containing 6×10^4 electrons per bunch. It was experimentally verified that one can search for the shortest bunch length by maximizing the CSR power signal. The monitor is especially suitable for applications requiring measurement of very short bunch lengths at low charge per bunch.

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