DIAGNOSTICS FOR ULTRASHORT BUNCHES*-

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Abstmct

Recently, producing and maintaining short bunches in accelerators has become a forefront issue. Examples of accelerators that require short bunches are high quality nuclear physics accelerators, free electron laser driver accelerators, next generation linear colliders, and linac-based fourth generation light sources. Large bodies of work have accumulated at various sites on producing, measuring, and maintaining ultrashort bunches. In this paper such work is reviewed, with particular emphasis placed on diagnostic techniques that may be applied in the subpicosecond rms bunch duration domain. Instrumentation based on both time domain and frequency domain methods are discussed: in the frequency domain, coherent radiation detection techniques in the far infrared receive special emphasis. In addition to the usual problem of measuring the bunch longitudinal distribution function, it is also important to have efficient ways to control the bunch length in short bunch machines. Solving this problem involves instruments with somewhat different properties than the standard ones. Consequently, some space is devoted to several devices, both in use and proposed, that are useful in the problem of controlling ultrashort bunches.

1 INTRODUCTION

Interest in short bunches arises from the requirements of high beam quality in potential applications. High quality nuclear physics accelerators, free electron laser drive accelerators, next generation **linear** colliders, and fourth generation light sources all require short time duration beam pulses, with rms durations of order 1 psec or smaller. Many mechanisms have been proposed for achieving short bunches: **RF** and magnetic bunching, short pulse, high phase space density production from laser photocathode sources, and combinations of all three of these methods. In practice, in order to verify the design and optimize the operation of such accelerators, it is necessary to obtain information on the bunch duration at various strategic points along the accelerator beam line. In this review, instruments to obtain pulse duration information will be discussed. In two prior publications, Wang (1, 2] has reviewed many of the prominent features and results in this field up to the time of the 1997 Particle Accelerator Conference. Results reported at that conference and subsequently to that conference will be emphasized here, under the assumption that the reader is familiar with these references. Following W&g, frequency domain methods and time domain methods will be discussed. The need to do cross-comparisons between the various techniques is essential to obtain an accurate understanding of the results of measurements.

In addition to the measurement problem, one would like to have efficient mechanisms to control the bunch distribution. Instruments designed for the control problem can have properties that are somewhat different from those of the measurement problem, allowing data to be acquired and analysed more rapidly than is typical in measurements of the distribution. Thus, devices more specialized to the problem of correcting and optimizing the measured distribution are discussed. In the final part of the paper future directions are explored.

2 FREQUENCY DOMAIN TECHNIQUES

For the most part, frequency domain methods are based on detecting some form of coherent radiation emitted by short bunches. The radiation power is

$$P(\lambda) = P_{inc}(\lambda)[N + N(N-1)f(\lambda)] \qquad (1)$$

where $P_{inc}(\lambda)$ is the incoherent emission spectrum for a single electron, N is the number of electrons in the bunch, and $f(\lambda)$ is a form factor describing the time coherence of the emission. In terms of the normalized longitudinal distribution function S(z),

$$f(\lambda) = |\int_{-\infty}^{\infty} S(z) e^{2\pi i z/\lambda} dz|^2$$

is the square of the Fourier transform of S(z). By measuring the frequency distribution of the power, one obtains information about the longitudinal distribution function.

These techniques may be grouped according to whether a direct spectrum measurement is made or an autocorrelation measurement is done, according to generating radiation type, and according to the type of detector used. In the early measurements, coherent **synchrotron** radiation [3] or coherent transition radiation [4] was detected directly. More recently, the **au**tocorrelation technique suggested in a paper by Barry [5] has become the more prevalent method [6].

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The following types of coherent radiation have been used to obtain information about short bunches: coherent synchrotron radiation (CSR), coherent transition radiation (CTR), and coherent diffraction radiation, which arises when a short beam bunch passes through a foil with a hole through it. In addition, recent proposals involve coherent Smith-Purcell radiation.

The principal advantage of coherent synchrotron radiation is the non-invasive nature of the system. Its disadvantages are its relatively low power level and the fact that the incoherent spectrum changes as a function of wavelength, making the analysis of measurement results somewhat more difficult. Also, as has been clearly recognized only recently, beam dynamic effects can change the bunch duration in such bends, an additional complication.

Transition radiation has the advantages of relatively high power levels and a flat incoherent emission spectrum. However, a pure transition radiation device can be destructive of the beam, and can fail at higher electron beam powers, making it unsuitable as a continuous beam monitor. Because of these two disadvantages, interest has been growing in using foils with holes ≈ 1 cm in diameter as sources of diiaction transition radiation. An experiment has been completed confirming the effect and some of the details of the change of the incoherent emission spectrum at high frequencies [7]. However, it is not clear whether the transition to continuous beam monitoring will be straightforward.

Smith-Purcell radiation is proposed at UCLA [8] and at Los Alamos [9]. The main advantage compared to CSR is relatively higher power; the main advantage over CTR is the noninvasive character of the monitor. The disadvantages are high wavelength dependence of the incoherent emission, and the relatively high sensitivity of the emission characteristics to the *transverse* position of the electron beam. Both of these problems can perhaps be solved given time.

In such measurements a wide variety of detectors is used: Golay cells [4], pyroelectric detectors [10], Shottky diodes [11], cooled bolometers (3, 12], photoacoustic detectors [13], and quite recently even high temperature superconductors [14]. Cooled bolometers, Golay cells, and the photo-acoustic detectors have flat frequency response in the wavelength scales of interest. Pyroelectric detectors nominally have this property; interference effects in some commercial detectors have led to problems in some measurements. In addition, the bolometers have relatively high sensitivity at the cost of liquid helium cooling. Schottky diodes also achieve high sensitivity, at the cost of limited detector bandwidth and directional response in the device. Their main advantages are high speed, 1 MHz response times are demonstrated [11], and simplicity.

Two somewhat different techniques, interesting because they are both noninvasive, have been proposed at Berkeley [15] and SLAC [16]. They are classified as frequency domain techniques because an autocorrelation or a spectrum of the bunch distribution are obtained, respectively. The Berkeley method involves examining fluctuation spectra in the incoherent emission from different bunches, and using statistical means to extract the autocorrelation of the bunch distribution. The calculations reported involve gaussian bunches and show that the rms length calculated from the method using test data reproduce that of the assumed distribution to within several percent in the case that they reported. Presently, it is not clear whether the results to be obtained from this method are substantially better than a standard autocorrelation measurement, to balance the increased complexity in the data aquisition and analysis inherent in this method. In the SLAC method, a laser beat wave is produced with the beat frequency of order the bunch length to be measured. The beat wave interacts with the high energy bunches through Compton effect; a modulation depth, which is proportional to the amplitude of the Fourier transform of the distribution at the beat frequency, is measured. As the beat frequency is varied, different wavelengths in the bunch distribution are probed, allowing one to determine the amplitude of its Fourier transform. At present, given the large expense needed to put such a system together, it remains to be seen whether this method is to be preferred for shorter bunches.

All of the frequency domain methods suffer from a fundamental limitation. Neither an autocorrelation measurement nor a spectrum measurement can unambiguously determine the bunch distribution, because the phase information necessary to obtain the Fourier transform of the bunch distribution is lost in the measurement. Usually, the experimenter is reduced to assuming a particular bunch distribution shape, and doing parameter fits of measured data to try to obtain derived values of the distribution parameters. For example, the rms bunch length usually reported is found by assuming guassian bunches and doing a data fit. While such an analysis is intellectually satisfying if one has some reason to believe that the distribution is in fact gaussian, such approximations are very questionable when dealing with beams from linacs [17]. Methods of phase retrieval under minimal phase assumptions [18], while perhaps yielding better results than data fitting, are still somewhat ambiguous without real information about the distribution dependence [19]. Getting good phase information is a main open question in the frequency domain techniques.

3 TIME DOMAIN TECHNIQUES

With time domain techniques, one tries to measure directly a quantity proportional to the bunch micro-current as a function of time. The quintessential measurement device is the streak camera, which detects synchrotron radiation emitted by the bunch electrons. Unfortunately, for the short time scales of interest in this review, few commercial devices exist. One anticipates that progress in faster and faster streak cameras will continue to occur [20], and hopes that costs will drop and operational complexity will be reduced with time. A resolution of 4 psec FWHM is quoted for high-charge bunch measurements at CERN [21].

The other widely used time domain measurements are the zero-phasing measurement and the deflecting cavity technique [22]. Both rely on changing relative phases of RF fields, in longitudinal and transverse cavities, respectively. Such phases are easily measured to of order the phase equivalent of 100 fsec. Unfortunately, these techniques are highly destructive of the beam, and are usually somewhat involved as to data aquisition and analysis.

In the zero-phasing measurement, a longitudinal (accelerating) mode is phased to the zero-crossing of the accelerating wave. A linear energy ramp is induced front-to-back in the bunch. A distribution function is obtained by transversely diagnosing the beam at a dispersed location. In a more involved variant of this idea, the phase of the accelerating wave is varied, allowing tomographic reconstruction of the complete beam longitudinal phase space [23]. Recently, progress has been made on the problem of subtracting out effects of the initial transverse distribution of the electrons on such measurement results, and on using three-phase measurements to obtain the slope (i.e. σ_{56}) of the measured distribution [24]. Usually, the final accelerating cavit(y/ies) of the injection beam line is/are used for the measurement, and the beam should be relativistic.

In a deflecting cavity measurement, a transverse (deflecting) mode is phased to zero-crossing. The deflection direction is chosen to be perpendicular to the dispersed direction, allowing a real-time monitor of the longitudinal phase space to be developed. Compared to the zero-phasing method, an additional RF cavity is needed, and the same transverse subtraction must be done in order to obtain the longitudinal distribution. If these measurements are done at low energy, or high charge-per-bunch, space charge effects can significantly affect the beam; addiig to the uncertainty in the final results.

Another time domain method is due to ‘Iron [25]. The device is based on detecting secondary electrons from a wire that intercepts the beam. A fraction of the secondaries is collected and passes through a toroidal resonator. As in the zero-phasing technique above, a time-dependent energy increase is given to the secondaries, which are energy analysed in a magnetic spectrometer. The main limitation on resolution is the phase spread generated in propagating the secondaries from the emission wire to the resonator. This spread is reduced by negatively biasing the wire. Resolutions of 50-100 fsec, competitive with the best zero-phasing results, are claimed with a reasonably modest device.

4 BUNCH LENGTH CONTROL

The bunch length control problem is really somewhat different than the bunch length measurement problem, although solving the latter problem does provide a solution to the former problem. One might expect an ideal monitor system to have the following properties:

- The monitor is continuous.
- The monitor should run in the “background”.
- It has high sensitivity to changes that might occur
- And the ability to distinguish all possible sources of change.
- Its response times is of order 1 sec or less.

Continuous monitoring is important in an operational setting for two reasons. First, if a continuous signal is available to a computer, possibilities exist for automatic control of the bunch length. Second, the signal may be logged and archived, allowing one to perform long-term correlation studies between the bunch length and specific aspects of machine performance. It is preferable that the monitor be non-invasive in order that the monitor process run in the background. High sensitivity allows one to make corrections more rapidly and with greater certainty. In an automatic control environment, it is better to have more measurement data than control variables, so that one is able to unambiguously compute updates. The final item is somewhat disputable, depending on how invasive the monitor really is. If the monitor is truly (i. e., to the facility users) non-invasive and can run in the background, having slow updates is reasonable. On the other hand, if the monitor ‘is disruptive and takes a long time to complete the measurement process, the monitor is likely to be used sparingly in actual operations. Operating at a rate faster than a second, beyond typical human/control system response times, is usually not necessary.

None of the options discussed so far satisfies ail of the ideal properties; up to the present effort has concentrated on the more academic problem of measuring the bunch distribution function. Two devices which illustrate the problem and possible future directions are the phase transfer device at Jefferson Lab [26], and multifrequency coherent synchrotron radiation devices [12].

The phase transfer device at Jefferson Lab is particularly strong regarding items three and four above [27], but it is invasive and measurements are completed at a 0.05 Hz rate. Data is displayed in a way that allows easy optimization of the bunch length. Recently, it has been found that Tschebyshev polynomials provide a convenient expansion basis for nonlinear trans-

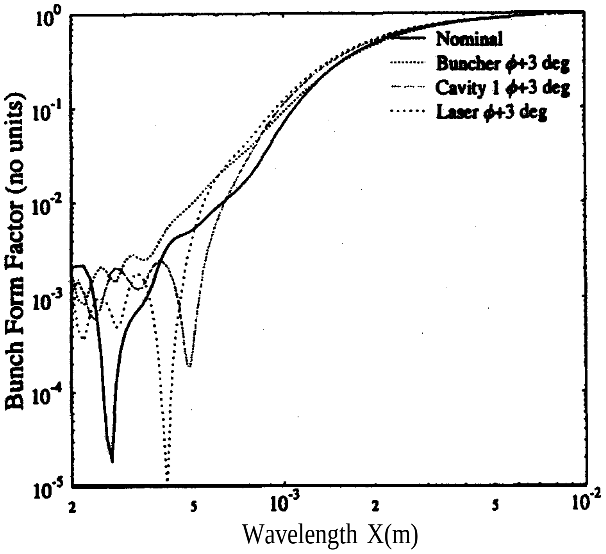

Figure 1: Form factor from simulated distribution of Jefferson Lab's Infrared Free Electron Laser

fer functions [28]. The expansion coefficients are easily computed by computer and are directly related to particular phase errors in the RF cavities in the CEBAF injector; automatic control of the bunch distribution is possible.

Another device that provides information on the bunch shape is the multifrequency coherent synchrotron radiation monitor. In this device, parallel channels detect coherent radiation in different frequency bands, yielding a realtime spectrum of the coherent emission. An example of a design based on an array of helium cooled bolometers is discussed in Ref. [12]. With proper calibration, such a device provides a realtime spectrum of the bunch distribution. Because a multifrequency device can provide relative power levels into different frequencies, the device is useful for detecting bunch distribution changes even if all of the channels are not calibrated absolutely.

For example, consider bunch distributions generated by the infrared free electron laser (IRFEL) at Jefferson Lab [29]. Using a simulated bunch distribution and the Klimontovitch distribution

$$\rho(z) = \sum_{i=1}^{N} \delta(z - z_i)/N$$

where z_i is the longitudinal coordinate of the ith particle in the simulation, the form factor evaluates to

$$f(\lambda) = \sum_{i=1}^{N}\sum_{j=1}^{N} e^{2\pi i(z_i - z_j)/\lambda}/N^2.$$

Examples for the IRFEL injector are shown in Fig. 1, where the form factor is shown for nominal conditions out of the injector, and for conditions where parameters controlling the bunching in the injector are varied off nominal conditions. Because the power is proportional to the form factor and because the different errors have. different consequences in the measured distribution, an ideal situation arises from the point of view of bunch length control. The different type of errors have unique signatures that once measured, may be used to supply the appropriate corrections.

5 FUTURE DIRECTIONS

One may anticipate at least five areas of research that will be important in the future: intercomparisons of different techniques, multifrequency parallel measurements, single shot measurements, resolving the phase problem, and extracting low frequency information for the frequency domain techniques.

Unfortunately, given the inherent uncertainties in the various techniques of short bunch measurement, and given that their errors are not understood quantitatively, it is still not clear whether any given single measurement is entirely significant. The field is not mature enough that a single measurement type has become standard, and there have been relatively few instances of detailed cross-comparisons of the various techniques. It seems therefore likely, that at least in instances where the detailed longitudinal distribution is important, cross comparisons will be necessary for deeper results.

In the area of bunch length control, it seems likely that multifrequency parallel detection measurements will become common. The advantages of this approach: (1) continuous logging and archiving possibilities, (2) high sensitivity, and (3) relatively high bandwidth in obtaining a result, become compelling when day-to-day operations become essential.

Single shot measurements are still not possible. The highest demonstrated bandwidth is with Schottky diodes approaching a MHz. It is not clear whether either these devices or more exotic possibilities can be pushed into a domain where single shots may be analysed. Perhaps completely new methods will have to be developed to analyse single shots.

Solving the spectral phase problem is useful to pursue. The problem is known not to have an unambiguous solution from other fields of physics and mathematics. However, it is possible that if enough is known ‘about the expected distribution a priori, it may be possible to eliminate enough of the ambiguity to yield useful results.

Finally, all of the frequency domain methods have problems at low frequency. The wavelengths eventually become large enough that diffractive effects become significant. Finding good extrapolation techniques or finding good models for making corrections on the measured spectra may lead to improved results in the final indicated distribution.

6 CONCLUSIONS

Extensive work has been completed in the attempt to characterize the longitudinal distribution of the beam bunches in particle accelerators. Although the results of individual experiments are still somewhat questionable and uncertain, broad agreement has been obtained that (1) short bunches (< 1 psec rms) may be obtained reproducibly, (2) measured distributions can provide guidance for optimiig the bunch length, and (3) such optimizations provide meaningful improvement in overall linac performance. The bunch length should be measured in high performance linacs by at least one (and preferably several) of the methods reviewed in this paper. A large portion of the paper was spent reviewing the various techniques proposed for and used on short electron beam bunches. Both time domain and frequency domain methods have been considered. The current state of the art has been summarized and speculations about important future directions are given.

In the case of the CEBAF accelerator at Jefferson Lab, it has been extremely useful to separate the problem of continuous beam bunch length monitoring from the problem of bunch length optimization. Having a calibrated monitor for the first application, and using phase transfer functions for the latter application is the approach taken at Jefferson Lab. From an operational point of view, having measurement data available that provide a direct indication of the proper correction method, considerably facilitates day to day operation of the linac.

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