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# OVERVIEW OF BUNCH LENGTH MEASUREMENTS*

Alex H. Lumpkin
Advanced Photon Source
Argonne National Laboratory

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# Overview of bunch length measurements*

Alex H. Lumpkin

Argonne National Laboratory, Advanced Photon Source, Argonne, IL 60439 USA

## ABSTRACT

An overview of particle and photon beam bunch length measurements is presented in the context of free-electron laser (FEL) challenges. Particle-beam peak current is a critical factor in obtaining adequate FEL gain for both oscillators and self-amplified spontaneous emission (SASE) devices. Since measurement of charge is a standard measurement, the bunch length becomes the key issue for ultrashort bunches. Both time-domain and frequency-domain techniques are presented in the context of using electromagnetic radiation over eight orders of magnitude in wavelength. In addition, the measurement of microbunching in a micropulse is addressed.

**Keywords**: particle and photon beams, bunch length, streak camera, frequency and time domain, coherent radiation, overview.

## 1. INTRODUCTION

Interest in ultra-bright particle beams with high peak current has continued to grow as the abilities to generate the beams and to characterize the ultrashort beams have evolved in recent years. It has been noted that given a low beam emittance from a photoelectric injector (PEI) gun of 1-2π mm mrad, the critical problem turns to generating ultrashort bunches with kA peak currents[1,2]. The gain length for a self-amplified spontaneous emission (SASE) free-electron laser (FEL) is strongly dependent on peak current. Towards this end, the ability to measure electron beam bunch duration and shape become a critical aspect of carrying out forefront R&D towards future light sources including FELs. I have been asked to provide an overview of bunch length measurement techniques that updates the subset of diagnostics challenges I described in the preceding FEL Challenges conference[3].

My approach will be slightly different from talks that concentrate on either time-domain techniques[4] or frequency-domain techniques[5]. *Several representative examples will be cited to illustrate that* we now take advantage of detecting electromagnetic radiation from the x-ray regime (1Å) to the Far infrared (FIR) mm-wave regime (about eight orders of magnitude in span) to address bunch lengths from 30 ps to sub-100 fs. During the 1990's, following the initial observation of the coherent synchrotron radiation emission process at wavelengths at or longer than the physical bunch length[6], the processing of such frequency domain data to deduce bunch duration in the few-ps to 100-fs regimes has spread rapidly in the accelerator community[7-10]. More recently, an initial measurement of a 7-GeV particle beam bunch length, using x-rays emitted from a storage ring bending magnet and an x-ray streak camera, has opened the opposite end of the spectrum[11]. The longitudinal profile or bunch shape determination is indeed a more difficult task for the frequency-domain techniques while the time-domain techniques have difficulties at the sub-100 fs regime at present. This author does note the very useful summaries given by D. X. Wang at PAC'97[12], G. Krafft at DIPAC'97[13], M. Ferianis at EPAC'98[14], and W. Leemans at Linac'98[15]. These four reports supplement the information provided in the 1995 Micro Bunches Workshop proceedings[16]. As a complementary issue, some recent results in microbunching within a micropulse will be addressed which are directly relevant to the FEL process.

## 2. BACKGROUND AND RELEVANT CHALLENGES

In order to characterize the particle beam, we generally rely on a prompt conversion process of some kind to allow us to detect the information field. For the purposes of this work we are considering bunch durations much shorter than the response time of phosphors or fluorescent mechanisms (these are typically greater than 1 ns.). For detection in the 1- to 100-ps regime, the standard UV-visible streak camera technology of the 1990's provides temporal resolutions in the 1.5-ps (FWHM) or 0.6-ps (σ, for a Gaussian shape) arena. Ultrafast single-sweep streak cameras with 200-fs (FWHM) or 85-fs (σ) resolution are now marketed[17]. The extension to the detection of x-ray photons (either beams or x-ray synchrotron radiation (XSR)) is more challeng-

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ing because the fundamental photoelectron energy spread is larger when x-rays initiate the event rather than UV-visible photons[11]. However, some work is reported at the sub-ps domain and 100-fs resolution is a target of some companies. Prompt conversion mechanisms compared to 1 ps are optical transition radiation (OTR), Cherenkov radiation (CR), optical synchrotron radiation (OSR), x-ray synchrotron radiation (XSR), undulator radiation (UR), Smith-Parcell radiation (SPR), etc.

Laser-based techniques are becoming more prevalent with the use of Ti: sapphire lasers with 50- to 100-fs pulse lengths and energies of 40 mJ that are commercially available. Leemans has recently provided an overview of these techniques for reference 15. His own work included the use of Thomson-scattered laser photons with resulting energies of 30 keV to map out the 5-10 ps longitudinal profile of a 50-MeV electron beam. Since his laser pulse was 100 fs, he projected temporal resolution was possible to that level.

Another technique is based on the optical gating of a crystal with the ultrafast laser to map out an IRFEL laser pulse's bunch length. This differential optical gating (DOG) technique has been demonstrated recently at the sub-ps level[18]. An alternative is to mix the radiation emitted by a charged-particle beam with the laser in a barium borate (BBO) crystal. Again, a profile can be generated with a scanning technique[19].

As mentioned in the introduction, a rapidly expanding area of diagnostics uses the generation of coherent radiation where intensity goes as $N^2$, where N is the number of particles. Basically, all of the conversion mechanisms listed above for incoherent, visible light production are candidates. Coherent transition radiation (CTR) and coherent synchrotron radiation (CSR) have been the more widely used, although coherent diffraction radiation (CDR)[20], coherent off-axis undulator radiation (COUR), etc. are possible.

In Fig. 1, an example of a calculation of the CSR spectrum emitted for a 0.3-ps-long bunch and a 0.5-ps-long bunch is shown from Ref. 12. Although spectral measurements were initially done, more recently a Michelson interferometer technique is used to correlate the signal intensity observed versus one movable mirror position.

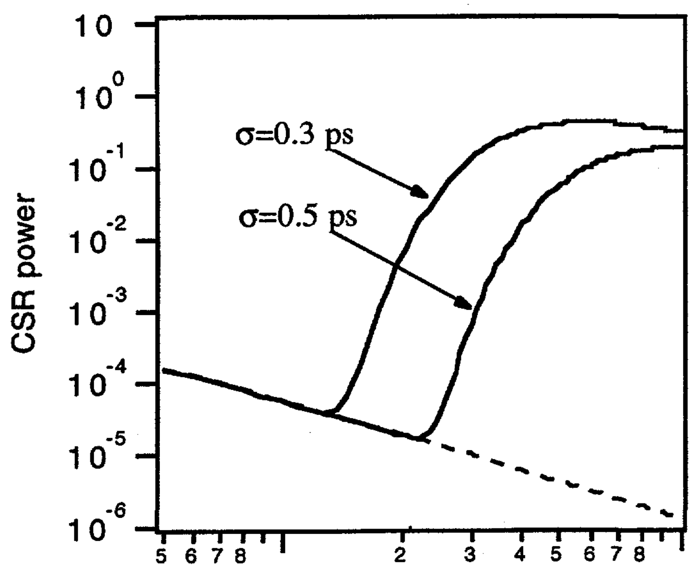

Fig. 1 Examples of calculated CSR power in the FIR for bunch lengths of 0.3 and 0.5 ps. The shorter the bunches, the shorter the wavelength at which coherent emission occurs. Courtesy of D. X. Wang (© IEEE 1997).

An example of such a system built by U. Happek (Univ. of Georgia) for Jefferson Lab is shown in Fig. 2. Detector sensitivity issues for radiation more than 2-4 mm in wavelength limit these applications on the long bunch end while on the short end, the absorption bands of atmospheric gases or effects of the beam splitter must be assessed carefully. Golay cell detectors are room temperature devices with a reasonable sensitivity in the FIR regime. A cryo-cooled bolometer extends the sensitivity to these radiations.

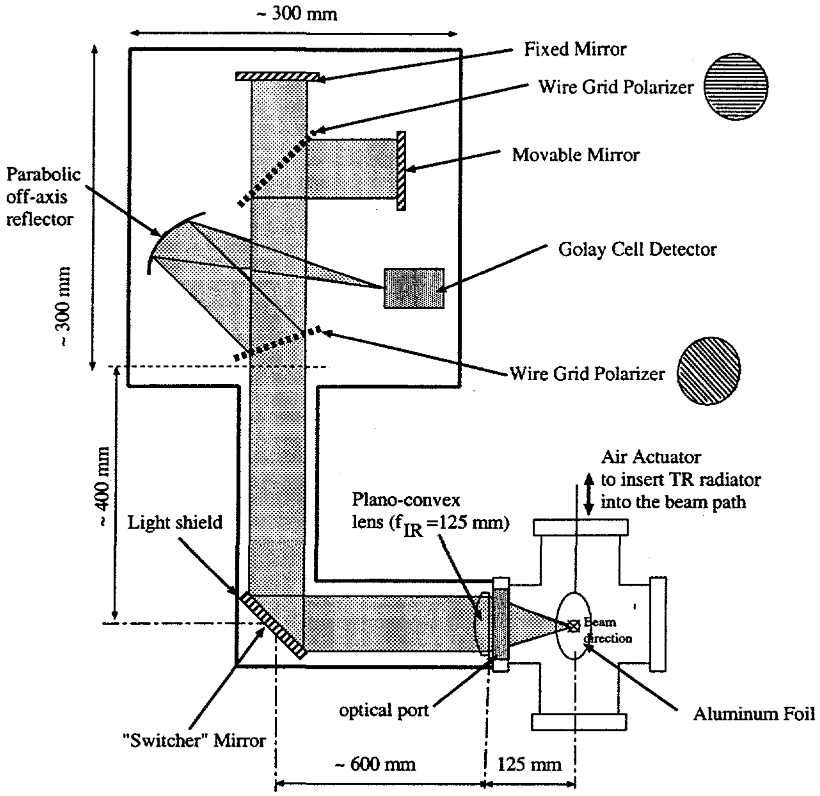

Fig. 2 A schematic of the CTR bunch length monitor at the Jefferson Lab IRFEL facility. The aluminum foil is the transition radiation converter, and the crystalline quartz lens and mirror are used to transport the radiation to the polarizing interferometer. (Courtesy of P. Piot)

There are some alternative uses of rf deflector cavities[4] or zero-phasing of the linear accelerator cavities as reported by D. X. Wang[21] that provide profile determination also in the sub-100-fs regime. Experiments at both Jefferson Lab and Cornell[22] have consolidated our understanding of the frequency domain techniques by providing complementary measurements. This is in addition to cross-comparisons to streak camera measurements performed in Japan[23].

## 3. EXAMPLES OF RECENT DEVELOPMENTS

In this section some representative examples of bunch length measurements will be presented. Although bunch duration is more readily obtained than shape or profile information in the frequency domain, there has been progress in the latter. At least three cross-comparisons of a frequency domain technique with a time-domain technique have been done in the last few years[21-23]. Additionally, the evolving field of microbunching is very promising. In this section the examples will be cited in the context of the radiation spectrum utilized to make the measurements as a pedagogical device.

### 3.1 FAR-infrared/mm-wave regime

This wavelength regime is of course dominated by the coherent radiation processes since photoelectric probabilities are limited. As an example, the IRFEL laboratory at Jefferson Laboratory (JLAB) has commissioned in 1998 a polarizing Michelson interferometer for use as a CTR bunch length monitor. The schematic of this device is shown in Fig. 2. The e-beam interacts with the Al foil to generate both OTR and CTR. The CTR is transported to the interferometer, and the Golay cell is used as the broadband detector. A sample and hold circuit and a triggered digitizer are used to process the signal for each scan position of the movable mirror. The interferogram is then processed to calculate the original bunch duration. An example of the data for a 1-ps pulse is shown in Fig. 3. A simple method has been reported by several users, including JLAB, when the integrated signal strength of CTR is mapped out as a function of rf linac or buncher phases. As shown in Fig. 4, the strongest integrated signal is well correlated with the shortest bunch of the core, as shown in Fig. 5. For cross comparisons, the zero phasing technique was also used in the IRFEL as well as the CEBAF. In the latter case, an 84-fs (rms) bunch length was reported[21]. Another variation on this is reported by staff at the Swiss Light Source linac. They recently used two specific bandpass filters in the FIR to normalize their calculated spectral intensity curves. This provided a reasonable result[24].

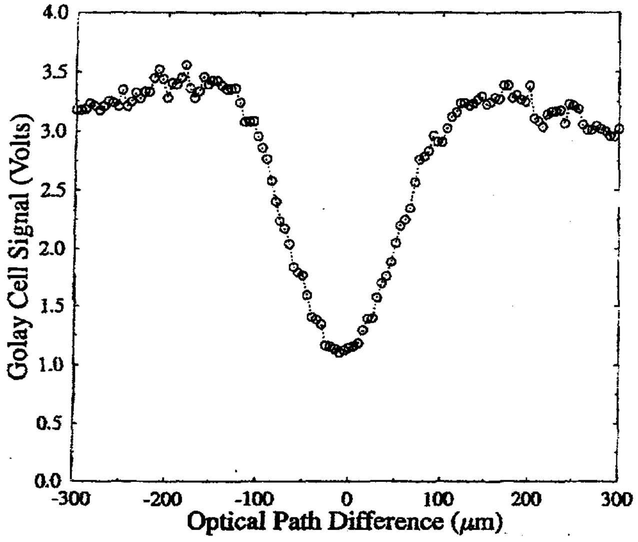

Fig. 3 An example of a CTR interferogram from the CTR monitor in Fig. 2. A bunch length less than 1 ps (FWHM) is determined. (Courtesy of G. Krafft)

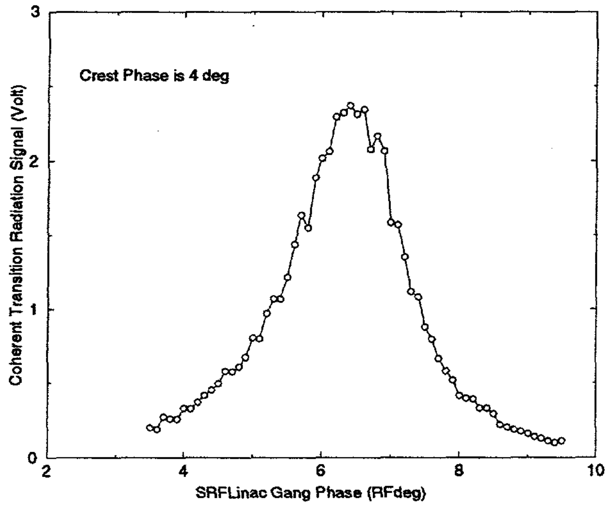

Fig. 4 The dependence of the CTR power in the Golay cell versus the "gang" phase of the IRFEL linac at Jefferson Lab. The minimum bunch length of 94 μm (rms) or 310 fs (rms) was obtained at + 6.5 rf degrees at 1497 MHz. (Courtesy of P. Piot)

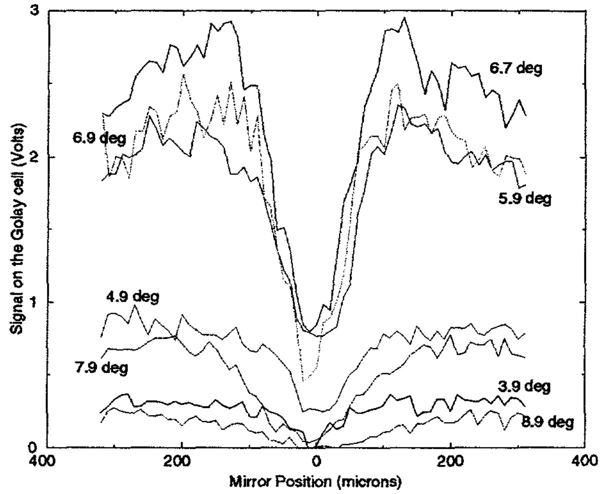

Fig. 5 A series of CTR interferograms versus the "gang" phase of the IRFEL linac. These illustrate that the CTR power may be used to minimize the bunch length of the core of the electrons, but may be insensitive to tails. (Courtesy of P. Piot)

Recently Schneider et al. reported another example of CTR interferometer work using a Hilbert transform technique to extract asymmetric shape information on the Cornell linac. They also used an rf-phasing technique coupled with a subsequent energy spectrometer to map the longitudinal distribution and perform a comparison of the beam bunch profiles[22].

### 3.2 UV-visible regime

In the UV-visible regime we can include the standard streak camera technology and frequency mixing with an ultrashort laser. The first technology has demonstrations reported to the 100-fs regime with a single-sweep streak camera[17]. Using synchroscan techniques, the demonstrations on lasers have been at the 250-fs regime.

As an illustration of a challenge in the technology, a measurement of the APS linac bunch length is shown in Fig. 6(a) (without) and Fig. 6(b) (with) a 550 × 40 nm bandpass filter on the OTR signal to the camera. The unfiltered data have basically the full visible, broadband spectrum transported to the camera and through the input optics barrel. Depending on the lens material and the optical components used, the chromatic temporal dispersion contribution to photon arrival time at the photocathode results in the "blurred" bunch length of ~ 9 ps (σ). When the 40-nm-wide filter is used, the effect is substantially reduced, and the observed beam bunch length (including the temporal resolution) is only 4.1 ps (σ). Such an effect is even more critical to sub-ps work. One solution is to use a 1- to 10-nm-wide bandpass filter, but at the sacrifice of signal statistics. This effect could make a 1-nC micropulse difficult to measure. Possible alternatives are either use of reflective optics in the input barrel or use of a grating to compensate the variable arrival times with wavelength at the photocathode. At Duke University, a deep ultraviolet (DUV) streak camera uses such an input reflective optics to transport DUV light and to address the arrival time issue. The signal intensity is a real practical challenge for work in the 100-fs regime with streak cameras, which is not normally the case for the frequency domain and coherent radiation. The inherent narrowband spectrum of lasers would eliminate the need for a filter.

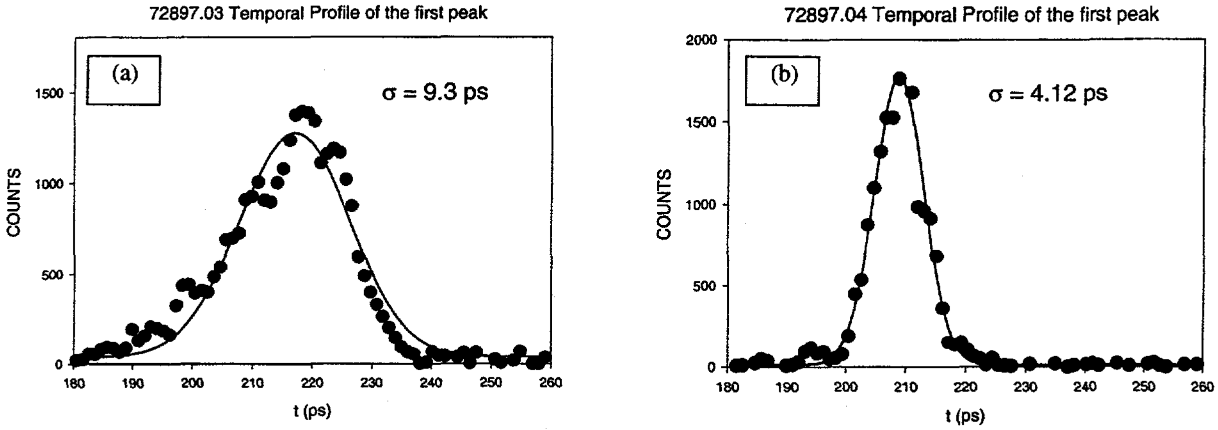

Fig. 6 Streak camera temporal profiles of the APS linac beam at 600 MeV without (a) and with (b) the 550 × 40 nm bandpass filter. Chromatic temporal dispersion is a limiting effect to measuring shorter bunches broadband radiation.

The other area involves the use of ultrashort laser pulses to mix with the visible radiation emitted by the electron beam in a suitable nonlinear crystal. The mixed wavelengths provide a profile similar to those done at the Advanced Light Source (ALS) with synchrotron radiation[19]. In this case, the 2-eV radiation was sum-frequency mixed in a BBO crystal with 1.55-eV radiation from a short pulse (< 100 fs) Ti: $Al_20_3$ laser. By scanning the laser arrival time with respect to the electron bunch, a 16.6-ps (σ) bunch length was assumed. Another example involves using the laser pulse as a gate in the nonlinear medium to map out the IRFEL pulse length at Stanford University[18].

### 3.3 VUV and x-ray regimes

In the VUV and x-ray regimes there are very few particle-beam bunch length measurements to date. Two examples are the Thomson scattering experiment performed by W. Leemans et al. on a 50-MeV electron beam[25] and a unique x-ray synchroscan measurement by Lumpkin and Yang on the 7-GeV APS storage ring beam[11]. Since the first case was just available at the time of FEL Challenges I and presented then[2], I will only address the x-ray streak measurement here.

A schematic of the bending magnet source and beamline is shown in Fig. 7. The Hamamatsu C5680-36 camera was positioned on three stacked translation stages to provide remote control of the x, y, and z(t) positions. The synchroscan unit was phase-locked to 117.3 MHz, the third subharmonic of the storage ring rf accelerator frequency. As shown in Fig. 8, the focus mode image provides a true horizontal profile, while the 50-μm vertical extent of the strip photocathode slices the vertical profile and establishes one limiting contribution to the temporal resolution. The limiting resolution was ~ 4 ps (σ) on sweep range 2, but a three times faster sweep range is available in the camera. The observed bunch length of 28 ps (σ) is averaged over 30 ms. This same tube could be phase-locked to 119.0 MHz and used to measure undulator radiation from the APS SASE FEL experiment in the future. In the UV laser regime we have recorded 0.6-ps resolution, and this value would gradually degrade until the estimated 1.2 ps at 0.5 Å. This particular tube also has dual sweep features. Another x-ray tube architecture, developed for the European Synchrotron Radiation Facility (ESRF) by the University of Michigan, is reported to deliver sub-ps resolution using a laser-triggered circuit[26]. The laser would then be phase-locked to the rf of the accelerator in some way in the proposed pump-probe experiments at ESRF[27].

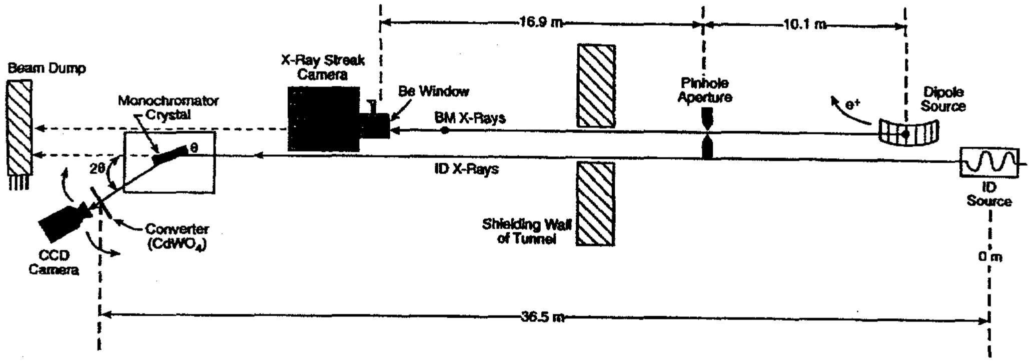

Fig. 7 A schematic of the diagnostics beamline at APS using a bending magnet source of XSR. The x-ray pinhole images the scene onto the x-ray streak tube photocathode.

### 3.4 Microbunching

Very interesting developments are occurring in the direct detection of the microbunched structure within a single micropulse. This microbunching can be induced via interactions with the electromagnetic fields of a co-propagating laser as at Brookhaven National Laboratory (BNL)[28] or by the optical fields of the evolving FEL process as at Los Alamos National Laboratory (LANL)[29]. This microbunching is, in fact, necessary for the coherence feature of the FEL. This structure can be detected via the use of CTR as done in both the BNL and UCLA/LANL experiment. D. Rule has provided an analysis of detector bandwidth effects in such experiments[30]. Figure 3 of Ref. 29 shows the IR spectrum observed from the SASE process at 13 μm and from the e-beam generated CTR. Extensions of this type of measurement to the visible regime could occur within the BNL and APS projects. Although there are fewer electrons within the shorter wavelength period, the signals should be adequate--particularly if saturation is achieved in the FEL. In Fig. 9 the calculated bunching fractions along the undulator sections of the APS SASE project are shown for a fundamental at 517 nm[31]. Initial experiments will be performed at the end of the undulator where the bunching should be maximized and approaching 10%.

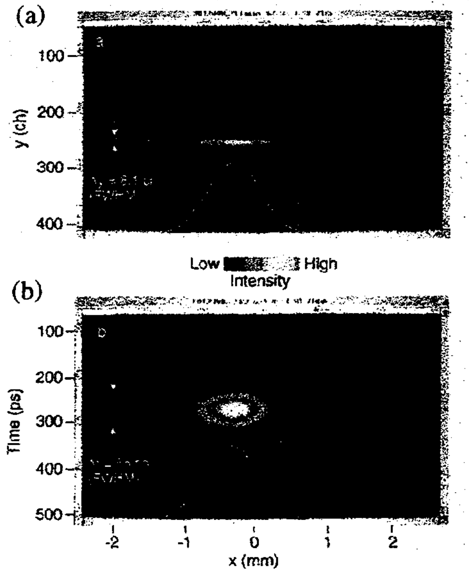

Fig. 8 Examples of the x-ray synchroscan streak camera images in (a) focus mode and (b) synchroscan sweep mode. The observed bunch length was 65 ps (FWHM) or 28 ps (σ) performed with 4-ps resolution.

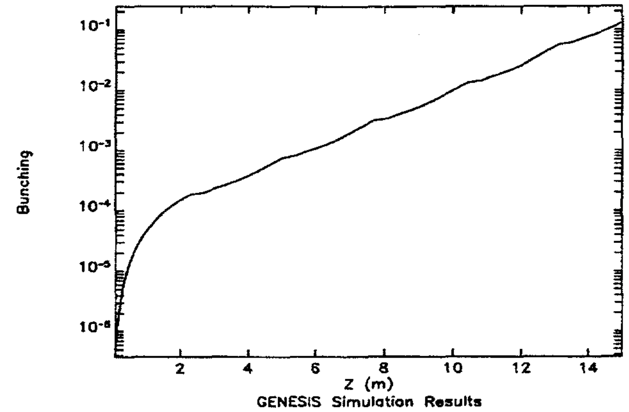

Fig. 9 A calculation of the microbunching fraction in the micropulse along the APS SASE undulator sections. The nominal SASE fundamental is at 517 nm in this GENESIS code calculation. (Courtesy of Y. Chae)

### 3.5 Overview

These combined techniques and results are summarized in a rather different way in Fig. 10. The horizontal axis is the wavelength of radiation used to measure the observed bunch length on the vertical axis. The horizontal axis covers a rather striking eight decades of wavelength given in μm and nm, and the vertical axis covers six decades. This is a semi-quantitative display within each order of magnitude. There are obvious clusters of results in the λ-Δt measurement space. As mentioned earlier, the thrust to the 1-mm regime was initiated by the use of the coherent radiation terms from transition radiation, synchrotron radiation, diffraction radiation, etc. The experiments at Tohoku, Cornell, Stanford, Vanderbilt, UCLA, and JLAB are examples. The available beams were typically 0.5 to 5 ps although one Stanford result was at 150 fs. Another obvious cluster involves a subset of the UV-visible streak camera measurements in the 300- to 800-nm regime with results typically of 2-6 ps on linacs and 20-30 ps on storage ring beams. The shortest bunch measured was with 80-fs resolution at Tokyo University[32]. There is a leap on the horizontal axis into the 1Å regime with the Thomson scattering experiment and the x-ray streak camera measurements.

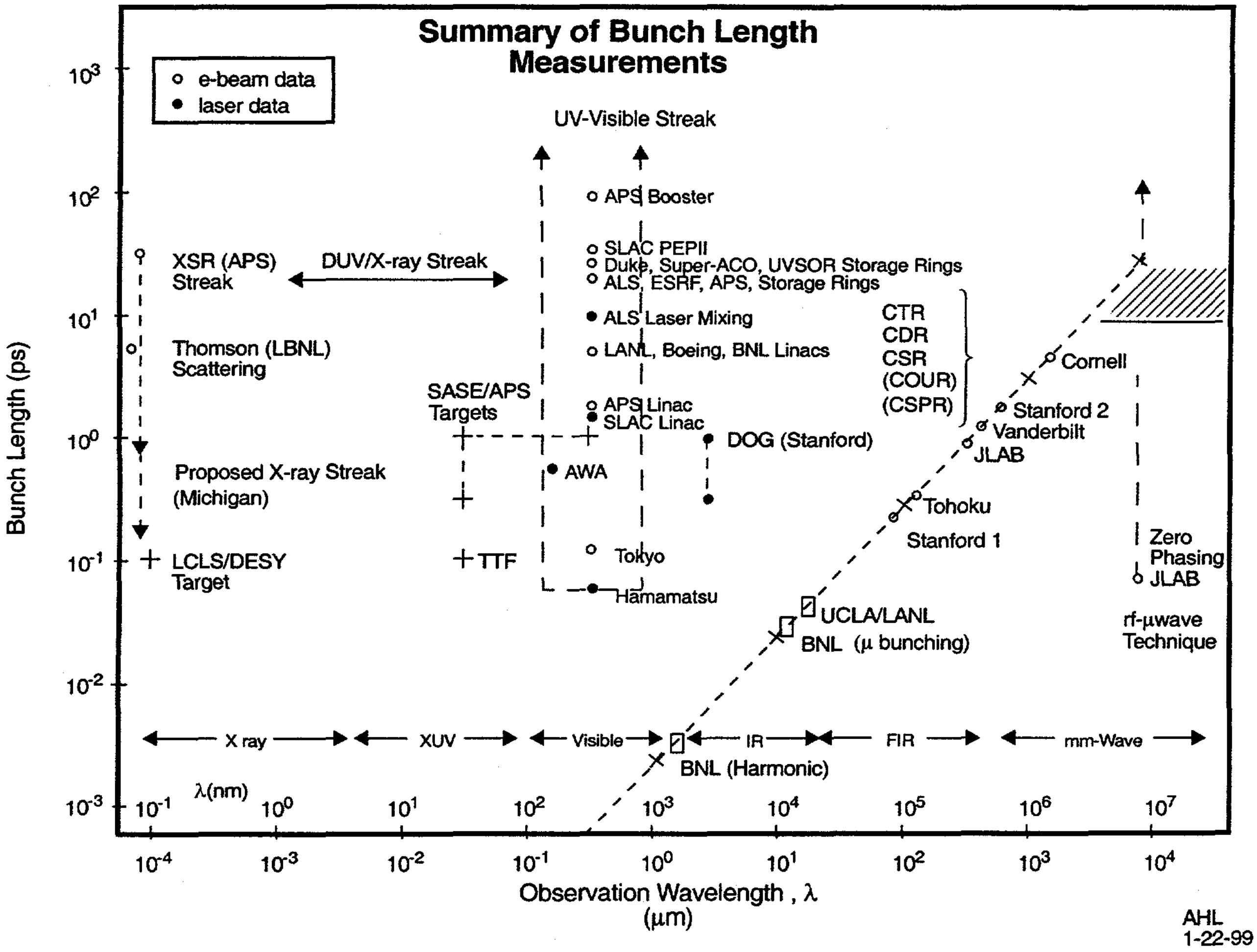

Fig. 10 A representation of the bunch length measurement techniques characterized by the radiation wavelength detected in the optical diagnostics. The horizontal axis is given in μm and nm, and the vertical axis is in ps. The data are sorted by order of magnitude. The open circles are e-beam data results.

The Linac Coherent Light Source (LCLS) and the Deutsches Elektronen Synchrotron (DESY) target of 100-fs bunches for a 1-Å x-ray source is noted as well as the intermediate target at the APS SASE and BNL SASE experiments with the plus (+) symbol. Diagnostics capabilities are realistic at those targets with some further development time. Plans for using CDR, COUR, and CSR are nearing implementation. It is noted that for very short bunches, the coherent radiation actual moves towards the IR-visible wavelength detectors much as the microbunching field has shown us. In addition, the streak camera capabilities from the visible to the x-ray regime apply to FEL output photon beams as well as the e-beam characterization. Any of these nonintercepting techniques would apply to high power applications.

## SUMMARY

In summary, the diagnostic techniques to address the ultrashort bunches are rapidly developing. The challenges remain for both the time-domain (sub-100-fs resolution) and frequency domain (single shot and less ambiguous profiles) techniques such that a combination of them would be prudent. A caveat on bunch profile determination with frequency domain techniques when weak halos or tails exist in the time domain should be particularly heeded. Finally, the gauntlet may have been tossed back to the accelerator builders to generate more ultrashort bunches and at higher peak currents.

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