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First Measurements of Subpicosecond Electron Beam Structure by Autocorrelation of Coherent Diffraction Radiation+

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Abstract

We report the initial measurements of subpicosecond electron beam structure using a nonintercepting technique based on the autocorrelation of coherent diffraction radiation (CDR). A far infrared (FIR) Michelson interferometer with a Golay detector was used to obtain the autocorrelation. The radiation was generated by a thermionic rf gun beam at 40 MeV as it passed through a 5-mm-tall slit/aperture in a metal screen whose surface was at 45° to the beam direction. For the observed bunch lengths of about 450 fs (FWHM) with a shorter time spike on the leading edge, peak currents of about 100 A are indicated. Also a model was developed and used to calculate the CDR from the back of two metal strips separated by a 5-mm vertical gap. The demonstrated nonintercepting aspect of this method could allow on-line bunch length characterizations to be done during free-electron laser experiments.

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1. Introduction

A recurrent theme of several recent conferences and workshops that addressed diagnostics for free-electron lasers (FELs) has been the designation of the nonintercepting feature as critical [1-4]. This feature is particularly of interest in the measurement of longitudinal bunch profile, since this can be used with a charge measurement to determine the e-beam peak current. This latter parameter is one of the most essential to obtaining and understanding the FEL's gain. Many of the operating FEL laboratories use techniques that intercept (coherent transition radiation screens) or interrupt (zero-phasing rf) the beam transport to the undulators [5,6]. We report here the first (to our knowledge) measurement of sub-0.5-ps e-beam profiles using a nonintercepting technique based on coherent diffraction radiation (CDR). In a previous measurement by Shibata et al. [7], the forward CDR and the electron beam struck a downstream radiation pick-off mirror after the circular aperture. In our experiment the radiation was generated by a thermionic rf gun beam at 40 MeV as it passed through a 5-mm-tall slit/aperture in a metal screen whose surface was at 45° to the beam direction. The backward CDR was evaluated with a far infrared (FIR) Michelson interferometer that used a Golay cell as the detector. The longitudinal profile was evaluated from the fast Fourier transform (FFT) of the autocorrelation and the use of the minimal phase approximation [8]. The beam was transported at the same time to a downstream electron spectrometer. The results have been compared to complementary, intercepting coherent transition radiation (CTR) and streak camera measurements. Since the micropulse charge was typically 30-50 pC, the macropulse was either 8 or 40 ns long, and the beam energy was only 40 MeV, the CDR-based technique appears to be applicable to extensions of

CTR techniques at several FEL laboratories (e.g. Vanderbilt [5], Stanford [9], Jefferson Lab [6], etc.) that have beams with more integrated charge in a macropulse. A model was also developed and used to calculate the CDR from the back of two metal strips separated by 5-mm vertical gap centered on the beam axis. We also performed complementary measurements using CTR.

2. Experimental Background

The Advanced Photon Source (APS) injector linear accelerator (linac) consists of an S-band thermionic rf gun and α magnet that allow a macropulse of 8 to 40 ns in length to be injected into the accelerator as shown in Fig. 1 [10]. The micropulses each have about 20 to 50 pC of charge, so bunch lengths of less than 500 fs (FWHM) are needed in order to reach the target 100-A peak currents. In gun optimization studies [11] we have found specific regimes where the core of the beam has transverse emittances of the order of 8 to 12 π mm mrad. The nominal beam properties at the station where these measurements were performed are given in Table 1.

The standard beam profile station on the linac uses an intercepting Chromox screen with a video camera. For investigating bright beams, we have modified the station at 40 MeV. In this case one actuator has a Ce-doped YAG single crystal with mirror at 45 degrees to the beam for beam position and profile information with high conversion efficiency. The second actuator with a kinematic positioner has a metal screen with a 5-mm-tall slit aperture machined into it beginning 1.5 mm above the beam centerline when it is inserted. This design was a compromise dictated by the need to use an alignment laser to position properly the Michelson interferometer and detector below the beamline. The alignment laser was injected into the beamline upstream of the location so that the angle of specular reflection could be determined from the metal screen. By steering the e-beam on the centerline of the beamline, the solid metal is intercepted for optical transition radiation (OTR) or CTR studies. Steering the beam vertically a few mm allowed the beam to pass through the aperture and to be viewed on the downstream electron spectrometer. With this latter steering, the CDR experiments were performed. In addition to the visible beam image downstream, we also used the rf beam position monitor (BPM) sum signal as a relative current monitor before and after the CTR/CDR screen. We tracked these signals during the course of the interferometer mirror position scans.

The CTR and CDR are generated from the metal surface or “metal strips,” respectively, seen by the beam. The radiation leaves the beam pipe through a crystalline quartz window and is colliminated by a 100-mm focal length crystalline quartz (z-cut) plano-convex lens. A Michelson interferometer is used to analyze the spectrum of the coherent radiation or, equivalently, to perform an autocorrelation of the emitted transition radiation pulse as described in reference 12. An Inconel-coated beam splitter is used to generate the two beams used in the autocorrelation. One beam's path length can be adjusted by a computer-controlled mirror stage. A Golay detector, Model OAD-7, obtained from QMC Instruments Limited, was used as the broadband FIR detector. Signal levels of a few hundred mV were obtained with 200-mA macropulse average current. The analog data were processed and digitized with an APS-built gated integrator module and Hewlett-Packard waveform digitizer. EPICS was the platform used to track the signal-versus-mirror position, α-magnet current, or scraper position [13].

3. Analytical Background

A model was developed and used to calculate the CDR spectral emissions from the back of two metal strips separated by a vertical gap centered on the beam axis, as schematically shown in Fig. 2. The spectral emissions were calculated for nominal cases at 50 MeV, 100-pC/μ pulse, 80 pulses. The calculation was compared to measured spectra reported by Shibata et al. [7]. Sensitivities of the CDR spectrum to beam offset from the center of the slot and to slots of various widths were assessed. Model guidance supported the 5-mm vertical gap for our nominal 1-ps case at 40 to 50 MeV. A brief outline of the approach is given below.

Coherent radiation by a bunch of electrons can be expressed as the product of a term representing the radiation process for a single particle and a term, which takes into account how much of the total charge in the bunch radiates together, constructively in phase. Thus the spectral, angular distribution of the radiation can be expressed as

$$\frac{d^2W}{d\omega d\Omega} = \frac{d^2W_1}{d\omega d\Omega} B_N, \tag{1}$$

where $d^2W_1/d\omega d\Omega$ is the spectral angular distribution for the single particle radiation process, either transition radiation (TR), synchrotron radiation, or diffraction radiation (DR), for example. In the present case, $d^2W_1/d\omega d\Omega$ is taken to be the single-particle diffraction radiation process. B_N is the coherence factor for a bunch of N electrons. The term B_N is related to the square of the Fourier transform of the spatial distribution of the bunch:

$$B_N = N + N(N-1)F(\boldsymbol{k}), \tag{2}$$

with

$$F(\boldsymbol{k}) = \left[Q^{-1}\Im\{\rho(\boldsymbol{r})\}\right]^2. \quad (3)$$

Here

$$\Im\{\rho(\boldsymbol{r})\} = \int \rho(\boldsymbol{r}) e^{-i\mathbf{k}\cdot\mathbf{r}}\, d\boldsymbol{r} \quad (4)$$

is the bunch charge form factor, i.e., the Fourier transform of the charge distribution of total charge Q=Ne. The first term in Eq. (2) yields the incoherent radiation produced by N electrons in the bunch, while the second term gives the coherent production, which is proportional to N^2. A simple Gaussian model for the bunch form factor is used to calculate CDR for various cases relevant to the APS linac.

Note that, for F($\boldsymbol{k}$) to be sizeable, the beam rms radius σ and the wavelength of interest λ must be such that for angles θ of order $1/\gamma$,

$$\sigma \leq \sqrt{2}\gamma\lambda\!\!\!^{-}, \quad (5)$$

where $\lambda\!\!\!^{-} = \lambda/2\pi$. The wavelengths of interest are determined by the longitudinal part of F($\boldsymbol{k}$) such that the rms bunch length

$$\sigma_z \leq \lambda\!\!\!^{-}. \quad (6)$$

Clearly a relativistic effect allows the beam radial dimensions to be of the order of γ times $\lambda/2\pi$ and radiate coherently, while the wavelength for coherent radiation must be greater than the longitudinal dimension of the bunch (~$2\sigma_z$). Since the number of electrons N in a bunch is typically quite large, F($\boldsymbol{k}$) can actually be much less than unity and there will still be coherent radiation.

A computer program to calculate coherent diffraction radiation as a function of wavelength was written and applied to the general cases of interest here [14]. Figure 3 shows the calculated spectra of CDR from a slit for a 50-MeV electron beam comprising

8 nC in a macropulse for bunch lengths from $\sigma_t = 0.2$ to 6 ps. As expected, the form factor results in significant enhancements of radiation at wavelengths about three times longer than the bunch length.

4. Experimental Results and Analysis Procedures

All the data have been obtained since the last FEL conference in 1999. The thermionic rf gun gradient was deliberately set higher than for the standard settings used for generating beam for injection into the storage ring. The higher gradient enhances micropulse charge, and when used with the proper α magnet setting and low-energy scraper setting, results in a brighter core beam.

For simplicity the beam was first evaluated using the CTR signals from Station-1 by steering onto the beam centerline. We then steered the beam upward and sent the beam through the aperture. The CDR FIR signal was lower than the CTR FIR signal but still sufficient to obtain an autocorrelation as seen in Fig. 4. A fast Fourier transform was performed to assess the spectral content. Using the observed amplitudes from 20 to 40 cm^{-1} as reference, the amplitudes for longer wavelengths were extrapolated [15] (as shown in Fig. 5). The corrected spectrum was used in recalculating the autocorrelation, and then the longitudinal profile was calculated using the minimal phase approximation of Lai and Sievers [8]. In Fig. 6 we show a comparison of the CTR and CDR data, respectively. A similar longitudinal distribution was obtained in both cases with a FWHM distribution of ~ 450 fs. The bunch distribution shows a spike, which was determined to be on the leading edge by the zero-phasing rf technique and a streak camera measurement. Note that the single-particle DR production is explicitly wavelength dependent. This difference between TR and DR is not yet included in the analysis of the data. The difference would become even smaller at higher gamma. For the nonintercepting CDR case, the energy distribution was observed downstream of the aperture's location, and the rf BPM sum signals from locations before and after the aperture were used to confirm the transmission of beam. These particular data are with a 40-ns-long macropulse, but we subsequently obtained an autocorrelation with an 8-ns-long macropulse that was optimized for self-amplified spontaneous emission (SASE) gain experiments [13].

Summary

In summary, we have obtained the first, to our knowledge, nonintercepting measurements of sub-0.5-ps electron beam bunch profiles using backward CDR. The measurements were done with $\gamma < 100$ and for quite small charges in a micropulse (20-50 pC). The total macropulse charge of 1 to 4 nC and these other conditions support the application to several operating FEL experiments, which could benefit from the nonintercepting feature. The simplest extensions would occur at labs that already use a CTR-based monitor, such as Vanderbilt, Stanford, and Jefferson Lab. The scaling also indicates that at higher γ the CDR approaches the CTR signal strengths for an appropriate aperture so even the Linac Coherent Light Source project may benefit.

6. Acknowledgements

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Figure Captions

Fig. 1 A schematic of the initial portion of the injection linac for the APS. In these experiments the beam from thermionic rf gun #2 was accelerated to 40 MeV by the L2-AS1 accelerating structure after which the diagnostics station was located (courtesy of J. Lewellen, ANL)

Fig. 2 Schematic of geometry for diffraction radiation production by two finite width, infinitely long, reflecting strips. Here the y axis is in the plane containing the velocity vector v and the normal to the plane of the aperture. Radiation is emitted in the direction of **k**.

Fig. 3 Calculated spectra of CDR from a slit for a 50-MeV electron beam with 8 nC total charge and bunch lengths of $\sigma_t = 0.2, 0.5, 1.0, 3.0$ and 6.0 ps.

Fig. 4 The CDR autocorrelation from the FIR interferometer. Note the horizontal scale of mirror position in μm would be doubled for optical path difference.

Fig. 5 The amplitude spectrum derived from the autocorrelation and corrected spectrum at long wavelength (low wavenumber).

Fig. 6 Longitudinal bunch profiles derived from the corrected autocorrelation amplitude spectrum using CTR (upper) and using CDR (lower). The bunch distribution is sub-0.5 ps (FWHM) for the 40-MeV beam.

Table 1: APS Linac Beam Properties at Station-1 in the Low-Emittance Mode (rf Thermionic Gun)

rf frequency (MHz)	2856
Beam energy (MeV)	40-50
Micropulse charge (pC)	20-50
Micropulse duration (ps)	0.2 - 1.0 (FWHM)
Macropulse length (ns)	40, 8
Macropulse repetition Rate (Hz)	6
normalized emittance (π mm mrad)	~12 ± 4 (1σ)

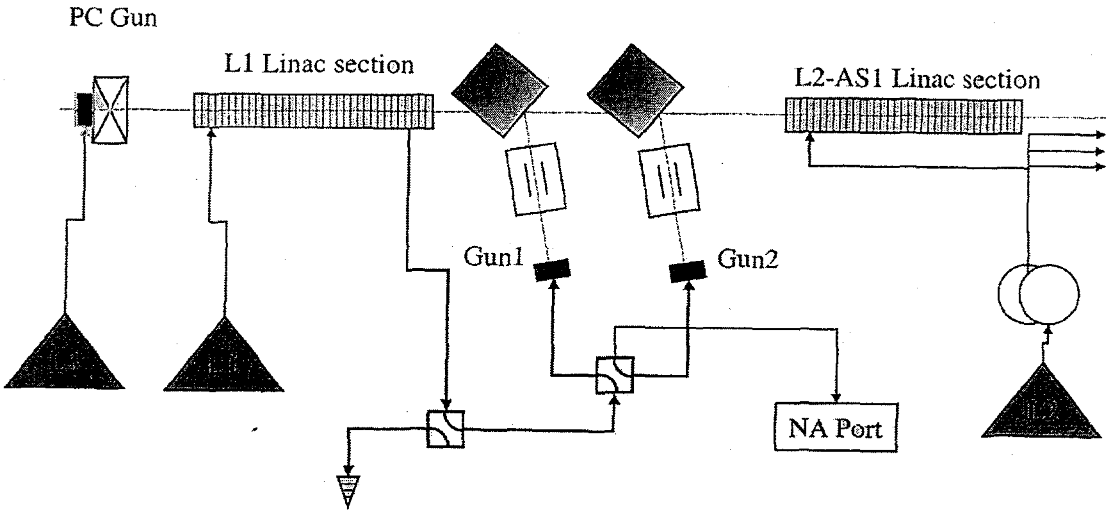

PC Gun
L1 Linac section
L2-AS1 Linac section
Gun1
Gun2
NA Port

Fig. 1

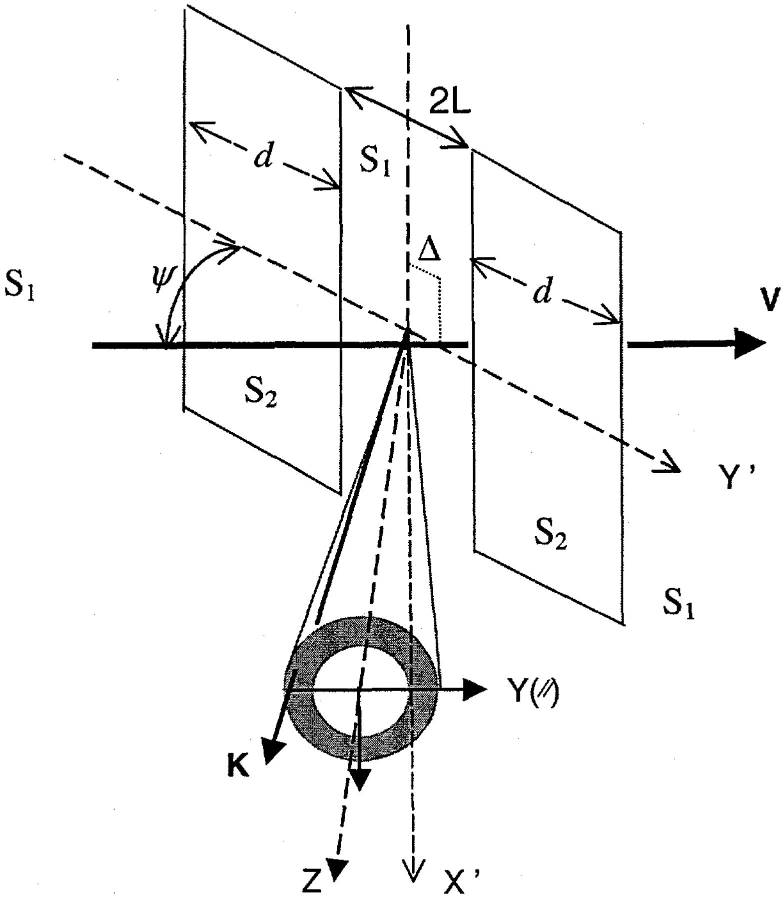
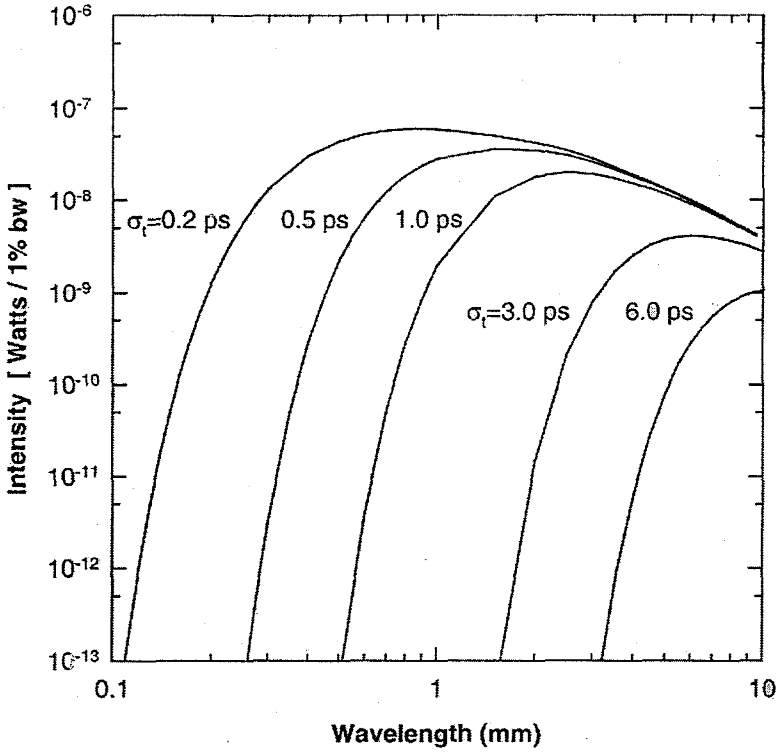


Fig. 2



10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
Intensity [Watts / 1% bw]
σ_t=0.2 ps
0.5 ps
1.0 ps
σ_t=3.0 ps
6.0 ps
0.1
1
10
Wavelength (mm)

Fig. 3

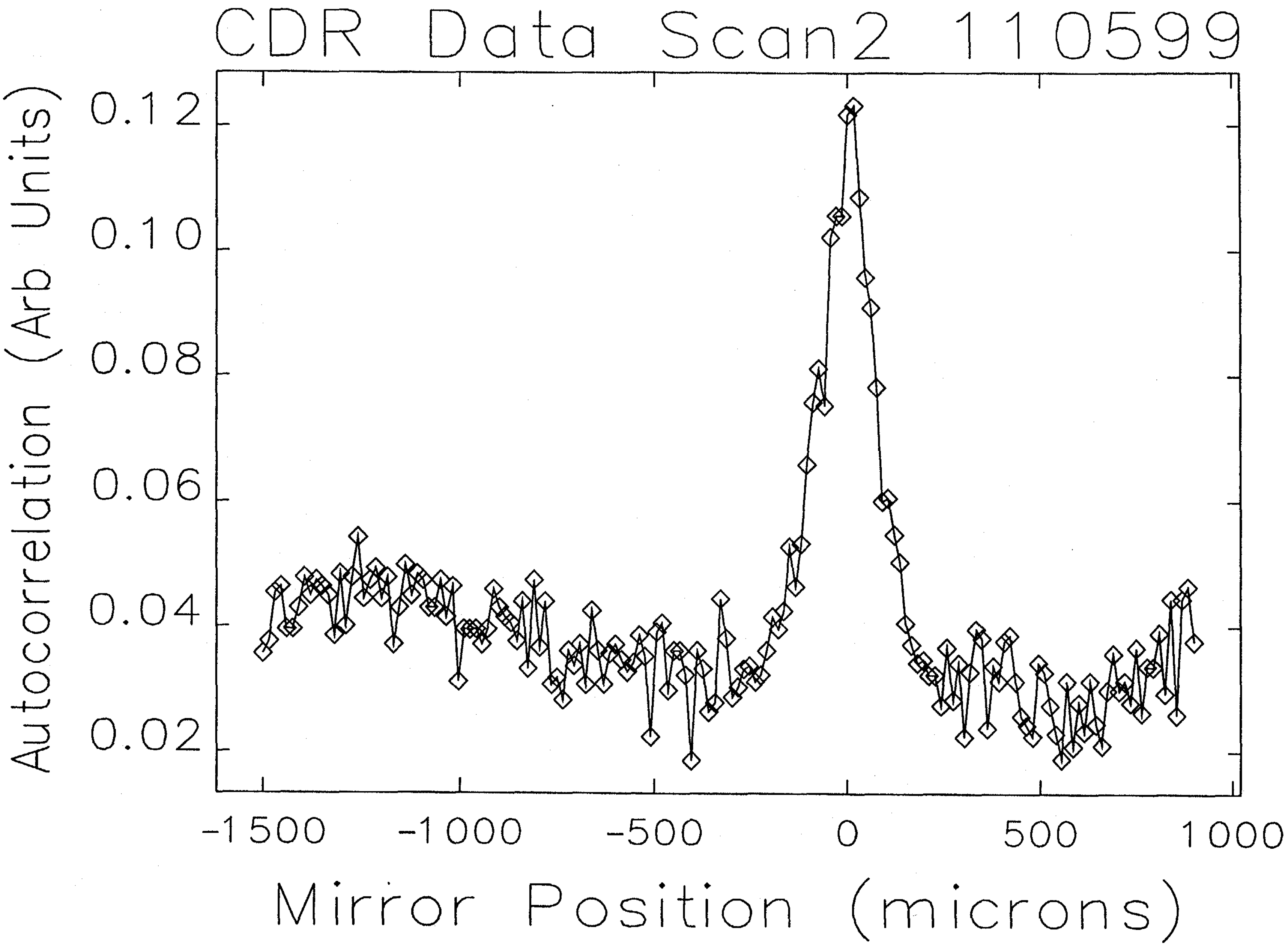

CDR Data Scan2 110599
Autocorrelation (Arb Units)
0.12
0.10
0.08
0.06
0.04
0.02
-1500
-1000
-500
0
500
1000
Mirror Position (microns)

Fig. 4

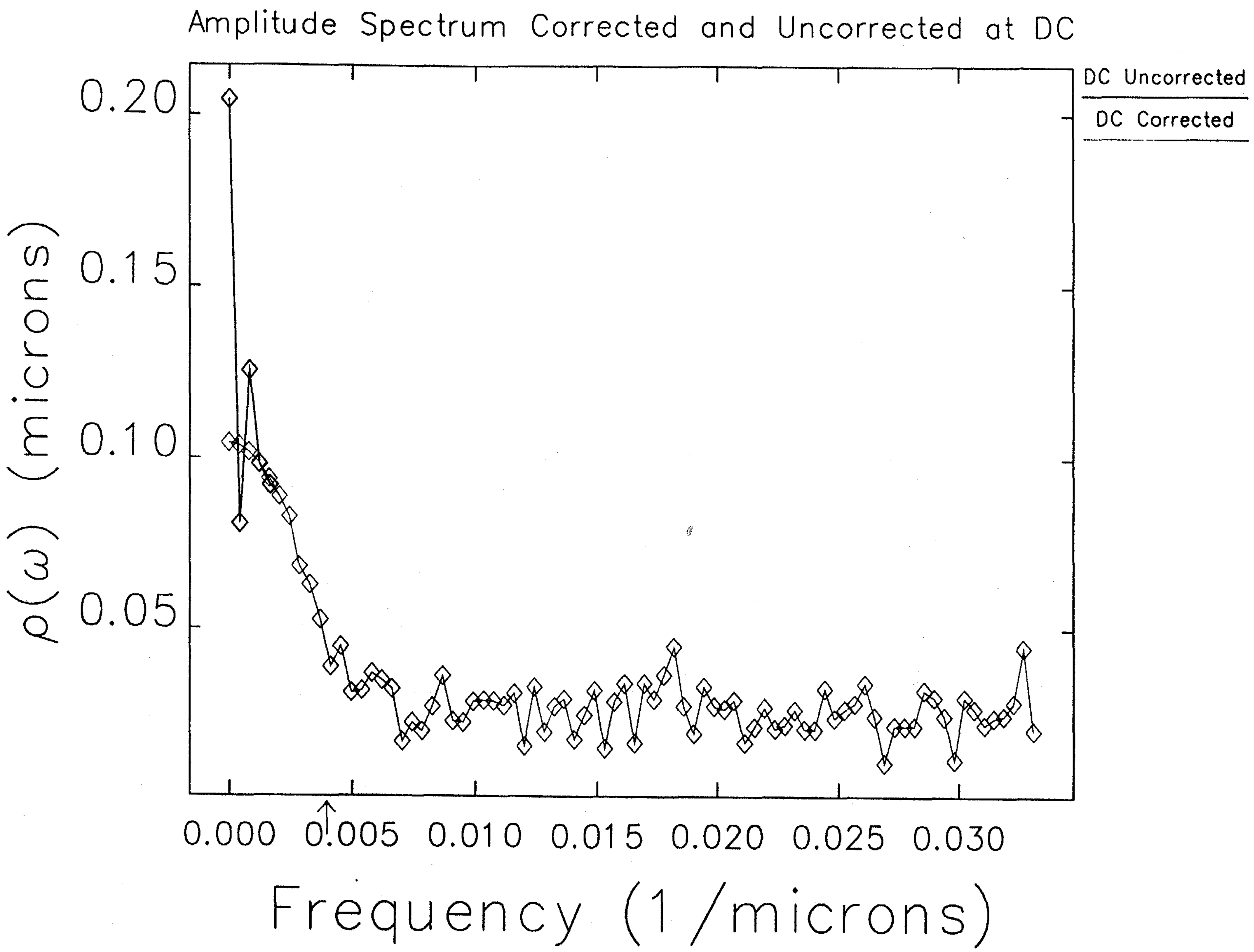

Amplitude Spectrum Corrected and Uncorrected at DC
DC Uncorrected
DC Corrected
ρ(ω) (microns)
0.20
0.15
0.10
0.05
0.000
0.005
0.010
0.015
0.020
0.025
0.030
Frequency (1/microns)

Fig. 5

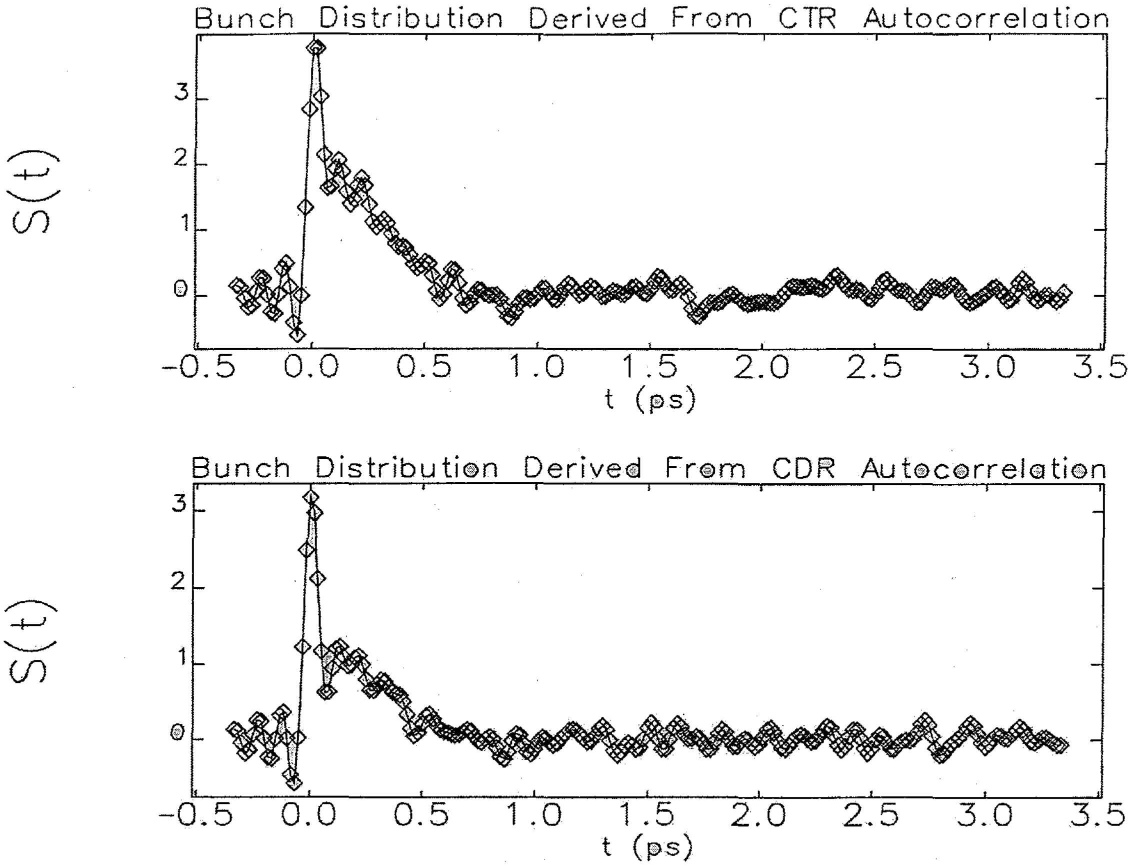

Bunch Distribution Derived From CTR Autocorrelation
S(t)
0
1
2
3
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
t (ps)
Bunch Distribution Derived From CDR Autocorrelation
S(t)
0
1
2
3
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
t (ps)

Fig. 6