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Electron Beam Bunch Length Characterizations Using Incoherent and Coherent Radiation on the APS SASE FEL Project*

A.H. Lumpkin, B.X. Yang, W.J. Berg, J.W. Lewellen, and N. S. Sereno

APS, Argonne National Laboratory

and

U. Happek

Physics Dept., Univ. of Georgia

The Advanced Photon Source (APS) injector linac has been reconfigured with a low-emittance rf thermionic gun and a photocathode (PC) rf gun to support self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiments. One of the most critical parameters for optimizing SASE performance (gain length) is the electron beam peak current, which requires a charge measurement and a bunch length measurement capability. We report here initial measurements of the latter using both incoherent optical transition radiation (OTR) and coherent transition radiation (CTR). A visible light Hamamatsu C5680 synchroscan streak camera was used to measure the thermionic rf gun beam's bunch length ($\sigma \sim 2$ to 3ps) via OTR generated by the beam at 220 MeV and 200 mA macropulse average current. In addition, a CTR monitor (Michelson Interferometer) based on a Golay cell as the far infrared (FIR) detector has been installed at the 40-MeV station in the beamline. Initial observations of CTR signal strength variation with gun α-magnet current and interferograms have been obtained. Progress in characterizing the beam at these locations and a comparison to other bunch length determinations will be presented.

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1. Introduction

Since longitudinally bright beams are needed for self-amplified spontaneous emission (SASE) free-electron laser (FEL) experiments, one of the most critical parameters for optimizing SASE performance (gain length) in actual experiments has been the electron beam peak current [1]. This requires both a charge measurement and a bunch length measurement capability. The reconfiguration of the Advanced Photon Source (APS) injector linac with a low-emittance thermionic rf gun and a photocathode (PC) rf gun to support visible light SASE experiments [2-4] has stimulated development of our bunch length measurement capabilities. We have made initial measurements of the thermionic rf gun beam using incoherent optical transition radiation (OTR) and a streak camera. In addition, we have installed a far infrared (FIR) interferometer for use with coherent transition radiation (CTR) and for the potential determination of bunch duration. We have done preliminary measurements of the FIR CTR to minimize the bunch length from the thermionic rf gun. Plans have also been developed to use one 2.4-m-long undulator section as a source of spontaneous emission radiation (SER) whose bunch length will be directly related to e-beam bunch length. The latter measurement is at the FEL location so it directly supports the simulations of SASE performance. Finally, a brief comparison of these results to the present field of bunch length measurements will be presented.

2. Experimental Background

The APS facility's injector system uses a 250-MeV S-band electron linac and an in-line S-band 450-MeV positron linac. At this time the primary electron gun for storage ring injection is a thermionic rf gun designed to generate low-emittance beams (< 8 π mm mrad) and configured with an α magnet to inject the beam just after the first linac accelerating structure [3]. Both in-line linacs can be phased to produce 100- to 650-MeV electron beams when the positron converter target is retracted.

2.1 Streak Camera Considerations

As discussed previously [5], the linac's standard intercepting screens are based on Chromox of 0.25 mm thickness with a 300-ms decay time. We have complemented these slow-response screens with OTR screens and/or a Ce-doped YAG single crystal/mirror assembly. Only the OTR screens have a fast enough response time (<100 fs) for addressing the few-ps bunch lengths involved. In this case, the OTR screen was installed in a station at the end of the second linac, and the light was transported out of the tunnel, using two 150-mm-diameter achromat lenses, to an optics table where the Hamamatsu C5680 streak camera was located. We used the synchroscan vertical plug-in unit (Model M5675) phase-locked to 119.0 MHz, the 24th subharmonic of the 2856-MHz linac frequency. The sweep range was separately calibrated by using the green component of the frequency-doubled Nd glass laser (that is also used as the PC gun drive laser [4]) with an etalon that could be mounted on the front of the streak camera. A correction factor of 1.2 for the look-up table of another synchroscan module was determined for the fastest camera range (R1) from the observed positions of the multiple streak images generated by the reflecting mirror with 50-ps spacing in the etalon.

2.2 CTR Monitor and Interferometer

Coherent transition radiation is generated using a metal mirror oriented at 45° with respect to the electron trajectory. The radiation leaves the beam pipe through a crystalline quartz window and is collimated by a crystalline quartz (z-cut) plano-convex lens [6]. 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 [7].

To construct a compact, cost-effective and simple-to-align interferometer, we used the basic Michelson design (Fig. 1). The instrument features 75-mm-diameter optics and has dimensions of only $275 \times 125 \times 100$ mm^3. Conventionally, Michelson interferometers are equipped with Mylar beamsplitters for far infrared operation, however, the efficiency of these beamsplitters is strongly wavelength dependent and, in general, insufficient in the mm-wave region. Thus, for the analysis of the longitudinal dimension of electron bunches, the more complex polarizing Michelson or Martin-Puplett interferometers are commonly used, incorporating a pair of fragile, free-standing wire grid polarizers that yield a flat response down to a wavelength of 25 μm (for a standard grid constant of 12.5 μm). While a number of polarizing Michelson interferometers for bunch length measurements have been operated at Cornell [8], Vanderbilt [9], Jefferson Lab [10], and UCLA [11], the main disadvantage of these instruments is the complicated alignment procedure.

In our novel design we use a metal-coated beamsplitter that combines the simplicity of a Michelson interferometer with the flat spectral response of a polarizing Michelson interferometer. A thin Inconel film is deposited on a 2-μm-thick beamsplitter, with the thickness of the film adjusted to give 25% reflection and 25% transmission, wavelength independent for $\lambda > 2\ \mu m$. The metal film is strongly absorbing (50%), leading to a factor of four lower throughput compared to an ideal beamsplitter, but this disadvantage is more than outweighed by the compact design, low cost of the beamsplitter compared to freestanding wire grid polarizers, and the ease of alignment using a simple alignment laser. While the high frequency cut-off of the present instrument is limited by the quartz window and lens, we note that this design can be adapted for operation in a vacuum chamber. A vacuum instrument eliminates the quartz window, and, with the lens replaced by reflecting optics, this design potentially can be used to analyze extremely short electron bunches with a width of several μm.

The CTR interferometer was constructed at the University of Georgia and installed at the 40-MeV station, one accelerating section downstream of the rf gun's α magnet. A beam splitter is used to generate the two beams that are used in the autocorrelation. One beam's path length can be adjusted by a remotely controlled mirror stage. A Golay detector, Model OAD-7, obtained from QMC Instruments Limited was used as the broadband FIR (low frequency cut off of about 4 mm) detector. Signal levels of a few hundred mV were obtained with 200-mA macropulse average current. Initial data were digitized in a Hewlett-Packard oscilloscope, while subsequent data were processed with an APS-built gated-integrator module. EPICS was the platform used to track the signal vs alpha magnet current or mirror position.

3. Results and Discussion

In this section thermionic rf gun beam results from the streak camera and the CTR monitor are reported.

3.1 Streak Camera Results

The thermionic rf gun macropulse is composed of about 110 micropulses spaced by 350 ps. For a macropulse current of 205 mA, the micropulse charge is about 72 pC. In order to obtain a streak image with OTR, we used the synchroscan feature to synchronously sum four micropulses out of each of ten macropulses so about 2.9 nC were integrated in the image shown in Fig. 2. The bunch length with corrections for the calibration is 6.8 ps (FWHM) or 2.9 ps (σ-estimated) for an α-magnet current of 145A. There is a slight asymmetry in the shape that is "time-reversed" by the two deflection directions of the sinusoidal sweep as expected. The scraper in the α magnet was installed subsequently, and the effects of the scraper position on the observed bunch profile and at higher beam currents will be studied in the future.

3.2 CTR Tests

The FIR interferometer was mechanically installed in May 1999. The initial experiments on the 40-MeV rf thermionic gun beam included a bunch length optimization experiment with the α-magnet current as the varied parameter. In this case the observed Golay detector signal goes as the inverse of the bunch length. As shown in Fig. 3, the detector signal clearly peaked at an α-magnet setting of 137 A. The signal (and inferred bunch length) changed by almost a factor of two when the α-magnet current was varied from 132 to 139 A. A nearby rf BPM monitor's sum signal was used to track the beam current transported to this station, which decreased by only about 4% during the scan. The remote control of the mirror stage is under development, and an initial autocorrelation experiment for bunch length determination has been done. The CTR signal is plotted versus the moveable mirror position for a fixed α-magnet current in Fig. 4. The width of the peak is a measure of bunch length, and these data indicate a portion of beam at the sub-ps level. Simulations indicate a narrow spike in the longitudinal profile that is not completely resolved by the streak camera. Further studies with these complementary diagnostics are planned.

3.3 Discussion

These measurements can be placed in context with other measurements by the summary plot of measured bunch length versus observation or "active" wavelength first developed in Ref. 12 and shown in Fig. 5. In the 2-D space of measurements to date, the 2-3 ps regime with a visible light streak camera falls in a cluster with other measurements on linear accelerator systems. The set of measurements using coherent radiation techniques whether they be transition, synchrotron, diffraction radiation (DR), etc. fall in the FIR-mm regime generally just as the present data. The addition of a bunch compressor on the APS project would push our measurements deeper into the sub-ps regime. We anticipate replacing the CTR screen with a polished mirror with a machined aperture to develop the nonintercepting DR aspect of bunch length determinations in the coming year.

4. Summary

In summary we have performed initial bunch length determinations on the thermionic rf gun beam using both incoherent OTR and CTR. These techniques can support the measurement of the high peak-current micropulse needed for the APS SASE FEL experiments. Tests with the PC rf gun beam are expected in the coming year. The combination of e-beam sources and measurement techniques being developed at the facility should facilitate progress on both gun performance optimization and diagnostic capabilities.

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Figure Captions

Fig. 1 Schematic of the compact FIR Michelson interferometer installed on the APS linac. The dimensions of the instrument are (without detector) 275 x 125 x 100 mm^3. The collimated coherent transition radiation enters the instrument from the top and is split by the metal coated beamsplitters in two beams that are reflected off a fixed mirror (M1) (bottom) and a moveable mirror (M2). The recombined reflected beams are focused onto the detector by an off-axis parabolic metal mirror (PM).

Fig. 2 Example of synchroscan streak images of the thermionic rf gun's beam micropulse-averaged bunch length ($\sigma \sim 3$ps). The streak axis is the vertical axis and the two images came from both deflection directions in the sine wave.

Fig. 3 Plot of the CTR signal measured by the Golay cell versus the rf gun's α-magnet current. The peak signal at 137 A corresponds to the minimum bunch length.

Fig. 4 Plot of the FIR autocorrelation showing the observed CTR signal versus movable mirror position. The width of the peak is a measure of bunch duration and the optical path length difference is twice the mirror movement. Sub-ps structure is indicated by these data.

Fig. 5 Summary plot of bunch length measurements organized as bunch length in ps versus the observation or "active" wavelength of the technique used.

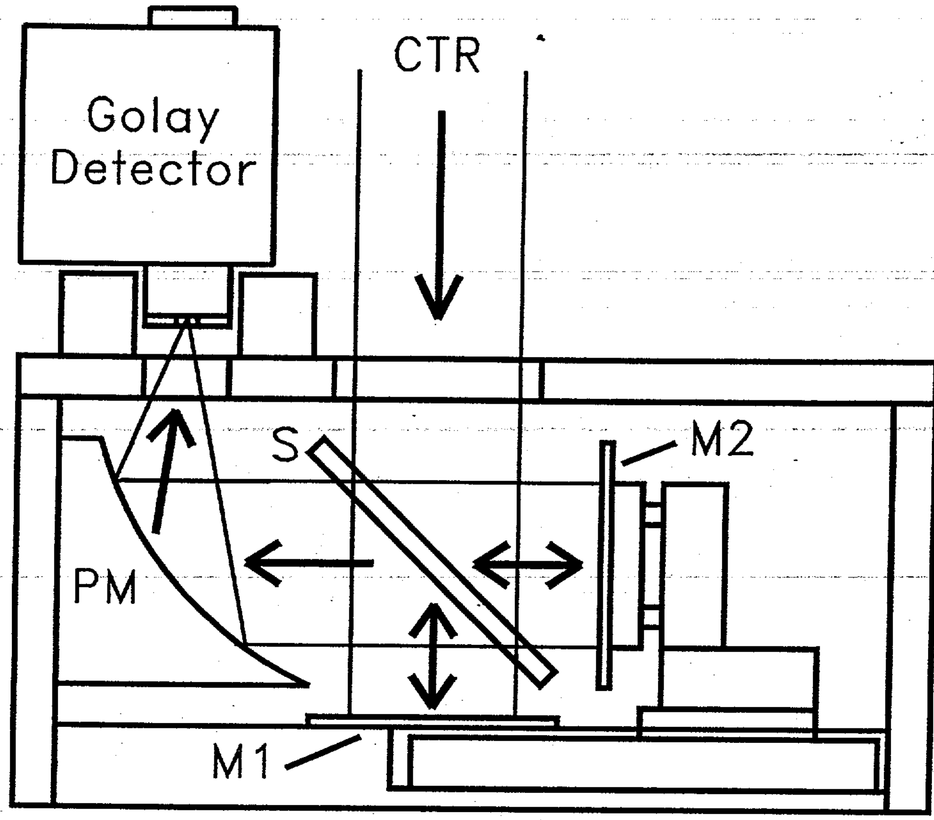

Fig. 1

Fig. 2
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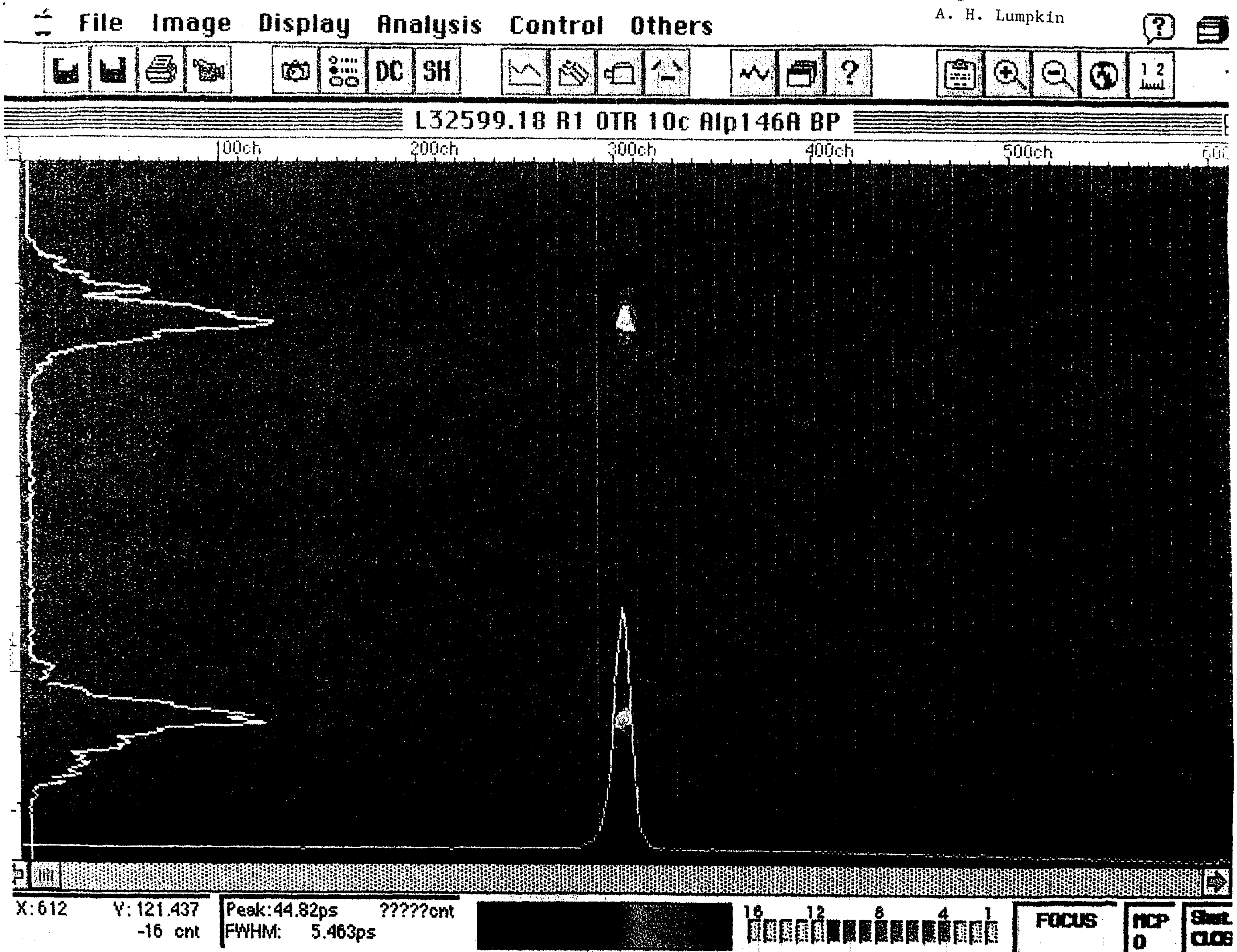

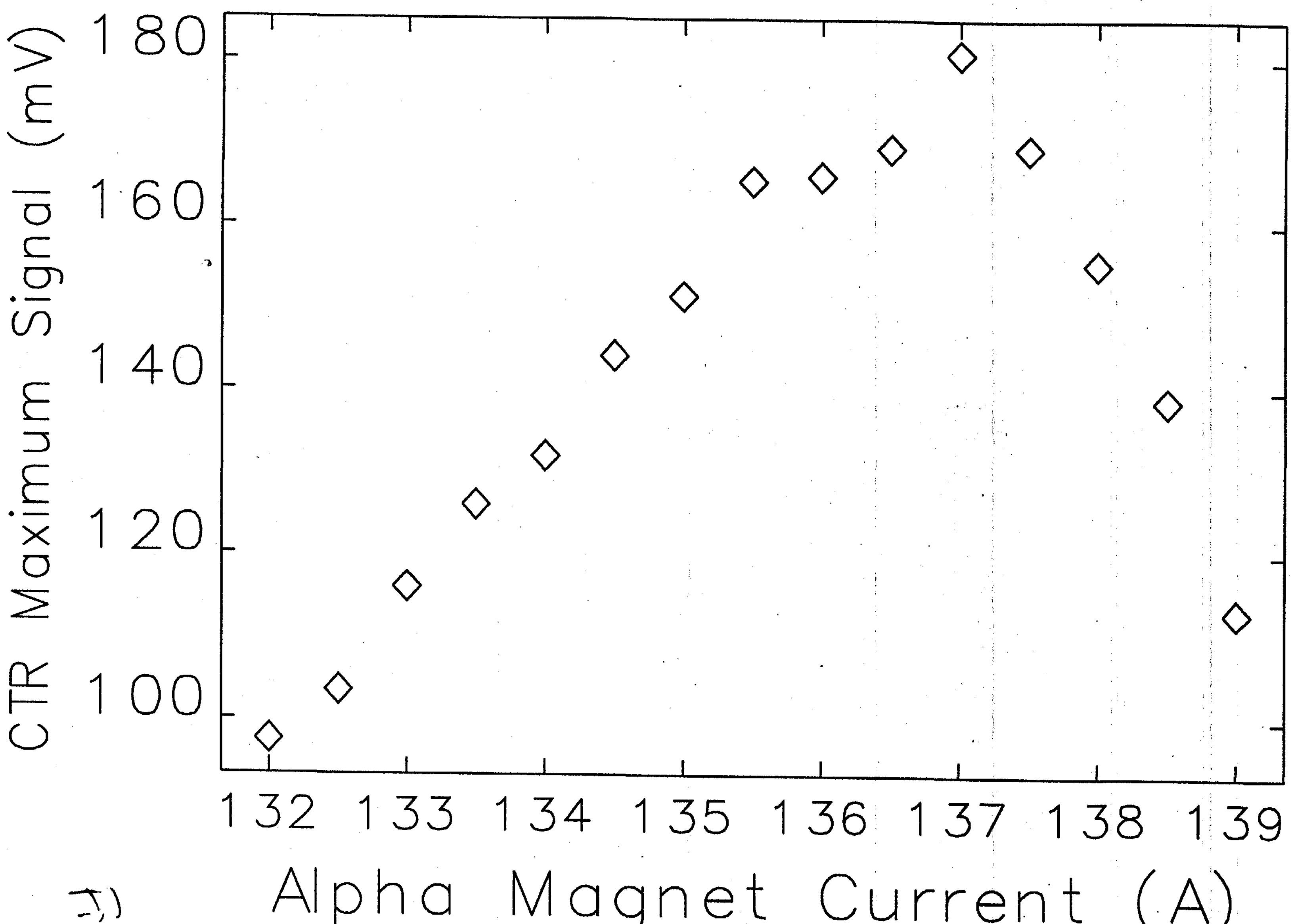
180
160
140
120
100
CTR Maximum Signal (mV)
132
133
134
135
136
137
138
139
Alpha Magnet Current (A)

Fig. 3

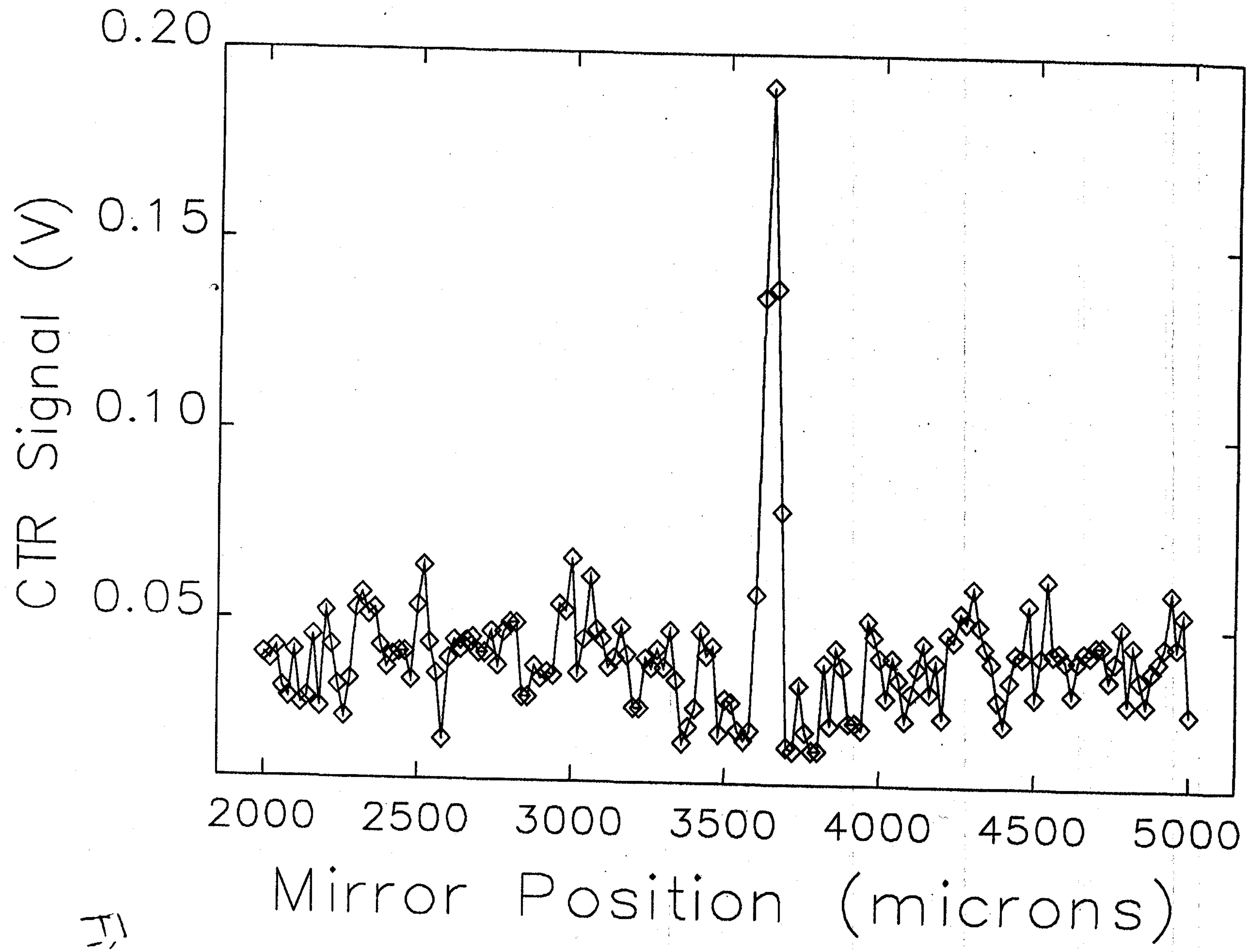
0.20
0.15
0.10
0.05
CTR Signal (V)
2000
2500
3000
3500
4000
4500
5000
Mirror Position (microns)

Fig. 4

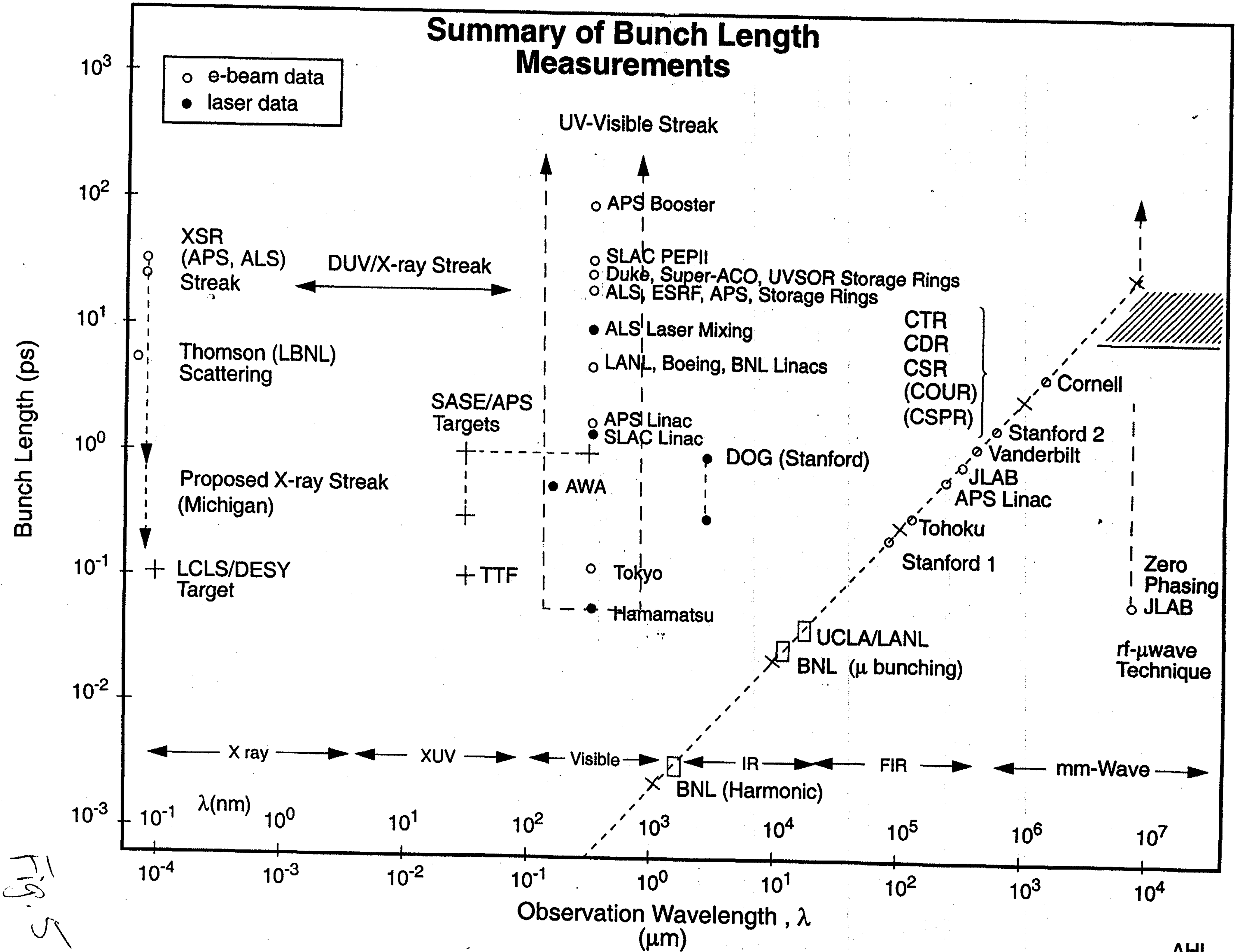

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Fig. 5