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# Characterization Techniques for the High-Brightness Particle Beams of the Advanced Photon Source (APS)*



by

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## ABSTRACT

The Advanced Photon Source (APS) will be a third-generation synchrotron radiation (SR) user facility in the hard x-ray regime (10-100 keV). The design objectives for the 7-GeV storage ring include a positron beam natural emittance of $8 \times 10^{-9}$ m-rad at an average current of 100 mA. Proposed methods for measuring the transverse and longitudinal profiles will be described. Additionally, a research and development effort using an rf gun as a low-emittance source of electrons for injection into the 200- to 650-MeV linac subsystem is underway. This latter system is projected to produce electron beams with a normalized, rms emittance of ~ 2 $\pi$ mm-mrad at peak currents of near one hundred amps. This interesting characterization problem will also be briefly discussed. The combination of both source types within one laboratory facility will stimulate the development of diagnostic techniques in these parameter spaces.

## 1. INTRODUCTION

The high brightness particle beams of the Advanced Photon Source (APS) will present an interesting characterization challenge. The APS will be a third-generation synchrotron radiation (SR) facility designed to provide high-brightness x-ray beams for research in the 5- to 100-keV energy regime.[1] To attain the brightest x-ray beams, the circulating 7-GeV particle beam (positrons) has a design objective of a natural emittance of $8 \times 10^{-9}$ m-rad at an average beam current of 100 mA. For 10% vertical coupling this would lead to $7 \times 10^{-10}$ m-rad vertical emittance. The accelerator subsystem will include a 200-MeV electron linac followed by an electron-to-positron conversion step, a 450-MeV positron linac, a 450-MeV positron accumulator ring (PAR), a 0.45-to-7-GeV injector synchrotron (IS), the 7-GeV storage ring, and the transport lines and test lines. Proposed/planned methods for measuring the transverse and longitudinal profiles using ultraviolet and x-ray SR imaging techniques will be discussed.

Additionally, a research and development effort using an rf gun as a low emittance source of electrons for injection into the 200- to 650-MeV linac subsystem is underway.[2,3] This latter system is projected to produce electron beams with a normalized, rms emittance of ~ $2\pi$ mm-mrad at peak currents near 100 A, properties close to the parameter space defined as of interest in the Fourth Generation Light Source Workshop.[4] This interesting characterization problem will also be briefly discussed. The combination of both source types at one laboratory facility will provide the challenges for development of the necessary diagnostic techniques in these newer parameter spaces of low-emittance beams. Data useful to the high brightness radiation community for benchmarking other design activities should result from the commissioning of these two APS sources.

## 2. BACKGROUND

Space precludes providing a complete description of the accelerator facilities for the APS but some background information is needed. The baseline electron source is a thermionic gun followed by a 200-MeV linac operating at an rf frequency of 2.8 GHz, and a maximum macropulse repetition rate of 60 Hz. The base injector (gun, bunchers, and 45-MeV accelerating structure) was operated April through June 1992 as the injector linac test stand. The design goals include 14-ps-long micropulses, separated by 350 ps in a 30-ns macropulse with a total macropulse charge of 50 nC. The 200-MeV linac beam will be focused to a 3-mm spot at the positron-production target. The target yield is about 0.0083 positrons per incident electron with a solid angle of 0.15 sr and an energy range of 8±1.5 MeV. The positrons will then be focused by a pulsed solenoid and about 60% of them will be accelerated to 450 MeV. Commissioning of these two linacs with electron beams is to be completed by December 1993. The 450-MeV positrons are injected into the horizontal phase space of the PAR at a 60-Hz rate. As many as 24 macropulses can be accumulated as a single bunch during each 0.5-s cycle of the injector

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synchrotron. The injector (or booster) synchrotron (IS) accelerates the positrons to 7 GeV at which energy they can be extracted and injected into the designated rf bucket of the storage ring. A schematic of the APS accelerators which lists the number of diagnostic stations is given in Fig 1.

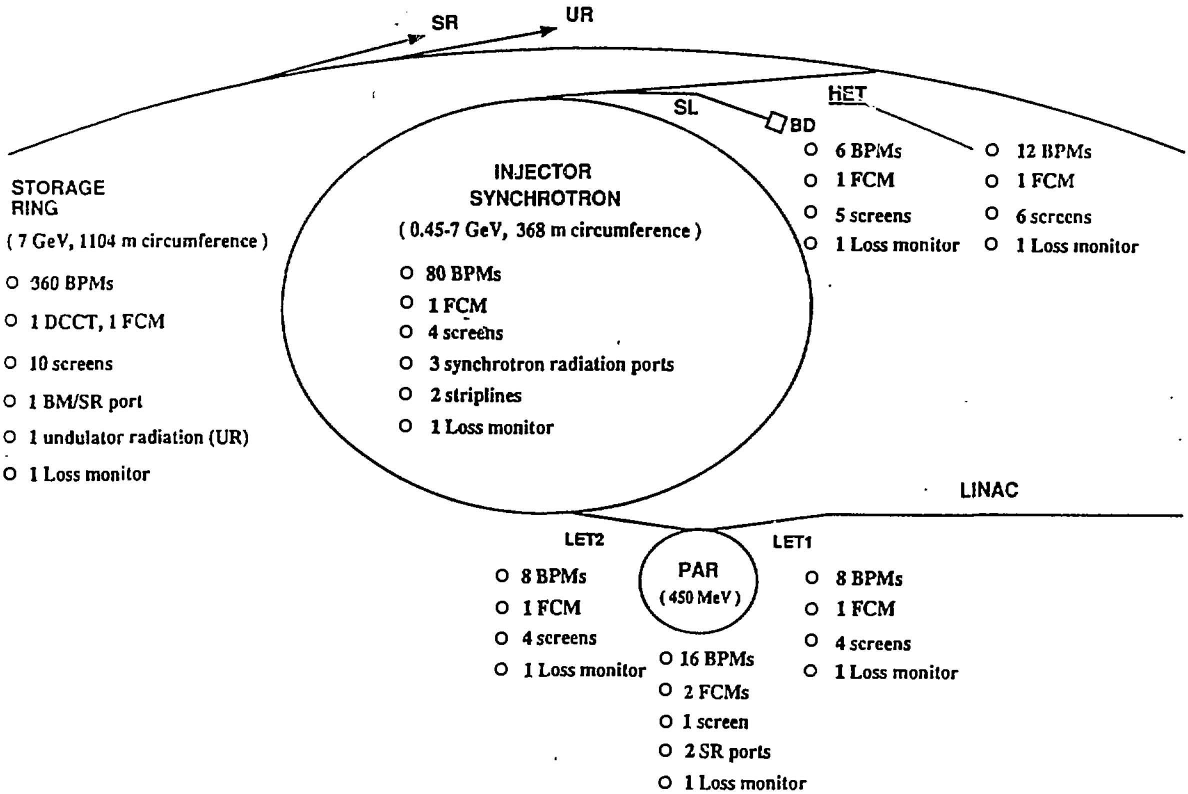


Fig. 1. A schematic of the APS subsystems showing the diagnostics for those other than the two linacs.

Several features of the subsystems are provided in Table 1. The peak current, bunch length, and charge per pulse are given for the low energy transport (LET) lines between the linac and the PAR and the PAR and synchrotron, respectively. The high energy transport (HET) parameters are also provided. The revolution time, bunch length, and average currents are also provided in Table 1 for the rings. Additional parameters of interest for diagnostic design for the two largest rings are given in Table 2.

An undulator test line is being considered at 650 MeV. In this mode, the tungsten positron conversion target will be retracted and the 450-MeV linac rephased to accelerater electrons to 650 MeV (700 MeV possibly). This would involve the switch to the rf thermionic gun which is projected to provide normalized, edge emittances of about 10 $\pi$ mm-mrad at peak currents near 100A. This gun provides beams a few orders of magnitude colder than the standard thermionic gun. This gun may allow micropulse bunch lengths $\sigma_t$ < 1 ps to be attained via filtering and magnetic compression techniques (in the alpha-magnet). Many of the critical beam parameters identified in the Fourth Generation Light Source Workshop would be approached by this undulator test line electron beam.

**Table 1** APS Parameters for Beam Diagnostics

| | LET 1 | LET 2 | HET |
|---|---|---|---|
| PEAK CURRENT | 8 mA | 11.9 A | 28.9 A |
| BUNCH LENGTH | 30 ns | 0.29 ns | 122 ps |
| INTENSITY PER PULSE | $1.5 \times 10^{9}$ positrons | $2.2 \times 10^{10}$ | $2.2 \times 10^{10}$ |
| CHARGE PER PULSE | 240 pC | 3.5 nC | 3.5 nC |
| PULSE RATE | 60 Hz | 2 Hz | 2 Hz |

| | PAR | IS | SR |
|---|---|---|---|
| RF FREQUENCY | 9.77 or 117 MHz | 351.93 MHz | 351.93 MHz |
| REVOLUTION TIME | 102.3 ns | 1.228 us | 3.68 us |
| NUMBER OF BUNCHES | 1 | 1 | 1 to 60 |
| MIN BUNCH SPACING | — | — | 20 ns |
| BUNCH LENGTH | 30 ns → 0.29 ns / 0.92 ns | 122 ps | 35 to 100 ps |
| MIN AVE BEAM CURRENT | 1.4 mA<br>1 linac pulse injected | — | 0.22 mA<br>for single bunch |
| MAX AVE BEAM CURRENT | 33.4 mA<br>24 linac pulses injected | 4.7 mA | 5 mA<br>for single bunch |
| MAX INTENSITY | $3.6 \times 10^{10}$<br>24 linac pulses injected | $3.6 \times 10^{10}$ | $2.2 \times 10^{10}$<br>per bunch per mA |

**Table 2** Accelerator Parameters for Diagnostics

| Parameter | Storage Ring | Inj. Synch. |
|---|---|---|
| Energy (GeV) | 7 | .45 - 7 |
| RF Freq. (MHz) | 351.93 | 351.93 |
| Harmonic No. | 1296 | 432 |
| Min. Bunch Spacing (ns) | 20 | 1228 |
| Rev. Period (μs) | 3.68 | 1.228 |
| No. of Bunches | 1-60 | 1 |
| Max. Single Bunch Current (mA) | 5 | 4.7 |
| Bunch Length ($2\sigma$) (ps) | 35-100 | 61-122 |
| Damping Times $\tau_{h,v}$ (ms) | 9.46 | 2.7 @7GeV |
| Tunes $\nu_h, \nu_v$ | 35.22,14.30 | 11.76,9.80 |
| Damping Time $\tau_s$ (ms) | 4.73 | 1.35 @7GeV |
| Synch. Freq. $f_s$ (kHz) | 1.96 | 21.2 |

## 3. MEASUREMENTS OF LOW-EMITTANCE, HIGH-BRIGHTNESS BEAMS

The challenges of measuring low-emittance, high-brightness beams vary with the actual parameter space one is facing and whether it is in a circular accelerator or linear accelerator situation. The two APS cases of the 7-GeV stored positron beam and the 0.65-GeV linac electron beam push the demonstrated diagnostics envelope on either the transverse or the longitudinal phase space side.

### 3.1 Stored Beam, Transverse Measurement

The 7-GeV positron beam of the APS has a natural emittance , $\varepsilon = 8\times10^{-9}$ m-rad (unnormalized, rms). In fact, the baseline operations at 100 mA and with 10% vertical coupling leads to a vertical emittance,

$$\varepsilon_y = \frac{X\varepsilon}{1+X} \approx 7.2 \times 10^{-10}\,\text{m-rad} .$$

Assuming the invariant emittance ellipse is given by the standard formalism with Twiss parameters, the transverse profile sizes are:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x} \quad , \quad \sigma_y = \sqrt{\beta_y \varepsilon_y} \quad .$$

Our baseline method is to determine the β-function from the beam transport information and to combine it with the measurement of transverse beam profile projections on the x or y axis. The beam size of the core is generally addressed, but evaluations of the beam halo are also possible with extended dynamic range[5]. The observed beam size is generally the convolution of a number of contributions (the betatron emittance, dispersion/energy spread, system resolution, source diffraction limits, etc.). Under the assumption they can be treated in quadrature,

$$\sigma_{x,obs} = [\beta_x \varepsilon_x + \eta^2 (\frac{\sigma_E}{E})^2 + (\sigma_{DP})^2 + (\sigma_{Res})^2 + (\sigma_{ph})^2]^{\frac{1}{2}}$$

where

$\sigma_{DE}$ = dispersion effect x energy spread, $\eta \frac{\sigma_E}{E}$

$\sigma_x = (\beta_x \varepsilon_x)^{\frac{1}{2}}$
$\sigma_{Res}$ = detector resolution
$\sigma_{DP}$ = diffraction limit
$\sigma_{ph}$ = pinhole resolution.

In the APS bending magnet source $\beta_x$ and $\beta_y$ are about 1.7 m and 18 m, respectively. At the baseline 10% vertical coupling we expect transverse profiles with $\sigma_x \approx 110$ µm and $\sigma_y \approx 100$ µm. For imaging in the ultraviolet with $\lambda \sim 220$ nm, we expect $\sigma_{DF} \approx 40$ µm so reasonable quantitative measurements are possible. For 1% vertical coupling, the implied vertical profile reduces by $10^{1/2}$ to about $\sigma_y = 30$ µm. So for this push in the accelerator parameters we intend to use x-ray pinhole imaging with an aperture of about 20-µm diameter, and a magnification of 4 to 5. The $\sigma_{ph}$ would be about 10 µm then and allow us to even push towards the .1% vertical coupling regime from the diagnostics point of view. Recent tests at NSLS have reported .2% vertical coupling.[6] A schematic for the beam profile imaging using either the UV or x-ray components of synchrotron radiation is shown in Fig. 2.

In either case of ultraviolet synchrotron radiation imaging or x-ray synchrotron radiation imaging, we expect to use gated, intensified cameras to allow single bunch, single turn profile measurement capability. Fig. 3 shows an example of prototype data from the diagnostic line at SSRL. The timing of the microchannel plate gate was stepped through the bunch pattern in the storage ring and off the trailing edge in time. This allowed us to track the integrated image intensity for N = 2, 1, 0 bunches in the time window. The discrete steps in the observed image intensity for the three cases demonstrated the single bunch (~ 1 nC) was imageable. By combining the video detection with an EPICS platform for on-line image analysis, the size of the beam and the emittance calculation (assuming $\beta_x$, $\beta_y$ are measured and stable) will be done at 5 to 10 Hz.

An additional complementary approach will be based on the known effects of particle beam quality on observed undulator radiation properties.[7] The opening angle of the synchrotron radiation at 7 GeV is about 70 µrad and this is unfortunately large compared to the 7-µrad particle beam divergence. One might attack this by using either an N = 100 period undulator to reduce the divergence by a factor of 10 or a coupled undulator approach where $N_D \sim 100$. Both options are under consideration at this time. The more recent formalism involving Twiss parameters determination from undulator radiation is of particular interest.[8]

### 3.2 Stored Beam, Longitudinal Measurement

The beam initially injected into the storage ring will undergo a longitudinal damping process as well. The final bunch length attained will likely depend on beam current/bunch and the magnitude of various wakefield effects. In an earlier workshop to address the possible instabilities in APS, it was estimated the bunch length would be ~30% longer for the 5-mA/bunch case than the low current case.[9] Recently, L. Emery has started a series of calculations of the dynamics of longitudinal phase space during the damping process.[10] The projections on the time or phase axis are directly addressable by synchroscan and dual-sweep-streak camera techniques demonstrated on linac beams, undulator beams, and in the last few years at Tristan and LEP as well.[11] For APS the expected baseline will be $\sigma_t \sim 16$ ps, after damping from the synchrotron ($\sigma_t \sim 60$ ps). The dynamics of these parameters are quite interesting, as shown in Figs. 4-6. In Fig. 4 the actual bunch length variation is plotted turn by turn. On the time scale of turns (at 3.68 µs per turn), noticeable oscillations are seen every 72 turns. In Fig. 5, the average phase position is shown with a phase position variation from 0 to -16 ps. This is easily tracked simultaneously with the bunch length by the dual-sweep streak technique. The energy spread and central value is also dynamic, and Fig. 6 shows the energy vs. phase space on a time track as the beam "spirals" in to the final location in the 2-D space. The projections in the time axis are already addressed; the average energy projections could be assessed by a BPM located in a dispersed region or by time-resolving the undulator spectrum. The same image processing system can process the observed profiles and positions for phase and bunch length measurements at 5-10 Hz. The DC current measurements will be provided by the Bergoz parameteric current transformer at the heart of the DCCT. The charge per bunch will be determined by an integrating current transformer with fast processing electronics to gate on a selected bunch.[12]

### 3.3 Linac Beam, Transverse Measurement

Although emittance measurements will be planned early in the injection into the first linac, the emittance at 200 to 650 MeV will be measured in a straight, 10-m-long drift section that bypasses the PAR. The baseline method will be based on a three-screen technique with the center screen in the middle of the 10-m section. With imaging resolutions planned at 25 µm (FWHM) by using the optical transition radiation (OTR) screens and the appropriate magnifications, the accuracy should be in the 15-20% domain. Making a beam waist or minimum at the center screen will simplify the calculations from the transverse beam projections. Additionally, cross-comparisons of several techniques (including two-screen, OTR interferometers, interference spectroscopy, and quadrupole field scan) with the baseline technique are planned. The OTR

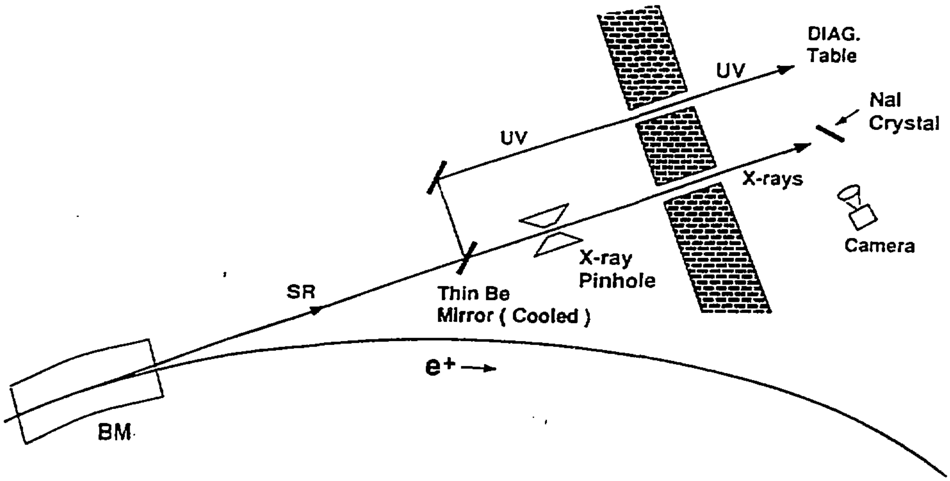


Fig. 2. A schematic of the positron beam imaging via bending magnet synchrotron radiation (UV and X-ray components).

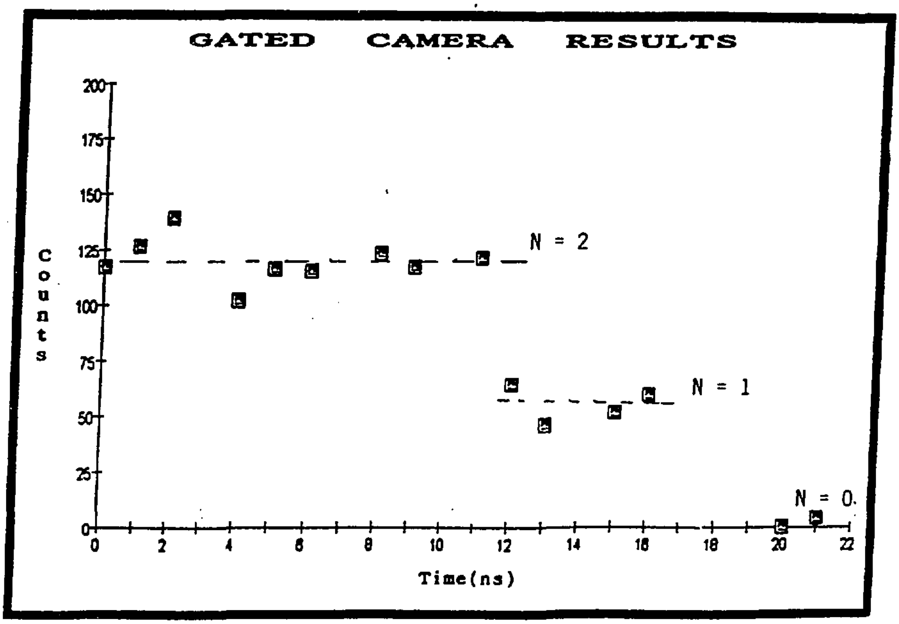


Fig. 3. Gated camera results from SSRL show observation of single electron bunch (N=1) is possible with visible synchrotron radiation.

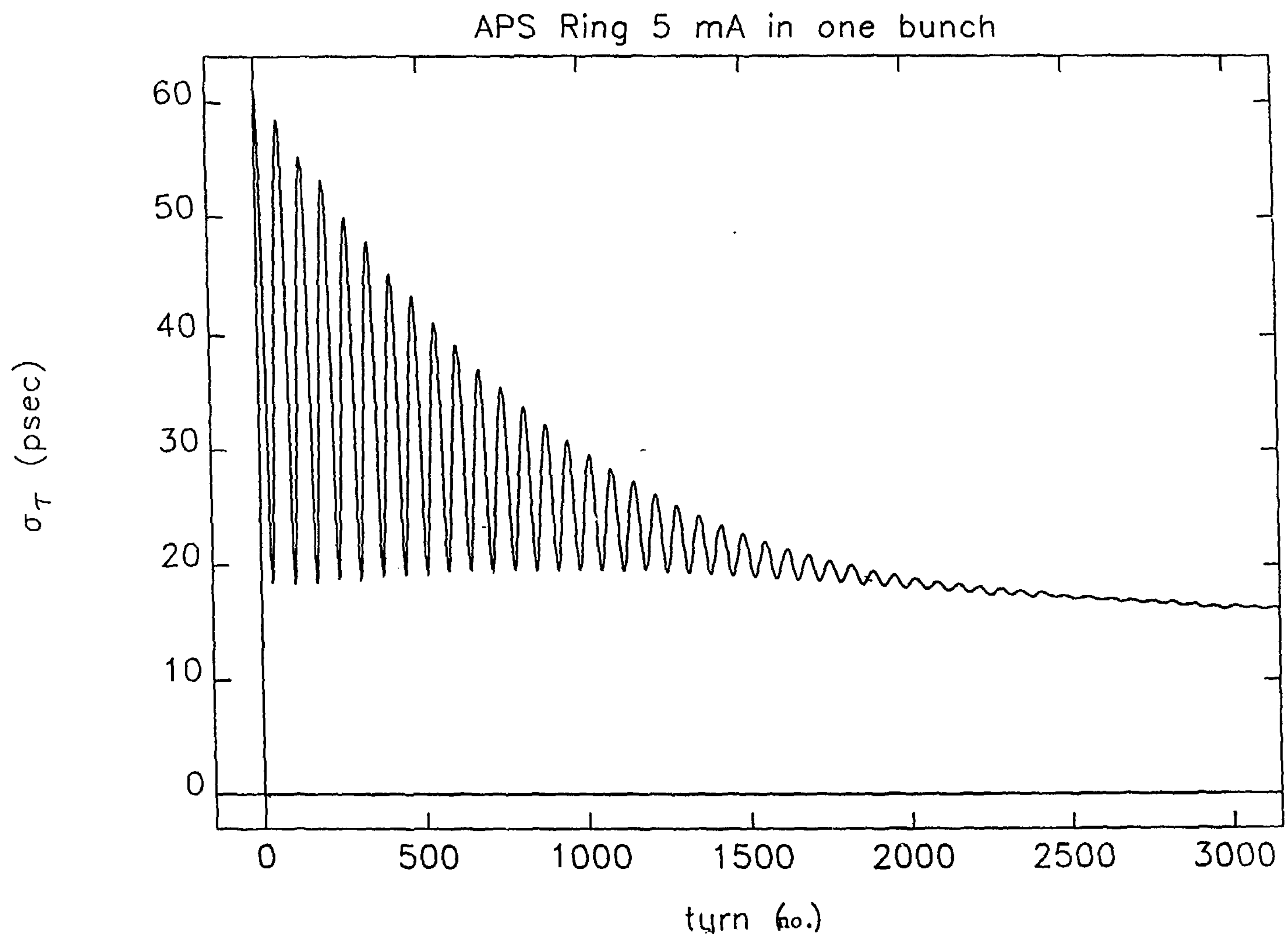


Fig. 4. Simulation of the damping of the positron bunch's temporal length versus turn number in the storage ring.

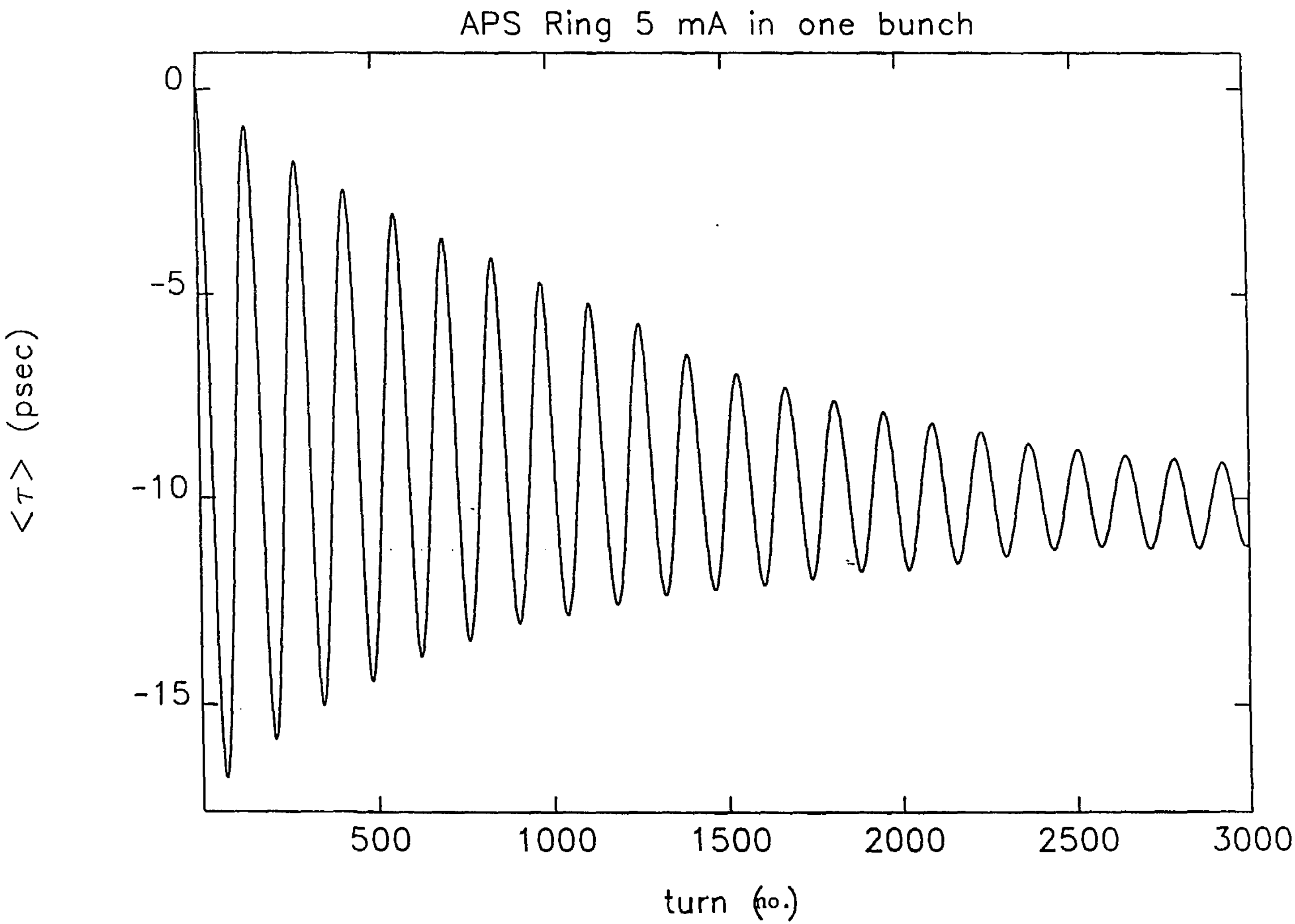


**Fig. 5. Simulation of the variation of bunch phase during damping in the storage ring.**

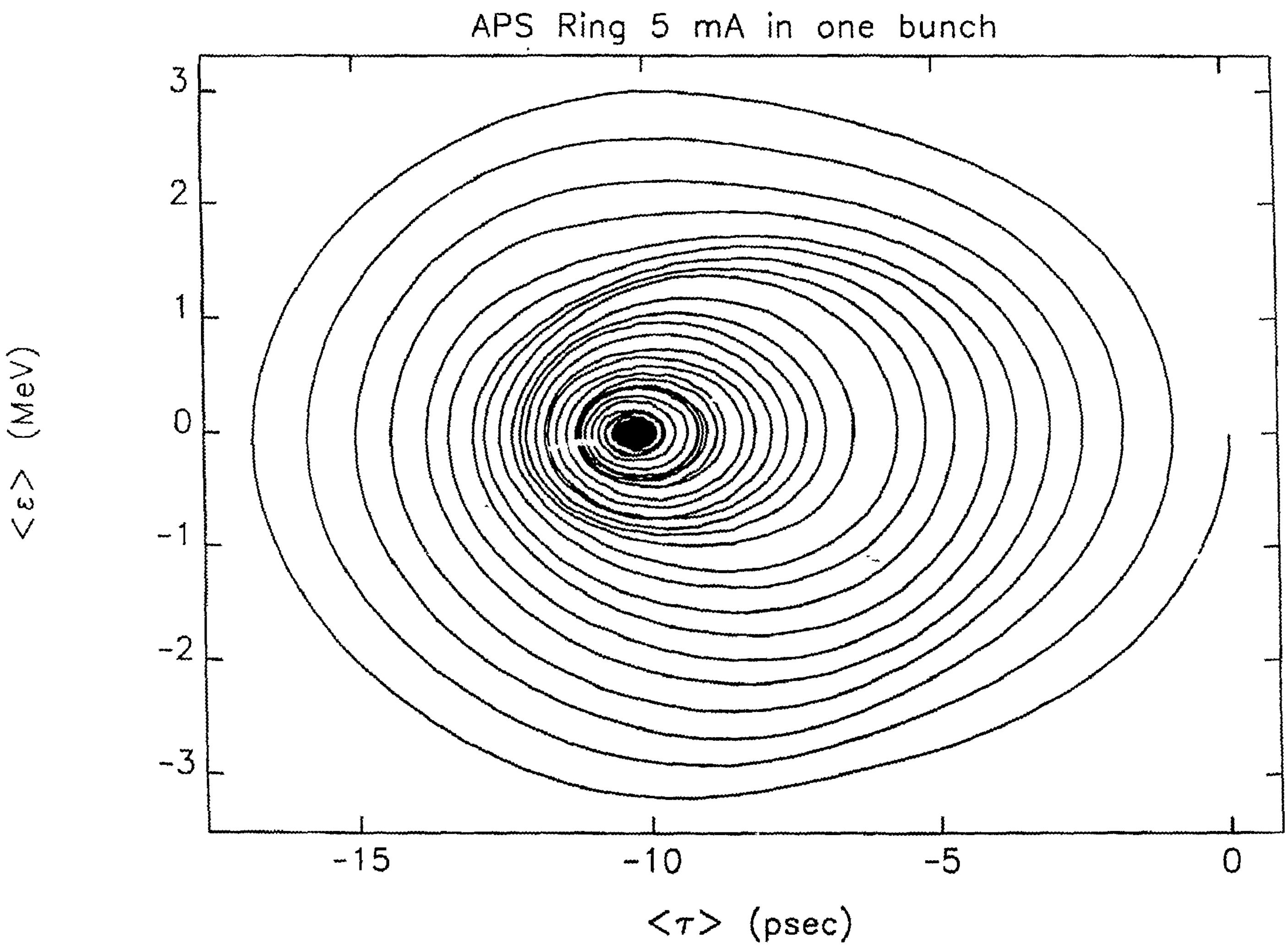


Fig. 6. Simulation of the longitudinal phase space (average energy and average phase) damping dynamics in the storage ring.

interferometer aspects are based on a collaboration with D. Rule and R. Fiorito.[13] With two quadrupoles upstream of the drift section some adjustment of the partition between transverse spot size and beam divergence is possible. The nominal values are $\sigma_{x,y}$ = 50 to 100 μm and $\sigma_{x',y'}$ = 20 to 100 μrad. The critical factor in the interferometer work is whether the beam scattering by the first foil is smaller than the beam divergence. The same image processing system will be applied to these data.

### 3.4 Linac Beam, Longitudinal Measurement

Under the optimized conditions for low peak current, the longitudinal profile is anticipated to be 5 to 10 ps at the base of the profile, implying $\sigma_t$ = 1 to 2 ps. Bunch length will be determined by a streak camera using either OTR[14] or some other prompt mechanism. Any of the three OTR screens in the 10-m bypass line are candidates as the source. If even shorter bunch lengths become possible, an alternative measurement technique based on coherent transition radiation and correlation technique would be explored. It would first be qualified against the streak camera measurements in the few ps regime. Peak currents greater than 100 A are feasible but with a trade-off on beam emittance and brightness. Depending on the effects of space charge, one could approach the parameter space needed to generate coherent UV radiation from a few-meter-long undulator.

## 4. SUMMARY

In summary, key charged-particle beam characterizations are being addressed at the APS which relate to the issue of high-brightness beams and the potential photon beams from them. These systems include both the stored beam of the APS main ring and the prospective low-emittance, 650-MeV beam in the undulator test line. The parameter spaces involved result in extending the envelope of these established diagnostic techniques. Accelerator physics studies will push the design parameters even further. Data useful to the high-brightness radiation community for benchmarking other design activities should result from the commissioning of these two APS sources. In this manner, they may provide part of the transition to the next generation of sources.

## 5. ACKNOWLEDGEMENTS

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