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MEASUREMENTS OF INTRA-BEAM SCATTERING AT LOW EMITTANCE IN THE ADVANCED LIGHT SOURCE

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Abstract

The beam emittance at the interaction point of linear colliders is expected to be strongly influenced by the emittance of the beams extracted from the damping rings. Intra-beam scattering (IBS) potentially limits the minimum emittance of low-energy storage rings, and this effect strongly influences the choice of energy of damping rings [1]. Theoretical analysis suggests that the NLC damping rings will experience modest emittance growth at 1.98 GeV, however there is little experimental data of IBS effects for very low-emittance machines in the energy regime of interest.

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory is a third-generation synchrotron light source operating with high-intensity, low-emittance beams at energies of approximately 1 - 2 GeV, and with emittance coupling capability of 1% or less. We present measurements of the beam growth in three dimensions as a function of current, for normalized natural horizontal emittance of approximately 1 - 10 mm-mrad at energies of 0.7 - 1.5 GeV, values comparable to the parameters in an NLC damping ring.

Using a dedicated diagnostic beamline with an x-ray scintillator imaging system, measurements of the transverse beamsize are made, and bunch length measurements are made using an optical streak camera. Emittance growth as a function of bunch current is determined, and compared with preliminary calculation estimates.

1 ALS MACHINE PARAMETERS

1.1 General Parameters

The Advanced Light Source (ALS) is a third generation synchrotron radiation facility at Lawrence Berkeley National Laboratory, California. The machine, of circumference 196.8 m, operaties typically between 1.5 to 1.9 GeV, with 1 - 2 mA per bunch in approximately 300 bunches in multibunch mode, with bunch length typically 15 ps at 1.5 GeV. Up to 35 mA per bunch may be stored in two-bunch mode. Bunch volume is increased through the use of harmonic cavities in typical operations, in order to improve the Touschek lifetime. The RF system is 500 MHz, and momentum compaction 1.6 x 10^{-3}. Beam parameters for energies at which IBS studies were performed are shown in table 1. Figure 1 shows the triple-bend achromat (TBA) cell, with lattice functions.

For user operations, the machine is typically operated with emittance coupling of 3 - 6 %, to increase the Touschek beam lifetime. The machine is capable of much smaller coupling, and values below 1% may readily be achieved.

Correction of closed orbit distortion and vertical dispersion is achieved through use of the 96 BPM's, 94 horizontal correctors, and 72 vertical correctors. BPM's have approximately 1 micron resolution (multi-turn, 190 averages in approximately 0.5 sec.) Beam-based alignment is used in most quadrupole locations, and a closed-orbit distortion of approximately 50 μm is typical in the arcs, and <10 μm in the straights.

Table 1: ALS parameters

Energy / GeV	0.7	1.0	1.5
Natural energy spread / x 10^{-4}	2.8	4	6
Normalized natural emittance / 10^{-6} m rad	1.0	2.9	10
Damping times, x,y,E / ms	147, 216, 128	52, 74, 44	15, 22, 13

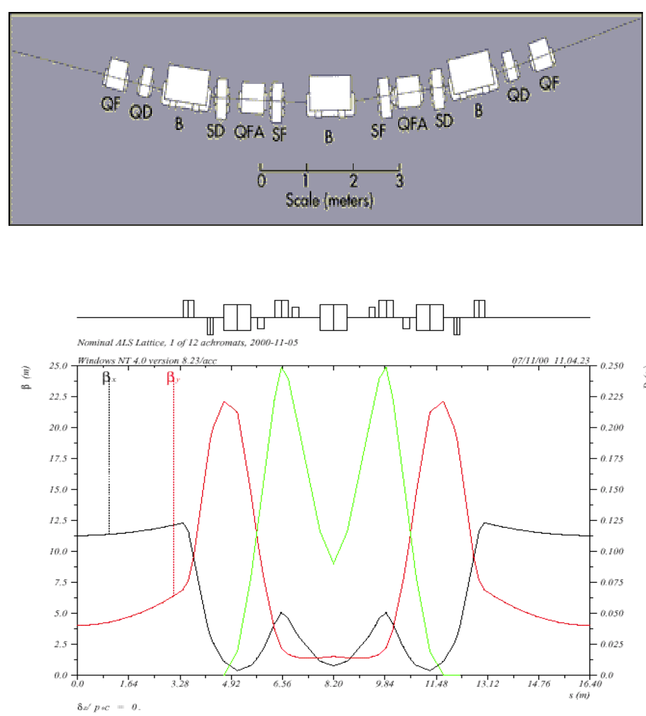

Figure 1: ALS cell and lattice functions.

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1.1 Machine set-up

The machine is set-up by correcting the orbit including RF frequency, setting tunes to optimal values determined from known non-linear dynamics, setting chromaticities, and iterating on tune and orbit corrections. Orbit correction is to quadrupole centers as determined by beam-based alignment.

A model of the lattice is generated from an orbit response matrix using the code LOCO [2,3]. Residual beta-beating can be corrected to less than 1% rms, and is typically 3%. Figure 2 shows residual beta-beat measured at 1.5 GeV without additional correction, with an rms value of 1.3% in the horizontal and 2.2% in the vertical. Measured dispersion is shown in figure 3, showing a typical residual vertical dispersion of 5.2 mm rms. Emittance measurements made with an x-ray beamline (see section 2.2) agree to better than 5% with calculated natural emittances.

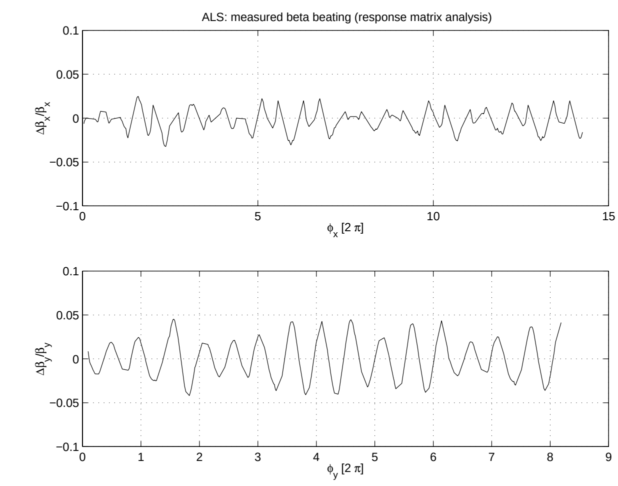

Figure 2: Measured ß-beat.

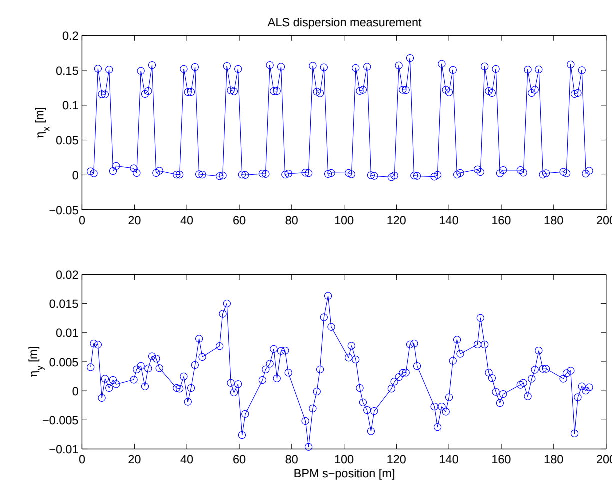

Figure 3: Measured dispersion.

2 DIAGNOSTICS

2.1 Diagnostic beamline 3.1

We use an x-ray beamline (designated 3.1) dedicated for use as an imaging diagnostic, with a source point in the first dipole magnet of a TBA cell. The dipole bend angle is 10°, and the beamline source point is downstream of the center tangent. At this point $ß_y$ varies rapidly, $ß_x$ is smoothly varying with distance along the orbit, and the dispersion is relatively small. Lattice functions at the source point are approximately $ß_x$ = 0.4 m, η_x = 0.03m, $ß_y$ = 19 m, η_y = -0.01 m. Dispersion is readily determined at the source point by measuring beam centroid motion as a function of rf frequency. The beamline location in an arc cell is shown in figure 4.

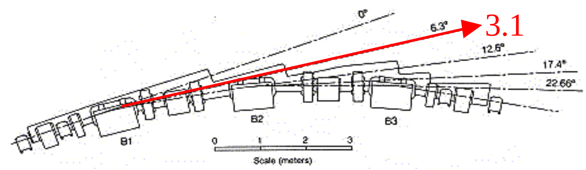

Figure 4: Diagnostic beamline 3.1.

The imaging optics are shown in figure 5. The optical system is a Kilpatrick/Baez mirror system, which produces a 1:1 image of the source on a bismuth germinate crystal. At 1.5 GeV, the optical resolution of the system determined by lifetime and beamsize measurements is less than 10 µm. At this energy or the correction factor is not significant for smallest beamsizes measured. Resolution at lower energies requires further study.

Carbon neutral density filters are used to avoid saturation of the optics and to block visible light. An optical microscope magnifies the visible light image from the crystal scintillator onto a 640 x 480 pixel CCD camera, with pixel resolution of approximately 4 µm.

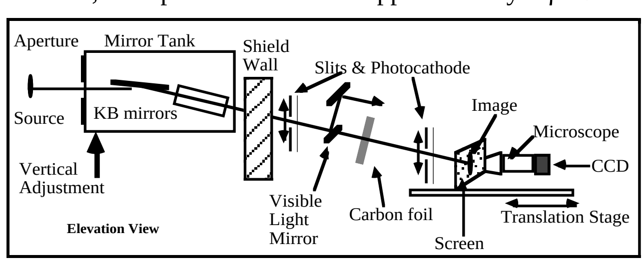

Figure 5: Diagnostic beamline optics

CCD output is read into processing software and a 2-D Gaussian fit is derived for the x,y beam distribution. Since the betatron axes are not in the horizontal and vertical planes at the source point, the fitting routine must find these axes before deriving σ_x and σ_y. This effect is significant since the axes may be rotated by up to 30°, depending on coupling. The error in the fit is typically ±0.5 µm.

2.1 Streak camera

Inserting a mirror into the optical path allows visible light to be brought onto a Hammamatsu C5690 streak camera. Since the insertion of a mirror interrupts the optical path for transverse beamsize measurements, simultaneous observations of longitudinal and transverse beam dimensions are not possible. Streak camera output is recorded and analyzed offline. Statistical averaging is used to determine FWHM values.

3 MEASUREMENTS

3.1 Measurement technique

Measurements of transverse and longitudinal beam sizes are made in single-bunch mode after setup in multibunch mode. A single-bunch current of 1 mA is 0.67 nC or $4.2x10^9$ electrons. Beam current and beam dimensions are recorded as the current decays naturally (for higher current), and by knockout using a pulsed magnet when the lifetime becomes excessive. Coupling is minimized by careful machine set-up and use of the four skew-quardupole families in the ALS. Measurements are made for a given coupling value first in the transverse plane, then in the longitudinal direction. Coupling is increased by changing quadrupole settings to move the tune to a coupling resonance. The coupling resonance is broadened by the use of skew-quadrupoles.

3.2 1.5 GeV

At 1.5 GeV intra-beam scattering is not expected to be significant, and it is known that potential well distortion and microwave instability are significant [4]. No significant effects attributable to IBS were observed. Figure 6 shows bunch length as a function of current for different coupling factors and RF voltage. Increase of transverse bunch sizes is observed and can be consistently explained by energy spread increase due to microwave instability. No difference in bunch length was observed between low-coupling and full-coupling conditions.

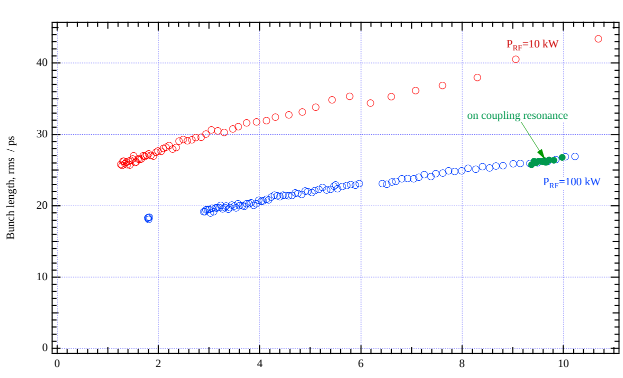

Figure 6: Bunch length measurements at 1.5 GeV

3.3 1.0 GeV

Figure 7 shows the measured horizontal and vertical bunch size and bunch length as a function of bunch current, under different conditions of emittance coupling. Measurements were made at low coupling (2% to 6%), and at high coupling (30% to 50%). It can be seen that the bunch length is increased in the low-coupling case, which is evidence for intra-beam scattering.

The beamsizes at lowest current, 0.25 mA, correspond to normalized emittances of $\gamma\varepsilon_x=4x10^{-6}$ m-rad, $\gamma\varepsilon_y=0.07x10^{-6}$ m-rad, assuming natural energy spread.

For the high-coupling case, changes in transverse dimensions as a function of current are attributed to tune shift with current of approximately $4x10^{-4}$ per mA due to broadband transverse impedance, moving the tune off the coupling resonance.

3.2 0.7 GeV

Growth rates from intra-beam scattering are expected to increase very rapidly at lower energies, and at 0.7 GeV we expect IBS effects to be strong.

Due to suspected limitations in the resolution of the x-ray optics at such low energies, the transverse beamsizes were not recorded during this set of measurements.

Bunch length was measured for different RF voltages, as a function of beam current, on and off coupling resonance. Figure 8 shows the variation of bunch length under these conditions. The increase in bunch length in the off-resonance case is taken as evidence of IBS

4 COMPARISON WITH THEORY

Accurate IBS calculations require knowledge of the contribution to energy spread from the microwave instability, and also bunch lengthening from potential well distortion.

IBS calculations using both the Bjorken-Mtingwa and the Piwinski formalism's have been made for the ALS lattice under assumed conditions of potential well distortion and energy spread from microwave instability at 1.5 GeV. They predict a small effect due to IBS under these conditions, a result consistent with measurements.

At lower energies, however, the potential well distortion and energy spread from microwave instability are not well characterized in the ALS. Assuming no contribution from these effects, we calculate the transverse emittances, and the energy spread, to increase by a factor of 3 to 5 over 0-10 mA per bunch, resulting in a bunch volume increase of 5 to 11. We observe an increase of approximately 6.

5 DISCUSSION

The desire for low emittance at relatively low energy in the NLC damping rings has lead to IBS studies at machines with some similar parameters. Table 2 shows relevant parameters for the NLC damping rings design.

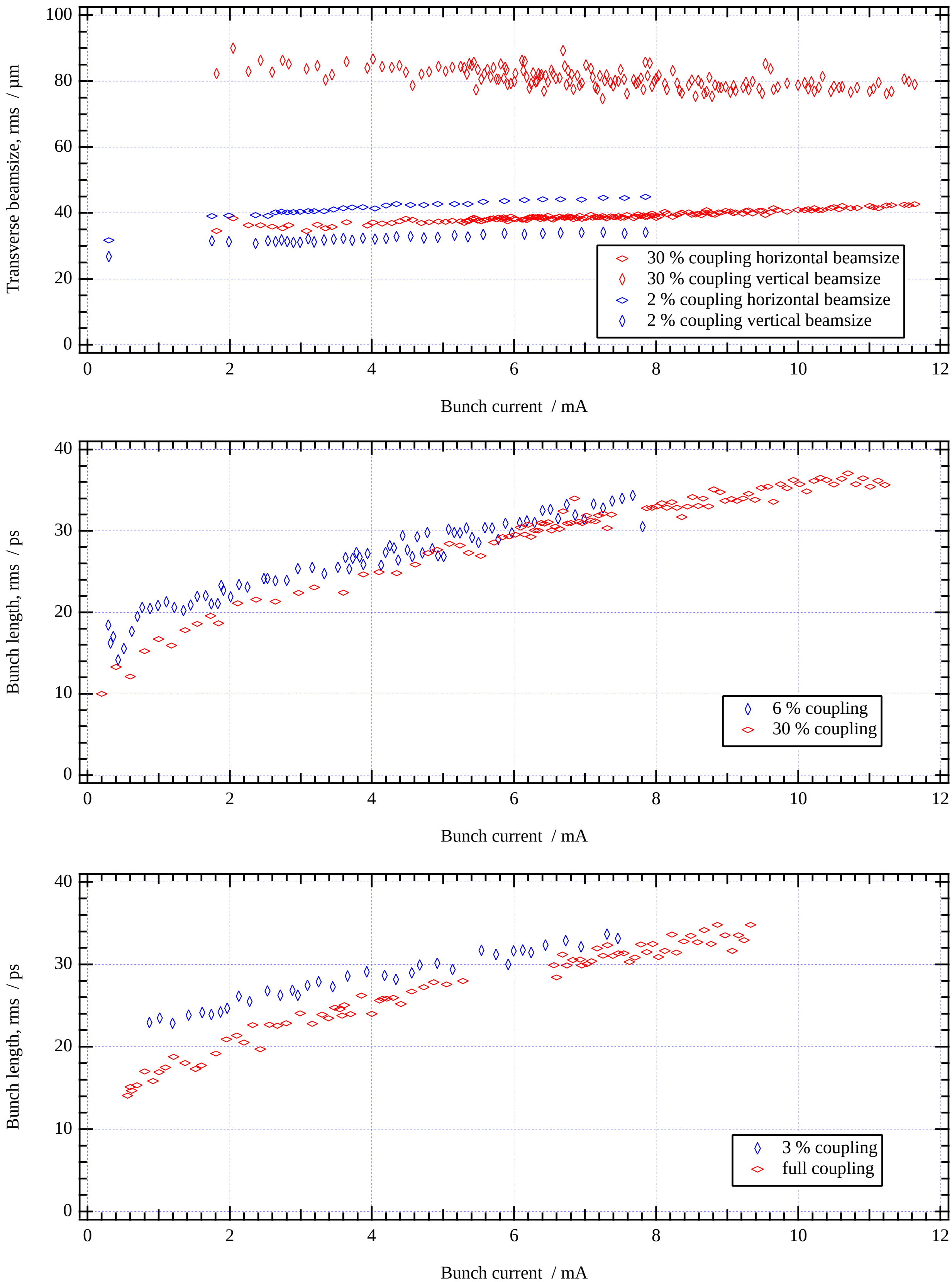

Figure 7: Horizontal, vertical bunch size, and bunch length measurements at 1.0 GeV, as a function of bunch current, and a variety of emittance coupling settings.

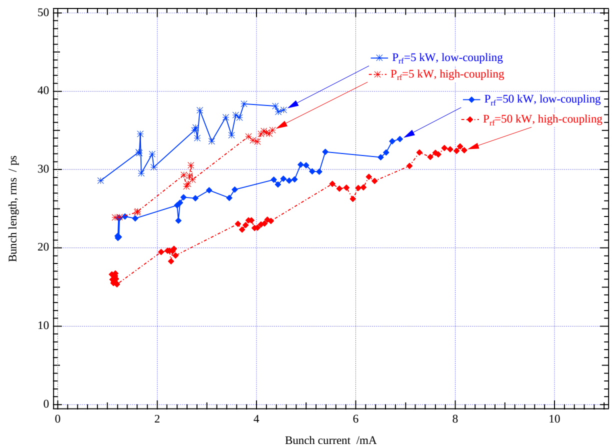

Figure 8: Bunch length measurements at 0.7 GeV

Table 2: NLC main damping ring parameters

Energy / GeV	1.98
Natural energy spread / x 10^{-4}	9.1
Normalized natural emittance / 10^{-6} m rad	2.3
Damping times, x,y,E / ms	4.79, 5.03, 2.58

While the some of the parameters at the ALS do not match those of the NLC damping rings (especially the damping times), the emittance is similar and comparison with theory will allow better understanding and confidence in calculations. In addition, differences in the impedance between machines complicate comparisons, particularly due to potential well distortion and microwave instability. Emittance growth has also been studied at the Accelerator Test Facility at KEK, Japan [5], under conditions similar to the design parameters for an NLC damping ring.

More detailed calculations of IBS are currently in progress. Measurements to date are consistent with preliminary calculations. For future measurements, we plan to have available additional optical diagnostic, with different source point parameters. Data from multiple observation points allows separation of energy spread and transverse emittance. Continued measurements are planned, and measured data will be used to compare with theory and allow improved understanding and confidence in theoretical predictions.

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