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BUNCH LENGTH MEASUREMENTS IN SPEAR3[§]

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Abstract

A series of bunch length measurements were made in SPEAR3 for two different machine optics. In the achromatic optics the bunch length increases from the low-current value of 16.6ps rms to about 30ps at 25ma/bunch yielding an inductive impedance of -0.17Ω. Reducing the momentum compaction factor by a factor of ~60 [1] yields a low-current bunch length of ~4ps rms. In this paper we review the experimental setup and results.

INTRODUCTION

Bunch-length measurements in storage rings historically provide valuable confirmation of operational machine parameters and a means to infer global impedance [2]. More recently, as synchrotron radiation science moves toward THz applications and short-pulse x-ray research, a premium has been placed on production of short bunch lengths [3]. A 10ps FWHM (4ps rms) bunch, for instance is an important milestone to enable studies of a new class of dynamical systems [4]. Following this line, we have begun to characterize bunch length as function of bunch charge under different operating conditions.

SPEAR3 is a 3GeV, 18-cell, double-bend achromat light source capable of storing up to 500ma with a 1.2MW, 3.2MV rf system [5]. In the 15nm-rad achromat optics, the typical single-bunch current is 0.3-1.5ma with a natural bunch length of 16.6ps. A single-bunch current limit of 25ma is imposed by thermal limits. With $\eta^*=0.1$m dispersion in the straight-sections, the emittance has been lowered to 10nm-rad [6] but bunch length measurements are not yet available. Studies with reduced momentum compaction ($\eta^*<0$) have produced σ_τ~4ps rms at low single-bunch current. The following sections discuss the streak camera setup and measurements in the achromatic and low-alpha modes of operation.

STREAK CAMERA SETUP

The SPEAR3 diagnostic beam line [7] utilizes an in-vacuum, 18^o horizontal mirror to deflect visible dipole radiation onto an optical bench. Discrete apertures are set for an acceptance of 3.5x6 mrad while a horizontal 'cold finger' blocks the x-ray core of the beam. At 15m from the source, an f=2m, 150mm diameter objective lens focuses the beam into a system of mirrors and relay lenses leading to different diagnostic stations (Fig. 1).

For bunch length measurements, two dual-axis Hamamatsu C5680 streak cameras were used at different times: (1) the analog ALS camera equipped with the 119MHz APS syncroscan module, and (2) the 119MHz PEP-II system equipped with a digital camera. In each case, a microscope objective lens focused 550nm light onto the camera input slit. An effective PSF was measured in the focus mode and vertical R2 and R3 sweep speeds were calibrated with a glass etalon and/or etalon supplied by Hamamatsu. R1 sweep speed (~0.43ps/pixel) was deduced from bunch length measurements at R2. In the case of the ALS camera, chromatic dispersion of ~50pixel/250nm in R2, or about 0.2ps/nm was measured through the input barrel by using a series of color filters.

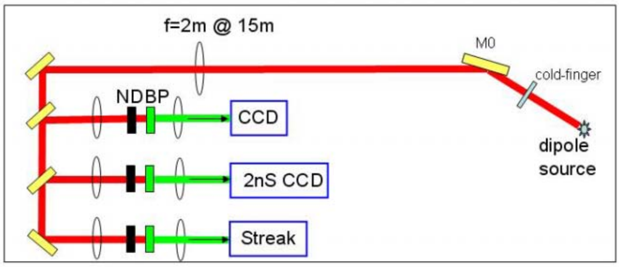

Figure 1: SPEAR3 diagnostic beam line.

Initial bunch length measurements with the ALS camera *without* synchroscan suffered from pulse-to-pulse timing jitter and a low photon count rate. Multiple frame 'movies' were accumulated to increase statistical accuracy of the data - numerically fitting values for beam centroid and rms spot size produced statistically viable results.

Installation of the 119MHz APS syncroscan module lead to more systematic measurements yet the system still suffered from synchronization issues associated with the analog camera. The PEP-II camera was commissioned at SPEAR without significant problems.

ACHROMAT OPTICS

Due to limited camera availability, most measurements were taken in the achromatic optics mode. Initially we triggered the sweep plates with a decimated version of the ring clock (1.28MHz) with significant shot-to-shot timing jitter. We post-processed this data to obtain the average. The camera was set up to record ten independent streaks per frame; each data set acquired 500 frames. Due to the low current per bunch, the statistics in each streak were low, typically only a few thousand counts. The data from each streak could then be considered as a small sampling

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of the total bunch radiation. If the system were stable, the underlying distribution would be Gaussian.

Using the zeroth, first, and second moments of each streak to obtain an initial estimate, we fit the data to a Gaussian distribution. The data from two representative streaks are pictured in Fig. 2. A histogram of the 5000 σ's from the data taken with 600μA per bunch produced a Gaussian plot, showing that the underlying distribution was also Gaussian and suggesting that the bunch was stable at this current.

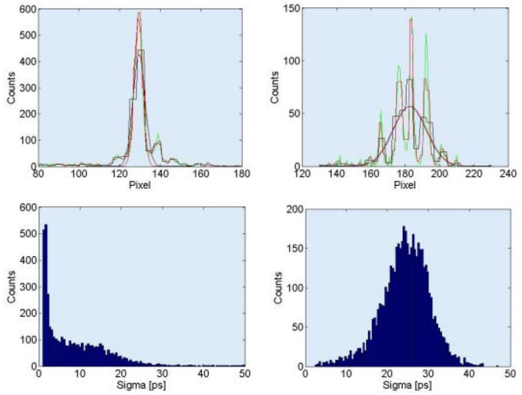

Figure 2: Examples of Gaussian fits for 100μA/bunch, wide- (100 μA) and normal distributions (600μA/bunch).

At 100μA per bunch current, the results were significantly different. The two representative streaks are plotted in Fig. 2 at this current, showing the variance of the data. The histogram of the σ's for this data is clearly not Gaussian, showing that the beam is definitely not stable. The conclusion from both of these results is that the bursting of the beam observed [3] and predicted [8] occurs at 100μA currents, while the beam is already well above saturation at 600μA per bunch.

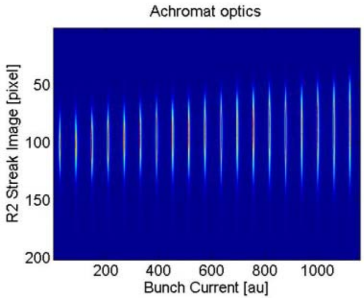

Figure 3: Bunch lengthening in the achromatic optics.

After installing the APS synchroscan module, shot-to-shot jitter was minimized but ~1ps rms phase-noise remained on the beam. Figure 3 shows a composite plot of syncroscan images captured in R2 during a non-uniform progression of single-bunch current from 165μA/bunch to 24ma/bunch. The corresponding image profiles in Fig. 4 show the bunches 'leaning' into the rf potential as a result of resistive-wall impedance.

Using FWHM data reported by the C5680 software, the rms bunch-length is plotted as a function of single-bunch current in Fig. 5. For nominal operating conditions (0.3-1.5ma/bunch) bunch lengthening is <5%. To extract the inductive impedance, we used Zotter's bunch length scaling law [2],

$$\left(\frac{\sigma_z}{\sigma_{zo}}\right)=\left(\frac{\sigma_z}{\sigma_{zo}}\right)^3+\frac{1}{\sqrt{2\pi}}\frac{\alpha_c I_b}{\nu_s^2 E/e}\left(\frac{R}{\sigma_{zo}}\right)^3\cdot \mathrm{Im}\left(\frac{z_0^{\|}}{\mathrm{n}}\right)_{eff}$$

where the first term on the RHS can be attributed to optics ($\sqrt{\alpha}$) and the second term to inductive impedance. A numerical fit to the data yields σ_{zo}=16.7ps and Im{Z/n_{eff}} =-0.17Ω, indicating a smooth vacuum chamber.

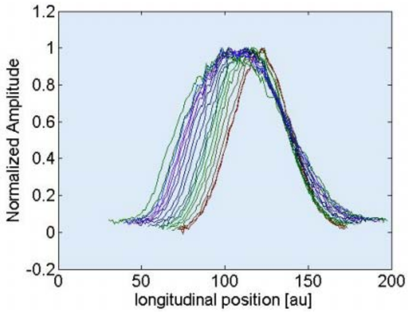

Figure 4: Single-bunch profile distortion.

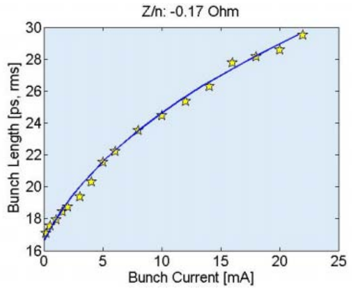

Figure 5: rms bunch length vs. single-bunch current. The fitted curve yields σ_τ=16.7ps and Z/n=-0.17Ω.

LOW-ALPHA OPTICS

Bunch length measurements were repeated during tests of several low-alpha lattices. Since the achromatic momentum compaction factor (α_1=0.0012) yields a relatively short bunch length, in principle only a modest reduction by $\sqrt{\alpha}=4$ is required to reach 4ps rms at low current. Figures 6a,b show two sets of synchroscan images taken with α/21 and α/59. Progressing from left to right across the α/21 data set, for example the current increases from 18μA/bunch to 1000μA/bunch in non-equal increments.

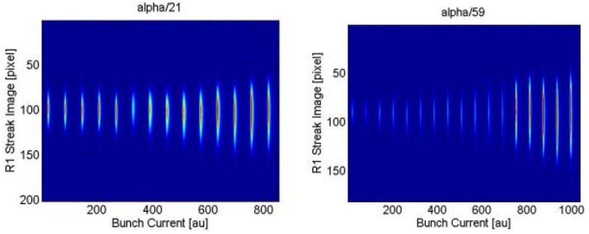

Figure 6: Streak camera images of bunch lengthening as a function of current with α/21 and α/59 optics.

Figure 7 shows rms bunch length in the $\alpha/21$- and $\alpha/59$-optics plotted as a function of single-bunch current. By removing both the experimental PSF and 1ps rms timing jitter in quadruture, the low-current values are 4.63ps and 3.08ps rms, respectively. Direct $\sqrt{\alpha}$-scaling would yield 3.6ps and 2.2ps rms natural bunch lengths. Fits of the data to theoretical scaling laws are contained in [1]. To achieve these values may require less charge/bunch or careful control of α_2. The green-dot data point (2.5 ps rms) was measured with $\alpha/240$ and 1.12ma distributed in 280 bunches.

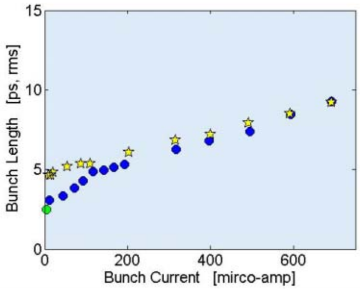

Figure 7: FWHM bunch length as a function of I_b for alpha/21 (yellow stars) and alpha/59 (blue circles) optics. Green indicates 4μA, 2.5ps rms bunch at $\alpha/240$.

With an eye to increasing average beam intensity, Figure 7 indicates it is possible to produce σ_τ~4ps rms with single bunch currents of order 100μA. Preliminary tests with 17mA in 280 buckets (67μA/bunch) produced σ_τ=3.82ps rms while 99mA in 280 buckets (350μA/bunch) produced σ_τ=6.38ps rms. Both measurements are consistent with Fig. 7 indicating no severe multi-bunch instabilities.

In parallel with the streak camera program, bolometer measurements showed some signature of THz SR 'bursting' at high single bunch currents.

SUMMARY AND FUTURE WORK

An initial series of bunch length measurements utilizing the ALS/APS and PEP-II streak cameras confirmed the theoretical bunch length for the nominal SPEAR3 optics. and demonstrated the efficacy of bunch-length reduction by lowering momentum compaction. Both syncroscan and non-syncroscan measurements were used in the process.

As indicated in Fig. 8, SPEAR3 can generate the <10ps FWHM bunch lengths. We are presently working to achieve this condition with up to 100ma total beam current, reliable injection and active orbit control.

Future measurements include bunch length characterization in three modes of operation: achromatic optics (15nm-rad), low-emittance optics (10nm-rad, η_x^*=0.1) and low-alpha (short bunch) optics. In each case, effective impedance, pulse shape distortion and the effect of RF voltage can be evaluated. A more comprehensive study would measure bunch length as η_x^* in the straight-sections is progressively scanned from positive to negative values with data correlation to beam cross-section, effective impedance and stability.

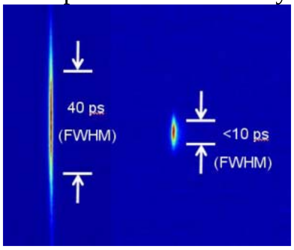

Figure 8: Syncroscan image in achromat and $\alpha/59$ optics.

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REFERENCES

[1] X. Huang, et al., 'Low-Alpha Mode for SPEAR3', these proceedings.

[2] B. Zotter, 'Potential-Well Bunch Lengthening', CERN SPS/81-14 , Geneva (1981), J.-M. Ko, et al., 'Impedance Estimates from Bunch Lengthening in the Pohang Light Source', JJAP 44, 1A (2005) and R. Dowd, et al., 'Measurements of Impedance and Beam Instabilities at the Australian Synchrotron, these proceedings.

[3] see for example J. Feikes, et al., 'Toward Sub-Picosecond Electron Bunches: Upgrading Ideas for BESSYII', EPAC 2006, J. Feikes, et al., 'Compressed Electron Bunches for THz-Generation – Operating BESSY in a Low Alpha Mode', EPAC 2004 and ICFA Workshop on Frontiers of Short Bunches', http://www.lnf.infn.it/conference/sbsr05/.

[4] Y. Acremann, et al., 'Time-Resolved Imaging of Spin Transfer Switching', PRL 96, 217202 (2006).

[5] R. Hettel, et al., 'The Completion of SPEAR 3', EPAC04.

[6] J. Safranek, et al., 'SSRL Accelerator Physics Update', these proceedings. Note that power loss from IDs reduces natural emittance by 2-3 units.

[7] J. Corbett, et al., 'The SPEAR 3 Diagnostic Beamlines', PAC 2005 and 'Commissioning of the SPEAR3 Diagnostic Beam Lines', EPAC 2006.

[8] G. Stupakov and S.Heifets, 'Beam Instability and Microbunching due to Coherent Synchrotron Radiation', Phys. Rev. ST Accel. Beams 5, (2002).