SHORT BUNCH MEASUREMENTS IN SPEAR3 §

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Abstract

Recent advances in the theory of short-bunch beam physics and direct observations of short-bunch operation in storage rings have lead to an improved understanding of the potential for and limitations of low momentum compaction lattices (low-α). This approach has been used SPEAR3 to generate ~2.5ps rms bunches for moderately short x-ray pulse applications. In this paper, we examine bunch length scaling as a function of α and single-bunch current in order to generate a scaling law similar to BESSY-II [1]. Multi-bunch current limits are considered for low- and high repetition rate experiments.

INTRODUCTION

In recent years storage ring physics has seen a resurgence of interest in low-momentum compaction lattices for both THz radiation and short x-ray pulse production. Several workshops, review papers, theoretical developments [2-3,4,5-7] and an increasing number of experimental results [1,8-10] have produced a body of knowledge of sufficient depth that proposals for dedicated short-bunch storage rings are now possible [11]. Several storage rings operate periodically in short-bunch mode to produce THz radiation for scientific applications.

In many cases, the short pulse, longitudinal charge distribution is dominated by the short-range CSR wakefield which limits the total charge/bunch to relatively low values. Above predictable current thresholds, 'bursting' instabilities generate intense THz radiation which has been explained using models based on the Vlasov equation with the collective force of the CSR wake acting as the driving term [5,6]. Similarly, attempts to model bunch-lengthening by incorporating both shielded- and un-shielded CSR in the wakefield term of the Haissinski equation have proven successful [2,3].

In this paper we report on a series of low-α measurements at SPEAR3. The nominal operating bunch length is of order 20ps rms but some users are interested in <4ps rms bunch lengths to enhance time resolution. We need therefore only reduce α by a relatively modest value of ~ α/50 to achieve the goal. Nevertheless, rapid onset of bunch lengthening is observed along with evidence of bursting at higher single-bunch currents. Bunch length scaling with both α and current closely follows the scaling law previously reported in research at BESSY-II [1].

LOW-α OPERATION IN SPEAR3

SPEAR3 nominally operates with a double-bend achromat cell configuration but with positive dispersion in the straight sections to yield ε_x~10nm-rad at 3 GeV beam energy and 3.2MV accelerating voltage. By tuning the dispersion function between positive and negative values, however, the synchrotron integrals change resulting in either longer, low transverse-emittance bunches or short, high transverse-emittance bunches, respectively. By driving dispersion in the straight sections to negative values, the argument of the synchrotron integral $I_4 = \frac{1}{L}\oint \frac{\eta}{\rho} ds$ cancels in the dipoles leading to the quasi-isochronous condition (α~0) and consequently short bunches. Unfortunately, operation at low-α also comes at the cost of low synchrotron tune ($\nu_s \propto \sqrt{\alpha}$) and reduced instability thresholds. On the other hand, by reducing α by only a factor of ~50, the SPEAR3 beam remains relatively stable and up to 100μA bunches can be operated without undo bunch lengthening.

STREAK CAMERA CONSIDERATIONS

The SPEAR3 diagnostic beam line receives visible/UV SR from a standard dipole magnet. Bunch length measurements are made by imaging the source onto the input slit of a dual-axis Hamamatsu C5680 streak camera with 119MHz syncroscan and an ORCA digital camera. As reported in [12], we estimate the inherent resolution of the streak camera imaging 550nm light with 40nm FWHM in syncroscan mode is σ_{res}=2.16ps rms. The additional effect of synchrotron oscillations will modulate the pulse delay time further reducing system resolution. Measurements of short bunch lengths therefore represent a combination of systematic and random effects. By way of Gaussian de-convolution we have

$$\sigma_{act}^2 = \sigma_{meas}^2 - \sigma_{rip}^2 - \sigma_{res}^2 \qquad (1)$$

where σ_{act} is the actual rms pulse length, σ_{meas} is the measured rms value, σ_{rip} represents ripple on pulse arrival time and σ_{res} is the camera resolution. Typical exposure times for syncroscan measurements are 120ms, so the ~kHz ripple effect is significant. Under conditions with minimum ripple, σ_{rip}=1ps, and the combined term $\sqrt{\sigma_{rip}^2 + \sigma_{res}^2}$ is 2.38ps. Since this value can change with α and stability of the RF system on a given day of measurement, it is important to quantify both σ_{res} and σ_{rip} carefully as the pulse lengths of interest are of the same order as the system resolution.

Figure 1 shows a typical synchrotron oscillation as seen in the dual-scan mode. The central black-dotted line represents the centroid value calculated from a 6-pixel wide Gaussian boxcar fit moving along the horizontal axis. In this case the rms ripple is ~2.0ps.

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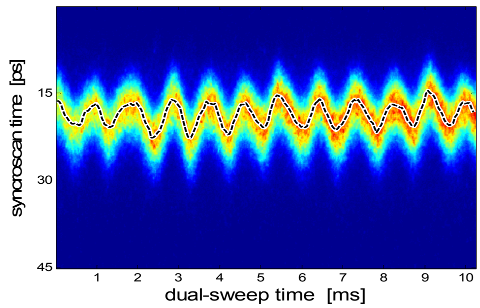

Figure 1: Sychrotron oscillations observed in Hamamatsu C5680 R1 dual scan mode. Fast vertical sweep range is 45ps, slow horizontal sweep time is 10ms.

LOW-α BUNCH LENGTHENING

The electron bunch length was measured in syncroscan mode for a series of momentum compaction factors and a range of single-bunch beam currents. For these experiments, the momentum compaction values are relative to the 'achromatic' optics with α_{ac}=0.00117 and f_s~10kHz. A 'matched' lattice was established at α_{ac}/59, and f_s was then varied by tuning the dispersion-focusing quadrupoles in the center of the DBA cells. In this range of α-values, only small changes in magnet current (<1%) create large variations in momentum compaction. At each magnet setting, α and f_s were recorded along with bunch length as a function of single-bunch current.

Following the lead of BESSY-II [1], the data was plotted on a log-log scale using almost exactly the same BESSY-II format, and then fit to

$$\left(\frac{\sigma}{\sigma_o}\right)^4 = \left(\frac{f_s}{f_{s,o}}\right)^4 + \left(\frac{I}{I_o}\right)^n \qquad (2)$$

where σ_o is the zero-current bunch length, $f_{s,o}$ is the baseline synchrotron frequency and both I_o and n are variable parameters. The exponent 'n' is intimately connected to the bursting threshold [5] and observations of short-bunch bursting in SPEAR3 are reported in [13].

Rather than find the best numerical fit to all four parameters $\{\sigma_o, f_{s,o}, I_o, n\}$ in Eq. 2, we imposed nominal values of σ_o=16.8ps and $f_{s,o}$=10kHz and found values of I_o=3.8mA and n=1.7 using 'chi-by-eye' fitting. The results are shown as blue dots (data) and blue lines (Eq. 2) for four values of f_s corresponding to reductions in α by 7.5, 11.7, 25.1 and 51.6, respectively. For this dataset the bunch length measurements were deconvolved with σ_{res}=2.16ps and σ_{rip}~2.0ps as per Eq. 1 and Fig. 1.

Also included in the plot are calculated curves for f_s=0.5kHz (α~3x10^{-6}) and f_s=10kHz (α~1x10^{-3}) using the same fitted values for $\{\sigma_o, f_{s,o}, I_o, n\}$. The open blue circles represent f_s=1.5kHz data taken on a separate day with higher top-end single-bunch current values. Interestingly, Y.Cai has found SPEAR3 bunch lengthening can be numerically modeled using a single inductive chamber impedance parameter for all but the very short-bunch data where CSR impedance dominates [14].

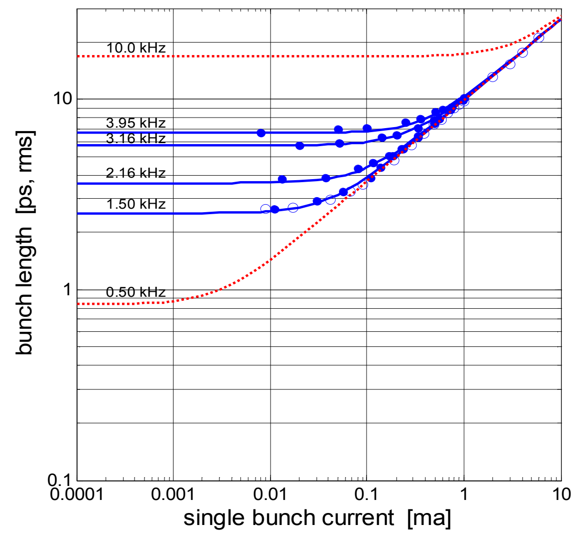

Figure 2: Low-α mode bunch lengthening. 0.5kHz and 10kHz curves extrapolated from Equation 2.

MULTI-BUNCH FILL

Bunch-lengthening in the low-α optics was also measured in a 280-bunch fill pattern. In this case, we used both the dual-axis, box-car analysis described above to extract bunch length and single-axis syncroscan measurements with both arrival time ripple and camera-resolution de-convolution. The results shown in Fig. 4 indicate that a) at higher total beam current, the bunch length is slightly increased relative to the equivalent single-bunch value, and b) the box-car method slightly over-estimates bunch length, potentially due to the finite time integration interval.

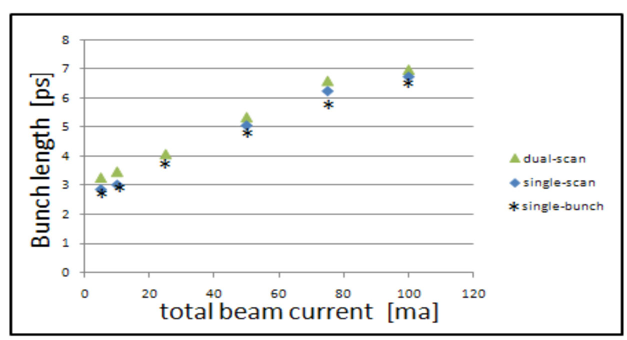

Figure 3: Multibunch fill with single-bunch superimposed.

PUMP/PROBE APPLICATIONS

Of particular interest at SPEAR3 are synchronized TiSa-laser (pump), x-ray beam (probe) experiments to measure fast chemical dynamics. For certain classes of measurements, it is desirable to reduce the x-ray probe beam duration to <10ps FWHM (~4.0ps rms). Referring back to Fig. 2, the maximum single-bunch currents will limited to <100μA or I_{total}~30ma in the nominal 280 bunch fill pattern. Total current is also important for applications requiring high flux THz CSR.

Laser-pulse repetition frequency and/or sample relaxation times can also restrict total beam current. The TiSa laser presently in operation at SSRL, for instance, produces 0.5μJ pulses at a maximum rate of 5MHz. To avoid interference from adjacent electron bunches, a symmetric 4-bunch fill pattern is optimum.

Referring to Fig. 5, we can plot total beam current as a function of x-ray pulse repetition frequency based on the desired photon pulse length. For each curve the 1MHz (single-bunch) current is extracted from Fig. 1 at the point where 5% bunch lengthening occurs. The two calculated red lines again correspond to f_s=0.5kHz (α~3x10^{-6}) and f_s=10kHz (achromat) optics, respectively. In the case of the f_s=10kHz curve, the baseline current at 1MHz was set to 2mA because a) chamber impedance influences bunch length in the few mA range, and b) 2mA is the single-bunch current for 500mA with 280 bunches.

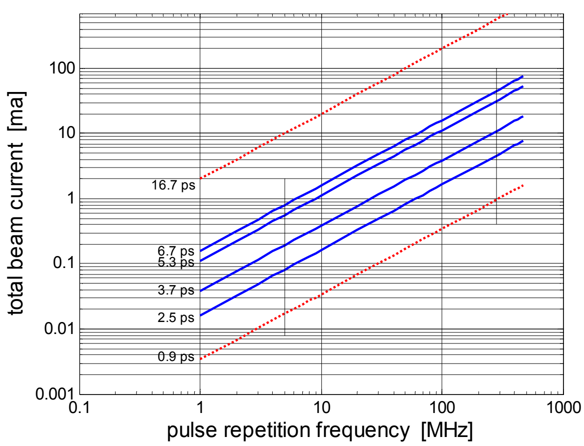

Figure 5: Total beam current vs. pulse rate for the range of bunch lengths corresponding to Fig. 1.

The two vertical bars in Fig. 5 indicate where 5MHz (laser-limited) and 476MHz (280 bunch train) pulse repetition occur. Assuming 4-bunch, 4 ps rms operation at 5MHz, for instance, the *total* beam current is restricted to ~400μA. To circumvent this restriction one could operate at lower values of α and allow bunch lengthening to the desired value. In the case of 4ps pulses, for example, the total beam current could be increased to about 50% by using f_s=0.5kHz optics instead of the 3.15kHz optics (see Figure 1). Potential drawbacks include bunched-beam bursting dynamics and reduced optical and orbit stability.

SUMMARY AND FUTURE WORK

Short bunch operation in the low-α mode at SPEAR3 shows good agreement with scaling laws previously observed at BESSY-II. Data analysis is complicated by streak camera resolution and synchrotron oscillations when the bunch length is reduced near the resolution limit. Bunch lengthening in the multi-bunch regime is comparable to the single bunch case and scaling laws for total beam intensity as a function bunch length are developed.

Future work includes further development of ultrafast capability for time-resolved x-ray experiments at SPEAR3 in the ~1ps regime, bolometer measurements to monitor THz bursting at the diagnostic beam line and development of an IR/THz beam line [15].

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