ELECTRON BEAM LONGITUDINAL PROFILE MEASUREMENTS AT HIGH CHARGE IN THE APS-U PARTICLE ACCUMULATOR RING*

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Abstract

Reduction in the extracted PAR bunch duration has been observed after modifications including reduced impedance kicker chambers and higher 12th harmonic amplitude rf. Recent PAR charge requirements for storage-ring operations are 5-6 nC per bunch for 216 many-bunch mode at 200 mA and 14-15 nC per bunch for 48-bunch timing mode at 130-140 mA. At these charge levels, extracted RMS bunch durations of 400 ps and 490 ps, respectively have been measured. 20 nC is required for 200-mA timing mode. PAR bunch length has been obtained from a fast light detector diagnostic known as the bunch duration monitor (BDM). We have recommissioned the Hamamatsu C5680 streak camera using both M5677 slow vertical sweep scan and M5675 synchroscan units for comparison with the BDM. Bunch length and calibration data from the streak camera have been obtained and will be discussed.

INTRODUCTION

Operation of the Advanced Photon Source Upgrade (APS-U) storage ring, demands higher charge from the injectors including the particle accumulator ring (PAR). Increased charge leads to a growth in PAR bunch length which can lead to inefficient injection into the booster synchrotron.

For 48-bunch, timing-mode operation at 200 mA, a single 16-nC bunch must be delivered to the APS-U storage ring (SR). This charge must first be injected in to the booster synchrotron for acceleration to 6 GeV. Both the booster and SR rf operate at 352 MHz. Booster charge is supplied by the particle accumulator ring (PAR) which stores electrons from the linac at 425 MeV in a single bunch. This bunch must fit well within the 2.84-ns booster rf bucket for efficient injection. An rms bunch duration of ≤ 600 ps (1410 ps, FWHM) is required to achieve ≥ 85% injection efficiency into the booster [1]. Because of injection losses in the booster and the storage ring, approximately 18 nC is required from the PAR. At this high charge, the bunch length will grow and instabilities may appear limiting injection efficiency. We measure the PAR bunch length with two optical diagnostics, a streak camera and a metal-semiconductur-metal (MSM) photodetector known as the bunch duration monitor (BDM) [2]. Both diagnostics detect optical synchrotron radiation from the PAR beam. Recent changes to the PAR have been undertaken to increase its charge storage capacity including solide-state low-level rf, solid-state harmonic rf amplifiers providing higher rf voltage, and reduced impedance kickers. After these modifications had been made, a significant reduction in bunch duration was observed with the BDM. The streak camera was recommissioned to verify these observations.

ANALYSIS

The distortion of the bunch comes from a number of sources. Assuming a sinusoidal restoring force, large excursions from the bucket center cause the force to become nonlinear. Another source come from wake fields.

We follow the analysis given by Chao [3] of potential well distortion, where the effect of longitudinal wake fields on bunch shape is investigated for a filamentary line charge of density ρ. For a purely resistive impedance or equivalently a wake field defined for the special case of $W'(z) = S\delta'(z)$, where δ is the delta function, a closed form expression for the line charge density may be written as,

$$\rho(z) = \frac{\sqrt{2/\pi}\,\exp(-(z-z_o)^2/(2\sigma_z^2))}{\alpha\sigma_z[\coth(\alpha N/2) - \mathrm{erf}((z-z_o)/(\sqrt{2}\sigma_z))]}, \quad (1)$$

where

$$\alpha = \frac{r_0 S}{\eta\sigma_\delta^2\gamma C}, \quad (2)$$

$$S = \left|-i\left(\frac{c^2}{\omega_0}\right)\left(\frac{Z_0^{||}}{n}\right)\right|, \quad (3)$$

$$N = \int_{-\infty}^{\infty}\rho(z)dz, \quad (4)$$

r_0 is the classical electron radius, η the slip factor, σ_δ the fractional energy spread, γ the Lorentz factor, C the PAR circumference, ω_0 the revolution frequency, and $Z_0^{||} = \xi Z_0$. $Z_0^{||}$ is the total longitudinal impedance, Z_0 is the impedance of free space, and ξ is a factor depending on the geometry of the chamber and fields at the wall to be determined by the fit. Fits are carried out using the self-describing data set (sdds) toolkit command `sddsgenericfit` [4, 5]. Parameters solved for in the fit are α, N, σ_z, z_0, and A. N is taken as the total charge rather than Eq. (4) and A is used to adjust the amplitude to account for effects such as variations in streak camera micro-channel plate (MCP) gain.

MEASUREMENTS

Streak Camera

Data recorded with the synchroscan unit were obtained during a study shift on January 31, 2026. The measured pulse duration is sensitive to MCP gain; too much gain drives

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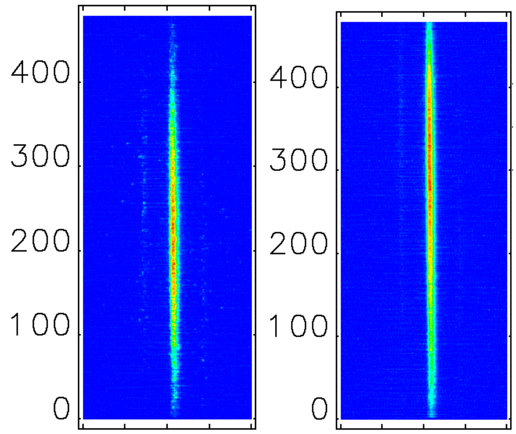

Figure 1: Left: 1 nC and right: 12.7 nC synchroscan streak camera images of the PAR bunch after 12th harmonic compression. Vertical axis is time; full scale is 1495 ps.

the output into saturation which inflates the result. Bunch duration may also differ from even to odd video field on a given PAR cycle. Finally, adjusting the phase delay to shift the distribution within the available range may also affect the fit, especially at higher charge. Operating the streak camera with the synchroscan unit required use of its slowest scan mode, range 4 or R4; in this mode, the maximum time window was 1495 ps. At low charge ($\leq$ 5nC), the bunch profile fits within the R4 range; however at higher charge, a portion of the distribution extends beyond the window. Low- and high-charge synchroscan profiles are presented in Fig. 1.

The integrated profiles after background subtraction and fits for these data sets are plotted in Fig. 2. The low-charge profile is fit well with a pure Gaussian profile, whereas the high-charge case clearly leans upstream.

Bunch Duration Monitor

The BDM provides the PAR bunch duration by deconvolving the output signal with the impulse response function of the detector and amplifier front end and has been in use since 2017 [2]. BDM diagnostics have been used successfully in both the PAR and booster [1, 6, 7].

We compare Gaussian and Haissinski (Eq. (1)) fits of a BDM profile recorded near the end of the PAR cycle in Fig. 3. Eq. (1) is a better fit to the leading edge of the bunch as it leans forward at higher charge; in this case, 13 nC. The FWHM bunch length from the Gaussian fit, $\tau_F = 2\sqrt{2\ln 2}c\sigma_t$=31.6 cm, is approximately 8% larger than that from the Haissinski result. Behavior of the bunch profile was examined as a function of harmonic gap voltage. Profiles for 22, 26, and 30 kV with a circulating charge of 17.5 nC (20 linac pulses injected) are presented in Fig. 4. Here N values are roughly consistent with the number of bunch electron (17.5 nC $= 1.092 \times 10^{11} e$); however, α increases with voltage and the bunch length drops.

We examine the FWHM bunch duration from both simple Gaussian and Haissinski fits versus RF12 voltage at 17.5 nC in Fig. 5. In this data set, the duration determined from the Gaussian fit is less than Haissinski up to approximately

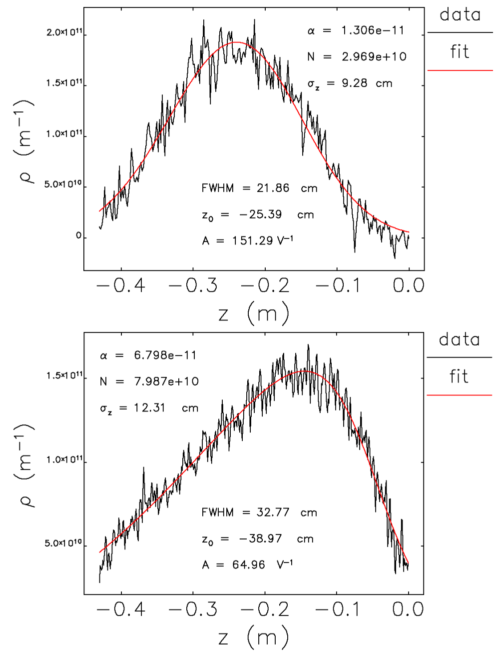

Figure 2: Integrated profiles and purely resistive Haissinski fits for the streak camera data shown in Fig. 1. Top: 1 nC; bottom: 12.7 nC.

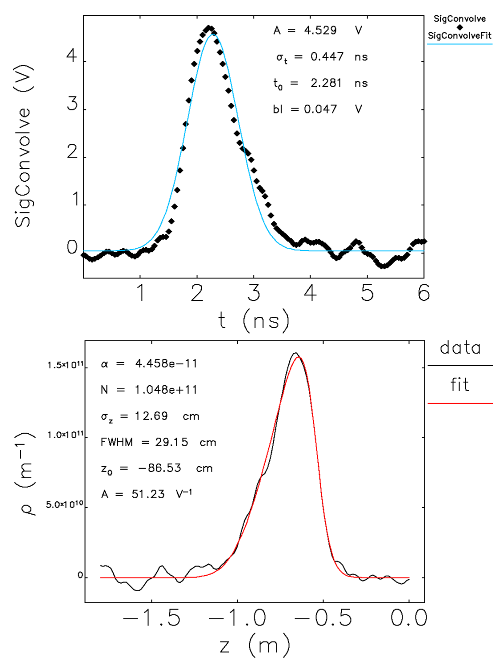

Figure 3: Top: Gaussian fit in time and bottom: Haissinski fit in space to a 13-nC bunch signal from the BDM.

28.5 kV after which the Gaussian is slightly larger. According to the Haissinski-modeled data, the bunch duration is reduced by approximately 30% as the voltage is raised from 22 to 30 kV.

The dependence of bunch duration on RF12 voltage is changed somewhat at lower charge, Fig. 6. Here the PAR bunch charge was reduced to 13 nC. This is the charge level typically used for present APS-U 48-bunch, timing-mode operation.

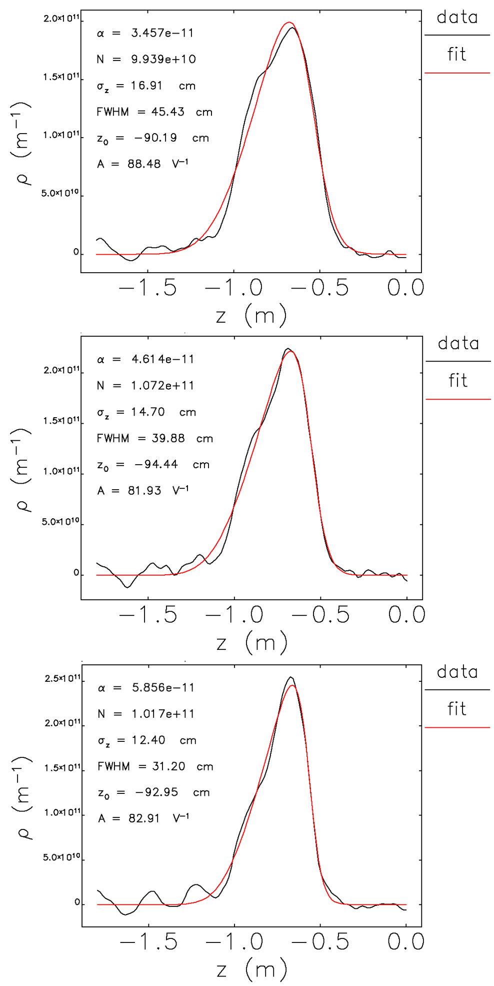

Figure 4: BDM data and Haissinski fits to 17.5 nC bunches at 22 kV (top), 26 kV (middle) and 30 kV (bottom) harmonic rf voltages.

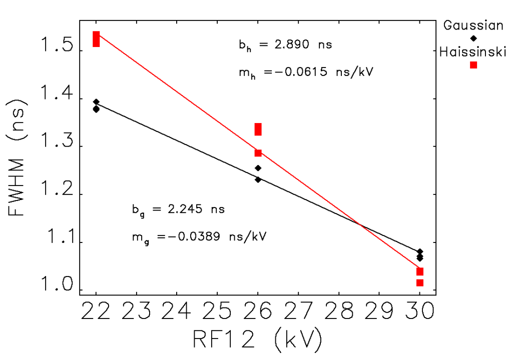

Figure 5: Variation of bunch duration with RF12 harmonic voltage from both simple Gaussian and Haissinski fits. Bunch charge was 17.5 nC.

A comparison of bunch duration versus charge from both the streak camera and BDM diagnostics is presented in Fig. 7. The agreement is generally good.

DISCUSSION

The streak camera video capture system uses an NTSC format where even and odd fields are recorded separately at a

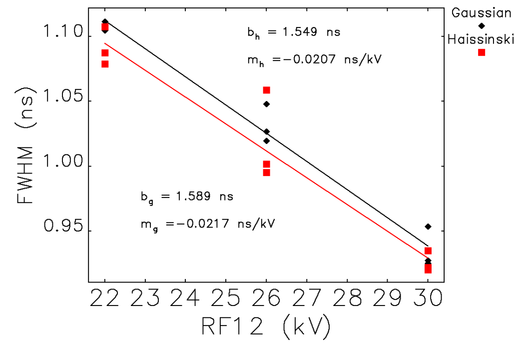

Figure 6: Variation of bunch duration with RF12 harmonic voltage from both simple Gaussian and Haissinski fits. Bunch charge was 13 nC

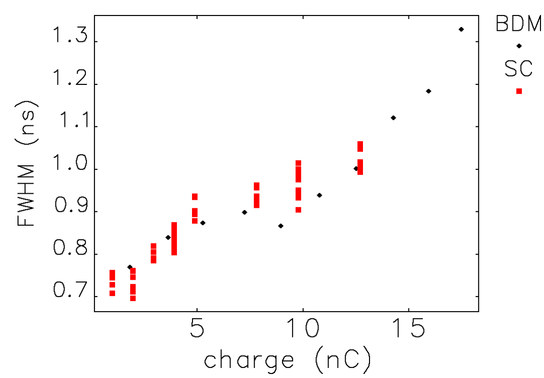

Figure 7: Comparison of streak camera and bunch duration monitor data for PAR 12^{th} harmonic rf amplitude of 26 kV. All data are based on Haissinski fit results.

60 Hz rate; thus the fields are separated in time by 16.67 ms with the full field generated at 30 Hz. Thus in synchroscan mode, the image is generated over many thousands of turns and beam motion, if present, will tend to smear and enlarge the temporal profiles. Also in the R4 synchroscan range, the streak images occupy a large fraction of the full field (484 lines); therefore, processing the even and odd fields separately by averaging over missing lines is justified.

SUMMARY

One of the main goals of this work was to verify the improved (reduced) bunch duration (length) we have recently observed with the BDM by using a streak camera. The streak camera results show good agreement with the BDM-derived data. Another goal was to obtain a more accurate measurement of PAR bunch duration from both streak camera and BDM diagnostics. The closed-form Haissinski method provides a better match to the distributions at higher charge (> 5nC) than does a simple Gaussian fit. At lower intensities, the bunch becomes more Gaussian in shape and both fits yield similar duration values.

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