BUNCH CLEANING STRATEGIES AND EXPERIMENTS AT THE ADVANCED PHOTON SOURCE*

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Abstract

The Advanced Photon Source (APS) design incorporated a positron accumulator ring (PAR) as part of the injector chain. In order to increase reliability and accommodate other uses of the injector, APS will run with electrons, eliminating the need for the PAR, provided another method of eliminating rf bucket "pollution" in the APS is found. Satellite bunches captured from an up to 30-ns-long beam from the linac need to be removed in the injector synchrotron and storage ring. The bunch cleaning method considered here relies on driving a stripline kicker with an amplitude modulated (AM) carrier signal where the carrier is at a revolution harmonic sideband corresponding to the vertical tune. The envelope waveform is phased so that all bunches except a single target bunch (eventually to be injected into the storage ring) are resonated vertically into a scraper. The kicker is designed with a large enough shunt impedance to remove satellite bunches from the injection energy of 0.4 GeV up to 1 GeV. Satellite bunch removal in the storage ring relies on the single bunch current tune shift resulting from the machine impedance. Small bunches remaining after initial preparation in the synchrotron may be removed by driving the beam vertically into a scraper using a stripline kicker operating at a sideband corresponding to the vertical tune for small current bunches. In this paper both design specifications and bunch purity measurements are reported for both the injector synchrotron and storage ring.

1 INJECTOR SYNCHROTRON BUNCH CLEANING

The APS storage ring is designed to be filled one bunch per cycle at a 2-Hz rate. The principal bunch cleaning requirement is to prepare a single bunch by removing any beam that gets captured in all but a single bucket of the 432 possible injector synchrotron buckets. The bunch cleaning method presented here is based on an rf stripline kicker that is used to deflect the beam vertically into a scraper. Each kicker stripline is driven by a 250-watt broad-band (10 kHz-220 MHz) amplifier. The injector synchrotron ramps linearly from injection (350 MeV) to extraction (7 GeV) in 223 ms. Bunch cleaning will be done at relatively low energies starting at the synchrotron injection energy to about 1 GeV so that the kicker amplifier power requirement is minimized.

Originally, injector synchrotron bunch cleaning was to be accomplished by driving the rf kicker with an amplitude modulated (AM) signal. The choice of AM is motivated by the fact that the kick must be zero at the bucket containing the bunch to be injected into the storage ring. The AM signal has the form,

$$V(t) = A(n\omega_o)\cos((\mathrm{m}-\nu)\omega_o \mathrm{t}) \quad (1)$$

$$A(n\omega_o) = V_o \sin(\frac{n\omega_o \mathrm{t}}{2}), \quad (2)$$

where $A(n\omega_o)$ is the amplitude term, ω_o is the injector synchrotron revolution frequency, $\nu = 0.8$ is the fractional vertical tune, and n, m are integers. The AM voltage waveform given by Eq. (1) has frequency components at the standard sum and difference frequencies

$$\omega_{\pm} = \{(n \pm m) \mp \nu\}\omega_o, \quad (3)$$

which represent revolution harmonic sidebands at the tune frequency. Driving at a tune sideband enhances the effectiveness of the kicker because radiation damping is very small at the synchrotron injection energy and so large resonant centroid beam displacements are possible. Ultimately, the maximum amplitude is limited by the amplitude dependent tune shift due to sextupoles and Landau damping in the injector synchrotron. The parameter n is chosen so that the period of the amplitude term given by Eq. (2) is at minimum equal to the length of the linac pulse in injector synchrotron buckets (10 buckets for a 30-ns linac pulse). The value $n = 36$ statisfies this requirement so that $A(n\omega_o)$ has a period of 12 buckets. The parameter m is chosen to minimize bandwidth, which requires that $m = 0$.

The basic advantage of this system is that it minimizes the bandwidth required of all system components (hybrids, splitters, amplifier). The drawbacks, however, include the fact that any particles injected into buckets that happen to be at a zero crossing of the amplitude term will not be removed. A remedy to this problem would be to switch the value of n part way through the bunch cleaning cycle to the next lower half integer. Another drawback is that buckets near a zero crossing for $A(n\omega_o)$ receive only a fraction of the maximum kick. A way to increase the kick applied to buckets adjacent to a zero crossing would be to use a square wave for $A(n\omega_o)$ or increase the power output of the amplifier. On balance, these drawbacks complicate the implementation of a bunch cleaning system based on an AM

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waveform and outweigh the single advantage of minimum bandwidth required of system components.

A simpler method was therefore chosen to perform synchrotron bunch cleaning at APS. The idea consists of driving the kicker at a vertical tune sideband so that the beam is removed at a vertical scraper. When the bucket containing the bunch to be injected into the storage ring passes the kicker, a fast gallium arsenide switch turns off the rf briefly so no kick is applied. This system is shown in Fig. 1. The principal component of this system is a fast switch with a risetime of 1.5 ns gated once every injector synchrotron turn. The speed of the switch is dictated by the requirement that the injection bucket receive no kick and buckets adjacent to it must receive a maximum kick from the kicker. This means that the switch must turn on and off in at least one rf period less the full width tenth maximum (FWTM) bunch length of 1 ns or 1.84 ns. In practice, the smallest bandwidth component will determine the system's overall speed.

The speed of the switch requires the 180° hybrid, high-power amplifiers and kicker to be broad-band devices. The broad-band hybrid is a relatively inexpensive off-the-shelf item and the stripline kicker is an inherently broad-band device to be described in the next section. The two high power amplifiers are, however, quite expensive due to both the bandwidth and high power requirement. The amplifier chosen was available in house and has a bandwidth of 220 MHz (250 watt) and therefore a rise time of 4.54 ns. This rise time is a bit long but should be adequate if the switch is commanded to start turning off the rf 1.5 rf periods (4.3 ns) before the target bunch passes the kicker. The switch must turn the rf back on as soon as the injection bunch passes. The slow amplifier rise time ultimately means that bunches adjacent to the target bunch will receive approximately 67% of the maximum available kick from the kicker. This should not be a practical problem as long as enough time is allowed for resonant displacement of the adjacent bunches to build up and saturate (in practice a few thousand turns).

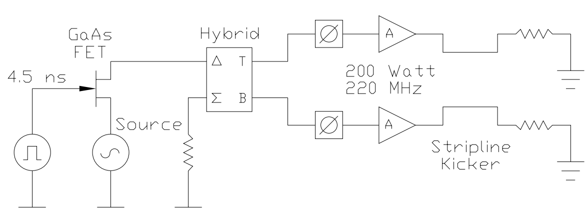

Figure 1: Time domain bunch cleaning schematic circuit diagram.

2 HIGH SHUNT IMPEDANCE STRIPLINE KICKER DESIGN

The bunch cleaning system described in the previous section relies on a high shunt impedance stripline kicker to deflect the beam. This kicker is a modified version of the APS 352-MHz quarter-wavelength stripline kicker used for injector synchrotron tune measurements. The new kicker was modified by decreasing the stripline vertical separation by a factor of two, thereby increasing the kicker shunt impedance [1]. Figure 2 shows the kicker geometry. Each stripline is electrically connected and mechanically supported via a vacuum feedthrough at each end. The elliptical injector synchrotron vacuum chamber is mechanically matched to the smaller cross section kicker chamber by a transition piece.

MAFIA calculations [2] show that the shunt impedance of the new kicker is a factor of nine larger than that for the original tune measurement kicker. Measurements made for beam energies near injection using the tune measurement kicker show that for 180 watts total input power, the beam was deflected approximately 1 mm at a vertical scraper. The modified kicker should therefore be able to deflect the beam at least 5 mm at the scraper at injection using two 250-watt amplifiers. This amount of deflection should be more than adequate to keep the injection bunch well clear of the vertical scraper.

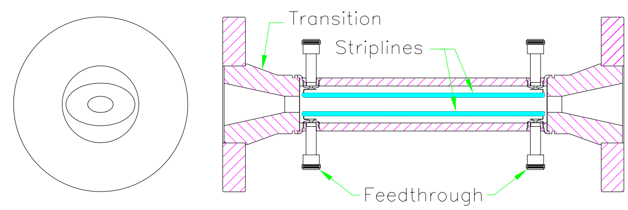

Figure 2: High shunt impedance kicker design.

3 STORAGE RING BUNCH CLEANING

Storage ring bunch cleaning is required in the event some charge remains in satellite buckets after cleaning in the injector synchrotron. The bunch cleaning system considered here relies on the fact that any satellite bunches injected will necessarily have much less current than the injected bunch. The small satellite bunches will therefore have a tune that is different from the large current bunches, due to the vertical transverse coupling impedance (mostly generated by the APS small-gap chambers [3, 4]). The satellite bunches can be removed by selectively driving the beam using a kicker at (or very near) the single particle tune frequency. The resonantly driven bunches can be removed by a suitably positioned vertical scraper.

This method was tested during storage ring machine studies time. The ring was filled with a standard user pattern consisting of six 1.67-mA bunches filled in buckets 0 through 5, followed by 25 2.00-mA bunches starting at bucket 72 and separated by 36 buckets (the storage ring consists of 1296 buckets) for a total current of 60 mA. Then 25 0.1-mA "contamination" bunches to be cleaned were filled three buckets downstream of each of the 25 2.00-mA bunches. The first six bunches are used to reliably trigger the BPM system so that orbit correction (both real time

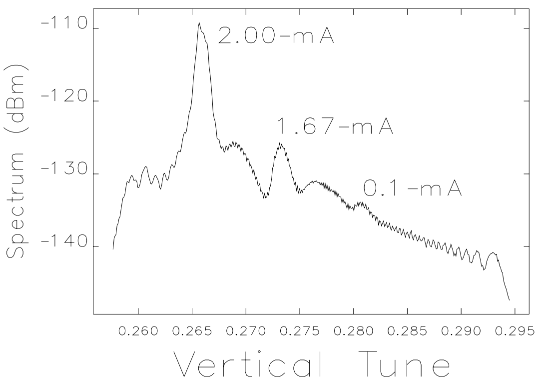

Figure 3: Storage ring tune spectrum for bunch cleaning 6+25 user pattern and 25 0.1-mA contamination bunches.

and slow) can be used to keep the beam fixed. Figure 3 shows the tune spectrum for this pattern. The large peak at $\nu_y = 0.266$ is due to the 2-mA bunches, the peak at $\nu_y = 0.274$ is due to the 1.67-mA bunches, and the peak at $\nu_y = 0.281$ is due to the 0.1-mA bunches. Figure 4 shows the APS bunch purity monitor triggered to view once per turn only the 25 2.00-mA bunches and 25 0.1-mA bunches. The purity monitor diagnostic counts photons incident on a photomultiplier and bins them in time. The figure shows the large current bunches as the central peak and the 0.1-mA bunches both upstream and downstream of the large current bunches (downstream is toward zero bunch position in the figure) on a log scale. Since the 25 0.1-mA bunch pattern was filled only downstream of the large bunches, the diagnostic shows that during injection some of the 0.1-mA bunches were unintentionally filled upstream of the large bunches.

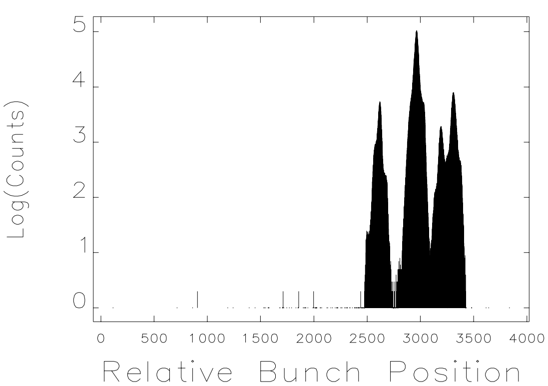

Figure 4: APS bunch purity monitor showing the 25 2.00-mA bunches and 25 0.1-mA bunches.

The bunch cleaning experiment used the tune measurement stripline kicker to drive the beam. The vector signal analyzer (VSA) was used as a signal source set to drive the tune of the 0.1-mA bunches. A vertical scraper was slowly moved toward the beam while orbit correction was running to keep the orbit fixed. Figure 5 shows the bunch purity monitor after the scraper had been moved to a position to intercept the resonantly driven 0.1-mA bunches. The figure shows that the charge remaining in the satellite bunches was five orders of magnitude below the 2.00-mA bunch. The final beam current remaining was 52.5 mA, indicating that some of the beam in the desired user fill pattern was also removed. This is because the tune measurement striplines only produce approximately 20-30 microns centroid displacement when driven at full power. Any fast fluctuation in beam position that orbit correction cannot correct can therefore result in beam loss from the user pattern. The cleaning efficiency can be greatly improved by driving the small bunch beam centroids resonantly to larger amplitudes. This can be accomplished by using a higher shunt impedance kicker and/or more powerful amplifier.

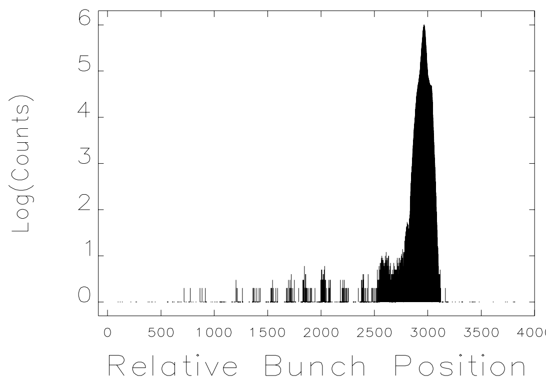

Figure 5: APS bunch purity monitor showing only the 25 2.00-mA bunches remaining after removal of the 25 0.1-mA bunches.

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