PRECISE SYNCHRONOUS PHASE MEASUREMENTS*

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Abstract

Precise measurements of storage ring synchronous phase helps to understand the machine impedance and improve the high current performance. We present different methods tested at NSLS-II, including the streak camera measurement, relative phase measurement from a high sampling frequency oscilloscope by comparing the beam signal and reference signal. Both streak camera and scope method have high precision to measure the synchronous phase (<1ps). Other methods to measure the synchronous phase include the I-Q detection from BPM electronics, FPM scope have been tested as well. We have used these systems to study the synchronous phase shift at different beam current, RF voltages and ID gaps. Recent results will be presented and discussed in the paper.

INTRODUCTION

Knowledge of stored electron beam synchronous phase and its relative drift at different beam current and RF voltages can be used to determine important beam parameters.

Total energy loss while electron beam going around the storage ring is due to synchrotron radiation and parasitic energy loss. The energy loss was compensated by the RF cavities. Beam finds the synchronous phase to balance the energy. The synchronous phase is determined by

$$eV_{rf}\sin(\phi_s+\Delta\phi)=U_{sr}+U_{pt} \tag{1}$$

where V_{rf} is the cavity voltage, ϕ_s is the synchronous phase at 0-current, $\Delta\phi$ is the synchronous phase drift at higher current, U_{sr} is the energy loss per turn due to synchrotron radiation, U_{pt} is the parasitic energy loss due to impedance.

At low bunch current, parasitic energy loss due to wakefield can be neglected, bunch synchronous phase and energy loss per turn due to synchrotron radiation has the relation

$$eV_{rf}\sin\phi_s=U_{sr} \tag{2}$$

To measure the synchronous phase, we compare the beam signal relative to the cavity field or reference signal. Due to cable and signal processing delays, measured synchronous phase may have a constant phase offset to the actual synchronous phase.

$$\phi_s=\phi_m+\phi_0 \tag{3}$$

where ϕ_m is the measured synchronous phase and ϕ_0 is the constant due to delays. Substitute Eq. (3) in to Eq. (2), we get

$$eV_{rf}\sin\phi_m\cos\phi_0+eV_{rf}\cos\phi_m\sin\phi_0=U_{sr} \tag{4}$$

Let's define:

$$x=eV_{rf}\cos\phi_m \\ y=eV_{rf}\sin\phi_m \tag{5}$$

Eq. (4) can be written as:

$$y\cos\phi_0+x\sin\phi_0=U_{sr} \tag{6}$$

By measuring the synchronous phase ϕ_m at different V_{rf} and fitting the x, y variables, energy loss per turn can be calculated from the fitting slope and offset. In the meantime, constant phase delay ϕ_0 can be fitted as well hence the absolute ϕ_s can be calculated from the measured ϕ_m. The method has been applied to measure the energy loss at different damping wiggler (DW) gaps [1], when there was one DW commissioned. Now, all three damping wigglers have been commissioned together with other insertion devices (ID). We are now able to measure the energy loss per turn with different DW and ID gaps.

It is important to measure synchronous phase precisely, especially to study the parasitic energy loss. NSLS-II low level radio frequency (LLRF) signal processing box [2] is able to measure the cavity field amplitude and phase with very good resolution (< 0.1 deg). Dedicated BPM button SUM signal is used to measure the beam phase using the same LLRF box. Unfortunately the BPM measured phase sees large current and fill pattern dependency. Separately, synchronous phase can be calculated from the forward and reflected power measured from the RF cavities [3].

Fill pattern monitor system [1] can resolve the beam arrival time (synchronous phase) with ~5ps resolution. Due to clock signal jitter and digitizer sampling rate, it is difficult to improve the resolution with this method. There is no longitudinal bunch by bunch feedback in the NSLS-II ring, a bunch by bunch (BxB) feedback digitizer [4] can be configured to measure longitudinal bunch arriving time. The digitizer measured ADC counts need calibration to have the phase information, with good knowledge of bunch current information.

Other methods to measure the synchronous phase include: BPM I-Q detected phase; streak camera measured bunch centroid; relative phase of BPM signal to reference signal measured with high sampling rate scope. BPM I-Q detected phase is sensitive to the environmental temperatures, even with temperature regulated rack of 0.1degC, the resolution is not sufficient. Both streak camera and scope methods have very high precision. In the next sections, we present recent study results using these tools.

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BPM I-Q PHASE

NSLS-II BPM electronics [5-6] measures the beam position by I-Q detection method; the amplitude signal of each button is used to calculate the positions. In principle the I-Q detected phase is related to the beam arrival time. BPM FPGA firmware has been updated to have the phase measurement capability in turn-by-turn (TbT, 378 *kHz* for NSLS-II storage ring) and 10 *Hz* rate.

BPM measured TbT phase had ~0.35 degree RMS noises, peak-to-peak noise can be up to 2 degrees. TbT phase data is useful to measure large phase oscillating beam, for example to optimize the injection timing. Phase data in 10Hz rate has much better resolution. However, the measured phase is sensitive to the environmental temperatures. Fig. 1 shows one of the BPM button measured phase in ~6 hours period. Rack temperature had ~0.5 °C peak-to-peak temperature variation which is reflected on the BPM electronics temperature sensors as well. All four buttons in the BPM see the similar trend with environment temperature variation. It's clear that measured phase is well correlated with the temperature. Fitting slope is ~0.034 rad/°C. Additionally, BPM measured position typically has 1-3 um/°C drift.

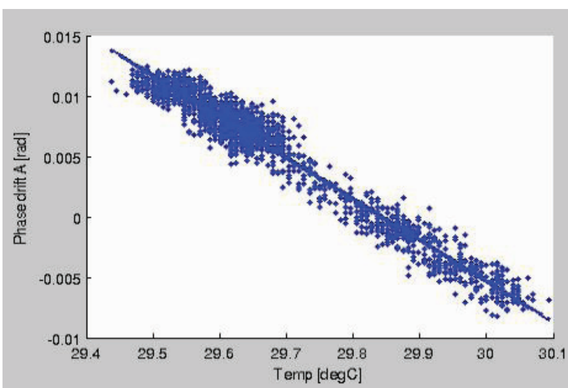

Figure 1: BPM measured phase affected by environment temperatures.

BPM measured phase has relative large measurement error and is sensitive to temperature drift. For precise synchronous phase measurement, we typically use the following two methods: streak camera and high sampling rate scope.

STREAK CAMERA PHASE MEASUREMENT

Streak camera has been widely used in accelerators to measure longitudinal profiles and bunch lengths. The camera image centroid can be used to determine the beam phase. NSLS-II streak camera has 125MHz synchroscan clock divided from master oscillator reference signal (500MHz).

To measure the phase drift due to parasitic energy losses, a single bunch is filled with various storage currents. To compensate the possible drift of 125MHz clock, reference bunches with small per bunch current was filled. Similar technique has been used at other facilities, for example [7-8]. Fig. 2 left side shows the streak camera image with main bunch current of 0.5mA, there were ~10 reference bunches with 0.1mA/bunch. The reference bunches are separate by 4 buckets so that their synchroscan images arrive at the same location on streak camera (the camera synchro-scan frequency is ¼ of RF frequency). The main bunch is located with 2 + 4*n* buckets away from the reference bunches, where *n* is an integer number. In this particular example, the reference bunches were filled at bucket #2:4:38 and main single bunch was at bucket #80.

Image centroid of reference bunches and the main bunch can be fitted to measure the relative synchronous phase drift. The result is shown on right side plot in Fig. 2. Where blue circles were streak camera results with three damping wigglers gap closed, V_{rf} = 3*MV*. As a comparison, the scope measured synchronous phases (see next section) are plotted as red star. Error bar was calculated from the RMS value of 10 measurements.

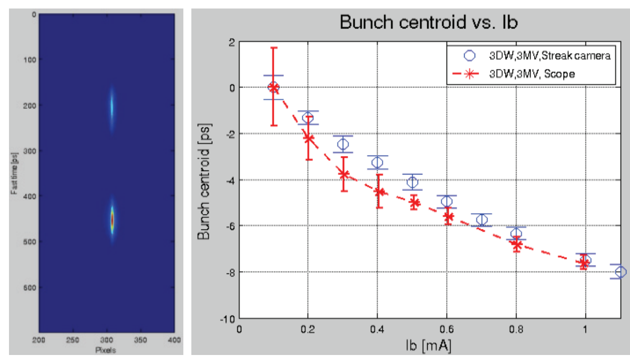

Figure 2: (left) Streak camera synchronous phase measurement with reference bunches; (right) Measured single bunch phase drifts with bunch current.

RF cavity phases were measured to be very stable when single bunch current increases. This means the streak camera (or scope) measured single bunch phase shift was real and it's due to longitudinal broadband impedance. At V_{rf} = 3*MV*, there were about 8*ps* drift per 1*mA* single bunch current (~1.45°), this is corresponding to a parasitic energy loss of 74*kV/mA* (loss factor $k_{//}$ = 28*V/pC*). Same measurement was carried out at V_{rf} = 2*MV*, the bunch centroid drift slope was similar (~8*ps* per 1*mA*) which gives $k_{//}$ = 18*V/pC*.

Bunch length results are available from these measurements, at higher single bunch current, there were significant bunch lengthening observed at NSLS-II storage ring [9-10]. Longer bunch length affects the synchronous phase shift as can be seen in Fig. 2, where the centroid slope is less at higher bunch current.

OSCILLOSCOPE MEASURED PHASE

A 20GHz sampling rate oscilloscope has been setup to measure the beam phase and reference clock phase. Compared to the streak camera measurement, the scope method has comparable resolution and sees little long term drifts. No reference bunches are needed so that measurement can be carried out with flexible fill pattern and current. Similar method has been used at [11].

Button BPM signal is fed to scope channel #1, after low and band pass filters. The bandwidth was +/-10MHz with carrier frequency at 500MHz. Second channel of the scope is measuring the reference clock signal from master oscillator. Fourier spectrum phases (@500MHz) of digitized data from both channels were compared to measure the relative phase.

Long term stability of the method was tested during top off operation, there was ~0.1 deg phase drift for the duration of 8-hours, similar level of RF cavity phase stability was observed. The long term drift can come from the long Heliax cable which distributes the 500MHz reference signal to the test station. Measurement resolution of the method itself has been checked by feeding the same 500MHz signal to both channels, it was ~5.8mdeg RMS.

When only a very small fraction of the machine was filled, like the case with single bunch studies, the scope measured phase has larger errors. Several single bunches can be filled to improve the signal to noise ratio. Fig. 2 synchronous phase result was actually measured with 10 single bunches. Fill pattern was well controlled to have small bunch to bunch current variation.

ENEGY LOSS MEASUREMENTS

From Eq. (4), energy loss per turn can be measured by measuring the synchronous phase change at different RF voltages. With the precise phase information from the scope, synchrotron radiation energy loss has been measured with different ID gaps, at low per bunch current.

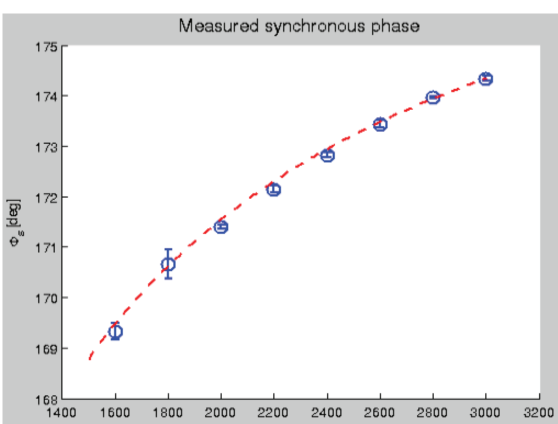

Figure 3: Measured synchronous phase drift with RF voltage in bare lattice. Red dash lines is the calculated synchronous phase based on fitted U_{sr} of 297 kV.

Figure 3 gives the example with all ID gaps open. Where blue circles are the measured synchronous phase, and red dash line is calculated phase. The bare lattice synchrotron radiation energy loss was measured to be 297kV. Table 1 summarizes the energy loss per turn measurement results, with comparison to the theoretic values. First five rows in the table were measured from low per bunch current to ignore the parasitic energy loss. The measured synchrotron radiation energy losses agree (< 3%) with the calculated values at different DW gaps. Closing 10 IVUs to their nominal values increased the synchrotron radiation by 81 keV. The last four rows in the table compare the energy loss with low/high bunch current. As the bunch lengths vary when RF voltage changes, this method is probably not as reliable to measure the longitudinal loss factor, compared to the direct phase measurement in single bunch. Looking at the energy loss results with IVUs gap open and close, it's likely that the parasitic energy loss is lower when the IVU gaps are closed which can be due to smaller taper angles when gap is closed. Further study is necessary to confirm the observations.

Table 1: Energy Loss Results with Different ID Gaps

IDs	$U_{mea.}$ [kV]	$U_{calc.}$ [kV]	Note
Bare	297	287	15.6mA/1000 bunches
1DW	422	412	27.0mA/1000 bunches
2DW	527	538	26.9mA/1000 bunches
3DW	654	664	26.7mA/1000 bunches
3DW+IVUs	735	-	26.1mA/1000 bunches
3DW	660	-	0.11mA per bunch
3DW	697	-	0.67mA per bunch
3DW+IVUs	748	-	0.13mA per bunch
3DW+IVUs	766	-	0.72mA per bunch

SUMMARY

Different methods to measure the synchronous phase have been developed at NSLS-II storage ring. Digital BPM I-Q detection phase can be useful if the environmental temperature is well regulated. Especially with large number of BPMs in the ring, averaged phase can give reliable phase measurements. Streak camera and high sampling rate oscilloscope have been proved reliable to precisely measure the synchronous phase. The tools have been used to study the parasitic energy loss and synchrotron radiation energy losses at various ID gaps.

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