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ONLINE TOUSCHEK BEAM LIFETIME MEASUREMENT BASED ON THE PRECISE BUNCH-BY-BUNCH BEAM CHARGE MONITOR*

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Abstract

Beam lifetime is a very important issue at high current operation of light source. Most of the existing lifetime monitor can only be measured for average lifetime. However, the life-related physical formula is only strictly established for a single bunch. In order to describe the behaviour of all electron bunches completely and accurately, a precisely bunch-by-bunch charge monitor has been developed at SSRF. Two-phase sampling based peak seeking method is introduced to avoid the influence of longitudinal oscillation on the sampling point, thanks to this, the resolution of the BCM was below 0.02%. Utilizing the advantages of BCM's high refresh rate and high resolution, the system can meet the requirement of monitor the bunch-by-bunch beam lifetime, measure Touschek lifetime and vacuum lifetime. In this paper, experiments and analysis will be described in detail.

INTRODUCTION

The beam current and its lifetime are two of the most important parameters of an electron storage ring. They are used to not only characterize the beam quality and machine status, but also to quantify the injection efficiency for weighing the injector/storage-ring matching.

The average beam current is measured to control injections during top-up operations, calculate the average lifetime and stability of the beam, and calculate the injection efficiency to determine whether the beam loss during an injection is tolerable.

The charges of the bunches are used to check the filling pattern and determine how to make the next injection to achieve the designed pattern, such that the desired filling pattern and the operation mode can be sustained.

The total lifetime in an electron storage ring consists of the lifetime of the beam electron residual gas scattering, the electron-electron scattering within the bunch, also the quantum excitation. There might also come a situation in which the values of the Touschek lifetime, vacuum lifetime, and quantum lifetime are needed, especially during machine studies.

The contribution to the total beam lifetime can be described as:

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{quantum}} + \frac{1}{\tau_{touschek}} + \frac{1}{\tau_{vacuum}}. \quad (1)$$

Where τ_{total} the total lifetime, the indices quantum, Touschek and vacuum denote the different components of the lifetime. Among them, Touschek lifetime is related with the beam charge, and the other two independents of the beam charge. Hence, the above formula can be rewrite as:

$$\frac{1}{\tau_{total}} = k_{touschek} Q + \frac{1}{\tau_{vacuum+quantum}} \quad (2)$$

Touschek lifetime is the most important mechanism for long-term particle losses in a storage ring. The online bunch-by-bunch Touschek lifetime monitor can provide a toolkit for complete and accurate representation of the behaviour of all electron bunches; it is also a precise bunch - by-bunch beam charge monitor, which can be used to do accurate measurement, correlation analysis and transient instability study of a single bunch.

The current of the beam injected into the storage ring typically decays exponentially over time. The goal of this system is to achieve on-line beam life measurement, and the injection period of SSRF running in top-up mode is about 5 minutes, so BCM must at least be able to distinguish the change of a single bunch charge at 1 minute during the period of decay.

Assume that when the current is 240mA and the beam life is 20 hours. According to the theoretical formula, in the decay mode, the change in flow intensity should be as shown in Fig. 1 below.

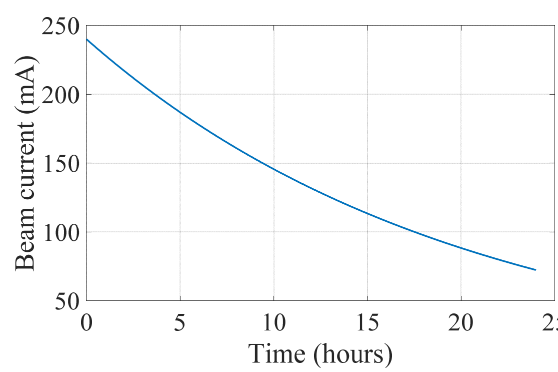

Figure 1: Current change diagram in the decay mode.

In this mode, the amount of current change in a minute is probably 0.2 mA. Assuming that each bunch changes the same value, the amount of change in the charge of 500 bunches should be 0.4 pC, for a 500 pC bunch, the amount of change is about 0.1%. Hence, the resolution of the BCM should be better than 0.1%, and the refresh rate should be higher.

In order to realize the online bunch-by-bunch lifetime monitor, four necessary conditions must be available:

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- Precise bunch-by-bunch beam charge measurement, the resolution should be better than 0.1%;
- Refresh rate of the beam charge monitor should be faster enough, based on this, the system can accumulate enough points when fitting the lifetime;
- BPM data and DCCT simultaneous acquisition, DCCT data can be used to calibrate the beam charge value;
- In order to select single bunch as the probe, the filling pattern should satisfy the amount of charge is unevenly distributed.

System that can meet the above four conditions has been completed, and preliminary experimental verification and application have been carried out. The specific principles and experimental contents will be described in detail in the following sections.

RESEARCH FOUNDATION AND CHALLENGES

SSRF is a multi-bunch, high current, advanced third generation synchrotron light source. The main parameters of the SSRF storage ring are listed in Table 1.

Table 1: Main Parameters of SSRF Storage Ring

Parameter	Value
Beam energy(E)	3.5GeV
RF frequency	499.654MHz
Current	240mA
RF harmonic number	720
Bunch charge	~0.5nC
Bunch length	14.4ps
Synchrotron frequency	0.007
Time pulse repetition rate	2Hz

And the typical filling pattern of SSRF is showed as Figure 2.

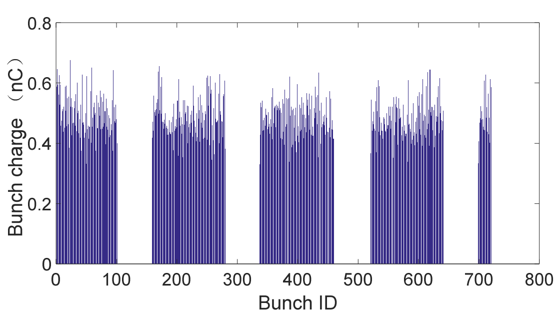

Figure 2: Typical Filling pattern of SSRF.

SSRF's research on bunch-by-bunch beam lifetime measurement began in 2009, this paper is based on the research foundation [1-5].

A most simple and efficient approach with adequate dynamic range is using the sum signals from a BPM and calibrated by the DCCT. Due to the limitation of ADC sampling rate, commonly using peak point sampling to represent relative bunch-by-bunch charge distribution.

The previous BCM (Beam charge monitor) can be effectively used for injection mode monitoring. In order to realize the online bunch-by-bunch beam charge monitor, the challenges that need to be faced are as follows

- Reduce the impact of sampling phase jitter. The sampling method of the former bunch-by-bunch BCM may introduce system error due to synchrotron oscillation;
- Remove the crosstalk introduced by the limited bandwidth of the system;
- BPM data and DCCT simultaneous acquisition, use DCCT to calibrate BPM sum signal;
- High refresh rate.

SYSTEM SETUP

Consider the above requirements and the challenges, a precise online bunch-by-bunch beam charge and beam lifetime monitor has been established at SSRF.

The description of the system structure will be expanded separately from the hardware and software.

Hardware

Schematic of the whole system is showed as Figure 3.

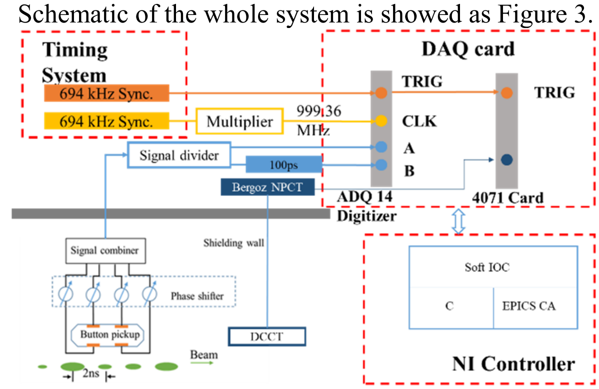

Figure 3: Schematic of the online bunch-by-bunch beam charge and lifetime monitor.

The biggest change in the new system is the two-phase sampling based peak seeking method. In order to enhance the measurement system error caused by synchrotron oscillation, the data acquisition system adopts this new sampling method. The BPM sum signal is divided into two ways, and the phase difference between the two channels is 100ps. Before employing this method, calibration of the peak value should be carried out [6].

Software

Software is the core of the entire system and needs to solve the following problems:

- BPM data and DCCT simultaneous acquisition;
- Crosstalk removal;
- Increase data refresh rate.

Software flow chart is showed as Figure 4.

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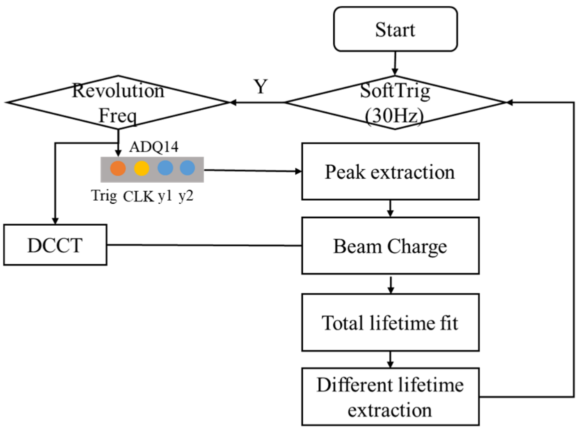

Figure 4: Software flow chart.

In order to realize online measurement, the system needs to ensure that the order of bunch train at each data acquisition event is aligned, which is commonly referred to as the external trigger mode. However, the external trigger frequency provided by SSRF is 2Hz. Such a frequency cannot meet our needs. If the revolution frequency or RF frequency is selected, the ADC board cannot respond. This article proposes a combination of software triggering and the revolution frequency as a hardware trigger to achieve a data refresh rate and meet the purpose of synchronous alignment sampling. The final data refresh rate is determined by the frequency triggered by the software, the value is 30Hz.

In the data acquisition part, the software realizes synchronization to obtain data from DCCT and BPM acquisition boards.

From the ADQ 14, the BPM data y1,y2 were captured, a dedicated algorithm has been developed to extract the peak value of the BPM sum signal and remove the crosstalk introduced by the low bandwidth of the system.[6] DCCT value can capture directly from Bergoz NPCT.

After calibrated by DCCT data, the peak value of BPM can be transfer to beam charge value.

Finally, a fitting algorithm can be used to extract beam lifetime.

PERFORMANCE

The new system has been described at previous sections, its performance will be described in this section, which will be divided into two parts: beam charge and beam lifetime measurement

Beam Charge Measurement

For the performance of charge measurement, the uncertainty of measurement is usually the main concern.

Figure 5 shows a comparison of the bunch-by-bunch charge measurement of the new and old BCM. The red line indicates the peak point result of the new BCM, while the green and blue indicate the result of the old BCM.

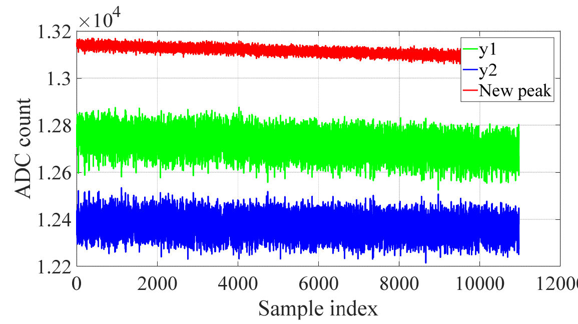

Figure 5: Comparison of the new and previous BCM.

Figure 5 shows that the new BCM New BCM delivers better performance with higher resolution and accuracy.

Measurement uncertainty is one of the most important indexes of the instrumentation. The uncertainty of the new BCM is 6 ADC counts, while the previous system is 31, at the same time, the uncertainty of the ADC itself is 2. This result verifies that the new peak extracting method successfully removes the effects of sampling phase jitter.

Based on the new bunch-by-bunch BCM mentioned in above sections, the measurement of beam charge can reach to 0.014%, 0.076 pc @ 0.5 nC, and the data refresh rate is 30Hz. The result of beam charge monitor was showed as Figure 6.

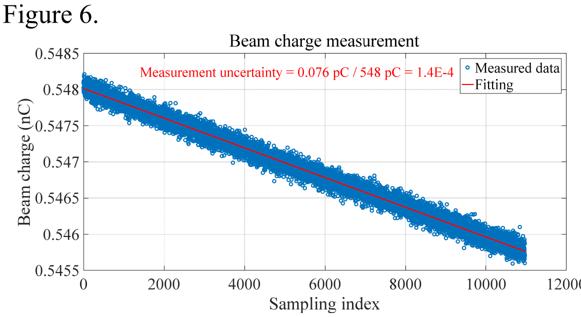

Figure 6: Measurement uncertainty of the new BCM

With this high refresh rate and high accuracy bunch-by-bunch BCM, it is able to be used to do online bunch-by-bunch beam lifetime measurement.

Beam Lifetime Measurement

Figure 7 shows the bunch charge decay event for about 4 minutes. The data can be used to study differential lifetime of individual bunch in storage ring. Since the lifetime is dominated by the intra-bunch scattering effect, lifetime of each bunch will differ from bunch to bunch.

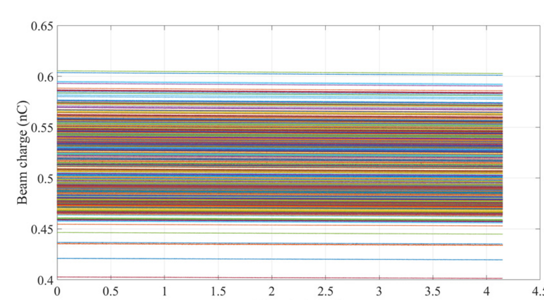

Figure 7: Decay event for about 4 minutes.

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Figure 8 is the total lifetime versus the bunch charge during three different injections. According to formula, the Touschek factor is related to the slope of the linear fitting, and the vacuum lifetime can be measured with the intercept of y axis [6].

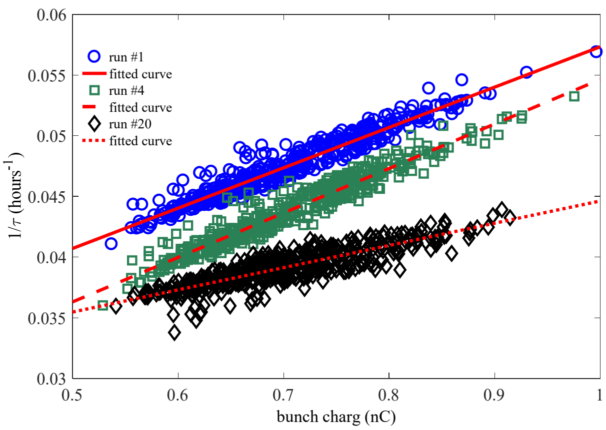

Figure 8: Beam lifetime measurement after three inject events.

In general, the total lifetime of a single bunch, the Touschek factor of the beam, and the lifetime independent of the charge can be measured online in minutes.

APPLICATION

Thanks to the high refresh rate and precise bunch-by-bunch BCM, it is able to observe transient instability.

The physical aperture is one of the most convenient parameters to adjust. Collimators and scrapers are used to select a portion of the beam by blocking or deflecting the unwanted electrons. The locations of the blades determine the physical aperture at that position of the vacuum chamber. Because they can provide some reliable data, they are still worth studying.

An experiment was designed to observe the relation between the lifetime and the physical aperture. We changed the gap of a vertical scraper and measured the bunch-by-bunch charges. Figure 9 shows the instantaneous state when the bunches with large charge are scraped with a beam scraper.

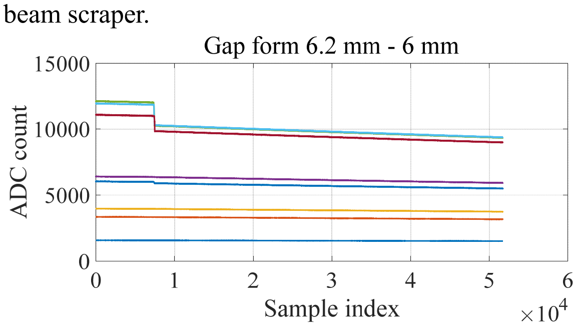

Figure 9: Situation when the gap of scraper changes from 6.2 to 6 mm.

It can be seen from the figure that the bunch of large charge is obviously scraped by the scraper, the occurrence of instability lasted for 0.7s, which is also the time of the scraper movement.

Another phenomenon is that it can be found that a small charge group is not scratched, and its charge amount is kept stable. From another aspect, it is proved that the system effectively sees the moment of single bunch instability.

Figure 10 is the situation when the gap of scraper becomes smaller.

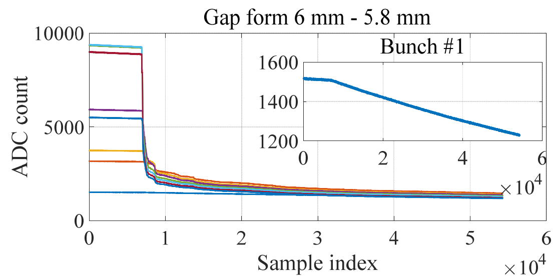

Figure 10: Situation when the gap of scraper becomes smaller.

Figure 10 shows that when the gap of the scraper change from 6 to 5.8 mm, almost all large charge bunches has been scrapped, while the smallest bunch has not been scrapped. Despite this, the decay trend or lifetime of its charge can see a significant inflection point, which may be due to the multi-bunch instability. This proves that the system can be used to observe subtle instability and multi-bundle instability.

In theory, when the physical aperture changes, the beam lifetime will also change accordingly. Figure 11 is the lifetime versus gap of scraper.

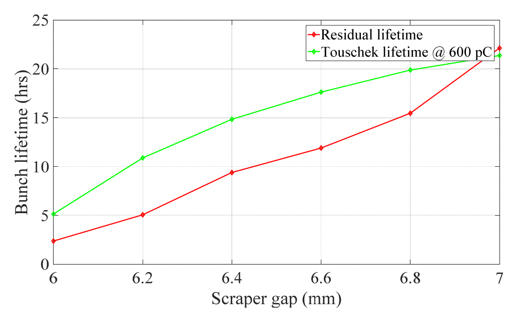

Figure 11: Touschek lifetime @ 600 pC and other lifetime during change the gap of scraper.

The trend of Touschek lifetime and the charge independent lifetime agrees well with the theoretical formula.

CONCLUSION

A precise bunch-by-bunch BCM system, based on the BPM sum signals and the two-phase sampling based peak seeking method, has been developed at the SSRF. The relative resolution of the measurement of the bunch charge is better than 0.02%. Data refresh rate can reach to 30 Hz.

Based on this system, online single bunch lifetime monitor can be realized, the cost time of one event is only a few minutes. It can be used to do Touschek and vacuum lifetime analysis.

This new lifetime monitor will be useful during machine study.

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REFERENCES

[1] S.T. Huang, Y.B. Leng, Y.B. Yan, Development of the bunch-by-bunch beam current acquisition system at SSRF. Nucl. Sci.Tech.20, 71(2009).

[2] Y.B. Leng, Y.B. Yan, L.Y. Yu et al., Monitoring the charge bunch-by-bunch for the SSRF storage ring: development and appliction. Nucl.Sci.Tech.21, 193(2010).

[3] Z.C. Chen, Y.B. Yang, Y.B. Leng et al., Wakefield measurement using principal component analysis on bunch-by-bunch information during transient state of injection in a storage ring.Phys.Rev.STAccel.Beams17,112803 (2014).

[4] Y. Yang, Y.B. Leng, Y.B. Yan et al., Development of the bunch-by-bunch beam position acquisition system based on BEEcube.Nucl.Sci.Tech.27,47(2016).

[5] Y.B.Leng, Y.B.Yan, W.M.Zhou et al., Precise beam current measurement for storage ring using beam position monitor. High Power Laser Part. Beams 22. 2973-2978.

[6] F.Z.Chen., Z.C.Chen, Y.M.Zhou.et al., Touschek lifetime study based on the precise bunch-by-bunch BCM system at SSRF, NUCL SCI TECH (2019) 30: 1.