Online Touschek beam lifetime measurement based on the precise bunch-by-bunch beam charge monitor

Bo Gao, Yongbin Leng, Fangzhou Chen, Yimei Zhou

BI Group, SSRF

IBIC 2019

8-13 September

Outline

- Introduction & Background
- System Setup & Performance
- Application
- Summary
- Acknowledge

Introduction & Background

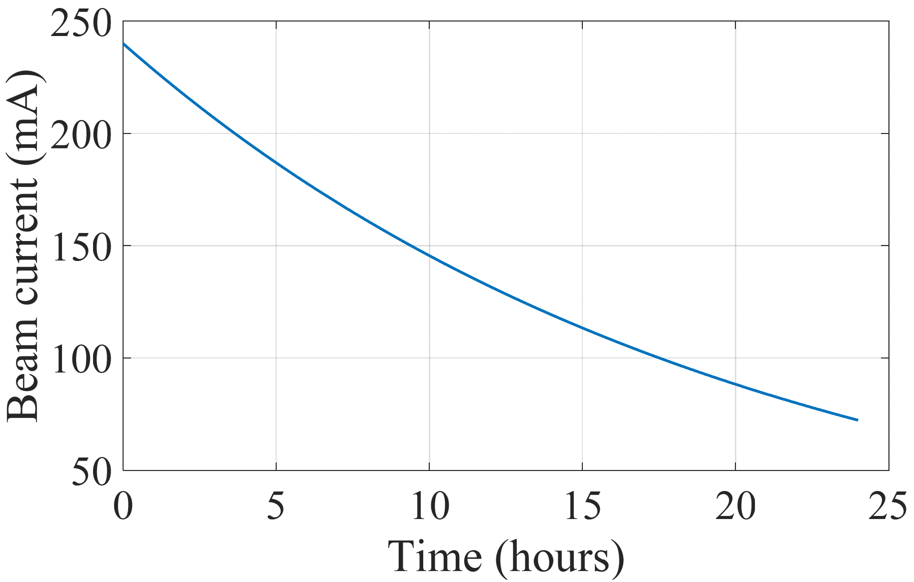
What is beam lifetime?

Lifetime

- The current of the beam typically decays exponentially over time;
- Very important issue at high current operation of light source;
- Important for stable and uninterrupted experiment for beam line users;
- Most of the existing lifetime monitor can only be used to measure average lifetime.

$$I(t) = I_0 e^{-t/\tau} \qquad \tau \approx -\frac{I}{\Delta I}\Delta t$$

τ *is lifetime*



Theory of beam lifetime

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{touschek}} + \frac{1}{\tau_{vacuum}} + \frac{1}{\tau_{quantum}}$$

Touschek lifetime

$$\frac{1}{\tau_{\mathrm{T},\frac{1}{2}}} = \frac{r_e^2 c q}{8\pi e \gamma^3 \sigma_z} \frac{1}{C} \oint_C \mathrm{d}s \frac{F\left(\left[\frac{\delta_{\mathrm{acc}}(s)}{\gamma \sigma_{x'}(s)}\right]^2\right)}{\sigma_x(s)\sigma_{x'}(s)\sigma_y(s)\delta_{\mathrm{acc}}^2}$$

- Charge related
- Carry more information and reflect more beam parameters

Vacuum lifetime

$$\frac{1}{\tau_{\mathrm{e}}[\mathrm{s}]} = \frac{4\pi r_e^2 c N_A}{R\gamma^2} \frac{\langle \beta_y \rangle}{A_y[\mathrm{m} \cdot \mathrm{rad}]} \frac{P[\mathrm{Pa}]}{T[\mathrm{K}]} \sum_i^n Z_i(Z_i + 1) N_i r_{p_i}$$

$$\frac{1}{\tau_{\mathrm{b}}[\mathrm{s}]} = \frac{4\pi r_e^2 c N_A}{137R} L(\delta_{\mathrm{acc}}) \ln \frac{183}{\sqrt[3]{Z}} \frac{P[\mathrm{Pa}]}{T[\mathrm{K}]} \sum_i^n Z_i(Z_i + \xi) N_i r_{p_i}$$

- Charge independent

Quantum lifetime

$$\tau_{\mathrm{q}} = \frac{\tau}{2} \frac{e^{\xi}}{\xi}$$

- Charge independent

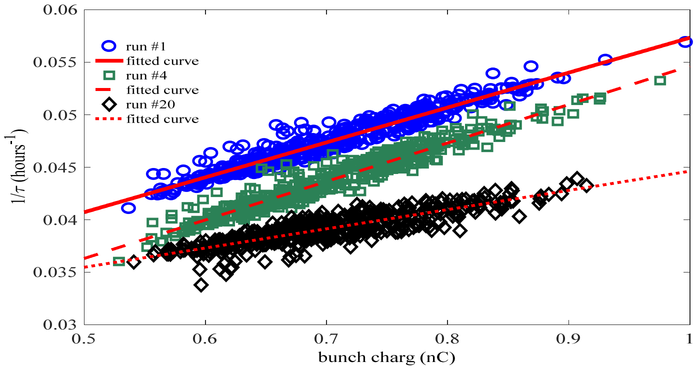
Why BxB lifetime measurement?

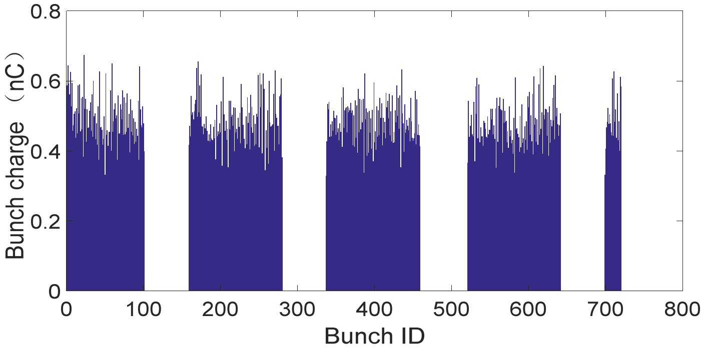
- The life-related physical formula is only strictly established for a single bunch, and the approximate parameters are required for the bunch;
- Necessary condition of online Touschek lifetime measurement;
- Toolkit for complete and accurate representation of the behavior of all electron bunches;
- Precise bunch by bunch beam charge monitor
  - Toolkit for accurate measurement and correlation analysis of every bunch;
  - Beam loss of small charge bunch;

How to do online Touschek lifetime measurement?

$$\frac{1}{\boxed{\tau_{total}}} = k_{touschek}\boxed{Q} + k_{vacuum}P$$

- High BxB charge measurement resolution <0.1% , able to distinguish the change of single bunch' charge in 1 minute (about 0.4 pC);
- High refresh rate > 10Hz (The faster the better)
- BPM data and DCCT simultaneous acquisition
- Filling pattern (The amount of charge is unevenly distributed)





Roadmap

2009	2014	2019

The beginning of BxB beam charge monitor @ SSRF

Nuclear Science and Techniques **21** (2010) 193–196

Monitoring the charge bunch-by-bunch for the SSRF storage ring: Development and application

LENG Yongbin* YAN Yingbin YU Luyang YUAN Renxian
CHEN Zhichu ZHOU Weimin

Shanghai Synchrotron Radiation Facility, Shanghai Institute of Applied Physics, Shanghai 201800, China

Abstract Bunch charge uniformity controlling is very important for top-up operation of the storage ring. In order to monitor filling pattern and measure the bunch charge precisely, a PXI waveform digitizer-based data acquisition system has been developed to retrieve bunch charge information from BPM pickup signals. An effective sampling rate is extended to 400 GHz by waveform rebuilding technology, which overlays multi-turn data into single turn with real time sampling rate of 8 GHz. An on-line evaluation indicates that resolution and linearity of the charge measurement are better than 0.5% at input range of 0.5–12 nC.

Key words Beam diagnostics, Bunch charge monitor, Filling pattern, Top-up, SSRF

1 Introduction

Top-up operation mode of the storage ring is to be used at SSRF to minimize the dependence of beam current on machine parameters, The variation of bunch charges is required to be less than 10%. Thus, a precise bunch charge and filling pattern monitoring is necessitated. Table 1 shows that the BCM (beam charge monitor) specification can be achieved by directly sampling BPM (beam position monitor) pickup signal[1–3] or synchrotron radiation signal[4].

Table 1 SSRF BCM Specifications.

Parameters	Specifications
Analog bandwidth	≥ 250 MHz
Data updating rate	≥1 Hz
Bunch charge resolution	Better than 1%
Interface	EPICS CA

The SSRF storage ring adopts the technique of the button BPM pickups and the PXI (PCI eXtensions for Instrumentation) waveform digitizer-based solution, due to the easy configuration and good linearity[5]. This helps to have a full knowledge of time domain structure of the beam, bunch-by-bunch with a sub-nanosecond time resolution.

2 System setup

2.1 Basic idea

As a common diagnostic component in an electron storage ring, a four-button BPM pickup carries the information of beam position and intensity. Assuming the bunch charge (Q_0) was in Gaussian distribution at a bunch length σ, the beam intensity is given by

$$I(t) = \frac{Q_0}{\sqrt{2\pi}\sigma}\exp\left(-\frac{t^2}{2\sigma^2}\right) \quad (1)$$

the peak value of the four-button sum signal is

$$V_{peak} = k(r,\theta)Z\sqrt{\frac{e}{2\pi}}\frac{Q_0}{\sigma^2} \quad (2)$$

where, $k(r,\theta)$ is a calibration factor determined by cross section structure of the vacuum chamber and beam position, Z is transfer impedance of the measurement system, r and θ are polar coordinates of the beam position. Treating $k(r,\theta)$ as a constant k_0[6] and defining a scaling factor (K_Q), V_{peak} can be obtained by Eq.(3),

The beginning of Touschek lifetime measuremnt, based on history data

Chinese Physics C Vol. 38, No. 7 (2014) 077005

Experimental study using Touschek lifetime as machine status flag in SSRF*

CHEN Zhi-Chu(陈之初)[1,2;1)] LENG Yong-Bin(冷用斌)[1,2;2)] YUAN Ren-Xian(袁任贤)[1,2]
YAN Ying-Bing(阎映炳)[1,2] YU Lu-Yang(俞路阳)[1,2]

[1] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China
[2] Shanghai Synchrotron Radiation Facility, Chinese Academy of Sciences, Shanghai 201203, China

Abstract: The stabilities of the beam and machine have almost the highest priority in a modern light source. Although a lot of machine parameters could be used to represent the beam quality, there is no single parameter that could indicate the global information for the machine operators and accelerator physicists. For the last few years, a new parameter has been studied as a beam quality flag in the Shanghai Synchrotron Radiation Facility (SSRF). Calculations, simulations and detailed analysis of the real-time data from the storage ring have been made and the interesting results have confirmed its feasibility.

Key words: Touschek lifetime, beam quality, storage ring

PACS: 29.20.db, 29.27.Fh, 29.85.Fj **DOI:** 10.1088/1674-1137/38/7/077005

1 Introduction

Beam quality is of great importance for a light source that aims at providing stable synchrotron radiation for scientific research. A couple of machine parameters have been maturely used in most third generation storage rings around the world to indicate the beam status, such as the transverse beam size/emittance from a pin-hole camera, the variance of the close orbit from the BPM system, etc. Other parameters, such as the beam length/energy spread from a streak camera, are also monitored in some facilities. However, monitoring a single parameter seems not enough to reflect the beam status while monitoring all of them simultaneously would eventually confuse the operators.

During the selection of the necessary parameters to be monitored, using the beam current to get some factor of the beam was believed to be a competitive economic proposal. Although the beam lifetime could interpret the beam status in some way, it is related to the beam charge so no convenient reference is available to say if the beam is in good status. Further processes are still needed to make this proposal a feasible solution.

1.1 Beam lifetime

A bunch containing N charged particles (electrons in most third-generation synchrotron radiation sources) in a storage ring decays due to a variety of mechanisms. Some of the non-trivial causes are: quantum lifetime (emission of synchrotron radiation), Coulomb scattering (elastic scattering on residual gas atoms), Bremsstrahlung (photon emission induced by residual gas atoms), and the Touschek effect (electron-electron scattering).

The charged particles are assumed to be electrons in this article unless otherwise noted.

The relative loss rate at a given time of the quantity of the beam defines the lifetime τ:

$$\frac{1}{\tau} \equiv -\frac{\dot{N}}{N} = -\frac{\dot{Q}}{Q}, \quad (1)$$

where $Q=-eN$ is the charge of the electron bunch.

The beam lifetimes due to the quantum character of synchrotron radiation, the Touschek effect, the elastic Coulomb scattering and the inelastic bremsstrahlung between the electron beam and the pure nitrogen gas are given by [1]

$$\tau_{qu} = \frac{1}{2}\tau_w\frac{e^{\xi}}{\xi}, \quad (2)$$

$$\frac{1}{\tau_{tk}} = \frac{r_c^2 cQ}{8\pi e\sigma_x\sigma_y\sigma_\ell}\frac{\lambda^3}{\gamma^2}D(\epsilon), \quad (3)$$

$$\tau_{cs}(\text{hours}) = 10.25\frac{(cp)^2(\text{GeV}^2)\epsilon_A(\text{mm}\cdot\text{mrad})}{\langle\beta(\text{m})\rangle P(\text{nTorr})}, \quad (4)$$

Online Touschek lifetime monitor for single bunch

Nuclear Science and Techniques
September 2019, 30:144 | Cite as

Touschek lifetime study based on the precise bunch-by-bunch BCM system at SSRF

Authors Authors and affiliations

Fang-Zhou Chen, Zhi-Chu Chen, Yi-Mei Zhou, Ning Zhang, Bo Gao, Xing-Yi Xu, Yong-Bin Leng

Article
First Online: 24 August 2019

Abstract

Continuous tracking of bunch charges is the key to maintain stable operations in a storage ring in top-up mode. Recently, a precise bunch-by-bunch beam-current measurement (BCM) system has been developed at the Shanghai Synchrotron Radiation Facility. To avoid the influence of longitudinal oscillation on the amplitudes of the sampling points, a method called two-point equilibrium sampling is introduced. The results, obtained during routine operation time, show that the relative resolution of the measurement of the bunch charges is better than 0.02%. With this high resolution, the new BCM system is able to monitor the bunch-by-bunch beam lifetime. By using the filling pattern information, the Touschek lifetime and the vacuum lifetime can also be calculated. In this paper, the principle of the new method and the experiments is presented in detail.

Keywords

Beam-current measurement | Bunch-by-bunch | Touschek lifetime | Vacuum lifetime | SSRF

System Setup & Performance

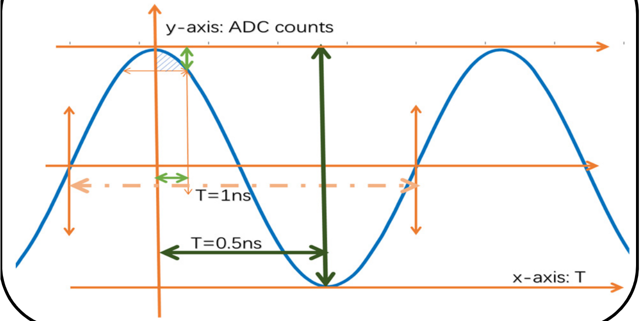
- Challenges for precise BxB BCM
- System setup (hardware)
- System setup (software)
- Performance

System Setup & Performance

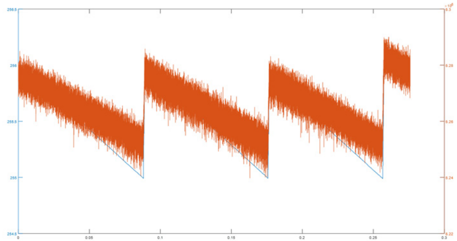
- Challenges for precise BxB BCM
- System setup (hardware)
- System setup (software)
- Performance

Challenges for precise BxB BCM

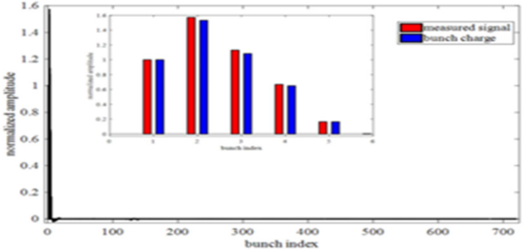
Sampling phase jitter



BCM calibrated by DCCT



Crosstalk between bunches



SSRF solutions

New hardware

- New bunch-by-bunch beam charge monitor introduce "Two-phase sampling based peak seeking method", to minimize the effect of the sampling phase jitter;
- Hardware and software triggered combination (30 Hz)

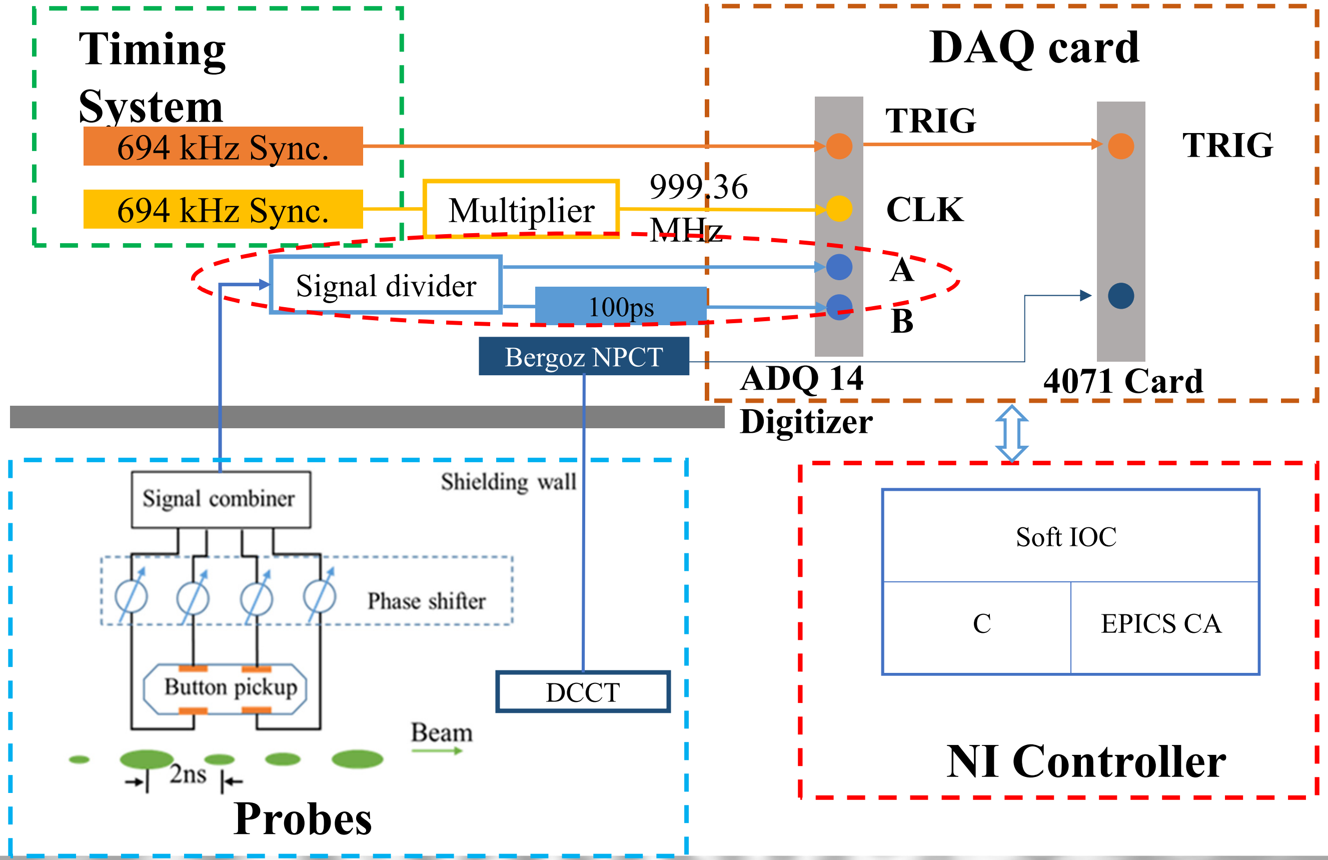
New software

- BPM data and DCCT simultaneous acquisition;
- Crosstalk analysis and minimization;
- New underlying data acquisition software based on C.

System Setup & Performance

- Challenges for precise BxB BCM
- System setup (hardware)
- System setup (software)
- Performance

System setup （Hardware）

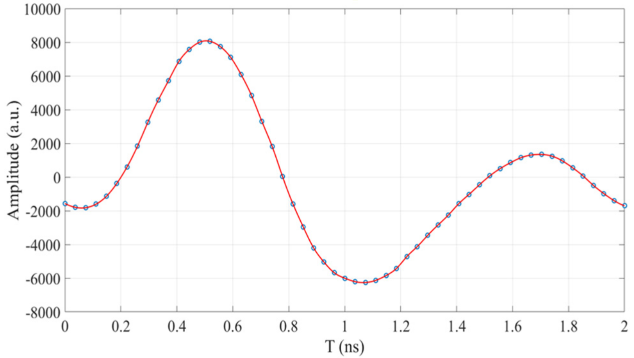


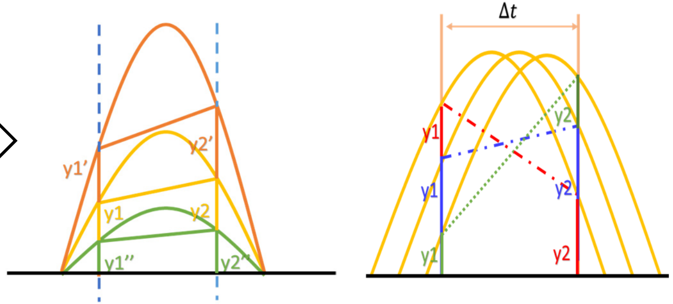
Two-phase sampling based peak seeking method

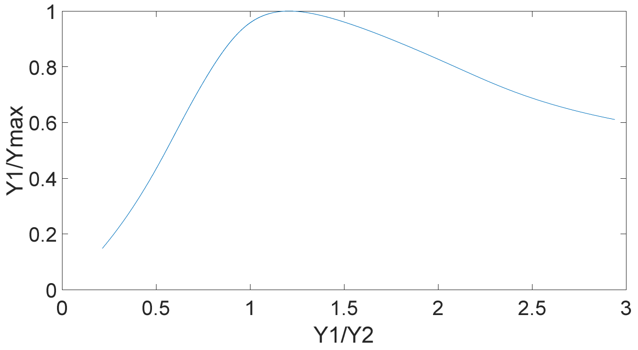
Target: Minimize the impact of sampling phase jitter

Method: Two-phase sampling based peak seeking method

BPM sum signal





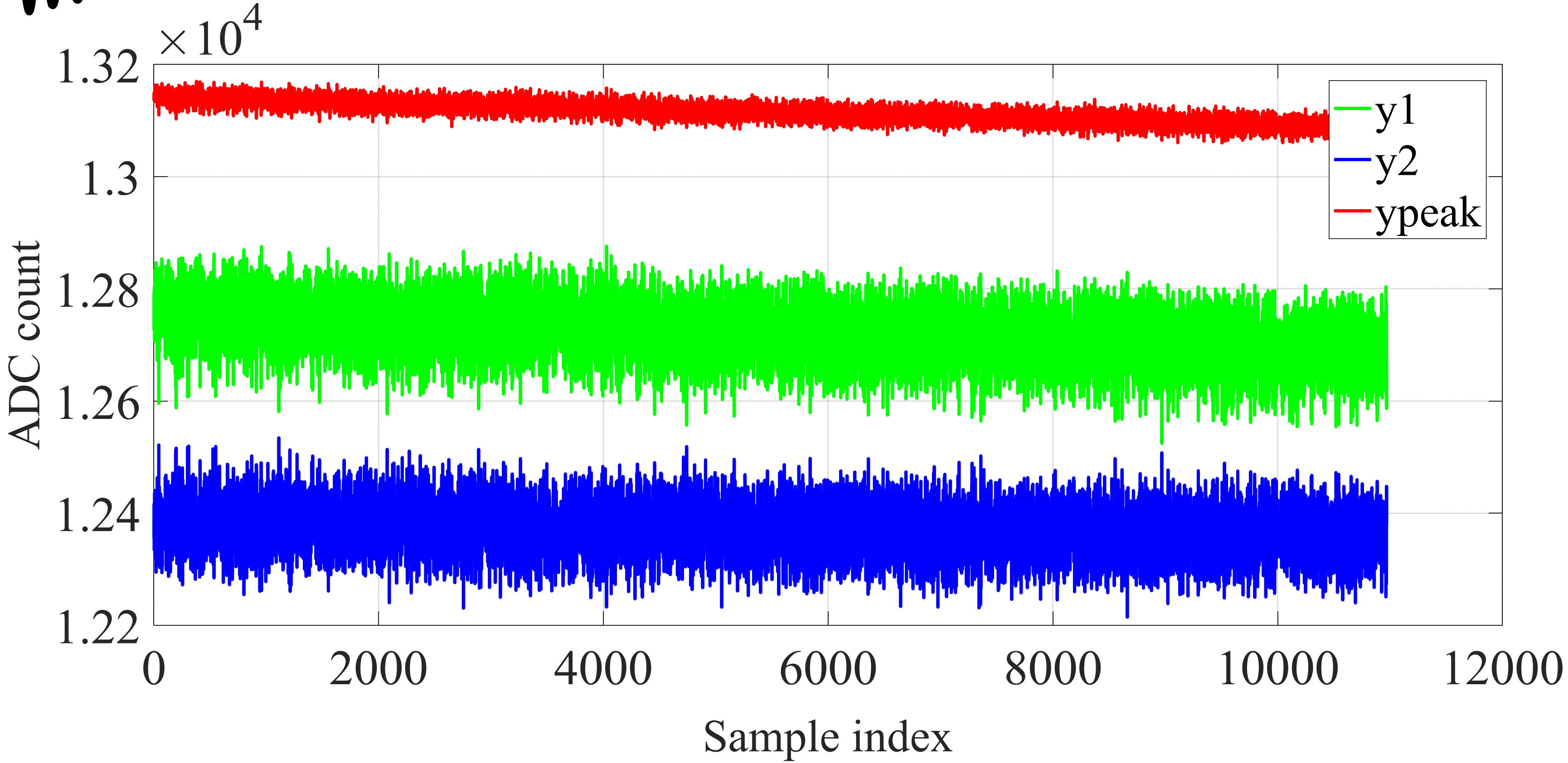


$$\frac{y_1}{y_{peak}} = f\left(\frac{y_1}{y_2}\right)$$

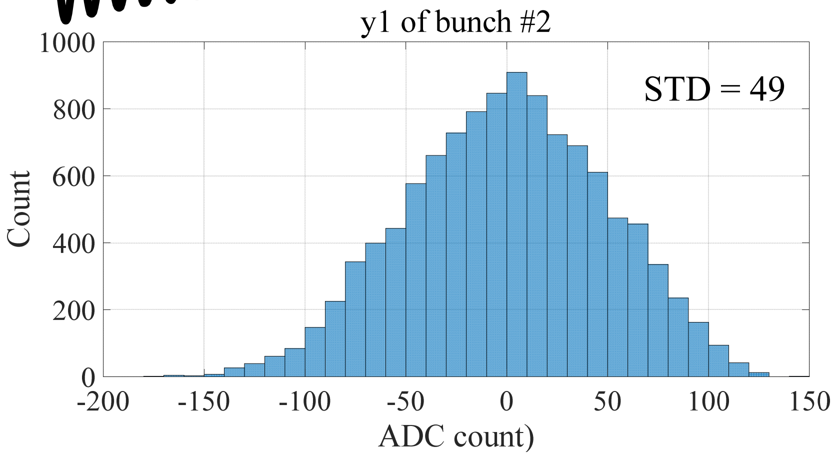
System Setup & Performance

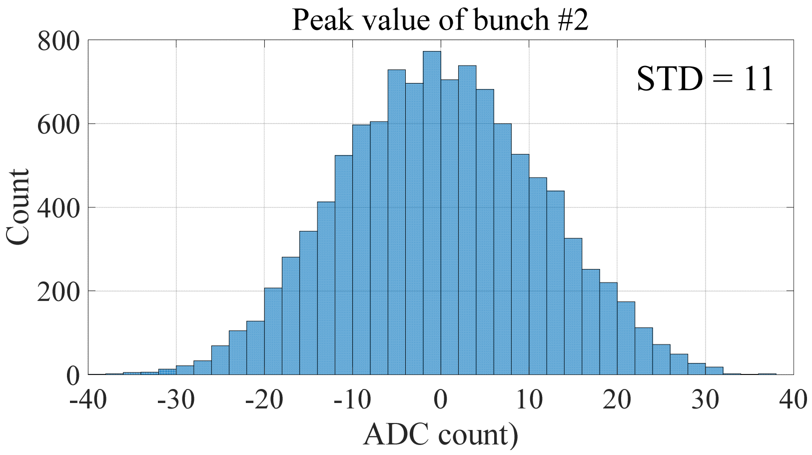
- Challenges for precise BxB BCM
- System setup (hardware)
  - Performance
- System setup (software)
- Performance

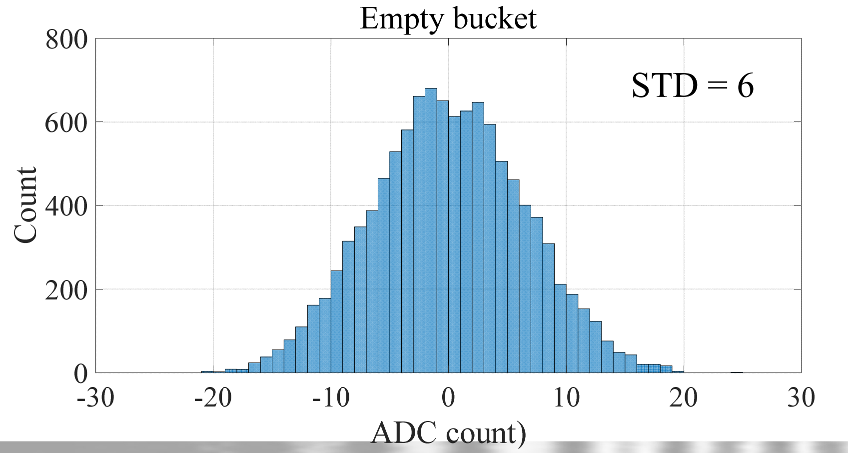
Performance



Performance







Conclusion:

The new sampling method basically minimized the influence of sampling phase jitter!

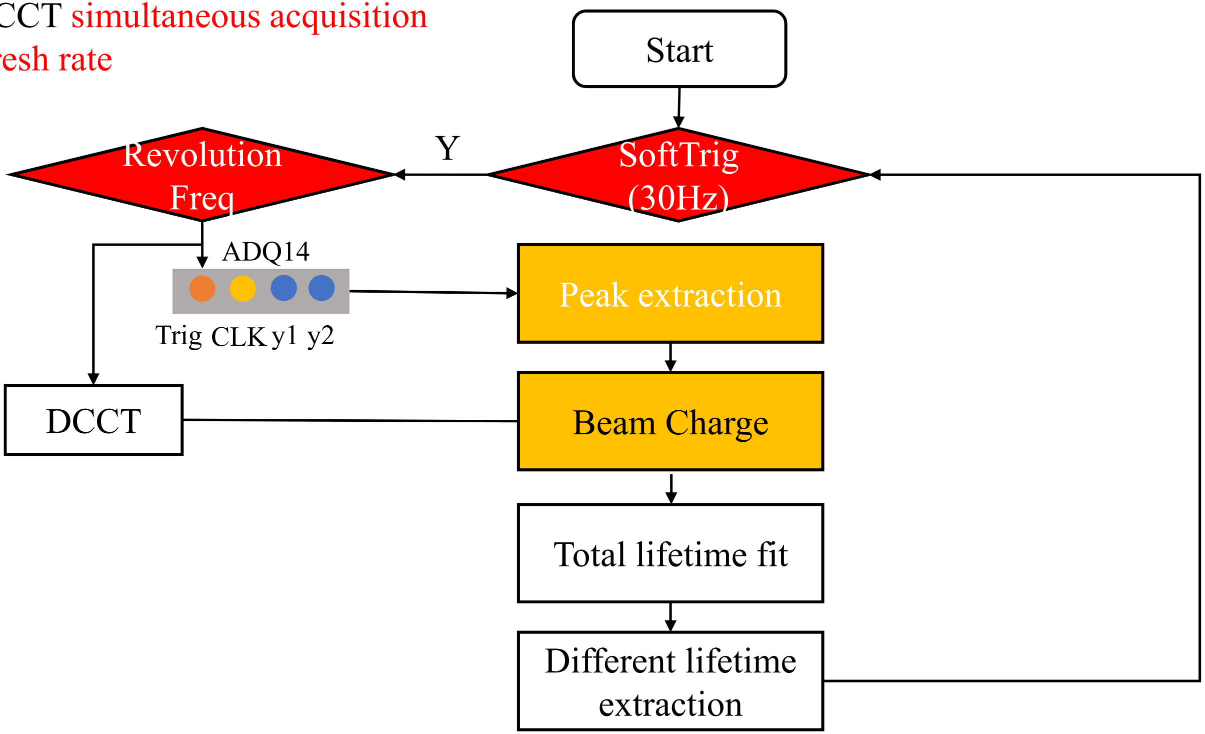
System Setup & Performance

- Challenges for precise BxB BCM
- System setup (hardware)
- System setup (software)
- Performance

System setup (software)

Target:

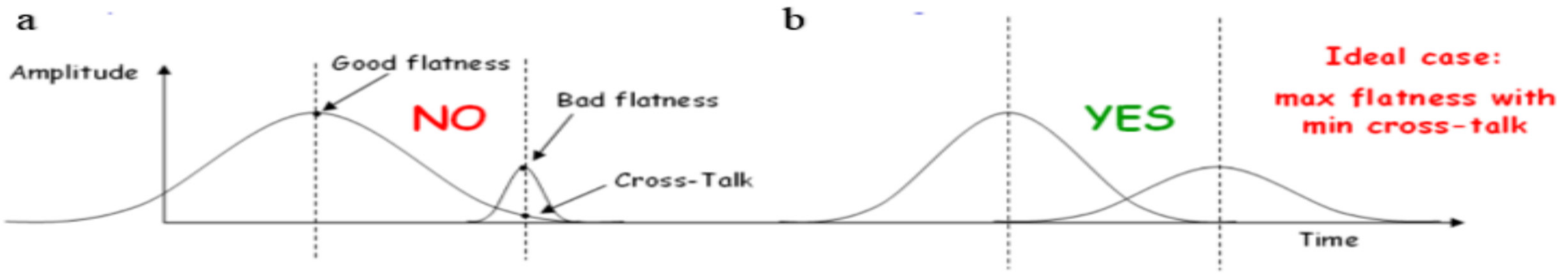
- Crosstalk minimization
- BPM data and DCCT simultaneous acquisition
- Increase data refresh rate

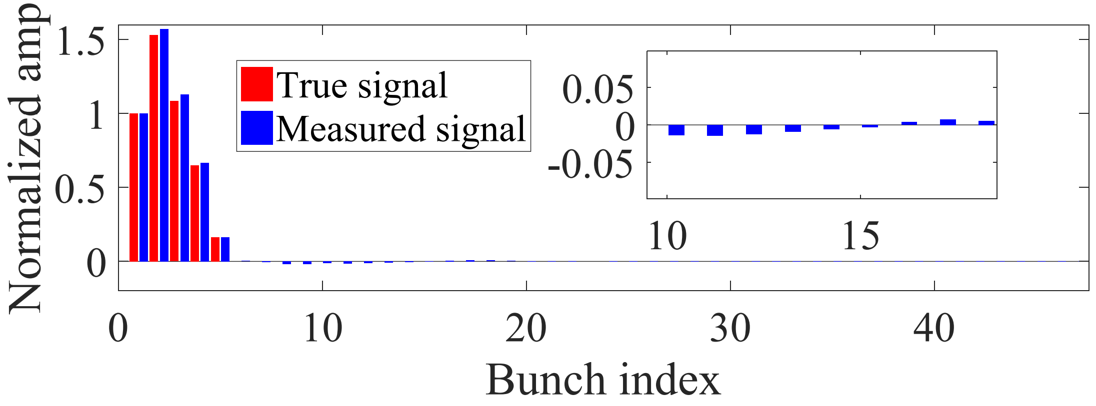


Bunch crosstalk analysis

Target: Minimize the crosstalk between bunches due to the limited bandwidth of the system

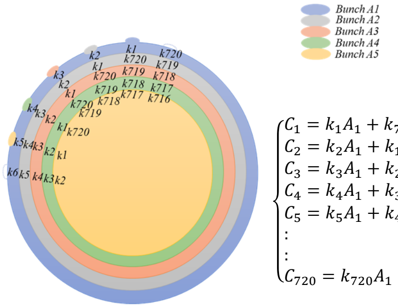
Method: Use signal captured by the 6G BWD oscilloscope as the true signal



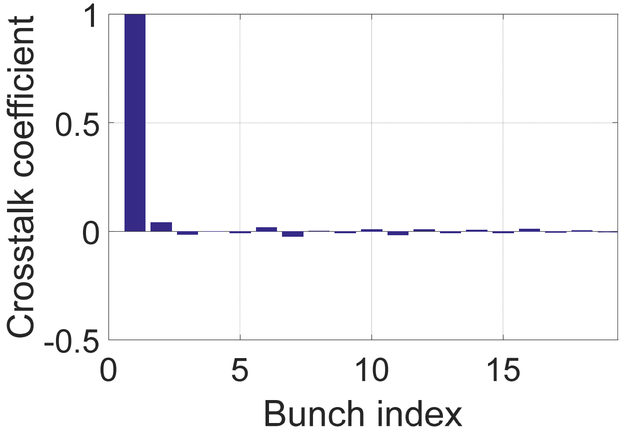


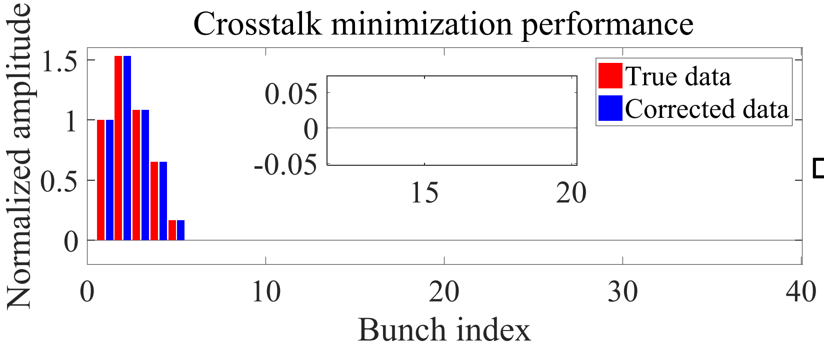
Bunch crosstalk minimization

Crosstalk coefficient matrix



$$\begin{cases} C_1 = k_1A_1 + k_{720}A_2 + k_{719}A_3 + k_{718}A_4 + k_{717}A_5 \\ C_2 = k_2A_1 + k_1A_2 + k_{720}A_3 + k_{719}A_4 + k_{718}A_5 \\ C_3 = k_3A_1 + k_2A_2 + k_1A_3 + k_{720}A_4 + k_{719}A_5 \\ C_4 = k_4A_1 + k_3A_2 + k_2A_3 + k_1A_4 + k_{720}A_5 \\ C_5 = k_5A_1 + k_4A_2 + k_3A_3 + k_2A_4 + k_1A_5 \\ \vdots \\ \vdots \\ C_{720} = k_{720}A_1 + k_{719}A_2 + k_{718}A_3 + k_{717}A_4 + k_{716}A_5 \end{cases}$$





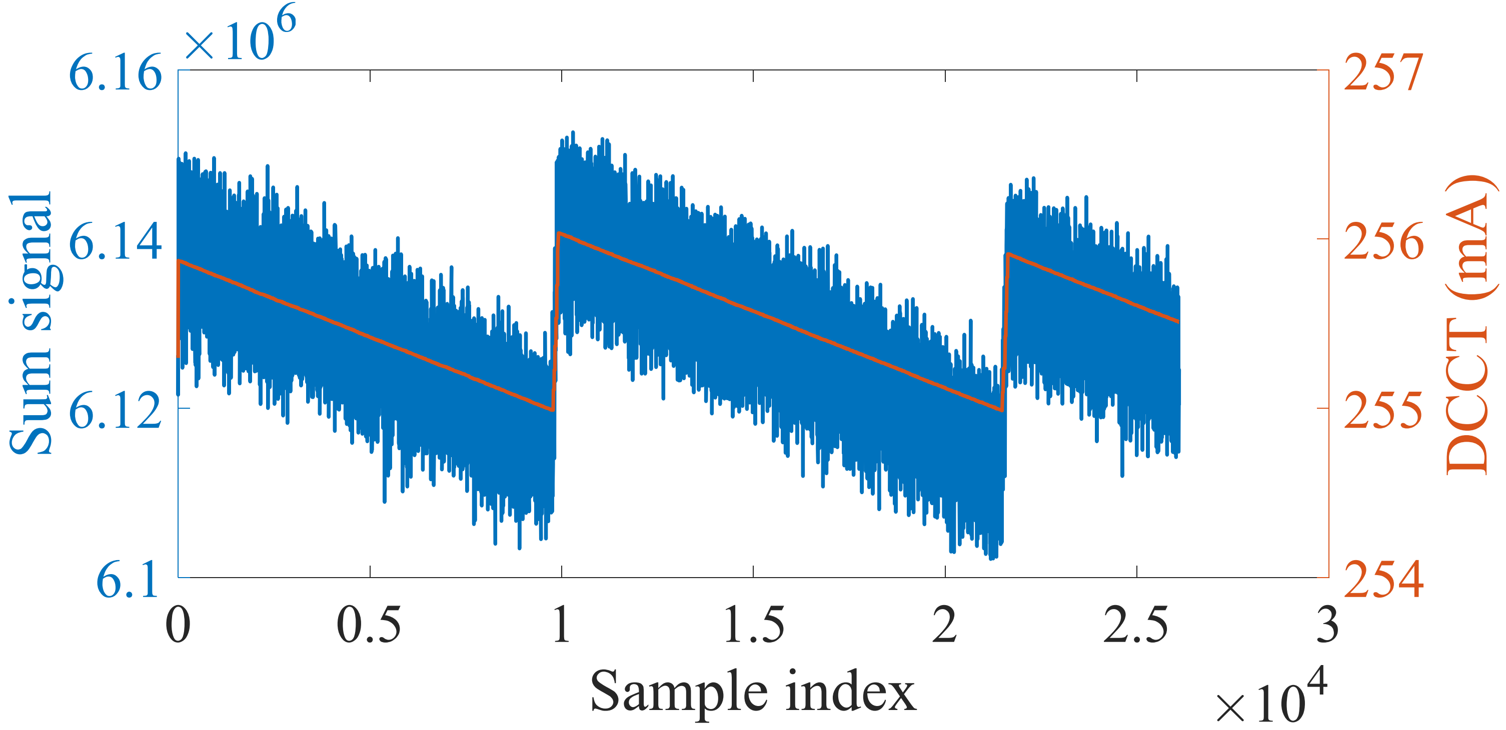
Conclusion:

- This method is able to minimize the crosstalk;
- The corrected data is closer to the true value.

Bunch-by-bunch charge measurement

Target: Bunch-by-bunch charge measurement, transfer voltage of BPM electrode to charge

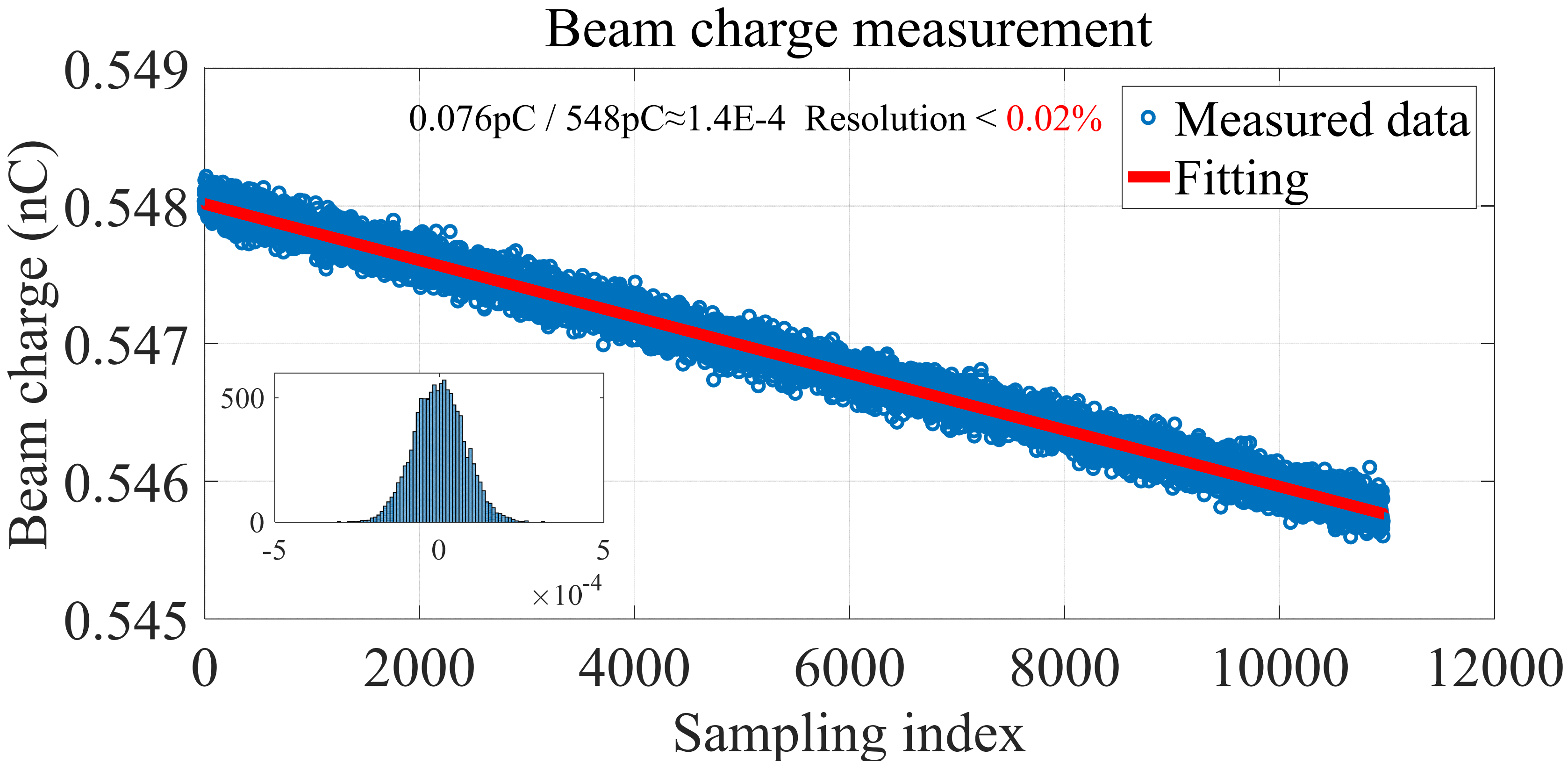
Method: BPM data and DCCT simultaneous acquisition, use DCCT to calibrate BPM sum signal.



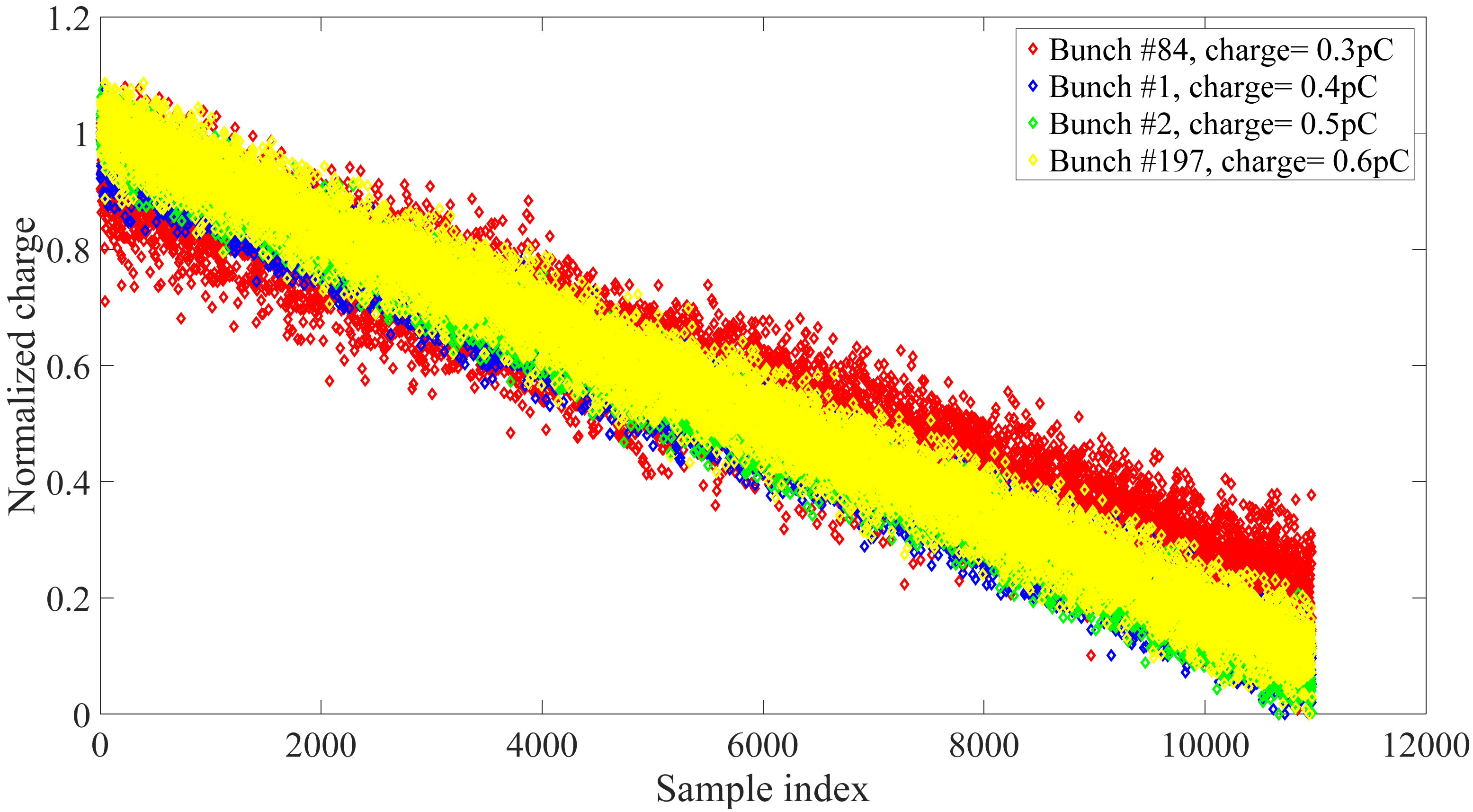
System Setup & Performance

- Challenges for precise BxB BCM
- System setup (hardware)
- System setup (software)
- Performance

Performance (charge measurement resolution)

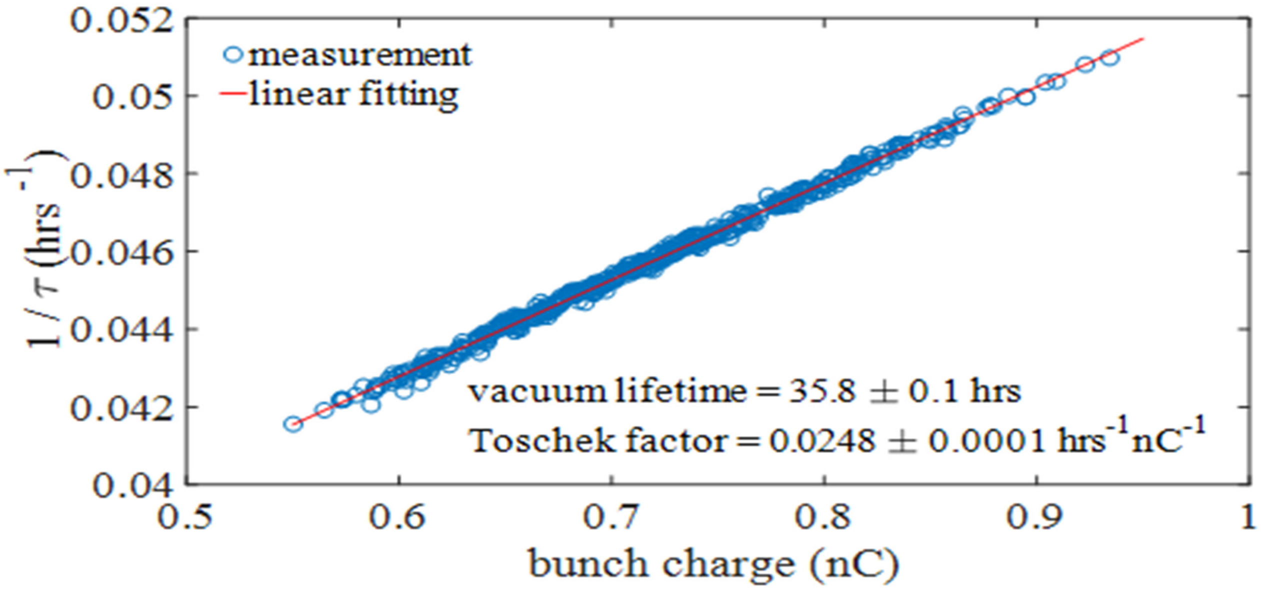


Bunch-by-bunch charge measurement



Performance（Touschek lifetime measurement）

$$\frac{1}{\tau} = k_{Touschek} Q + \frac{1}{\tau_{vacuum}}$$



The best result of life measurement: relative error is up to 1%

System performance conclusion

- Impact of Sampling phase jitter has been effectively minimized;
- Crosstalk between bunches has been effectively minimized;
- Realize synchronous acquisition of DCCT and BPM data;
- Data refresh rate: 30 Hz;
- Resolution of beam charge measurement better than 0.02%;
- Beam lifetime measurement of every bunch.

Application–Online lifetime measurement

- Physical aperture study
- Long time average lifetime analysis
    - Abnormal events
    - Beam loss analysis

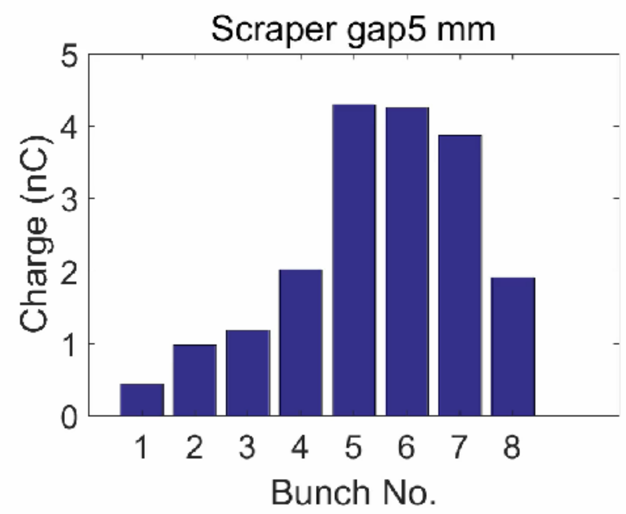
Application–Online lifetime measurement

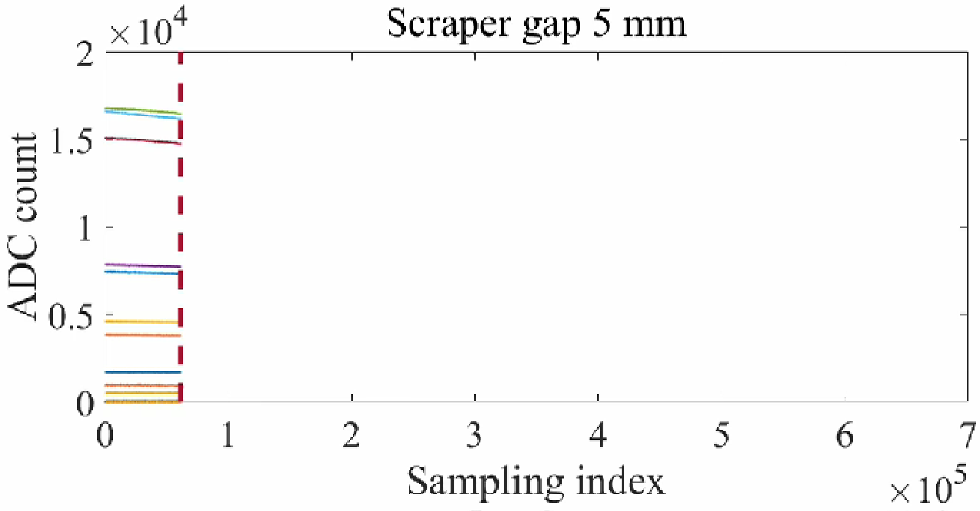
- Physical aperture study
- Long time average lifetime analysis
    - Abnormal events
    - Beam loss analysis

Application – Physical aperture study

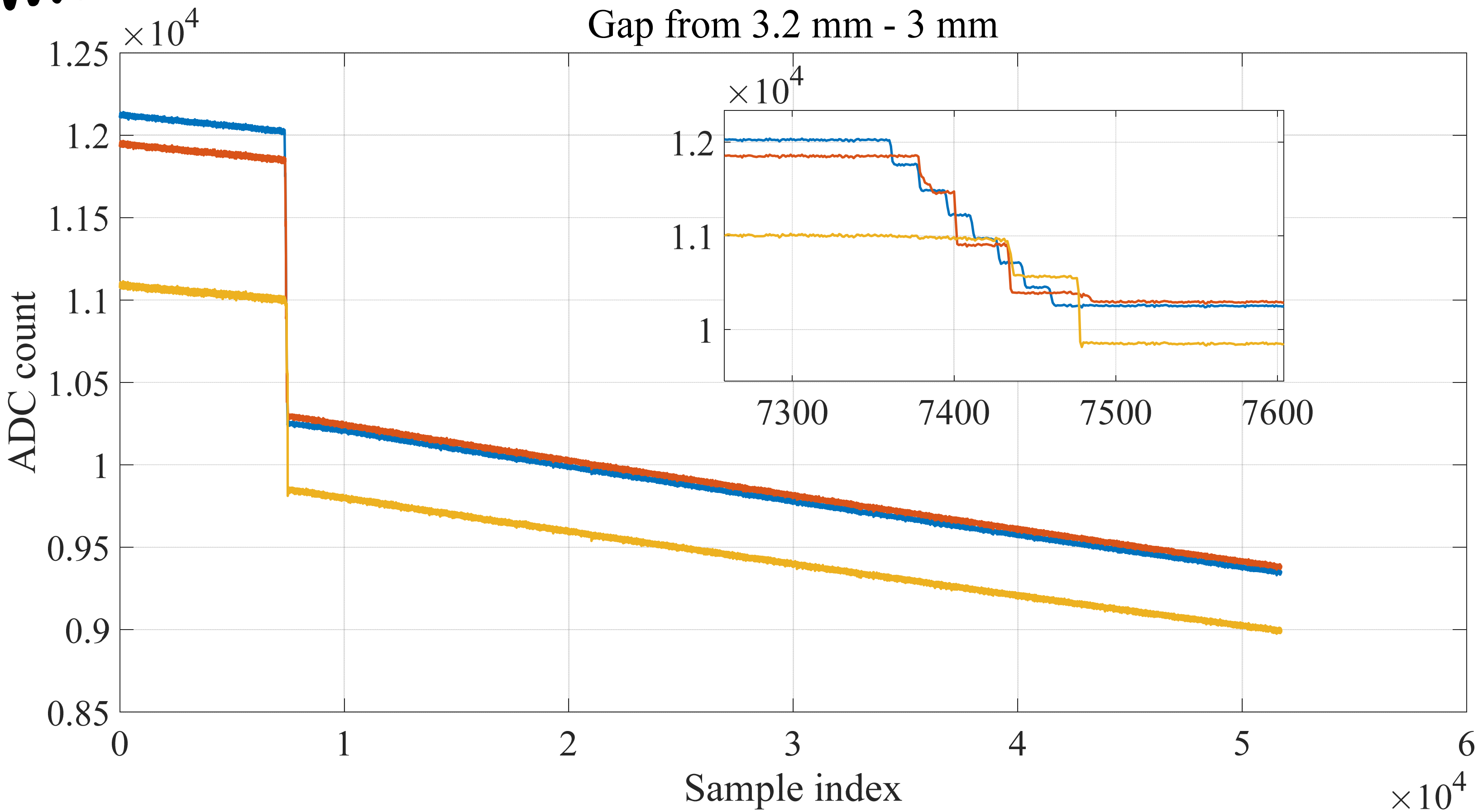
Target: Study the effect of physical aperture on beam lifetime, verify performance of the new system

Method: The locations of the blades determine the physical aperture at that position of the vacuum chamber.

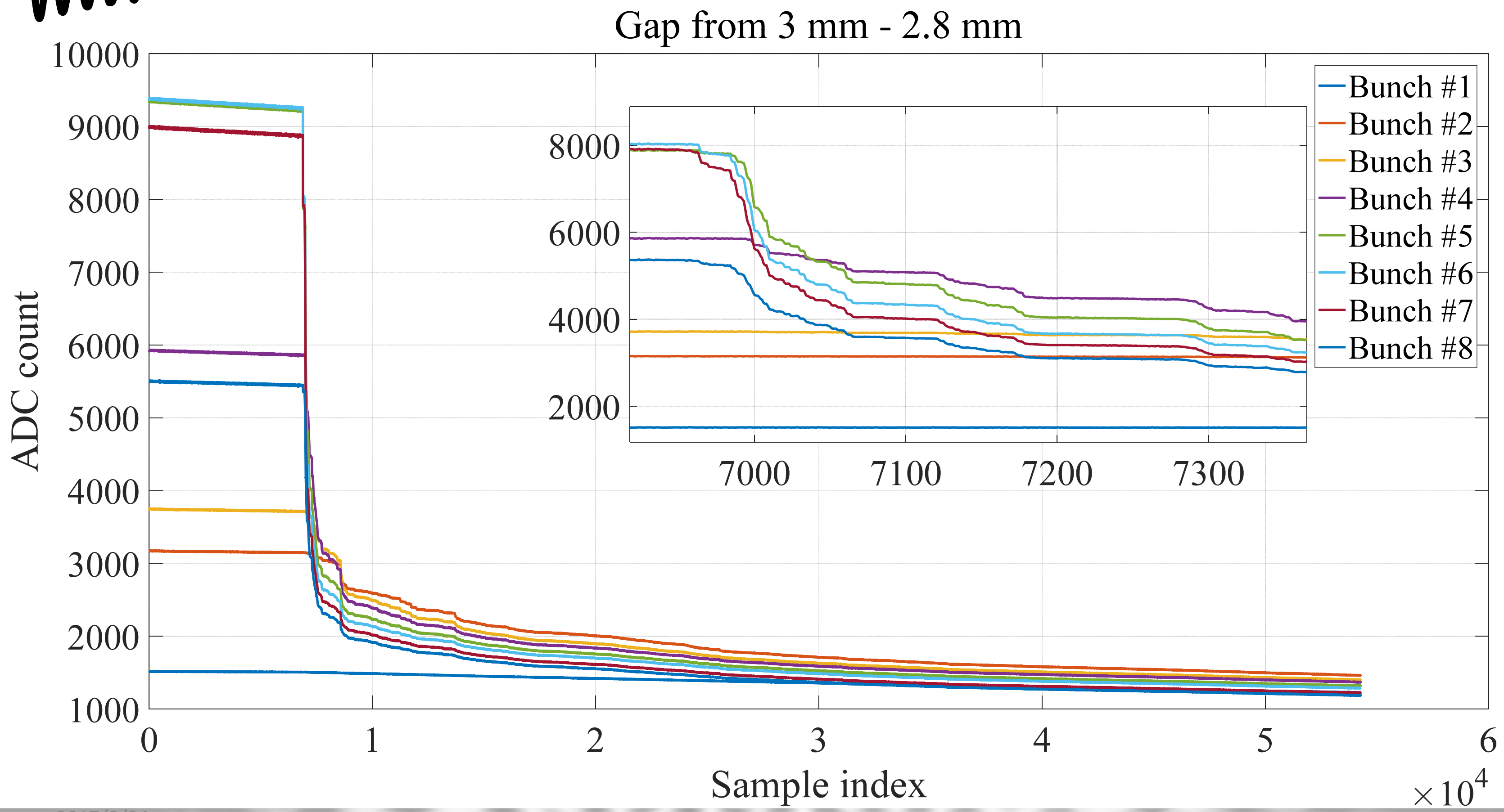




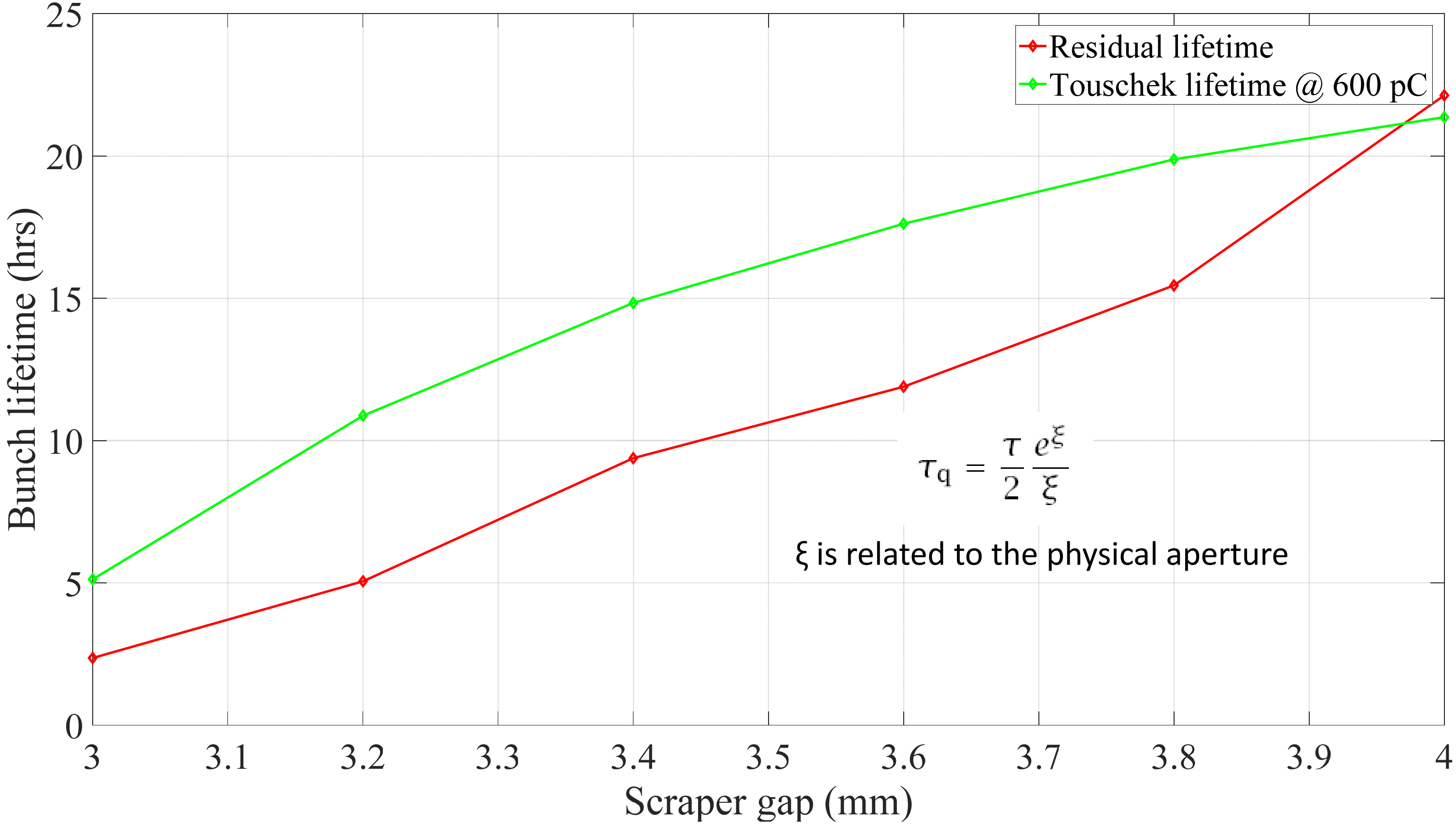
Application – Single bunch instability



Application (Multi-bunch instablity)



Application-Different lifetime



$$\tau_q = \frac{\tau}{2}\frac{e^{\xi}}{\xi}$$

ξ is related to the physical aperture

Physical aperture experiment summary

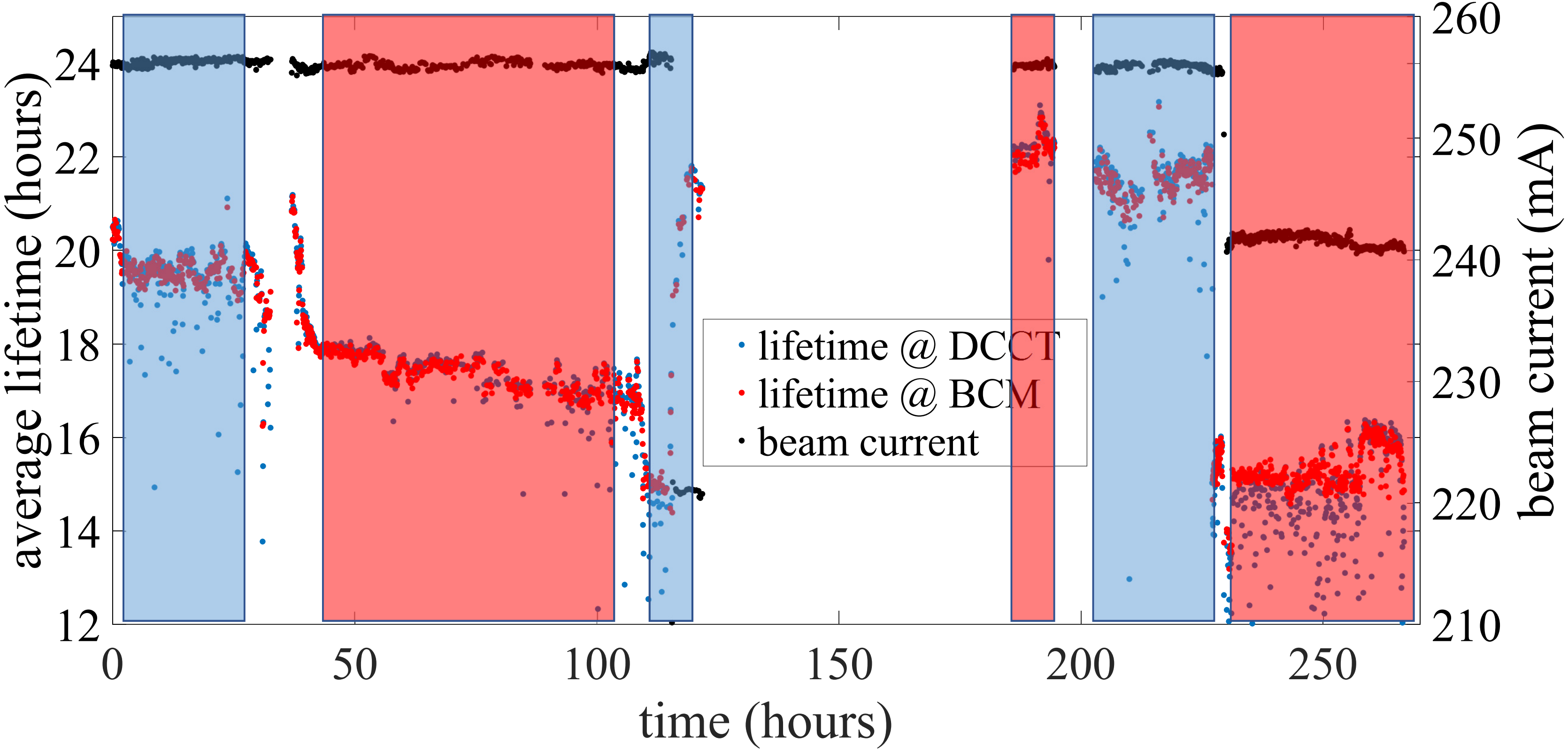
- The new system is able to extract different lifetime
- Can be used to effectively observe the instantaneous changes of the bunch
- Can be used as a toolkit to research beam instabilities

Application–Online lifetime measurement

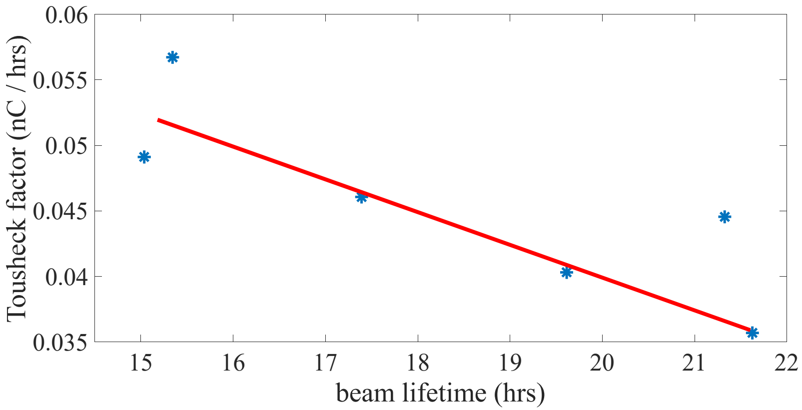
- Physical aperture study
- Long time lifetime analysis
  - Abnormal events
  - Beam loss analysis

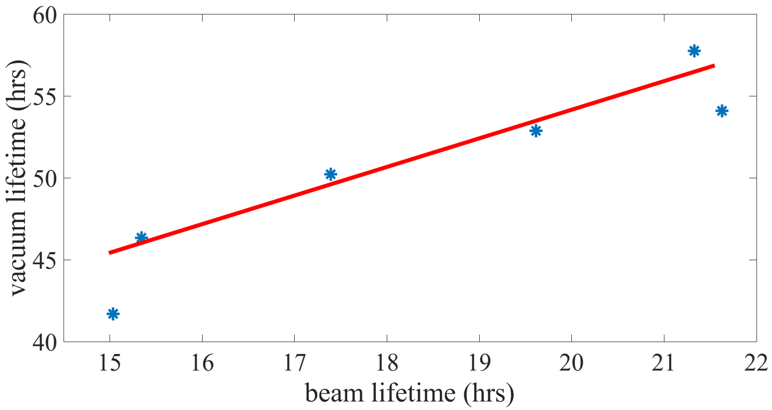
Long time data analysis summary

2019/6/28 – 2019/7/8



Long time data analysis summary

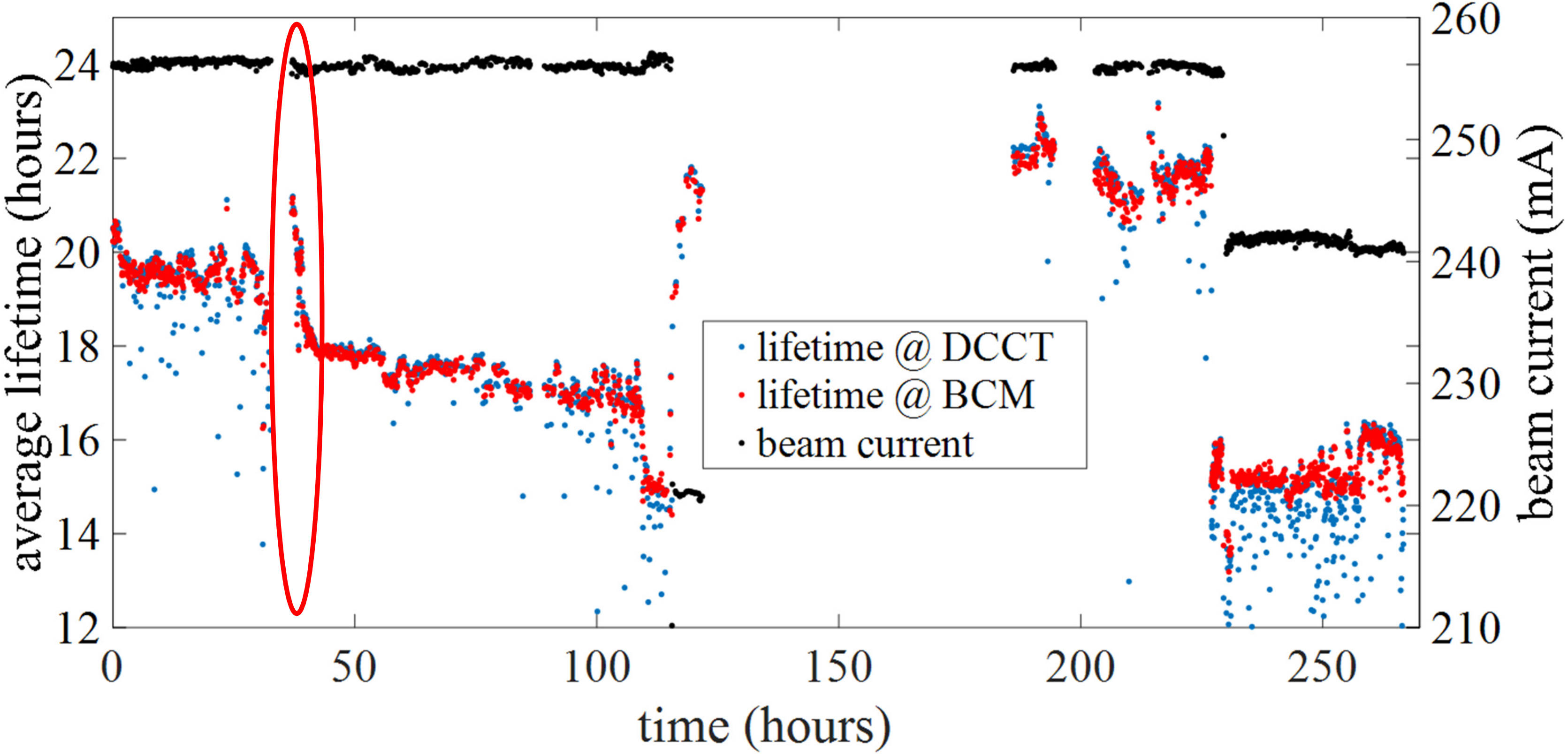




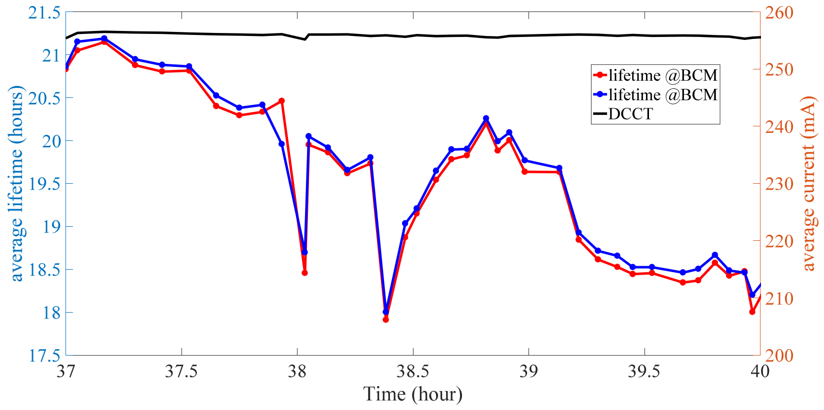
Beam Current (mA)	Average Lifetime (hrs)	Tousheck Factor (nC/hrs)	Vacuum Lifetime (hrs)
256.2	19.6	0.040	53
255.9	17.4	0.046	50
256.6	15.0	0.049	42
220.9	21.3	0.045	58
256.0	21.6	0.036	54
241.5	15.3	0.057	46

- The main factor affecting the total lifetime at SSRF storage ring is the Touschek lifetime;
- The total lifetime of the beam at different time periods was significantly negatively correlated with the Touschek factor, which was in line with expectations;
- Although vacuum lifetime is not a major contributor, it is also positively correlated with total lifetime;
- There is no obvious dependence on Touschek factor, vacuum life and average beam current;

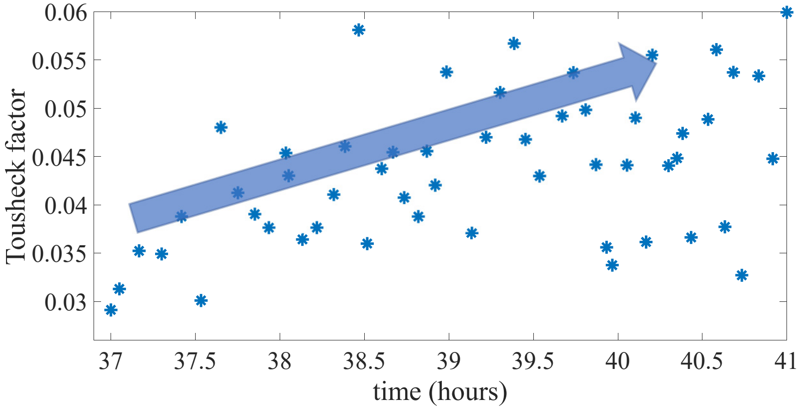
Long time average lifetime analysis

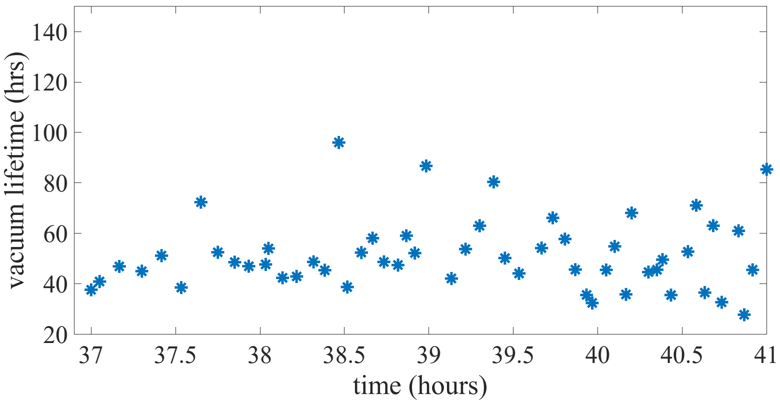


Long time average lifetime analysis – event 1

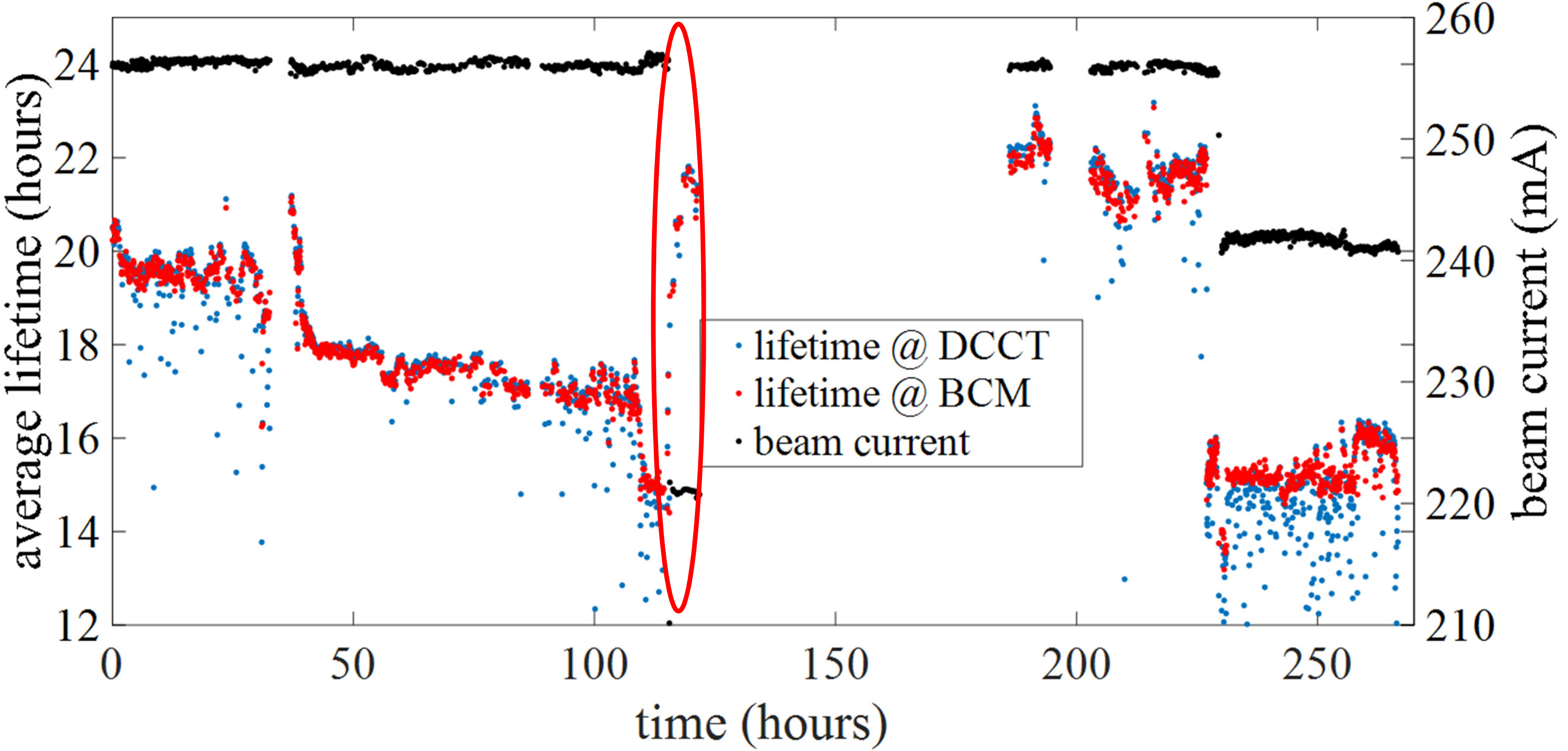


- The average lifetime obtained by DCCT is consistent with the results obtained by BCM;
- When the total lifetime becomes smaller, the Touschek factor obviously has an upward trend, and the vacuum life is basically unchanged.

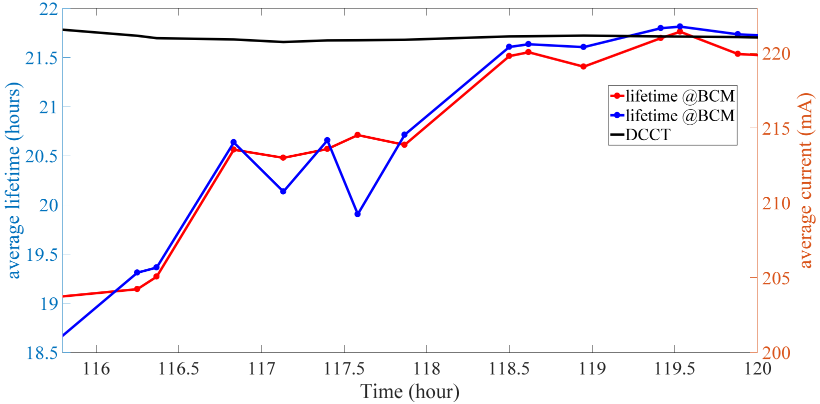




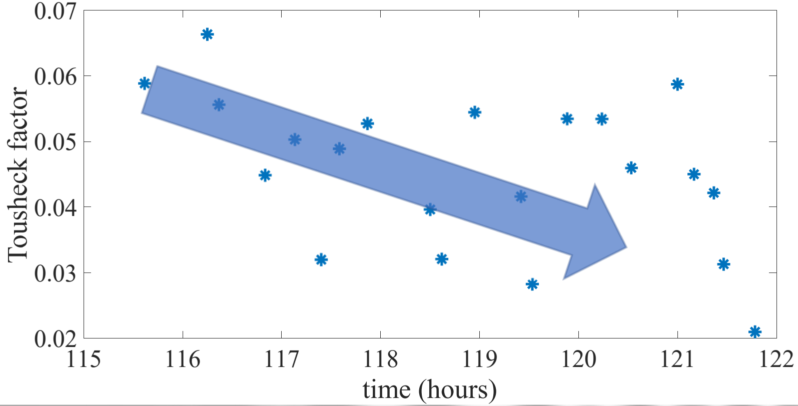
Long time average lifetime analysis

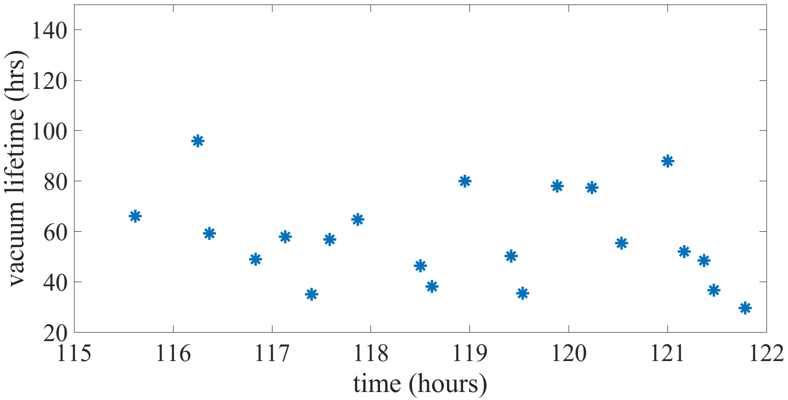


Long time average lifetime analysis – event 2

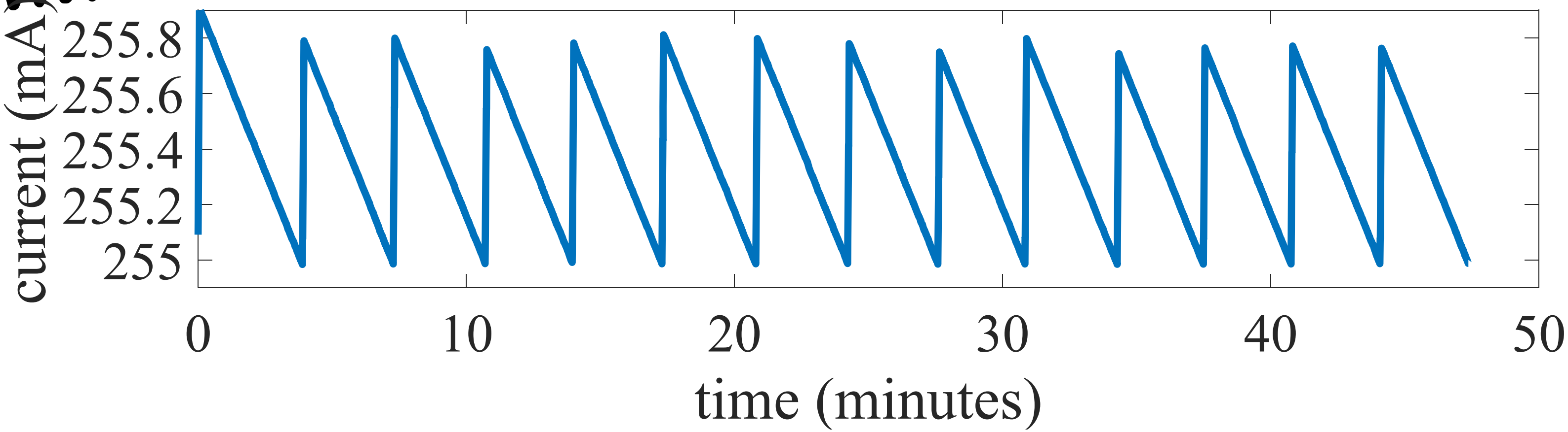


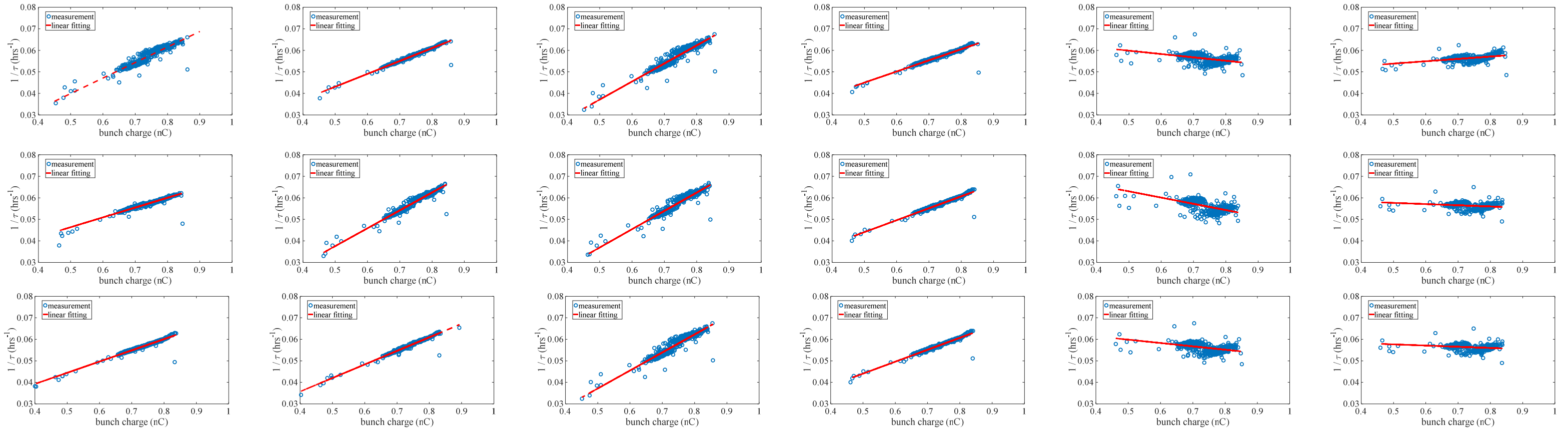
- The average lifetime obtained by DCCT is consistent with the results obtained by BCM;
- When the total lifetime becomes larger, the Touschek factor obviously has a downward trend, and the vacuum life is basically unchanged.



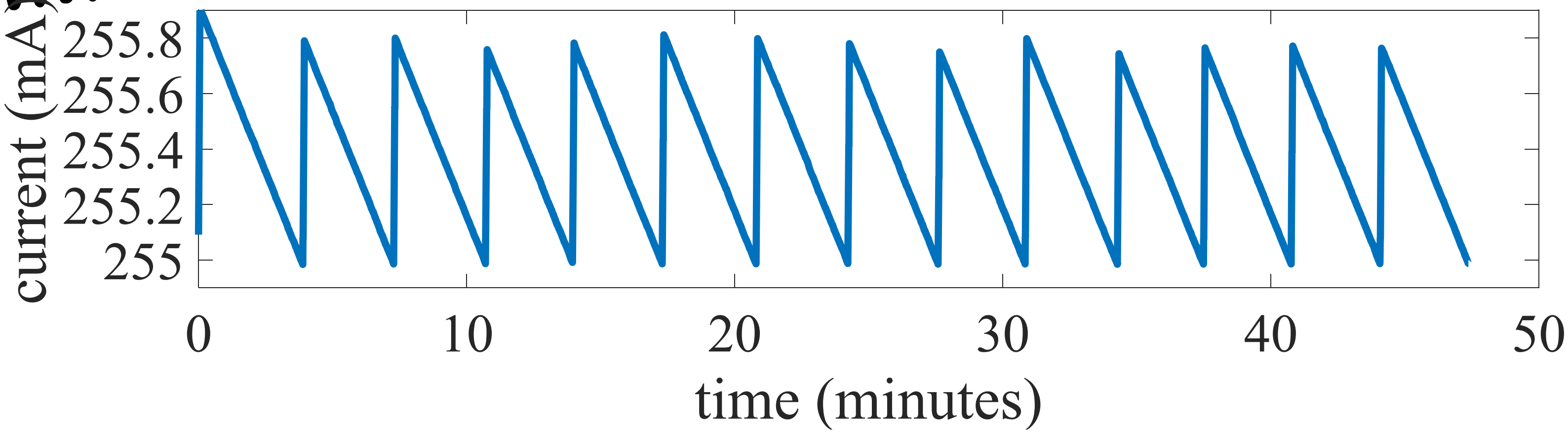


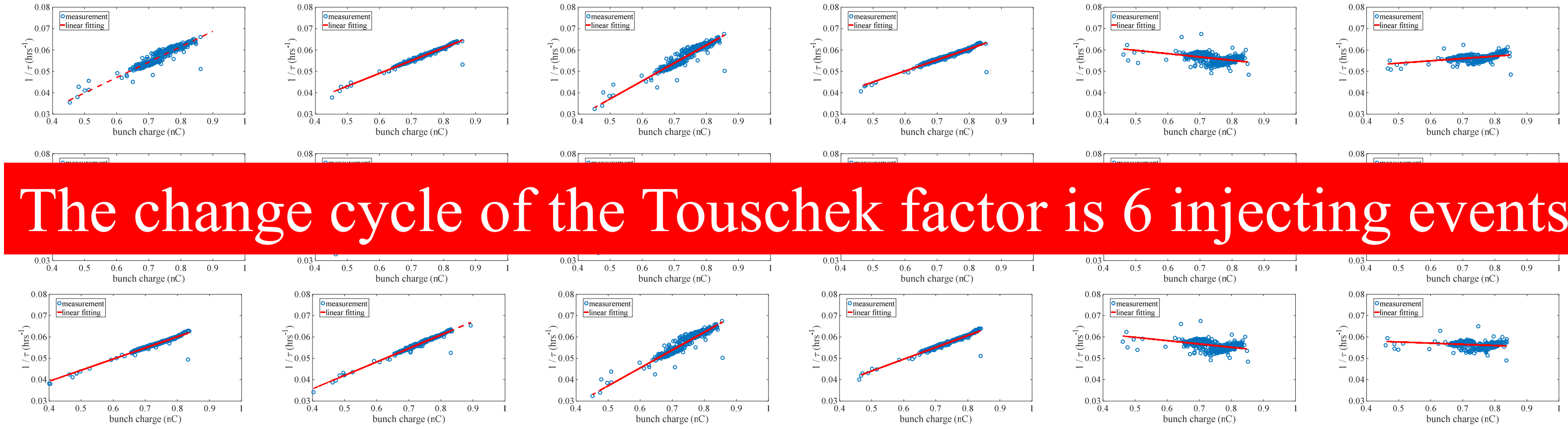
Interesting phenomenon





Interesting phenomenon





The change cycle of the Touschek factor is 6 injecting events.

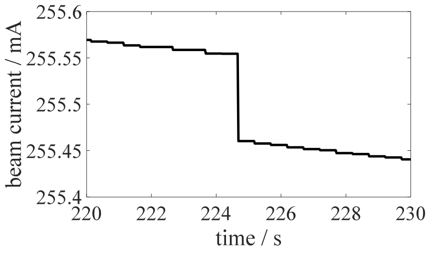
Application

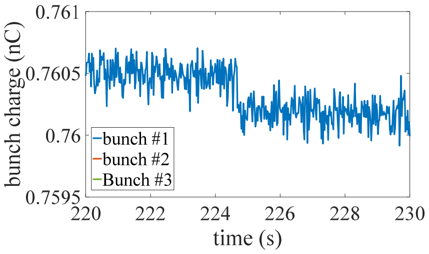
- Physical aperture study
- Long time average lifetime analysis
  - Abnormal events
  - Beam loss analysis

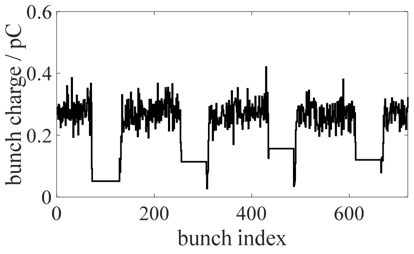
Beam loss analysis

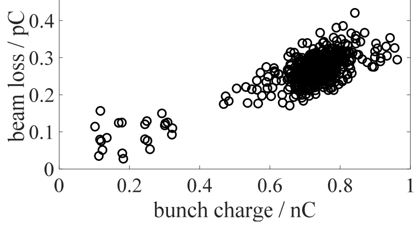
Motivation: Beam loss is very common in accelerator operation; analysis of beam loss is important for accelerator operation and optimization.

Average current (Beam loss event preliminary tracking) + Bunch charge curve (Further analysis of bunch behavior) + Beam loss distribution (Relationship with the position of the bunch) + Beam loss vs charge (Relationship with the charge of the bunch)





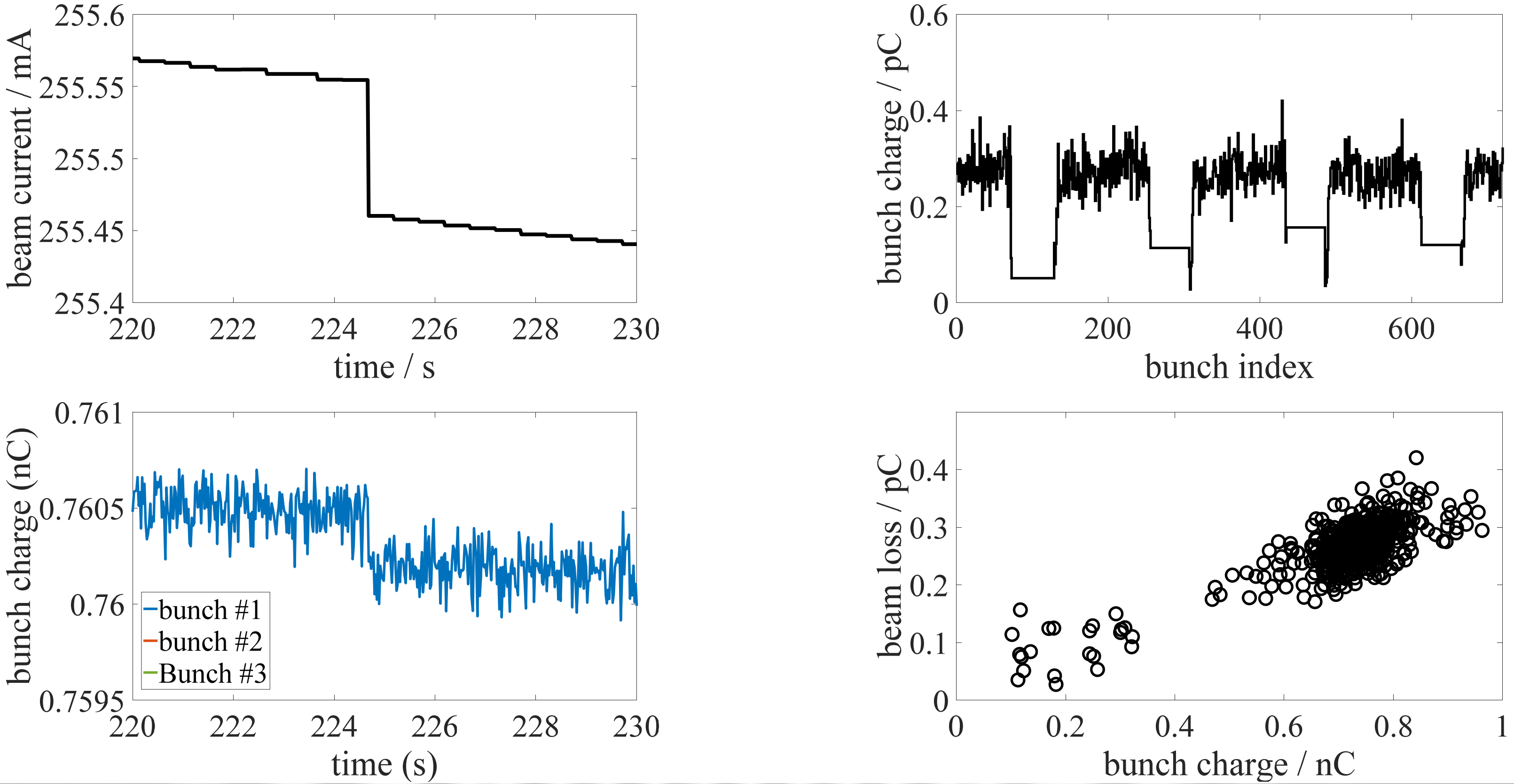




The preliminary judgment of the type and cause of the beam loos with these four analyses.

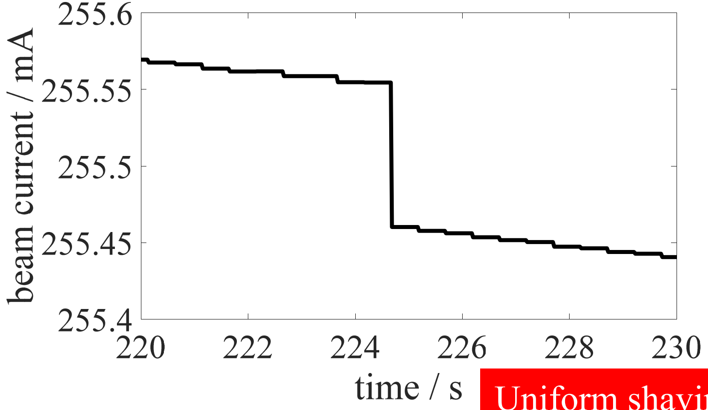
Beam loss analysis-Uniform beam loss

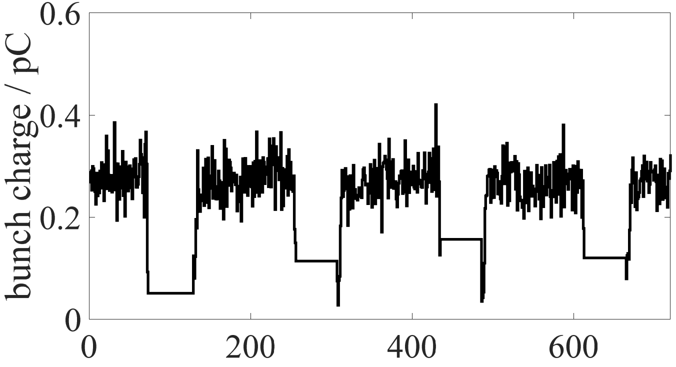
2019.06.28, 14:08, beam loss 100uA, 0.3pC for single bunch



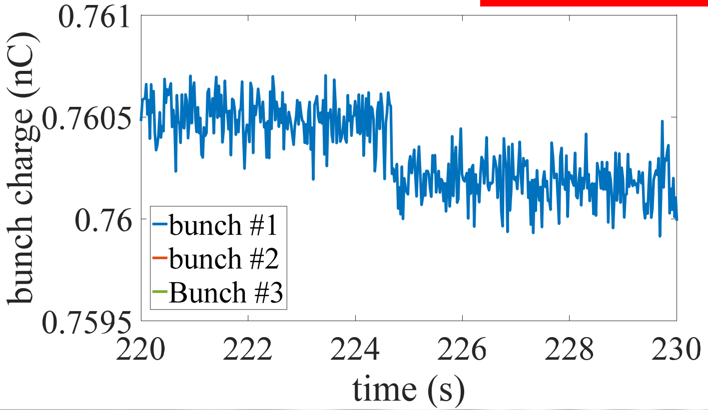
Beam loss analysis-Uniform beam loss

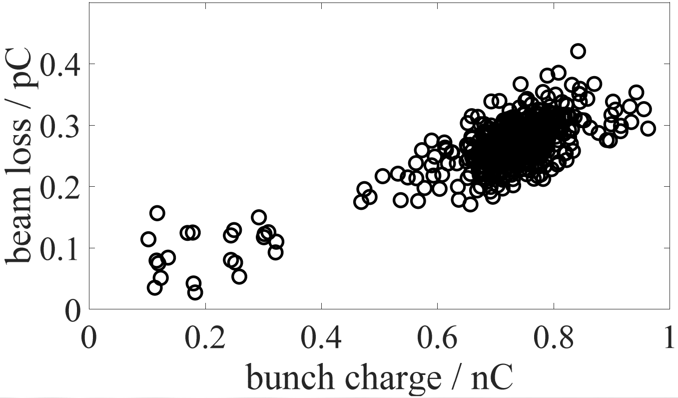
2019.06.28， 14:08， beam loss 100uA， 0.3pC for single bunch





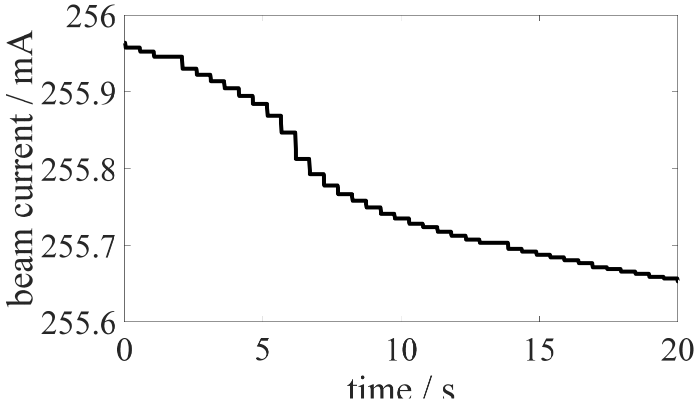
Uniform shaving maybe caused by physical aperture changes

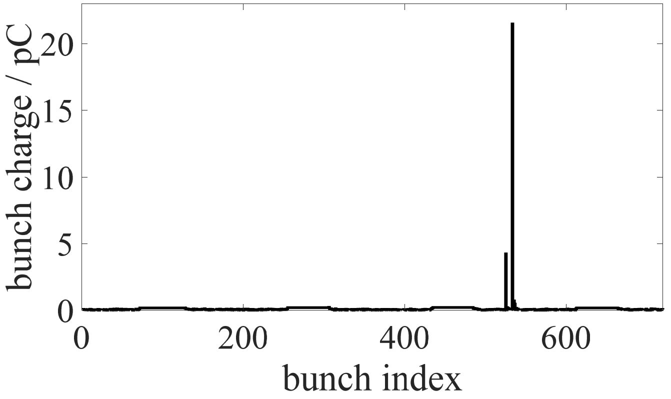


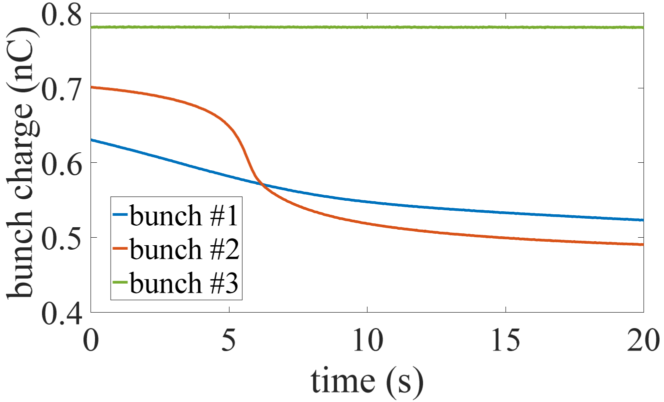


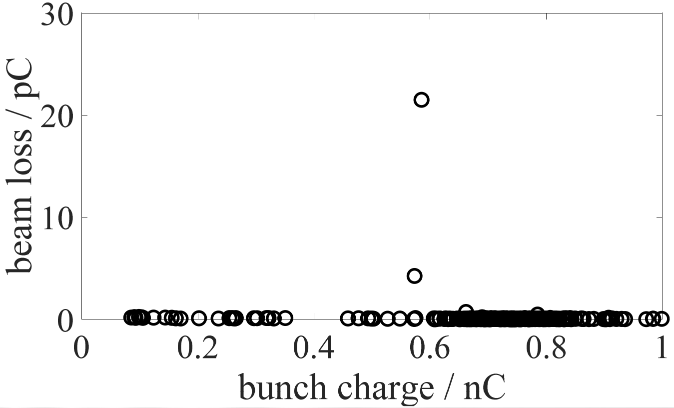
Beam loss analysis- multi individual beam loss

2019.07.01, 04:16, beam loss 300uA, two individual bunches (100-200uA)



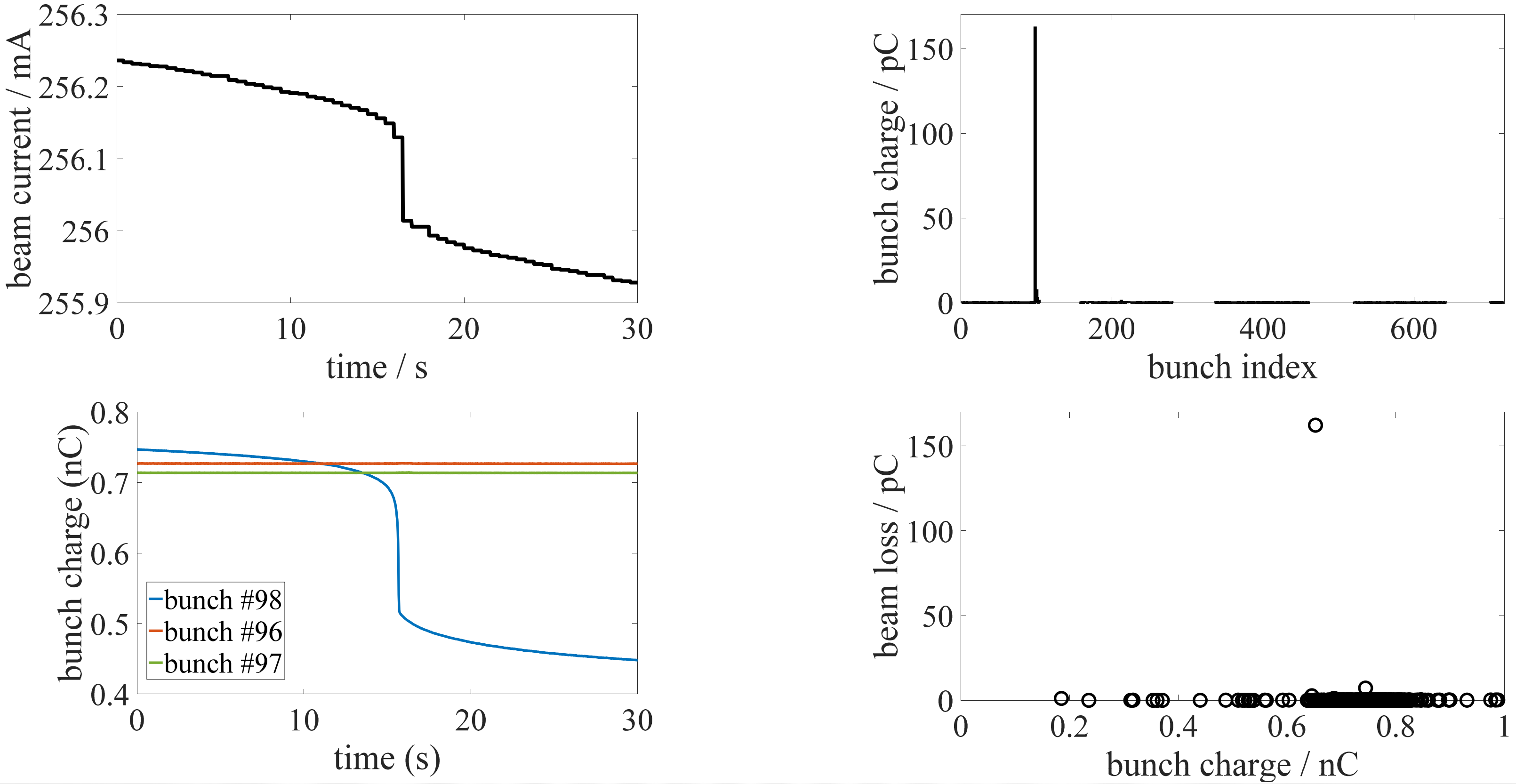






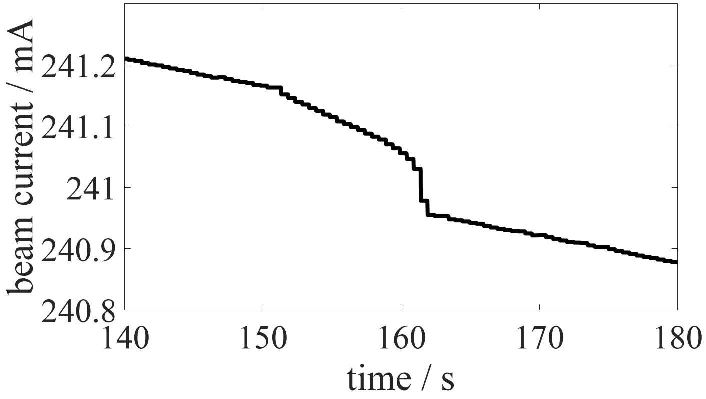
Beam loss analysis（3）

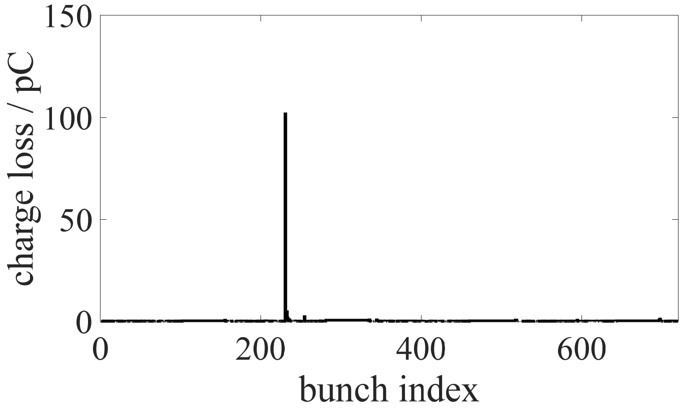
2019.07.05，22:18，beam loss 110uA，single bunch instantaneously dropped

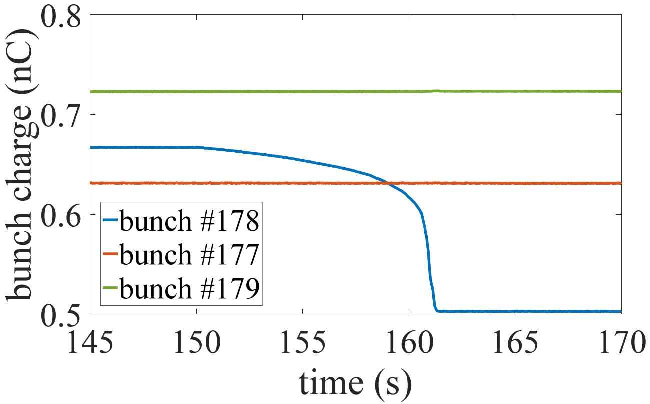


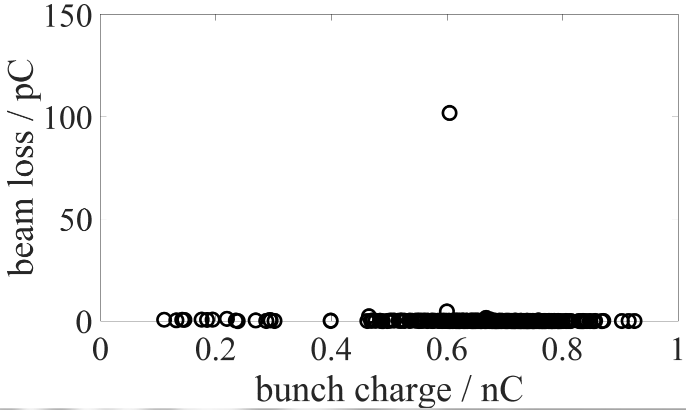
Beam loss analysis（4）

2019.07.07， 15:04， total beam loss 110uA， single bunch









Summary

Summary

- Bunch by bunch beam charge measurement resolution better than 0.02%, thanks to the two-point sampling method;

- Realized online bunch by bunch beam lifetime measurement during user operation;

- Touschek lifetime measurement's time cost from 'hours' to 'minutes';

- Toolkit to do sudden beam loss analysis.
    - Six different beam loss phenomena were found in the experiment:
        - Single bunch instabilities
        - Multi-bunch instabilities
        - Uniform shaving
        - the others need to be further studied combined with other tools.

Acknowledge

- Appreciated for the support from National Natural Science Foundation of China (No. 11375255 and No. 11375254) and National Ten-thousand Talents Program

- Appreciated for the help from beam physics group and beam operation group of SSRF in beam experiment

- Appreciated for the help of the colleagues

- Appreciated for the guidance of my supervisor Yongbin Leng

Thanks for your attention

Contact: gaobo@zjlab.org.cn

IBIC
MALMÖ, SWEDEN
International Beam Instrumentation Conference
8-12 SEPTEMBER 2019

上海同步辐射光源
Shanghai Synchrotron Radiation Facility

Application (Multi-bunch instablity)