BEPCII PERFORMANCE AND BEAM DYNAMICS STUDIES ON LUMINOSITY*

C.H. Yu †, Y. Zhang, Q. Qin, J.Q. Wang, G. Xu, C. Zhang, D.H. Ji, Y.Y. Wei, J. Xing, X. H. Wang, X.M. Wen, Z. Duan, Y. Jiao, N. Wang, Y.M. Peng, Y.Y. Guo, S.K. Tian, Y.S. Sun, J. Wu, T. Yue, X.Y. Huang, Z.C. Liu, H.F. Ji, S.D. Gu, Key Laboratory of Particle Acceleration Physics and Technology，Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Abstract

The upgrade of the Beijing Electron Positron Collider, BEPCII, is now in a good performance for both high energy physics and synchrotron radiation experiments. The luminosity at the design energy of 1.89 GeV reached the design value 1.0×10^{33} cm^{-2}s^{-1} recently. A lot of work, including accelerator physics study and technical progress, has been done for the luminosity enhancement, not only at the design energy, but all the energy region run for HEP experiments from 1.0 to 2.3 GeV. The performance of BEPCII and the process of luminosity enhancement will be described in detail.

INTRODUCTION

The Beijing Electron-Positron Collider (BEPC) has been well operated not only for high energy physics, but also for synchrotron radiation application for more than 15 years since 1989. Its upgrade scheme, BEPCII, is a double-ring collider, in which two beams have same energies. It aims at the research of τ-charm physics with a designed luminosity of 1.0×10^{33} cm^{-2}s^{-1}, which is about two orders higher than BEPC at the beam energy of 1.89 GeV. The two new rings of BEPCII have been built in the existing BEPC tunnel while keeping the machine as a synchrotron radiation source. According to the requirements of high energy physics, BEPCII has been operated in a large energy region from 1.0 GeV to 2.3 GeV since 2009 [1]. The performance of the BEPCII as a synchrotron radiation source provides a high flux of synchrotron radiation at the beam energy of 2.5 GeV for 14 beam lines about 3 months every year.

ROAD TO THE DESIGN LUMINOSITY

Commissioning with Designed Lattice

The layout of BEPCII as a double-ring collider is shown in Figure 1, with the main parameters shown in Table 1. The BESIII detector was installed in May 2008. The commissioning of BEPCII with the designed lattice at the energy of 1.89 GeV started on June 22nd, 2008. Both electron ring (BER) and positron ring (BPR) accumulated beams successfully on June 22nd and June 26th, respectively. Tuning on collision started on July 16th, 2008. The luminosity reached 1.3×10^{32}cm^{-2}s^{-1} with the beam current of 520 mA*520 mA before December 2008. A long time was taken to study the source which caused a strong longitudinal instability shown in Figure 2 in both BPR and BER. Dipole mode oscillation was observed in BER, while both dipole and quadrupole mode oscillation were observed in BPR.

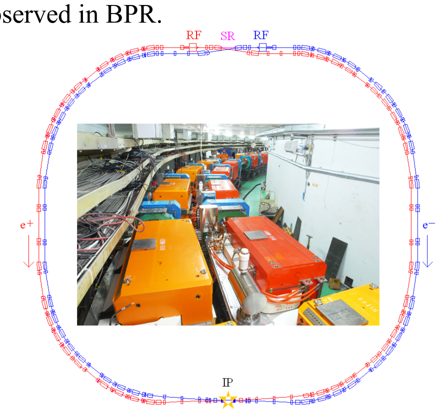

Figure 1: Layout of BEPCII as a collider.

Table 1: Main Design Parameters of BEPCII

Parameters	Values
Operation energy	1.0~2.1 GeV
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	9.8 mA
Circumference	237.5 m
Number of particles	4.5×10^{12}
β function at IP β_x/β_y	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point υ_x/υ_y	6.53/5.58
Harmonic number	396
Bunch number	93
Bunch spacing	2.4 m
RF voltage	1.5 MV
RF frequency	499.8 MHz
RF cavity number per ring	1
Energy loss per turn	121 keV
Synchrotron radiation power	110 kW
Damping time $\tau_x/\tau_y/\tau_E$	25/25/12.5 ms
Natural energy spread	5.16×10^{-4}
Momentum compaction	0.0235
Natural bunch length	1.35 cm
Crossing angle at IP	11×2 mrad
Beam-beam parameter	0.04
Luminosity	1.0×10^{33}cm^{-2}s^{-1}

* Work supported by NSFC U1332108
† yuch@ihep.ac.cn

Copyright © 2016 CC-BY-3.0 and by the respective authors

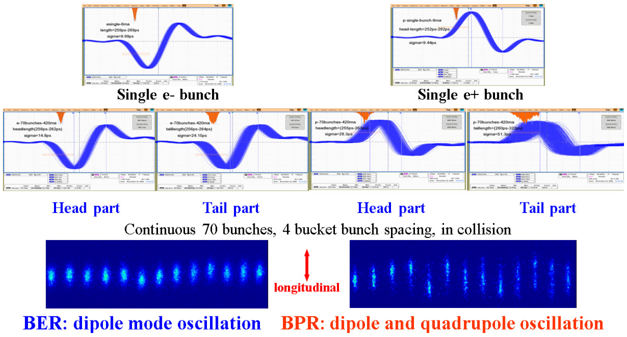

Figure 2: Longitudinal multi-bunch instability.

Two profiles, which caused the quadrupole mode oscillation in the BPR, were removed in Jan. 2009. Collision tuning resumed on February 2nd, 2009. The maximum luminosity reached 2.3×10^{32} $cm^{-2}s^{-1}$ with a beam current of 520 mA*520 mA on April 12th, 2009 during the operation for high energy physics.

During the period of dedicated machine study the horizontal tune was moved from 6.530 to 6.505 on May 5th, 2009. The luminosity reached 3.3×10^{32} $cm^{-2}s^{-1}$ with beam current of 520 mA*520 mA in 10 days. The maximum beam-beam parameter reached 0.021. However, the dipole mode oscillation in longitudinal direction still existed in both BER and BPR, which led to obvious luminosity reduction.

Longitudinal feedback systems were installed into BPR and BER during the summer shutdown in 2009. The commissioning of BEPCII with longitudinal feedback system began on December 18th, 2009. The longitudinal instability was suppressed effectively so that the luminosity was improved about 30%. The data taking at the energy of 1.89 GeV started from the beginning of 2010. The beam current and luminosity were improved step by step, together with the control of detector background and the luminosity optimization systematically. The maximum beam current and luminosity reached 750 mA and 6.49×10^{32} $cm^{-2}s^{-1}$, respectively until April 28th, 2011, the time that BESIII began the data taking plans for other energy points(1.0~2.3 GeV).

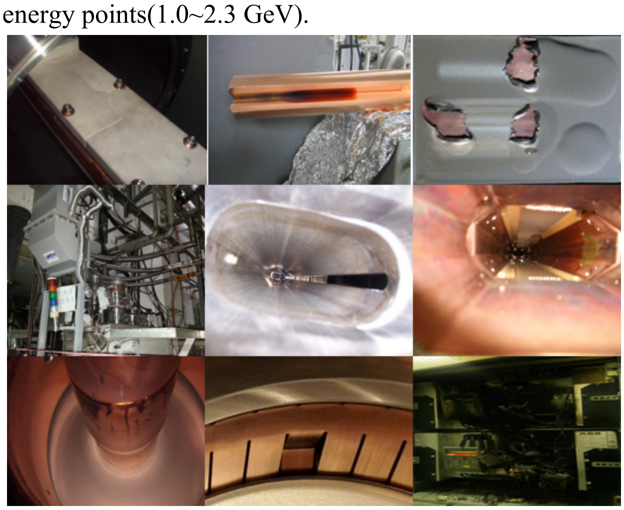

Figure 3: Some hardware failures which limited the increase of beam current.

There are two limitations to restrict the luminosity improvement. One is the beam current, and the other is beam-beam parameter. It's very hard to increase the beam current, especially above 700 mA due to heating problem, which were mainly caused by synchrotron radiation power and high order mode. Several serious hardware failures were happened during the operation, such as kicker magnet, RF coupler, SR monitor, bellows, feedback system, etc., shown in Figure 3. The beam-beam parameter was suppressed obviously under 0.033 at any bunch current shown in Figure 4 even with sufficient collision tuning for the luminosity optimization. Bunch lengthening effect was considered to explain the phenomenon. Several bunch length measurements by streak camera had been done. However no believable results were obtained due to worse measurement accuracy.

Lattice Upgrade to Control the Bunch Length

There is only one RF cavity for each ring due to the limitation of free space in the tunnel. It's unavailable to suppress bunch length by increasing the voltage of RF cavity. A new lattice was designed to control the bunch length [2] with the main parameters shown in Table 2. The natural bunch length was reduced from 1.35 cm to 1.15 cm by decreasing the momentum compaction from 0.0235 to 0.0170. More collision bunches are required since the designed bunch current is reduced from 9.8 mA to 7.0 mA with lower emittance for the consideration of bunch lengthening. The bunch spacing is modified from 4 RF buckets to 3, which will lead to a slight luminosity reduction due to stronger parasitic collision.

Table 2: Main Parameters of Low Momentum Compaction and Low Emittance Lattice

Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	7.0 mA
β function at IP β_x/β_y	1.0 m/1.5 cm
Horizontal emittance	100 nm·rad
Working point υ_x/υ_y	7.505/5.580
Harmonic number	396
Bunch number	130
Bunch spacing	1.8 m
RF voltage	1.5 MV
Momentum compaction	0.0170
Natural bunch length	1.15 cm
Beam-beam parameter	0.04
Luminosity	$1.0\times10^{33}cm^{-2}s^{-1}$

Since BESIII doesn't take data at the energy of 1.89 GeV during period of April 28th, 2011 to 2018. A dedicated machine study to test the new lattice at the energy of 1.89 GeV was performed during February 28th to March 7th, 2013. The restriction to the beam-beam parameter was broken, as shown in Figure 4. The maximum beam-beam parameter reached 0.043.

ISBN 978-3-95450-147-2

Copyright © 2016 CC-BY-3.0 and by the respective authors

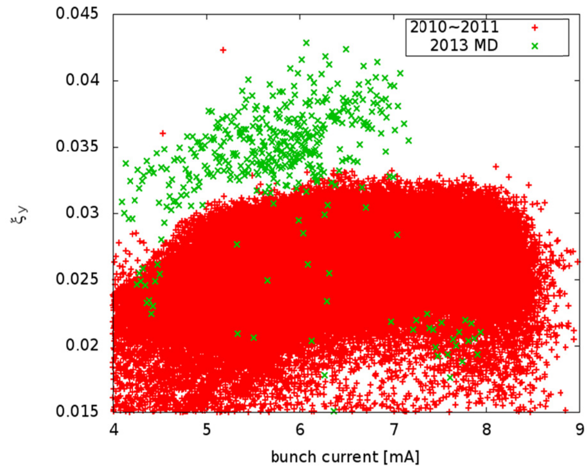

Figure 4: Comparison of beam-beam parameter with the schemes of different bunch lengths.

During the commissioning with 130 bunches, the transverse multi-bunch instability was too serious to keep beam stable by the feedback system. The luminosity optimization was done with 120 bunches. The maximum stable beam current was 750 mA. The maximum luminosity reached 7.08×10^{32} $cm^{-2}s^{-1}$ with the beam current of 734 mA*735 mA while the beam-beam parameter was 0.0349. The beam-beam parameter was reduced about 20% comparing to the less bunch number case. It's impossible to realize the designed luminosity 1.0×10^{33} $cm^{-2}s^{-1}$ with the new lattice parameters without upgrade of feedback system.

Optimized Lattice to Realize $1.0\times10^{33}cm^{-2}s^{-1}$

The bunch number should be controlled as less as possible to keep beam stable with a high beam current. The lattice with low momentum compaction was improved. The emittance was increased from 100 nm to 122 nm to increase the collision bunch current so that the bunch number can be relatively less. The beta function at the IP was reduced from 1.5 cm to 1.35 cm to decrease the necessary beam current for the luminosity of $1.0\times10^{33}cm^{-2}s^{-1}$.

Table 3: Main Parameters of Low Momentum Compaction and Large Emittance Lattice

Parameters	**Values**
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	8.3 mA
β function at IP β_x/β_y	1.0 m/1.35 cm
Horizontal emittance	122 nm·rad
Working point υ_x/υ_y	7.505/5.580
Bunch number	110
Bunch spacing	1.8 m
Momentum compaction	0.0181
Natural bunch length	1.15 cm
Beam-beam parameter	0.04
Luminosity	$1.1\times10^{33}cm^{-2}s^{-1}$

The optics model was improved in the new lattice design, with all the bending and quadrupole magnets being defined with nonlinear fringe field instead of original hard edge model for the well control of the nonlinearity.

Dedicated machine studies to test the updated lattice at the beam energy of 1.89 GeV were performed in Nov. 2014 and April 2016. The maximum beam-beam parameter reached 0.040 with the bunch current of 8.6mA in Nov. 2014, shown in Figure 5. The collision bunch current was improved obviously so that the relatively less bunch number could be expected for the high beam current to realize the design luminosity. During the commissioning in Nov. 2014, the maximum stable beam current was 730 mA due to series hardware failures. The maximum luminosity reached 8.53×10^{32} $cm^{-2}s^{-1}$ with the beam current of 696 mA*707 mA and 92 bunches while the beam-beam parameter was 0.0397 on Nov. 20th, 2014.

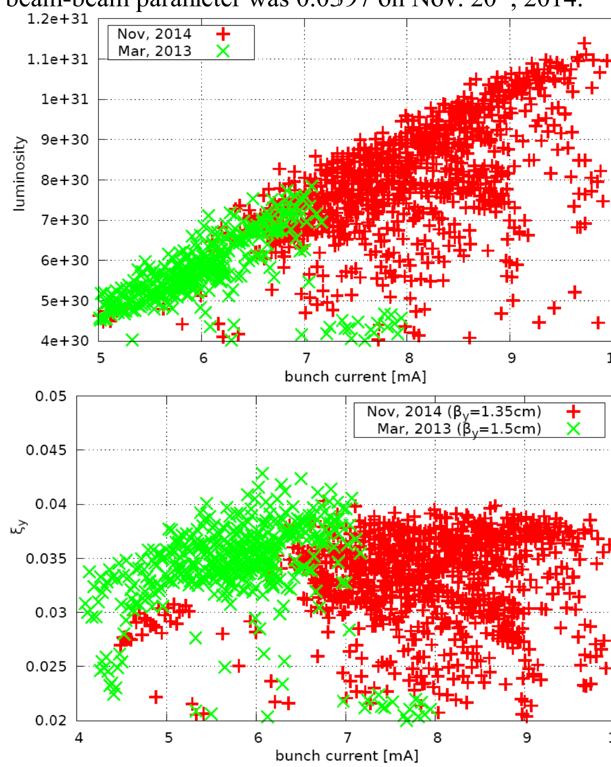

Figure 5: Luminosity for single bunch collision and corresponding beam-beam parameter of the updated lattice.

The stable beam current reached 910 mA with 105 bunches while the hardware failure was few during the commissioning in April 2016. Filling pattern optimization was the most important step to get higher luminosity when the beam current was higher than 800mA. The design luminosity of $1.00\times10^{33}cm^{-2}s^{-1}$ was achieved with the beam current of 849 mA*852 mA and 119 bunches while the beam-beam parameter reached 0.0384 on April 5th, 2016. However, the luminosity could not be higher even the beam current was higher than 850 mA because the multi-bunch instability was too strong to be suppressed effectively by the feedback system. The dedicated measurement and analysis are carried out. The upgrade plan to improve the feedback system has been proposed.

Copyright © 2016 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-147-2

A lower vertical beta function of 1.2 cm at the IP was tested for the luminosity optimization during the dedicated machine study period. But it was not successful due to quite low beam-beam parameter. Different coupling coefficients were tested for the luminosity optimization. 1.0% was the suitable choice for BEPCII to keep collision beam stable and luminosity higher.

Collision Tuning System of BEPCII

The collision tuning system was developed from 2003. It consists of BESIII solenoid compensation [3], global coupling correction, X-Y coupling tuning at the IP, relative orbit deviation tuning, optics deviation tuning, chromaticity ($dQ_{x,y}/dE$, $d\beta_{x,y}/dE$, $d\alpha_{x,y}/dE$) knob, etc.

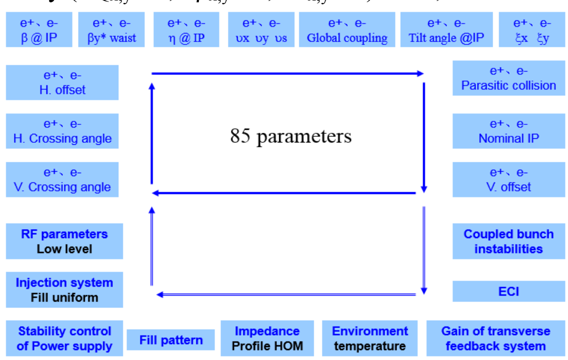

Figure 6: Collision tuning loop of BEPCII.

About 85 parameters, which could be scanned during the online routine luminosity optimization. The collision tuning loop of BEPCII is shown in Figure 6. The luminosity reduction caused by deviations and multi-bunch instability could be eliminated effectively.

Luminosity Evolution at the Energy of 1.89 GeV

The luminosity evolution at the energy of 1.89GeV is shown in Figure 7. There were four major periods for the luminosity tuning at the energy of 1.89 GeV. From Jan. 2010 to April 2011, within which the BESIII detector took data. March 2013, Nov. 2014 and April 2016 were the dedicated machine study periods in a few weeks.

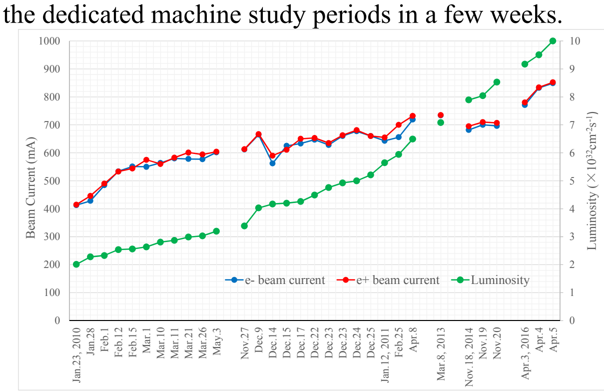

Figure 7: Luminosity evolution at the energy of 1.89GeV.

OPERTION WITH ENERGY 1.0~2.3GEV

Lattice Selection for Different Energy Region

The operation energy of BEPCII is decided by the BESIII working plan. The operation energy region of BEPCII is from 1.0 to 2.3 GeV. Actually, BEPCII has been operated in this energy region with a full energy injection according to the requirements of high energy physics. The energy region is quite large so that it is very important to select lattice parameters for the optimized luminosity. The energy region was separated into three parts: from 1.0 GeV to 1.6 GeV, 1.6 GeV to 1.9 GeV and 1.9 GeV to 2.3 GeV. The horizontal Emittance is the key parameter for the low energy region for the consideration of collision bunch current and bunch number. Bunch length is the key parameter for the high energy region due to voltage limitation of RF cavity. The main lattice parameters for low and high energy regions are shown in Table 4 and Table 5, respectively.

Table 4: Main Lattice Parameters for Low Energy Region

Parameters	Values
Beam energy	1.0 GeV
β function at IP β_x/β_y	1.0 m/1.2 cm
Horizontal emittance	54 nm·rad
Working point υ_x/υ_y	6.505/5.580
Momentum compaction	0.0286
Natural bunch length	0.6 cm

Table 5: Main Lattice Parameters for High Energy Region

Parameters	Values
Beam energy	2.3 GeV
β function at IP β_x/β_y	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point υ_x/υ_y	7.505/5.580
Momentum compaction	0.017
Natural bunch length	1.5 cm

The Operation Status from 1.0 GeV to 2.3 GeV

During the past 5 years, data taking at 21 low energy points and 106 high energy points have been finished as scheduled. The peak luminosity estimation and realization at different beam energy are shown in Figure 8.

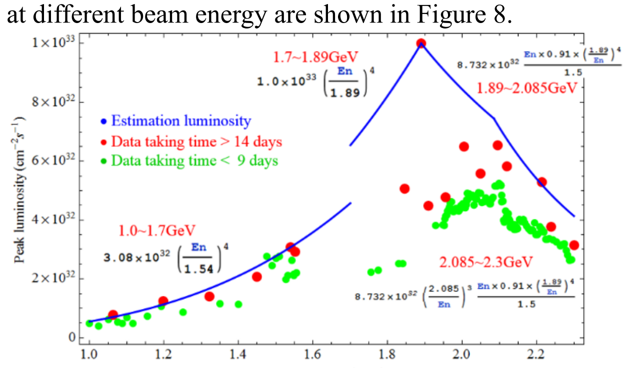

Figure 8: The peak luminosity from 1.0 GeV to 2.3 GeV.

BEPCII is optimized at 1.89 GeV and the RF system can provide a maximum 110 kW beam power with the beam current of 910 mA. For the operation of high energy region the beam current had to be decreased due to the limitation of RF power. Moreover, the bunch length and emittance could not be well controlled so that the beam-beam parameter was lower than expected. For the opera-

Copyright © 2016 CC-BY-3.0 and by the respective authors

ISBN 978-3-95450-147-2

tion of low energy region there was no restriction of beam power and bunch length. However, the multi-bunch instability was very serious due to longer damping time. The injection efficiency was also affected by the longer damping time. The beam current was limited by the ability of feedback system. The statistic of beam-beam parameter is shown in Figure 9.

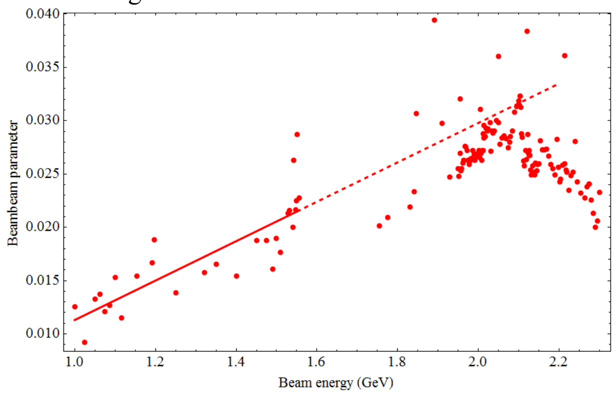

Figure 9: The maximum beam-beam parameter achieved at different beam energies.

SYNCHROTRON RADIATION RUNNING

The outer rings of BER and BPR are connected to be the third ring BSR, which is designed as a synchrotron radiation facility, as shown in Figure 10 with the main parameters shown in Table 6. There are 14 beam lines including 8 extracted from 5 wigglers in the BSR. Every year, 3 months dedicated experiment time is spent to the users.

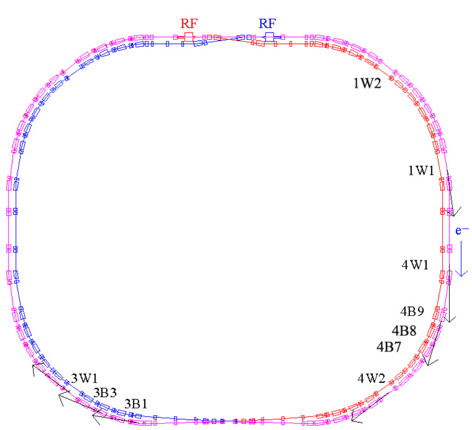

Figure 10: Layout of BSR as a synchrotron radiation facility.

The operation for synchrotron radiation facility was designed as a decay scheme. Beam from linac was injected into storage ring every 6 hours. The dedicated machine study for top-up operation started in April 2014. With the well control for both injecting beam and circulating beam and well control of radiation dose for both detector and beam stations, top-up operation was realized on October 27th, 2015. The operation from decay mode to top-up mode is shown in Figure 11.

Parasitic operation with 2 wigglers on was realized in 2014 after the fine tuning for the luminosity. During the data taking of high energy physics, 9 beam lines of synchrotron radiation facility, which are distributed in the outer ring of BER, could provide synchrotron light for the users without affecting the luminosity.

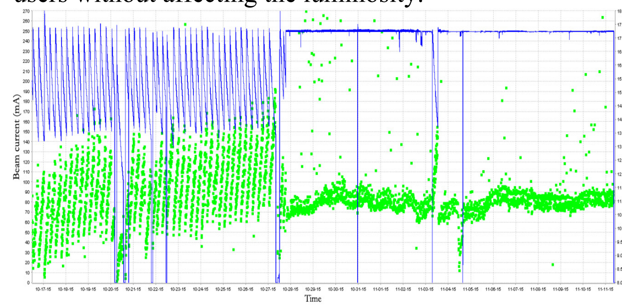

Figure 11: The beam current and lifetime in decay mode and top-up mode during one month SR operation.

Table 6: Main Parameters of the BSR Lattice

Parameters	Values
Energy	2.5 GeV
Beam current	250 mA
Circumference	241.13 m
Horizontal emittance	160 nm·rad
Harmonic number	402
RF voltage	3.0 MV
RF frequency	499.8 MHz
RF cavity number	2
Energy loss per turn	336 keV
Synchrotron radiation power	84 kW
Damping time $\tau_x/\tau_y/\tau_E$	12/12/6 ms
Working point υ_x/υ_y	7.28/5.20
Natural energy spread	6.66×10^{-4}
Momentum compaction	0.0165
Natural bunch length	1.2 cm

CONCLUSION

BEPCII is now in a good performance for both high energy physics and synchrotron radiation users. The design luminosity of 1.0×10^{33} cm^{-2}s^{-1} has been achieved with continuous efforts of luminosity optimization and hardware improvements. Top-up injection has been realized for synchrotron radiation facility. The top-up operation of the collider is being studied for much higher integral luminosity.

REFERENCES

[1] M. Ablikim *et al.*, “Observation of a Charged Charmoniumlike Structure in e+e−→π+π−J/ψ at s = 4.26 GeV”, Phys. Rev. Lett. 110, 252001, June 2013.

[2] Yuan Zhang *et al.*, “LATTICE OPTIMIZATION OF BEPCII COLLIDER RINGS”, in *Proc. IPAC’14*, Dresden, Germany, paper THPRI007.

[3] C. H. Yu *et al.*, “THE COUPLING COMPENSATION AND MEASUREMENT IN THE INTERACTION REGION OF BEPCII”, in *Proc. EPAC’04*, Lucerne, Switzerland, paper MOPLT078.

Copyright © 2016 CC-BY-3.0 and by the respective authors