BEPCII Performance
&
Beam Dynamics Studies on Luminosity

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for the BEPCII accelerator team
May 10, 2016

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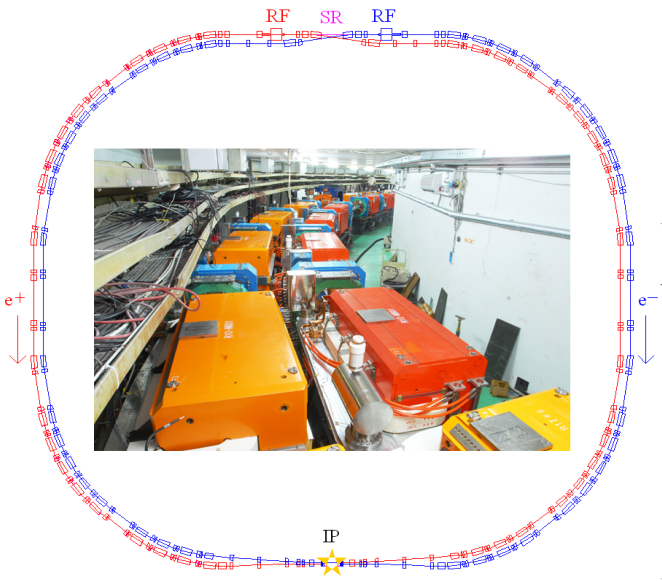
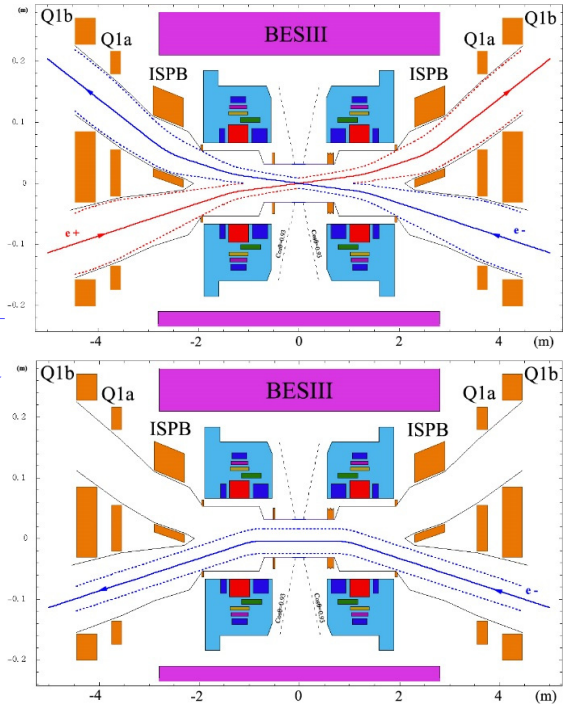
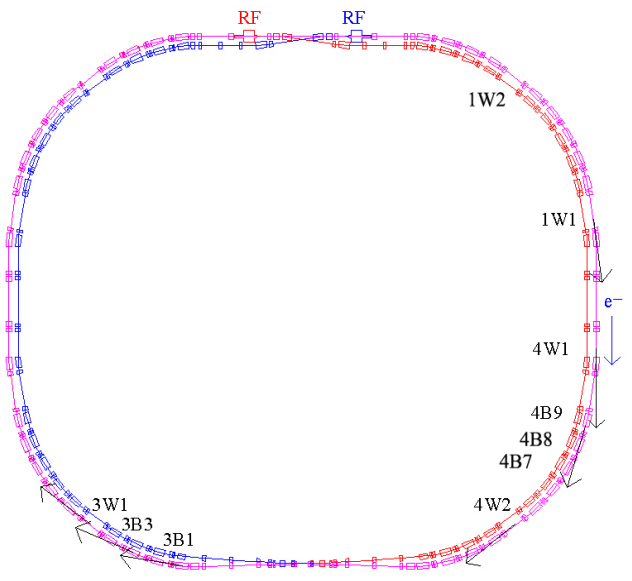
1. Overview of BEPCII operation



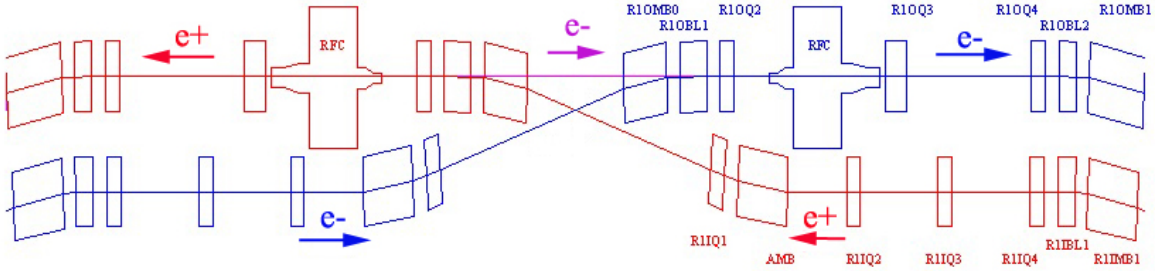




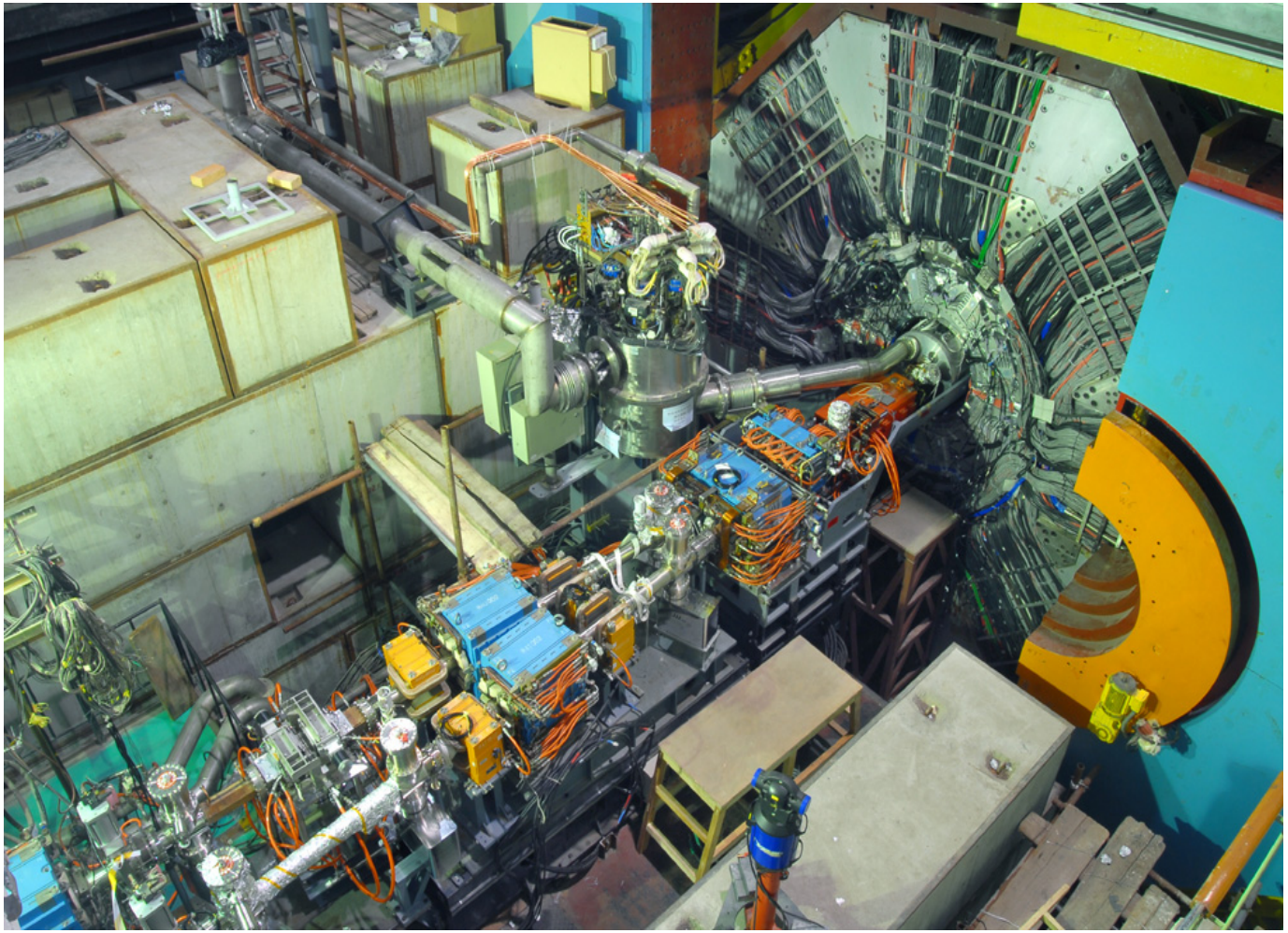
Collider

SR Facility

January 2004	Construction started
Mar.28, 2008	Installation of detector started
Jun. 22, 2008	BEPCII Commissioning started
May 13, 2009	Luminosity reached $3.3\times10^{32}cm^{-2}s^{-1}$
Apr. 5, 2016	Luminosity reached $1.0\times10^{33}cm^{-2}s^{-1}$



Integrated of IR in May 2008



Operation schedule

- ✓ 2008.6.22 -2008.12.18 Luminosity commissioning & Detector tuning
- ✓ 2008.12.18-2009.1.20 Synchrotron radiation operation for users
- ✓ 2009.1.20-2009.1.31 Installed movable masks, remove profiles
- ✓ 2009.2.1-2009.3.2 Luminosity commissioning @1.89GeV
- ✓ 2009.3.2-2009.4.14 High energy physics, 100M $\psi(2S)$ events @1.84GeV
- ✓ 2009.4.14-2009.5.19 Luminosity commissioning, $L=3.3\times10^{32}cm^{-2}s^{-1}$
- ✓ 2009.5.19-2009.6.1 High energy physics, @1.825GeV
- ✓ 2009.6.1-2009.7.31 High energy physics, 200M J/ψ events@ 1.55GeV
- ✓ 2009.12.18-2011.4.28 High energy physics @ 1.89GeV
- ✓ 2011.4.28- now High energy physics @ 1.0-1.6GeV and 1.9-2.3GeV

Main parameters achieved in collision mode at 1.89GeV

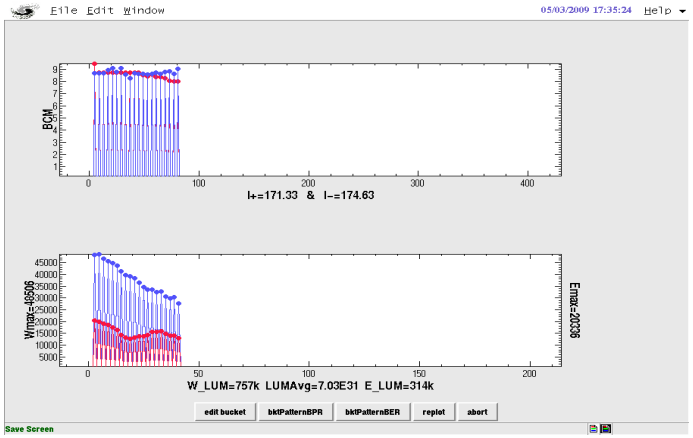
parameters	design	Achieved (Not at the same time)	
		BER	BPR
Energy (GeV)	1.89	1.89	1.89
Beam current (mA)	910	910	910
Bunch current (mA)	9.8	>10	>10
Bunch number	93	119	119
RF voltage	1.5	1.5	1.5
Beam-beam parameter	0.04	0.043	
β_x^*/β_y^* (m)	1.0/0.015	1.0/0.0135	1.0/0.0135
Inj. Rate (mA/min)	200 e^- / 50 e^+	>1000	>100
Lum. ($\times 10^{33}cm^{-2}s^{-1}$)	1.0	1.0	

2. Road to 1.0×10^{33} $cm^{-2}s^{-1}$ @1.89GeV

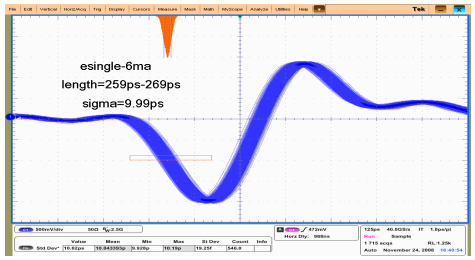
Commissioning with designed lattice

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	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point	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	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	$1.0\times10^{33}cm^{-2}s^{-1}$

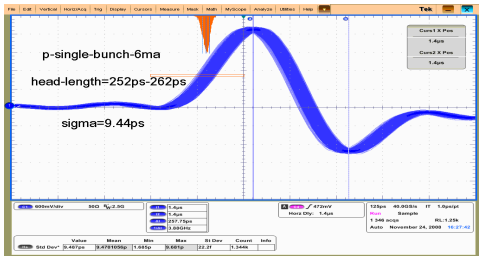
- BEPCII started on Jun. 22, 2008. BER and BPR accumulated beam successfully on Jun. 22 and Jun. 26 respectively.
- The luminosity reached **$1.3\times10^{32}cm^{-2}s^{-1}$ @ ~520mA*520mA** before Dec. 17, 2008. A long time was taken to study the source which caused a strong longitudinal instability in both BPR and BER.



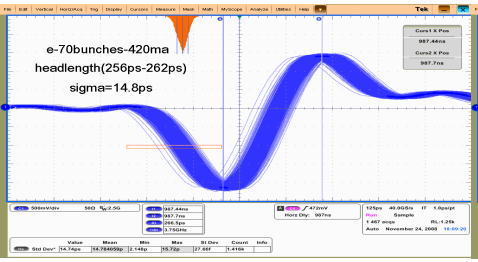
Dipole and quadrupole mode oscillation

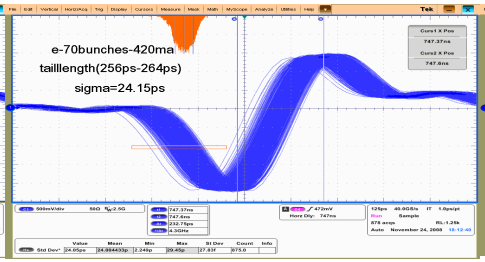


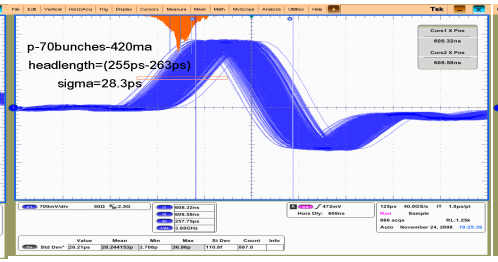
Single e- bunch

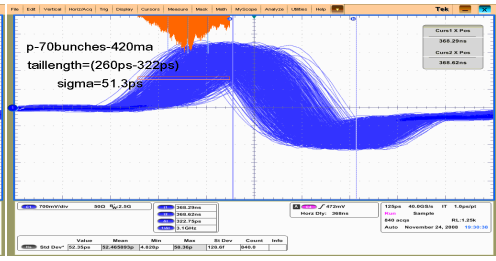


Single e+ bunch



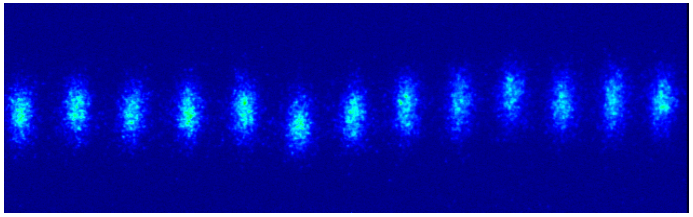




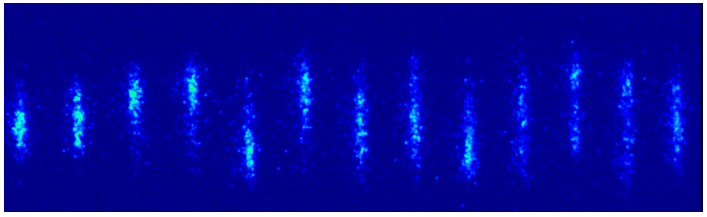


Head part **Tail part** **Head part** **Tail part**

Continuous 70 bunches, 4 bucket bunch spacing, in collision

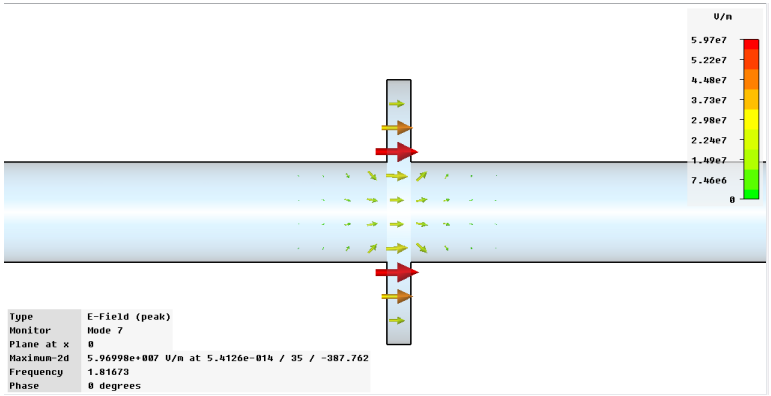


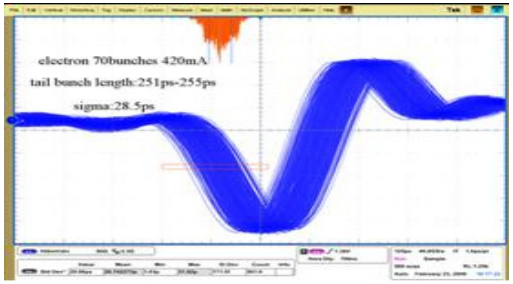
longitudinal



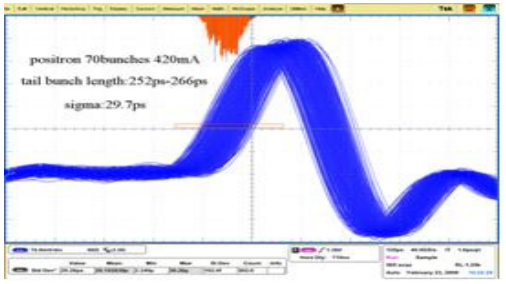
BER: dipole mode oscillation **BPR: dipole and quadrupole oscillation**

Quadrupole mode oscillation in BPR was removed





BER tail bunch



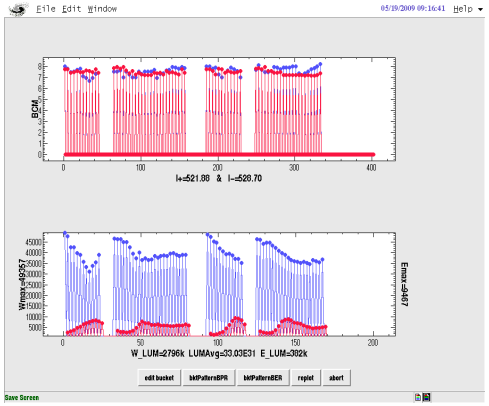
BPR tail bunch

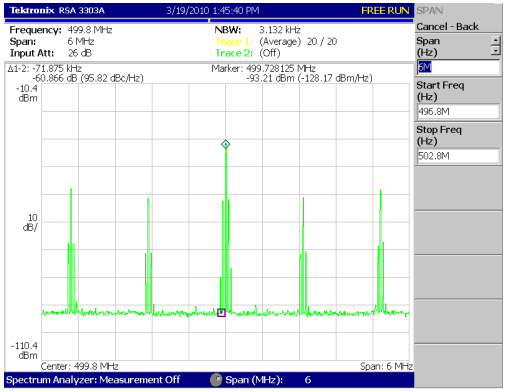
Continuous 70 bunches, 4 bucket bunch spacing, in collision

Profile in BPR

(HOM simulated by T.M. Huang)

Two profiles in the BPR were removed in Jan. 2009.

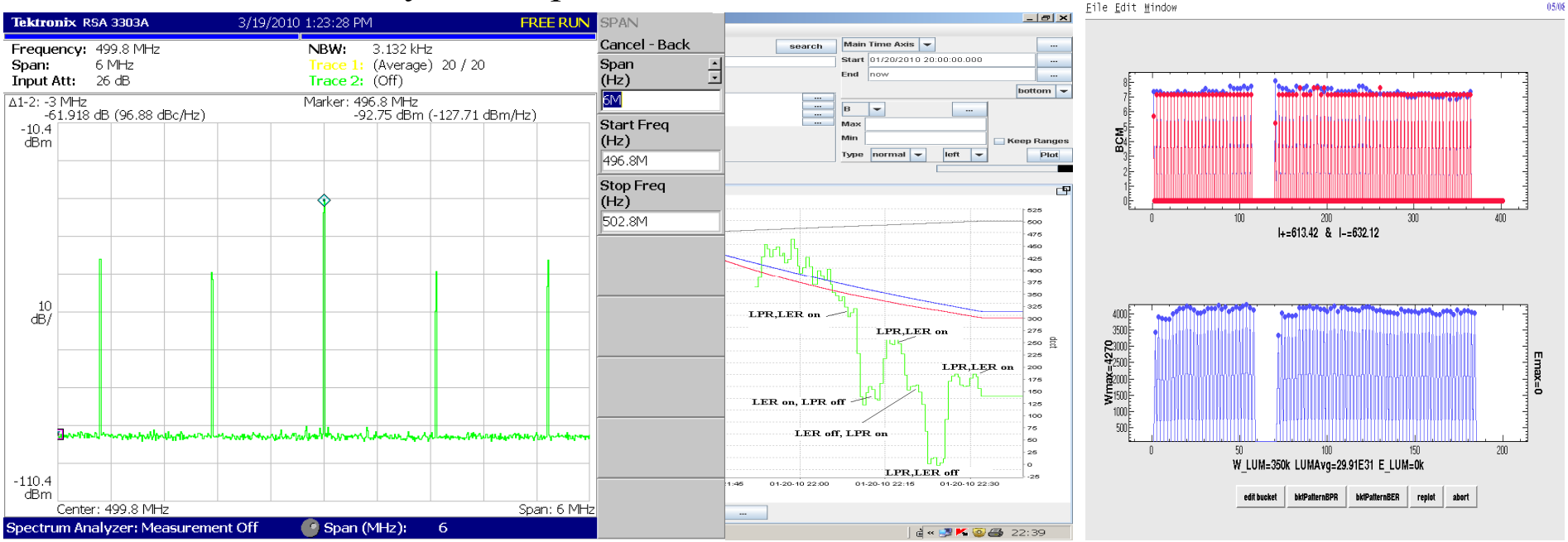




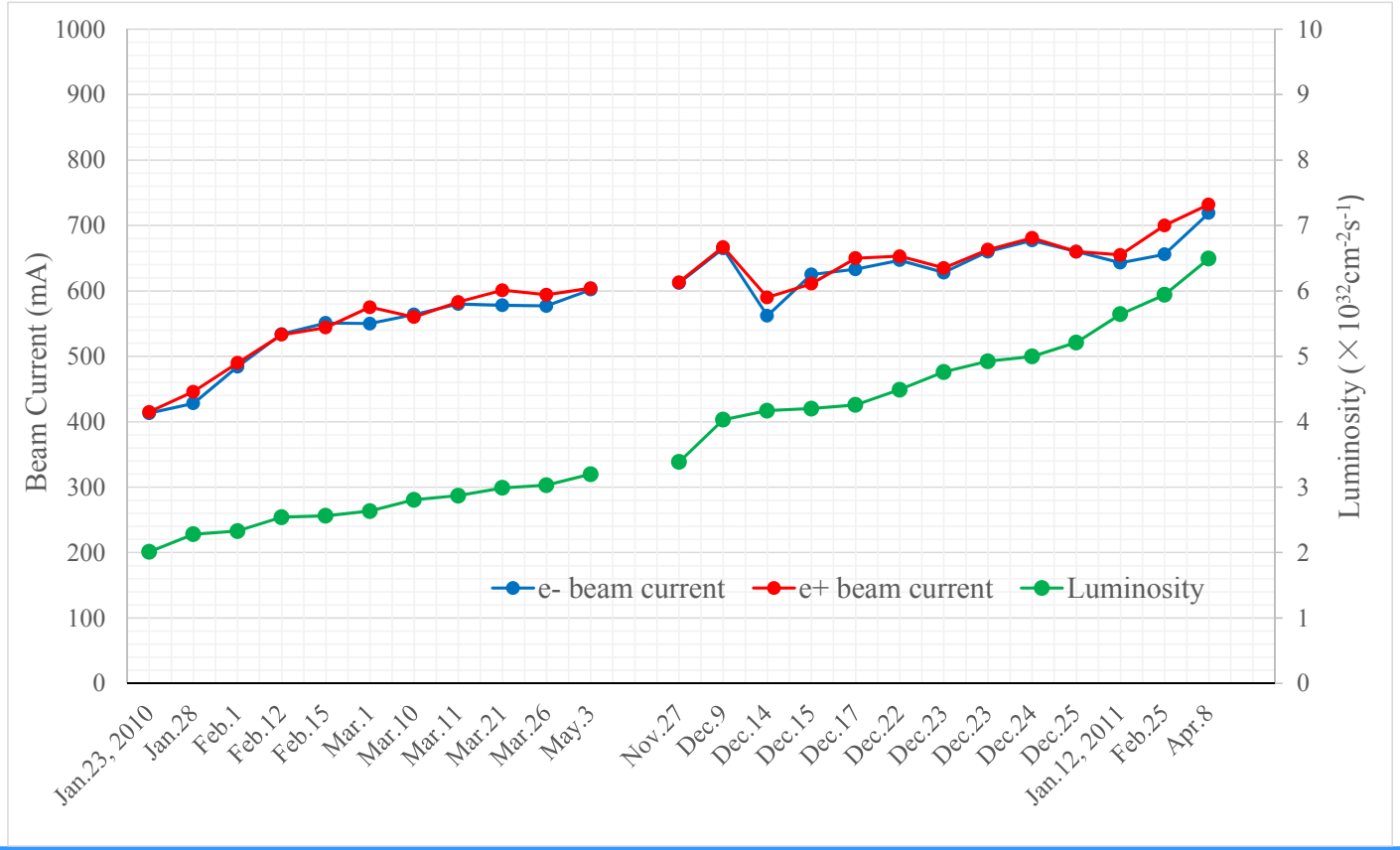
After that luminosity was improved from $1.3\times10^{32}cm^{-2}s^{-1}$ to $2.3\times10^{32}cm^{-2}s^{-1}$.

Dipole mode oscillation in longitudinal direction in both BER and BPR still existed. The luminosity of tail bunch reduced obviously

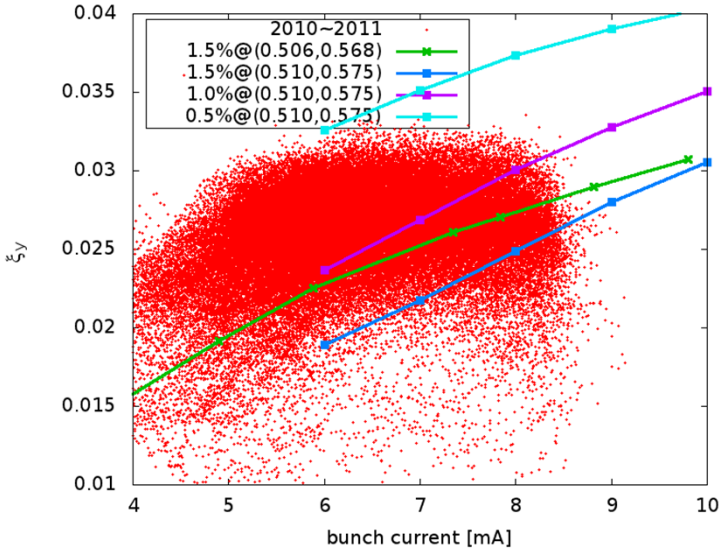
- The horizontal tune was moved from 0.53 to 0.505 on May 5, 2009. The luminosity reached **$3.3\times10^{32}cm^{-2}s^{-1}$ @ ~520mA*520mA** in 10 days.
- **Longitudinal feedback systems** were installed into BPR and BER during the summer shutdown in 2009. The commissioning of BEPCII with longitudinal feedback system began on December 18th, 2009. The longitudinal instability was suppressed effectively so that the luminosity was improved about 30%.

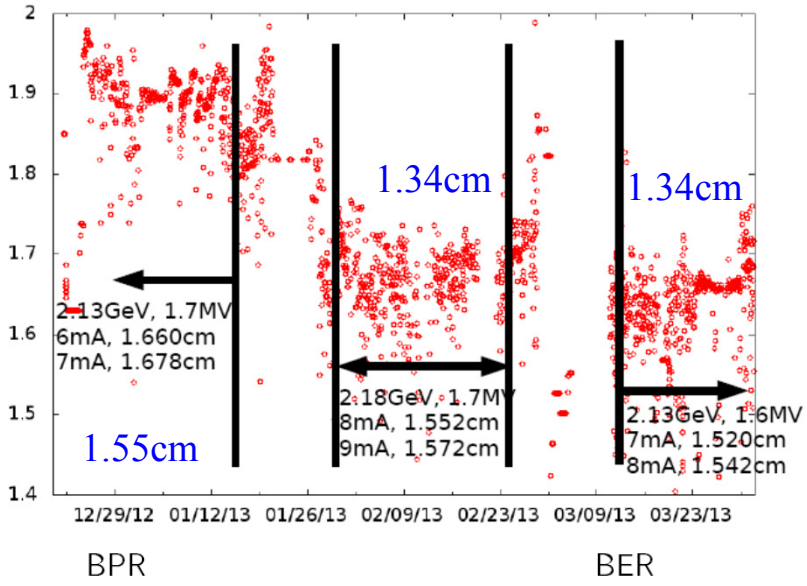


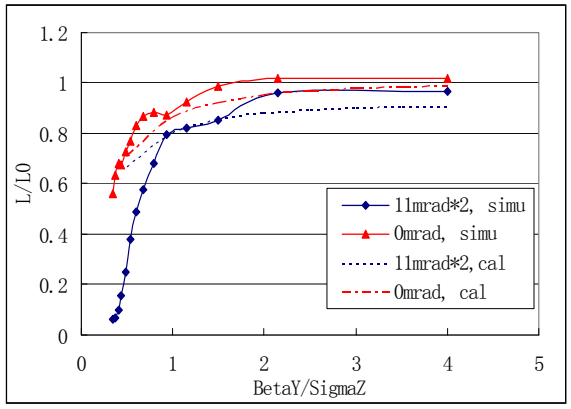
The data taking at the energy of 1.89 GeV started from the beginning of 2010. The beam current and luminosity were improved step by step, together with the control of detector background and the luminosity optimization systematically. The maximum beam current and luminosity reached **750 mA** and **6.49×10^{32} 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)

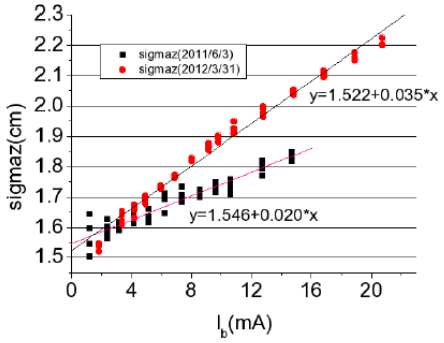


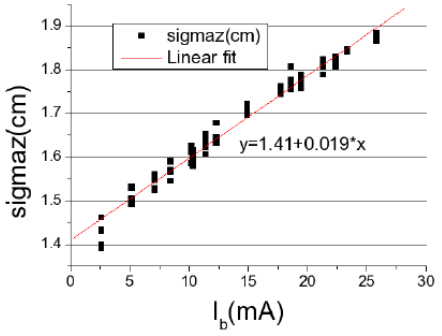
The beam-beam parameter was suppressed obviously under 0.033 at any bunch current even with sufficient collision tuning. Bunch lengthening effect was considered to explain the phenomenon.





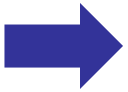






Commissioning with upgrade lattice

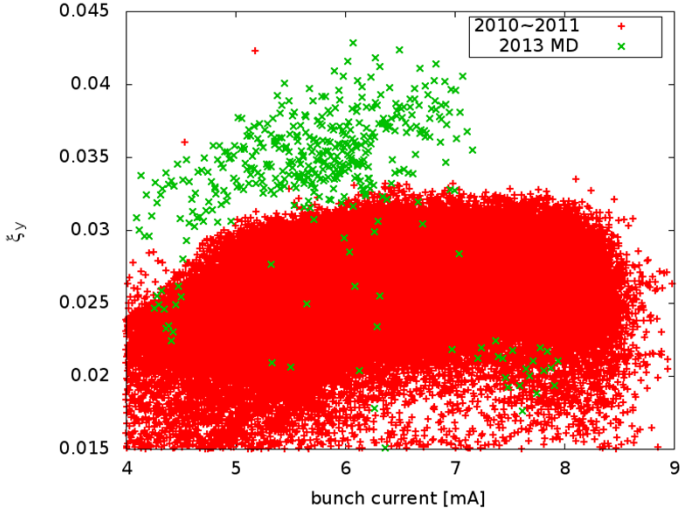
Parameters	Values
Operation energy	1.0~2.1 GeV
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	9.8 mA
Circumference	237.5 m
Number of particles	4.5×10^{12}
β function at IP	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point	6.53/5.58
Harmonic number	396
Bunch number	93
Bunch spacing	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	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	$1.0\times10^{33}cm^{-2}s^{-1}$

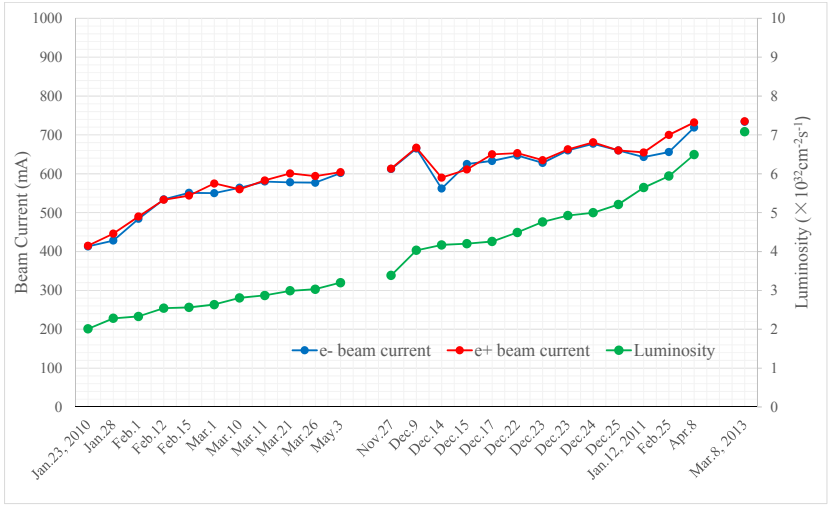


Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	7.0 mA
β function at IP	1.0 m/1.5 cm
Horizontal emittance	100 nm·rad
Working point u_x/u_y	7.505/5.580
Harmonic number	396
Bunch number	130
Bunch spacing	1.8 m
RF voltage	1.5 MV
Momentum compaction	0.0170
Natural bunch length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

A new lattice was designed to control the bunch length. 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 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**. The maximum beam-beam parameter reached **0.043**.





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} @ 734 mA*735 mA** while the beam-beam parameter was 0.0349.

Commissioning with upgrade lattice

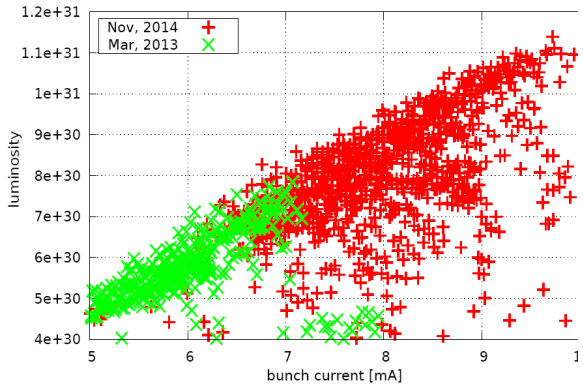
Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	7.0 mA
β function at IP	1.0 m/1.5 cm
Horizontal emittance	100 nm·rad
Working point	7.505/5.580
Harmonic number	396
Bunch number	130
Bunch spacing	1.8 m
RF voltage	1.5 MV
Momentum compaction	0.0170
Natural bunch length	1.15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

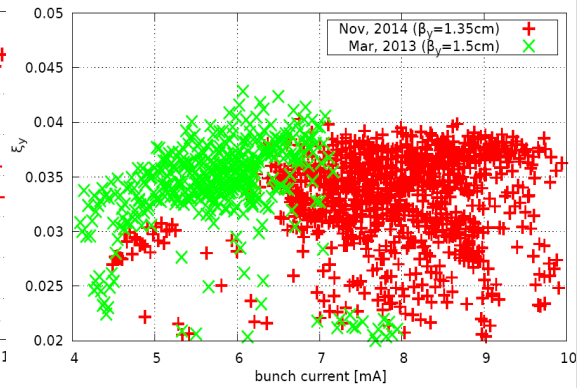
Parameters	Values
Optimized energy	1.89 GeV
Beam current	910 mA
Bunch current	8.3 mA
β function at IP	1.0 m/1.35 cm
Horizontal emittance	122 nm·rad
Working point	7.505/5.580
Bunch number	110
Bunch spacing	1.8 m
Momentum compaction	0.0181
Natural bunch length	1.15 cm
Beam-beam parameter	0.04
Luminosity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

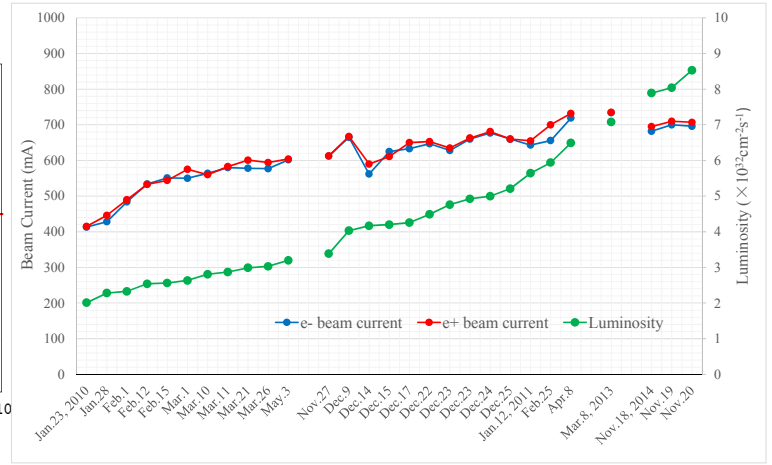
The bunch number should be controlled as less as possible to keep beam stable with a high beam current. The lattice with low momentum compaction was improved. The emittance was increased **from 100 nm to 122 nm** to increase the collision bunch current.

Commissioning with upgrade lattice

The maximum beam-beam parameter reached **0.040** with the bunch current of 8.6mA in Nov. 2014.

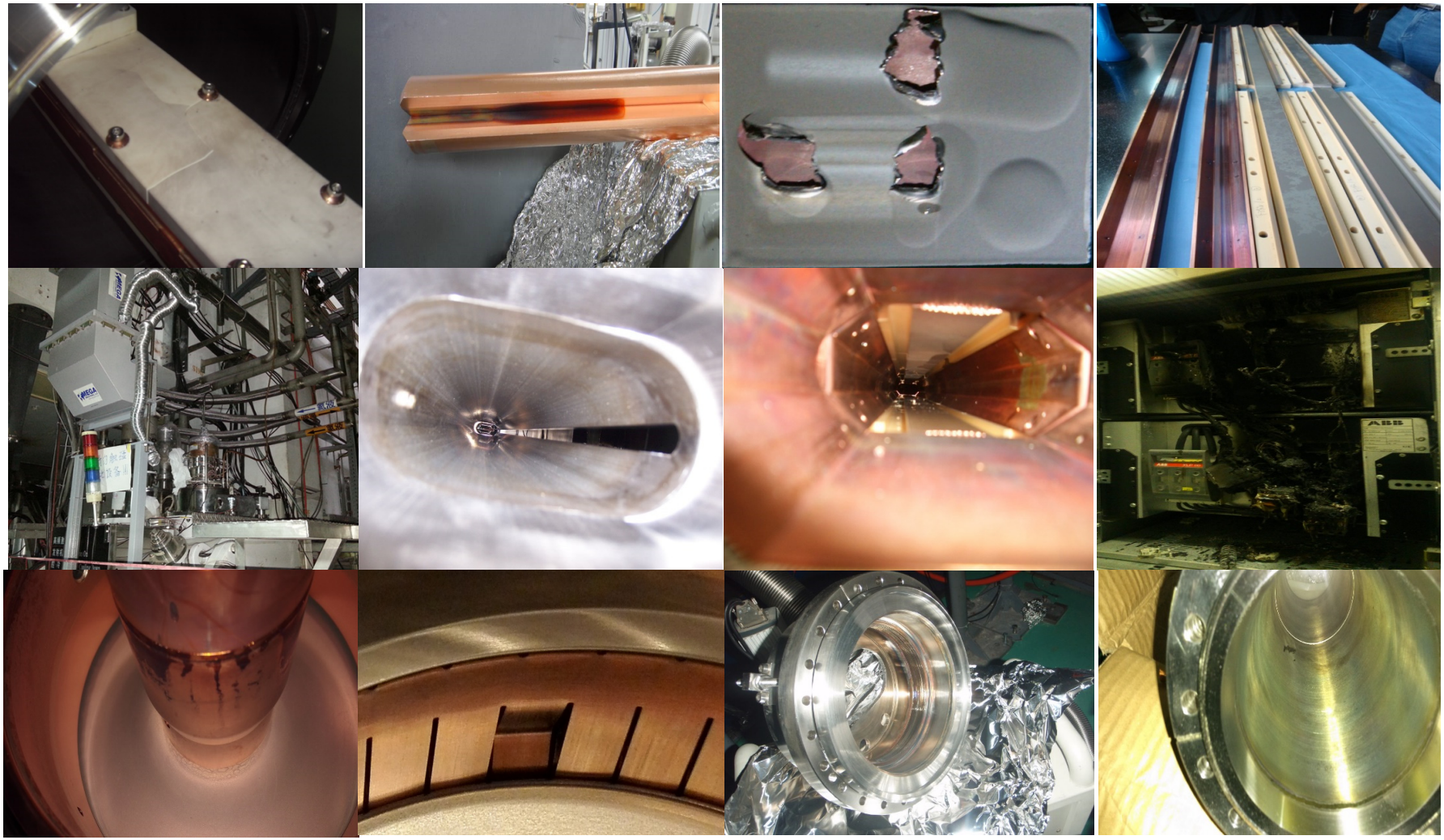






The maximum stable beam current was 730 mA due to series hardware failures. The maximum luminosity reached **8.53×10^{32} $cm^{-2}s^{-1}$** with the beam current of 696 mA*707 mA and 92 bunches while the beam-beam parameter was 0.0397 on **Nov. 20th, 2014.**

Hardware failures which limited the increase of beam current



Hardware failures which limited the increase of beam current

1, Dedicated machine study at 1.89GeV (Nov.4～13 , 2013)
Failure of RF coupler from Nov. 6

2, Dedicated machine study at 1.89GeV (Jan. 25～Feb. 5, 2014）
Failure of cryogenic system from Jan. 28

3, Dedicated machine study at 1.89GeV (Mar. 30～Apr. 6)
Failure of transverse feedback system

4, Dedicated machine study at 1.89GeV (May 29～Jun. 8)
Failure of longitudinal feedback system

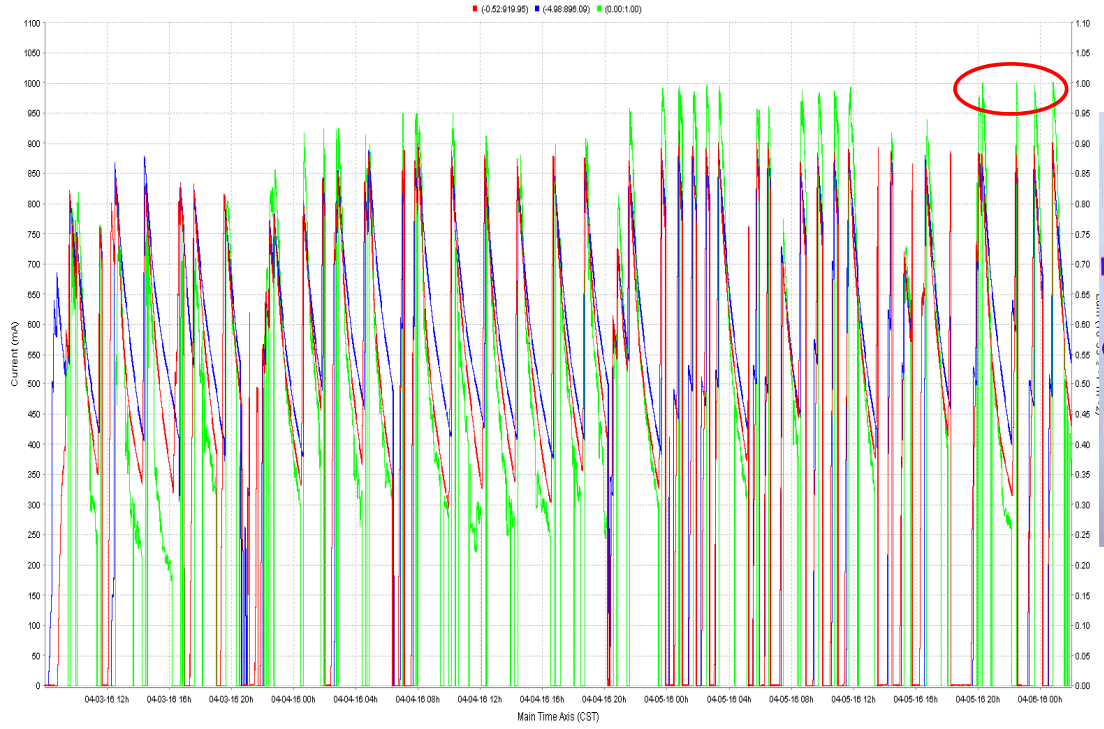
5, Dedicated machine study at 1.89GeV (Nov. 1～Dec. 26, 2014）
Failure of RF coupler

6, Dedicated machine study at 1.89GeV (Mar. 7～14, 2015)
Failure of power supply from Mar. 8.

7, Dedicated machine study at 1.89GeV (Nov. 11～Dec. 19）
Vacuum leak of RF cavity

$1.0\times10^{33}cm^{-2}s^{-1}$ was achieved on Apr.5, 2016

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 **$1.0\times10^{33}cm^{-2}s^{-1}$** 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**.



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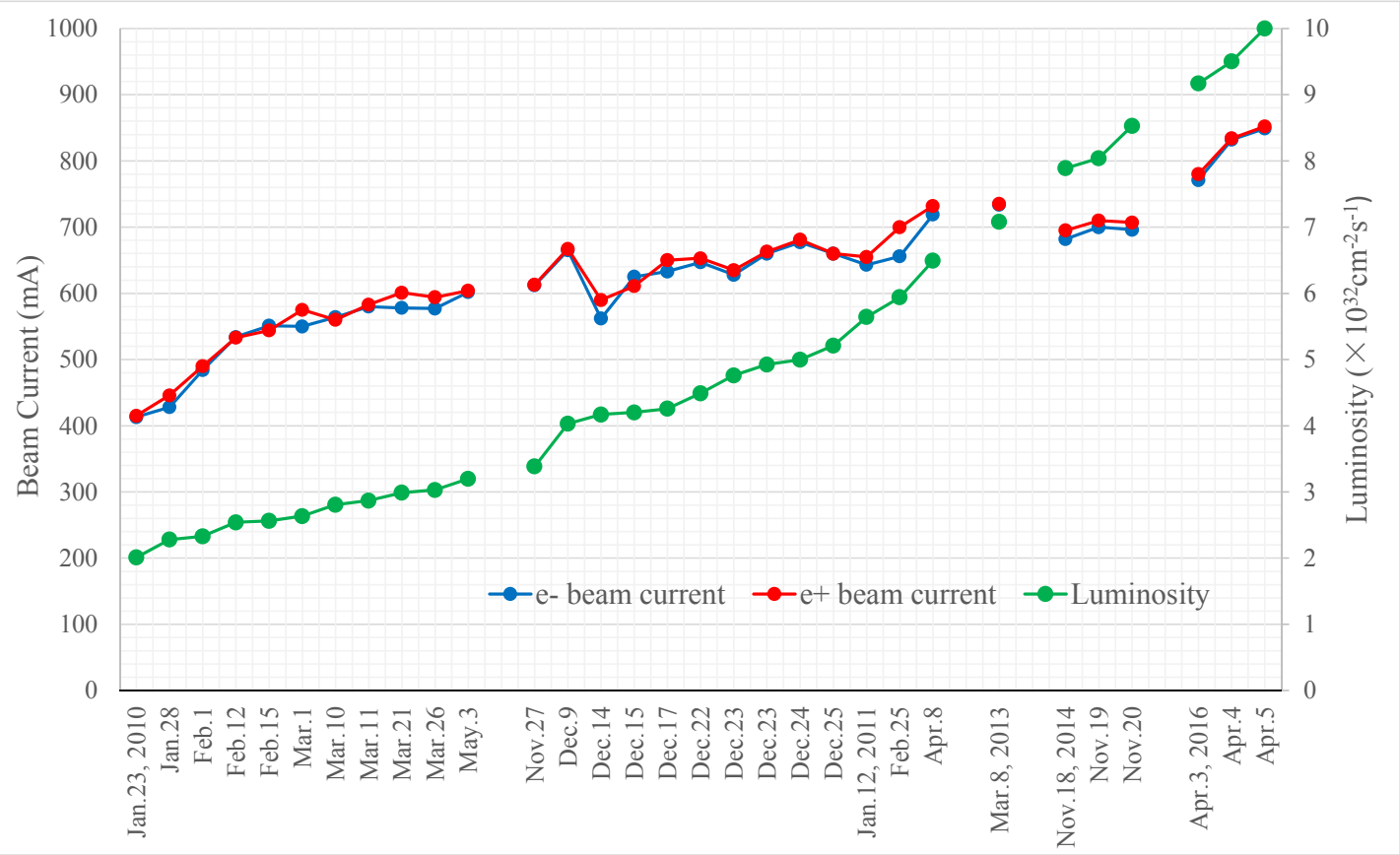
Luminosity 10.00 E32/cm^2/s

	e+	e−
Energy [GeV]	1.8831	1.8831
Current [mA]	849.18	852.31
Lifetime [hr]	1.53	2.30
Inj.Rate [mA/min]	0.00	0.00

$1.0\times10^{33}cm^{-2}s^{-1}$ was achieved on Apr.5, 2016

Celebration !

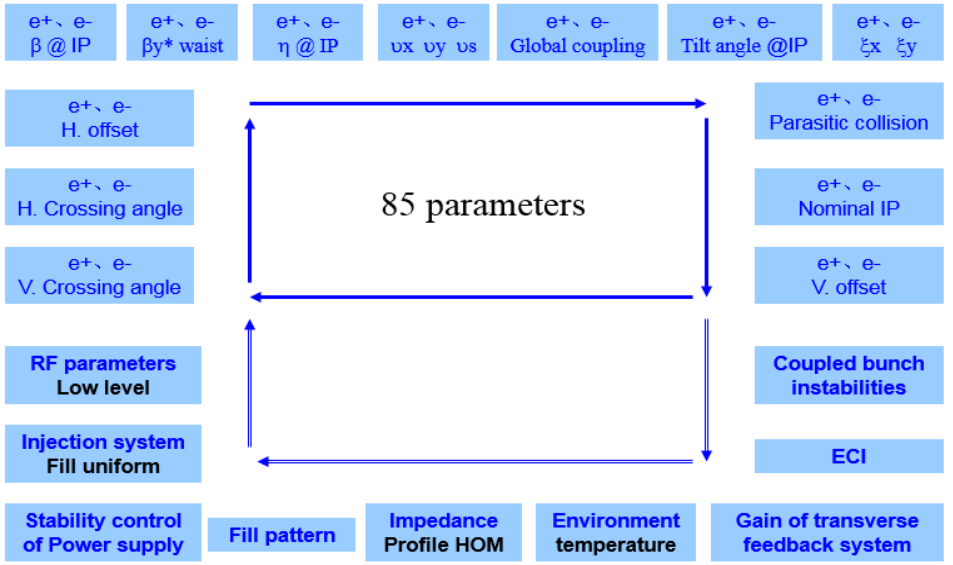


The luminosity could not be higher even the beam current was higher than 850 mA because the multi-bunch instability was too strong to be suppressed effectively by the feedback system. The dedicated measurement and analysis are carried out. The upgrade plan to improve the feedback system has been proposed.

Collision tuning system of BEPCII

The collision tuning system was developed from 2003. It consists of BESIII solenoid compensation, 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.

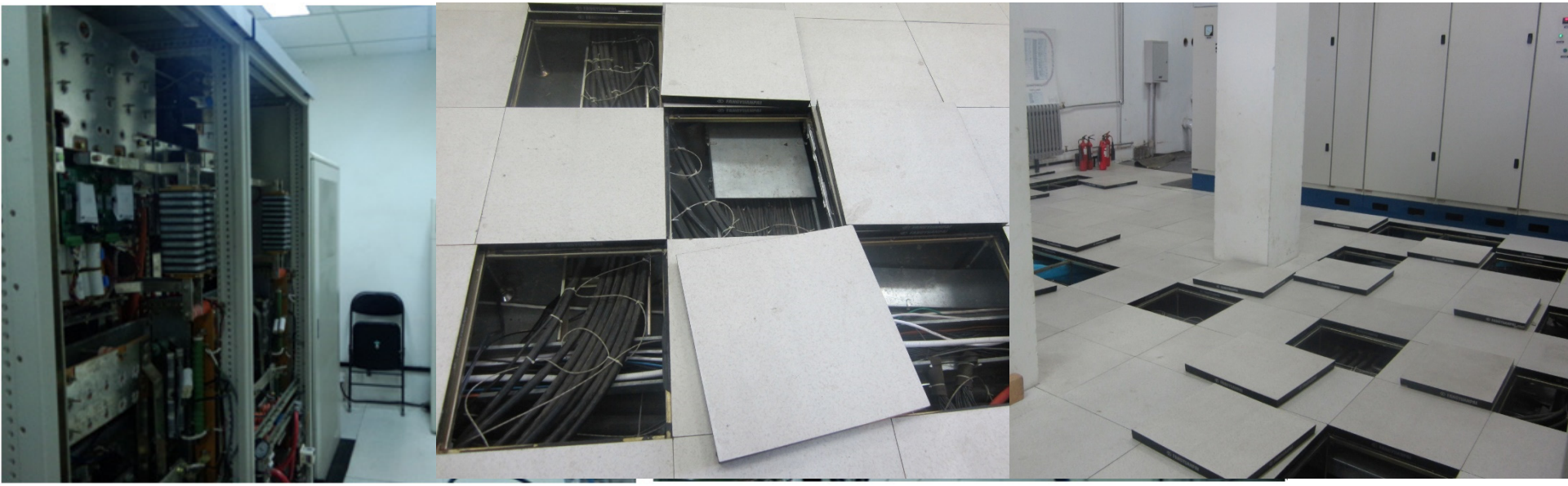
$$L(\mathrm{cm^{-2}s^{-1}}) = 2.17\times10^{34}(1+R)\xi_y \frac{E(\mathrm{GeV})k_b I_b(\mathrm{A})}{\beta_y^*(\mathrm{cm})} \times \mathbf{F_R}$$



The luminosity reduction caused by deviations and multi-bunch instability could be eliminated effectively.

3. Operation with energy 1.0~2.3GeV

The operation energy of BEPCII is decided by the BESIII working plan. The operation energy region of BEPCII is designed from **1.0 to 2.1 GeV**. Actually, BEPCII has been operated in the energy region from **1.0 to 2.3 GeV** with a full energy injection according to the requirements of high energy physics.



Status of power supply @2.1-2.3GeV

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. **Bunch length** is the key parameter for the high energy region.

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

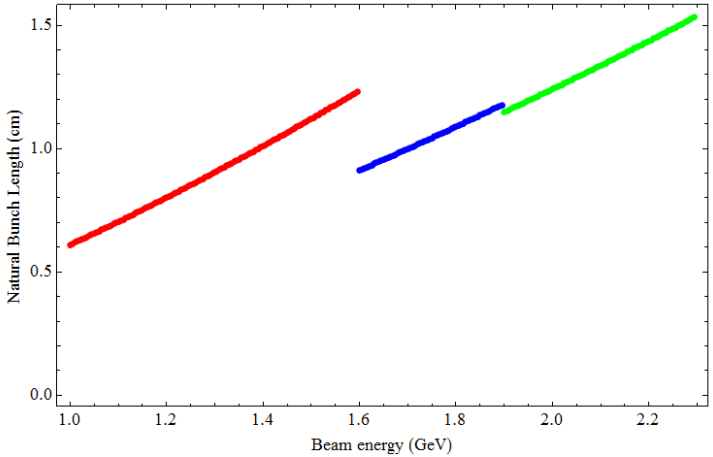
Low energy

Parameters	Values
Beam energy	1.89 GeV
β function at IP b_x/b_y	1.0 m/1.35 cm
Horizontal emittance	122 nm·rad
Working point u_x/u_y	7.505/5.580
Momentum compaction	0.018
Natural bunch length	1.15 cm

Medium energy

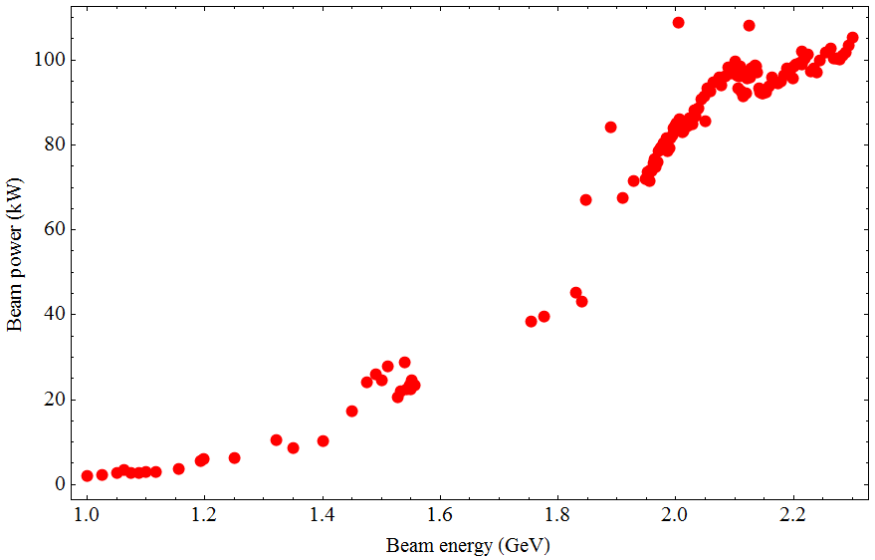
Parameters	Values
Beam energy	2.3 GeV
β function at IP b_x/b_y	1.0 m/1.5 cm
Horizontal emittance	144 nm·rad
Working point u_x/u_y	7.505/5.580
Momentum compaction	0.017
Natural bunch length	1.5 cm

High energy

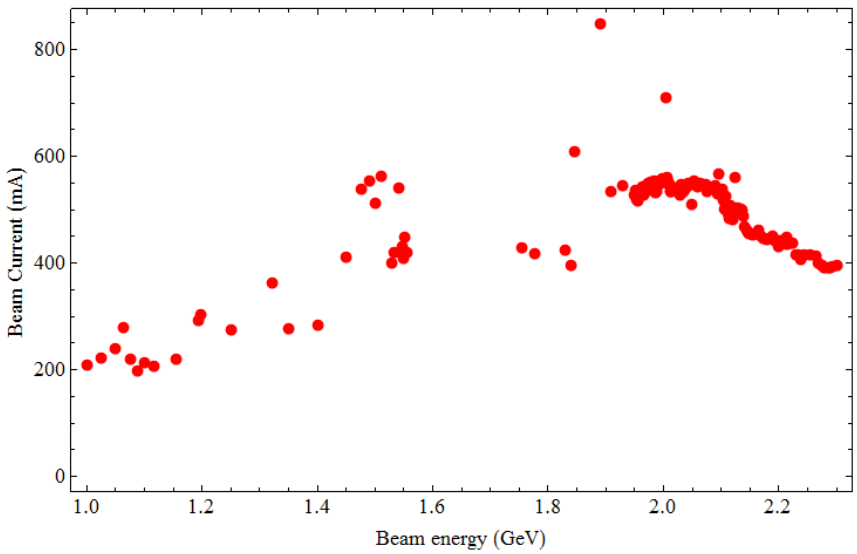


Physics data in the past years

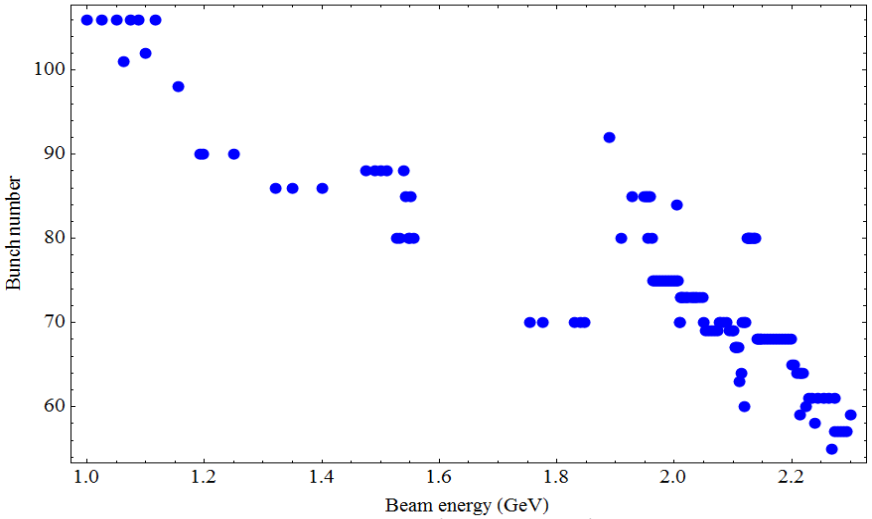
- **2009:** 106 M ψ(2S) , 225 M J/ψ
- **2010:** 900 pb^{-1} ψ(3770)
- **2011:** 1800 pb^{-1}ψ(3770) ; 470 pb^{-1}@4.01 GeV
- **2012:** 0.4 billion ψ(2S); 1 billion J/ψ; 100pb^{-1}@R value
- **2013:** 2.0 fb^{-1} Y(4260), 0.5 fb^{-1} Y(4360); 200pb^{-1} @R value
- **2014:** 780pb^{-1}@R value; 500pb^{-1}@4.6GeV; 1.0fb^{-1}@Y(4420); ~250pb^{-1}@E_b=2.0-2.3GeV
- **2015:** 100pb^{-1}@E_b=1.08GeV; 500pb^{-1}@R value (1.0-1.6GeV)
- **2016:** 1.5 fb^{-1}@Eb=2.09 GeV



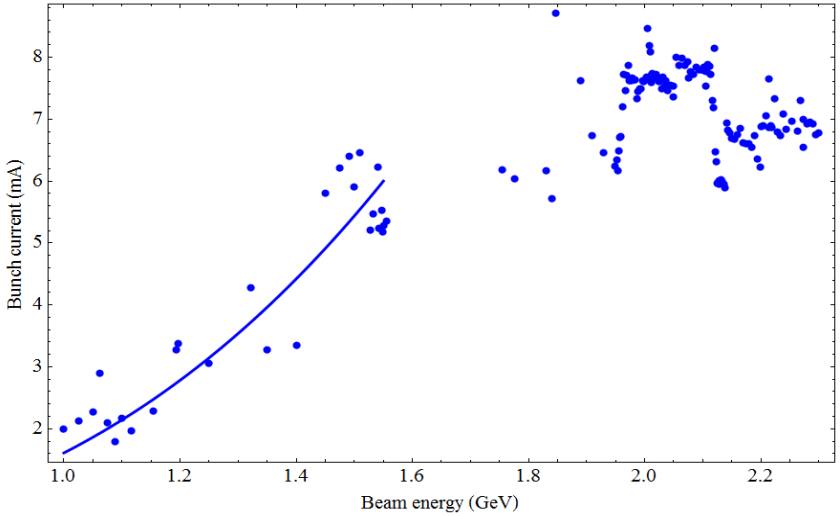
Beam power



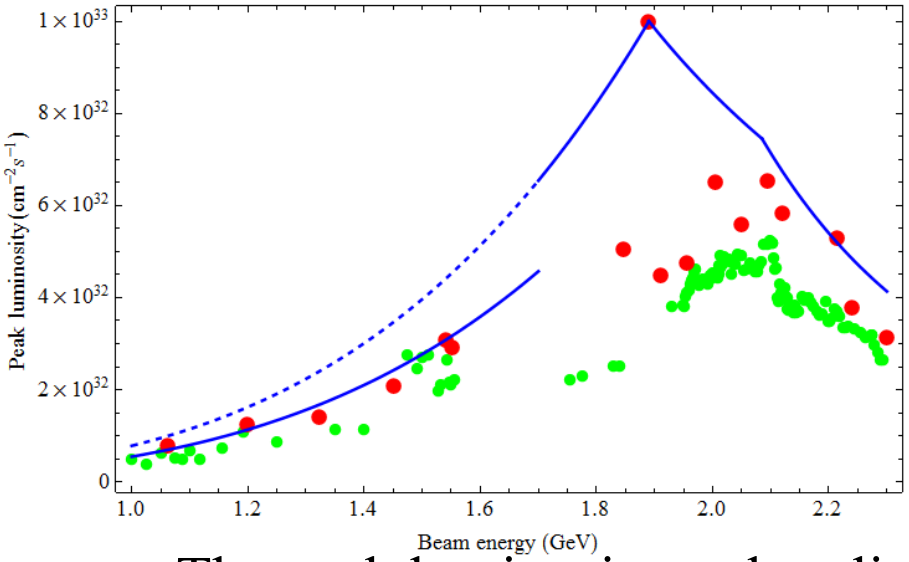
Beam Current

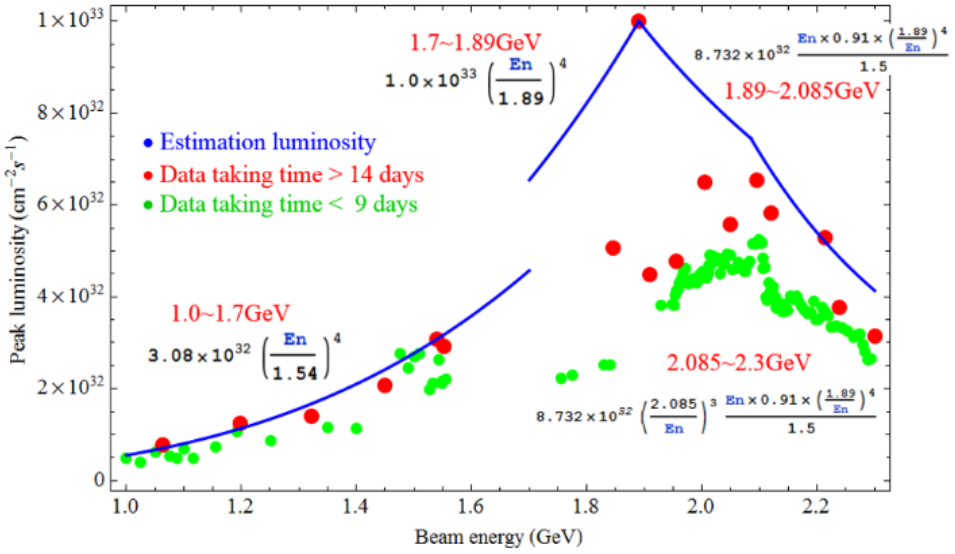


Bunch number

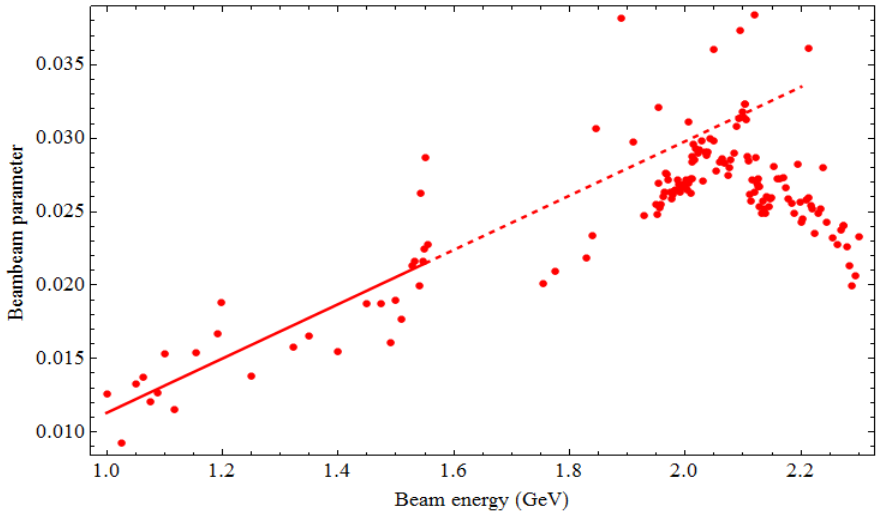


Bunch Current





The peak luminosity and scaling laws from 1.0 GeV to 2.3 GeV



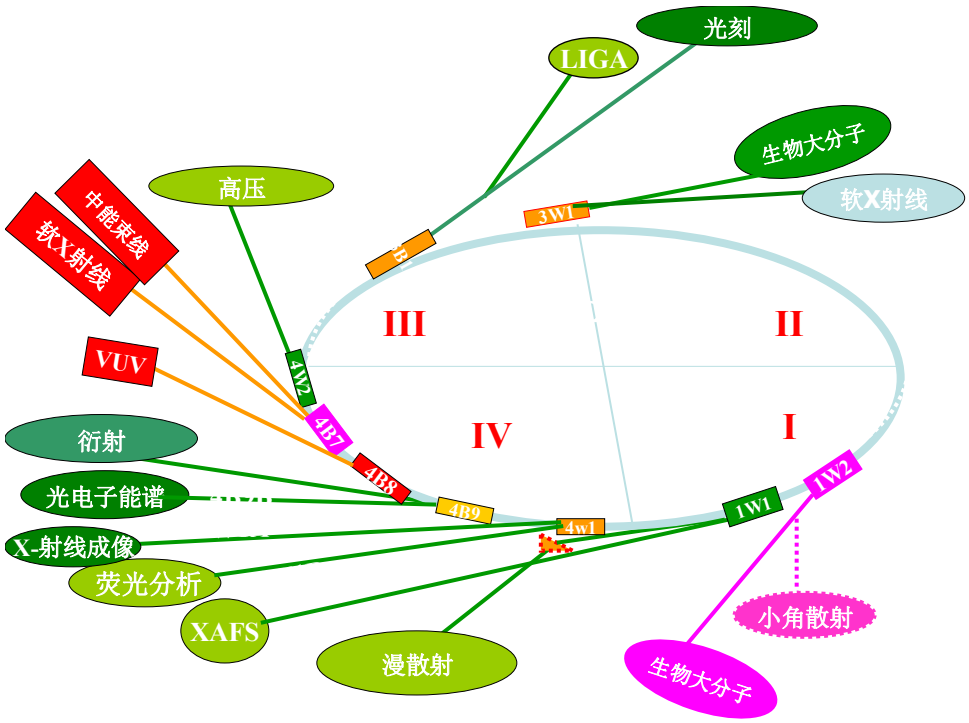
For the high energy region the beam current had to be decreased due to the limitation of RF power. The bunch length and emittance could not be well controlled.

For the low energy region the multi-bunch instability was very serious due to longer damping time. The injection efficiency was also affected by the longer damping time.

4. Synchrotron radiation running

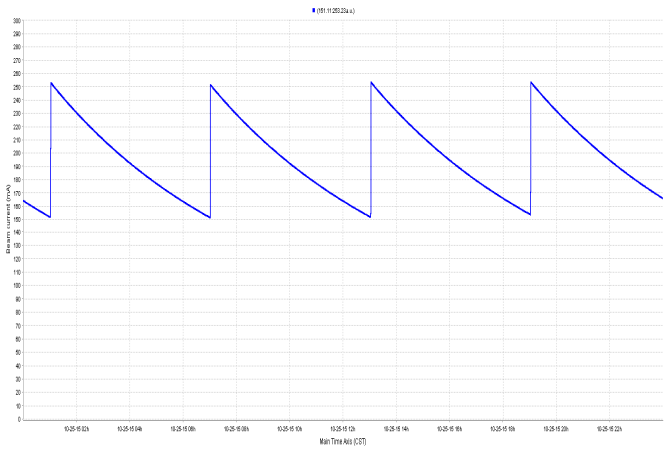
BSR and beam lines

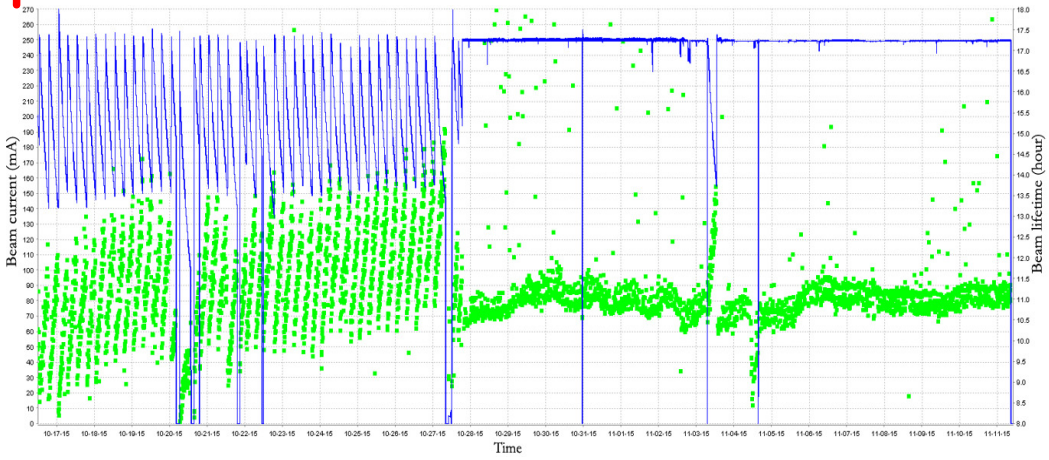
Parameters	Values
Energy	2.5 GeV
Beam current	250 mA
Circumference	241.13 m
Horizontal emittance	160 nm·rad
Harmonic number	402
RF voltage	3.0 MV
RF frequency	499.8 MHz
RF cavity number	2
Energy loss per turn	336 keV
Synchrotron radiation power	84 kW
Damping time	12/12/6 ms
Working point	7.28/5.20
Natural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



There are 14 beam lines including 8 extracted from 5 wigglers in the BSR. Every year, 3 months dedicated experiment time are spent to the users.

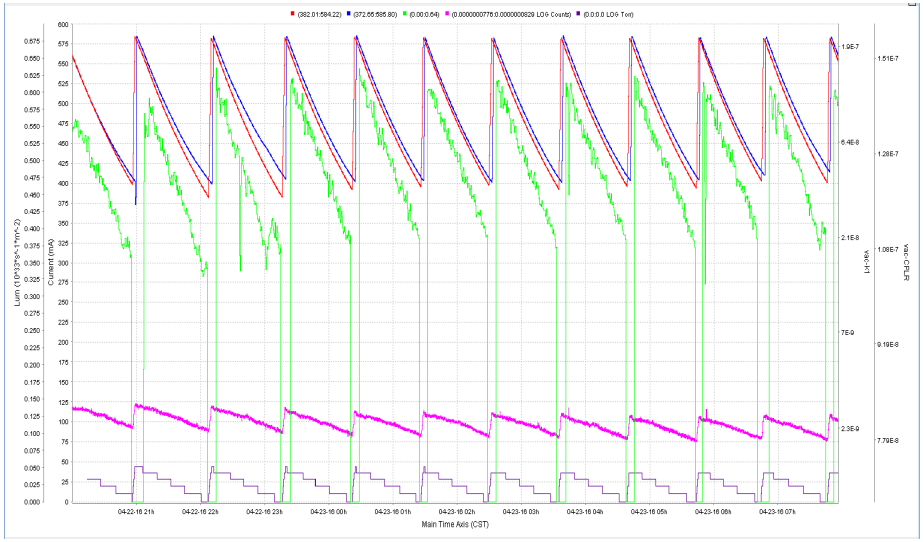
Top-up operation of BSR was realized on Apr.5, 2016

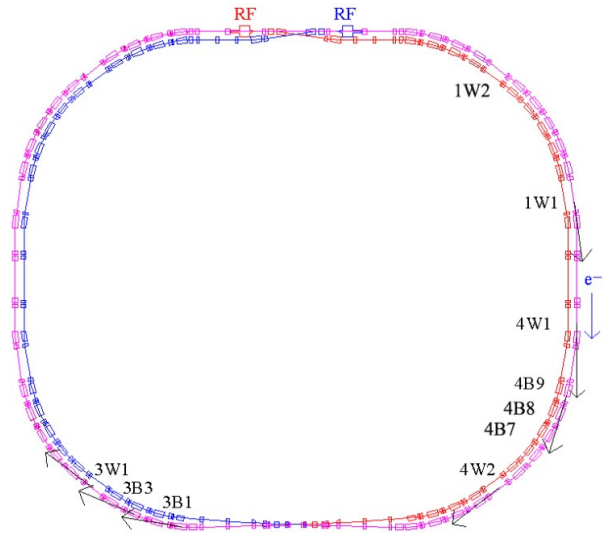




The operation for synchrotron radiation facility was designed as a decay scheme. Beam from linac was injected into storage ring every 6 hours. The dedicated machine study for top-up operation started in April 2014. With the well control for both injecting beam and circulating beam and well control of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

Parasitic operation of collider





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.

5. Summary

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.

Thank you !