PERFORMANCE AND PROSPECTS OF BEPCII

Qing Qin for the accelerator team of BEPCII,
Institute of High Energy Physics, CAS, P. O. Box 918, Beijing 100049, P.R. China

Abstract

BEPCII, the major upgrades of BEPC (Beijing Electron Positron Collider), is a double-ring e^- and e^+ factory-like collider, working at the beam energy range from 1 GeV to 2.1 GeV and being optimized at 1.89 GeV with the design luminosity of $1\times10^{33}cm^{-2}s^{-1}$. It has been in user-operation since Sept. 2009, delivering beams to both high energy physics and synchrotron radiation experiments. Peak luminosity is gradually enhanced to 2/3 of the design value under the efforts of commissioning and hardware improvements. In this paper, the accelerator physics study accompanied with the luminosity evolution will be given and the key components of some hardware systems will be described. The operation performance of the machine is summarized, and the future of BEPCII is foreseen.

INTRODUCTION

Being consisted of a linac, two transport lines, two storage rings (BER and BPR, standing for e^- and e^+ rings, respectively) and one detector, the BEPCII runs as a factory-like collider for HEP experiment, and a dedicated synchrotron radiation (SR) facility, using two outer halves of each collider ring as the third ring (BSR). Figures 1 and 2 show the layout of the whole machine and the storage rings, respectively.

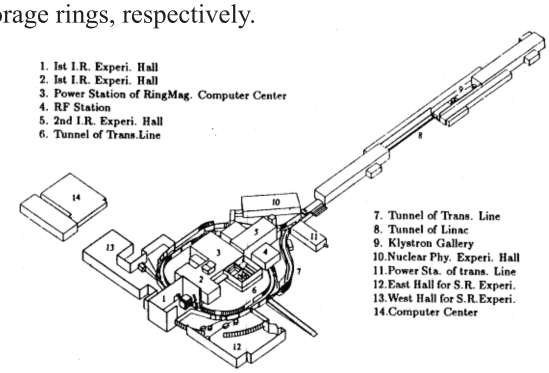

Figure 1: Layout of BEPCII.

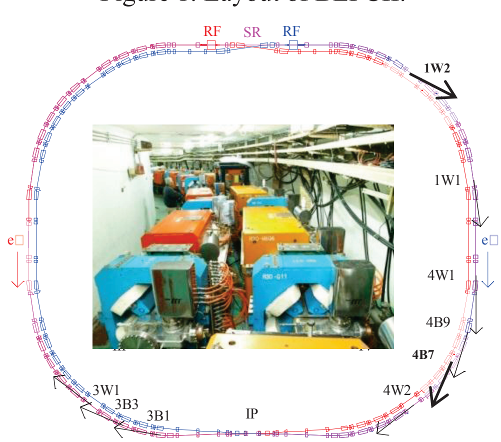

Figure 2: Storage rings and tunnel of BEPCII.

"One machine with two purposes" is the characteristic of the BEPCII, which means the machine can provide beams not only to high energy physics (HEP) experiments, but also the SR users with different lattice models. Some main design parameters of these two operation modes are listed in Table 1.

Table 1: Main Design Parameters of BEPCII

Energy for collision	GeV	1.89
Beam current in collision	mA	910
Energy for SR	GeV	2.5
Beam current in SR	mA	250
Injection energy	GeV	1.89 – 2.5
Injection rate (e^+, e^-)	mA/min	50, 200
Luminosity	$cm^{-2}s^{-1}$	1×10^{33}

As described in refs. [1] and [2], the commissioning of BEPCII started from Nov. 2006 with the dedicated SR mode. The SR operation for users started from Dec. 2006, and every year after then, about 3 months were devoted to SR users. There are total 15 beam lines running during the dedicated SR operation. Alternatively, three phases of luminosity commissioning, starting from March 2007, were carried out. The luminosity of BEPCII exceeded $3.0\times10^{32}cm^{-2}s^{-1}$ in May 2009, which passed the national inspection of the project. From Sept. 2009, delivering beams to HEP and SR users occupied the routine operation of the machine. In March 2010, the parasitic SR mode, which means to provide beam to SR users when BEPCII is running for the HEP experiments, was succeeded in operation with 6 beam lines working (4 from dipoles, and 2 from a wiggler). In 2011, with the efforts of commissioning, BEPCII's peak luminosity reached $6.49\times 10^{32}cm^{-2}s^{-1}$ during the data taking of $\psi(3770)$. HEP experiments at different beam energy were carried out. SR operation was also improved with the horizontal emittance of beam decreased.

ACCELERATION PHYSICS ISSUES

Accelerator physics plays the key role in the luminosity commissioning and routine operation of BEPCII. Beam studies on luminosity enhancement focus on the lattice correction, beam-beam issue, beam instability, and so on. Table 2 lists the design parameters of the two collision rings and the SR ring lattices.

Beam Optics Correction

In the original design, both BER and BPR have the same magnetic lattices with the super-period number of 1. Figure 3 shows the Twiss functions of the whole BER and BPR rings. In order to have a big emittance and a high beam current for collision, a quasi-FODO structure with 10 dipoles and 2 missing dipoles in each arc was applied. The lattice was also used in the BSR, but re-matched to optimize the emittance and the beam parameters at the ports of beam lines. Figure 4 shows the Twiss functions of the BSR ring.

Table 2: Main Design Parameters of BEPCII Rings

Parameters	BER/BPR	BSR
Beam energy (GeV)	1.89	2.5
Circumference (m)	237.53	241.13
Beam current (A)	0.91	0.25
Bunch current (mA) / No.	9.8 / 93	~1 / 160 - 300
Natural bunch length (mm)	13.6	12.0
RF frequency (MHz)	499.8	499.8
Harmonic number	396	402
Emittance (x/y) (nm·rad)	144/2.2	140
β function at IP (x/y) (m)	1.0/0.015	10.0/10.0
Crossing angle (mrad)	±11	0
Tune (x/y/s)	6.54/5.59/0.034	7.28/5.18/0.036
Momentum compaction	0.024	0.016
Energy spread	5.16×10^{-4}	6.67×10^{-4}
Natural chromaticity (x/y)	–10.8/–20.8	–9.0/–8.9
Luminosity ($cm^{-2}s^{-1}$)	1×10^{33}	—

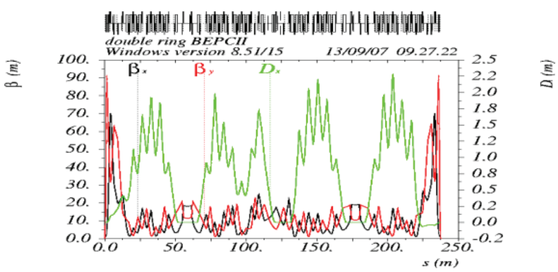

Figure 3: Twiss functions in both BER and BPR.

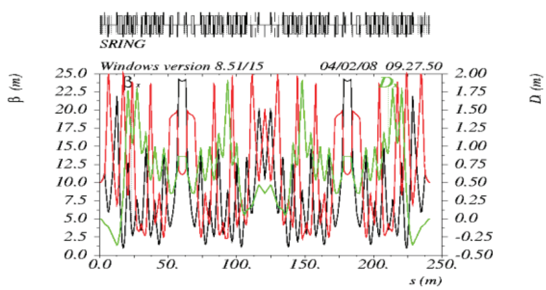

Figure 4: Twiss functions in BSR.

To correct the beam optics, the code LOCO [3] is used to find the fudge factors, coefficients to be multiplied to quadrupole strengths, based on the method of response matrix. Before 2010, we corrected all the quadrupoles powered by independent power supplies, excluding the superconducting quads (SCQ) near the interaction point (IP) and other two 2-in-1 quads close to SCQ's [4]. One SCQ controls two beams in each side of IP, and each 2-in-1 quad, which means two beam pipes in one magnetic yoke, is powered by one power supply. All these special magnets were treated as ideal ones without any strength compensation. Then the results of optics correction showed that a big fudge factor (more than 10%) had to be assigned to Q02's in the interaction region (IR), and the vertical β function at the IP (β_y^*) deviated from the design value by at least 10%.

In later 2010, when the machine was run at ψ(3770), the optics correction was done with the two SCQ's to be considered. A careful calculation showed that the strength of each SCQ should multiply a fudge factor of 0.994, say about 0.6% reduction on its strength. After this correction, the abnormal fudge factors of Q02's disappeared, and the measured β_y^* was close to the design value. The energy change due to correctors applied to orbit correction was also considered in the method of response matrix. Table 3 lists the main beam parameters after the optics correction. Figure 5 shows the measured and design β functions.

Table 3: Optics Parameters after Correction

Parameters	BPR		BER	
	Setup	Meas.	Setup	Meas.
Hori. tune @0.53	6.536	6.5357	6.537	6.5345
Hori. tune @0.51	6.509	6.510	6.5078	6.507
Vert. tune	5.600	5.6050	5.607	5.6063
Hori. chromaticity	1.0	1.6	1.0	1.4
Hori. chromaticity	1.0	1.6	1.0	1.4

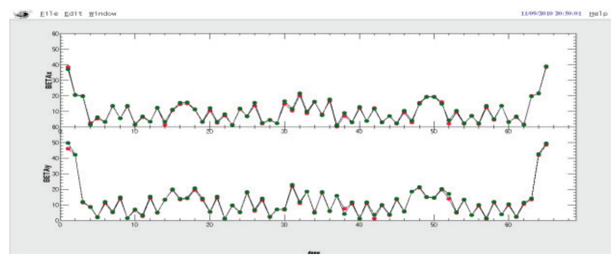

Figure 5: Measured β functions along BER compared with design value (green: design value, red: measured).

Closed orbit correction based on the measured response matrix was first done to make sure that beams traversed across each quad's center. Gains of BPMs and fudge factors of corrector magnets could be got from response matrix measurement, and were used in the optics correction. After the optics correction at the tune region of 0.53, the fudge factors of all quads could be adopted when the tunes of two rings were moved to the region of 0.51. Tunes of these two regions are shown in the two lines of "Hori. Tune" in Table 3.From Table 3 and Fig. 5, optics correction is parameterized by the tunes and beta beating of two rings. Normally, the good optics correction can lead the transverse tunes to be as close to the design values as $\Delta\nu$=0.001~0.005, and the beta beating is around 10% after the correction.

Luminosity Commissioning

Knobs for luminosity tuning, such as orbit and crossing angle offsets at IP, beta waist at IP, rolling angle of bunch, coupling items at IP, etc., were already described in [2]. Here we mainly discuss some key issues and the physics behind, which affect the luminosity.

Background of detector somehow plays one of the important roles in the data taking of detector from the point of view of accelerator. Simulations and operation experiences from other particle factories tell us that higher luminosity will be got when the horizontal tune moves

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towards half integer. In BEPCII, the luminosity got to its first milestone, 3.1×10^{32} cm^{-2}s^{-1} in May 2009, at ν_x = 6.51. But at that time, the high background, shown as the dark current of the detector when taking data, prevented BEPCII from working at ν_x = 6.51. Efforts on background study showed that the Touschek effect and beam-gas scattering were the main sources of high dark current. Further simulation showed that the dynamic effects of beta function and emittance change due to beam-beam at ν_x = 6.51 was much serious than at the tune range of 6.53, as shown in Fig. 6.

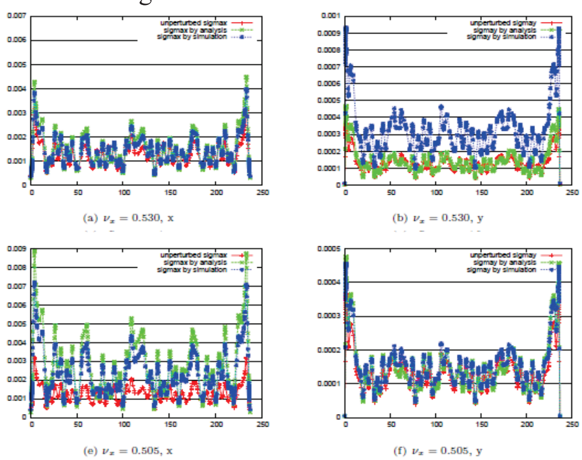

Figure 6: Twiss functions due to beam-beam interaction along the ring at different νx region (upper: ν_x = 6.53, lower: ν_x = 6.51; left: hori. direction, right: vert. direction)

Figure 6 tells us that the β function of the ring working on ν_x = 6.506 varies much larger than the ring working on ν_x = 6.53. This contributes a lot to the dark current of detector. Optimization on beam orbit, working points, and collimators in the IR, can ameliorate the background.

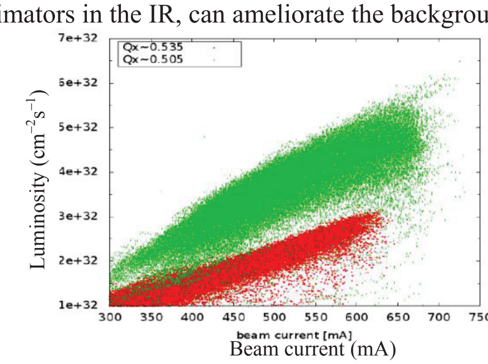

Figure 7: Luminosity at different tune region (red: ν_x ~ 6.53; green: ν_x ~ 6.51).

During the commissioning, we also found that the vertical separation at the north crossing point affected the dark current of detector. With these efforts on background improvement, the data taking for HEP experiment was finally succeeded in operating the collision rings at ν_x = 6.51, and even as close to half integer as ν_x = 6.506. The peak luminosity at this working point is about 20-30% higher than that at ν_x = 6.53, shown in Fig. 7. In Fig. 7, some results got from other luminosity tuning methods are also included.

Coupling coefficient is another key point in luminosity commissioning. Based on the orbit response, the coupling coefficient $\bar{C}_{12}$ can be corrected globally. During the luminosity tuning, we follow the parameterization of coupling in [5].

In the case of weak coupling, which is the situation of most rings, a horizontal corrector can not only cause a horizontal deflection along the ring, but also a vertical orbit distortion. The vertical distortion comes from two parts: local coupling at BPM and the horizontal corrector. The ratio of vertical orbit distortion to that in horizontal direction can be expressed as [6]

$$\frac{\Delta y_{cod}}{\Delta x_{cod}} = \bar{C}_{b,22}\mathrm{Cof}_1 + \bar{C}_{b,12}\mathrm{Cof}_2 + \bar{C}_{c,11}\mathrm{Cof}_3 + \bar{C}_{c,12}\mathrm{Cof}_4 \quad (1)$$

and $\bar{C}_{b,12}$ is chosen as the coupling coefficient to optimize the global coupling. Here, "b" stands for BPM and "c" for corrector. In BEPCII, there are only 4 skew quads in each collision ring, which is not enough to do the coupling correction, so the 36 well-distributed sextupoles in each ring are used to optimize the global coupling. Figure 8 shows the result of coupling correction with this method.

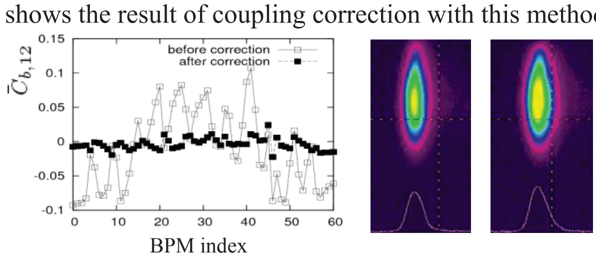

Figure 8: Global coupling correction (left) and beam spot before (middle) and after (right) correction.

Luminosity enhancement is the final result of all the efforts of optimization, including beam optics correction, transverse coupling optimization, beam manipulation at the IP with different knobs, transverse and longitudinal feedback systems, etc. Background reduction was also benefit from these measures, accompanied by luminosity enhancement. Luminosity with multi-bunch is based on the optimization of single bunch luminosity.

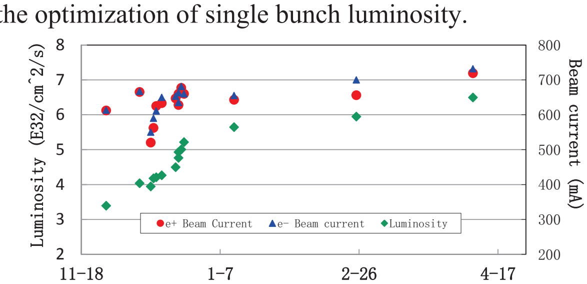

Figure 8: Luminosity enhancement from 11/10 to 05/11.

Up to now, the peak luminosity was got with 88 bunches for each beam. Figure 8 shows the luminosity enhancement during Nov. 2010 to May 2011, with the above tuning methods. The peak luminosity reached 6.492×10^{32} cm^{-2}s^{-1} during the data taking of ψ(3770).

Beam Instabilities

Both single bunch and multi-bunch instabilities were observed in the commissioning and routine operation.

Transverse feedback system was installed and used at the beginning of the machine running. When the beam current got to higher and higher, a strong longitudinal quadrupolar oscillation was found and luminosity was affected a lot. The impedance source in the BPR causing this kind of instability was found and removed in early 2009. Then the luminosity was enhanced a lot. Late 2009, a longitudinal feedback system was installed in each ring, and the observed longitudinal dipolar oscillation was cured. These two feedback systems are beneficial to beam injection, collision with high beam current, luminosity in collision, and SR operation.

Bunch lengthening is the main topic of the single bunch instability in BEPCII collision rings. Streak camera was used to measure the bunch lengthening. Taking BER as an example, the measured bunch lengthening of electron beam is shown in Fig. 9.

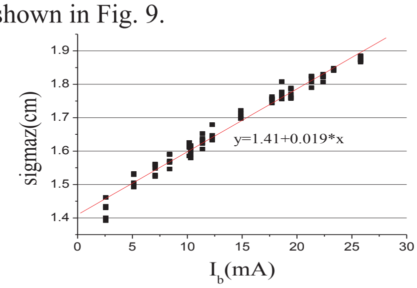

Figure 9: Bunch lengthening measured in BER.

From the measurement, we can get the low frequency impedance, which determines the bunch lengthening in the regime of potential well distortion. The result is L = 121 nH, and $|Z_{//}/n|_0 = 0.96\Omega$. The measured low frequency impedance is about 4 times bigger than the design values. The additional source of impedance may come from the kicker of longitudinal feedback, which was used in PEP-II before with a calculated inductance of about 20 nH. The increased impedance also degrades the threshold of beam instability, especially the multi-bunch instabilities. The bunch lengthening is also more serious than expected, so the way of reducing β_y^* seems not so effectively to increase luminosity. Re-design and improvement of the feedback kicker is considered to lower the impedance.

Beam-beam Interaction

Along with the luminosity commissioning, beam-beam studies were carried on. In Fig. 10, simulations on beam-beam parameter ξ_y at different coupling are compared with the achieved values in routine operation, and the cases w/ and w/o the contribution of bunch lengthening.

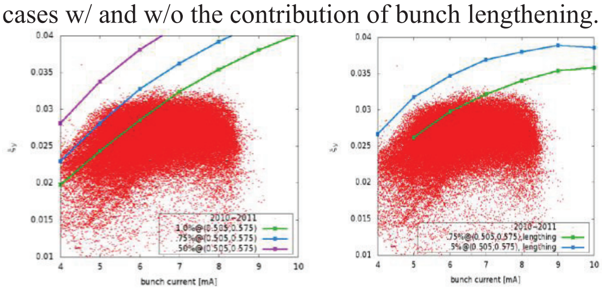

Figure 10: Beam-beam parameter in different coupling (lines), with bunch lengthening (right) or without (left).

The highest beam-beam parameter (ξ_y) that we have got was 0.0327 in the ψ(3770), and 0.0279 in the J/ψ energy. Non-linearity at the arcs along each ring is also studied in the beam-beam simulations. The result shows the non-linearity causes a 5% luminosity reduction.

Another key role affecting the luminosity is the vertical separation at the north crossing point (NCP) of two rings. In the original design, the vertical separation at NCP is $5\sigma_x$. But in the real operation, beam-beam simulation shows that the luminosity is seriously affected by the vertical separation of two beams at NCP as the bunch current increases. Figure 11 shows the beam-beam parameter as a function of horizontal and vertical separations at the NCP.

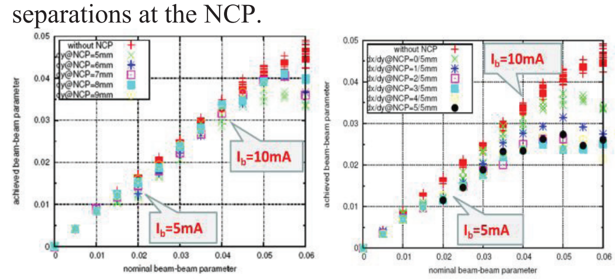

Figure 11: Beam-beam parameter vs. vertical separation at NCP (left) and horizontal separation (right, vert. separation = 5mm).

The beam-beam study on vertical separation at NPC directly caused a component movement at this region. In the summer of 2011, the chambers and magnets of two rings, including the NCP were shifted by 15 cm to the west, which is ¼ of the space of two successive RF buckets. After this action, the beams are separated in horizontal now, with a separation of 46 mm, or $40\sigma_x$, which is large enough to keep the beam-beam parameter as beam current increases.

HARDWARE IMPROVEMENTS

Besides the movement of elements in the NCP region described in previous section, some hardware systems are being upgraded after the machine passed the national acceptance and test in 2009.

Linac Energy Promotion

Some of the HEP experiments requires as high beam energy as 2.2 – 2.3 GeV, which is nearly the up limit of the magnets' strengths along the inner ring of BEPCII. In the original design, the full energy injection can only afford the e^- beam to such a high energy, since the e^+ beam needs to be produced by the 240 MeV e^- beam bombing the tungsten target. Thus, four additional sets of microwave power source of the linac, including klystrons, modulators, and other auxiliaries were installed. With these new sets of power source, the full energy injection of e^+ beam can be realized at 2.3 GeV. All the upgrade of linac will be finished at the end of this year.

Longitudinal Feedback System

Only transverse feedback system was considered in the design of BEPCII. After observing the serious effect of

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longitudinal dipolar oscillation accompanied with high beam current, we decided to introduce the longitudinal feedback system (LFS) in each ring to recover the luminosity. With the help of SLAC and KEK, two sets of LFS were installed in two rings in the fall 2009, and were commissioned in early 2010. The peak luminosity gets benefits from the LFS, with an increase of ~20% [2]. Moreover, in recent HEP running on J/ψ energy, we found energy spread due to beam instability was also reduced. The evidence of this comes from the reaction cross section of collision at J/ψ energy. Before we had the LFS, the reaction cross section is 2860 nb calculated from the off-line HEP data in 2009. Now, this cross section reaches 3100 nb with the LFS on. In a word, the LFS promotes the effective luminosity or the efficiency of data taking.

In addition, a new compressor of cryogenic system was installed in parallel to the existing ones as a backup, to guarantee the routine operation. And four newly installed wire scanners for beam size measurement at the transport line can be used to optimize the injection efficiency.

ROUTINE USER OPERATIONS

HEP Operation

BEPCII runs as a collider for 5–6 months each year. In the past two and a half years, BEPCII was run at different beam energy, such as ψ(3770), D_s, ψ′, τ lepton and J/ψ for HEP data taking. Figure 12 shows the operation status for a period of data taking at ψ(3770) in last April.

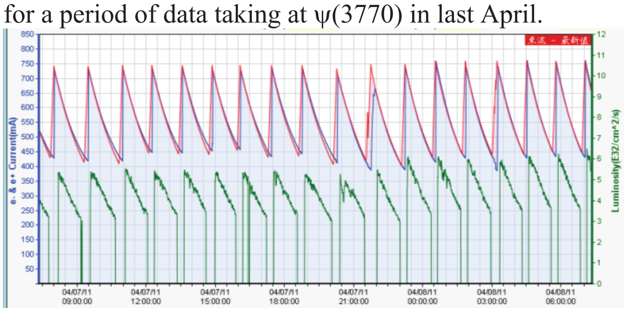

Figure 12: Data taking at ψ(3770) within 24 hrs in 2011.

The integrated luminosity per day reached the record of $29pb^{-1}$ at ψ(3770) in 2011. The peak luminosity at Ds energy also got to 6.5×10^{32} $cm^{-2}s^{-1}$ At J/ψ energy, 1.55 GeV, we got 2.74×10^{32} $cm^{-2}s^{-1}$ at 422*441mA, which is about 56 times higher than that of BEPC.

Dedicated Synchrotron Radiation Operation

Being operated at 2.5 GeV, the BEPCII can provide SR light to users similar to a 2^{nd} generation light source. Beam spots were kept to be squeezed by the means of optimizing the lattice and emittance of BSR. Now, the emittance of the dedicated SR lattice is about 105 nm·rad, with all five wigglers on. A slow orbit feedback was applied, and the position drift of e^{-} beam at the source point insy BSR was controlled with a p-p value of ~ ±10 μm. Each year, we have about 3 months to operate the dedicated SR mode. The beam availability was gradually increased to 98.5%, and the MDF was decreased to about 0.5 hour last year.

Parasitic SR Operation

Requested by the SR users, the wiggler 1W2 is in use during the HEP operation together with other 4 beam lines extracted from dipoles. Higher beam current in collision leads to a large SR flux. The effect of wiggler to the luminosity degrade, was compensated by means of global optics correction, taking 1W2 as an error of magnetic field. Six beam lines can be operated during the HEP running. The parasitic SR operation brings a big amount of machine time to SR users.

PROBLEMS AND PROSPECTS

Though we had some progresses on the BEPCII's luminosity enhancement and operation to users, we still have a lot of problems to be solved in the near future. Failures happened more frequently when the beam current gets higher. Stability of hardware needs to be promoted in routine operation.

To achieve the design value of luminosity, measures including higher bunch current, more bunch numbers are the first priorities. Some experiments on short bunch spacing were done, but the luminosity was far from the expectation. Figure 13 shows the direction of luminosity enhancement.

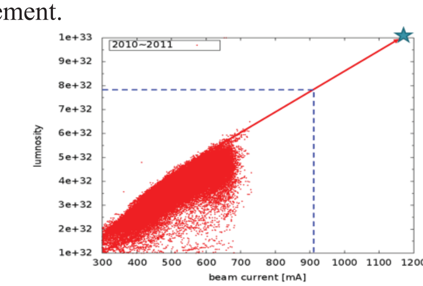

Figure 13: Luminosity expectation extrapolated from the achieved value.

To reach the goal of luminosity, much time on machine study is necessary. In addition, more tuning knobs of luminosity are needed, and feedback control for those frequently-changing parameters is important to keep a stable routine operation. As a possible potential of HEP experiments, polarization scheme is being considered. In the SR operation, top-off injection has been tested and is hoped to realize in the near future.

The way to get to the design luminosity of BEPCII and better performance is still long, but very promising.

ACKNOWLEDGMENT

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