STATUS AND PERFORMANCE OF BEPCII*

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Abstract

BEPCII is the upgrade project of Beijing Electron Positron Collider (BEPC) with its design luminosity of 1×10^{33} $cm^{-2}s^{-1}$ at the beam energy of 1.89GeV. The construction of BEPCII was completed in May 2008, when the detector worked together with the machine. The collider has been operating for high energy physics since May, 2009, and for synchrotron radiation users since 2007. The status and updated performance of BEPCII are reported here.

INTRODUCTION

BEPCII contains a linac, two transport lines and three storage rings. Among three rings, two are in parallel for e^- and e^+ beams, respectively, and named as BER and BPR. It locates in the original tunnel of the collider, BEPC, using as many BEPC's magnets as possible and keeping all the BEPC beam lines extraction ports unchanged. The collider was designed as a factory-like one with a design luminosity of $1\times10^{33}cm^{-2}s^{-1}$ at the beam energy of 1.89GeV. BEPCII is characterized as "one machine, two purposes", which means to provide beam not only for high energy physics experiment, but also for synchrotron radiation (SR) users in parasitic or dedicated mode. The two halves of the outer rings are connected as an SR ring, the third ring named as BSR, with 9 beam lines extracted from 5 wigglers, and 6 beam lines from bending magnets, as shown in Fig. 1.

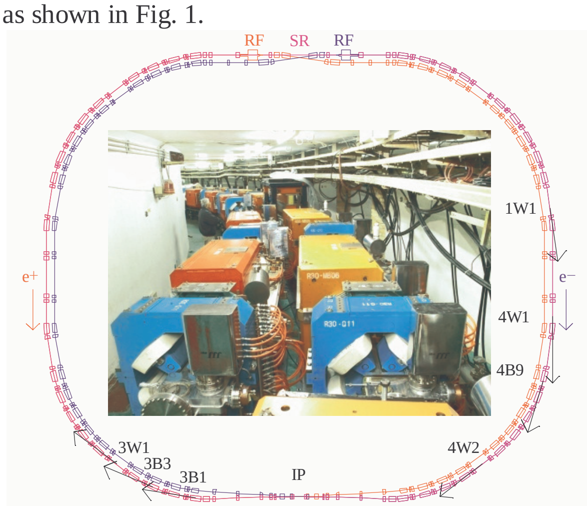

Figure 1: Layout of the BEPCII storage rings.

The linac finished its construction in 2004 and started commissioning in 2005. After the installation of storage rings for one and a half years, the commissioning of the rings started from Nov. 2006. Later, in 2007, the linac reached all the design parameters. Table 1 lists the main design parameters of BEPCII. In this paper, the linac upgrades are first described. Then the commissioning of the storage rings in last year is reviewed, and finally the operation of BEPCII for the users is given.

Table 1: Main design parameters of the 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}

LINAC STATUS AND NEW UPGRADES

During last summer, the new sub-harmonic bunching system was installed in the linac front end, as shown in Fig. 2. It consists of two sub-harmonic bunchers (SHBs) operated at the frequencies of 142.8MHz for SHB1 and 571.2MHz for SHB2, respectively, and followed by an S-band 4-cell buncher. The new bunching system aims at promoting bunching efficiency and making a single bunch per pulse to ensure an efficient and fast injection, and to minimize the background to the colliding beam detector during the injection. Furthermore, a two-bunch operation scheme will be employed to almost double the positron injection rate as expected.

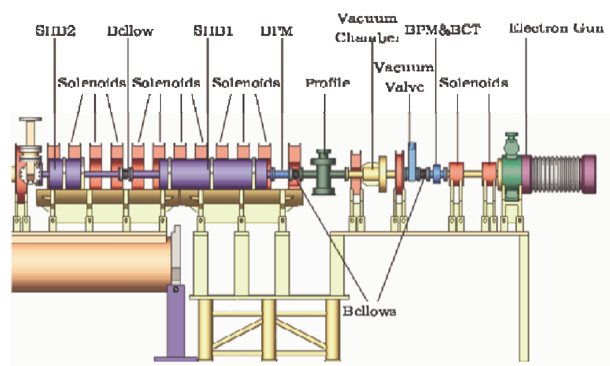

Figure 2: The front end of the BEPCII linac.

The new sub-harmonic bunching system is composed of buncher cavities, the solid state power sources and the LLRF system.

The buncher cavities' characteristics, the requirement of the power source and the LLRF systems are given in Table 2 [1]. The new bunching system works well in general. A single bunch with the bunching efficiency of higher than 90% has been obtained, shown in Fig. 3. The rms bunch length of about 10ps was measured in an economical way with the harmonic analysis method. The measured electron beam emittance of 0.1mm·mrad and the energy spread of 0.4% are within the design goals.

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With the new bunching system the primary electron beam current hitting on the positron convert target as well as the downstream positron beam current are increased by ~20%.

Table 2: Characteristics and requirements for the sub-harmonic bunchers

Sub-system	Characteristics and requirements	SHB1	SHB2
Buncher cavity #	Operation frequency	142.8MHz	571.2MHz
	Q_L	4046	5391
	Coupling factor	1.04	0.97
	Tuning range	240kHz	1.2 MHz
	Gap spacing	40mm	30mm
	Power required	14kW	7kW
Solid state amplifiers*	Output power	20kW	10kW
	Pulse width	~60μs	~60μs
	Phase variation in pulse	1°	1°
	Power flatness	2 %	2 %
	Repetition	50Hz	50Hz
LLRF*	Amplitude stability	1.5%	1.5%
	Phase stability	1.5°	1.5°

#tested parameters, *requirements

Figure 3: Single bunch measured with a BPM downstream the bunching system.

However, we met the beam current instability in the operation. With a lot of machine studies, it is found that this instability comes from the phase shift of the SHB's frequency signal generator and the temperature is not well controlled for the signal generator. The SHB's phase shift causes the change of beam bunching, leading to the change of the downstream beam current. We have to adjust the SHB's phases during the operation to keep the beam current constant. Now these two important devices are being rebuilt and the SHB's phase feedback system is being considered, too. After the improved hardware to be installed in the coming summer, the two-bunch operation scheme will be soon commissioned, as the next step, aiming at doubling the positron injection rate to the ring.

Now, with the sub-harmonic system, the maximum injection rate can be as high as ~80 mA/min of e^+ beam, and ~400 mA/min for e^- beam.

COMMISSIONING OF STORAGE RINGS

The storage ring commissioning of BEPCII were carried out in three phases, as already described in [2] and [3]. In Phase III, the detector, upgraded BEijing Spectrometer (BESIII), had been rolled in the tunnel, and was commissioned together with the collider. Here we will mainly focus on the commissioning from last May.

Beam Optics Realization

The linear lattices of BER and BPR were designed similar as that in the BEPC, except for the interaction and RF regions. Quasi-FODO cell, which means different quadrupoles' strengths for each cell, is adopted in the arcs. The IR, RF and injection regions are dispersion free. The detailed lattice design can be found in [4]. Response matrices were measured after the BPMs' offsets were got. The software tool LOCO [5] was used to correct the strength of quadrupoles due to any induced magnetic errors after beam orbit correction, and a fudge factor was calculated to compensate each quadrupole's strength. After the compensation, the relative errors between the measured and theoretical β functions are around 10%, and the errors between the LOCO fitting and theoretical β functions are less than 3%. The measured transverse tunes are also very close to the design ones.

Though the detector solenoid is well compensated with 3 pairs of anti-solenoids, it still affected the Twiss function around the ring. By setting the fudge factor of the super conducting quadrupole (SCQ) coils near the IP, the vertical β-function around the ring is shown in Fig. 4.

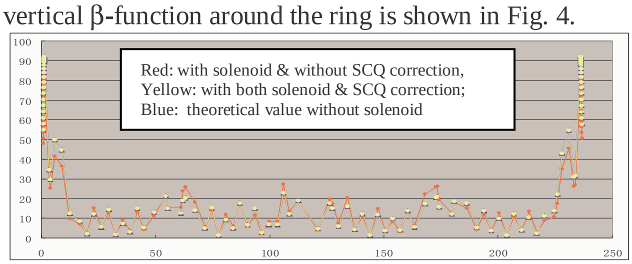

Figure 4: Vertical β function around the ring before and after the SCQ correction.

With these corrections, some main beam parameters of both BER and BPR are close to the design values, ensuring the beam injection, high beam current, and luminosity.

Beam Injection

Same as the BEPC machine, the single turn and multi-injection scheme is adopted in the BEPCII, with one Lambertson septum and two kickers, which has a phase advance of π in between. The residual closed orbit distortions during injection, which could be minimized as small as 0.1mm in average by adjusting the strengths and delay time of two kickers. While the coupled bunch instability is cured by the transverse feedback system, the bunch current thus could be uniformly controlled according to the bunch current monitor in each ring during injection.

Luminosity Commissioning

Single bunch collision was commissioned first, started with the beam-beam scan at the IP for the horizontal and vertical offsets and their diversions. The waist of β function at the IP is also tuned to optimize the luminosity. Coupling at IP, chromaticities, longitudinal position of the IP, etc, are also tuned to get a higher luminosity. All these were already discussed in [2] and [3]. The initial transverse working points were chosen according to the simulation results of beam-beam effect. The tunes were optimized by scanning with respect to the measured luminosity in the case of multi-bunch collision. Figure 5 shows the on-line tune scan with respect to the luminosity.

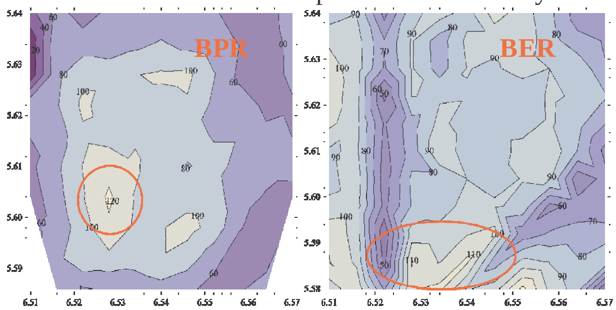

Figure 5: On-line tune scan with respect to luminosity.

In Fig. 6, the tunes adopted in collision with maximum luminosity are circled in red, which locates at the regions of (6.53, 5.59). At this tune region, the maximum luminosity with single bunch collision was ~5×10^{30}cm^{-2}s^{-1} at 8mA×8mA.The luminosity is measured with zero degree luminosity monitors (ZDLM), which can give the bunch-by-bunch luminosity, and is also cross-checked with the end-cap calorimeter of the detector.

Instability Issues

When the luminosity went up, as well as the beam currents, a kind of beam instability occurred, and the luminosity increase was blocked. When the bunch number increased together with the beam current, the bunch-by-bunch luminosity decreased along the bunch train, as shown in Fig. 6.

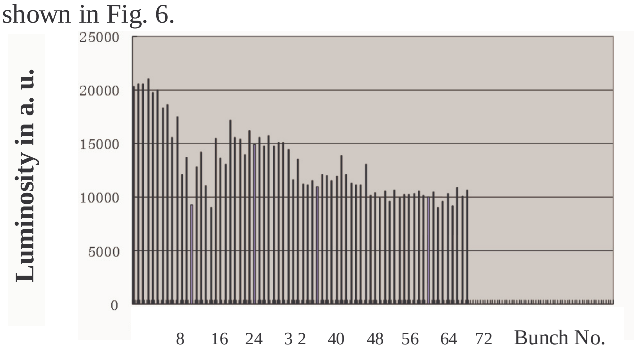

Figure 6: Bunch-by-bunch luminosity degrade along bunch train (same e^+ & e^- bunch currents).

More experiments, including one long bunch train in one beam to collide with two short bunch trains in the head and tail of another beam, different β_y at the IP to observe the luminosity decrease, bunch size measurements along the trains, longitudinal oscillation observation with oscilloscope and BPM signals, etc., were carried out to try to find the source of luminosity degrade [3]. Finally, one extra screen monitor on the BPR, which was used for initial e^+ injection, was found to be the main source of the impedance. The annular slot of the monitor flange contributed the main medium R/Q impedance, confirmed by both impedance calculation and instability simulations, and thus the bunch lengthening occurred due to the longitudinal quadrupole oscillation.

After removing this extra monitor from the BPR, we commissioned the luminosity again, and the luminosity along the bunch train recovered a lot, shown as Fig. 7. But, still, the longitudinal dipole oscillation exists in both rings, and it was believed that longitudinal feedback system is needed to cure this instability.

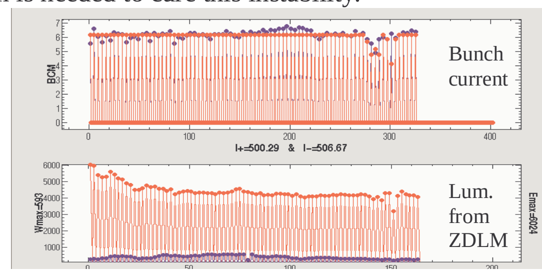

Figure 7: Bunch-by-bunch luminosity after the monitor removed from the BPR.

The luminosity was enhanced further when the transverse tunes moved towards half integer, say, in the region of (0.51, 0.57), and finally reached 3.3×10^{32}cm^{-2}s^{-1}, 1/3 of the design value in May, 2009. Figure 8 gives the luminosity evolution.

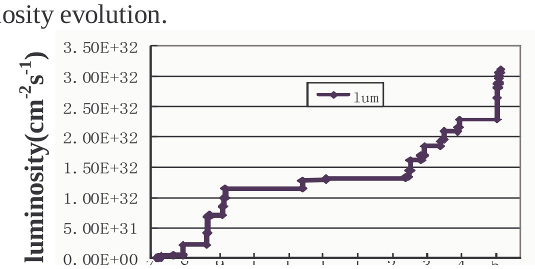

Figure 8: Luminosity trend from Sep. 2008 to May 2009.

In the summer shutdown of 2009, longitudinal feedback systems were installed in both rings to cure the longitudinal instability, and were commissioned in Jan., 2010.

With the longitudinal feedback system, we measured the instability mode of the positron beam with the multi-bunch case. Figure 9 gives the instability mode analyzed by the longitudinal feedback system.

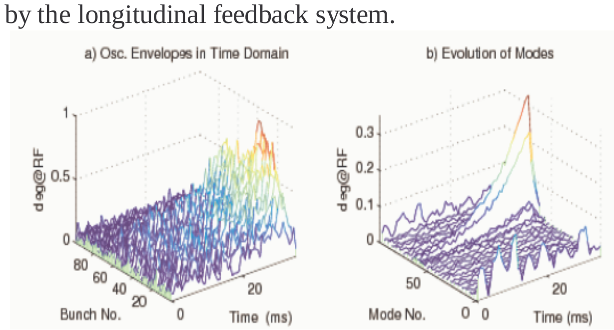

Figure 9: The instability mode of e^+ beam in time domain.

Figure 10 shows the rise time of the instability mode. It can be seen that the mode 63 of the e^+ beam is the most unstable one, with a growth time of 10ms. The beam current during the measurement was about 180mA. The longitudinal feedback system can provide a damping to the beam with the damping time of 1.5ms, so the instability can be suppressed.

With the longitudinal feedback systems in both rings, the luminosity along bunch train became uniform, shown as Fig. 11. Table 3 lists the main achieved parameters for the collision mode.

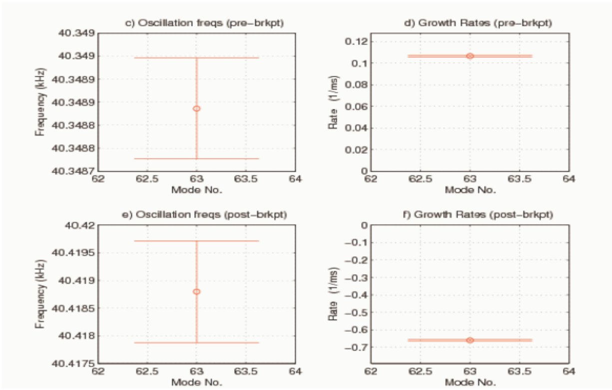

Figure 10: Eigenmode of instability analyzed with the longitudinal feedback system.

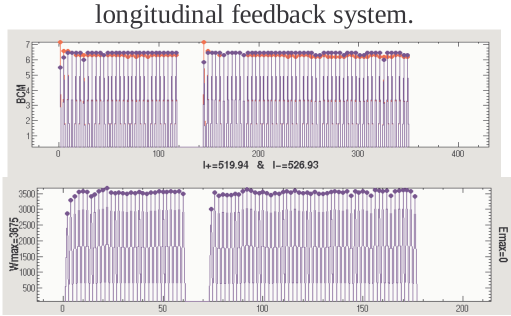

Figure 11: Bunch by bunch luminosity with longitudinal feedback system.(upper: bunch current, lower: luminosity)

Table 3: Main achieved parameters of BEPCII

Parameters	Design	Achieved (BER, BPR)
Energy(GeV)	1.89	1.89, 1.89
Beam current (mA)	910	700, 700
Bunch current (mA)	9.8	≥10, ≥10
β_x^*/β_y^* (m)	1.0/0.015	~1.0/0.014, ~1.0/0.014
Inj. rage (mA/min)	$200e^-$, $50e^+$	>200, >50
Trans. tune (x/y)	6.53/5.58	6.508/5.58, 6.51/5.585
RF voltage (MV)	1.5	1.5, 1.5
Luminosity ($cm^{-2}s^{-1}$)	10×10^{32}	3.3×10^{32}

Background of the Detector

Background of the detector is an important issue in the commissioning and operation of BEPCII. Shown as the dark current of the different layers of the detector, the background comes mainly from beam-gas and Touschek effects. It is difficult for the detector to work at high dark currents in the high energy physics experiment. To suppress the dark current of the detector, we totally installed 14 moveable or fixed collimators around the two rings. Of all 14 collimators, 4 are in the interaction region, 4 in the arcs, and 6 in the injection regions. The apertures of the collimators are decided from the results of simulations and experiments. About 50% background was reduced by optimizing the collimators' position. But the dark current still hinders the increase of beam current in collision. In the background experiment, the dark current varied in parabolic as the single bunch current increases when the bunch number was fixed, as shown in Fig. 12. It is also shown that few dark current comes from collision itself, but the single beams.

Since the vacuum of BPR is worse than that of BER, the dark current at higher beam current of the BPR is larger than that of BER. The background is hoped to ameliorate when the vacuum improves further, and then the beam current could be enhanced. When we shifted the transverse tunes of the two rings, e.g., from (6.53, 5.59) to (0.51, 0.57), the dark current gets larger though the total beam current keeps unchanged. This limits the beam current, and further study is necessary.

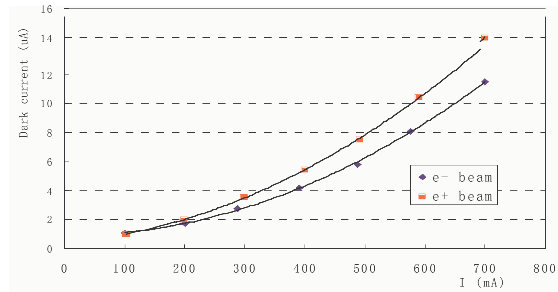

Figure 12: Dark current as a function of beam current.

OPERATION OF BEPCII

One machine with two purposes is the main character of BEPCII, which means to deliver beams not only for high energy physics, but for synchrotron radiation users too. Usually, BEPCII runs for high energy physics for 6 months a year, and 3 months for SR users dedicatedly.

Operation for High Energy Physics

Besides the luminosity commissioning, we operated BEPCII for the data taking at the energy of ψ(2S) and J/ψ last year, and ψ(3770) this year. The peak luminosity during the data taking of ψ(3770) reached 3.2×10^{32} $cm^{-2}s^{-1}$. Figure 13 is a typical plot of high energy physics running.

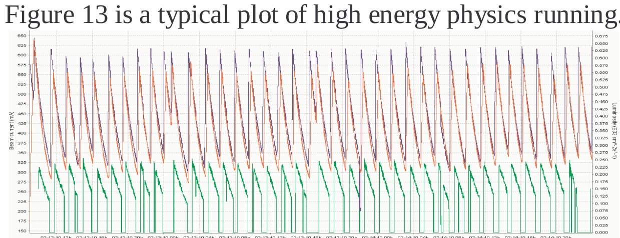

Figure 13: e^+ and e^- beam current (in red and blue) and luminosity (in green) for the ψ(3770) operation in 2010.

In the operation of high energy physics, an efficiency of 50–60% is achieved, in which 60–70% of the machine time is given to the detector, and ~80% of the detector time is contributed to collect the physics events. Injection takes about 30% of the machine time. In 2010, with the effort of tuning luminosity with the wiggler 1W2, we realized to deliver SR light from 1W2 to the users when the BES detector took data. The maximum integrated luminosity of one day can be $13pb^{-1}$, with the wiggler 1W2 closed during the operation.

Operation for SR Users with Dedicated SR Mode

With BSR, which is the third ring of BEPCII, we can run the machine with the dedicated SR mode. Since 2007, we provided SR light to users every year. In the routine operation for the SR mode, the beam energy is 2.5GeV, with the maximum beam current of 250mA. Five wigglers, among which there is an in-vacuum wiggler, can provide SR light to users via 9 beam lines. Other 6 beam lines are extracted from dipoles. From 2008, full energy injection was realized, which promoted the operation efficiency greatly. Figure 14 shows the typical beam currents and lifetime during the routine operation.

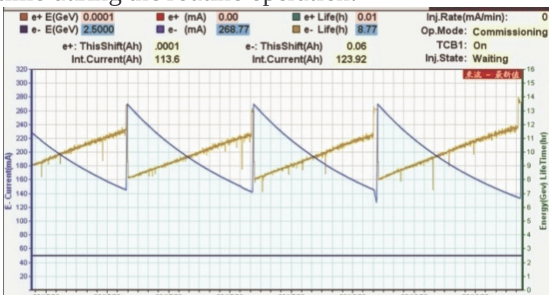

Figure 14: Typical beam current and lifetime during the routine operation for SR users.

By optimizing the lattice [7], a relatively small emittance of 100nm at 2.5GeV, with all the wigglers on, was realized this year in operation. The emittance of the previous lattice is about 160nm. During the dedicated SR operation, beam loss due to ion effect happened sometimes.

HOM Heating Problems

As the beam currents increased, some vacuum components of the beam chamber were damaged due to their structure, or the defects in original materials. Heating due to higher order modes (HOMs) became serious.

The first big trouble of the BEPCII ring came from the shielded bellows downstream the in-vacuum wiggler. The bad contact of the RF finger in the shielding of bellows caused HOM heating, and then vacuum leakage happened in April, 2009, shown in Fig. 15. A modified finger contact was then designed, and replaced the old one soon.

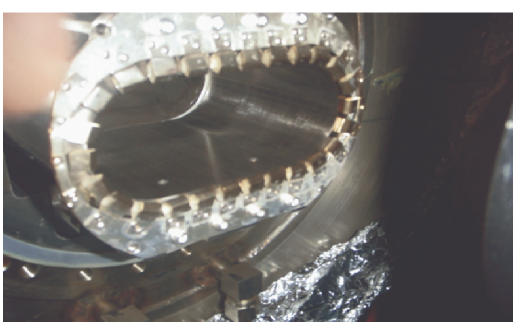

Figure 15: Damaged bellows and its RF fingers.

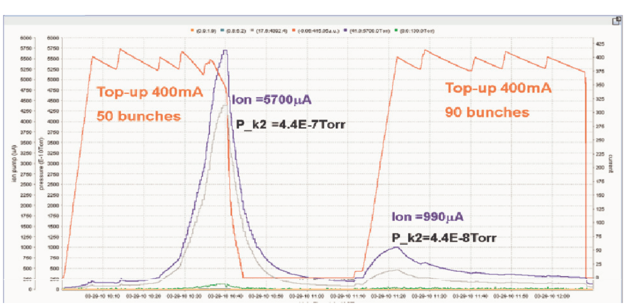

Figure 16: HOM experiment to confirm the problem.

Another serious trouble occurred in the March of this year. One of the metal-coated ceramic plates inside the injection kicker of BPR cracked due to unknown reason. Therefore, the HOM heating made the vacuum pressure of the kicker worse and worse, deteriorating the beam performance severely. Figure 16 shows the HOM experiment carried on to confirm the problem of the kicker.

DISCUSSIONS AND SUMMARY

BEPCII reached its primary design goal after 3 phases of commissioning, and started to run for high energy physics experiment from last year. The sub-harmonic buncher system was installed in the linac of BEPCII, and now it works more and more stable. Two-bunch injection is also expected to realize in the near future to promote the injection rate.

Though 1/3 of the design luminosity was achieved, the dark current of the detector constrained the beam current for collision. Thus the beam-beam interaction parameter is far from the design value. Simulations show that the crossing angle lowers the luminosity, and in the real running, the luminosity of multi-bunch collision is not linearly increased as the bunch number. The multi-bunch effect, which limits the luminosity, is not so clear and needs to study further. Some conventional measures on luminosity enhancement are being considered, such as more collision bunches and smaller β_y at the IP.

The operations of both high energy physics and SR need stable performance of all the hardware. To deliver beam simultaneous to both users of high energy physics and SR is the highlight of BEPCII, though now only one wiggler is used in the collision mode. As the beam current gets higher and higher, effects from HOM need to be monitored carefully during the routine operation.

Some other measures of enhancing luminosity, such as the crab waist scheme adopted in DAFNE, which got a lot of benefits, is also being studying now. But this will need the change of the interaction region, and even the end-cap of the detector. To run the machine more and more stable, and promote the operation efficiency, hardware reliability and stability are needed to be improved further.

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