THE BEPCII: CONSTRUCTION AND INITIAL COMMISSIONING

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Abstract

The BEPCII, as a natural extension of the BEPC (Beijing Electron-Positron Collider), is a double ring e-e+ collider and a synchrotron radiation (SR) source with its outer ring, or SR ring. As an e-e+ collider, the BEPCII will operate in the beam energy region of 1-2.1 GeV with design luminosity of 1×1033cm-2s-1 at 1.89 GeV. As a light source, the SR ring operates at the beam energy of 2.5 GeV with the design intensity of 250 mA. The project started construction in the beginning of 2004. The upgrade of the injector linac completed in late 2004. The BEPC ring dismount started in July 2005. Installation of the storage ring components except the superconducting (SC) insertion magnets completed in early November, 2006. The improvement of the cryogenics of SC megnets is in progress. The commissioning of the SR ring with conventional magnets in the interaction region (IR) started on Nov. 13 and the first electron beam stored on Nov. 18. The BEPCII has been operating for SR users since Dec. 25, 2006 at 2.5 GeV with the peak beam current of 100-150 mA. The beam lifetime increases steadily and reached about 7 h at beam current of 80 mA with an accumulated beam dose of 45A·h. This paper provides an overview of the construction and initial commissioning of the BEPCII.

GENERAL DESCRIPTION

The BEPCII serves the purposes of both high energy physics experiments and synchrotron radiation applications. The details of the BEPCII design can be found in its design report [1]. The goals of the BEPCII are shown in Table 1.

Table 1: The design goals of the BEPCII

Beam energy	1–2.0 GEV
Optimum energy	1.89 GEV
Luminosity	1×10^{33} cm^{-2}s^{-1} @189 GeV
Linac injector	Full energy inj.: 1.55–1.89GeV Positron inj. rate ≥50 mA/min
Dedicated SR	250 mA @ 2.5 GeV

Serving as a collider, the BEPCII will operate in the beam energy region of 1.0-2.1 GeV so that its physical potential in τ-charm range is preserved. The design of the BEPCII aims at a high luminosity. The luminosity of an e^+-e^- collider is expressed as

$$L(\text{cm}^{-2}\text{s}^{-1}) = 2.17\times10^{34}(1+r)\xi_y \frac{E(GeV)k_b I_b(\text{A})}{\beta_y^*(\text{cm})}, \quad (1)$$

where $r=\sigma_y^*/\sigma_x^*$ is the beam aspect ratio at the interaction point (IP), ξ_y the vertical beam-beam parameter, β_y^* the vertical β-function at IP, k_b bunch number in each beam and I_b the bunch current. The strategy for the BEPCII to reach the design luminosity is to apply multi-bunch collisions (k_b=93) with double rings and micro-β at IP with short bunches whose length is compatible to the β_y^* value. The layout and installed double-ring accelerator units in the BEPCII tunnel are shown in Fig. 1.

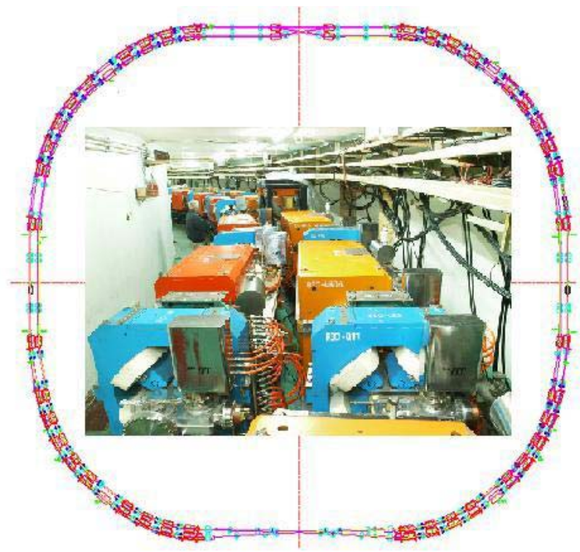

Figure 1: Layout and installed double-ring units.

The inner ring and the outer ring cross each other in the northern and southern IP's. The horizontal crossing angle between two beams at the southern IP, where the detector locates, is 11mrad×2 to meet the requirement of sufficient separation but no significant degradation to the luminosity. While in the northern crossing region, the two beams cross horizontally and a vertical bump is used to separate two beams, so that the optics of the two rings can be symmetric. For the dedicated synchrotron radiation operation of the BEPCII, electron beams circulate in the outer ring with a pair of horizontal bending coils in SC magnets serving this purpose and in the northern IP a bypass is designed to connect two halves of the outer ring. The machine physics issues are intensively studied [2].

The milestones of the BEPCII are as follows:

January 2004	Construction started
May. 4, 2004	Dismount of 8 linac sections started
Dec. 1, 2004	Linac delivered e^- beams for BEPC
Mar. 19, 2005	First e^+ beam of 50mA obtained
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Nov. 13, 2006	BEPCII ring commissioning started
Nov. 18, 2006	First e^- beam stored in the ring
Dec. 25, 2006	Beams with 2.5 GeV, ~100 mA, ~3h lifetime provided for SR users

Table 2: Main Parameters of the BEPCII.

Parameters	Unit	Collision	SR
Energy	GeV	1.89	2.5
Circumference	m	237.53	241.13
RF frequency	MHz	499.8	499.8
RF voltage	MV	1.5	1.5~3.0
Beam emittance	nm·rad	144	120
Bunch number		93	200-300
Beam current per ring	A	0.91	0.25
Injection energy	GeV	1.89	1.89
β function at IP	m	1/0.015	–
Crossing angle	mrad	11×2	–
Beam-beam Parameter		0.04	–
Luminosity	$cm^{-2}s^{-1}$	1.0×10^{33}	–

THE INJECTOR LINAC

The BEPC injector is a 202-meter electron/positron linac with 16 RF power sources and 56 S-band RF structures. The BEPCII requires the injector in two aspects. One is the full energy of e^+ and e^- beams injected into the storage rings, i.e. $E_{inj} \geq 1.89$ GeV; the other is e^+ injection rate ≥ 50 mA/min. To realize the full energy top-off injection up to 1.89 GeV, the klystrons are replaced with the new 45-50 MW ones and the modulators upgraded with new pulse transformer oil tank assembly, PFN's, thyratrons, charging choke and DC power supplies. In order to compensate the RF phase drift due to various factors, an RF phasing system is developed.

The technical measures taken for increasing positron intensity in the BEPCII injector can be summarised as following: to increase the e^- beam current on e^+ target from 2.5A to 6A, the repetition rate from 12.5Hz to 50Hz, the bombarding energy for e^+ from 140MeV to 240MeV; to develop a new positron source to increase the yield from 1.4% to 2.7%, and to apply two-bunch injection scheme. Though the pulse length reduced from 2.5 ns to 1ns, the total gain factor of the e^+ intensity can be about 20 times higher than the BEPC. The new developed positron source is pictured in the Fig. 2.

Figure 2: The new developed positron source.

All the new hardware subsystems, including the electron gun, the 40MeV pre-injector, the 200MeV booster section and the positron source of the linac were installed in the summer 2004 after dismounting the old devices. Figure 3 shows the BEPCII linac injector.

Figure 3: The BEPCII linac injector.

It took less than one month to start up the machine and process the new systems before the linac provided electron beams for the dedicated SR operation of the BEPC storage ring starting from the beginning of the December 2004. The commissioning of the linac for e^+ beam has been carried out during the machine studies. The first e^+ beam of 50mA was obtained at the linac end on March 19, 2005. The e^- beam current output from the gun is ~10A, and ~6A at the positron converter target which is the same as simulation. All of the 16 RF power sources were rebuilt, and stably work at 50pps. The new control and beam instrumentation systems make the machine commissioning and operation more convenient. The performance of the linac is listed in Table 3, showing that its design specification is reached.

Table 3: The results of the linac commissioning.

	Unit		Measured	Design
Energy	GeV		1.89	1.89
Beam current	mA	e^+	61	40
		e^-	>500	500
Emittance	mm·mr	e^+	0.4	0.4
		e^-	0.09	0.1
Energy spread	%	e^+	-	0.5
		e^-	0.5	0.5
Repetition rate	Hz		50	50
Pulse length	ns		1.0	1.0

The linac is now well operated for e^- injection in the SR operation with the beam orbit and beam energy stabilities better than ±0.1mm and ±0.1%, respectively, shown in Fig. 4.

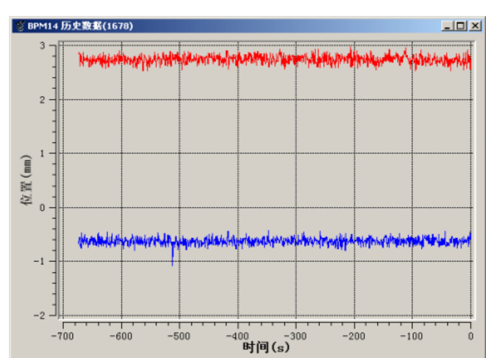

Figure 4: Beam orbit stability in the linac operation.

THE STORGE RINGS

RF system

The SC RF cavities are chosen for its advantage of large accelerating gradient and well-damped HOMs. Two SC cavities are installed in the BEPCII with one cavity in each ring to provide necessary RF voltage of 1.5 MV. Each cavity is powered with a 250 kW klystrons. The horizontal high power test gives the Q values of 5.4×10^8 and 9.6×10^8 at V_{rf}=2 MV for the west and east cavities, higher than the design values of 5×10^8 at 2 MV. Figure 5 pictures the cavity in installation.

Figure 5: A superconducting cavity in installation.

Magnets and power supplies

The BEPCII will reuse 44 BEPC bends and 28 quads. There are 267 new magnets, including 48 bends, 89 quads, 72 sextupoles, 4 skew quads and 54 dipole correctors, need to be produced. Most magnets were fabricated in the IHEP workshop. The magnets were measured with both rotating coils and straight wires. The results are in agreement each others within 10-3. Figure 6 pictures a quadrupole magnet with rotating coil measurement. There are 1 electric and 3 permanent wigglers in the storage rings serving as SR wavelength shifters. Among the 3 permanent wigglers, two are out-vacuum and one in-vacuum.

Figure 6: A quadrupole magnet in measurement.

To provide required flexibility for BEPCII operation with various modes, each arc quadruple is excited with an independent power supply. There are all together 345 power supplies in the storage rings. The power supplies have been installed, connected to the magnets and tested. Their current stability is better than 1×10^{-4}.

Injection Kickers

In order to meet the challenges both on the filed uniformity and low coupling impedance, a modified slotted pipe kicker has been developed with the coating strips on ceramic bar instead of metallic plates as the beam image current return paths. With the careful design and manufacture, the measured field uniformity is better than ± 1% in the central plane, ± 2% in y=5mm plane, ± 5% in y=10mm plane, shown in Figure 7.

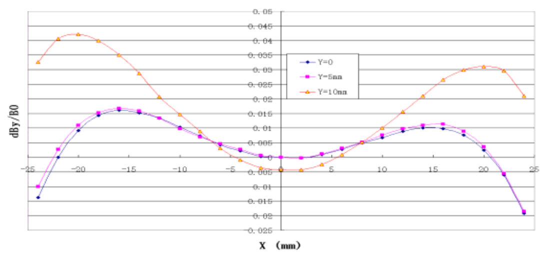

Figure 7: Measured field uniformity of a kicker.

Vacuum System

The BEPCII imposes two challenges to the vacuum system, one is the vacuum pressure, and the other is the impedance. The design dynamic vacuum pressure are 8×10-9 Torr in the arc and 5×10-10 Torr in the IR. Antechambers are chosen for both e+ and e rings. For the e+ ring, the inner surface of the beam pipe in the arc is coated with TiN in order to reduce the secondary electron yield (SEY). Measurement results show that the maximum SEY is 1.6-1.9 after the coating, seen in Fig. 8.

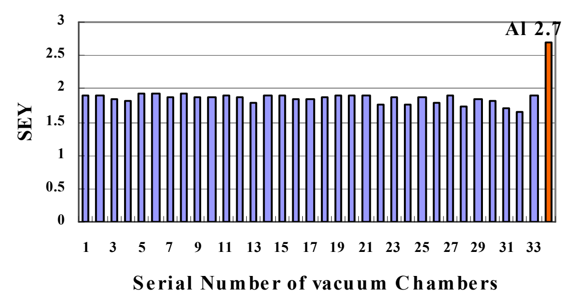

Figure 8: measured SEY of TiN-coated chambers.

IR and SC Insertion Magnets [3]

The IR has to accommodate competing and conflicting requirements from the accelerator and the detector. Many types of equipment including magnets, beam diagnostic instruments, masks, vacuum pumps, and the BESIII detector must co-exist in a crowded space. A special pair of superconducting magnets (SCQ's) is placed in the IR. Each SCQ consists of a main and a skew quadrupoles, 3 compensation solenoids and a dipole coils, to squeeze the β function at IP, compensating the detector solenoid and to serve as the bridge connecting outer ring for SR operation, respectively. The SCQ's were produced and will be measured when the cryogenics is ready. Some special warm bore magnets in IR such as septum bending magnet and two-in-one quadrupoles have been manufactured, tested and installed. The magnetic field measurement results confirm the design. Figure 9 shows two SCQ's and some warm magnets installed in the IR.

Figure 9: SCQ's and some warm magnets installed in IR.

Instrumentation and Control

The instrumentation system consists of 136 beam position monitors (BPM's), 2 DCCT's, 2 bunch current monitors and 2 synchrotron radiation monitors. Transverse feedback systems are equipped in order to damp beam instabilities. The control system is based on the EPICS environment, providing a friendly man-machine interface for operators. The instrumentation and control systems have been examined during the commissioning.

Cryogenics system

The BEPCII cryogenics system is composed of four sub-systems: the central cryogenic plant and three satellite cryogenic systems for the RF cavities, the SCQ magnets, and the SSM detector solenoid. Two 500W refrigerators serve the purpose to cool the SC devices at 4.5K, one for the cavities and another for the magnets. The cavity side cryogenics has been in normal operation, while the magnet part is being improved to solve the problem of the control Dewar, valve boxes and current leads.

COMMISSIONING AND OPERATION

The operation of the BEPC completed on July 4, 2005, and then dismount of the old ring started. After 16 months' hard work, the storage ring installation was finished in early November 2006 except the cryogenics of the magnets. It was decided to install conventional magnets in the IR to start storage ring commissioning and SR operation. In the meantime, the improvement of the cryogenics system and measurement of the SC magnets are being carried out at the BESIII off-line position. Figure 10 shows the IR with conventional magnets and Table 4 gives some results of the SR ring commissioning.

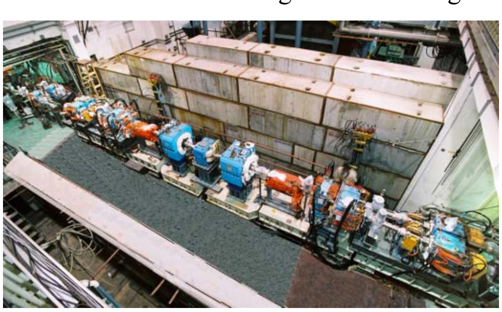

Figure 10: IR with conventional magnets.

Table 4: Some results of the SR ring commissioning.

Parameters	Unit	Measured	Design
Operation Energy	GeV	2.5	2.5
Injection energy	GeV	1.89	1.89
Circumference	m	241.127	241.130
RF voltage	MV	1.5	1.5~3.0
Tunes ($\nu_x/\nu_y/\nu_s$)		7.27/5.40/ 0.0242	7.27/5.37/ 0.0249
Bunch number		~100	200-300
Beam current	mA	200	250

The commissioning of the storage ring started on Nov. 13, 2006. One turn beam signal was observed with a beam position monitor on the first day. In the early morning of Nov. 18, circulating beams without RF and stored beams with RF were obtained, seen in Fig. 11. Figure 12 exhibits the beam image with the SR monitor.

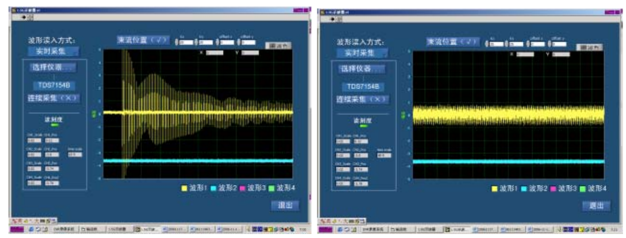

Figure 11: Circulating & stored beam with a BPM.

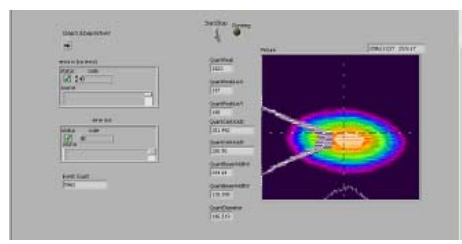

Figure 12: Beam image signal with the SR monitor.

The hardware systems were tested and debugged during the commissioning. It took a few days to calibrate the power supplies with a larger current range to reduce magnet setting errors at low field. Misconnection of some corrector power supplies was found and amended; cables of the BPM's were re-calibrated; and some "bad" BPM's, judged by the 3-button check, were disabled. The orbit correction with transfer functions was performed. The residual rms orbit distortion after correction is reduced to 0.42mm and 0.27mm on the horizontal and vertical planes, respectively, shown in Figure 13.

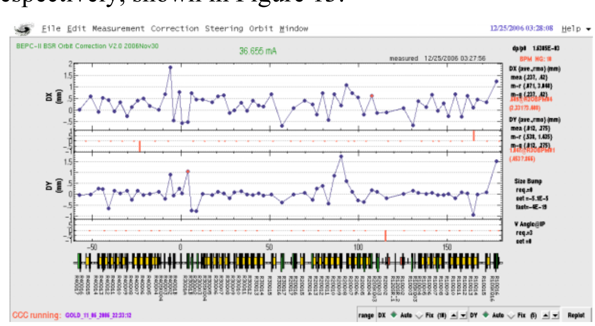

Figure 13: Residual orbit distortion after correction.

Twiss parameters were measured and compared to the designed values. The results are displayed in Fig. 14 and Fig. 15. It can be seen from Figure 14 that the measured β-functions agree to the designed values within about 5% after correction with response matrix method. Figure 15 shows that the measured dispersion agreed well with the design values within 0.1-0.2 m.

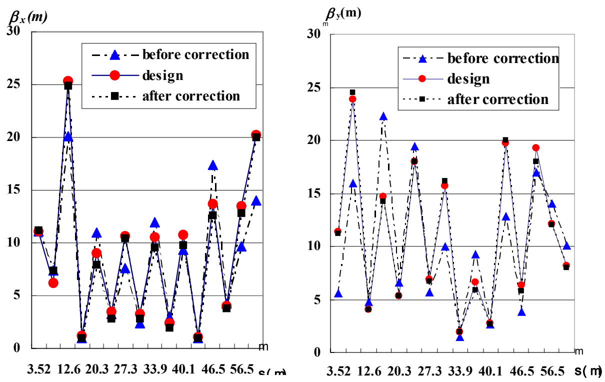

Figure 14: Measured and designed β-functions.

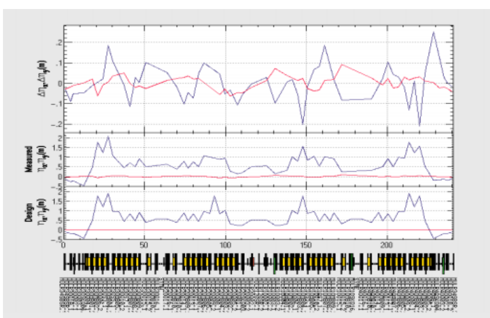

Figure 15: Measured and designed η-function.

Maximum beam current at 1.55 GeV and 1.89 GeV reached 250 mA with no limit indicated. By improving the vacuum pressure along with the accumulation of beam dose, beam lifetime increases smoothly. Figure 16 demonstrates how the SR cleaning improves vacuum pressure and then the beam lifetime. The beam lifetime gets to 7 hours at beam current of 80 mA when beam dose accumulated to 45 A·h.

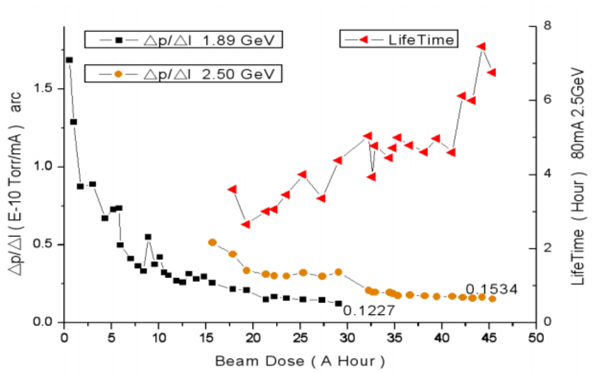

Figure 16: Vacuum and beam lifetime vs. beam dose.

The commissioning together with SR beam lines was carried out with local orbit adjustment. Beams have been provided for SR users since Dec. 25, 2006, when beam current was about 100 mA with a lifetime around 3 h at 2.5 GeV. Since then, the performance has been improving continuously. Now, the peak beam current reaches 150 mA at 2.5 GeV with a lifetime about 4 h and three fills a day. Fig. 17 displays beam current and lifetime in a day.

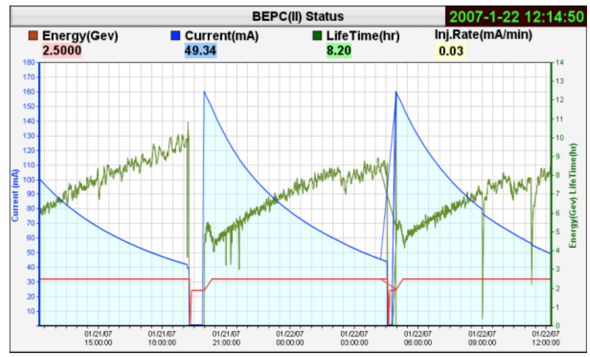

Figure 17: Beam current and lifetime in a day.

About 80 SR experiments were carried out by users with 9 beamlines. As an example, Figure 18 exhibits the protein sm424 in serine degradation pathway of the structural genome of streptococcus mutans during the recent BEPCII operation.

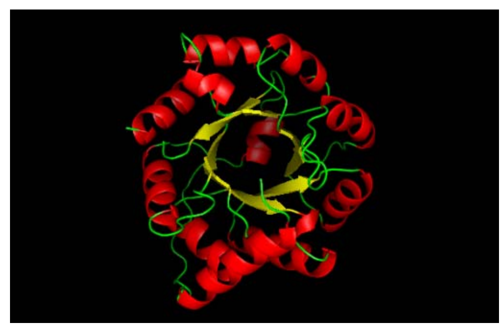

Figure 18: An example of the SR Users' experiments.

PLAN AND SCHEDULE

The first round SR operation will be ended on Feb. 1, 2007. Commissioning for the e- ring, the e+ ring and e+-e- collision will be followed. The second round SR operation of one month will be arranged in June. The SCQ's tested in the off-line position during the commissioning should be ready for installation in July. After the SCQ's are installed, the BEPCII commissioning will be continued. The information of the BESIII detector can be found in the reference [3]. It is expected that the luminosity would be high enough for the BESIII detector to start up by the end of 2007.

REFERENCES

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