CONSTRUCTION AND COMMISSIONING OF BEPCII

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Abstract

BEPCII is the major upgrade of BEPC (Beijing Electron-Positron Collider). It is a double ring e^+-e^- collider as well as a synchrotron radiation (SR) source, which consisted of the two outer half rings. As a collider, BEPCII operates in the beam energy region of 1-2.1GeV with design luminosity of 1×10^{33}cm^{-2}s^{-1} at 1.89 GeV. As a light source, the SR ring operates at 2.5GeV and 250 mA. Construction of the project started in the beginning of 2004. Installation of the storage ring components completed in October 2007. The BESIII detector was moved to the Interaction Region (IR) on May 6, 2008. In accordance to the progress of construction, the beam commissioning of BEPCII is carried out in 3 phases: Phase 1, with conventional magnets instead of superconducting insertion magnets (SIM's) in the IR; Phase 2, with SIM's in the IR; Phase 3, joint commissioning with the detector. The luminosity reached 2.3×10^{32}cm^{-2}s^{-1} at 1.84GeV. This paper summarizes the progress on the construction of BEPCII and its commissioning in 3 phases focusing on the third phase.

GENERAL DESCRIPTION

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

Table 1: The design goals of the BEPCII

Beam energy	1–2.1GEV
Optimum energy	1.89GEV
Luminosity	1×10^{33}cm^{-2}s^{-1} @1.89GeV
Linac injector	Full energy inj.: 1.55–1.89GeV Positron inj. rate ≥50 mA/min
Dedicated SR	250mA @ 2.5GeV

Serving as a collider, BEPCII operates 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 BEPCII aims at high luminosity. Luminosity of an e^+-e^- collider is expressed as

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

where $r=\sigma_y^*/\sigma_x^*$ is beam aspect ratio at interaction point (IP), ξ_y is vertical beam-beam parameter, β_y^* is vertical β-function at IP, k_b is bunch number in each beam and I_b is bunch current. The strategy for 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

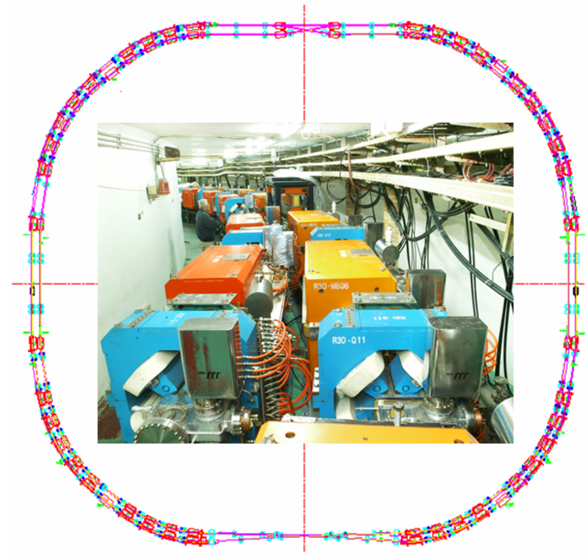

Figure 1: Layout and installed double-ring units.

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 2×11mrad to meet the requirement of sufficient separation but no significant degradation to luminosity. In the northern crossing region, two beams cross horizontally and a vertical bump is used to separate them. For the dedicated SR operation, electron beams circulate in the outer ring by means of a pair of horizontal bending coils in the SIM's while in the northern crossing a bypass is designed to connect two halves of the outer ring.

The milestones of 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 in the linac obtained
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Nov. 13, 2006	Phase 1 commissioning started
Nov. 18, 2006	First beam stored in the ring
Mar. 25, 2007	First e^+-e^- collision realized
Oct. 24, 2007	Phase 2 commissioning started
Jan. 29, 2008	Luminosity reached 1×10^{32}cm^{-2}s^{-1}
May 6, 2008	BESIII detector installed in the IR
June 22, 2008	Phase 3 commissioning started
July 19, 2008	First event detected with BESIII
April 12, 2009	Luminosity reached 2.3×10^{32}cm^{-2}s^{-1}
April 14, 2009	BESIII collected 100M ψ(2S) events

THE INJECTOR LINAC

The BEPC injector is a 202-meter e^--e^+ linac with 16 RF power sources and 56 S-band RF structures. BEPCII requires the injector in two aspects. One is the full energy of e^- and e^+ beams injection for the storage rings, i.e. $E_{inj} \geq$ 1.89 GeV; 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 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 RF phase drift due to various factors, an RF phasing system was developed.

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 2 shows the BEPCII linac injector.

Figure 2: 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 in beginning of December 2004. The commissioning of the linac for e^+ beam was carried out during machine studies. The first e^+ beam of 50mA was obtained at end of the linac on March 19, 2005. The performance of the linac is listed in Table 2, showing that its design specification is reached.

Table 2: 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^+	0.45	0.5
		e^-	0.5	0.5
Repetition rate	Hz		50	50
Pulse length	ns		1.0	1.0

THE STORGE RINGS

The BEPCII storage rings consist of three rings, i.e. the e^- ring (BER), the e^+ (BPR) ring and the SR ring (BSR). The e^- and e^+ rings are identical, while the SR ring takes two outer halves of the e^- and e^+ rings.

RF System

Two superconducting RF cavities are installed in BEPCII with one cavity in each ring，providing RF voltage of 1.5 MV. Each cavity is powered with a 250kW klystron. High power test gives the Q values of 5.4×10^8 and 9.6×10^8 at V_{rf}=2MV for the west and east cavities, higher than design values of 5×10^8 at 2MV. Figure 3 pictures a superconducting RF cavity under installation in the tunnel.

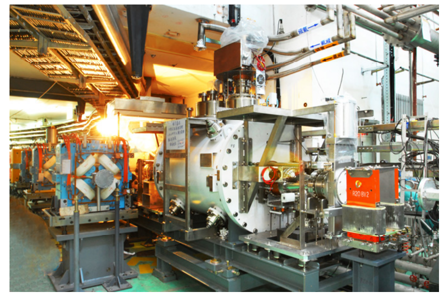

Figure 3: A superconducting RF cavity in installation.

Magnets and Power Supplies

BEPCII reuses 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, were produced. The magnets were measured with both rotating coils and stretch wires. The results are in agreement with each other within 10^{-3}.

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 current stability of the power supplies is better than 1×10^{-4}.

Injection Kickers

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

Vacuum System

BEPCII imposes two challenges to the vacuum system, one is vacuum pressure, and the other is 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.

IR and SC Insertion Magnets

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 (BEijing Spectrometer) detector co-exist in a crowded space. A special pair of superconducting insertion magnets, the SIM's, is placed in the IR. The SIM's and some special warm magnets in the IR such as septum bending magnets and two-in-one quadrupoles were installed in the IR in Oct. 2007. The BESIII detector was moved to the IR in May 2008, shown in Fig. 4.

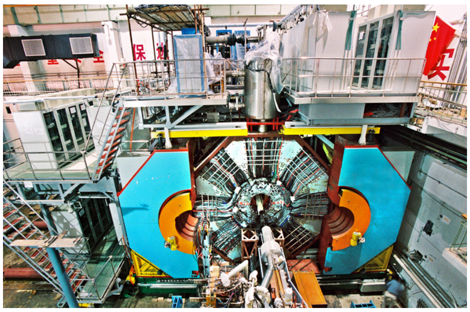

Figure 4: BEPCII interaction region and BESIII detector.

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.

Cryogenics System

The BEPCII cryogenics system is composed of four subsystems: a central cryogenic plant and three satellite cryogenic systems for the RF cavities, the SIM 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 system has been in operation since problems of the control Dewar, valve boxes and current leads for SIM's were solved in May 2007.

COMMISSIONING AND OPERATION

The phase 1 commissioning was from Nov. 13, 2006 to Aug. 3, 2007. In this phase, 100mA e^- by 100mA e^+ beam collision was achieved with β_y^*=5cm, while the estimated luminosity reached the level of BEPC. Two rounds of synchrotron radiation operation were arranged during that period. The beam performance and commissioning results were reported on the APAC07 [2] and PAC07[3].

After the SIM's and corresponding vacuum chambers were installed into the IR in the summer of 2007. The second phase commissioning was carried out from October 24, 2007 to March 28, 2008. The maximum beam current in each ring exceeded 550mA and the luminosity was estimated as higher than $1\times10^{32}cm^{-2}s^{-1}$ by a zero degree luminosity detector. In this phase, the dedicated SR mode was run for about one month, with peak beam current of 250mA. The beam performance and main commissioning was reported on the Factory08 workshop and EPAC08 [4].

The third phase commissioning [5] started out from June 22, 2008 after the detector was moved into the IR. Up to now, the beam current for each ring achieved was more than 700mA for BPR and 650mA for BER, respectively. The luminosity exceeded $1.0\times10^{32}cm^{-2}s^{-1}$ when the e^+ and e^- beam currents reached to about 350mA for collision in Sep. 2008. However, the luminosity did not increased proportionally when the beam currents got higher. The record luminosity achieved was $1.3\times10^{32}cm^{-2}s^{-1}$ by the end of 2008. A severe longitudinal oscillation was observed in BPR. A systematic study indicated that two reused screen monitors (SM) in BPR was suspected as the source for the instability. These two SM's were removed from BPR during the winter shutdown. Beam commissioning resumed on Feb. 1, 2009. Consequently, the longitudinal oscillation of positron beams was significantly reduced and luminosity was steadily improved with collision beam increase. From March 1, 2009, physics running at $\psi(2S)$ started and luminosity kept going up. The luminosity reached $2.3\times10^{32}cm^{-2}s^{-1}$.

Single Beam Performance

Orbit and optics correction

The closed orbit and optics correction was done based on the response matrix and its analysis using the LOCO (Linear Optics from Closed Orbits) method [6]. As the result, the measured beam optics functions are in good agreement with theoretical prediction with discrepancy within ±10% at most quadrupoles [7].

Detector solenoid compensation

After the detector moved into the IR in the 3rd phase commissioning, one key issue is to compensate the effect due to the Superconducting Solenoid Magnet (SSM) of the BESIII detector. To have perfect compensation, a scheme with three anti-solenoids (AS1~3) and a skew quadrupole was designed in the package of coils for the SIM. As a result, the measured coupling is less than 1% using tune split method. The only residual effect is additional focusing in both x and y planes. The strength of SCQ was reduced by 0.32% to compensate this effect and thus the β functions can be well restored as that without the SSM and ASM.

Injection

For beam injection, a two-kicker system is adopted. Thus the betatron phase advance between the two kickers is designed as π to form a local bump during injection. However, to reduce the residual orbit oscillation of the stored beam during injection, it's tricky to set the right timing and amplitude of the two kickers. This was done using the Libra BPM system. Thanks to the sameness between the waveforms of the two kickers, after the time delay and amplitude of the two kickers was optimized for the injecting bunch, the residual orbit oscillation of all the other bunches during injection can be reduced to around

0.1mm, corresponding to about $0.1\sigma_x$. This made it possible to inject beams during collision, as well as to get uniform filling of all buckets.

Beam current growth of BER and BPR

The growths of the beam current in the BER and BPR in the phase 3 commissioning are shown in Fig. 5 and the beam parameters achieved are listed in Table 3. However, during the phase 2 commissioning, a multipacting effect near the RF window of SC cavities (SCC) occurred when the beam current in both BER and BPR exceeded 100mA. Thus, a DC bias voltage was applied on the power coupler of the SC cavities to suppress it. This worked very effectively and the beam current of both rings could be improved steadily. Nevertheless, transverse feedback system has to be employed for smooth injection and stable operation at high beam current.

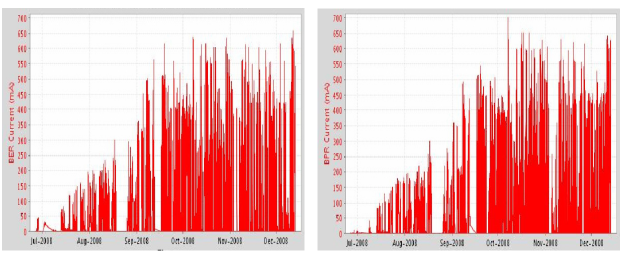

Figure 5: Current growth during the phase 3 commissioning in 2008, BER (left) and BPR (right).

Table 3: The main parameters of the BER and BPR

Parameters	Design	Achieved	
		BER	BPR
E (GeV)	1.89	1.89	1.89
I_{beam} (mA)	910	650	700
I_{bunch} (mA)	9.8	>10	>10
k_b	93	93	93
V_{RF} (MV)	1.5	1.6	1.6
ν_x/ν_y	6.54/5.59	6.54/5.61	6.54/5.61
ν_s	0.033	0.032	0.032
β_x^*/β_y^* (m)	1.0/0.015	1.0/0.016	1.0/0.016
Inj. rate (mA/min)	200(e^-) 50 (e^+)	>200	>50

Instabilities and feedback

The single bunch beam dynamics as well as collective effects are described in detail in Ref. [8]. An analog bunch-by-bunch transverse feedback (TFB) system has been adopted to cure the instabilities [9].

In transverse, coupled bunch instability was observed in both BER and BPR. In the BER, vertical sidebands near the RF frequency were observed on the spectrum analyzer. These may be due to resistive wall impedance. In the BPR, a broadband distribution of vertical sideband spectrum was observed, which can be attributed to the electron cloud instability (ECI). With carefully tuning of the TFB, the sidebands of couple bunch instabilities in both BER and BPR can be well suppressed.

Besides, streak camera was used to measure the bunch length, gated camera to measure vertical beam size blow up due to ECI, and no obvious grow up of the bunch size at the tail of the bunch train was observed. To prevent ECI, solenoids were winded on the vacuum chambers and can be put into use when needed.

In longitudinal, since SC cavities are used, the beam behaves fairly stable. However, synchrotron oscillation sideband was sometime observed along with beam current increase, so longitudinal feedback system is being developed.

Single-bunch Collision

Electron and positron beams in two rings were brought to collision at the IP by beam-beam scan. A luminosity monitor (LM) based on the detection of zero degree γ from radiative Bhabha process was installed. It can distinguish the luminosity bunch by bunch with a response fast enough to be used in the tuning procedure. Thus the beam parameters such as tune, coupling and local optics at IP were optimized to maximize the specific luminosity given by the LM.

The tunes for BER and BPR were set near (6.54, 5.61) after a tune scan. Optimization is also on the x-y coupling. This was done by adjusting the local vertical orbit in one sextupole in the arc. It is found that 1% coupling gives the best specific luminosity.

The local optical functions at the IP such as coupling and β_y waist were also adjusted with a set of quadupoles around the IP according to the luminosity.

With the above beam parameters optimized iteratively, the maximum bunch currents achieved in stable collision with high luminosity are 11mA×11mA, which is higher than the design of 9.8mA. However, the specific luminosity at high bunch current is low due to beam-beam blow-up, so there is still room for further optimization.

Multi-bunch Collision

Multi-bunch collision was practiced in two ways, one with relative high bunch current but small number of bunch, typically 7mA per bunch with 70 bunches, the other is with moderate bunch current, but 93 bunches as designed. At the same total beam current, it was expected that higher luminosity would be obtained in the former case. However, it was found that the luminosity for each pair of colliding bunches decreases along the bunch train, as shown in Fig. 6. Thus the luminosity does not increase proportional to the bunch number.

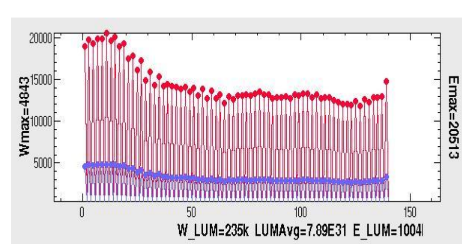

Figure 6: Luminosity profile along the bunch train.

Further studies on a long $e^+(e^-)$ bunch colliding with two short bunch trains in head and tail indicated that the problem was caused by e^+ beams. The transverse beam size did not increase observed by gated camera in single e^+ beam case. So it seems not caused by the electron cloud similar to other machines such as KEKB and PEPII.

It was observed from the streak camera that e^+ bunches are lengthened and more look like they are oscillating. Observation from oscilloscope confirmed this and the amplitude of oscillation increase along the bunch train, seen in Fig. 7.

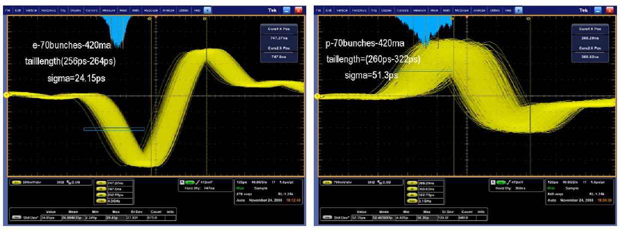

Figure 7: Longitudinal oscillation for bunch train tail. Left: e^- bunches Right : e^+ bunches

Then the possible sources could be HOM. There were two screen monitors temporarily used for the first turn injection of e^+ beams, became the most suspicious. It was found that there are gaps between flange and HOM can be trapped, as shown in Fig. 8.

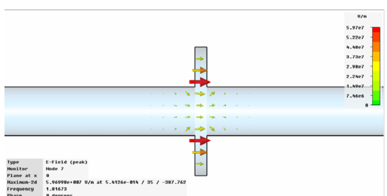

Figure 8: Trapped mode at a flange gap of the SM's.

From the impedance calculation, a mode with resonant frequency around 1.8GHz and shunt impedance of 80kΩ was found. Calculation shows that the field decay time is about 200ns which is shorter than the bunch train length and its frequency can be allayed to some of the longitudinal oscillation modes. It was decided to remove the SM's during the winter shutdown.

The commissioning resumed on Feb. 1, 2009. As expected, the longitudinal oscillation in the positron ring became much weaker and the amplitude gets same to that in electron ring, as shown in Fig. 9.

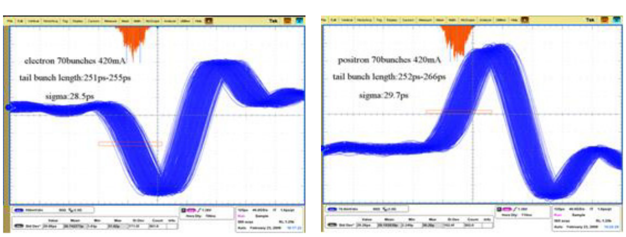

Figure 9: Longitudinal oscillation after the SM's removed. Left: e^- bunches Right : e^+ bunches

Correspondingly, the head to tail luminosity decrease mitigated as shown in Fig. 10.

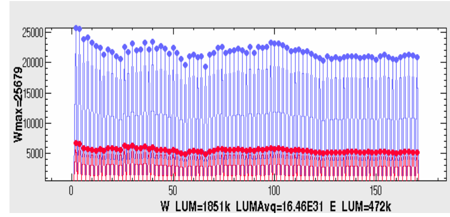

Figure 10: Display of Luminosity.

However, there are still some drops along the bunch train and the specific luminosity of multi-bunch case is still lower than that in single bunch with same bunch current. Systematic study on the longitudinal as well as transverse instability is underway.

Operation for High Energy Physics Experiment

The first round physics data taken was in last fall. Approximately 13M ψ(2S) events were obtained, which provided data for studies of the detector and its calibration. Second round data taking started on March 6, 2009, after a scan of the ψ(2S) peak. During this period, the machine commissioning was still went on, the peak luminosity of BEPCII increased steadily to $2.3\times10^{32}cm^{-1}s^{-2}$ with beam currents of 55 mA for both electrons and positrons. Till April 14, 2009, BESIII accumulated 100M ψ(2S) events which is the world's largest ψ(2S) data samples so far. After further commissioning, BEPCII and BESIII will turn to running at the J/ψ peak with the goal of collecting 270M J/ψ events in about one month. Figure 11 dysplays energy scan and event display for ψ(2S).

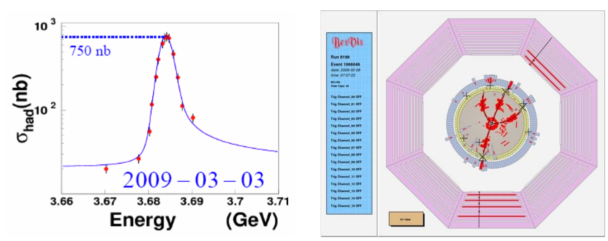

Figure 11: Energy scan and event display for ψ(2S).

Summary

The construction of BEPCII was completed; the commissioning has been carried out progressively and alternatively together with operations for both high energy physics and synchrotron radiation. However there are still a lot of issues for further studies, particularly to improve the specific luminosity at high beam currents.

REFERENCES

[1] BEPCII Group, BEPCII Design Report, Aug. 2001.
[2] C.Zhang et al, Proc. of APAC'07, India, Jan. 2007.
[3] J. Q. Wang et al, Proc. of PAC'07, U.S.A, July. 2007.
[4] J. Q. Wang et al, Proc. of EPAC'08, Italy, June. 2008.
[5] J. Q. Wang et al, ICFA BD newsletter, No. 48, 2009.
[6] J. Safranek et al, Proc. of EPAC'02, France, 2002.
[7] Y.Y.Wei et al, Proc. of Factories08, Russia, Apr. 2008.
[8] Q. Qin et al, Factories08, Russia, Apr. 2008.
[9] J.H. Yue et al, Factories08, Russia, Apr. 2008.