COMMISSIONING OF THE KEKB LINAC

Y. Ogawa, Linac Commissioning Group*
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305-0801 JAPAN

Abstract

The injector linac for the KEKB ring has been commissioned step by step since last autumn, while continuing the construction of the remaining parts as well as ordinary operation for beam injection into the Photon Factory. The commissioning has so far given quite satisfactory results: (1) A single-bunched beam with a charge of about 1.5 nC for direct injection into the ring was accelerated to the end of the linac (about 8 GeV). (2) A single-bunched beam with a charge of 6 nC for positron production was accelerated to a positron production target (3.3 GeV). Positron beams with a charge of about 0.5 nC have been successfully accelerated to the end of the linac (3.5 GeV) and transported to the beam line of the ring with a proper energy spread. (3) Various kinds of beam instrumentation have been employed and utilized for precise beam tuning and diagnosis.

1 INTRODUCTION

The construction of the KEKB linac [1] was completed on schedule at the beginning of May, 1998. The commissioning, which had been carried out step by step since October, 1997, has entered a full-commissioning phase at this moment so that two design beams for the KEKB ring could be realized: full acceleration of an electron beam (about 8.0 GeV) as well as the production of a large quantity of positrons and their acceleration (3.5 GeV).

The layout of the linac is shown in Fig. 1, comprising two parts: a newly constructed part (sectors A, B, C and J arc) and an upgraded part (sectors 1-5 and a beam switchyard). A beam starting from an electron gun passes two subharmonic bunchers (SHB1: 114.24 MHz and SHB2: 571.2 MHz) and an S-band bunching section (2856 MHz) to accomplish a single-bunched beam with a bunch width of about 10 ps (FWHM). After acceleration to the end of sector B (1.5 GeV), it enters into the J arc section, in which achromatic and isochronous conditions are fulfilled. It is then re-accelerated either to the end of the linac (8.0 GeV) or to the positron production target (3.3 GeV), depending on the operation mode. The 8-GeV electron beam is directly transported into the ring, while the produced positron beam is accelerated to the end of the linac (3.5 GeV) and passes into the ring injection line after an energy-compression system (ECS) located at the beam switchyard. In the case of positrons, the primary electrons also pass through a bunch-compression system (BCS) just before the target to decrease the bunch width so that a positron bunch-lengthening effect in the solenoids after the target can be partially compensated, realizing an appropriate bunch width for a positron energy spread.

Two operation modes (8-GeV, 1.2-nC electrons and 3.5-GeV, 0.64-nC positrons) have thus been almost established, realizing the designed beam characteristics.

For efficient commissioning, we have organized for the first time a linac-commissioning group comprising both members of the linac and the KEKB ring. We believe that it has made a great success in that linac beam parameters required for ring injection are being intensively pursued while sharing common commissioning experiences.

2 OUTLINE OF THE COMMISSIONING

Fig. 2 shows the results of commissioning concerning the beam positions and intensity in two operation modes of the KEKB linac: an 8-GeV electron beam and a 3.5-GeV positron beam. In the following sections, the beam-tuning process is discussed along with the beam flow of the linac.

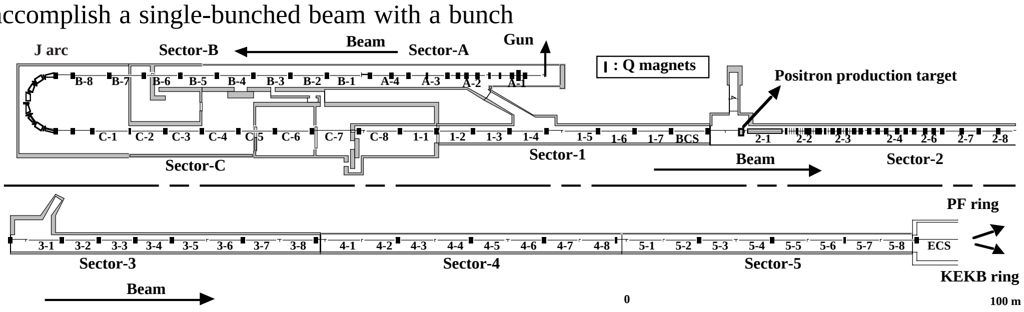

Figure 1: Layout of the KEKB linac. Sectors A, B, C and J-arc are newly constructed.

* N. Akasaka, A. Enomoto, J. Flanagan, H. Fukuma, Y. Funakoshi, K. Furukawa, T. Ieiri, N. Iida, T. Kamitani, T. Kawamoto, M. Kikuchi, H. Koiso, T. T. Nakamura, Y. Ogawa, S. Ohsawa, K. Oide, K. Satoh, M. Suetake, T. Suwada

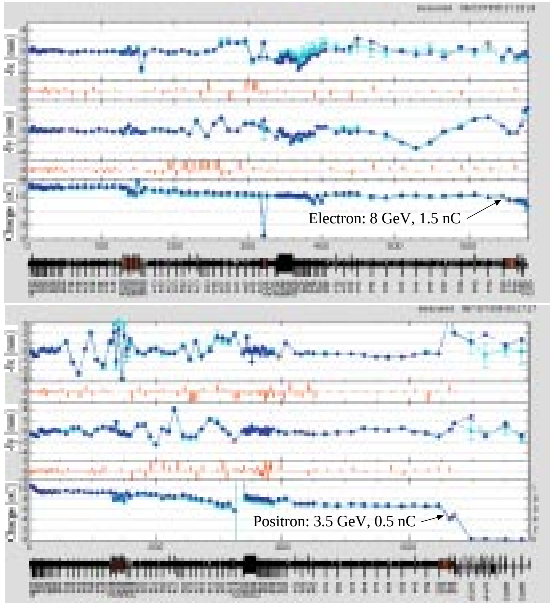

Figure 2: Two design beams have been achieved at the end of the linac: 8-GeV, 1.5-nC electron and 3.5 GeV, 0.5-nC positron beams.

2.1 Electron Gun and Its Orbit Measurement

The electron gun emits a beam with an energy of 200 keV and a pulse width of 2-3 ns (FW). The beam is immediately injected into the bunching section to form a single bunch in the S-band structure. Since the beam is still non-relativistic in this region, a solenoid-type focusing system is employed against strong space-charge forces among particles. It sometimes happens, however, that if a beam having even a slight inclination to the solenoid field axis is injected into this region, the central orbit may rotate in the magnetic field, causing an emittance growth. In order to prevent this kind of beam degradation, we not only checked the transverse components of the magnetic field, but also improved the alignment of the electron gun. As a result, the beam-orbit rotation is considerably minimized and the beam profile along the region becomes quite improved.

2.2 Tuning of Bunching Section

Tuning of the bunching section [2] has been carried out mainly by observing a bunch monitor with a streak camera (see Section 3.2) located at the end of the section. With proper powers fed into two SHB cavities, an S-band prebuncher and a buncher, as well as by precise tuning of the corresponding rf-phases, we succeeded to establish a single-bunched beam without any satellites. The bunch widths obtained in the 1.5-nC beam and the 10-nC primary beam for positron production are about 10 ps.

The energy spectrum is also measured at an energy-analyzing station at an energy of about 70 MeV, giving an energy spread of about 9% (FW).

2.3 Acceleration in Sectors A and B

In sectors A and B, the energy must reach the J-arc design energy of 1.5 GeV, which is realized by using 10 accelerator units with a margin of one unit. The last two units are used as a knob for adjusting the energy in a cross-phase configuration so as to compensate for any energy spread due to the slope of the sine function. In a high-current acceleration mode, the acceleration phase for the rest of units is set at an off-crest angle of about 15 degrees in order to minimize the energy spread, satisfying the J-arc energy acceptance of 2.8% (FW=4σ).

Beam transmission from the end of the bunching section to that of sector B is quite good, accomplishing almost 100% without any significant loss. It has been anticipated, however, that some problems related to wake-field effects might emerge for an intense primary electron beam with a charge of 10 nC. In fact, we sometimes observed some peculiar phenomena concerning beam profiles in high-current beam acceleration, while in beam acceleration with a small charge of 1.5 nC we found no such problems. Details concerning these items are discussed in Section 4.

2.4 Tuning of the J-arc Section

The J-arc section is designed to be achromatic and isochronous [3]. The achromaticity condition is fulfilled in the following manner:

- Measure the dispersion at all beam-position monitors (BPM: see Section 3.1) along the J-arc by changing the energy using the energy knob.
- Calculate the strengths of the quadrupole magnets so as to simulate the observed dispersion and obtain ratios to the set values.
- Set the strengths of the quadrupole magnets at the values calculated from the inverse ratios to the set values.
- Measure again the dispersion and iterate the process.

For the isochronicity condition, the same procedure is taken, except for the first step, which is replaced by:

- Measure the time delay with a streak camera system (see Section 3.2) at the end of the J-arc by changing the energy using the energy knob.

In achromaticity corrections, second-order effects are also cured by adjusting the strengths of the sextupole magnets.

The central energy in the J-arc is maintained at 1.5 GeV by introducing an energy feedback loop utilizing the energy knob. As mentioned in the previous section, we sometimes observed interesting phenomena related to a degradation of the beam quality, which made the beam transmission in the J-arc quite low. The cures obtained by using local bumps and adjusting the acceleration phases at sectors A and B were successfully tried, and are described in Section 4.

2.5 Acceleration in Sectors C and 1

In the midst of sectors C and 1, the newly constructed part and the upgraded part were joined together during the last week of March, 1998. In order to successfully make the prompt connection without causing any disturbances to the ordinary operation for the Photon Factory, we had prepared a temporary pre-injector comprising an electron gun and a bunching section at the first section of sector 1. Although two independent accelerators have been successfully connected without any obstacles, the short period for a connection has not allowed a satisfying alignment of the accelerator components. In fact, the beam losses in this region, which are suspected to be due to a misalignment, have so far not been avoided. A re-alignment of the linac is planned for this summer.

The largest amount of charge obtained for positron production was about 6 nC at the target, not reaching the design value of 10 nC. We expect a considerable improvement after a re-alignment.

2.6 Tuning of Primary Electrons at a e^+ Target

Primary electrons for positron production pass through BCS just before the target so as to partially compensate the bunch lengthening of positrons occurring in the following solenoids. The acceleration phases at sectors C and 1 are set at an off-crest angle of about 30 degrees, making the phase-space orientation for BCS. Although BCS worked quite well, fine-tuning will be carried out in the autumn.

Since the positron yield strongly depends upon the beam profile at the target, the beam waist was surveyed by changing the optics before the target. The minimum radius of the beam size was estimated to be around 1 mm, obtaining a maximum positron production.

2.7 Acceleration in Sectors 1-5

Acceleration in this region has proceeded without any problems for electron and positron beams. The beam characteristics have been measured for both beams at the end of sector 5, giving the quite satisfying results reported in Section 5.

2.8 ECS for e^+ beam

The energy acceptance required for the positron injection line to the KEKB ring is 0.5% (FW). In order to achieve this value, the positron beam is passed through ECS at the end of linac. An energy-compression ratio of about 0.5 was obtained: an energy spread of 1.7% (FW) became 0.8% (FW) after ECS. According to an analysis of the data (Fig. 3), it turns out that almost 90% of the positrons fall in the energy acceptance of the injection line. The remaining slight difference relative to the design value will be expected to be eliminated by fine tuning of the acceleration phases as well as that of BCS.

After passing through ECS, a positron beam with a charge of about 0.4 nC was successfully transported to the temporary beam dump in the midst of the injection line. Although the beam-loss monitors installed along the injection line showed an allowed level of radiation in this time of operation (5 pps), it turns out that for the full-injection mode (50 pps), the radiation level must be reduced by almost one half. This reduction will also be expected to be achieved with a proper tuning of the linac and the beam-transport line.

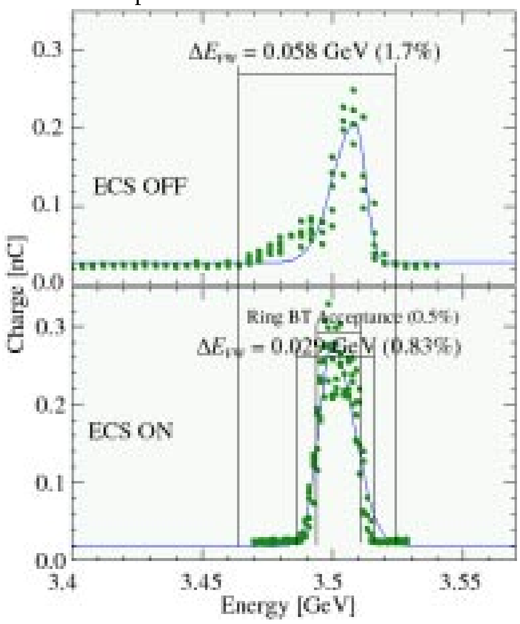

Figure 3: Energy spread of positron beams compressed into a half width by the ECS located at the end of linac, reaching almost the energy acceptance of the ring injection line.

3 BEAM INSTRUMENTATION

3.1 BPM Calibration

BPMs [4] installed in all quadrupole magnets have been quite efficient tools for beam diagnosis in the commissioning. We have performed several kinds of BPM calibrations using a beam: measurements of the position resolutions and offsets as well as estimations of the calibration factors by employing a recalibration method [5]. The obtained results are summarized in Table 1.

3.2 Bunch Monitor with a Streak-Camera System

Another important progress in beam diagnosis was the introduction of new streak-camera systems [6] for observing a bunch structure. Three systems (at the end of sector A and the J-arc, and just after the positron target) have been installed, while another one is being prepared at the end of the linac. One of the main features in the new system is an integration of hardware and software; all of the necessary steps to observe streak-signals are integrated, and the handling becomes quite simplified. Detailed descriptions can be found in the reference.

3.3 Test of Wire Scanner

As non-destructive beam-profile monitors, wire scanners have been tested concerning several aspects: a detection scheme and its configuration as well as a radiation-shield method. The results indicate that with a suitable configuration of the detector, wire scanners give a sufficient signal-to-noise ratio against a strong radiation environment. We are planning to install three sets (each comprising three or four wire scanners positioned at proper distances) at the end of sector B, J-arc and the linac, respectively, so that the twiss parameters can be calculated in nearly real-time using signals from three or four wire scanners at the same time. Details are to be presented elsewhere [7].

3.4 Wall Current Monitor: Charge Calibration

Although the quantity of charge is one of the key parameters, the calibration is not a simple task, especially in the case of a very short pulse, like a single-bunch beam (10 ps) in the S-band linac. We employed two methods: a relative calibration utilizing a signal from the beam-induced field observed at the end of accelerator section as well as an absolute one using a Faraday cup installed in the straight branch line at the entrance of the J-arc. Details will be presented elsewhere.

4 FINE TUNING OF INTENSE BEAM

4.1 Acceleration-Phase Tuning

The acceleration phase for an intense beam has been set at an off-crest angle of about 15 degrees in sectors A and B for achieving an energy acceptance of the J-arc (Section 2.3). On the other hand, it has been about 30 degrees off-crest in sectors C and 1 for BCS (Section 2.6). The maximum beam transmission in these regions, however, was obtained by even a finer adjustment of the acceleration phases in sectors A and B, so that they were slightly shifted in the inverse direction relative to each other. In this way, the beam profiles in the J-arc were greatly improved, suggesting the existence of transverse wake-field effects, which are clearly shown in the next section. A detailed analysis will be carried out during the next commissioning period.

4.2 Orbit Tuning

Local bumps have been introduced somewhere in sectors A and B, depending upon the beam state to improve the beam transmission in the J-arc and sector C. In calculations of a bump, dipole transverse wake-field effects are taken into account so that the bump can be closed. The bump, however, sometimes failed to close the orbit, possibly because quadrupole wake-field effects emerged when the beam profile-deformation was large. Incorporating quadrupole wake-field effects in bump calculations might be necessary during the next opportunity.

4.3 Method of Downhill Simplex

Since the beam intensity at a certain point of the linac depends upon many parameters upstream, it may happen that searching the optimum combination of parameters would be practically difficult. We tried the method of downhill simplex [8] for obtaining the maximum positron yield by changing the strength of a few upstream steering coils together with some acceleration phases. The results suggest that this kind of method could be useful in some cases. A more elaborate application of the method will be introduced in the future.

5 BEAM CHARACTERISTICS

The beam characteristics obtained during the commissioning are listed in Table I, compared with the designed target values. As far as the beam intensity at the end of linac is concerned, the target values have been nearly realized for electron and positron beams, though a slight increase of positrons may be required. The single-bunch purity is practically 100%, while the bunch length is not in agreement with the design value, which does not seem to be a serious problem. The emittance growth observed in sectors A and B for an intense beam might be reduced by the effective use of local bumps or the method of downhill simplex. The energy margin for ring injection is rather poor at this time of commissioning, but can be considerably improved during the next commissioning period. The energy spread of both beams falls at almost the energy acceptance of the injection line.

6 CONCLUSIONS

The first commissioning of the KEKB linac was successfully completed, reaching two major goals: 8-GeV acceleration of electron beams and 3.5-GeV acceleration of positron beams with sufficient quantity and quality. High-quality hardware completion of the machine was also verified and confirmed through commissioning, satisfying the beam characteristics required for the KEKB ring.

7 ACKNOWLEDGEMENTS

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Table I: Evaluation/Score of the KEKB Linac Commissioning

Beam Type	Electron Beam : 1.2 nC			Primary Electron Beam : 10 nC @ Target Positron Beam : 0.64 nC		
	Target Value	Achieved Value	Score	Target Value	Achieved Value	Score
Beam @ Gun						
Charge[*1]	1.5 nC	2 nC	A	13 nC	~ 14 nC	A
Pulse Width (FW)	2.0 ns	1.8 ns	A	2.0 ns	2.8 ns	B
Beam @ A1						
Charge[*1]	1.4 nC	1.9 nC	A	> 10 nC	11 nC	A
Satellite Bunch	< 2 %	0 %	A	< 2 %	~ 0 %	A
Bunch Width (FWHM)	5 ps	10 ps	B	16 ps	11 ps	A
Beam @ B8						
Charge[*1]	1.2 nC	~ 1.8 nC	A	> 10 nC	~ 9.5 nC	A
Transmission (A1-B8)	100 %	~ 95 %	A	100 %	~ 86 %	A
Energy	1.5 GeV	1.5 (Max 1.8) GeV	A	1.5 GeV	1.5 (Max 1.8) GeV	A
Energy Spread ($\pm 2\sigma$)	±1.4 %	±0.58 %	A	±1.4 %	±0.75 %	A
Energy Stability (p-p)	< 0.2 %			< 0.2 %	fast 0.1 %	A
After Feedback					drift< 0.2 %/h	A
Beam @ C1						
Charge[*1]	1.2 nC	~ 1.8 nC	A	> 10 nC	~ 9.0 nC	A
Transmission (J-Arc)	100 %	~ 100 %	A	100 %	~ 95 %	A
Bunch Width (FWHM)				16 ps	18 ps	C
Beam @ e^+ Target						
Charge[*1]				> 10 nC	~ 6.0 nC	C
Transmission (C1-17)				100 %	~ 67 %	C
Transmission (A1-17)				100 %	~ 57 %	C
Energy				3.5 GeV	3.3 GeV	B
Beam @ 21_45						
Charge[*1]				(e^+) >2 nC	~ 1.5 nC	A
e+ Conversion (/GeV)					~ 7.6 %/GeV	
Beam @ 23_43						
Charge[*1]	(e^-)	1.6 nC		(e^+) > 0.6 nC	~ 0.8 nC	A
Transmission (21-23)				30 %	~ 53 %	A
Beam @ 58						
Charge[*1]	1.2 nC	1.5 nC	A	(e^+) > 0.6 nC	~ 0.7 nC	A
Transmission (23-58)	(e^-) 100 %	94 %	A	100 %	~ 88 %	A
Transmission (A1-58)	(e^-) 100 %	79 %	B			
Transmission (21-58)					~ 47 %	A
e+ Conversion (/GeV)				~ 1.8 %/GeV	~ 3.5 %/GeV	A
Energy	(e^-) 8.0+0.8 GeV	8.0+0GeV	A	3.5 GeV	3.5 GeV	A
Energy Spread (FW)					±0.8 %	
Beam @ ECS						
Charge[*1]				(e^+) > 0.6 nC	~ 0.5 nC	B
Transmission (ECS)				80 %	~ 70 %	A
Energy				3.5 GeV	3.5 GeV	A
Energy Spread (FW)				±0.25 %	±0.4 %	B
Norm. Emittance (B_{mag})						
Injector $x(\times 10^{-6})$	60 m	71 (1.2) m	A	60 m	89 (1.0) m	A
$y(\times 10^{-6})$	60 m	66 (1.2) m	A	60 m	120 (1.1) m	B
B8 $x(\times 10^{-6})$	< 1600 m	230 (1.6) m	A	< 1600 m	770 (1.3) m	A
$y(\times 10^{-6})$	< 750 m	500 (1.8) m	A	< 750 m	760 (1.5) m	B
C1 $x(\times 10^{-6})$					800 (1.6) m	
$y(\times 10^{-6})$					820 (1.2) m	
23 $x(\times 10^{-6})$				(e^+)	5600 (6.5) m	
$y(\times 10^{-6})$				(e^+)	6600 (16) m	
57 $x(\times 10^{-6})$	1100 m			(e^+) 1600 m	2000 (1.3) m	B
$y(\times 10^{-6})$	1100 m			(e^+) 1600 m	2300 (1.6) m	B
Orbit						
Deviation(rms) Δx	< 0.1 mm	< 0.1 mm	A	< 0.1 mm	0.3 mm	B
Δy	< 0.1 mm	< 0.1 mm		< 0.1 mm	0.3 mm	B
Variation Δx	< 0.1 mm	< 0.1 mm	A	< 0.1 mm	±0.2 mm	B
Δy	< 0.1 mm	< 0.1 mm		< 0.1 mm	±0.2 mm	B
BPM						
Resolution	< 0.1 mm			< 0.1 mm	~ 0.1 mm	A
Offset[*2]	< 0.1 mm			< 0.1 mm	0.1~0.2 mm	A
Repetition Rate	50 pps	5 pps		50 pps	5 pps	

[*1]Under calibration, [*2]Calibrated

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