TOWARDS RELIABLE ACCELERATION OF HIGH-ENERGY AND HIGH-INTENSITY ELECTRON BEAMS

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Abstract

The KEK electron linac was upgraded to 8 GeV for the KEK B-Factory (KEKB) project. During commissioning of the upgraded linac, even while continuing SOR ring injections, we had achieved a primary electron beam with 10-nC (6.24×10^{10}) per bunch up to 3.7-GeV for positron generation. This could be classified as one of the brightest S-band linac's.

Since the KEKB rings were completed in December 1998, those 3.5-GeV positron and 8-GeV electron beams have been injected with excellent performance. Moreover, we have succeeded in switching among the high-intensity beams for KEKB and beams for two SOR rings with sufficient reproducibility.

After commissioning of the KEKB ring started, we launched a project to stabilize the intensity and quality of the high-current beams furthermore, and have accomplished it while investigating every conceivable aspect.

1 INTRODUCTION

The KEK B-factory (KEKB) project started in 1994 to study CP-violation in B-meson decays with an asymmetric electron-positron collider. The performance of the experiment depends on the integrated luminosity of KEKB, and hence the beam injection efficiency from the injector linac.

In order to achieve efficient full-energy injection, the original 2.5-GeV electron linac was upgraded up to 8 GeV, while enforcing the acceleration gradient by a factor of 2.5 and by extending the length of the facility by about 40%. Because of the site limit, two linac's with 1.7-GeV and 6.3-GeV were combined using a 180-degree bending magnet system to form a J-shape linac. Also the primary electron beam was designed to be 10 nC per bunch to produce 3.5-GeV positrons with 0.64 nC.

The upgraded electron/positron linac has been commissioned since the end of 1997, even while continuing injection to the Photon Factory (PF). We had overcome many practical difficulties, and had already achieved most of the designed beam parameters[1, 2].

However, to pursue the capability of the linac and KEKB to its utmost limit, we still continue to improve the quality of the beams.

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2 COMMISSIONING

The commissioning started at the end of 1997 using the first part of the linac just before completion of the upgraded linac. In order to carry it, a task force called the linac commissioning group was formed, in which 7 persons from the linac and 12 persons from the ring participated. This group later became a part of the whole KEKB accelerator commissioning group.

The beam was operated at the linac local control room at the beginning. After completion of the KEKB rings the operation rooms for the linac and the ring were merged with some computer network and video switch preparations. Part of the operation log-book has been recorded electronically to facilitate communication between local engineers and remote operators.

3 STABILITY AND RELIABILITY

After commissioning of the KEKB ring started, we realized that it was necessary to manipulate the beam delicately and continuously in order to maintain the quality of the high-intensity beams for a long term without degrading the injection performance. Thus, we have launched a project to stabilize the intensity and quality of the high-current beams.

3.1 High-Current Beam

At the beginning of the commissioning it was necessary to make much effort to transport a 10-nC electron beam on to the positron generation target. It was often difficult to maintain the beam for more than one hour. Otherwise, local bumps had to be made to cure beam instabilities, which were caused by a fluctuation of the accelerator equipment and transverse wake-fields.

Such difficulties, however, were gradually resolved after understanding the sources of the instabilities through careful beam studies, as surveillance systems were installed for rf systems and other equipment[4]. Since the commissioning had started before completing the whole linac, some part of the accelerator equipment was not operated at the optimum condition. The largest contributions to the instabilities came from many parameters in the pre-injector section[3].

Thus, we had realized that it was important to study the tolerances of beams to each parameter. Table 1 shows some of those results.

Table 1: Tolerances of a 10-nC beam

Parameter	Tolerance
Gun high voltage	± 0.38 %
Gun timing	± 45. ps
SHB1 (114MHz) phase	± 1.1 deg.
SHB2 (571MHz) phase	± 1.3 deg.
Buncher phase	± 1.7 deg.
Buncher power	± 0.47 %
Sub-booster-A phase	± 3.5 deg.
Sub-booster-B phase	± 4.0 deg.

These tolerance values were obtained to keep 90% of the maximum beam current at the positron production target by changing only one parameter around a good set of parameters. Software to find a correlation was used in order to acquire these data[5].

For a long, term each parameter may drift independently. If the room temperature changes, most parameters may correlate with it. Thus, while the above tolerance values are good references to consider the beam stability, the parameters of the equipment have to be kept within much better limits.

In order to stabilize the equipment parameters following the above guidelines, stabilization software, which will be described later, was implemented as well as hardware improvements.

After such a challenging effort, we achieved a primary electron beam with 10-nC (6.24×10^{10}) per bunch up to 3.7-GeV for positron generation, without any loss at the 180-degree bending system. This could be classified as one of the brightest S-band linac's.

3.2 Four Beam Modes

It was anticipated that it might degrade the performance of the linac to switch beams between four injection modes. After a high-current beam was achieved, we sometimes found that the beam parameters were not optimal. Actually, the beam parameters in the four beam modes are quite different, as shown in Table 2.

Table 2: Beam Modes of the Linac

	KEKB		PF	PF-AR
	HER	LER		
Energy	8 GeV	3.5 GeV	2.5 GeV	2.5 GeV
Particle	e^-	e^+	e^-	e^-
Charge	1.28 nC	0.64 nC (10 nC)[1]	0.2 nC	0.2 nC
Repetition	50 Hz	50 Hz	25 Hz	25 Hz
Refill				
Time	1-2 min.	5-10 min.	3-5 min.	3-5 min.
Interval	1 - 2 hr.	1 - 2 hr.	24 hr.	2 - 4 hr.

The major challenging issues here were reproducibility of the beams in one of four modes, the reliability of switching and the switching speed to improve the integrated luminosity.

In this area, software to switch the beam modes had been developed since the beginning of the commissioning. In order to accomplish the above tasks, the software was refined, especially in the magnet initialization for the reproducibility and in recovery of the equipment failures for the reliability. It can even be re-configured easily in several aspects by an operator. The details are described elsewhere[6].

Using this enhanced software, the loss time caused by beam mode switching was made negligible, and the beams became well reproduced over frequent mode switches. The switching time for the KEKB modes became 90 to 120 seconds, which is acceptable. Thus, it is not a major issue at the linac any more.

There are several plans for experiments that use high-energy electrons in the linac. An example is the slow positron facility for solid-state and particle physics[7]. While the priorities of these experiments are currently low, new beam modes for them may be added to the routine operation if it is possible to solve new switching issues.

3.3 Beam Feedback Loops

Even with the efforts on beam stabilization and reliable beam mode switching, it was sometimes necessary to tune the equipment parameters delicately in order to maintain some beam parameters in the long term. Only some experts could tune the beam and it took some time.

Simple feedback loops to limit energy fluctuations of the beams had been installed since the beginning of the commissioning[8]. Also the same software was applied to stabilize equipment parameters, as already described above. It was also applied to stabilize the beam orbits. More than 30 feedback loops have been installed and are working depending on the beam modes. The details are described elsewhere[6].

These feedback loops have improved short-term linac stability, and have cured long-term drifts as well.

3.4 Beam Optics

In order to reproduce the beam well under different conditions, the beam optics along the linac must be understood well. We have investigated several aspects to find any discrepancy between the design and the real optics.

In order to measure the beam emittance well, both the Q-magnet-scan method and wire scanners have been used depending on the locations. The errors in energy gain evaluations along the linac were not small, unfortunately. We are trying to refine it using a gain derived from the rf measurement, beam energy measurement by an analyzer magnet and a longitudinal wake-field estimation.

[1] 3.7-GeV primary electron beam.

Using such beam information, software systems were developed to match the beam optics at the fixed energy[9] and to re-match the optics after a rf-power reconfiguration[10]. They are used daily, although it does not cover the whole linac yet, since we have several matching points along the linac.

The effect of the transverse wake-field is not small, especially with high-intensity beams, and it degrades the beam emittance and the stability. Evaluation and reduction of the wake-field effects have been tried with some success[11]. Quadrupole wake-field effects were also observed for the first time[12].

4 OPERATION STATISTICS

With the help of the above-mentioned improvement, the linac operation has become fairly reliable. The total operation time in FY 1999 was 7296 hours, which was greatly increased owing to full KEKB operation[1]. The availability of the linac for injection was 99.0%, which have been much improved.

The average intensity of the positron in spring 2000 was 0.62 nC, which is just less than the safety limit at the beam-transport line.

5 MORE CHALLENGES

5.1 Discharge in Accelerator Structures

The discharge in the accelerator structures at sections A1 (buncher and the first normal structure) and 21 (positron generator) became severe in March, 2000, where the beam charge (and loss) is high and is surrounded by solenoid coils. It was found that the discharge frequently occurred near the trailing edge of the rf pulses.

Thus, the wave guides at these sections were re-arranged to shorten the pulse width, and the rf-power was optimized to the improved beams with lower voltage. Then, such a discharge decreased the rate to less than once a day.

Since it is important to understand the phenomena deeply, a test stand for such stations was built for investigating discharge phenomena as well as for the conditioning of accelerator structures.

5.2 Two Bunch Acceleration

In order to double the positron beam charge, it is considered to have two bunches in a linac rf pulse. Because of the rf synchronization scheme between the linac and the ring, those bunches have to be separated by 96 ns at minimum[2].

A preliminary study was made on this two-bunch scheme, which produced promising results on the energy compensation of the second bunch with a careful rf-pulse timing control. The energy difference was estimated to be 2.5% for the 8-nC beam comparing the longitudinal wake-field with the one for a low-intensity beam. Devices for this scheme are under preparation.

[2] 275th bucket in the linac and 49th bucket in the ring

6 CONCLUSIONS

In commissioning of the KEKB injector linac we have overcome challenging issues and have accomplished a stabilization project, investigating every conceivable aspect. The linac is providing fairly stable beams with very high availability.

During normal operation, operators rarely change the beam parameters. Instead, software for beam-mode switching and feedback loops takes care of them. Since the charge limit at the beam-transport line induced by the safety reasons will be removed soon, the performance of the linac may be more enhanced.

Throughout this improvement, we obtained valuable experiences on tolerance studies and stabilization technique of the timing and rf systems, especially at the buncher section. We also gained knowledge concerning the physical phenomena of the beams particularly of an emittance growth. They are indispensable for the design and construction of the next-generation accelerators, such as a linear collider, an FEL and an injector for super-high-luminosity machines.

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