OPERATIONAL PERFORMANCE OF POSITRON PRODUCTION FROM TRUNGSTEN SINGLE-CRYSTAL TARGET AT THE KEKB INJECTOR LINAC

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Abstract

A new tungsten single-crystal target has been applied for positron production at the positron source of the injector linac at the KEK B-factory (KEKB); this experiment was carried out from September 2006 to June 2007 (~10 months). Systematic studies were carried out on the positron production efficiency (PPE) using tungsten crystals of various thicknesses, and using 4- and 8-GeV electron beams at the test beamline, during the period 2000–2005. Finally, the thickness of the tungsten crystal was optimized at 4 GeV, and a target fabrication technique and a crystal-axis alignment technique were developed in 2006. Subsequently, the tungsten crystal target was installed at the KEKB positron source without making any significant modifications to the positron source. During this period, data on the positron production, particularly, the PPEs and stabilities of the primary electron and positron beams, were obtained. In this report, the long-term operational performance of positron production with a tungsten crystal target at the KEKB positron source is presented.

INTRODUCTION

In order to enhance the luminosity in the KEKB colliding experiment, the conventional tungsten target at the positron source of the KEKB injector linac was replaced with a tungsten single-crystal target in September 2006 [1].

The use of a crystal-assisted positron source for improving the PPE was first proposed by Chehab, *et al.* in 1989 [2]. This approach is beneficial as it improves the PPE and reduces the heat load on the crystal target as well. When high-energy electrons impinge on such a single crystal in the direction of the crystal axis, intense low-energy photons are produced owing to channelling radiation and coherent bremsstrahlung. These intense photons may generate a large number of e^+e^- pairs in the same crystal target. Hence, a larger number of positrons is expected to be produced from a crystal target than from the conventional heavy-metal target.

Our approach to using a tungsten single-crystal target for positron production is similar to that proposed by Chehab. In our approach, the 14-mm-thick ($4X_0$) tungsten plate used earlier, was replaced by a 10.5-mm-thick tungsten crystal, which has a transverse size of 5×5 mm^2 and a <111> crystal axis, without any significant modification of the accelerator layout. On the basis of previous systematic measurements, it was determined that maximum PPE could be achieved with a 10.5-mm-thick tungsten crystal at 4 GeV [3].

Impingement of a 4-GeV primary electron beam on the crystal target in the direction of the crystal axis resulted in a 25% increase in the positron yield and a 20% decrease in steady-state heat load on the crystal target when compared to those observed when using the tungsten plate [1]. On the basis of these observations, a tungsten crystal target was used at the KEKB for generating intense positron beams. Further, the positron intensity obtained using this tungsten crystal target was the highest among the positron intensities observed at the KEKB since the commencement of its operation in 1999.

The tungsten crystal target was used in positron production for ~10 months following its installation at the KEKB. This long-term operation may provide useful information regarding radiation damage of the crystal target and the stability of the positron beams.

THE KEKB POSITRON SOURCE

The KEKB positron source comprises a positron production target and a positron capture section. The target is composed of a tungsten single crystal, and the capture section is employed as a so-called quarter wave transformer (QWT). The design and performance of the KEKB positron source have been described elsewhere [4, 5]. Positrons are generated by the impingement of the 4-GeV primary electron beam on the target. The average beam power is 2 kW at a maximum repetition rate of 50 Hz. On average, the typical transverse beam radius is 0.7 mm (rms), and the typical horizontal and vertical normalized emittances are 660 mm·mrad (rms) and 360 mm·mrad (rms), respectively, at the target. The horizontal (vertical) angular spread at the target is estimated to be 0.2 (0.1) mrad (rms). These angular spreads must be within the critical angle, which is 0.61 mrad, for axial channeling at 4 GeV in a tungsten crystal.

The positron capture section comprises a 45-mm-long pulse solenoid with a field strength of 2 T, an 8-m-long DC solenoid with a field strength of 0.4 T, and two each of 1-m-long acceleration and 2-m-long acceleration structures installed inside the DC solenoid. Positrons with an average energy of 10 MeV are generated from the target. These positrons are captured by the two types of solenoidal magnetic fields (created by the pulse solenoid and the DC solenoid), the QWT, and then accelerated in the succeeding accelerator sections to an energy of ~70 MeV. The electrons generated along with the positrons are stopped by a positron/electron separator (chicane) that comprises of four rectangular magnets, and a beam stopper, which is located at the center of the chicane. The geometrical acceptance of the capture section is

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approximately 420 mm·mrad and the typical momentum acceptance is approximately 24% at a momentum of 10 MeV/*c*.

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Long-Term Stability of the Positron Production Efficiency

Positron production using the tungsten crystal target was carried out at the KEKB between September 2006 and July 2007. The PPE and the other various data on positron production were obtained under the nominal operational conditions during this term.

Figure 2 (a) shows the long-term time trace of the PPE obtained for the first bunch with the tungsten crystal target. The PPE data, recorded from October 2005 to the end of June 2006, obtained using the conventional tungsten target, are shown in Fig. 2 (b), for comparison. The PPE is defined as a ratio (N_{e^+}/N_{e^-}) for each beam pulse, where N_{e^+} is the number of positrons captured in the positron capture section, and N_{e^-} is the number of the primary electrons. It can be seen that the PPE varies moderately in this interval. The variational range of the PPE is from a minimum of ~14% to a maximum of ~26%. The solid line in Fig. 2 indicates the average PPE (20%) obtained for the previously used tungsten target. Beam tuning was performed twice (September 2006 and January 2007) in order to adjust the injection angles of the primary electron beam to the desired value. The injection angles were adjusted by two sets (x and y) of upstream steering magnets in order to maximize the positron intensities. Moderate variations, similar to those in PPE, can be observed in other beam parameters such as the intensities of the primary electron and positron beams, and the transverse positions of the primary electrons impinging on the target during this term.

The variational ranges are 7.3–9 nC/bunch (~21%) and 1.2–2 nC/bunch (~45%) for the intensities of the primary electron and positron beams, respectively. The transverse positions of the primary electron beams on the target were varied within ±1 mm. The injection angles were relatively stable (< ±0.4 mrad), because the feedback controls for the injection angles were implemented since December 2006 by using the upstream steering magnets and beam-position monitors (BPMs). During this term, the integrated electron flux incident on the crystal target was ~5×10^9 nC/mm^2. No notable damage was caused to the crystal structure after this irradiation.

The correlation between the PPE and other beam parameters was investigated in order to determine the cause for the moderate variations in the PPE; however, no clear correlations could be observed. Therefore, it was concluded that these long-term variations were probably caused by other unknown beam parameters that could not be measured nondestructively, such as the beam sizes, beam energy, energy spreads, and bunch length.

Aperture Analysis of the KEKB Positron Source with Three BPMs

In this study, we report a simple analysis of the long-term variations in PPE on the basis of the results of an aperture analysis of the KEKB positron source with three BPMs. The data for the crystal target are sampled in four time regions in the time trace of the PPE (corresponding to the regions I–IV in Fig. 2 (a)). The regions I–IV typically give the highest, middle, lowest, and higher values of PPE, respectively. The data obtained for the previously used tungsten target are similarly sampled in three time regions. Both sets of data were used in the aperture analysis, which is described in the following paragraph.

A beam orbit is defined using three successive BPMs in positron production. The two BPMs upstream the path of the primary electron beam measure the intensity and the horizontal (x) and vertical (y) beam positions of the primary electron beam before it impinges on the target. The third BPM measures the intensity, and the horizontal (x) and vertical (y) beam positions of the positron beam after it has passed through the positron capture section (Fig. 3 (a)). Here, goodness (G) of the orbit linearity is defined by $G = \sum\sqrt{(x_i - x_0)^2/3}$ (i = 1–3) and $x_0 = \sum x_i / 3$ (i = 1–3), where x_i is the horizontal position measured with the i-th BPM and x_0 is the average orbit position. G also represents an rms position for the orbit measured with three BPMs. The goodness G, for y, is defined in a manner similar to that for x. Figures 3 (b) and (c) show schematic drawings corresponding to $G = 0$ (good orbit) and in the case of $G > 0$ (bad orbit), respectively. For $G > 0$, it was expected that the small aperture of the positron capture section could cause a certain amount of beam loss, thereby reducing the positron intensity. On the other hand, in the case of $G = 0$, the positrons are ideally captured, without any additional beam losses.

Figure 4 shows the variations in the PPE as a function of G. The data points are plotted for both the tungsten crystal (W_c) and the previously used tungsten target (W_a). The results show that small aperture clearly affects the variations in PPE, because the PPE decreases in the region where $G \sim 0.5$ mm; furthermore, the decrease in PPE is the same in the case of both W_c and W_a. Within the region of $G \sim 0.5$ mm, the higher PPEs are kept to be ~ 0.25 and ~ 0.2 on average for the crystal and the previous tungsten target, respectively. The PPE of the tungsten crystal is clearly higher than that of the previous target in this region. These results indicate that the radiation damage to the tungsten crystal target is not very severe.

SUMMARY

The first long-term application of a tungsten single-crystal target for positron production was successfully carried out from September 2006 to July 2007 in the KEKB operation. The stabilities of the primary electron and positron beams and variations of the PPE were investigated on the basis of the results of orbit analysis using three BPMs. The results showed that the crystal target suffers very less radiation damage even after long-term operation, during which time the integrated electron flux incident on the crystal target was ~ 5×10^9 nC/mm^2.

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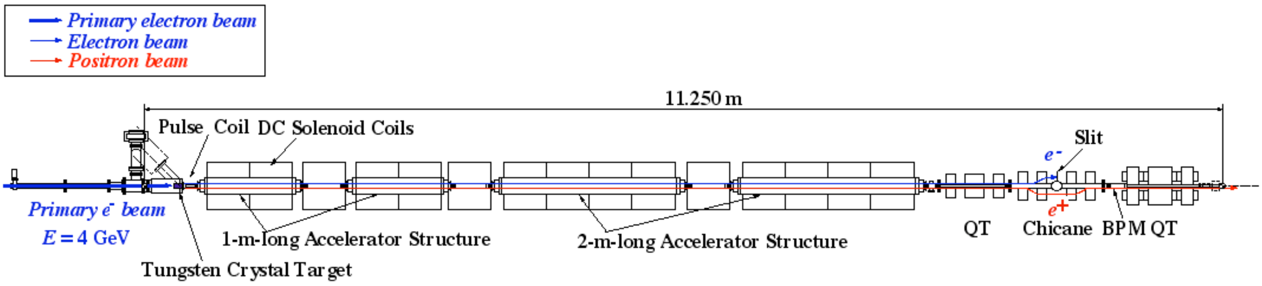

Figure 1: Layout of the positron source at the KEKB injector linac. (QT: quadrupole triplet.)

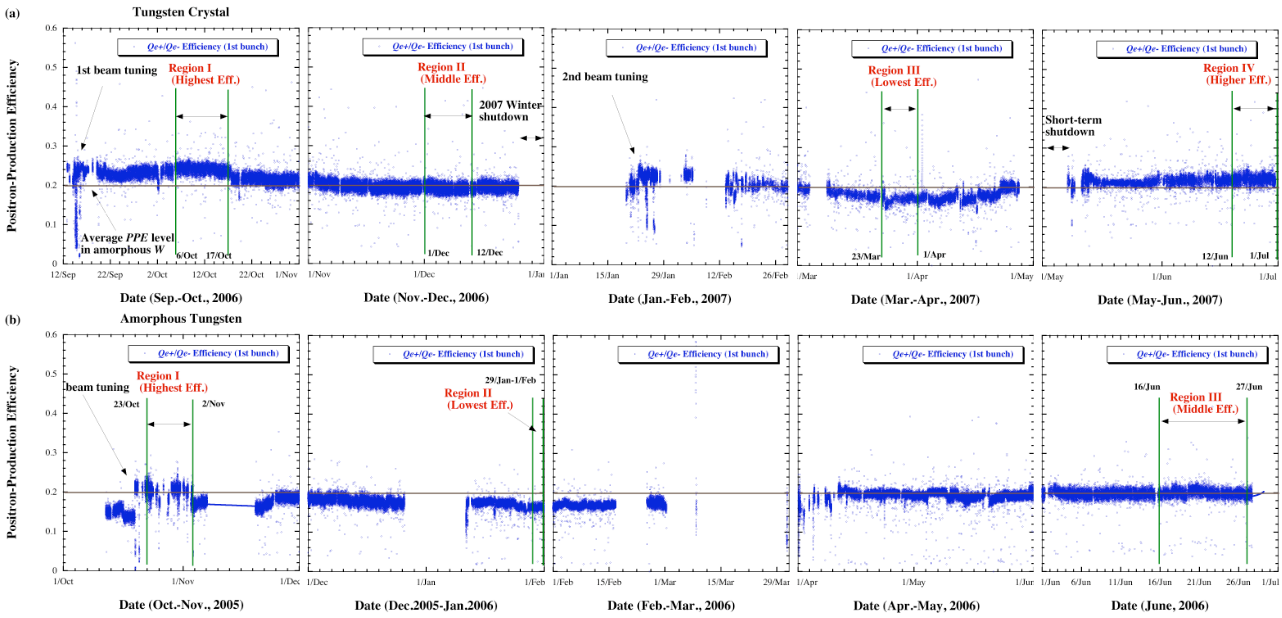

Figure 2: Long-term time traces of the PPEs obtained with (a) W_c and (b) W_a in the KEKB operation during 10 months.

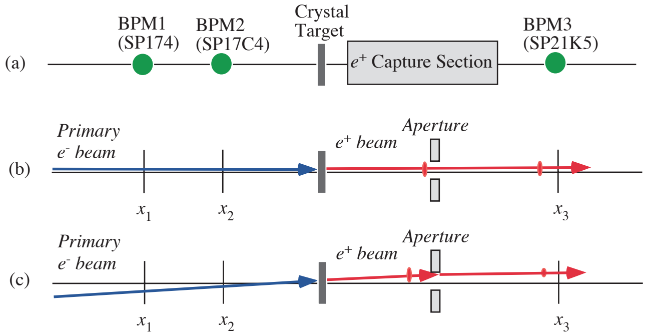

Figure 3: Schematic drawings of the aperture analysis using three BPMs in positron production at the KEKB. (a) Layout of the three BPMs, and schematic orbits of a primary electron and positron beam expected (b) for $G = 0$ (good orbit) and (c) for $G > 0$ (bad orbit).

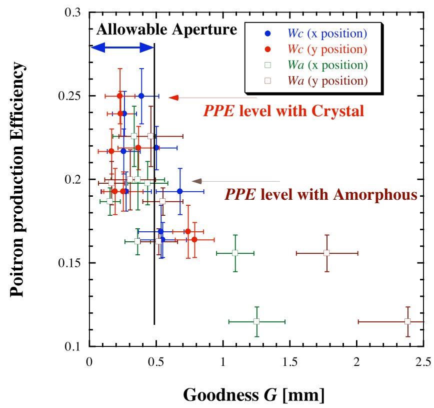

Figure 4: Variations in the PPEs as a function of the goodness G. The data sampled in different time intervals are plotted for both the W_c and W_a targets.