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Abstract

We have investigated quenching phenomena of channeling radiation through positron production from a silicon crystal hit by a single-bunch electron beam with high-bunch charge at the 8-GeV electron/positron injector linac. The crystal axis, $\langle 110 \rangle$, was aligned to the electron beam with a precise goniometer, and positrons produced in the forward direction with a momentum of 20 MeV/c were detected with a magnetic spectrometer. Positron yields were measured by varying the charge in a bunch with a typical bunch length of ~10 ps from 0.1 nC to 2 nC. The corresponding instantaneous current density ranged from 0.15×10^4 to 1.2×10^4 A/cm^2. The results show that, at these current densities, the positron yield is proportional to the bunch charge within the experimental accuracy, which implies that no non-linear phenomena are observed in channeling radiation.

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Key words: Channeling radiation; Coherent Bremsstrahlung; Positron source; Crystal target; Solid-state plasma

1 Introduction

Recently, there has been a revival of interest concerning a possible existence of high-density solid-state plasma through the quenching of channeling radiation in a crystal at high-bunch charges [1]. There have been long-standing investigations on a dynamical interaction between a crystal lattice and channeling electrons that produce high-density plasma in a crystal because it has a high potentiality for a very high acceleration gradient compared with a conventional gaseous plasma [2].

When an electron beam impinges on a crystal target along the crystal axis, electrons emit channeling radiation [3] through electromagnetic interactions between the crystal lattice and the electrons. Such electromagnetic interactions may cause collective vibration of the crystal lattice along with static thermal vibration. The collective vibration of the crystal lattice may be elastic for a low-intensity electron beam, while it would break at high intensity (or in strong electromagnetic fields) over the elastic limit. Thus, it is expected that these phenomena may cause quenching of channeling radiation in a crystal. Quenching phenomena of channeling radiation at high intensity is one of remarkable features for the possible existence of a solid-state plasma, which may be related to a phase transition induced by strong electromagnetic fields in a crystal.

Carrigan *et al.* [4] previously reported their experimental results on quenching of channeling radiation at high-bunch charges with an electron beam of 14.4 MeV at the Fermilab A0 photoinjector. They found no evidence of channeling radiation quenching at 8 nC per electron bunch with a typical bunch length of 7 ps (r.m.s). Recently, he also gave a very interesting review talk on it along with a discussion of previous experiments and the present status towards plasma acceleration [1]. Despite being a very attractive subject, very little has been done experimentally at electron energies greater than 50 MeV, and no clear theoretical clarification has been brought into this subject in the past. Our purpose is to experimentally investigate the behavior of channeling radiation in a crystal in a high-energy region by using 8-GeV electrons.

So far, we have performed experimental studies of positron production from an

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axially-oriented monocrystalline target at the KEKB electron/positron injector linac. The purpose of these studies has been to investigate the possibility as a high-intensity positron source for next-generation e^+e^- colliders.

A series of experiments have been reported elsewhere [5–7]. In these papers, it is shown that the positron yield is greatly enhanced under electron channeling conditions. It was shown that 4-8 GeV channeling electrons effectively produced an increased amount of high-energy photons through channeling radiation (CR) and coherent bremsstrahlung (CB), and that the e^+e^- pair-production process successively produced positrons after these radiation processes. Therefore, it is very interesting to use a high-intensity single-bunch beam delivered from the KEKB injector linac in order to investigate channeling radiation phenomena through positron production in the energy range of several GeV. We believe that our investigation may be unique because it is expected to indicate clear experimental signatures on channeling radiation quenching by measuring the positron yields depending on the bunch charges.

In the following sections, we report on an experimental study of positron production using 8-GeV channeling electrons impinging on a 2.55-mm-thick silicon crystal at high-bunch charges.

2 Experimental setup

2.1 Beam line and experimental setup

Our experiment was performed at the energy-analyzer line in the beam switchyard of the KEKB electron/positron injector linac [8]. A single-bunch electron beam with a typical bunch length shorter than 10 ps (FWHM) and with an energy of 8 GeV was used at a repetition rate of 25 Hz. For positron production the electron beam hit on a silicon crystal target with a thickness of 2.55 mm ($0.0272\,X_0$), whose $\langle 110 \rangle$ axis was oriented to the electron-beam direction. Figure 1 shows a schematic drawing of the experimental setup. The crystal target was mounted on a precise goniometer. Positrons produced in the forward direction were momentum-analyzed at a momentum of 20 MeV/c at maximum by a magnetic spectrometer, where the bending angle was 60° from the beam axis. Collimators installed before and after the magnetic field defined the positron trajectory. Two kinds of positron detectors were used: a total-absorption-type lead-glass calorimeter and a thin (3-mm thick) acrylic (Lucite) Cherenkov detector. The first one measured the total energy of positrons in a bunch, and the second one measured the number of positrons passing through the spectrometer. Since the positrons were emitted within a 10-ps interval in a wide intensity range, depending on the bunch charge, Cherenkov light was read-out

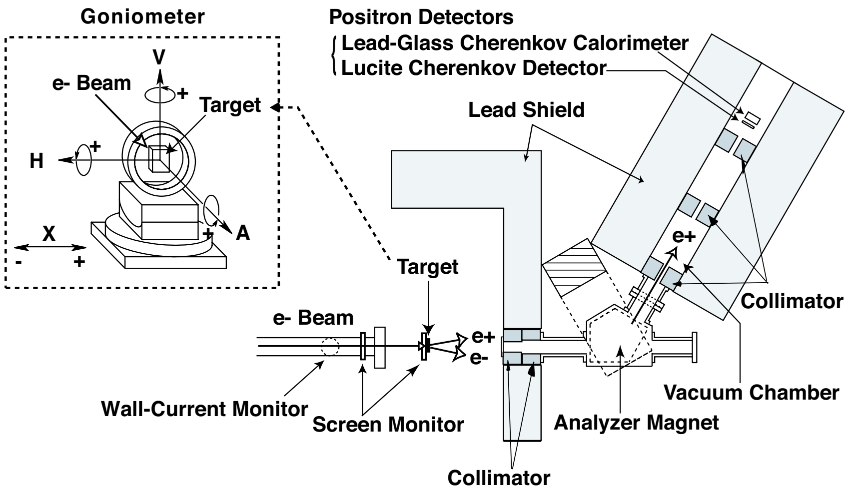

Fig. 1. Schematic drawing of the experimental setup.

with two photomultipliers (PMTs), each having a neutral-density-filter with a different attenuation factor in front. The gain ratio between the high-gain PMT channel and the low-gain PMT channel was 3. All of the collimators and detectors were installed in a vacuum chamber kept at a vacuum pressure of less than 10^{-1} Pa in order to reduce multiple scattering. The geometrical and momentum acceptance ($\Delta P \cdot \Delta\Omega$) was $(4.81 \pm 0.12) \times 10^{-4}$ MeV/$c \cdot$ sr, which was calculated by using the simulation code GEANT3 [9]. Other details were previously reported in Ref. [6].

2.2 PMT gain calibration with a laser-light pulse

The detector linearity is critically important for testing the quenching of channeling radiation. Before the measurements, the gain of the PMT was carefully checked as a function of the applied high voltage (HV), in which the input laser light intensity was adjusted within the dynamic range of the generated positron yield. A laser pulser (Advanced Photonic Systems APhS GmbH) delivering 60 ps pulses at a wavelength of 438.7 nm with a peak power of 1 mW was directly led to the PMT through a 30-m-long optical fiber. The output signal of the PMT was calibrated as functions of the HV and the laser intensity using the same analog-to-digital (A/D) circuit system in this experiment. The calibration results show that the nonlinearity of the PMT output can be calibrated within a measurement error of a few percents at the high-bunch charge region.

3 Experimental results

3.1 Beam characteristics

The beam parameters (bunch charge, bunch length, transverse beam sizes, and transverse emittances) were obtained before each measurement. The bunch charge was measured in the range of 0.1-2 nC by a wall-current monitor for each pulse. The transverse profile of the electron bunch at the target was measured with a fluorescent screen monitor. The beam images were acquired with a commercially available CCD camera provided with manually-controlled zoom lenses. The beam sizes were obtained with an eight-bit VME-based imaging technology frame grabber. The bunch length was obtained with an optical-transition radiation monitor with a high-resolution streak camera installed at sector A, where the beam energy was about 70 MeV. The angular divergences of the electron bunch were also measured with four successive wire scanners in the horizontal (H) and vertical (V) directions for 8-GeV electrons. The results of the beam characteristics are shown in Figs. 2 (a)-(d), which indicate the transverse beam sizes, the transverse angular divergences, the bunch length, and the bunch current density as a function of the bunch charge, respectively. Here, the transverse angular divergences of the electron bunch in the half width at half maximum (HWHM) were derived by using the transverse emittances and the measured beam sizes. It should be noted that the angular divergences of the electron bunch at the crystal target were enlarged due to multiple scattering at a vacuum window made of 30-μm-thick stainless steel (SUS304). The angular divergences caused by multiple scattering was about 53 μrad (r.m.s) for 8-GeV electrons. Even taking into account the multiple scattering, the angular divergences at the crystal target were much less than the critical angles (170 μrad for silicon crystal) for the channeling condition at 8 GeV [10]. The bunch current density in units of A/cm^2 was calculated by using the obtained beam parameters, depending on the bunch charge (see Fig. 2 (d)). Although the maximum bunch current density was obtained to be 1.2×10^4 A/cm^2 at a bunch charge of 1.9 nC, a clear degradation of the beam quality was seen at the high-bunch charge region, mainly due to strong wakefields and the space-charge effect during acceleration.

3.2 Two-dimensional crystal-axis scan

Before each measurement, high voltages applied to the PMTs were carefully adjusted in such a way that the output for the maximum positron yield stayed in the detector dynamic range. The positron yield was scanned by rotating the crystal axis with respect to the electron beam in two dimensions (around H

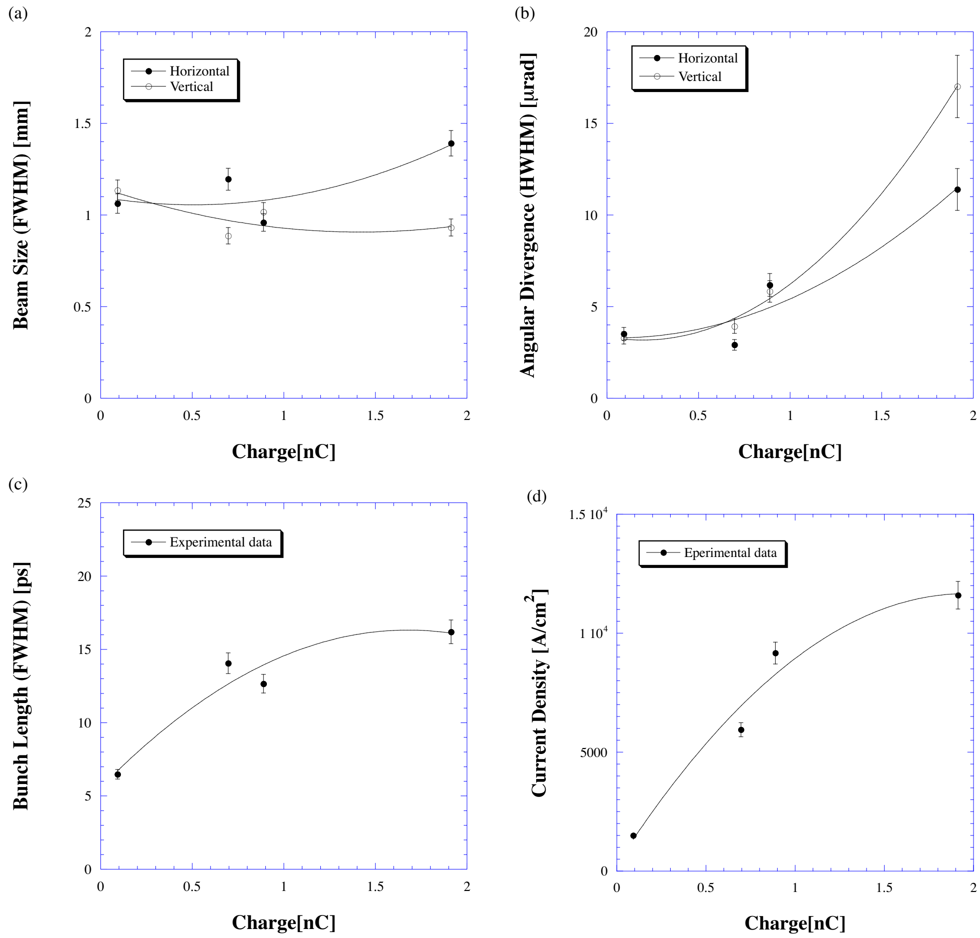

Fig. 2. Results of a beam characteristics measurement for an 8-GeV single-bunch electron beam. The results show (a) horizontal and vertical beam sizes, (b) horizontal and vertical angular divergences, (c) bunch length, and (d) bunch current density as a function of the bunch charge. The solid lines are guides to the eye for each measurement.

and V axes) by a new computer program. It was developed to automatically determine the crystal axis by scanning lattice points in the two-dimensional plane perpendicular to the beam direction. Figures 3 (a) and 3 (b) show the typical results of crystal-axis scanning obtained for the silicon target. We can clearly see the sharp peak corresponding to the $\langle 110 \rangle$ crystal-axis orientation.

3.3 Rocking curves

It is important to investigate the angular widths of the positron-yield peak (rocking curve), because it may indicate the characteristic features of channeling radiation. The relative positron yield was measured as a function of

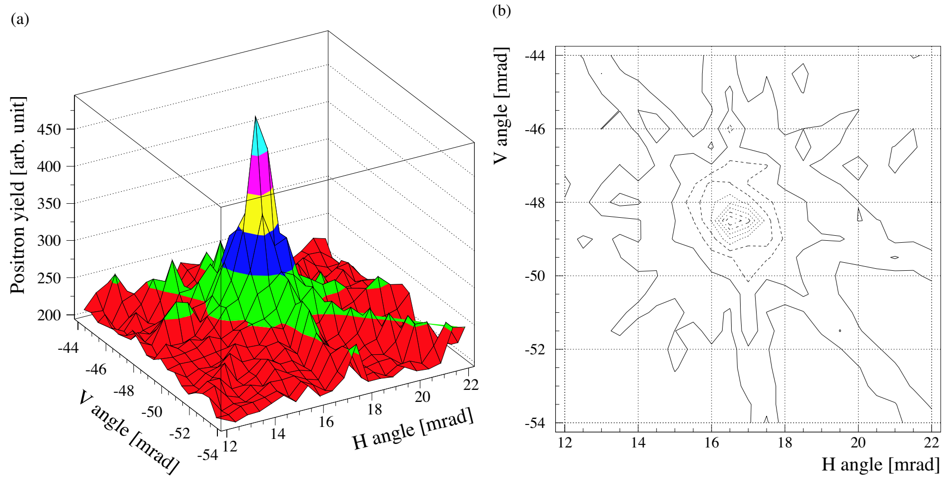

Fig. 3. Results of the two-dimensional scan of positron yields for a silicon target; (a) the lego plot and (b) the contour plot.

the goniometer rotational angle around the H axis, while the angle around the V axis was fixed at the angular position giving the maximum yield. The typical result concerning the rocking-curve measurements for the silicon target at a momentum of 20 MeV/c with a bunch charge of 1 nC is shown in Fig. 4. When the crystal axis was aligned along the incident electron-beam direction, a large positron-yield enhancement was observed with a factor of greater than ten. Lorentzian fitting functions were used in order to estimate the peak width in this experiment. The peak width is defined by the full width of a Lorentzian function, which is derived by the least-squares fitting procedure. Figure 5 shows the variations of the peak width as a function of the bunch charge obtained by the H and V rocking curves using the Lucite Cherenkov detector with different gains. Although the peak widths are clearly larger than the critical angle for axial channeling in silicon crystal, they are almost constant in the measured intensity range of the bunch charge. The results indicate that there are no abnormal behaviors for the positron production through channeling radiation.

3.4 Bunch-charge intensity dependence

All of the data for the measured positron yields were calibrated by using calibration curves obtained from the laser calibration after background-yield subtraction. In order to check the bunch-charge intensity dependence of the positron yield, we used the difference between the positron yield at the peak (on-axis yield) and that at the base region (off-axis yield), 25 mrad apart from the crystal axis.

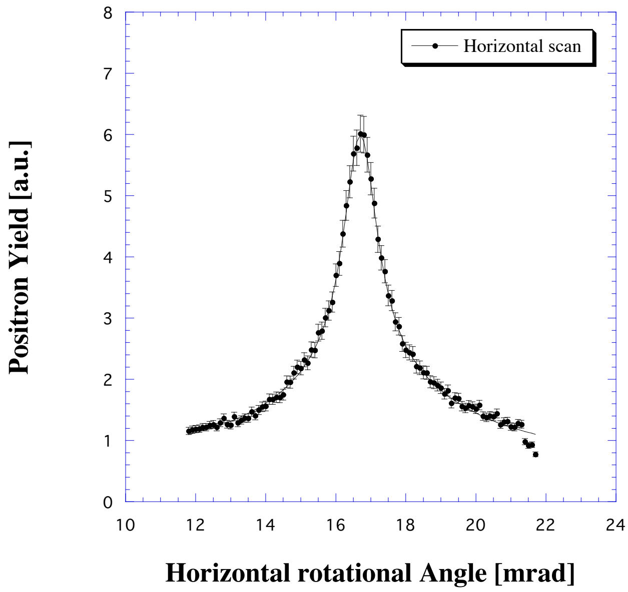

Fig. 4. Typical rocking curve measured for a silicon crystal at a bunch charge of 1 nC. The solid curve is a Lorentzian fit to the data.

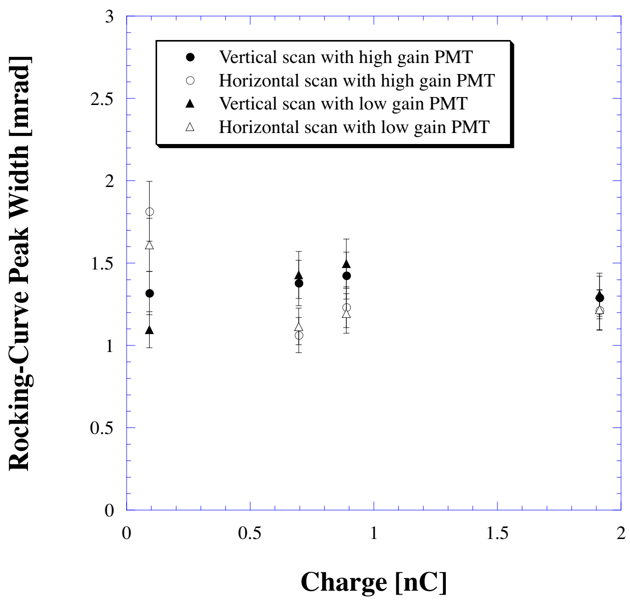

Fig. 5. Variations of the peak widths of the rocking curves measured for a silicon crystal as a function of the bunch charge.

The background is mainly caused by electromagnetic showers generated upstream of the beam line by off-momentum electrons and those generated at the collimators. The background yields increased with increasing the bunch charge in the measurements. The increase of the background yields was mainly due to the increase of these electromagnetic showers, which might be caused by a beam-quality reduction at a high-bunch charge. This is the reason why we used the difference of the two positron yields, because the ambiguity for the background-yield estimation was effectively reduced within the systematic errors of 10% level. After the background-yield analysis, data were obtained with the Lucite Cherenkov detector with the different gains as shown in Fig. 6. The results indicate that the positron yield increased linearly by the crystal effect to the bunch charge in the intensity range of 0.092-1.9 nC, where the range of the bunch current density was $(0.15\text{-}1.2)\times10^4$ A/cm^2, without any indication of abnormal channeling phenomena.

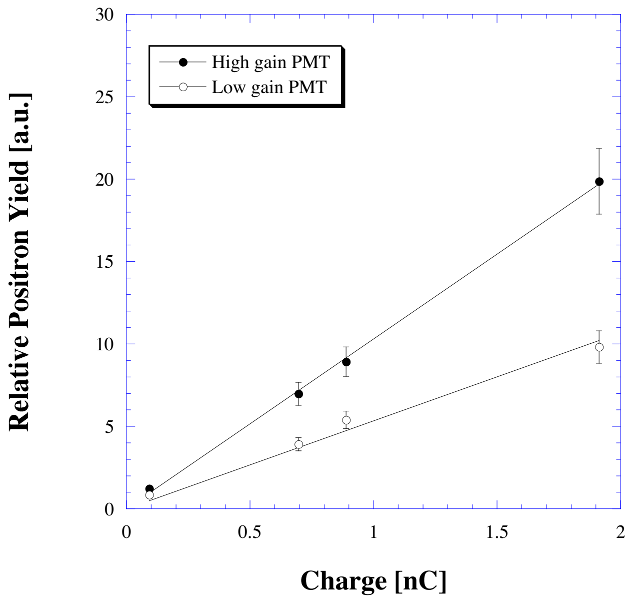

Fig. 6. Positron yields as a function of the bunch charge at a positron momentum of 20 MeV/c. The solid curves drawn through the data are the fitted linear functions.

4 Conclusions

A positron-production experiment by 8-GeV channeling electrons hitting an axially-oriented silicon crystal target with a thickness of 2.55 mm was successfully carried out at the KEKB electron/positron injector linac. The positron yields were measured at a momentum of 20 MeV/c as a function of the bunch charge in the intensity range of 0.1-2 nC, where the maximum bunch current density was 1.2×10^4 A/cm^2. The results show that when the $\langle 110 \rangle$ crystal axis was aligned along the incident electron beam direction, a large positron-yield enhancement (a factor of greater than 10) was observed compared with the non-aligned case. The results also indicate that the positron yields were proportional to the bunch charge within the experimental errors. The linear relation of the positron yield to the bunch charge indicates that no abnormal channeling radiation behaviors were observed in positron production up to the maximum bunch current density tested. This is of great benefit in applying such a crystal target to a high-intensity positron source required for next-generation high-luminosity e^+e^- colliders.

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