DEVELOPMENT OF CVD DIAMOND DETECTOR FOR BEAM CONDITIONING MONITOR AT THE SUPERKEKB LINAC

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Abstract

Positron beams in SuperKEKB are generated from electromagnetic showers by the interaction between primary electron beams and a tungsten target. In the SuperKEKB LINAC, a plate called spoiler will be placed in the upstream of the target to enlarge the beam spot size. If the beam-orbit control is in a correct way, radioactive rays originating from the interaction with primary beams can be observed near both the spoiler and the target. However, if the control is not successful and a primary beam with a small spot size is irradiated directly on the target, significant radiations are observed only near the target. If such a behavior is observed in the normal operation, primary beams must be stopped as soon as possible to protect the target. In order to monitor the radiation dose near both the spoiler and the target, we are now developing a radiation detector with high radiation tolerance, diamond detector. In this paper, we will present preliminary results of the beam tests for the diamond detector at the SuperKEKB LINAC.

SUPERKEKB LINAC

SuperKEKB is an electron-positron collider with an energy of 7 GeV and 4 GeV, respectively. The target luminosity is 40 times higher than that of KEKB [1], which amounts to $8{\times}10^{35}\mathrm{cm}^2\mathrm{s}^{-1}$. Therefore, SuperKEKB main ring requires a high current and low emittance beam to the SuperKEKB LINAC as shown in Table 1. In order to meet these requirements, photo-cathode RF gun and a damping ring are being developed for electron and positron beams, respectively.

In the SuperKEKB LINAC, positron beams will be generated from electromagnetic showers by the interaction between primary electron beams (3.3 GeV, 10 nC = $6.25{\times}10^{10}$ e^-) and a Tungsten target as shown in Fig. 1. Since the beam spot size on the target ($\sigma_{x,y}$) is ~ 0.2 mm, corresponding energy density for primary beams irradiated on the target reaches $1.6{\times}10^{12}$ GeV/mm^2.

TARGET DAMAGE THRESHOLD

Figure 2 shows the target damage threshold as a function of beam energy density and the number of beam-pulses exposed [2]. The result indicates that the damage depends only on the beam energy density and not on the number of beam-pulses. Corresponding damage threshold is estimated to be $2.0{\times}10^{12}$ GeV/mm^2, which is close to the beam energy density of the positron beams at the SuperKEKB LINAC. Therefore, a plate made of Al_2O_3 (d = 0.3mm) called Spoiler

Table 1: Required Parameters for SuperKEKB

	Phase 2 (e^+/e^-)	Phase 3 (e^+/e^-)
Bunch charge [nC]	2 / 2	4 / 5
Vertical emittance [mm mrad]	20 / 20	20 / 20
Horizontal emittance [mm mrad]	100 / 50	100 / 50
Energy spread [%]	0.1	0.1

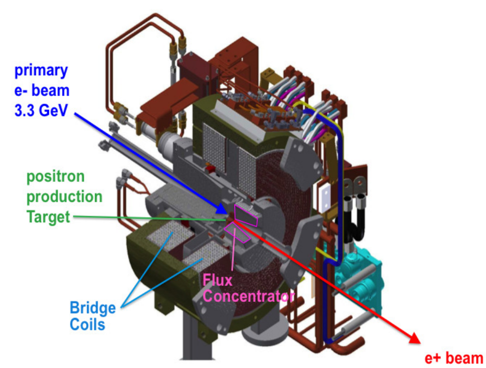

Figure 1: Positron production system at the SuperKEKB LINAC.

is placed in the 3m upstream of the target to protect the target. Due to the interaction with Spoiler, the beam spot size can be enlarged to 0.8mm in $\sigma_{x,y}$, resulting in an beam energy density of $0.1{\times}10^{12}$ GeV/mm^2.

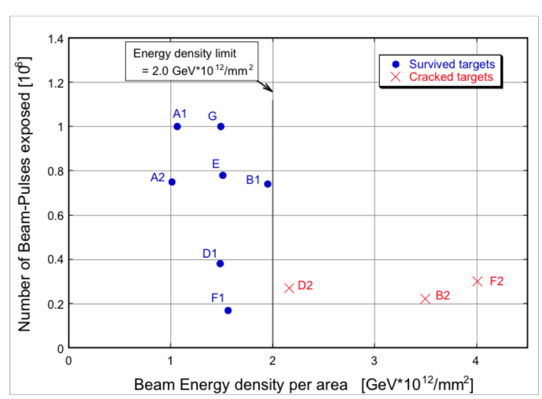

Figure 2: Target damage threshold as a function of beam energy density and the number of beam-pulses exposed [2].

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ALERT SYSTEM

To monitor the radiation dose near the positron production system, a radiation detector with high radiation tolerance, diamond detector, is planned to be installed. If the beam operation is as expected, there will be a significant radiation dose near both the spoiler and the target as illustrated in Fig. 3 (top). However, if the radiation is only observed near the target, this might indicate that the orbit control of the primary electron beam is not successful, and the focused beam might be directly irradiated on the target (Fig. 3 (bottom)). In this case, the beam operation must be stopped as soon as possible to prevent the target from breaking. In order to achieve this requirement, we are now developing two diamond detectors as an alert system, one for monitoring the radiation near the target and the other for spoiler.

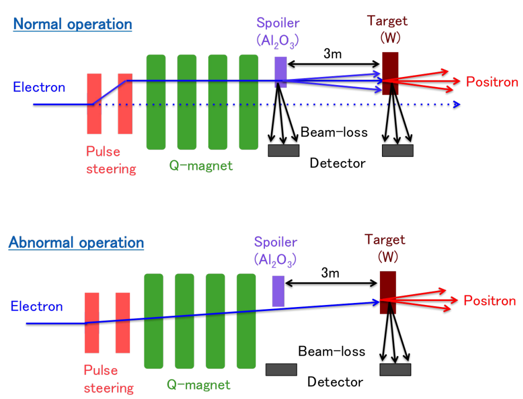

Figure 3: Schematic of positron production system in the normal (top) and abnormal (bottom) operation.

CVD DIAMOND

Physical Properties of Diamond

Table.2 shows the comparison of physical properties of diamond and silicon. Compared to silicon, diamond has a lot of advantages as a detector in a high radiation environment;

- Large mobility: Good timing response (~ nsec).
- Large displacement energy: high radiation tolerance (> ~10^{15}particles/cm^2).
- Large band gap: low noise due to small leakage current.

CVD Diamond

In our experiment, CVD (Chemical Vapor Deposition) diamond manufactured by Element Six is employed since it contains extremely low impurity in the crystal. Especially, single crystal CVD diamond with electronic grade [3] (2.0×2.0×0.5 mm) has been chosen for our measurement. Corresponding nitrogen density [N] and boron density [B] in the crystal is lower than 5ppb and 1ppb, respectively, and this ensures charge collection efficiency of 100 %. Three layers of electrodes are made to readout signals from the diamond; Ti(500nm)/ Pt(500nm)/ Au(2000nm). Ti layer is

Table 2: Comparison of Physical Properties of Diamond and Silicon

	Diamond	**Silicon**
Band gap [eV]	5.5	1.1
Electron mobility [cm^2/Vs]	1300-4500	1500
Hole mobility [cm^2/Vs]	2050-3800	500
Dielectric constant	5.7	11.9
e/h creation energy [eV]	13	3.6
e/h pairs per MIP [100μm^{-1}]	3600	8900
Displacement energy [eV]	43	13-20

used to obtain Ohmic contact on the diamond, and Au layer is used to prevents oxidation of the Ti and for wire-bonding. Pt layer can inhibits inter-diffusion between Au and Ti. After the metalization, diamond was annealed at 800 degree in Ar gas to create TiC on the surface, which acts as Ohmic contact.

Leakage Current Measurement

Once the electrodes are created on the diamond surface, leakage current was measured. As discussed in the previous section, the leakage current of the diamond should be small, fA - nA depending on the bias voltage. Figure. 4 shows the leakage current as a function of bias voltage for our detector. It was found that the measured leakage current (0.1mA@300V) is 10^6 times higher than that for typical diamond crystals. The leakage current of 0.1mA is nearly equals to the signal induced by 400 MIPs if we assume the time width of the diamond detector is 10 ns. However, such diamond detectors still can be used for our purpose. Since our diamond detectors will be installed near the positron target, the number of MIPs which penetrate the detectors is expected to surpass 10^4-10^5, and thus high S/N can be expected.

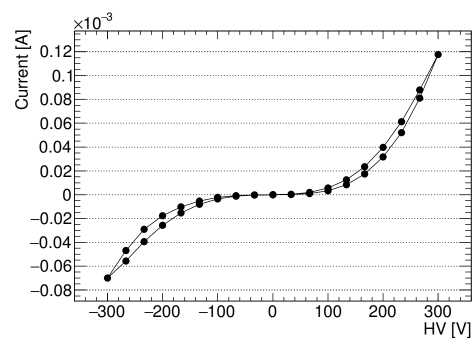

Figure 4: Leakage current as a function of bias voltage.

BEAM TEST AT THE SUPERKEKB LINAC

After the leakage current measurement, we performed beam tests to study the relation between the induced signal in the diamond detector and electron-beam charges. Figure 5

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shows the picture of the installed diamond detector with a dedicated PCB.

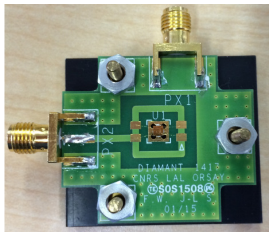

Figure 5: Installed diamond detector with a dedicated PCB.

Since the spoiler has not yet been installed at SuperKEKB LINAC, all the beam tests were performed in the configuration as illustrated in the Fig. 6.

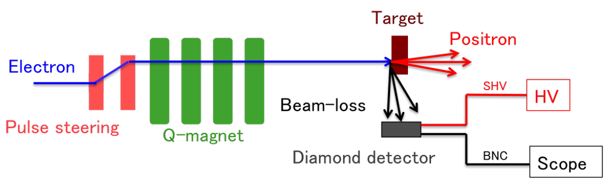

Figure 6: Schematic of the system used for the beam tests at the SuperKEKB LINAC.

In the measurements, the diamond detector was operated at -400V, and the corresponding leakage current can be seen in the Fig. 7. The observed baseline offset is consistent with the leakage current described in the previous section. The pulse height of the signal in the diamond detector is also much larger than the leakage current.

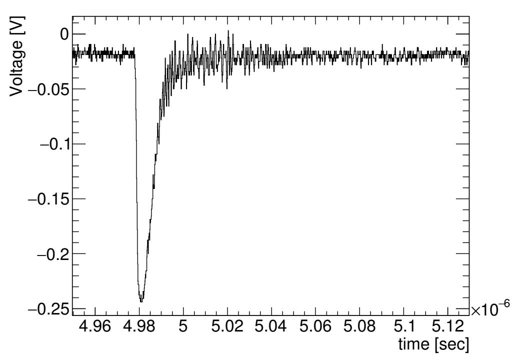

Figure 7: Typical waveform of the signal induced in the diamond detector.

Several-hour measurements were performed to check the long term stability of diamond signal. Figure. 8 and 9 show the collected charges in the diamond as a function of time. The results show that the signal was stable in several hours, and if there is a drop in the electron-beam charge, the diamond signal was decreased accordingly as shown in Fig. 9.

The relation between the induced signal in the diamond detector and electron-beam charges was also measured. The charges of primary electron-beams were changed from 3.5 to 6.5 nC. As shown in Fig. 10, the induced signal in the diamond detector is highly correlated with the electron-beam charges.

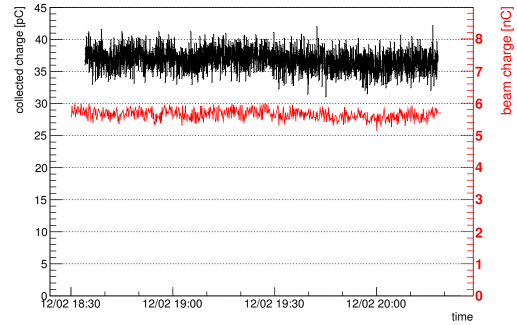

Figure 8: Collected charges in the diamond as a function of time.

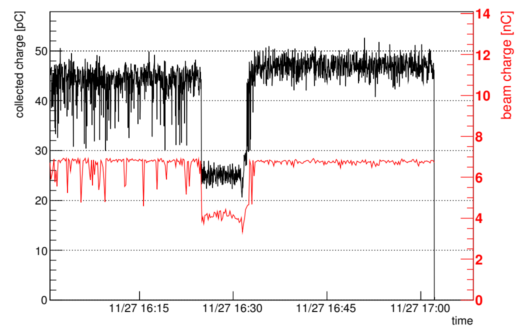

Figure 9: Collected charges in the diamond as a function of time.

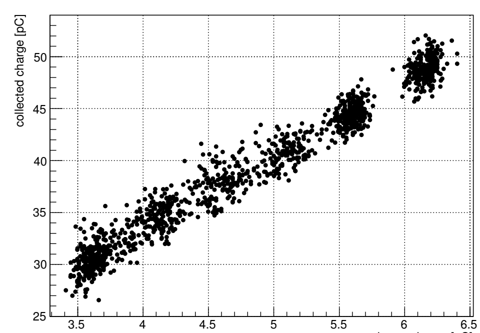

Figure 10: Relation between the induced signal in the diamond detector and electron-beam charges.

A Geant4 simulation was also performed to check if the observed signal in the detector is consistent with the expected values. In the simulation, all geometrical information of the target system is taken into account, and the number of electrons irradiated on the diamond is normalized to 6 nC. Figure. 11 shows the number of radioactive rays observed on a diamond detector as a function of the position where it is placed. In the actual experiment, the diamond detector

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is installed at the position where it equals to zero in the figure. The estimated number of radioactive rays in the target position is 1.2×10^4MIPs, which corresponds to 37 pC. This result is consistent with the obtained current shown in Fig. 11.

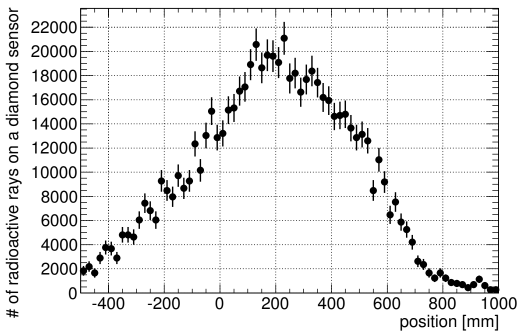

Figure 11: The number of radioactive rays observed on a diamond detector as a function of the position where it is placed.

CONCLUSION

In SuperKEKB LINAC, an alert system is necessary to protect the positron target. The radiation dose near the target is quite high, therefore we are now developing a detector with high radiation tolerance, diamond detector. We performed a beam test to measure the beam-loss near the positron target using diamond detector. Long-term stability and a clear correlation between the signal and beam charge were observed.

As a next step, we will determine the threshold for the alert system to sufficiently separate signal from background (leakage current). Then, we will install another diamond detector near the spoiler system and establish the alert system.

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