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STATUS OF DIAMOND DETECTOR DEVELOPMENT FOR BEAM HALO INVESTIGATION AT ATF2*

S. Liu [#], P. Bambade, F. Bogard, J-N. Cayla, H. Monard, C. Sylvia, T. Vinatier, LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
N. Fuster-Martinez, Instituto de Fisica Corpuscular, Valencia, Spain
I. Khvastunov, Taras Shevchenko National University of Kyiv, Kyiv, Ukraine
T. Tauchi, N. Terunuma, High Energy Accelerator Research Organization, Tsukuba, Japan

Abstract

We are developing a diamond detector for beam halo and Compton spectrum diagnostics after the interaction point (IP) of ATF2, a low energy (1.3 GeV) prototype of the final focus system for ILC and CLIC linear collider projects. Tests of a 500 µm thick sCVD diamond detector with a dimension of 4.5 mm×4.5 mm have been carried out with radioactive sources and with electron beam from PHIL low energy (<10 MeV) photo-injector at LAL. The tests at PHIL were done with different beam intensities in air, just after the exit window at the end of the beam line, to test the response of the diamond detector and the readout electronics. We have successfully detected signals from single electrons, using a 40 dB amplifier, and from an electron beam of 10^8 electrons, using a 24 dB attenuator. A diamond sensor with 4 strips has been designed and fabricated for installation in the vacuum chambers of ATF2 and PHIL, with the aim to scan both the beam halo (with 2 strips of 1.5 mm×4 mm) and the beam core (with 2 strips of 0.1 mm×4 mm) transverse distributions.

INTRODUCTION

The ATF2 beam line constructed at KEK in Japan aims to measure and stabilise the electron beam at 37 nm beam size at the IP. For this purpose, a "Shintake" monitor is used to measure the nanometer beam size. This monitor uses the interference pattern formed by two lasers as a target for the beam and measure the beam size by the modulation of the signal from the generated photons. The photons are detected by a photon detector, installed after a bending magnet located downstream of the IP. This tool is very sensitive to bremsstrahlung photons emitted when halo particles are intercepted in the last quadrupole magnets and in the vacuum chamber after the collision point [1].

The amount of beam halo is estimated to be 10^{-3} of the total beam as shown in the beam halo measurements using wire scanners [2]. Geant4 simulations with this amount of beam halo have been done to investigate the visibility of beam halo and the Compton recoil electrons [3]. For the detection of both beam halo and Compton electrons, a single layer of diamond detector with four strips will be positioned in the vacuum chamber after the post-IP bending magnet.

In order to test the response of the diamond detector and the readout electronics, tests of the diamond detector were done using radioactive sources and electron beam with different beam intensity. The diamond detector we used for our tests is a 4.5 mm×4.5 mm large and 500 µm thick single-crystal CVD diamond fabricated by the CIVIDEC company [4]. The diamond surfaces are metallised with gold electrodes with an area of 4 mm×4 mm. The capacitance of this diamond is around 3 pF and the measured dark current is in the range of 100 pA. Two PCBs are mounted on the two surfaces of the diamond for electrical contact. High voltage is applied to one side of the diamond and the signal is collected from the other side. The expected charge generated by 1 minimum ionization particle (MIP) passing through the 500 µm diamond is expected to be 2.88 fC with 100% charge collect efficiency (CCE). A 40 dB amplifier with 2 GHz bandwidth was used for the tests with the radioactive sources, and a 24 dB attenuator with 1.5 GHz bandwidth was used for large signal detection at PHIL.

TEST WITH RADIOACTIVE SOURCES

Tests with radioactive sources were performed in a specially equipped clean room at LAL before testing the diamond detector at PHIL with large intensity electron beam. These tests are the standard tests to characterize each individual diamond detector [5].

Test with ^{241}Am Alpha Source

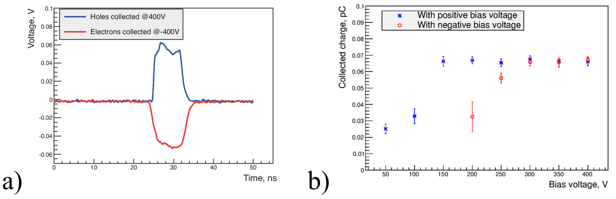

Figure 1: a) Signal from collected electrons (red line) and holes (blue line); b) Charge collected with ^{241}Am alpha source in diamond detector as a function of applied bias voltage: positive (blue stars) and negative (red circles).

To test the response to alpha particles, an ^{241}Am source with an activity of 3.9 kBq was mounted with a distance of 2 mm on the top center of the diamond, where a 1mm diameter hole was specially made on the PCB for this test. The energy of the alpha particles emitted from ^{241}Am source is around 5.4 MeV. The penetration depth of alpha particles with this energy is estimated to be less than 20 µm, which is small compare to the 500 µm thickness of

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[#] sliu@lal.in2p3.fr

diamond detector. Thus we can consider the deposited ionization charge as a thin charge layer and by changing the polarization on the two surfaces of diamond, we can collect electrons and holes separately.

Figure 1.a shows pulse shapes from electrons and holes from averaging 10 events and Figure 1.b shows the collected charges as a function of applied bias voltage. The collected charge get saturated by applying higher than 150V for the holes collection and higher than 300V for the electrons collection. The maximum collected charge at 400V is 66.1±2.5 fC for holes and 67.3±2.0 fC for electrons. As the mean ionization energy is around 13 eV in diamond, the expected charge from the alpha source is around 66.5 fC. Therefore, the CCE of this diamond sample is 100% for both electrons and holes at 400V.

Test with ^{90}Sr Electron Source

Figure 2.a shows the experimental setup for the test with ^{90}Sr source and the circuit of the diamond detector under test. The pulse shape of the signal from ^{90}Sr source is shown in Figure 2.b. The signal pulse shown is from averaging 1000 events. The FWHM of this pulse is around 4 ns.

As the signal was obtained with in self-trigger mode with 5 mV trigger level and the low energy electrons (<1.6 MeV) are not eliminated in the system, we collected a mean charge of 13.62 fC instead of 2.88 fC as expected for 1 MIP. A new system with external trigger will be used for the detection of MIPs.

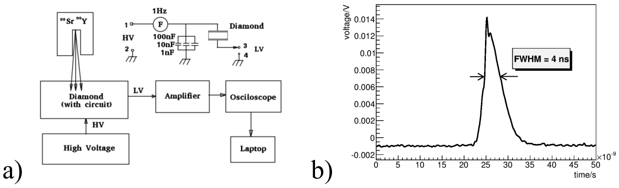

Figure 2: a) Measurement set-up for test with radioactive sources and circuit diagram of diamond detector; b) Averaged signal from ^{90}Sr source of 1000 events.

TEST AT PHIL

PHIL is a 5 m long photoinjector beamline at LAL, which provide an electron beam with low energy (<5 MeV), low emittance (10π*mm*mrad) and short pulse (7 ps) [6]. The bunch frequency at PHIL is 5 Hz. The electron beam charge can be varied from less than 1 pC to 2.2 nC at the exit window by changing the laser density shining the Mg cathode.

The charge of the electron beam can be measured by the two Integrating Current Transformers (ICT1 and ICT2) installed along the beam line. ICT1 is about 1 m from the cathode and ICT2 is just before the 18 μm thick Ti exit window, at the end of the 5 m straight line. After the exit window, the charge can be measured by another removable ICT (ICT3) or by a Faraday cup, the measurement ranges of which are from 10 pC to 2 nC. For the charge measurement below 10 pC, a YAG:Ce screen with a CCD camera can be used, this can bring the lower charge measurement limit to 1 pC. For lower than 1 pC measurement, we used a LANEX (R) screen, which has higher light yield and less blurring effects. The light emitted from the Lanex screen was calibrated with the charge measured by Faraday cup. Extrapolating that calibration below the sensitivity of the Faraday cup enabled the LANEX screen to be used for beam charges as small as 15±10 fC [7].

Experimental Setup for Test in Air

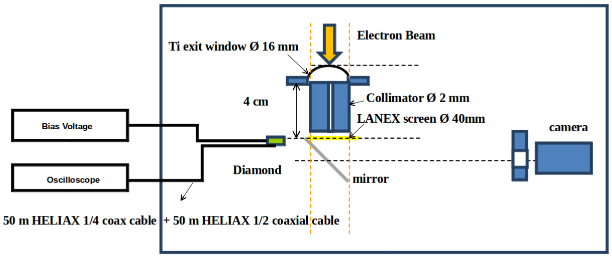

Figure 3: Experimental setup at PHIL.

Figure 3 shows the experimental setup for diamond detector test at PHIL. A 4 cm long Al collimator with 2 mm diameter was used to collimate the beam after the exit window. The diamond detector was mounted next to the LANEX screen on a transverse movable stage after the collimator. The output signal was connected with a 100 m long HELIAX RF coaxial cable to the control room, where we used an Agilent 6104 oscilloscope with 4 Gs/sec sampling rate and 1 GHz bandwidth to read the signal pulse. A 50 Ω feed through terminator was used to enable the 1 MΩ coupling on the scope. The scope was controlled remotely using Labview installed on the laptop.

Experimental Results

Figure 4.a shows an example of the pulse form for different beam intensity. The charge of the beam was measured by the LANEX screen. We can see the pulse width enlarges with the beam intensity. And the pulse amplitude start to get saturated after an injection of more than 2×10^6 electrons (32 pC) as shown in Figure 4.b. The saturation of pulse amplitude can be explained by the drop of bias voltage on the diamond detector when a large current go through the 50 Ohm terminator, which means a reduction on the electric field and consequently on the drift velocity of the electrons and holes. This might lead to electron-hole recombination if the collection time gets larger than the recombination time.

The impact of such recombination effects is currently being studied. A hint of saturation in the collected charge (obtained by integrating the signal pulse above the pedestal) can actually be seen in Figure 4.c for input charges larger than 2×10^7 electrons. Below such values, the response in terms of collected charge is linear. A factor 2 difference was observed with the expected signal as calculated multiplying the charge generated by 1 MIP (2.88 fC) by the number of electrons derived from the charge measurement using the LANEX. Several possibilities to explain this difference are being investigated at the level of the experimental setup, the diamond collection process, and the calibration of the LANEX.

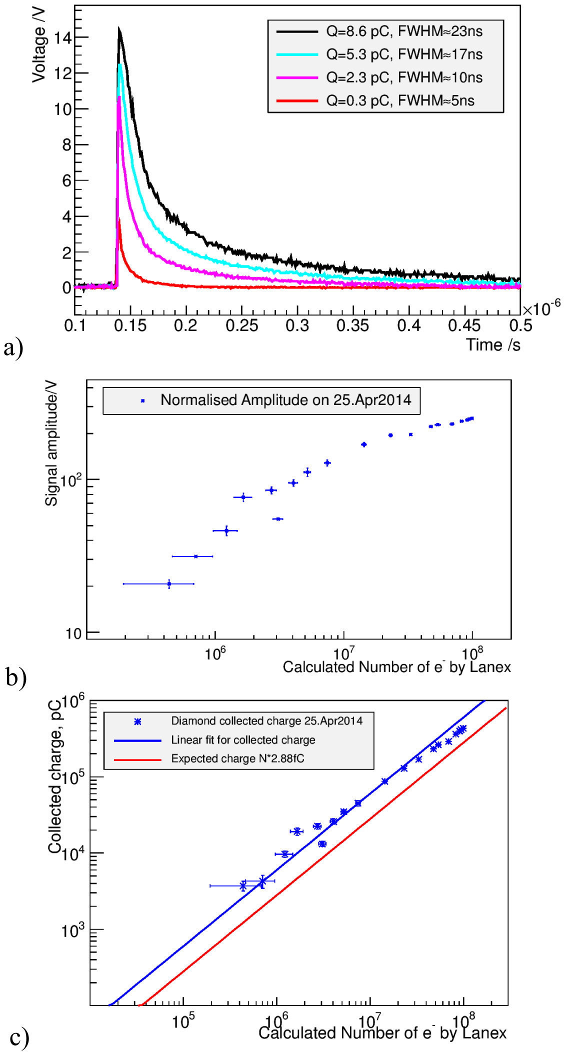

Figure 4: Test results with 3 MeV electron beam at PHIL: Pulse signal form for different injected beam intensity (a); Signal amplitude (b) and collected charge (c) as a function of number of input electrons.

Design for Diamond Detector in Vacuum

For the beam halo measurement at ATF2, a large signal range from ~10^4 /mm^2 for beam halo to ~10^7 /mm^2 for beam core is required. As the signal strength is proportional to the metallised effective surface on diamond, diamond detector with four strips was designed to cover this large dynamic range (see Figure 5.a). The two strips for beam halo scan are on the two sides, which have a dimension of 1.5 mm×4 mm and the other two in the center are for beam core scan with a dimension of 0.1 mm×4 mm. Besides, one 0.5 Ohm resistor was added to one of the narrow strips (CH2) to act as an current divider. The effect of this resistor on the signal form will be tested at PHIL.

The diamond detector will be installed in vacuum with a holder to scan the beam and beam halo. The mechanical design was done and fabricated at LAL as shown in Figure 5.b. The whole setup can be oriented either horizontally or vertically to scan in different axes. This design can be used both for PHIL and ATF2. Therefore, it will be installed and tested at PHIL before the implementation at ATF2.

The circuit for the diamond detector is shown in Figure 5.d, a low pass filter together with the charging capacitors are mounted on the backside of the ceramic PCB. The parameters of this circuit were set based on the following considerations:

- The cut-off frequency for high voltage power supply should be as low as possible to maintain the stability;
- The amount of charge stored on the capacitors should be large enough for measurements of large beam intensities, up to ~1 μC on the narrow strips;
- The charging time constant should be small to separate different bunches, the frequency of which is 5 Hz at PHIL and 3 Hz at ATF2;

The simulated cut-off frequency for the present circuit is 8 Hz with 500 μC maximum stored charge at 500 V and the charging time constant is 44 ms.

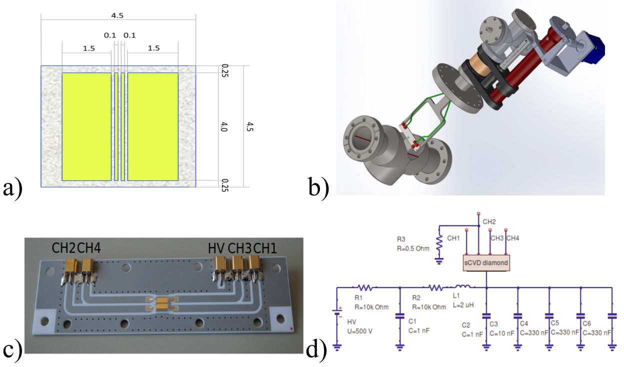

Figure 5: a) Design of diamond detector with four strips; b) Mechanical design for application in vacuum; c) Diamond detector mounted on the ceramic PCB fabricated by CIVIDEC; d) Circuit diagram for diamond detector with strips.

CONCLUSIONS AND FUTURE PLAN

A diamond detector is developed for the investigation of beam halo propagating model and for Compton recoil electron measurement at ATF2. Tests with a 4.5 mm×4.5 mm large and 500 μm thick diamond detector sample were carried out using radioactive sources and 3 MeV electron beam. Tests with electron beam were performed at PHIL in air in the range from 10^5 to 10^8 particles with measurable input charge. Linear response up to 10^7 was observed for the output charge. Signal broadening and saturation in the high intensity regime will be interpreted quantitatively using simulation. The design and fabrication of a diamond detector with 4 strips is completed. This new diamond detector is currently installed in vacuum at PHIL and will be tested before implementation at ATF2 in autumn 2014.

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