

# INVESTIGATION OF BEAM HALO USING IN VACUUM DIAMOND SENSOR AT ATF2\*

S. Liu, P. Bambade, F. Bogard, P. Corneise, V. Kubytskyi, C. Sylvia, LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

A. Faus-Golfé, N. Fuster-Martínez, IFIC (CSIC-UV), Valencia, Spain

T. Tauchi, N. Terunuma, KEK and SOKENDAI, Tsukuba, Japan

## Abstract

Beam halo transverse distribution measurements are of great importance for the understanding of background sources of the nano-meter beam size monitor at the interaction point (IPBSM) of ATF2 [1,2]. One of the most critical issues for the beam halo measurement is to reach high dynamic range. Two *in vacuum* diamond sensor beam halo scanners (DSv) with four strips each have been developed for the investigation of beam halo transverse distributions at ATF2. The first DSv was installed for horizontal beam halo scanning after the interaction point (IP) of ATF2, in Nov. 2014. It aims to measure the beam halo distribution with large dynamic range ( $\sim 10^6$ ), and investigate the possibility of probing the Compton recoil electrons produced in the interaction with the IPBSM laser beams. Studies to characterize the DS performance and measurements of horizontal beam halo performed in Nov.-Dec. 2014 are presented.

## INTRODUCTION

The investigation of beam halo transverse distribution is an important issue for beam loss and background control in ATF2 and in Future Linear Colliders (FLC). A DSv was installed downstream of the IP, 1.35 m from the BDUMP bending magnet exit at ATF2, to study the beam halo transverse distribution and the spectrum of the Compton recoil electrons produced in the interaction with the IPBSM laser beams at ATF2. In order to measure the beam core, beam halo and Compton recoil electrons simultaneously, a large dynamic range of  $> 10^6$  is needed [3]. Previous beam halo measurements using wire scanners have only reached a dynamic range of  $\sim 10^4$  [1,4,5]. However, a single crystalline CVD (sCVD) diamond sensor is not only sensitive to single electron but also tested to have a linear response up to  $10^7$  electrons [6]. Therefore, two sCVD DSv have been developed for our measurements.

Since the signal strength is proportional to the metallised effective surface on diamond, DSv with four strips was designed to help cover this large dynamic range [6]. The two strips for beam halo scanning are on the outer sides, with a dimension of  $1.5 \text{ mm} \times 4 \text{ mm}$  and the other two in the center are for beam core scanning with a dimension of  $0.1 \text{ mm} \times 4 \text{ mm}$ . After characterising the DSv, beam core and halo transverse horizontal distributions were measured in Nov.-Dec. 2014. Beam core measurements were used for the normalisation of the beam halo distribution.

\* Work supported by Chinese Scholarship Council, CNRS and P2IO LABEX

## EXPERIMENTAL SETUP

For the *in vacuum* application a ceramic PCB is used. The ceramic PCB uses silver-platinum conductor produced in thick-film technology. The PCB with the diamond sensor in the center is shown in Fig.1 (left), a low pass filter together with charging capacitors are mounted on the backside of the PCB [6].

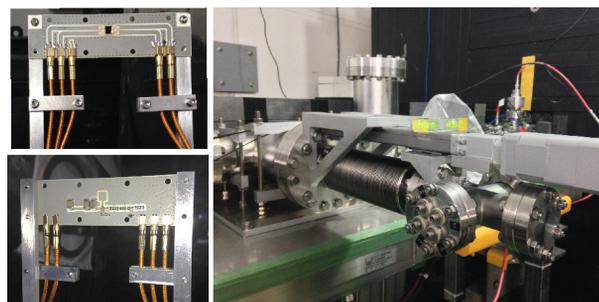


Figure 1: Layout of the DSv with the frontside (upper left) and backside (lower left) of the PCB and the motor used for the scan (right).

The DSv were fabricated by the CIVIDEC company [7] and the first set of it was installed in vacuum horizontally with a holder to scan beam and beam halo in the horizontal plane. The mechanical design was done and fabricated at LAL as shown in Fig 1 (right). The whole setup is 744mm long and it can be oriented either horizontally or vertically to scan in different axes.

## Data Acquisition System

In order to transfer the signal from the DSv installed in the post-IP region to the IP laser room, where the oscilloscope is located, we have chosen a high quality LDF1-50 1/4 inch thick Heliac low density foam coaxial cable (more than 20m). For the bias voltage supply we used the Keithley 2410 sourcemeter, which can supply a bias voltage of  $\pm 1000 \text{ V}$ . The whole data acquisition system is connected via Ethernet cables to the PC located in the control room. On the PC, Matlab is installed and used for system control and data taking. The oscilloscope we used is an Agilent oscilloscope with a sampling rate of 4 GS/s and an analogue bandwidth of 1 GHz. The motor we used for the DSv scan control is a stepper motor EMMS-ST-42-S-SEB-G2. The resolution of the steps is  $10 \mu\text{m}$  and the reproducibility accuracy is  $3 \mu\text{m}$ . The mover precision was set as  $50 \mu\text{m}$  for our experiment and the maximum scan range is 110 mm.

## Scope Vertical Range Setting

The measurement resolution depends on the vertical range (VR) applied on the scope setting. The Agilent scope we used has a vertical resolution of 8 bits and a vertical sensitivity of 2mV/div-5V/div. The measurement resolution of the scope can be calculated as  $\text{Resolution} = VR/2^8$ . Therefore with the min. scope range 2mV/div, we have the max. measurement resolution of 62.5  $\mu\text{V}$ .

For the measurements of beam halo, as a large dynamic range is required, the scope VR should be adjusted for different measurement range. To achieve this, one can either set the VR manually for a certain range of scan and change it for another range or change the VR at each position automatically. By changing the VR manually at each range, we observe a distribution with several steps, and normalization between the steps will be needed. However, by changing the VR automatically at each position, a continuous beam halo distribution can be obtained. A Matlab program is written and applied to find the optimised VR at each measurement point.

## DYNAMIC RANGE OF THE MEASUREMENT

The dynamic range of the measurement is limited on one side by the noise level given by the electromagnetic pick-up signal from the passage of the beam and on the other side by the linearity of the response of the DSv, which represent the lower and higher limits of our present setup, respectively.

### Lower Limit

Since the ceramic PCB on which the DSv is mounted is not shielded, when the beam passes by/through the PCB, current is induced on the signal readout lines on the PCB. The signal given by the induced current is called pick-up signal. Pick-up signal was observed during the tests using the DSv without applying a bias voltage. In Fig.2 (left) the pick-up signal on each channels is shown.

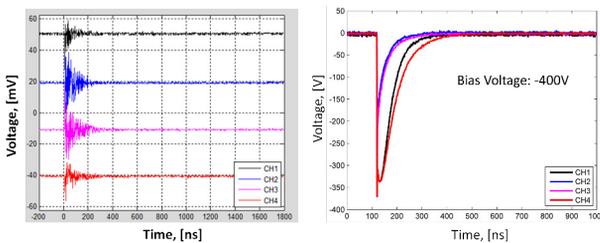


Figure 2: Left: waveforms for the pick-up signal; Right: signal from the beam taken when then the beam core is centered on each channel, the signal amplitude is shown taking into account the use of a 30 dB attenuator.

In principle, the DSv can measure signal from single electron using an amplifier. However, since the auto scope vertical range setting system take the signal amplitude as a criteria to define the VR, and the charge is integrated for the whole waveform, a relatively high amplitude of signal

pick-up caused a relatively high VR, consequently, a bad resolution. Besides, the integrated charge is not absolutely zero but  $\sim 3 \times 10^{-3}$  nC which correspond to  $\sim 10^3$  electrons. This defines the lower limit (noise level) of beam halo measurement for our present setups. However, this effect can be avoided by shielding the PCB, which is planed for the upgrade of the DSv.

### Higher Limit

The higher limit of DSv depends on the linearity response of the DSv, which is considered as one of the most important characterization aspects as it defines the linear region of operation and provides the normalization factor for the non-linear region.

In order to check the linearity, the beam intensity should be changed. This can be done in two ways: 1) change the input laser intensity for the photo-cathode; 2) change the DSv position in the beam core.

Since the ICT sensitivity is above  $10^9$  electrons, the beam intensity below  $10^9$  can not be measured correctly. Thus in order to get to the lower beam intensity we have to change the DSv position in the beam core. Fig. 3 (left) shows the positions we have chosen for the DSv during the measurements. The DSv was moved to 2 positions (A and B) with 2 mm distance from each other. At each position we changed the beam intensity from  $10^9$  to  $7 \times 10^9$  electrons and took 100 waveforms at each beam intensity. Before the measurements, the beam was aligned to center the DSv vertically, and then the beam core was scanned horizontally and fitted by the convolution function of a Gaussian and a uniform distribution given by the strip width [8]. One example of the fit for the measured beam core distribution by CH1 is shown in Fig.3 (left).

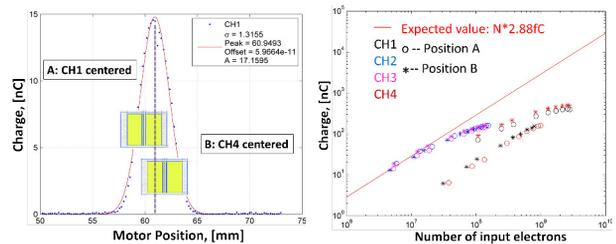


Figure 3: Positions chosen for the measurements of the linearity of the response of the DSv (left) and the measurement results (right).

For the calculation of the number of incident electrons, as the beam core follows a Gaussian distribution, the number of electrons intercepted on each channel  $N_{CH}$  at different positions can be calculated as:

$$N_{CH} = A \int_{-\frac{1}{2}l_x + D_x}^{\frac{1}{2}l_x + D_x} e^{-\frac{x^2}{2\sigma_x^2}} dx \int_{-\frac{1}{2}l_y}^{\frac{1}{2}l_y} e^{-\frac{y^2}{2\sigma_y^2}} dy \quad (1)$$

where  $A = N_t / (2 * \pi * \sigma_x * \sigma_y)$ ,  $N_t$  is the total number of electrons in the beam,  $l_x$  and  $l_y$  are the horizontal and vertical width of the strip,  $D_x$  is the horizontal position offset

from the beam center. The horizontal beam size ( $\sigma_x$ ) in the formula is the measured beam size by DSv, which can be obtained from the fit of the beam core. However, as the vertical beam size ( $\sigma_y$ ) can not be measured at the DSv location, it was extrapolated from the post-IP wire scanner (installed ~60 cm after the IP) measured beam size.

Fig. 3 (right) shows the measured linearity response of DSv at position A and B. From the figure it can be seen that the charge collected by CH2 and CH3 seems quite consistent, however, the CH1 and CH4 behave differently in the beam center and away from the beam center. At position A, where CH1 is centered to the beam CH4 has less charge collected, same behaviour for CH1 when CH4 is centered at position B. The reason for this behaviour is under investigation.

From Fig. 3 (right) it can be seen that the deviation of the signal from the expected value starts at the beam intensity of  $10^7$ , which is also consistent with the results we have obtained before using the in air DSv as reported in [6]. This can be explained by the voltage drop on the 50  $\Omega$  resistor on the scope. This voltage drop ( $V_{drop}$ ) is proportional to the number of input electrons and it will reduce the effective bias voltage on the DSv ( $V_{eff}$ ), which can be defined as:  $V_{eff} = V_{bias} - V_{drop}$ , where  $V_{bias}$  is the bias voltage applied on the DSv and  $V_{drop}$  can be read out directly from the waveforms on the scope and it changes together with the current. The waveforms taken with a 30 dB attenuator when the beam core is centered on different channels are shown in Fig. 2 (right). For  $10^7$  of input electrons, assuming a FWHM of pulse of 20 ns, the estimated voltage drop is ~75 V. As the charge collection efficiency (CCE) of the DSv depends on the effective bias voltage [9], when large voltage drop happens the drift velocity of electrons and holes are decreased, the charge collection time is extended which increase the possibility for recombination and thereby reduces the collected charge. This effect can be mitigated by adding a smaller resistor in parallel to the 50  $\Omega$ , as a current divider.

## BEAM CORE AND BEAM HALO MEASUREMENTS

The data taking and analysis procedures defined for the measurements are shown as below:

- **Horizontal and vertical alignment (VA):** the beam core is scanned using DSv to find the horizontal beam center; Then the vertical beam center was found by steering the beam vertically, the position with maximum signal strength on DSv correspond to the vertical beam center;
- **Post-IP wire scanner beam core scan:** the beam core is scanned using the post-IP wire scanner to get the horizontal and vertical beam size for verification;
- **DSv beam core scan:** the beam core is scanned again with the DSv by applying high bias voltage (-400 V), 30 dB attenuators are added for each channel;
- **Beam core fitting:** the beam core is fitted as mentioned before, beam size is obtained from the fit and the beam halo scan region is defined;

- **DSv beam halo scan:** the beam halo is scanned again using DSv with a bias voltage of -400V without attenuators in the region of  $<-3 \sigma_x$  and  $>3 \sigma_x$ ;
- **Data binning:** data binning is applied for the beam halo data to mitigate the fluctuation in the distribution. The number of bins is chosen in order to ensure at least 1 data point per bin. The value of each bin correspond to the mean value of its data.

An example of combined beam core and beam halo distribution for the data taken with CH1 is shown in Fig.4. The measured horizontal beam size for the beam core is ~ 1.5 mm (not taking into account the signal saturation). The measured charge for the beam core is normalized by the factor corresponding to 30 dB attenuation. It can be seen that dynamic range for this measurement is ~  $10^6$ . The noise level is at ~  $10^3$  pC. This is caused by the pick-up signal as mentioned before.

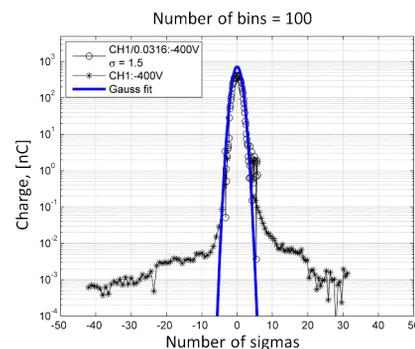


Figure 4: Beam core and beam halo distribution measured on CH1.

Two edges can be found on both sides of the beam halo distribution. These edges are caused by the cut of the beam halo by the apertures of the beam pipe installed after the BDUMP, which has a radius of 31.5 mm. The simulated value predicted a cut by the vacuum beam pipe installed after the BDUMP at around  $\pm 25.8 \sigma_x$  position, and the measured cut is at around  $\pm 20 \sigma_x$  position, which is quite consistent with the predicted value taking into account the optical mismatch factor observed between simulation and measurement.

## CONCLUSIONS AND PROSPECTS

A DSv with large dynamic range was designed for beam halo measurements at ATF2. A dynamic range of ~  $10^6$  was obtained covering both beam core and beam halo measurements. With the present design the dynamic range of the DSv is limited by the signal pick-up at the level of  $10^3$  electrons and by the non-linearity starts from  $10^7$  electrons.

For the signal pick-up, shielding of the PCB will be applied for the next set of the DSv. The non-linearity response of the DSv due to large voltage drop on the 50  $\Omega$  can be avoided by adding a smaller resistor. With these solutions, the dynamic range of the DSv can be further improved.

## REFERENCES

- [1] T. Suehara, M. Oroku, T. Yamanaka, H. Yoda, T. Nakamura, Y. Kamiya, Y. Honda, T. Kume, T. Tauchi, T. Sanukia, S. Komamiya, “Design of a Nanometer Beam Size Monitor for ATF2”, arXiv:0810.5467v1 (30 Oct. 2008).
- [2] G. R. White et al., “Experimental Validation of a Novel Compact Focusing Scheme for Future Energy Frontier Linear Lepton Colliders”, Phys. Rev. Lett. 112,034802 (2014).
- [3] S. Liu, P. Bambade, S. Bai, T. Tauchi, N. Terunuma, “Development of Diamond Sensors for Beam Halo and Compton Spectrum Diagnostics after the Interaction Point of ATF2”, MOPME003, Proc. IPAC2013.
- [4] S. Liu, P. Bambade, N. Fuster-Martinez, A. Faus-Golfe, S. Bai, D. Wang, J. Gao, “Measurements of beam halo transverse distribution using wire scanners at ATF2”, ATF-14-01 report (2014).
- [5] N. Fuster-Martinez, A. Faus-Golfe, F. Bogard, P. Bambade, S. Liu, S. Wallon, G. White, E. Marin, K. Kubo, N. Terunuma, T. Okugi, T. Tauchi, “Realistic beam halo model study in the Extraction Line of ATF2”, TUPTY019, to be published in Proc. IPAC2015.
- [6] S. Liu, P. Bambade, F. Bogard, J-N. Cayla, H. Monard, C. Sylvia, T. Vinatier, N. Fuster-Martinez, I. Khvastunov, T. Tauchi, N. Terunuma, “Status of Diamond Detector Development for Beam Halo Investigation at ATF2”, THPME092, Proc. IPAC2014.
- [7] E. Griesmayer, CIVIDEC, Austria, product catalogue.
- [8] Quentin King, “Analysis of the Influence of Fibre Diameter on WireScanner Beam Profile Measurements”, SPS-ABMTM/Note/8802 (2013).
- [9] V. Kubytskyi, S. Liu, P. Bambade, “Modeling/Measurement Comparison of Signal Collection in Diamond Sensors in Extreme Conditions”, MOPHA007, to be published in Proc. IPAC2015.