Application of Diamond and Sapphire Sensors in the Beam Halo Monitor for FLASH

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Abstract

The Beam Halo Monitor for FLASH, a subsystem of the beam dump diagnostics system, is described in this paper. The results of its commissioning during the "9 mA" experiment in September 2009 are given.

1 Introduction

FLASH (Free-electron LASer in Hamburg) [1, 2] is a high-gain free-electron laser (FEL) at DESY with maximal electron beam energy of 1.2 GeV, bunch charge up to 3 nC, bunch frequency up to 3 MHz and train length up to 800 μs. This is a user facility of the SASE (Self-Amplified Spontaneous Emission) FEL beam for applications in physics, chemistry, biology, material sciences, medical diagnostics and other fields. It is also a test facility for the European XFEL [3, 4] and the ILC [5, 6]. Safe electron beam dumping at FLASH is supported by a beam dump diagnostics system. A new beam diagnostics system became necessary after a beam loss induced vacuum leak occurred in September 2008. In order to avoid such leak in future a new system consisting of glass fibers, ionization chambers, a beam halo monitor (BHM) and beam position monitors (BPM) has been installed. The BHM - a vital part of this system, carrying 4 diamond and 4 sapphire sensors - has been installed inside the beam pipe during the upgrade of the FLASH beam dump line in summer 2009. It has been successfully commissioned and operated during the "9 mA" experiment [7].

2 System description

The new beam dump instrumentation for FLASH (see Figure 1) comprises glass fibers, ionization chambers, a BHM system and a magnetic BPM (also called "in-air" BPM) [8] operating in conjunction in order to prevent the damage of the beam pipe. The glass fibers and ionization chambers ensure that the beam does not hit the beam pipe downstream from the exit window. The BPM detects the center of gravity of the beam behind the exit window and helps to keep the beam centered. The BHM system ensures that the beam halo is also within the beam pipe, signaling earlier than the other systems when the beam approaches the beam pipe.

The module containing the BHM system has been installed in the last section of the electron beam pipe behind the vacuum window and directly in front of the dump. Four 300 μm thick pCVD diamond sensors with the area of 12×12 mm^2 and four 500 μm thick artificial monocrystalline sapphires with the area of 10×10 mm^2 are placed alternately and uniformly distributed in azimuthal direction inside caps. Both sides of the sensors had been covered with metalization: Ti/Pt/Au 50/50/200 (nm) for diamonds and Al/Ti/Au 50/50/200 (nm) for sapphires. The sensors positioned inside the beam pipe have to withstand high radiation doses. Samples of such sensors have been irradiated in a high intense electron beam at S-DALINAC and found to tolerate doses up to 10 MGy with moderate signal degradation [9]. Moreover, such diamond sensors have been proven to operate in intense electron beam with the bunch charge up to 1 nC in single bunch mode with repetition rate of 1 MHz at PITZ facility. The four pick-ups of the "in-air" BPM reside close to the BHM sensors as can be seen in Figure 2.

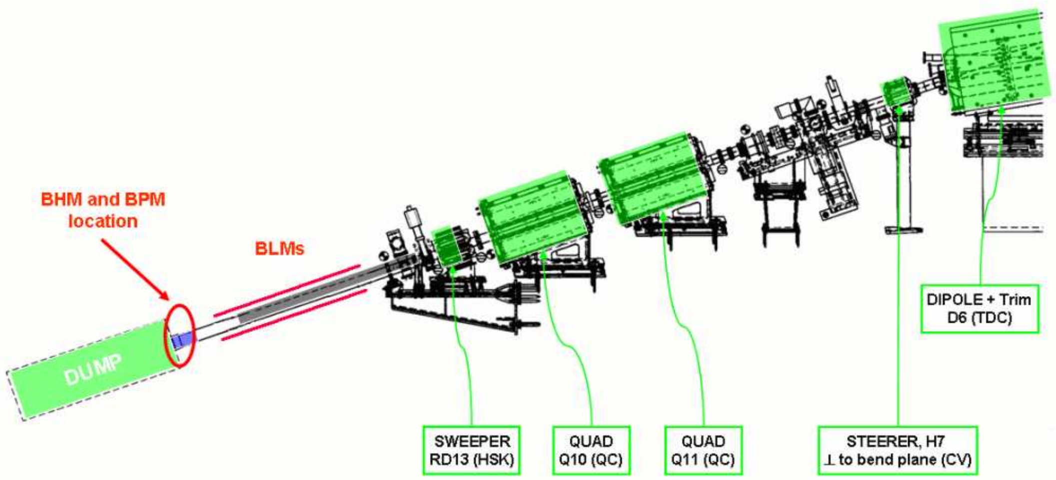


Figure 1: The FLASH beam dump line. The position of the parts of the beam dump diagnostics system is schematically shown (in red).

The sensors are operated as solid state ionization chambers. The bias voltage feed and signal readout scheme is shown in Figure 3. Three coaxial cables per sensor channel are used, two of them to provide bias voltage and one to readout the signal. The sensors are connected to a HV filter box with 4 meters long radiation hard GX 03272 D-06 cables. Coaxial cables of approx. 60 meters connect the filter box to the counting room which houses the readout electronics. The signals, filtered and limited, are routed to a fast direct conversion 14-bit ADC with 8 channels. It uses 1MHz clock which is aligned with the maximum of the BHM sensors' signals. Its input resistance is set to 10 kΩ.

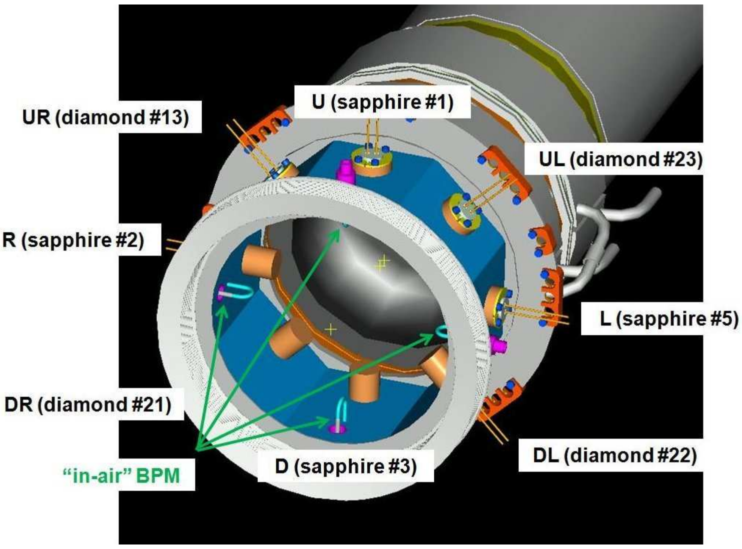


Figure 2: The position of the BHM sensors as viewed from the beam dump.

3 Results

In September 2009, after a short shutdown of FLASH, the so called "9 mA" experiment was carried out - a test run aiming to run long trains of 800 μs with bunch repetition rate of 3 MHz and bunch charge of 3 nC. That was also the first test for the new beam dump diagnostics systems including the BHM.

The operation of the BHM system has been checked in two stages. First there was a dedicated period of beam steering with increased sweeping radius and one bunch per train for the commissioning of the beam dump diagnostics systems. The second stage was carried out during normal multi-bunch machine operation.

As it is seen in Figure 4, all BHM sensors revealed signal in presence of the beam, although the beam was obviously off centered to the left.

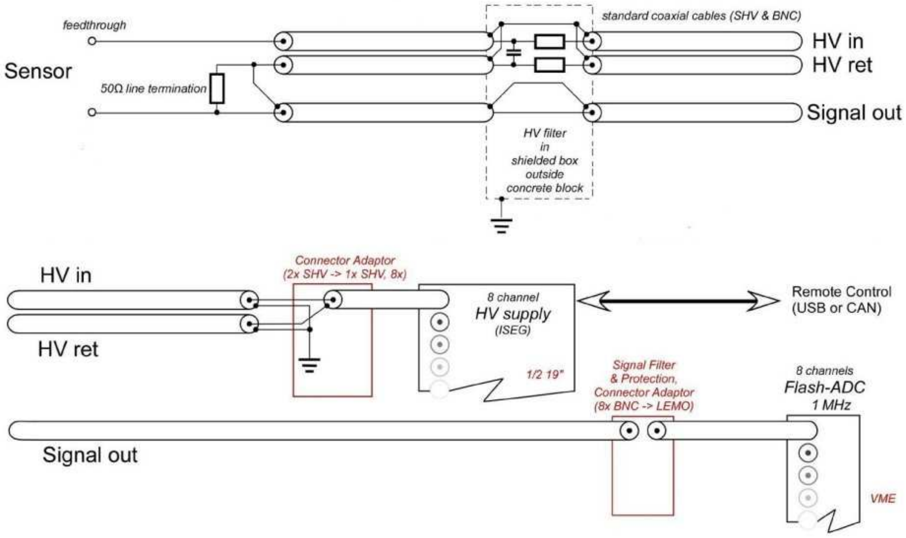


Figure 3: Bias voltage feed and readout scheme for each BHM sensor.

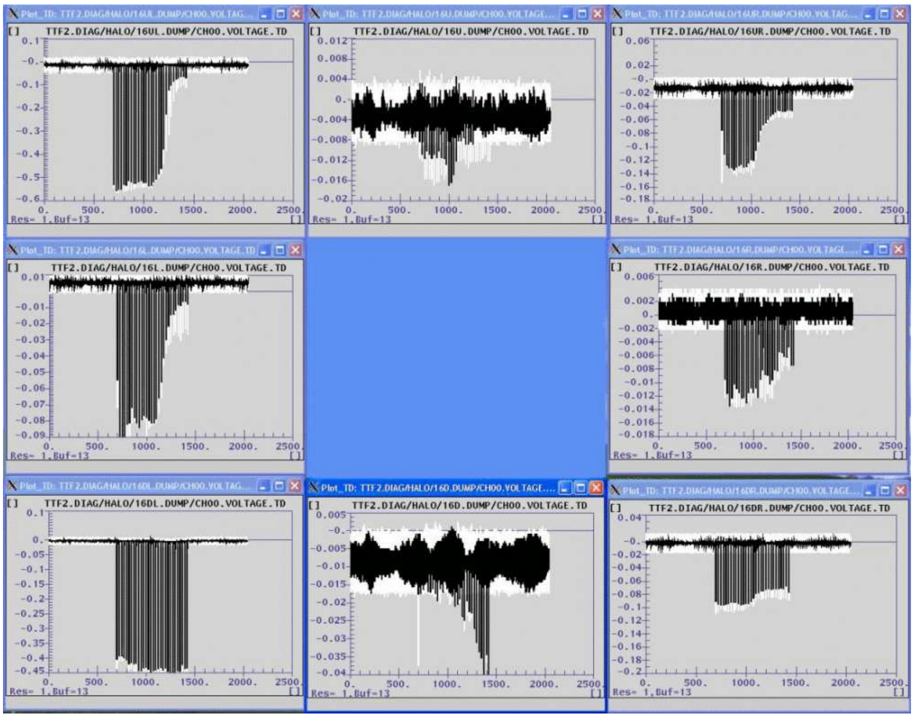


Figure 4: Digitized signals from all the BHM sensors (as seen by the incoming beam) as a response to 1 train of 30 bunches during multi-bunch operation.

3.1 Dedicated beam steering period

The single-bunch beam was moved during a period of approximately 20 minutes. The sweeping used to distribute the energy deposited by the beam to

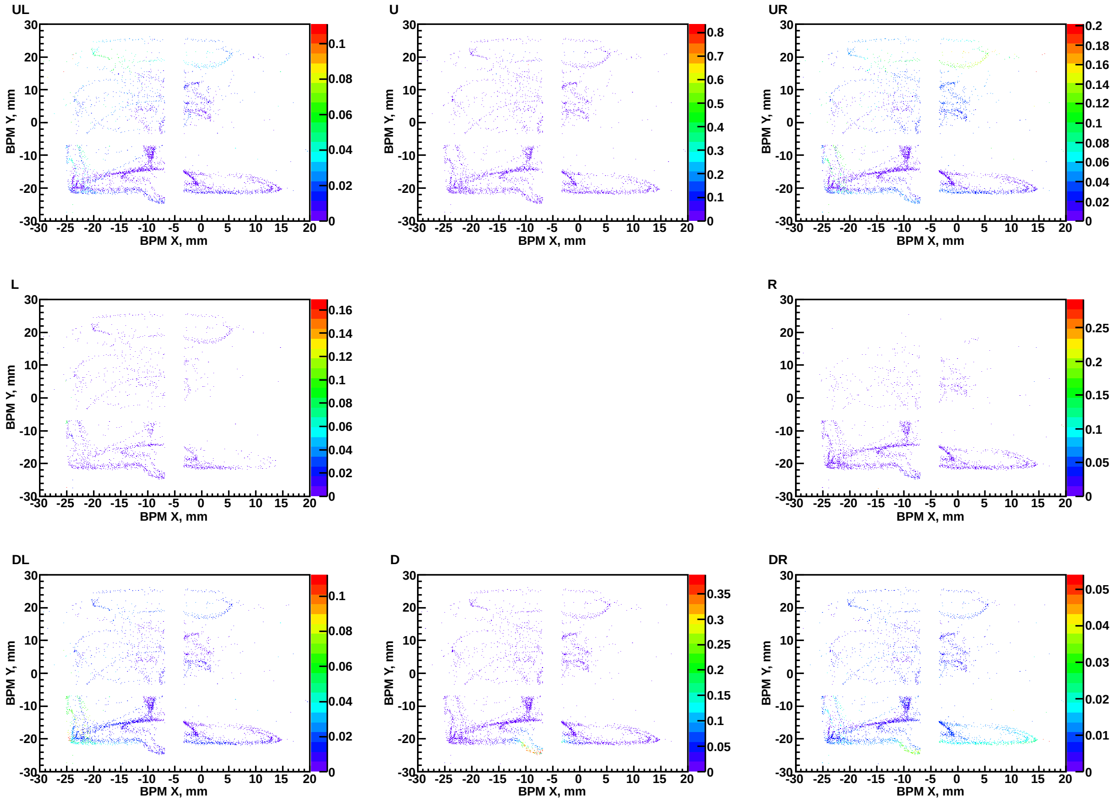


Figure 5: Average signals (color coded, in V per nC) from all the BHM sensors normalized to the bunch charge delivered to the dump (Eq. 1) as a function of the beam position during the beam steering period.

the exit window was at its maximal value. As a result the beam was brought closer to one or another sensor. The bias voltage was the same for the sensors of the same type: 40 V for diamonds and 400 V for sapphires.

One of the ways to prove the functionality of the BHM system is to plot the average signal in terms of the average response from a sensor normalized to the bunch charge delivered to the beam dump as defined in Eq. 1 as a function of the beam position determined by the BPM. The increase of the signal while the beam approached a certain sensor could be an indicator of the correct operation of the BHM system.

$$U_i^{av} = \frac{1}{n_i}\sum_{j=1}^{n_i}\frac{U_{i,j}}{Q_j} \quad (1)$$

where

U_i^{av} - average signal of a sensor for the beam in the ith position,

$U_{i,j}$ - sensor response to the jth bunch of the beam in the ith position (the numbering of the bunches is continuous over the observation period),

n_i - number of bunches detected in the ith position, Q$_j$ - charge of the jth bunch delivered to the dump.

Indeed, the average signal from a BHM sensor normalized to the bunch charge increased when the beam approached the corresponding sensor. This was observed for all diamond sensors and the closest to the beam sapphire sensor (marked "D") as shown in Figure 5. In some cases the effect was less pronounced. The reason for that could be slightly different charge collection efficiency of the sensors or non-symmetric halo shape.

The same data can be represented as a sensor response normalized to the bunch charge delivered to the beam dump as a function of the distance to the beam (see Eq. 2). This dependence is illustrated in the Figure 6.

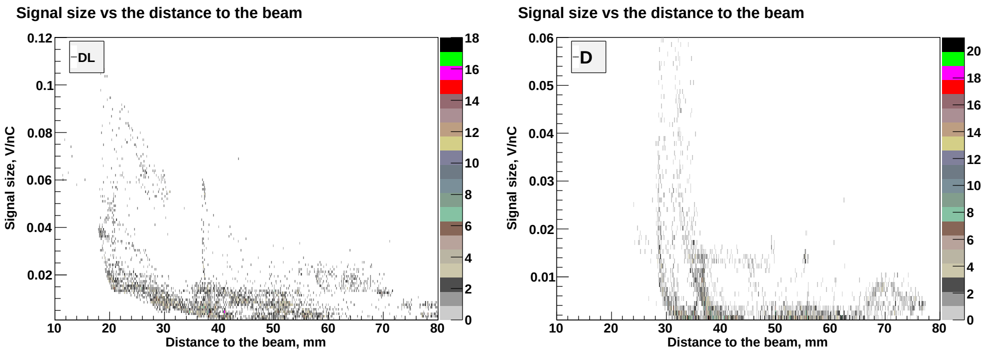
$$U_j^{res} = \frac{U_j}{Q_j} \quad (2)$$

where

U$_j^{res}$ - signal of a sensor for the jth bunch (the numbering of the bunches is continuous over the observation period),

U$_j$ - sensor response to the jth bunch,

Q$_j$ - charge of the jth bunch delivered to the beam dump.



(a) (b)

Figure 6: Signals normalized to the bunch charge delivered to the dump (Eq. 1) from a diamond sensor (a) and a sapphire sensor (b) as a function of the distance to the beam during the beam steering procedure. The density of the points in the plot is color coded.

The distance to the beam for a sensor is defined as the distance from the center of gravity of the beam detected by the BPM to the center of the inner edge of the sensor in the sensors plane. When the beam is centered inside the beam pipe the distances to all BHM sensors are equal to 50 mm. If the beam was close enough, for the sensors of both types the following was observed: the closer the beam the higher the signal from the sensor. The density of the values of the signal for a certain distance (color coded in Figure 6) shows the trend for the dependence. Under the same conditions the signals from the sapphire sensors were lower than the ones from diamonds. This enchanced the dynamic range of the system.

3.2 Normal multi-bunch operation

The signal observation as a function of beam position was continued during normal multi-bunch machine operation. In this regime the bias voltage for the sensors had been lowered down to 10 V for diamonds and 100 V for sapphires in order not to reach the current limit of the voltage source. Figure 7 shows two periods when the beam was in slightly different positions. The sweeping with usual radius was on. The beam was off-centered into the down-right position. All four diamond sensors and two closest sapphire sensors showed the significantly higher signals when the beam approached.

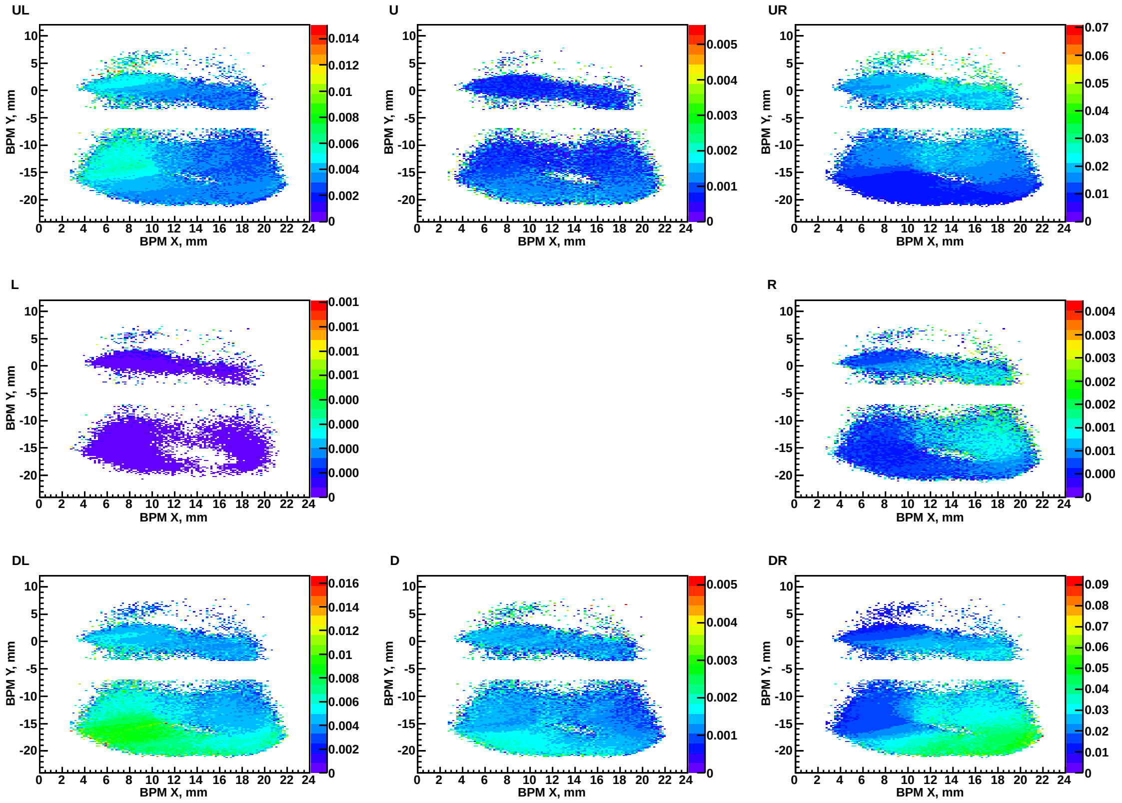
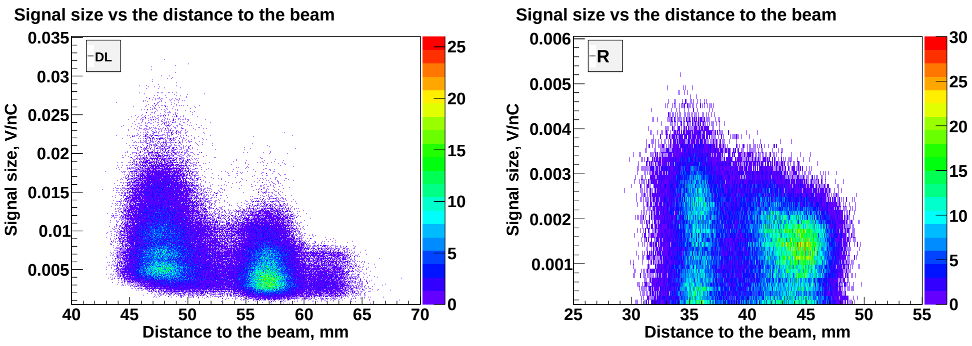


Figure 7: Average signals from all the BHM sensors normalized to the bunch charge delivered to the dump (in V per nC) as a function of the beam position during normal multi-bunch operation. Two periods with slightly different beam positions (considering sweeping) are shown.

The signals from the sensors were larger when the distance to the beam became smaller as shown in Figure 8.



(a) (b)

Figure 8: Signals from a diamond sensor (a) and a sapphire sensor (b) as a function of the distance to the beam during normal multi-bunch machine operation. The density of the points in the plot is color coded.

3.3 Conclusions

The BHM for FLASH with pCVD diamond and artificial sapphire sensors has been commissioned and proved to be operational. All the sensors responded to the presence of the beam, the response depended on the beam position thus giving the possibility to detect dangerous conditions when the beam approached the beam pipe. The signals from the sapphire sensors were lower enhancing the dynamic range of the system in combination with the more sensitive diamond sensors. In such a way the BHM is capable to detect small beam offsets and changes in beam halo distribution by diamond sensors and keep the functionality at larger offsets using sapphire sensors.

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