DIAMOND PARTICLE DETECTOR PROPERTIES DURING HIGH FLUENCE MATERIAL DAMAGE TESTS AND THEIR FUTURE APPLICATIONS FOR MACHINE PROTECTION IN THE LHC

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Abstract

Experience with LHC machine protection (MP) during the last three years of operation shows that the MP systems sufficiently protect the LHC against damage in case of failures leading to beam losses with a time constant exceeding 1ms. An unexpected fast beam loss mechanism, called UFOs [1], was observed, which could potentially quench superconducting magnets. For such fast losses, but also for better understanding of slower losses, an improved understanding of the loss distribution within a bunch train is required [2]. Diamond particle detectors with bunch-by-bunch resolution and high dynamic range have been developed and successfully tested in the LHC and in experiments to quantify the damage limits of LHC components. This paper will focus on experience gained in use of diamond detectors. The properties of these detectors were measured during high-fluence material damage tests in CERN's HiRadMat facility. The results will be discussed and compared to the cross-calibration with FLUKA simulations. Future applications of these detectors in the LHC to understand beam losses and to improve the protection against fast particle losses will be discussed.

HiRadMat FACILITY

The High-Radiation to Materials (HiRadMat) facility is dedicated to irradiate materials and accelerator components with high-intensity, pulsed proton or ion beams. The beam is extracted from the **S**uper **P**roton **S**ynchrotron (SPS) with an energy of 440 GeV/c and an intensity from so-called pilot bunches of 1×10^8 protons up to 288 bunches of $\sim 1.7 \times 10^{11}$ protons/bunch, i.e. in total: 4.89×10^{13} protons [3].

HIGH-FLUENCE EXPERIMENTS AND DIAMOND DETECTORS IN HIRADMAT

In 2012, three material damage test experiments with diamond detectors as part of the beam instrumentation were performed. Diamond detectors were used to measure the energy deposited by secondary particles. In the first experiment, called LPROT, copper cylinders were irradiated to study the damage potential of high energy beams and to verify simulations which have shown that the full impact of the LHC beam onto solid copper can cause a hydrodynamic tunneling effect [5]. In the second experiment, called UA9CRY, a silicon crystal, in the future probably used as primary deflector in the LHC collimation system, was irradiated to measure its robustness and integrity and to evaluate the risk associated to the installation of such a crystal in the LHC [6]. During the last experiment, called TPSG4, a SPS-diluter was irradiated. The diluter protects the septum magnets in the SPS against damage in case of a kicker failure. The robustness of the device and its protection capability was tested.

For these experiments three diamond detectors specially designed for high-fluence experiments in collaboration with CIVIDEC (Vienna, Austria) were used [4]. They consist of a pCVD diamond with a diameter of 5 mm, a thickness of 100 μm and gold electrodes with a diameter of 3 mm. The bias-voltage was 100-130 V, i.e. 1-1.3 V/μm. The charge collection efficiency (CCE) was assumed to be 4.75 %. Capacitors of 111 nF are installed to compensate for the detector discharge. The PCB with the diamond is mounted completely RF shielded and fitted in an aluminium box with a size of 5 x 5 x 1.5 cm^3. The circuit diagram of the used measurement system can be found in Fig. 1. The detectors have a nanosecond time resolution and therefore they are able to resolve bunch-by-bunch losses.

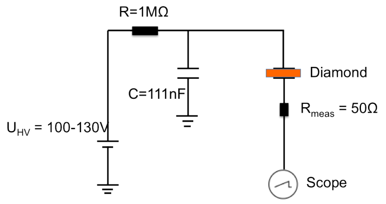

Figure 1: Circuit diagram of a diamond detector.

EXPERIMENTAL RESULTS

Figure 2 shows the measured signal for 144 bunches impacting on the target of LPROT. Figure 3 shows a zoom into the first bunches. This indicates the nanosecond time resolution of these detectors as the signals for single bunches were clearly resolved. The bunch spacing was 50 ns. The amplitude of the signal decreases after the first bunches. As the intensity of the bunches varies by less than 10 %, the drop in the signal is caused by the detector electronics. It can be explained by the discharge of the capacitor. To reduce the discharge effect, the detectors will be equipped

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with larger capacitors. A PSPICE simulation showed that by increasing the capacitance from the current 111 nF up to the maximum available capacitance of 470 nF will limit the decrease of the peak voltage down to 3 % from currently 15 %. Also polarization effects in the diamond contribute to the decrease of the signal.

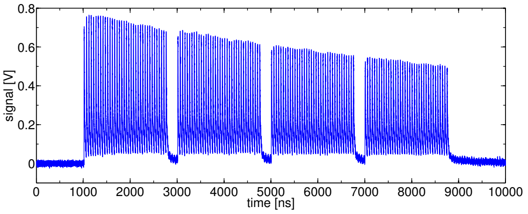

Figure 2: Signal of the diamond detector for 144 bunches impacting on the target of LPROT. Depicted is the measured voltage at 50 Ohm versus time for four bunch trains with 36 bunches of 1.5×10^{11} p each.

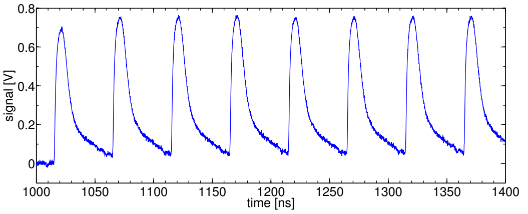

Figure 3: Zoom into the first bunches of the 144 bunches shot with a bunch spacing of 50 ns.

The data can be compensated for the discharge of the capacitor and the polarization effect. The uncorrected (blue) and corrected (green) number of charges per bunch of a 288 bunches shot on the target is shown in Fig. 4. Both curves are offset corrected.

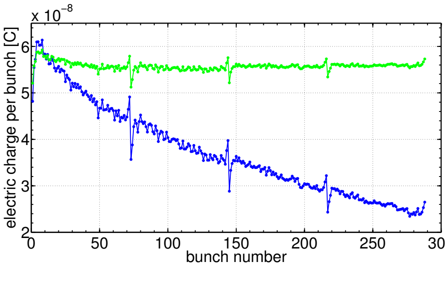

Figure 4: Charge per bunch for a 288 bunches shot on the target of TPSG4. The blue line shows the measured charge per bunch collected in the diamond particle detector. The green line is corrected for the discharge of the supply capacitor in the detector‘s electronics and polarization effects.

The offset of the signal is due to pile-up of the signals for the different bunches and due to leakage currents through the diamond. After the last bunch there is a decay in the signal over 1μs visible. This is caused by free trapped electrons in the diamond.

ALIGNMENT WITH DIAMOND DETECTORS

For the first time, diamond particle detectors were used to align a target to the beam. A stainless steel strip of the UA9CRY experiment was moved in steps through the beam and the created secondary particles were detected by two diamond detectors located downstream symmetrically around the beam axis. Figure 5 shows the measured peak voltage of the diamond detectors versus the position of the steel strip for different step sizes, normalized to the intensity. The maxima of these curves indicate the beam position. The amplitude was of the left and right detector is different due to the fact that the diamond detectors had a different sensitivity.

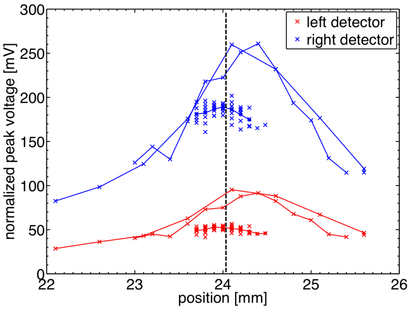

Figure 5: Peak voltage in the two diamond detectors (blue, red) versus position of the strips. The maxima of these curves indicate the beam position (marked with the dashed line). The amplitude was of the left and right detector is different due to the fact that the diamond detectors had a different sensitivity.

COMPARISON TO SIMULATIONS

FLUKA [7, 8] simulations were performed to evaluate the detector response. In these simulations the expected deposited energy in the diamond was calculated. The response per particle R_{pp} can be calculated as

$$R_{pp} = \frac{E_{dep}}{E_{ion}} \times q \times CCE, \tag{1}$$

where the deposited energy in the diamond is E_{dep}, the ionisation energy of a diamond is $E_{ion} = 13.1$ eV, the elementary charge of an electron is q and the charge collection efficiency is $CCE = 4.75\%$ [9]. The calculated R_{pp} for the three experiments can be found in Table 1. The collected charge as predicted by simulations of the detector versus the measured collected charge for the three experiments is depicted in Fig. 6. For LPROT (black dots) and the low intensity shots of TPSG4 (red dots) the measured results are in good agreement with the expectations. The high intensity shots of TPSG4 with 9.5×10^{10}, 1.1×10^{11}, 1.2×10^{11} p per bunch (red stars) show a lower than expected collected charge. This indicates a saturation of the diamond detector. Also the low fluence experiment UA9CRY (blue stars) shows a lower than expected collected charge. This indicates probably the sensitivity limit of the detector. The green line indicates the expected collected charge.

Table 1: Simulated and measured R_{pp} for the three experiments. For the UA9CRY experiment only the irradiation of the stainless steel strip was taken into account.

Experiment	simulated response per primary particle [C/pp]	average measured response per primary particle [C/pp]
LPROT	5.38×10^{-19}	5.07×10^{-19}
TPSG4	1.96×10^{-18}	2.8×10^{-18} (low int.)
		4.7×10^{-19} (high int.)
UA9CRY	4.4×10^{-22}	1.6×10^{-23}

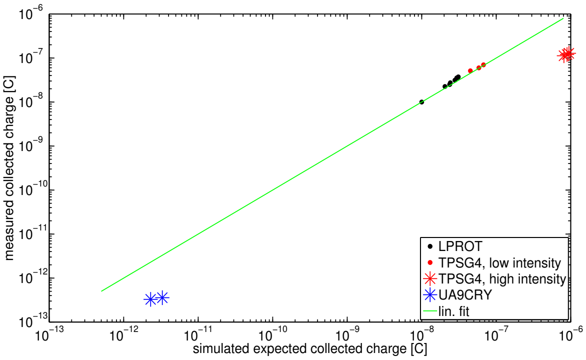

Figure 6: Simulated collected charge of the diamond versus the measured charge for the three described experiments: high intensity TPSG4 (red stars), UA9CRY (blue stars), LPROT (black dots) and low intensity TPSG4 (red dots). The green line indicates the expected collected charge.

Equation 1 can also be used to calculate the CCE, instead of assuming a constant value. The results show that the CCE in LPROT and low intensity TPSG4 agreed well with the assumed value of 4.75 %. For UA9CRY and high intensity TPSG4 the CCE was found to be equal to ∼ 1.6 % and ∼ 1.17 %, respectively, significantly less, due to the reasons stated earlier.

FUTURE USE OF DIAMOND DETECTORS FOR MACHINE PROTECTION ISSUES

Diamond particle detectors with their nanosecond time resolution could possibly be an additional way to measure the abort gap population in the LHC, detect bunch-by-bunch losses and fast losses caused by UFOs. Due to their high radiation hardness, heat resistance, small size and absence of active cooling, these detectors can be installed in different parts of the machine. It is planned to use diamond detectors for further machine protection studies like beam halo measurements.

CONCLUSIONS AND OUTLOOK

Diamond particle detectors have been successfully tested in CERN‘s HiRadMat facility, they were used during three experiments performed in 2012. Detector output signals were measured over 6 orders of magnitude. The results show their nanosecond time resolution and their agreement to simulations over 1 order of magnitude. In this paper the detector signal for single and multi-bunches have been presented and the decrease of the signal for multi-bunches was explained. To compensate for this effect, the increase of the capacitance in the detector was proposed. The efficiency of the detectors drops from 4.75 % to ∼ 1.17 % for high fluence experiments above 5×10^9 charged particles through the diamond. The UA9CRY experiment indicated the lower sensitivity limit of the used diamond detectors, which needs further investigations to know the exact limit. Diamond detectors have a high potential for machine protection applications. For the future it is planned to further characterize the diamond detectors with an electron beam to measure the charge collection distance (CCD) as well as to evaluate the CCE of the used diamond detectors.

ACKNOWLEDGMENT

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