# 3 MeV Proton Irradiation of Commercial State of the Art Photonic Mixer Devices

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***Abstract*—Ten identical novel commercial off-the-shelf near range sensors whose working principle is based on a time of flight measurement were irradiated with 3 MeV protons. Degradation effects were observed from $7{\cdot}10^{10}$ p/cm$^2$ on.**

## I. Introduction

Providing reliable and cost effective near range distance information about non-cooperative objects in space flight could be interesting to several space missions in the future. One could envisage for example docking to or servicing of non-cooperative objects, formation flying in small sat constellations and also rover missions. The growing interest in this technology is indicated by recent investigations.

In the PRISMA mission performed by the German Aerospace Center in collaboration with the Swedish Space Corporation a dual satellite mission was launched to demonstrate formation flying and on-orbit servicing in low earth orbit. They have shown an autonomous rendezvous down to 40 m only by GPS in 2011 [1].

Furthermore, the number of objects in the space debris population is increasing and the need for an active space debris removal becomes more important [2], [3]. Several active removal techniques were compared in [4] and [5] and the most promising techniques need a docking mechanism to capture the uncooperative target.

Docking to a tumbling non-cooperative object requires a robust sensor system. Such a sensor system needs to be reliable in changes of temperature, light conditions, object material and insensitive against radiation effects.

In case of space debris, ESA and NASA studies show that for a continued use of low earth orbit 5-10 objects need to be removed every year [4], [6]. This fact enforces the demand for an affordable system, especially since the question of the financial responsibility is still unclear.

To contribute to the development of a reliable and cost effective sensor system, we are investigating a combination of commercial off-the-shelf (COTS) distance sensors with different measurement principles. We expect to proof that a fusion of the measurements of three different sensors can help to counteract the degradation of the sensors under space environmental conditions and maintain the accuracy of the range measurements. We have chosen state of the art Photonic Mixer Device (PMD) sensors, RADAR sensors and a stereo camera system to investigate their suitability for a sensor combination.

The use of a PMD sensor for a robust pose estimation and motion prediction of small satellites in space was already conducted up to 20 m in [7], [8], [9]. These investigations demonstrate an algorithm which can identify a non-cooperative object to be tracked autonomously and is capable of dealing with moving rates similar to those expected in close range maneuver. Irradiation tests on PMDs proofing their robustness against radiation effects were to our knowledge not published yet.

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For our investigation we have chosen the EPC610 from Espros Photonics AG due to its low power consumption and small form factor.

The small thickness of the sensor and an easily accessible 3 MV Tandetron accelerator encouraged us to perform proton irradiation tests as a first step in our investigations. The aim of this work is to reveal the sensitivity against low energy proton latch ups and furthermore give an impression of the total ionizing dose hardness of the chosen PMD sensor. Here we only present the results of the 3 MeV proton irradiation. For a trustworthy interpretation of the radiation effects, further total ionizing dose tests with a $^{60}$Co source will be done. This summary only highlights the most interesting test results.

## II. Devices Under Test

The EPC610 sensor has an 8×8 pixel array on a 40 µm pitch. These pixels based on a combined CCD/CMOS 150 nm process are capable of demodulating intensity-modulated optical signals in parallel. By integrating them in an array on one single chip real-time 3D-imaging becomes possible by indirectly measuring the time-of-flight. The sensor is a system on chip with built-in data acquisition, signal conditioning, analog digital converter (ADC) and signal processing. It has several internal power management units and a Serial Peripheral Interface (SPI). For range measurements additional external light sources are necessary. The operational wavelength is 850 nm. The sensor measurement functionality supports distance and ambient light measurements with variable integration times and on-chip temperature measurement for drift compensation [10]. Figure 1 presents the test board developed for the radiation tests.

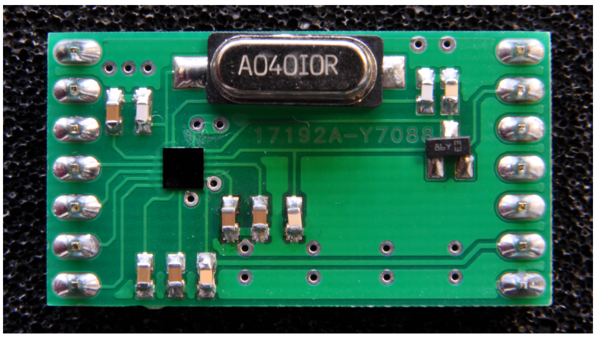


Fig. 1. Experimental test board with the EPC610 sensor chip for proton radiation testing.

The maximum operating range of the EPC610 depends on the modulation frequency of the transmitted signal. With a modulation frequency of 2.5 MHz a theoretical distance up to 60 m could be measurable. We conducted our measurements for degradation monitoring up to 12 m using a 10 MHz modulation frequency.

## III. Irradiation Test Plan

Proton tests with 3 MeV were done at the University of Jena. We determined with SRIM [11] a linear energy transfer (LET) of 0,093 MeV cm$^2$/mg for the first 60 µm, which exceeds the maximum sensor thickness of 50 µm. The square cross section area of the beam has an edge length of 9 mm. The EPC610 chip size is 3 mm × 3 mm.

Overall, we irradiated 10 identical sensors with an average flux of $1.3 \cdot 10^9$ p/cm$^2$/s $\pm\, 0.3 \cdot 10^9$ p/cm$^2$/s. Irradiations were done under vacuum. Fluences ranging from $2.5 \cdot 10^{10}$ p/cm$^2$ up to $5.0 \cdot 10^{11}$ p/cm$^2$ were applied. Thus, the dose absorbed in the sensors during our tests ranged between 37 krad(Si) and 750 krad(Si).

We decided to irradiate two sensors each up to the following fluences:

- $\Phi_1 = 2.5 \cdot 10^{10}$ p/cm$^2$
- $\Phi_2 = 5.0 \cdot 10^{10}$ p/cm$^2$
- $\Phi_3 = 1.0 \cdot 10^{11}$ p/cm$^2$
- $\Phi_4 = 1.5 \cdot 10^{11}$ p/cm$^2$
- $\Phi_5 = 5.0 \cdot 10^{11}$ p/cm$^2$

Distance measurements during the irradiation could not be performed due to the small size of the vacuum chamber of the test facility. Instead, distance measurements were carried out before and after the irradiation.

The following parameters were continuously observed during the test:

- Current consumption
- Modulation frequency
- ADC output of internal temperature sensor
- Ambient light
- Saturation of pixel

Additionally, precautions were taken to ensure that the device under test is not damaged due to latch ups during the irradiation. A latch up protection circuit was integrated into the test setup. For annealing, the sensors were stored after irradiation at a constant temperature of 30°C. Performance tests were carried out 100 h and 260 h after irradiation.

## IV. RESULTS

During the tests, no latch up has occurred in all of the 10 PMD sensors. The communication failed at a fluence of around $1.5 \cdot 10^{11}$ p/cm$^2$. All 6 PMD sensors which were irradiated with a fluence over $5.0 \cdot 10^{10}$ p/cm$^2$ have shown a significant error of the EPC610 internal temperature measurement after the exposure to a fluence of around $7.0 \cdot 10^{10}$ p/cm$^2$ (Figure 2). The ADC raw value of the internal temperature measurement shows a drop of around 650 least significant bit (LSB). Converted to a real temperature this drop would be equal to around 190°C, even though the temperature of the test board remained constant at room temperature. Presented in Figure 3, no significant rise in current consumption was observed up to $1.5 \cdot 10^{11}$ p/cm$^2$. Until the failure of the EPC610, the current consumption increased by 80 % up to 22 mA.

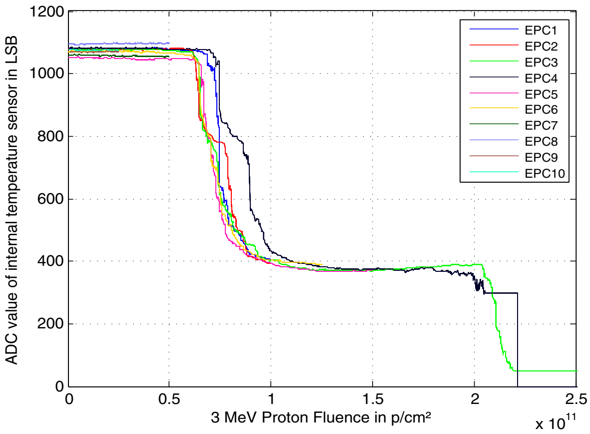


Fig. 2. The raw ADC output value of the internal EPC610 on chip temperature sensor during the irradiation shows a drop at around $7.0 \cdot 10^{10}$ p/cm$^2$ of circa 650 LSB.

Distance measurements up to 12 m after irradiation and annealing indicate no remarkable drifts. Post irradiation measurements indicate a higher noise floor. Figure 4 shows a simplified block diagram of one pixel. Incident photons of the modulated light reflected from the object generate electron hole pairs in the pixel under the photo gates. Applying appropriate control voltages to the photo gates, a characteristic potential distribution is built up in the buried channel. This potential is forcing the charges to drift to the left or right side where the photo elements detect the charges [12]. The photo gates are synchronously toggled with the modulation voltage $U_m$. A reset applies a defined voltage to the capacitors parallel to the photo elements. During the exposure the collected charges decrease the capacitor voltage. After a certain exposure time the voltage readout is done differentially by an ADC.

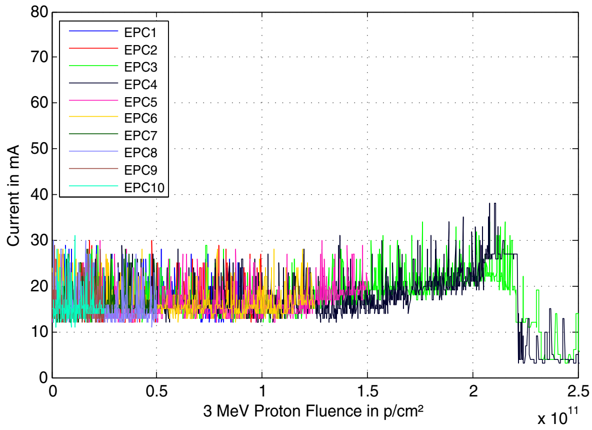


Fig. 3. The current consumption during the irradiation of the EPC610 sensor remained constant up to circa $1.5 \cdot 10^{11}$ p/cm$^2$.

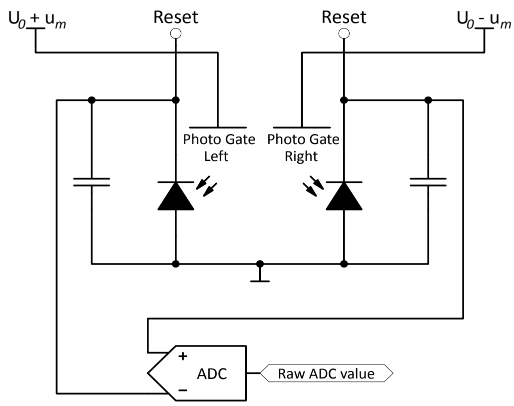


Fig. 4. Simple block diagram of a pixel of the EPC610 sensor, showing the photo diodes with the capacitors, the photo gates and the read out ADC.

If there is no backscattered modulated light, ideally the ADC output value should be zero. However, due to tolerances, the value is near around zero. This is depicted in the first column of Figure 5. Without any modulation light the ADC values of the ten EPC610 sensors are measured in a dark environment. Each colored square represents an image with a resolution of 8×8 pixels. After irradiation an obvious rise of the ADC value depending on the applied fluence is shown in the second column. The three sensors which failed after the irradiation test are coloured green. Annealing of 100 h and 260 h shown in the third and fourth column indicate no decrease of the ADC values. One of the two sensors irradiated with a fluence of $1.5 \cdot 10^{10}$ p/cm$^2$ was again operating after 100 h annealing.

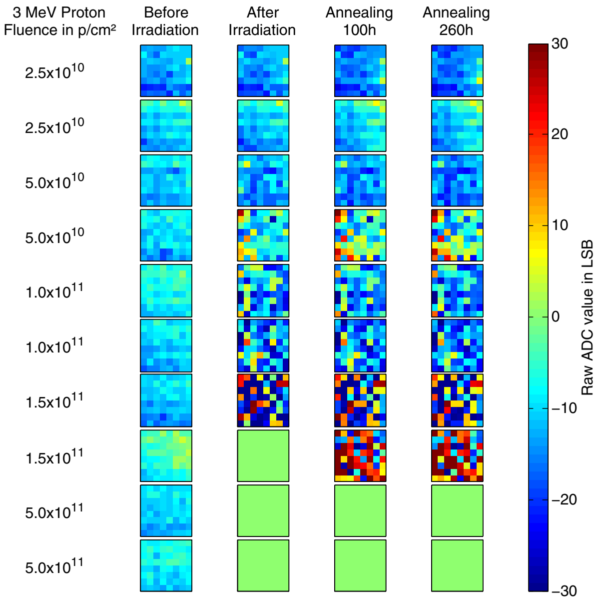


Fig. 5. 8×8 pixel images of each EPC610 sensors before and after irradiation and with annealing recorded without modulation light and in a dark environment.

## V. Conclusion

These radiation tests of the ten PMD sensors with 3 MeV protons suggest an immunity against low energy proton induced latch ups and a sufficient total dose hardness for short time missions.

Due to the sensitivity of the distance measurement against the sensor temperature, a calibration needs to be applied. Therefore, a precise knowledge about the correct internal temperature is necessary. An error as observed during this irradiation could lead to a useless distance result because of the calibration correction. Nevertheless, this phenomenon could maybe be used as a health indicator of the EPC610 sensor.

An increase of the pixel noise results in a lower signal to noise ratio. To counteract this degradation effect, an extended exposure time or a more powerful light source is needed. The EPC610 sensor is able to adjust its exposure time which could help to mitigate this degradation effect.

As already mentioned, this summary only highlights the results of our irradiation tests. For a trustworthy interpretation of the observed effects, a total ionizing dose test with a $^{60}$Co source is scheduled next.

## VI. Acknowledgments


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## References


[1] S. D'Amico, J.-S. Ardaens, and R. Larsson, "Spaceborne autonomous formation-flying experiment on the prisma mission," *Journal of Guidance, Control, and Dynamics*, vol. 35, no. 3, pp. 834–850, 2012.

[2] F. K. Chan, *Spacecraft collision probability*. Aerospace Press El Segundo, CA, 2008.

[3] B. B. Virgili and H. Krag, "Analyzing the criteria for a stable environment," in *AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, USA. AAS11*, vol. 411, 2011.

[4] K. Wormnes, R. Le Letty, L. Summerer, R. Schonenborg, O. Dubois-Matra, E. Luraschi, A. Cropp, H. Krag, and J. Delaval, "Esa technologies for space debris remediation," in *6th IAASS Conference:Safety is Not an Option, Montrel*, 2013.

[5] C. Trentlage and E. Stoll, "The applicability of gecko adhesives in a docking mechanism for active debris removal missions," 2015.

[6] J.-C. Liou, "An active debris removal parametric study for leo environment remediation," *Advances in Space Research*, vol. 47, no. 11, pp. 1865–1876, 2011.

[7] T. Tzschichholz, L. Ma, and K. Schilling, "Model-based spacecraft pose estimation and motion prediction using a photonic mixer device camera," *Acta Astronautica*, vol. 68, no. 7, pp. 1156–1167, 2011.

[8] L. Regoli, K. Ravandoor, M. Schmidt, and K. Schilling, "On-line robust pose estimation for rendezvous and docking in space using photonic mixer devices," *Acta Astronautica*, vol. 96, pp. 159–165, 2014.

[9] T. Tzschichholz, T. Boge, and K. Schilling, "Relative pose estimation of satellites using pmd-/ccd-sensor data fusion," *Acta Astronautica*, vol. 109, pp. 25–33, 2015.

[10] EsprosPhotonicsAG, "Datasheet epc610," 2015.

[11] J. F. Ziegler, M. D. Ziegler, and J. P. Biersack, "Srim–the stopping and range of ions in matter (2010)," *Nuclear Instruments and Methods in Physics Research Section*, vol. 268, no. 11, pp. 1818–1823, 2010.

[12] B. Büttgen and P. Seitz, "Robust optical time-of-flight range imaging based on smart pixel structures," *Circuits and Systems I: Regular Papers, IEEE Transactions on*, vol. 55, no. 6, pp. 1512–1525, 2008.