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Opening new windows for SiPMs in space experiments with the BETA ASIC

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Compactness, robustness and low-voltage operation are some of the characteristics that make silicon photomultipliers (SiPMs) attractive for space applications. Signals recorded by SiPMs on board satellites must be processed and digitized minimizing the size, cost and power consumption of the electronics. The BETA ASIC is a fully programmable chip designed to amplify, shape and digitize the signal of up to 64 channels, with a power consumption of only ~1 mW/channel. Thanks to its dual path gain, the BETA chip is capable of resolving single photoelectrons (phes) with SNR>5, while at the same time achieving a dynamic range of ~3500 photoelectrons. In this way, BETA can provide a cost-effective solution for the readout of SiPM in space missions. We briefly describe the key characteristics of the BETA ASIC, and present the evaluation of its performance when reading out an array of SiPMs, as well as the results of a test beam where the BETA was used for the readout of the fiber tracker (FIT) of the HERD experiment. Finally, we focus on the new possibilities for using SiPMs in space opened by the BETA ASIC beyond HERD, like the development of a radiation monitor for LISA.

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1. Introduction

Silicon Photomultipliers (SiPMs) are fast photosensors sensitive to extremely low photon fluxes with a photodetection efficiency that can be higher than 50%. Their robustness, compactness and low-voltage operation makes them particularly suitable for space missions [1] where volume and weight are always limited. In general, space experiments and applications employing SiPMs will require their signal to be processed and digitized minimizing the power consumption, the cost and volume of the electronics. In this context we developed BETA, a dedicated Front-End ASIC designed for SiPM readout in space applications [2].

The BETA ASIC will perform the readout of two subsystems of the future High Energy Cosmic-Radiation Detection (HERD) experiment [3]: The Fiber Tracker (FIT) [4] and the Plastic Scintillator Detector (PSD) [5]. The FIT will use scintillating fiber mats coupled to highly segmented SiPM arrays to measure the track of incident particles. The PSD will employ plastic scintillators coupled to SiPMs of different sizes to trigger gamma-ray events, providing a veto for charged particles. Both PSD and FIT require high signal-to-noise ratio (SNR) to resolve minimum ionizing particles and and high dynamic range for charge reconstruction. The FIT will be equipped with more than 200k SiPMs and hence demands to digitize as many channels as possible with a single ASIC. PSD will employ less SiPMs, but will require a relatively fast trigger signal from all channels to provide the trigger and veto signals. In this context we designed different versions of the ASIC, a 64-channel one that will be employed in the FIT and a 16-channel one with 16 indepent trigger ouputs that will be employed in the PSD.

In this work we provide a short description of the ASIC, its evaluation board and briefly describe the main differences between the different versions we developed. We also present results of the evaluation of its performance and discuss other potential applications of the ASIC, which are not necessary limited to space-based instrumentation.

2. The BETA ASIC

BETA is a 16-channel ASIC for SiPM readout designed in a CMOS 130 nm technology with a total area of 3.38×1.96 mm^2. Its main objective is to perform the signal processing and digitization with very low power consumption, large dynamic range and good SNR down to the single-photoelectron (phe) level. It outputs one ore more trigger signals and the charge collected by at least 16 SiPMs, providing a single serialized output with the digitized data. BETA has a dual-gain path with automatic path selection that allows having at the same time SNR for events of a few phe and high dynamic range up to a few thousand phes. For the details on the ASIC architecture, please see [2] and the dedicated article that is expected to be published soon.

Three different versions of the ASIC were designed:

- BETA-16R1, the initial release that was used to evaluate and optimize the ASIC performance. It provides a digital output with the collected charge in 16 channels and a trigger signal with the OR of the 16 channels.
- BETA-16R2, which has recently been released and in addition to the charge of 16 channels will also output 16 trigger signals (one per channel). This version will be used in the PSD.

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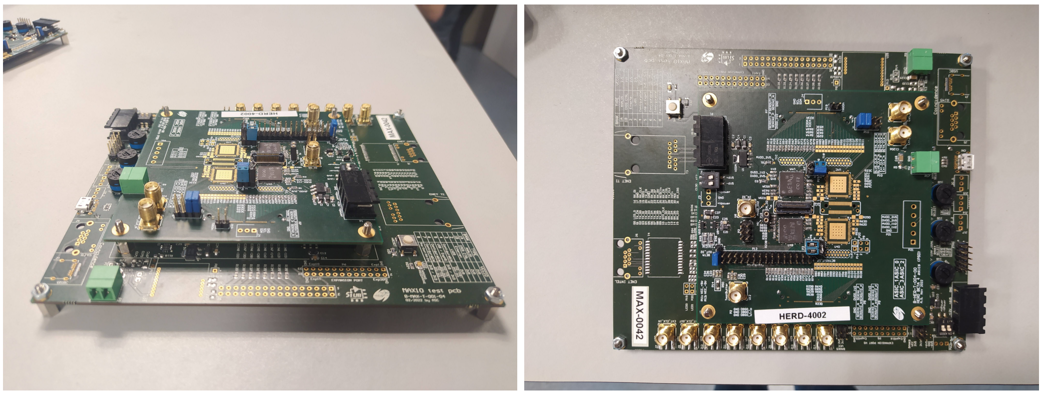

Figure 1: BETA measurement kit, which consists of a B-HER board that holds the BETA ASICs (on top) and a B-MAX board that holds an FPGA (on the bottom).

- BETA-64, which is under development and will provide one trigger per ASIC as BETA-16R1, but will be able to digitize up to 64 channels. This version will be employed in the FIT.

3. The BETA evaluation board

We developed the BETA measurement kit, available on request, that is almost plug-and-play and that can be used to easily configure the ASIC and exploit it functionalities. It consists of two printed circuit boards (PCBs): the B-HER board and the B-MAX board. Figure 1 shows the BETA measurement kit for the BETA-16R1.

The B-HER board can hold up to 4 ASICs and has dedicated connectors to plug-in SiPM arrays. An additional pin input allows connecting a single SiPM. Finally, the user can also inject an electric signal through a dedicated SMA input. The board also holds a probe that allows monitoring the different stages of the analog signal in all the channels of one of the ASICs.

The B-MAX board contains an FPGA that is used to control and configure the ASIC. It can be connected by USB to a PC where the user can control via software the different registers of the ASIC, launch acquisitions and receive the digitized data.

Among the several functionalities that the ASIC offers, the user will be able to configure the gain of the preamplifiers and shaper, the individual channel thresholds and to work with different trigger modes: internal, external, triggered by the FPGA clock or coincidence triggers of two or more ASICs. He will also be able to adjust the threshold of the automatic path selection that decides whether the high-gain (HG) or low-gain (LG) path will be digitized or even to override this path selection forcing one of the two gains.

4. Performance evaluation

We evaluated the performance of the BETA ASIC using the measurement kit described in section 3. We tested our systems with different SiPMs. The BETA measurement kit and the SiPMs were placed inside a dark box, where we flashed the sensors with a 405 nm pulsed laser driven by a PiL040X (jitter $<$ 3 ps and $<$ 45 ps pulse width). For each laser pulse the BETA ASIC digitized the charge measured in all the relevant channels.

The main generic performance parameters of the BETA are summarized in table 1. It not only fulfills the initial requirements imposed by the HERD mission, also its large dynamic range and low power consumption make the ASIC suitable for most space applications. Note that the power consumption is expected to be lower than 1 mW/channel in the 64-channel version of the ASIC (BETA-64).

Number of channels	$16^{a}/64^{b}$
Power consumption	1.4 mW/channel^{a}
PreAmplifier Gain (HG path)	6 – 70
PreAmplifier Gain (LG path)	0.25 – 3.75
SNR (single-phe)	$\sim 5^{c,d}$
Dynamic Range	>3800 phe^{c,d} / ~10 mA peak^{d}
Linearity Error (full range)	< 3%
Maximum operation rate	10 kHz

Table 1: Summary of the main performance parameters of the BETA ASIC.
HG: High Gain, LG: Low Gain.
^{a}BETA-16R1 and BETA-16R2
^{b}BETA-64
^{c} for SiPMs with a microcell size of 10 μm
^{d} with the nominal gain of the preamplifiers.

Figure 2 shows the charge spectra obtained in a single ASIC used to readout 16 of the 128 SiPMs of one of the Hamamatsu S13552-10 custom-made arrays that will equip the FIT modules and that we tested in a dedicated test beam at CERN. Each channel of the array has 3749 (23 × 163) microcells of 10 μm [4]. This array, with its small microcell size is optimized to achieve a large dynamic range in a few mm^2. Despite SiPMs with small microcells have a lower gain than those with larger ones, with this array we can achieve a SNR of ∼ 5 at the single-photoelectron level. As it can be seen in the plot, this SNR is enough to clearly identify at least the first ten phe peaks. These values were obtained using the nominal gain of the BETA preamplifiers: ∼10 for the HG path, ∼0.45 for the LG path. A higher SNR can be achieved using a higher gain, at the expense of a lower dynamic range.

We also characterized the BETA using a single Hamamatsu S13360-1350CS SiPM (with an area of ∼ 1.3× 1.3 mm^2). With a 50 μm microcell size, this SiPM has an intrinsic higher gain than the one used for the FIT and then we could achieve a SNR of ∼ 10 using the nominal gain of the BETA. Figure 3 shows a single-phe spectrum obtained with this sensor. To produce this plot we intentionally varied the intensity of the laser during the acquisition and we overrode the path selection forcing the HG path, in order to show that with the ASIC we are capable of identifying peaks corresponding to events of 1 to above 20 phes.

Even if the ASIC was not designed for fast-timing applications, the time resolution of the system (SiPM + ASIC) can be studied using the trigger signal, which is an OR of the 16 channels. The output is a binary pulse where the information of the arrival time of the signal is encoded in its rise time, while its width is related (non linearly) to the amplitude of the signal. As can be seen in the top panel of Figure 4, the number of phes recorded in an event can also be identified if we plot

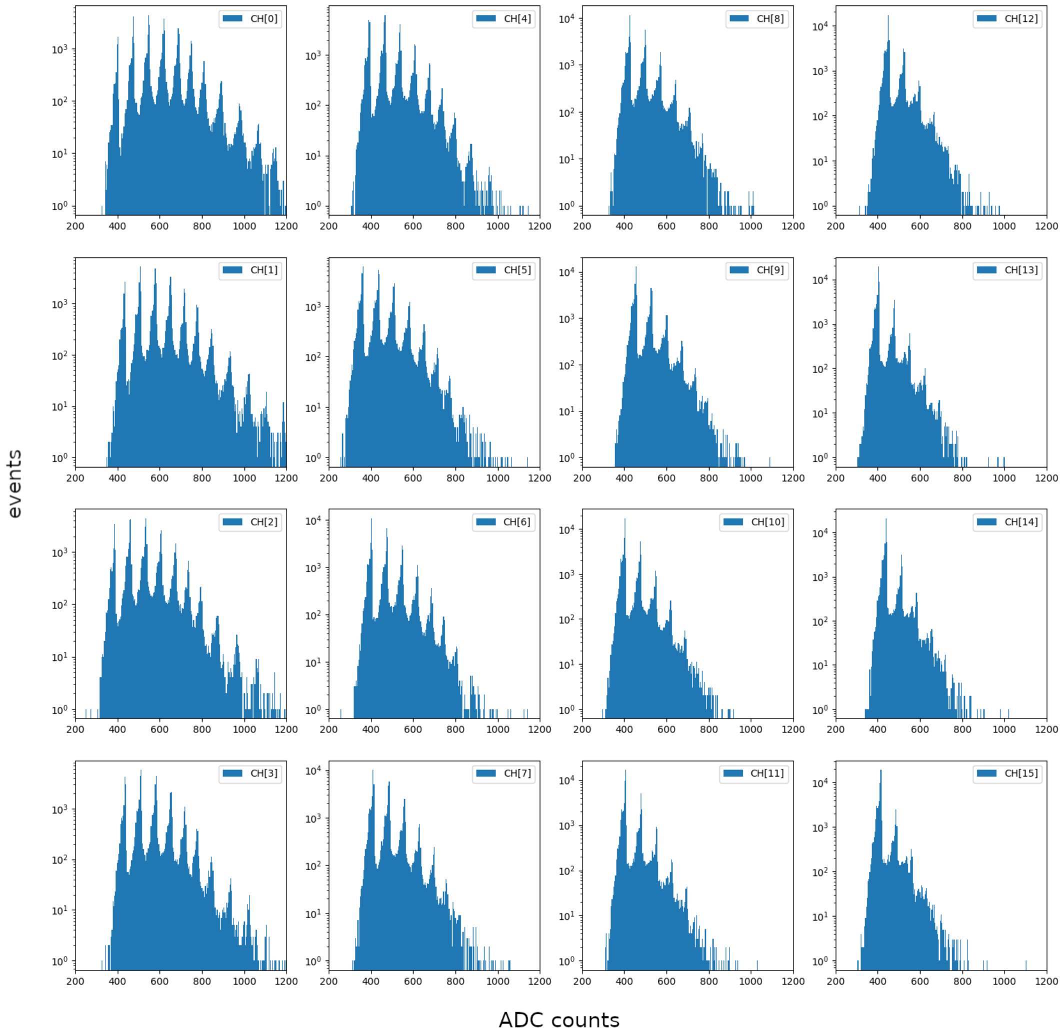

Figure 2: Single-phe spectra recorded in 16 channels of the Hamamatsu S13552-10 array that were exposed to laser pulses.

the arrival time of the trigger signal (delay with respect to the trigger given by the laser) versus its width. With this information we can evaluate the time resolution of the system for input signals of different intensities. With the S13360-1350CS SiPM the time resolution can go from $\sigma \simeq 1$ ns for signals of a single phe to below 200 ps for signals of 10 phes.

5. Discussion

In this work we described the key characteristics of the BETA ASIC and evaluated its performance with two different sensors from Hamamatsu: the 13552-10 array developed for the FIT and a commercial S13360-1350CS single SiPM. With the first one, which has a microcell size of 10 μm we could show that despite the intrinsic low gain of these SiPMs the BETA is capable of digitizing the signal of 16 channels with excellent SNR. We could also exploit the full dynamic range of the sensor: the SiPM, which has ~3800 microcells would saturate before the ASIC does. With the

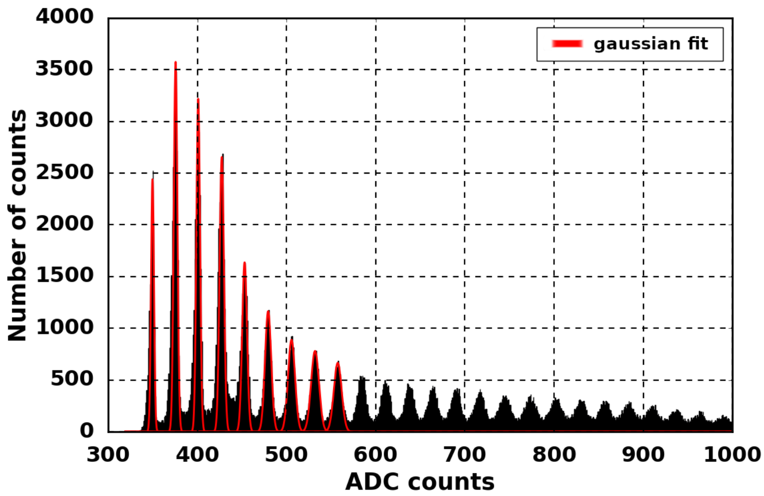

Figure 3: Single-phe spectrum recorded with a S13360-1350CS SiPM). The intensity of the laser was modified during the acquisition to obtain pulses from 1 to above 20 phe.

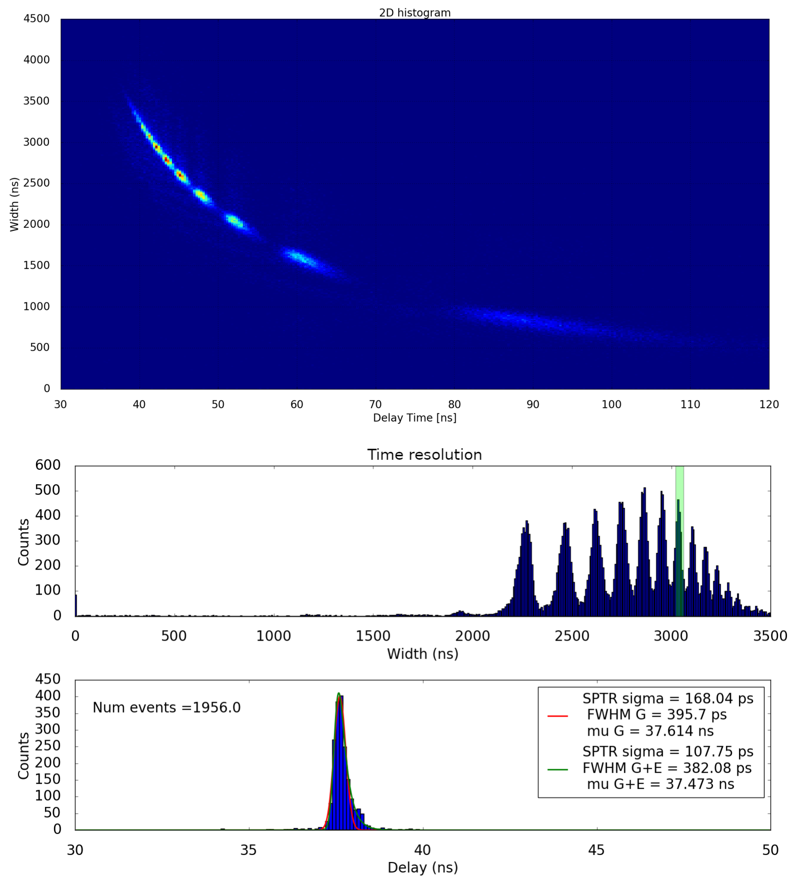

Figure 4: Top: Arrival time (delay) versus width of the BETA trigger signal. **Center:** Width distribution of the trigger signal for events over 3 phes. **Bottom:** Arrival time distribution for events of 10 phes. It has been fitted twice: using a Gaussian (red) and the combination of Gaussian and exponential functions (green).

S13360-1350CS SiPM, which with its 50 μm microcell size has the potential to provide a better timing performance, we found that the jitter of the ASIC trigger signal for events of ~10 phe is below 200 ps. This is particularly relevant for the trigger and veto signals that the PSD will provide.

In the BETA the digitization of the signal of 16 SiPM channels (64 in the future BETA-64 version) with large dynamic range and high SNR for single photons is achieved with a power consumption of only ~1 mW channel. This turns the BETA into a versatile ASIC that could be suitable for several applications as long as the expected data rates are below 10 kHz:

- BETA is particularly suitable for developing SiPM-based detectors for satellites where volume, weight and power consumption are critical. In effect, a detector employing the BETA ASIC was proposed as a radiation monitor for the future LISA [6] mission (see relevant contribution in this proceeding collection).
- BETA-64 could also be weel suited for space-based calorimeters, which may employ thousands channels and where charge identification should be done with high dynamic range and SNR [7].
- Same as with satellites, the BETA ASIC should facilitate the use of SiPMs in drones. This is could be particularly interesting in fields like agriculture [8] or environmental monitoring [9].
- The ASIC could also be suitable for ground-based applications. Especially (but not only) for portable systems, where power consumption and compactness are crucial [10].
- BETA-64 could be handful for those systems that require the digitization of several channels with high SNR in a reduced volume, like gamma cameras [11, 12].
- The ASIC could also be useful in large systems like muon detectors, which in the last years have been largely exploited in archaeology [13]. BETA-16R2, with its individual trigger outputs, could be suitable for these systems that are based on coincidence of several detectors with moderate timing requirements (of the order of ~1 ns).

Acknowledgments

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