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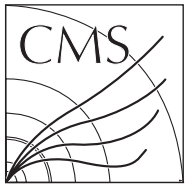

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The DC-DC Conversion Power System of the CMS Phase-1 Pixel Upgrade

Katja Klein for the CMS Collaboration

Abstract

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The power system of the Phase-1 pixel detector will be described and the performance of the new components, including DC-DC converters, DC-DC converter motherboards and various power distribution boards, will be detailed. The outcome of system tests in terms of electrical behaviour, thermal management and pixel module performance will be discussed.

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The DC-DC conversion power system of the CMS Phase-1 pixel upgrade

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ABSTRACT: The pixel detector of the CMS experiment will be exchanged during the year-end technical stop in 2016/2017, as part of the experiment's Phase-1 upgrade. The new device will feature approximately twice the number of readout channels, and consequently the power consumption will be doubled. By moving to a DC-DC conversion powering scheme, it is possible to power the new pixel detector with the existing power supplies and cable plant.
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KEYWORDS: Particle tracking detectors (Solid-state detectors); Si microstrip and pad detectors; Voltage distributions.

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Contents

1. Introduction

The present CMS pixel detector [1] has been designed to withstand an instantaneous luminosity of $1 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. To maintain the present excellent performance at higher instantanous luminosities, as expected to be delivered by the LHC after Long Shutdown 1, the pixel detector will be exchanged during the year-end technical stop in 2016/2017 [2]. The new device will feature additional detection layers, increasing the channel count by a factor of 1.9. Since the power consumption of the read-out chip (ROC) will not change, this leads to a factor of 1.9 increase in power consumption, and consequently an increase of losses on the 50 m long supply cables by a factor of $1.9^2 = 3.6$.

Due to the limited installation time and other constraints, both the cable plant and the power supplies have to be retained for the new system. CMS has therefore adopted a novel powering scheme based on the DC-DC conversion technique, with DC-DC converters installed in the detector volume, behind the supply cables. The DC-DC converters will receive an input voltage of 10 V and generate output voltages of 2.4 V and 3.0 V, respectively. With this conversion ratio of 3-4 a reduction of cable losses by a factor of about 10 will be achieved.

The DC-DC converters in the CMS pixel detector have to be sufficiently radiation tolerant, with an expected Total Ionizing Dose (TID) of 100 kGy and a fluence of $2 \cdot 10^{14}\,\mathrm{n_{eq}/cm^2}$, and must fit into the limited space available. Reliability, including immunity to single event upsets, is crucial, and degradation of the detector performance would be prohibitive.

2. The pixel power distribution system

2.1 Overview

The pixel detector requires four different voltages: low voltages (LV) of at least 1.7 V for the analogue part and at least 2.3 V for the digital part of the pixel module electronics, respectively; a high voltage (HV) of up to −600 V to deplete the silicon sensor, and an auxiliary voltage of 2.5 V. The bias voltage and the auxiliary voltage are delivered conventionally, without DC-DC converters. The pixel power supplies (PS), which are located on the balconies of the experimental cavern, are of type A4603 by CAEN. They have to be upgraded to be compatible with DC-DC conversion, by raising their output voltage and by switching from fast remote sensing to a slow voltage regulation. This implies installation of piggy-boards, already in hand, during the 2016/17 technical stop. Multi-service (MS) cables, consisting of three pieces with lengths of 43 m, 5 m and 0.5 m, respectively, connect the PSs to the pixel detector. The pixel detector is a 5 m long structure, with the pixel barrel (BPIX) and end caps (FPIX) in the centre, and mechanical support structures, called BPIX supply tubes and FPIX service cylinders, extending to both sides (Fig. 1 (left)). The DC-DC converters will be installed on the outside (inside) of the supply tube (service cylinder), at distances between 0.5 m and 2.2 m from the pixel modules, outside of the tracker acceptance. The number of DC-DC converters to be installed in the pixel detector amounts to about 1200 (800 for BPIX and 400 for FPIX).

In the following the BPIX power distribution will be discussed, as the FPIX power distribution system is similar, but less advanced.

Each supply tube is split into two half shells, each with eight parallel slots. The slots are organized in four segments along the beam direction, labelled from A (cable side) to D (module side). The components in slots A and B are shown in Fig. 1 (right). The DC-DC converters are plugged into a motherboard, located in segment A. Low voltage PCBs, referred to as extension boards, span segment B and connect to the connector boards in segment C. The connector boards receive 1 m long, low mass module cables. The bias voltage is distributed via a flex board. The so-called "CCU ring board" in segment B spans the whole half shell. Its purpose is to manage the communication with a variety of chips, including the DC-DC converters.

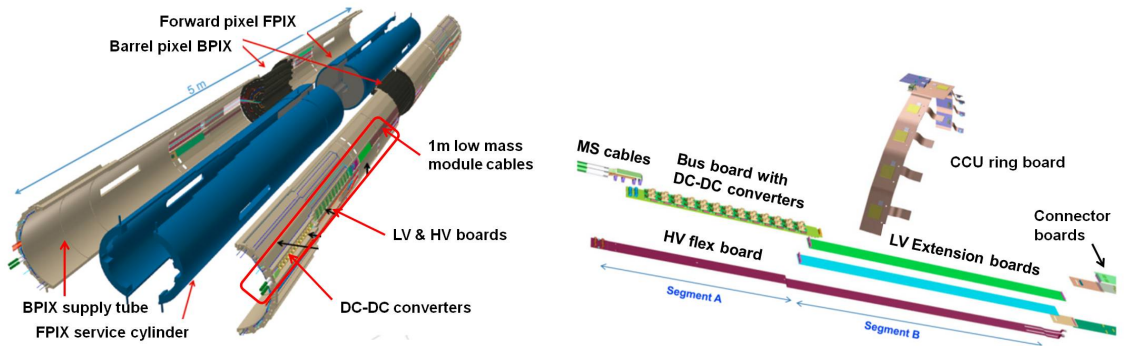

Figure 1. CAD drawing of the pixel detector including support structures, with one slot of the supply tube equipped with electronics components (left); and exploded view of the power electronics in segments A and B of the supply tube (right).

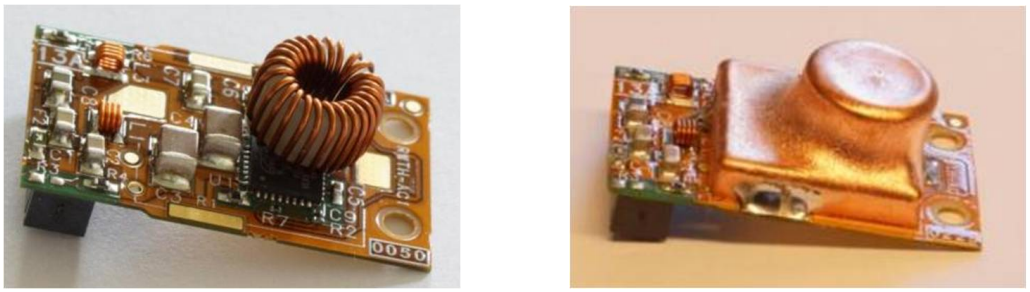

Figure 2. Photographs of a PIX_V13 DC-DC converter without (left) and with shield (right).

The DC-DC converters are organized in pairs. One pair provides the analogue and digital supply voltage for between one and four pixel modules.

2.2 The pixel DC-DC converters

The pixel project uses step-down converters of the "buck" type. The power transistors are embedded in a radiation-tolerant ASIC, the FEAST2 by CERN [3]. The chip also contains the voltage regulation circuit and control logic. Several protection features are implemented: input under-voltage lock-out, over-temperature protection and over-current protection. The chip can be enabled and disabled remotely, and it outputs a status bit.
The pixel DC-DC converters, named PIX_V13, have a footprint of 28 mm x 17 mm and a height of 8 mm (Fig. 2). The weight of the device amounts to about 2 g without and 3 g with shield, which is described below. The power transistors are set to switch at a frequency of 1.5 MHz. The inductor, required as energy buffer during the switching phase when the load is disconnected from the input, is an air-core toroid with a diameter of 9 mm and a height of 7 mm. The inductance is about 430 nH. Pi-filters are used at the converter's input and output to flatten the respective voltages.
Two variants are required. DC-DC converters that serve the analogue ROC circuitry produce an output voltage of 2.4 V and deliver output currents of between 0.4 and 1.7 A, while DC-DC converters that serve the digital module electronics (ROC and Token Bit Manager chip) have an output voltage of 3.0 V and provide currents between 0.7 and 2.4 A.
The PIX_V13 converters are equipped with an electro-magnetic shield, as shown in Fig. 2 (right). The shield serves three purposes: it reduces electro-magnetic emissions from the inductor, it segregates the noisy parts on the PCB from quiet parts, like the output side of the pi-filters, and it serves as a cooling contact for the inductor. The last of these requirements, together with space constraints in some regions of the BPIX supply tube, has resulted in a complex shape, with a cylindrical part around the coil and a wider box at the base. The cylindrical part is filled with thermal grease, to improve thermal contact. The shield consists of a 300 μm thick plastic body, thermo-formed from a polycarbonate Lexan foil, and a galvanically deposited copper layer of 60 μm thickness on the outer surface. Organic passivation is added to reduce corrosion. The effectiveness of the shield has been extensively studied. The magnetic field above the coil was mapped with a pick-up probe mounted on a scanning table, and it was found that the field is reduced by the shield to a negligible level.
The performance of the PIX_V13 converters, as well as that of several earlier prototypes, has been

studied in great detail ([4, 5], and references therein). Only a few aspects will be mentioned here. The efficiency amounts to 80 - 84 % for relevant input voltages and output currents. Great attention was payed to the reduction of conductive noise levels, both in terms of Differential Mode and Common Mode noise. The stability of the output voltage with respect to a variety of parameters was studied: load regulation (variation with output current; typically 8 mV/A), line regulation (variation with input voltage; 1-2 mV/V) and temperature variation (below 1mV/K). The cooling concept for the inductor has been proven to work, with coil temperatures reduced by, for example, 15 K for a 3.5 A output current.
Several hundred devices were produced during the pre-production phase. Mass production of 1800 PIX_V13 DC-DC converters will start at the end of 2014.

2.3 Low voltage distribution

A motherboard is required to route the input voltages to the DC-DC converters, to pass their output voltages to the detector and to distribute remote control signals to and from the DC-DC converters. The motherboards, called "DC-DC bus boards", are 452 mm long, 41 mm wide and have a thickness of 1.6 mm (Fig. 3 (top)). The DC-DC converters are arranged in pairs of 2.4 V and 3.0 V converters, with 13 pairs plugged into one bus board. Each board houses DC-DC converters for all four pixel barrel layers. The boards are very dense, with eight copper layers of 70 μm thickness, and a total delivered power of about 110 W. A board is fed by two multi-service cables, each delivering the power from one power supply unit. A total of 32 such boards will be installed on the supply tubes.
To bridge the distance between the bus boards in segment A of the supply tube and the connector boards in segment C, additional low voltage distribution PCBs are needed. These "extension boards" (Fig. 3 (middle)) are two-layer PCBs with a thickness of 0.6 mm and a width of 41 mm. Two boards are used in each supply tube slot: the board that distributes the low voltages of layers 1 and 2 is 749 mm long, whilst the board used for layers 3 and 4 is 733 mm long. The boards plug into the bus board on one side, and into small so-called "adapter boards" on the detector side. The

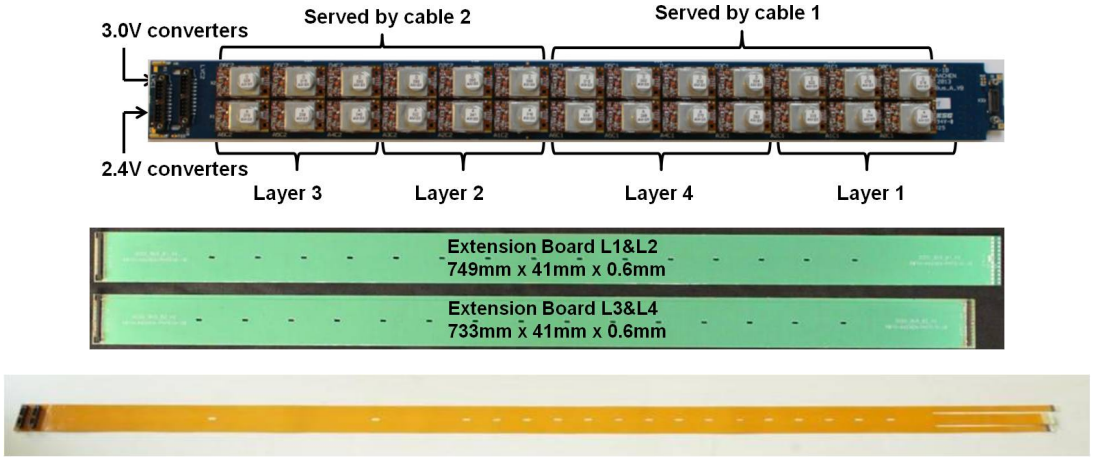

Figure 3. Photographs of a DC-DC bus board fully equipped with DC-DC converters (top), the low voltage extension boards (middle), and the HV flex board (bottom).The photographs are not to scale.

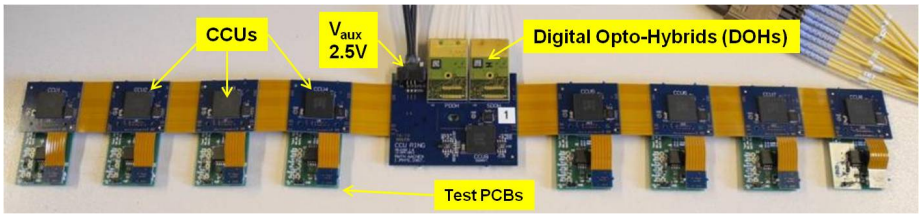

Figure 4. Photograph of the CCU ring board.

adapter boards provide the connectivity to the connector boards. The adapter and connector boards are still under development.
Good control over the voltage drops across the bus boards and extension boards is crucial, as the DC-DC converters do not feature remote sensing. The voltage drops across both boards together have been measured for all 26 lines and amount to between 100 and 200 mV, depending on the line. This is in excellent agreement with previous calculations.

2.4 High voltage distribution

On the supply tube the high – or bias – voltage is distributed via flexible Kapton boards, the "HV flex boards" (Fig. 3 (bottom)). They receive pig-tails from the multi-service cables on one side, and split themselves into three pig-tails on the detector side, which plug directly into the connector boards. The two-layer boards have to be very long (1.33 m) and also very thin (300 μm), as they are installed beneath the PCBs for low voltage distribution. Sixteen HV lines, grouped into four independent channels, have to be accomodated. The voltage specification is 1000 V for layers 1 and 2 and 600 V for layers 3 and 4, respectively. Various isolation tests with up to 2 kV under a variety of conditions (e.g. flushing with Nitrogen, to simulate the conditions in the pixel detector) have been performed. Currents in the range of tens of nano-Amps were observed, negligible compared to pixel module currents.

2.5 Control boards

In the present pixel detector, the Communication & Control Unit (CCU) [6], an ASIC designed by CERN, is used to program several chips, including the Pixel Opto-Hybrids. The control boards are presently located in the central slot of the supply tube. The CCUs allow the exploitation of the remote control features of the DC-DC converters, namely the possibility to enable and disable them remotely and to read their status flag, through the use of parallel ports (PIA channels). In order to minimize the length of the connections between CCUs and DC-DC converters, the control electronics have been re-arranged, with flex-rigid boards spanning one half-shell (Fig. 1). Pairs of 2.4 V and 3.0 V converters are handled together, as both are anyway required to operate the connected pixel modules. This halves the number of required connections. The 482 mm long boards (Fig. 4) have four copper layers in the rigid parts and two copper layers in the flexible interconnections.
The board houses eight CCUs, to control the electronics in eight supply tube slots. Each rigid part is plugged into a connector on the bus board, whilst Kapton cables connect to PCBs housing the Pixel Opto-Hybrids. The eight CCUs are connected to each other in a ring architecture. As in the

present detector, a redundancy scheme is implemented, which allows faulty CCUs to be bypassed, and requires a ninth CCU to close the ring. Each board receives signals from the off-detector electronics via Digital Opto-Hybrids, and houses also nine LVDSMUX chips.
The functionality of the CCU ring board was extensively and successfully tested, including the stability of the control ring over a period of 200 hours, the redundancy scheme, I^2C communication using dedicated test devices, and the communication with the DC-DC converters. In a test beam experiment with protons at Louvain-la-Neuve it was verified that the PIA ports do not suffer from single event upsets.

3. System tests

System tests are crucial for studying the electrical and thermal system behaviour as well as the performance of the pixel modules when operated with DC-DC converters. All available components were integrated at Aachen. The DC-DC converters were powered with the upgraded A4603 CAEN power supply via two 43.5 m long MS cables. A total of 26 PIX_V13 DC-DC converters were operated on a prototype of the bus board. Extension boards, the CCU ring board and the HV flex board were integrated. All those supply tube boards were incorporating the final layout. Since adapter and connector boards are not yet available, a custom patch panel was made to connect to a prototype of the low mass module cable. A single chip module with the close-to-final PSI46digV2.1 readout chip was used. The module was read out with a "Test Board", which is used for all lab tests of pixel modules. A custom-made load board allows individually adjustable currents (0 - 3 A) to be drawn from all 26 DC-DC converters. Cooling of the DC-DC converters is provided by a re-circulating CO_2 cooling system, as in the final system.

3.1 Electrical system behaviour

After verification of the basic functionality, recent work has concentrated on the dynamic behaviour during power-up and power-down transitions. With six or seven DC-DC converters connected to one PS channel, input currents of up to 6 A have to be delivered. Inrush currents are a potential issue and therefore a clean start-up has to be verified. In these tests, nominal currents as expected for the final pixel detector operation are drawn via the load board from all 26 DC-DC converters. While the DC-DC converters connected to one cable are always powered, the converters fed by the second cable are switched on or off. The total input current on this second cable is monitored with a current probe, and the input voltage at the bus board, as well as output voltages of selected converters, are probed and measured with an oscilloscope.
In the first series of tests the converter's remote control feature was used. When the input voltage is switched on and the converters are disabled, they go to a low-power standby state, not yet delivering an output voltage. Next, the converters were enabled via the CCU. A typical measurement is shown in Fig. 5 (left). The DC-DC converters go through a clean soft start of 0.5 ms duration, without significant voltage spikes or inrush currents. The input voltage drops, due to voltage drops on the supply cables, and is regulated back to the nominal 10 V via the slow regulation loop of the PS. The system starts up cleanly.
It was verified that the system can also be started without using the remote control. The converters are then always in an enabled state. As soon as the input voltage reaches a minimum of 5 V, the

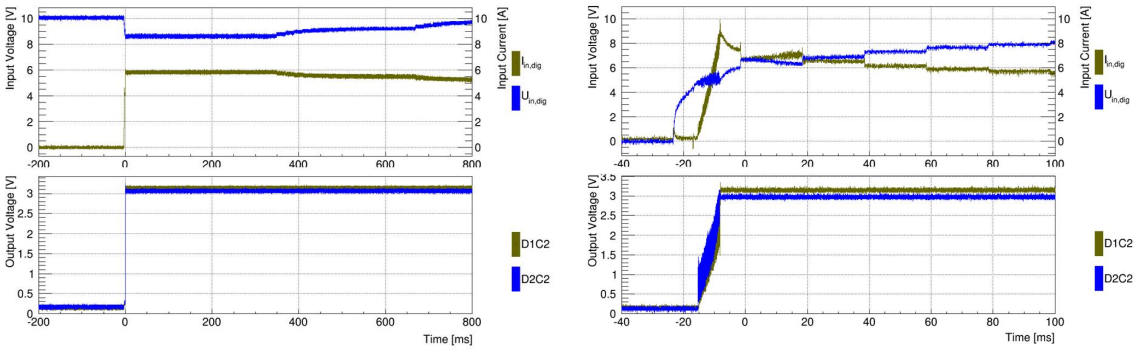

Figure 5. Behaviour during switching-on, with (left) and without (right) using the enable feature. The upper panels each show the input voltage $U_{in,dig}$ (blue) and the input current $I_{in,dig}$ (green) of the digital supply line. The lower panels each show the output voltages of two "digital" DC-DC converters (denoted as D1C2 and D2C2). The time bases on the left and right plots are different.

converters deliver an output voltage. In this case inrush currents are significant and the converters enter a soft start loop (Fig. 5 (right)), since the current rise causes the input voltage to periodically fall below 5 V, the under-voltage lock-out value. Nevertheless, also in such an unusual situation, corresponding to a CCU failure, the system can be switched on for up to 1.1 times the nominal load. Since unprogrammed pixel modules draw about half the nominal current, this is considered a sufficient margin.

3.2 Thermal management

The DC-DC converters need to be cooled, as the inefficiency of about 20 % leads to a heat load of up to 2 W per device. The chips are connected through thermal vias with a ground area on the back-side of the PCB. The over-temperature protection of the chip sets in at 103 °C. The inductor is cooled through its leads and also through thermal conduction to the shield, as detailed above.
The DC-DC converters are cooled through the same CO_2 cooling loops as the actual pixel modules, providing, together with other electronics such as the Pixel Opto-Hybrids, pre-heating of the CO_2. Aluminium cooling bridges (Fig. 6 (left)) are used to provide the thermal contact to the CO_2 pipes, which have an outer diameter of 2.2 mm in the supply tube area. The bridges consist of two pieces. The lower pieces are glued to the bus board, whilst the upper pieces are screwed to the lower pieces, such that the bridges clamp around the pipes. One pair of DC-DC converters is screwed onto each cooling bridge. Thermal grease will be applied between the bridge and the converters, to improve the thermal contact. An anodization layer on the bridges assures electrical isolation of the converters from the cooling system, in order to avoid ground loops.
The thermal management was studied by operating 26 DC-DC converters, screwed onto those bridges as they will be in the final system, with a recirculating CO_2 cooling system. Thermistors were attached to the pipes, the side faces of the bridges and to the top of the converter's shields. The CO_2 temperature was set to $-20\,°C$, the baseline temperature of the final system, and nominal loads were drawn from all DC-DC converters. The result is shown in Fig. 6 (right). The thermal gradient, ΔT, between the CO_2 and the shields depends on the load (which varies between layers), but is below 15 K for all DC-DC converters. Although the internal chip temperature is not known,

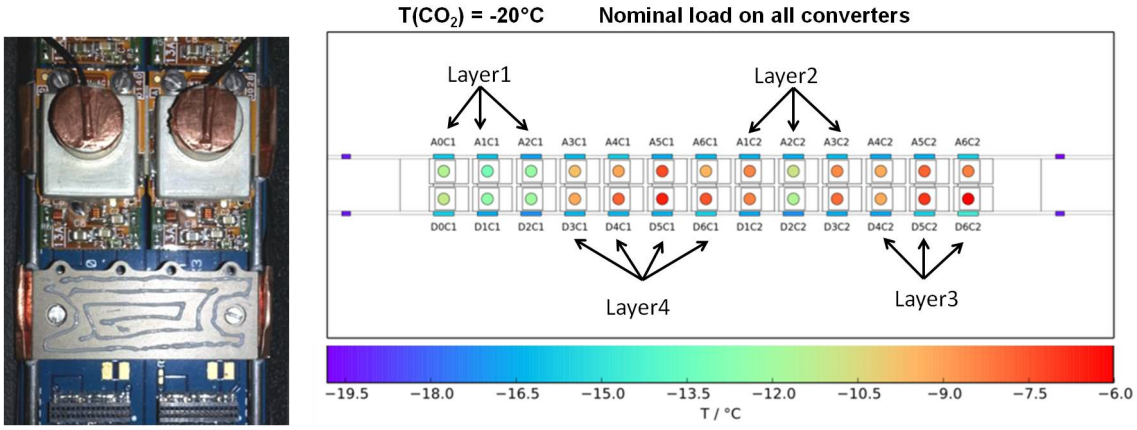

Figure 6. Left: Photograph of a section of the bus board. The CO_2 pipes and a cooling bridge are visible. The converters on the top are screwed to the next bridge. Right: Schematic drawing of the cooling set-up, with converters indicated. The measured temperatures on pipes, bridges and shields (round areas) are shown colour-coded. The DC-DC converter's load depends on the module layer they are serving (indicated).

and will be higher than the shield temperature, this result shows that the cooling concept works well, with the converter's temperature being well away from the critical value. Operation at room temperature will also be possible.

3.3 Pixel module performance

The DC-DC converter's working principle, namely switching relatively large currents at MHz frequencies, can adversely affect sensitive front-end electronics. The CMS pixel modules are intrinsically robust, due to on-chip linear regulators. Nevetheless, it must be experimentally verified that the operation with DC-DC converters neither increases the module's noise nor changes the threshold for the zero-suppressed digital readout.

So-called "S-curves" have been acquired and fit with an error function. The noise and threshold have been extracted as the width and 50 % efficiency point of the error function. The noise measurements are summarized in Fig. 7. Powering the single chip module conventially from the test board serves as a reference. For powering with DC-DC converters, several conditions have been tested. In the first test, the module was powered from DC-DC converters and the bias was taken from the CAEN PS. All 26 converters on the bus board were powered, but only the converter pair connected to the pixel module was delivering current. In the next step, the nominal loads were drawn from all 26 converters. Finally, the digital loads were changed with the frequency expected from the LHC beam structure, where orbit gaps of 3 μs length every 89 μs lead to a drop of the digital module activity, and thus a reduction of the digital power consumption. The inverse pattern, corresponding to only a few filled bunches circulating in the machine, was also tested. Under all circumstances, the noise was not significantly increased, and amounted to about 161 electrons. The threshold was also unchanged, and the chip could be trimmed to about 2000 electrons in all cases.

4. Conclusions

The CMS Phase-1 pixel detector will be powered via DC-DC conversion, and the power system

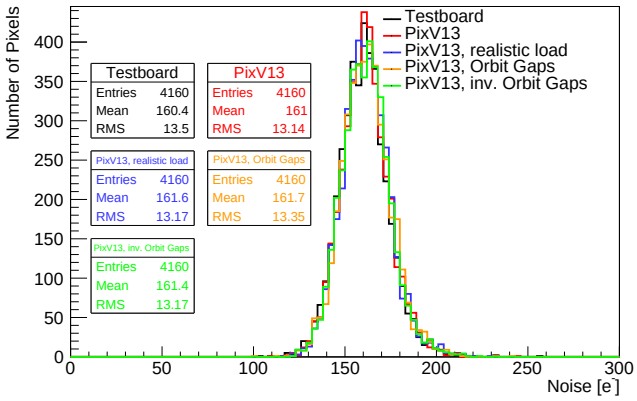

Figure 7. Histogram of the noise of 4160 pixels of one single chip module. The following measurements, described in detail in the main text, are shown: module powered from the test board (black); module powered from DC-DC converters and all converters on (red); in addition nominal load drawn from all converters (blue); digital loads in addition changed with orbit gap pattern (orange) and with the inverted pattern (green).

has been re-designed in order to be compatible with such a scheme. Final versions or close-to-final prototypes of all components exist and mass production of DC-DC converters will start end of 2014. Extensive tests of single components as well as the overall power system have been carried out and it was verified that the required specifications are met. From 2015 onwards, four new pixel modules will be operated within CMS, with two modules powered conventionally, and two modules powered from DC-DC converters. This so-called "pilot system" will provide valuable experience under even more realistic conditions.

Acknowledgments

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References

[1] CMS Collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004.

[2] CMS Collaboration, *CMS Technical Design Report for the Pixel Detector Upgrade*, CERN-LHCC-2012-016 (2012).

[3] F. Faccio et al., *FEAST2: a Production Grade 10W Radiation Tolerant DC/DC Converter*, these proceedings.

[4] K. Klein et al., *Development of a DC-DC conversion powering scheme for the CMS Phase-1 pixel upgrade*, 2014 *JINST* **9** C01048.

[5] K. Klein et al., *A DC-DC conversion powering scheme for the CMS Phase-1 pixel upgrade*, 2013 *JINST* **8** C02024.

[6] C. Ljuslin, A. Marchioro and C. Paillard, *The CCU25: a network oriented Communication and Control Unit integrated circuit in a* 0.25 μ*m CMOS technology*, CERN-2002-003 (2002).