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Conference Report

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Powering for Future Detectors: DC-DC Converters for the CMS Tracker Upgrade

L. Feld, W. Karpinski, Katja Klein, J. Merz, J. Sammet, O. Scheibling and M. Wlochal
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Presented at *VERTEX2011: The 20th Anniversary International Workshop on Vertex Detector*

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PROCEEDINGS OF SCIENCE

Powering for Future Detectors: DC-DC Converters for the CMS Tracker Upgrade

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To cope with the increased power requirements of future tracking detectors needed after the luminosity upgrade of the Large Hadron Collider (LHC) at CERN, novel powering schemes have been proposed. These include Serial Powering and powering via the DC-DC conversion technique. For the CMS pixel and strip tracker upgrades powering via DC-DC buck converters is foreseen. In this article, the current status of this development is described and measurements of important DC-DC converter characteristics such as efficiency and conductive and radiative noise emissions are presented. The mechanical and thermal integration into a future pixel detector is sketched and the results of system tests with CMS pixel modules are summarized.

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June 19 - 24, 2011
Rust, Lake Neusiedl, Austria

*Speaker.
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1. Novel powering schemes for tracker upgrades

Already today, the tracking detectors of the large LHC experiments - ATLAS and CMS - require many kilowatts of power. The front-end (FE) power consumption of the CMS strip tracker [1], for instance, amounts to about 34 kW. Currents are delivered from the power supplies to the detector via up to 50 m long cables, which results in Ohmic losses in supply cables of the same order of magnitude as the actual FE power consumption. The expected increase in track density after the foreseen luminosity upgrades of the LHC will require an increase in detector granularity and more complex and faster readout electronics, resulting in an even higher power consumption. The addition of a sufficient number of further cables is considered impossible: the services are barely accessible, cable channels are full already and the total current they can carry is limited for thermal reasons. Increasing the amount of material associated to current delivery inside the sensitive tracker volume itself is highly undesirable, as interactions of collision particles with the passive detector material decrease the physics potential of the detectors. It is therefore widely understood that novel powering schemes have to be exploited.

Two powering schemes have been proposed: Serial Powering [2] and powering via DC-DC conversion.

In Serial Powering, a number of detector modules are connected in series to a constant current source. In this way the current is “recycled” and the current of the chain corresponds to the current I_0 of a single module, with a corresponding Ohmic power loss of $R_{\text{cable}} \cdot I_0^2$. The material budget savings can be substantial, as a large number of modules can be connected in series and the number of additional electronic components is very limited. Shunt regulators and transistors in front of each module or readout chip are used to take away potential excess currents and to stabilize the operating voltage. In a heterogeneous system this can lead to significant inefficiencies. A characteristic feature of Serial Powering is the absence of a solid system ground, as the high potential of any given module is the reference potential for the next module in the chain. This has to be considered in the grounding and shielding concept and necessitates AC coupling of all communications.

The idea of the DC-DC conversion technique is to deliver the required power, $P = U \cdot I$, at a higher voltage, $r \cdot U$, and consequently with a lower current, I/r. The parameter r is called the conversion ratio. DC-DC converters are installed between the power supplies and the detector modules and convert the incoming voltage $r \cdot U$ to the required operating voltage U. Several modules can be powered in parallel from one DC-DC converter, and several DC-DC converters can be connected in parallel to one power supply. The Ohmic power loss from the total current I depends on r and amounts to $R_{\text{cable}} \cdot (I/r)^2$. For this approach, a magnetic-field tolerant, and in particular radiation-hard, DC-DC converter has to be developed. In a DC-DC conversion approach, a solid system ground exists and the grounding, biasing, control and communication schemes can be standard. Also, devices with very different power consumptions can easily be handled. However, limitations to the conversion ratio and the output current of the converters limit the possible reduction in the material budget. In addition, DC-DC converters are switching devices and the effect of switching noise on the sensitive front-end electronics is a concern.

While ATLAS is studying both powering schemes, with a focus on Serial Powering, the CMS Tracker collaboration has chosen DC-DC conversion for both its pixel and strip tracker upgrades as baseline.

2. Development of DC-DC buck converters for the CMS Tracker upgrades

2.1 The CMS Tracker upgrades

Around 2016, the CMS pixel detector will be replaced with a similar, but larger and improved device. Improvements include the mitigation of data losses during readout, as well as the reduction of the material budget due to the deployment of a CO_2 cooling system and the movement of electronic components out of the sensitive volume. Four barrel layers instead of three and three instead of two forward disks per side will, however, lead to an increase in the number of readout chips by a factor of 1.9 with respect to today. Since this would lead to unacceptable power losses in the cable trays, the installation of DC-DC converters outside of the sensitive pixel volume is foreseen. The conversion ratio will be modest (3-4) and is restricted by the input voltage limitation of the DC-DC converter of about 12 V and the required pixel operating voltages.

The exchange of the whole CMS tracker is currently foreseen for around 2022. It is expected that this future device will have smaller detector elements and thus many more readout channels than the current tracker. In addition, the use of tracking information in the Level 1 trigger is foreseen. In order to fulfill the future power requirements, DC-DC converters with as high as possible a conversion ratio (10 at maximum for an operating voltage of 1.2 V) is envisaged.

2.2 DC-DC buck converters

DC-DC converters can be based on a number of different working principles, each of which can be realized with different layouts [3]. For the application in tracking detectors, the "buck converter" has been identified as a promising variant [4]. It can deliver currents of several Amperes with a reasonable efficiency, it is comparably simple and compact, and the output voltage can be precisely regulated by means of a feedback circuit based on Pulse Width Modulation. Conversion ratios of up to 10 can be achieved. The basic schematic is shown in Fig. 1. Two power transistors T_1 and T_2 act as switches. The converter switches periodically and with a switching frequency, f_s, back and forth between stage 1, in which T_1 is closed and T_2 is open, and stage 2, where it is the other way round. The supply voltage is thus periodically connected to the load. For a lossless converter, the duty cycle, defined as the fraction of time when T_1 is closed, is related to the conversion ratio as $D = 1/r$. While the switches are usually housed in an ASIC, several passive external components are required in addition: an inductor acts as energy storage element, and filter capacitors bypass AC components. Challenges include the radiation-hardness of the required high voltage (12 V) tolerant power transistors, potential conductive and radiative emissions of switching noise and the necessity to use air-core inductors, as ferrite cores saturate in the 3.8 T magnetic field

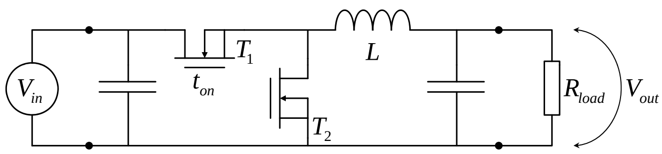


Figure 1: Simplified schematic of a buck converter. The regulation loop is not shown.

of the CMS solenoid. Maximization of the power efficiency and minimization of size and mass are intrinsically in conflict and application-specific compromises have to be found.

Within the CERN electronics department, ASICs for DC-DC buck converters are being developed for applications in High Energy Physics [5]. These ASICs include the power transistors and the regulation circuit. Irradiation studies have been performed for several candidate semiconductor technologies. The best candidate was functional with reasonable efficiency for doses of up to 300 Mrad and fluences of up to $5 \cdot 10^{15}$ p/cm^2. This technology with a feature size of 0.35 μm has been used for several ASIC prototypes, including the AMIS2, which is used by CMS for system tests. In parallel, work to improve the radiation hardness of an alternative technology is ongoing with a second supplier.

2.3 DC-DC converter development at RWTH Aachen University

DC-DC buck converters for applications within the CMS tracker are being developed at RWTH Aachen University. The current prototype, named “AC_PIX_V7”, is shown in Fig. 2. The two-layer PCB is equipped with the AMIS2 ASIC prototype from CERN. This ASIC accepts input voltages of up to 12 V and can provide output currents of up to 3 A when properly cooled. The device is configured to operate with a switching frequency of 1.3 MHz. The inductor is a custom-made plastic-core toroid with an inductance of about 450 nH and a DC-resistance of about 40 mΩ. Pi-filters, consisting of two capacitors and one inductor each, are installed at the in- and output.

The AC_PIX_V7 is equipped with a shield, whose purpose is threefold: 1) protection of the environment from radiated emissions from the inductor, 2) segregation of noisy parts of the board from quiet parts and thus reducing the conducted noise and 3) provision of a cooling contact for the coil. Details of all three aspects will be provided in subsequent sections. The shape of the shield is driven by mechanical constraints in the pixel application. Two technologies are under evaluation: shields based on a 90 μm thick body milled out of aluminium; and plastic caps coated with a thin metal layer (e.g. galvanic deposition of a 30 μm thick layer of copper on each side).
The footprint of the AC_PIX_V7 converter is 28 x 16 mm^2, and its weight, including the shield filled with heat-conductive paste, is below 3 g.

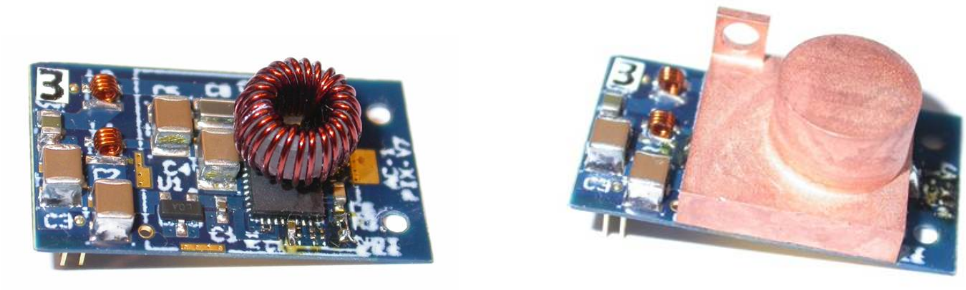


Figure 2: The AC_PIX_V7 DC-DC converter without (left) and with (right) shield. The shield shown in the picture consists of a plastic body, onto which a 30 μm thin copper layer was galvanically deposited. The lug is present for technical reasons and will be removed for the final version.

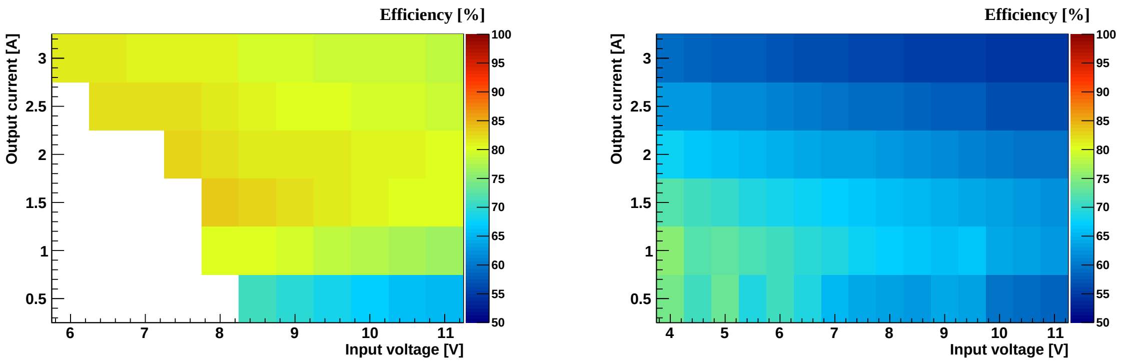


Figure 3: Efficiency as a function of input voltage and output current, for output voltages of 3.3 V (left) and 1.2 V (right). The measurements have been performed with the AC_PIX_V7 and an earlier prototype, respectively. White areas indicate bad voltage regulation, a known problem of this ASIC prototype.

2.4 Efficiency

The power efficiency is defined as the ratio of the output power to the input power. In a real DC-DC converter the efficiency can never reach 100 % due to unavoidable Ohmic losses in the chip (on-resistance of the transistors), in the wire bonds used to connect the chip, in the windings of the inductor etc. Contributions related to the current ripple usually decrease for higher switching frequencies. However, there are also losses related to the switching and driving of the transistors, which increase with switching frequency. Experimentally it has been found that the efficiency of the AMIS2 is maximal at a switching frequency of about 1 MHz. Figure 3 shows the measured efficiency as a function of input voltage and output current. For output voltages of 2.5 to 3.3 V, output currents of 2.8 A and conversion ratios of the order of 4, as required by the pixel detector, adequate efficiencies of 75-80% can be reached. However, under the conditions expected for the strip tracker (output voltages of 1.2 V; output current of 3 A; $r = 8 - 10$), the efficiencies are of the order of 55 %. A combination with an on-chip DC-DC converter based on switched capacitors (so-called charge pump) with a conversion ratio of 2 is therefore under consideration.

2.5 Conductive noise emissions

Conductive noise emissions, i.e. noise currents propagating through the cables, can travel to the sensitive front-end electronics and disturb their behaviour. Two modes are distinguished: in Differential Mode (DM) the noise flows through the power conductor and back through the return conductor, causing a fluctuation of power vs. ground ("ripple"). In Common Mode (CM), noise currents propagate both through power and return conductors and - e.g. by capacitive coupling - return back via the ground plane. Due to the switching nature of DC-DC converters conductive noise cannot be avoided completely; it is important though that it is minimized as much as possible.

The AC_PIX_V7 is equipped with pi-filters at the input and output, with an inductance of 12.1 nH and capacitances of about 20 μF, resulting in a cut-off frequency of the order of 400 kHz. While such pi-filters have been shown to be very effective for noise reduction [6], it has also been observed that noise can couple (inductively or capacitively) from noisy parts of the PCB (the main inductor, for instance) to nominally quiet parts, such as the "outgoing" components of the

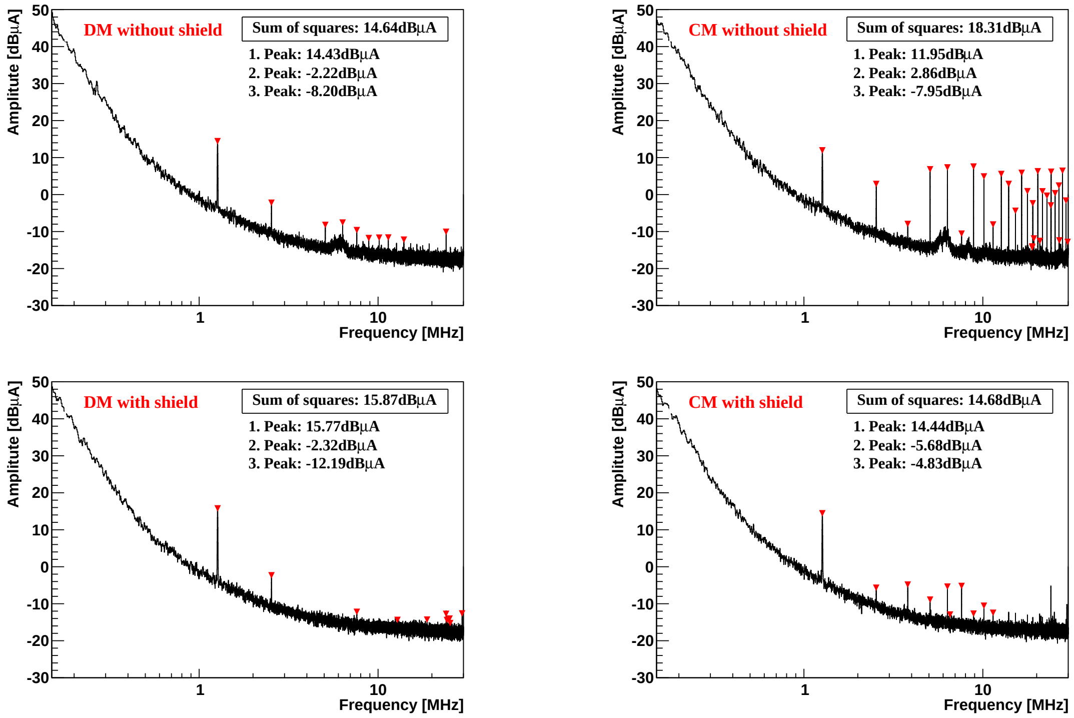


Figure 4: Noise spectra of one AC_PIX_V7 DC-DC converter, operated with an input voltage of 10 V and an output voltage of 3.3 V: Differential Mode without shield (top left), Common Mode without shield (top right), Differential Mode with shield (bottom left), and Common Mode with shield (bottom right). Numbers quoted in the right upper corner of the plots correspond to the sum of squares of all peaks up to 30 MHz, and the height of the switching peak and the first and second harmonic, respectively.

pi-filters [7]. To avoid such cross-coupling, the shield is used. It covers the part of the board where the noisy components are placed, and segregates them from the low-noise components [8].

Measurements of the DM and CM noise spectra are performed on a dedicated standard EMC set-up. The DC-DC converter is powered from a lab power supply via a Line Impedance Stabilization Network, and connected to an Impedance Stabilized Load. The noise currents in the in- or outgoing cables are picked up by a coil that is connected to a spectrum analyzer. Depending on how the cable conductors (power and return) are fed through the pick-up coil, both DM and CM can be measured. The transfer function of the coil is known and is taken into account. The whole set-up is installed on a solid copper reference ground plane.

Figure 4 shows DM and CM noise spectra with and without shield. The switching peak at 1.3 MHz is clearly visible. Without shield, a large number of higher harmonics are present in the CM spectrum up to the upper test frequency of 30 MHz (the readout electronics is most sensitive to frequencies below 10 MHz). Their strength is comparable to the switching peak. The presence of the shield reduces these high frequency components to a negligible level. The height of the switching peak is, however, not reduced by the shield. An increase of the switching frequency to a value where the shield is more effective is well possible, but leads to efficiency losses. System tests, such as the one described in Sect. 3.2, are needed to show if the conductive noise is acceptable.

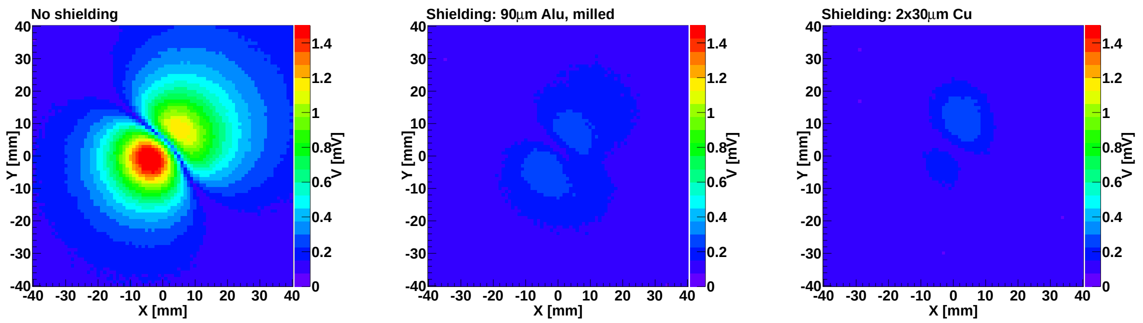


Figure 5: Scans of the magnetic field of an AC_PIX_V7 DC-DC converter, at a distance of 1.5 mm above the coil. The field component perpendicular to the PCB plane is shown. Compared are measurements without shield (left), with a 90 μm thick aluminium shield (center), and with a plastic shield surrounded with a 30 μm thick copper layer (right). All measurements have been performed with an input voltage of 8.5 V and an output voltage of 2.5 V.

2.6 Radiative noise emissions

Large and fast changing currents in the inductor cause magnetic radiation. In an air-core inductor magnetic field lines are not well confined within the volume close to the coil. Its magnetic near field can therefore induce noise in electrical components in the vicinity. The magnetic field can be minimized by appropriate shaping of the inductor and by shielding.

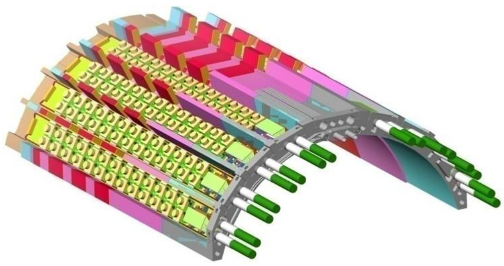
Relative measurements of the strength, extension and shape of the magnetic field are performed on a set-up based on a three-dimensional scanning table. A small pick-up coil is moved around the DC-DC converter. This pick-up probe is connected to a spectrum analyzer.

Previous optimization studies have resulted in the choice of a compact and tightly wound toroid with a height of 6 mm and outer and inner diameters of 8.0 mm and 3.6 mm, respectively. The magnetic field component perpendicular to the board is depicted in Fig. 5, left. A further reduction of the magnetic field can easily be achieved with shielding, as shown in the center and right plots. The first shield has been milled out of aluminium; its thickness amounts to 90 μm, plus a layer of 7.5 μm copper and 7.5 μm nickel on both sides to increase the solderability. The second example is a shield based on a PEEK (polyether ether ketone) body, which has been coated galvanically with a 30 μm thick layer of copper on both sides (Fig. 2). Both shields are effective. The manufacturing of the plastic/copper shield is significantly cheaper, which makes it currently the preferred solution. Thinner shields have been tried but are disfavoured due to their significantly worse shielding performance.

The manufacturing of the shield would be much easier and more cost-effective if the shield could be a simple box shape. However, due to space constraints in the pixel application (Sect. 3) this is not possible, and the shield has to be made out of a low height box (for segregation) and a cylinder for shielding of the inductor.

3. A DC-DC conversion scheme for the CMS pixel upgrade

The implementation of DC-DC converters into the pixel detector is already well defined. Here



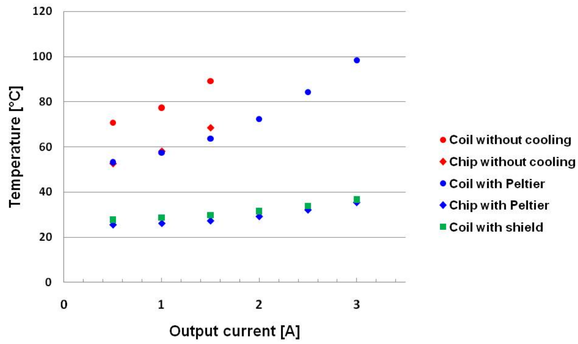


Figure 6: Left: CAD-drawing showing the back-end of the pixel supply tube. Right: Measured temperatures versus load current for the coil and chip without any cooling (red dots and diamonds), the coil and chip when cooled through the PCB backside (blue dots and diamonds) and finally the coil when it is cooled in addition via the shield (green squares).

the aim is to reduce resistive losses in supply cables rather than the reduction of the material budget inside the tracking volume. For the pixel barrel detector the DC-DC converters are therefore installed on the far end of the pixel supply tube (Fig. 6), at a distance of about 2 m from the pixel modules and at a pseudo-rapidity of $\eta \approx 4$, where $\eta = -\ln(\tan(\theta/2))$, with the polar angle θ being measured with respect to the counterclockwise proton beam direction. The contribution of the DC-DC converters themselves and of associated electronics to the material budget is not that crucial at this position, and the potential for electrical interference with the front-end electronics is much reduced. The channels in the supply tube provide sufficient space, and CO_2 cooling pipes are anyway routed inside these channels and can be used to cool the DC-DC converters.

One power supply unit will provide about 12 V to up to seven analog and seven digital DC-DC converters. The DC-DC converters then provide the analog voltage of 2.5 V or the digital voltage of 3.3 V for the pixel module electronics. Between one and four pixel modules are connected to one analog and one digital DC-DC converter. The modularity depends on the layer radius, as from the inside to the outside of the pixel detector the particle fluence, and thus the digital current of the read-out chip, decreases. With the chosen modularity the output current per converter remains below 2.8 A for an instantaneous luminosity of $2 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Up to 26 DC-DC converters will be installed per supply tube channel, arranged in two rows. They will be powered via a bus board, which will also carry the bias voltage lines.

3.1 Thermal integration

The power dissipation per channel will be of the order of 40 W for a DC-DC converter efficiency of 80 %. Good thermal integration is therefore mandatory. Two components of the DC-DC converters have to be cooled explicitly: the chip and the inductor. The chip is cooled via a large copper area on the backside of the board. The connection of the inductor to this area through its leads is not sufficient and the shield is therefore used as a cooling contact. Good contact between the windings and the inner shield surface is assured by the usage of heat-conductive paste inside the shield. The shield has four solder connections to the PCB.

An evaporative CO_2 system [9] is foreseen for the cooling of the future pixel detector. Aluminium cooling blocks in the supply tube channels will be clamped around the thin cooling pipes, and the DC-DC converter boards will be screwed onto these cooling blocks.

The temperature of both the chip and coil has been measured with an infra-red camera for various cooling conditions (Fig. 6, right). The measurements without shield and without external cooling show clearly that cooling is mandatory for currents above 1 A. When the board, still without shield, was cooled from the backside via a Peltier element to +20°C, the chip was cooled very well, while the coil temperature still rose to about 100°C. With the shield in place, the temperature difference between Peltier element and inductor stayed below 20 K. This result is in agreement with thermistor measurements inside the shielded coil and with Finite Element simulations.

3.2 System tests with CMS pixel modules

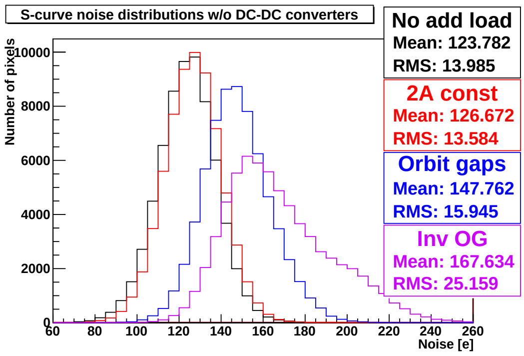
While it is crucial to measure and minimize the conductive and radiative noise emissions of DC-DC converters, the interference with the front-end electronics has to be studied in system tests with the detector modules themselves. In the past, extensive system tests with CMS strip modules have indicated their sensitivity to Differential Mode noise from the DC-DC converters [10]. The sensitivity of CMS pixel modules, which are equipped with the PSI46 readout chip [1] and make use of fast on-chip regulators, has now also been studied in system tests.

The set-up consists of one CMS pixel module that is read out with a lab data acquisition system. The power is provided from the original CMS power supply, which is connected via a 40 m long multi-service cable followed by one meter of thin low-mass wires (as foreseen for the pixel upgrade) to the pixel module. To compare this "conventional" powering system with a DC-DC conversion powering scheme, two converters are installed on a bus board prototype between the long and the thin cables, and provide the analog and digital detector voltage, respectively. A "load box" can in addition be connected to the power supply, to simulate the (constant or dynamic) load of additional modules. The pixel noise is measured with a threshold scan: for each pixel, the efficiency to detect a hit is measured with internal calibration pulses as a function of the pulse amplitude. The resulting so-called S-curve is fit with an error function and its width is used as a measure of the pixel noise. As can be seen in Fig. 7, the difference between conventional powering and powering with DC-DC converters is below 1 %, both for a single module and a constant additional load of 2 A, which is applied to simulate the maximal load current of the DC-DC converter.

The PSI46 ROC features sparsified readout. The digital activity of the chip depends therefore on the particle fluence. Large and fast load changes are expected at the SLHC due to the orbit gaps: every 89 μs there is a 3 μs long so-called abort gap, and the digital power consumption per converter thus drops quickly from - in the worst case - 2.7 A to 1.0 A. The stability of the power supply chain was assessed under this orbit gap pattern and under its opposite, i.e. assuming just a few filled bunches, for both conventional and DC-DC powering (Fig. 7). With DC-DC converters the pixel noise is much less affected, probably due to additional filters present on the DC-DC converters.

4. Summary

Novel powering schemes are mandatory for the tracking detectors required after the LHC lumi-



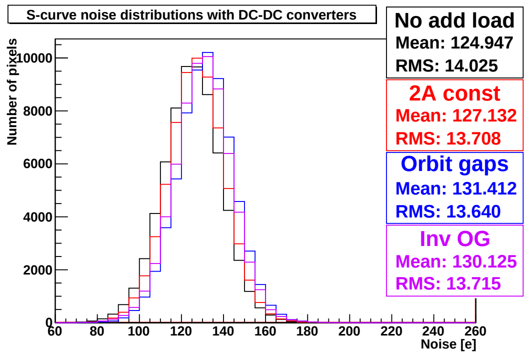


Figure 7: Distributions of the noise (width of the S-curve) of all pixels of one module. Measurements have been performed without (left) and with (right) DC-DC converters, for the following four cases: no additional load (black); an additional constant load of 2 A (red); a variable load as expected due to the orbit gaps (blue); and a variable load corresponding to an inverted orbit gap pattern (pink).

nosity upgrade. The CMS tracker community has therefore opted for DC-DC conversion powering schemes for its pixel and strip tracker upgrades. Efficient and low noise prototype buck converter boards based on the AMIS2 ASIC from CERN have been developed for application in the CMS tracker. The integration of DC-DC converters into the pixel system is already well defined, and system tests have shown that the pixel modules can be operated with these prototypes without performance degradation.

Work will continue with improved ASIC prototypes, expected to be available in late 2011.

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