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The Preparatory Phase of the Large Hadron Collider upgrade (SLHC-PP) is a project co-funded by the European Commission in its 7th Framework Programme under the Grant Agreement n° 212114. SLHC-PP began in April 2008 and will run for 3 years.

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1. EXECUTIVE SUMMARY

For the design of the upgraded trackers at the sLHC experiments, a solution based on buck DC-DC converters has been proposed, following an efficiency optimization study [1]. The powering scheme aims providing the power required by the front-end electronics while minimizing the thermal losses in the cables and in the detector volume, which in turn will reduce the material required for cooling.

The qualification of two radiation tolerant microelectronics technologies [2][3], up to the fluencies expected at the targeted locations has been a key factor to enable the success of the project. The baseline technology from On Semiconductor, formerly known as AMIS, concluded with the production of the AMIS2 power converter ASIC [4][5][5] that has been used for the development of power converter modules to be used with systems [6]. A second technology from the German foundry IHP was also initially qualified, although some radiation tolerance issues are still being solved now on the latest release of devices. Both technologies will enable a power conversion at the sLHC trackers with efficiencies greater than 80%.

The qualified AMIS2 ASIC was used to develop a power converter plug-in module [6]. The module is fitted with a compact connector so that it can be easily plugged into different front-end systems. This converter delivers an output current up to 3A with a nominal output voltage of 2.5V; this output voltage can however be tuned beyond 5V by modifying a pair of resistors to match the needs of specific systems. The module uses a custom made air core inductor that enables its use in presence of the 4T magnetic field present in the trackers volume.

The AMIS2 device is primarily designed to match the power required by future tracker front-end systems at the sLHC that are being developed in a 130nm technology. It must be noted that the systems available at this moment for tests are still implemented in the former 250nm technology that requires currents beyond 4A [7]. In order to test the compatibility of these systems with DC-DC converters, a plug-in module equivalent to the AMIS2 module but delivering up to 5A was developed on the basis of a commercially available device from Linear Technology. This alternate power module is a direct replacement of the AMIS2 module as it is implemented with the same form factor, using the same connector.

These power modules will be located in close proximity of the sensitive detectors; therefore the electromagnetic compatibility with the front-end system has been a critical aspect in this development [6]. An optimization method has been developed, through board layout and parts placement optimization. The selected toroidal structure of the coil results in reduced emissions of magnetic field; the addition of a low mass shield brings the ultimate noise confinement for both electric and magnetic field radiated noise [8].

The modules produced at CERN using the AMIS2 and the off-the-shelve device were used to power ATLAS tracker front-end modules at the University of Liverpool and at the University of Geneva [8]. The compatibility was fully validated through tests with full detector modules. These power converters are now being considered also for the powering of calorimeters at the CMS, LHCb and ATLAS experiments. Power modules using the AMIS2 ASIC were also produced at the RWTH Aachen University [9]. Those were used to power the sensitive CMS tracker silicon strip modules validating also their compatibility. The DC-DC converters from the Aachen University will be used in the upgrade of the CMS Pixel Detector [10][11].

2. POWER ASICS DEVELOPMENTS

The proposed DC-DC converters are intended to operate in the presence of very intense radiation levels. Following a complex radiation tolerance qualification process [2], two technologies were identified for their compliance with our targeted environment [3] and prototypes ASICs were developed [5]. The details concerning the development and qualification procedure were explained in a previous deliverable report[1]. Among those, the AMIS2 ASIC was selected for the integration onto power modules. The efficiency properties of this ASIC were measured for different operating conditions (Figure 1), ranging between 70% and 80%.

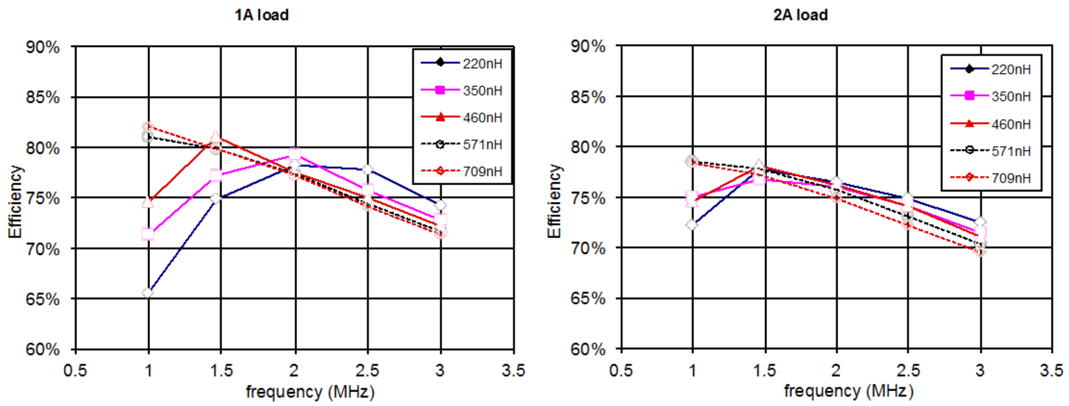


Figure 1: efficiency of the AMIS2 ASIC at 1A and 2A output currents.

The radiation tolerance of the AMIS2 chip was exhaustively explored (Figure 2) by means of the efficiency monitoring as function of dose or fluence [4]. A first test at high dose rate (77 krad/min) and at room temperature (30°C) up to 250 Mrad has put in evidence an increase of the losses around 1 Mrad of total dose that was afterwards recovered by annealing, reaching a minimum of efficiency slightly under 75%, which is still acceptable for the application. Some of these converters will be operated at low temperature (-30°C): although high dose rate effects are observed in this operation mode, a more realistic low dose rate test (47 rad/min equivalent) reveals an acceptable efficiency loss down to 70% around 1 Mrad, quickly recovering to 75% beyond this dose.

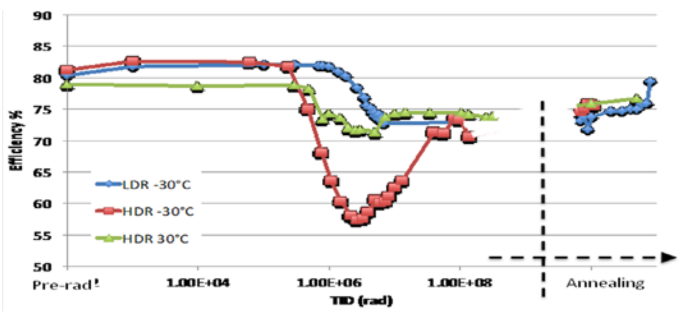


Figure 2: efficiency of the AMIS2 ASIC as function of the total ionizing dose.

[1] SLHC-PP-D8.1.2-1093314-v1 deliverable report.

Proton irradiation tests were also carried out on the AMIS2 prototype to qualify the technology against displacement damage up to an accumulated fluence of $5x10^{15}$ p/cm^2, showing a limited impact on the converter efficiency [5]. Heavy ions irradiation tests completed the qualification process to evaluate the sensitivity to single event effects (SEB and SEGR) without any observable disruption of the converter functionality.

The AMIS2 ASIC has been used as reference device for system tests and power module optimization. In the meanwhile, its design has been improved with the addition of on-chip linear regulators that power the internal control circuitry (AMIS3) and with the introduction of an adaptive dead time handling logic and of protection features (AMIS4) that will result in the improvement of efficiency together with a safer operation for front-end systems. AMIS3 and AMIS4 are due in 2011.

3. CONVERTER PLUG-IN MODULES

The AMIS2 ASIC has been used as reference device for the development of a very low noise converter at CERN: the AMIS2_EMC module (Figure 3) [8]. The module, with a typical size of 28mmx13.5mm, delivers a nominal output of 2.5 V up to 3 A from an input range comprised between 7 V and 12 V.

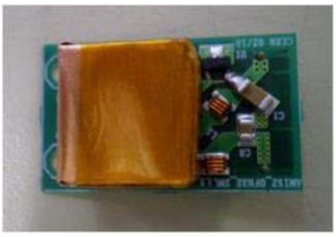


Figure 3: AMIS2_EMC prototype converter with shield.

Its main features are:

- Standardized interfacing connector and form factor.
- Addition of input and output common mode and differential mode filters.
- Uses a custom made 220nH toroidal inductor (designed in collaboration with Coilcraft) sitting above the ASIC.
- Optimized layout placement of parts to minimize the conducted noise.
- Addition of an electromagnetic shield to mitigate the radiated emissions (electric and magnetic emissions).

Compared with the best previous generation of DC-DC converter, the AMIS2_EMC module reaches an outstanding low level of conducted noise, at the limit of what can be measured with an EMI receiver (Figure 4).

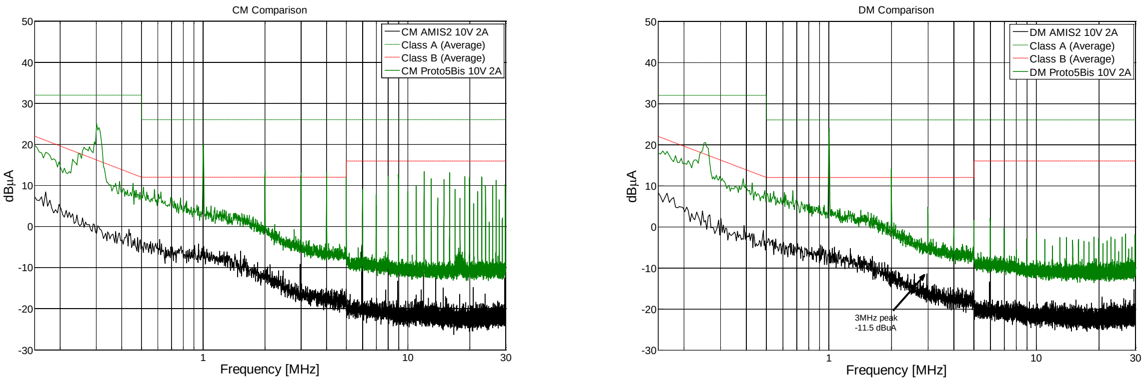


Figure 4: Common Mode (left) and Differential Mode (right) emissions of the AMIS2_EMC prototype (in black) compared to those of Proto5 (in green).

Having reduced the conducted emissions, the radiated noise is the remaining threat for the front-end systems powered by the nearby converter. The mitigation of this radiated noise is achieved by the addition of a shield that must be of low mass for being compatible with the trackers. A thin conductive coating is sufficient to block any radiated electric field, however the mitigation of magnetic emissions requires some thickness of conductive material. A network analyzer combined with a magnetic field coupling structure allows characterizing the magnetic shielding effectiveness for different shield topologies (Figure 5). The effectiveness of a copper loaded varnish, of a 35 µm copper tape and of a 50 µm copper coated plastic box are compared. The copper coating and the copper tape bring sufficient attenuation between 30 dB and 40 dB.

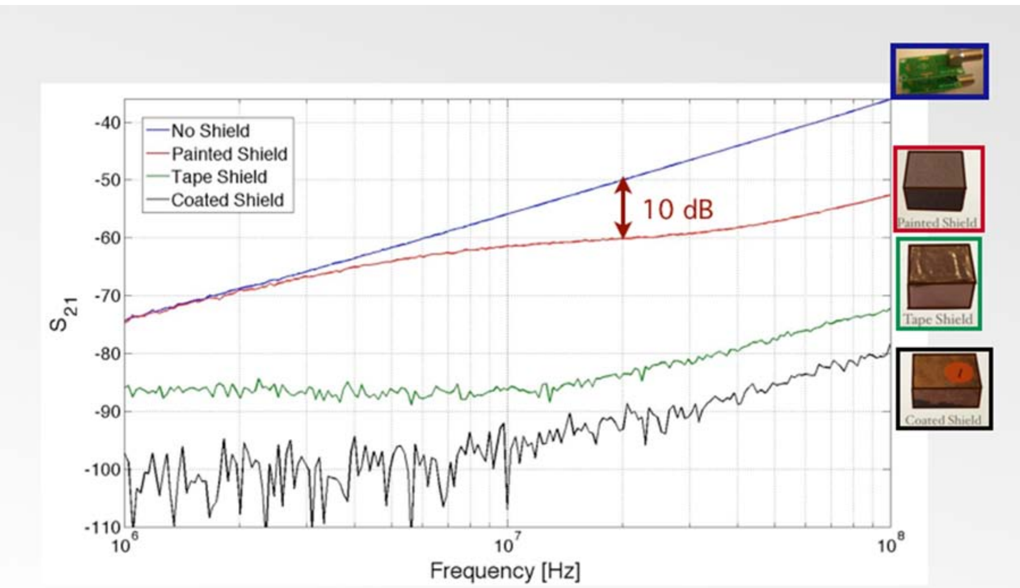


Figure 5: shielding effectiveness of copper painted shields, copper taped shields and copper coated shields

Similar developments have been carried out at the RWTH Aachen University for the development of a DC-DC converter module intended for the powering of the upgraded CMS pixel detector (Figure 6) [9]. The noise optimization method led here also to a very low noise converter module. The converter is fitted here with an aluminium case with a thickness of the order of 100 µm as electromagnetic shield and with a hand made inductor of 450 nH, delivering 3.3V from a 10V input bus.

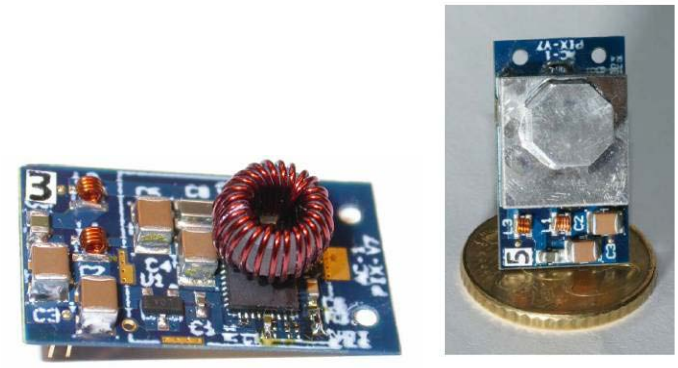


Figure 6: The PIX_V7 DC-DC converter developed at the RWTH Aachen university.

As in the case of the AMIS2_EMC module, the PIX_V7 converter achieves outstandingly low levels of conducted noise (Figure 7) that allow expecting high levels of electromagnetic compatibility with the front-end systems.

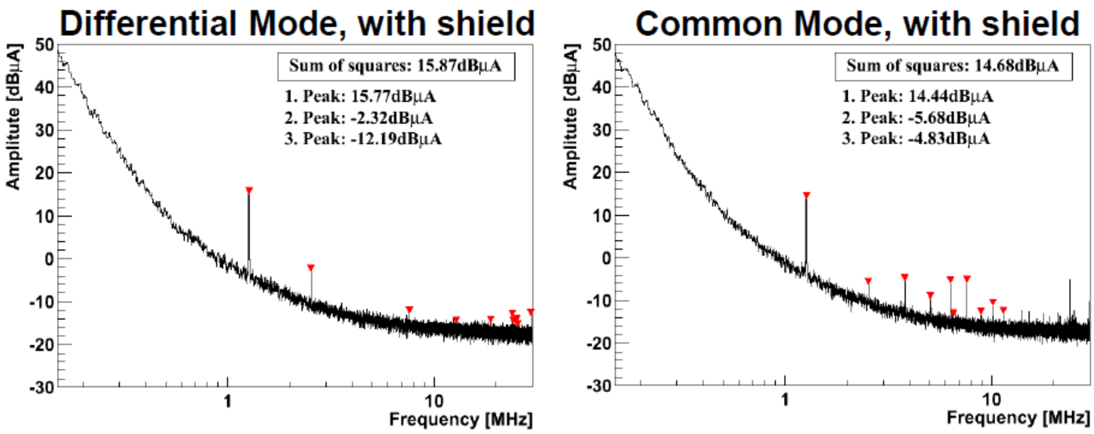


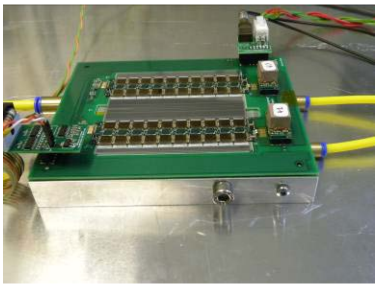
Figure 7: Differential and Common Mode noise spectra measured at the output of the PIX_V7 DC-DC converter for an input voltage of 10V, an output voltage of 3.3V and a switching frequency of 1.3MHz.

4. INTEGRATION WITH DETECTOR MODULES

The AMIS2_EMC module of CERN was designed for the powering of the ATLAS upgraded tracker that will use the future ABCN front-end ASICs in 0.13 µm technology. The design of this chip is currently in progress, and system tests need therefore to be carried out with the former ABCN chip in 0.25 µm technology [7]. This chip requires 2.5V instead of 1.2V, and a full module consumed more than 4A instead of less than 2A. Therefore a dedicated power module using the commercially available LT3605 chip was developed to allow delivering up to 5A needed by this front-end system [8]. Two versions of the tracker staves are actually competing; because of this the same design of the LT3605 based converter was implemented in two variants:

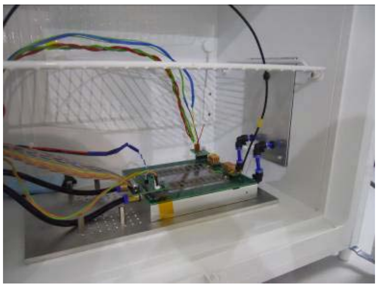
- The first variant is close to the AMIS2_EMC module, with a connector on its bottom edge. It is plugged onto a supermodule structure that will hold up to 8 double sided modules: it is known as SM01C converter.
- The second variant is intended to be glued on a stave structure holding 12 single sided modules. The converter is wire bonded to the stave service bus and to the module, hence it isn't fitted with any connector: it is known as the STV10DCDC converter.

The SM01C converter was first used to power a stave module at the University of Liverpool using a frame test structure (Figure 8). The module is made of a silicon strip detector equipped with two hybrid circuits, each of them carrying 20 front-end ABCN ASICs in 0.25 µm technology. Each hybrid was powered with one SM01C converter and system noise performance was evaluated through a standard data acquisition procedure. An increased noise is observable when using the painted shield, however a negligible fluctuation is observed when using the SM01C converter with a copper tape shield. The same test was repeated using the STV10DCDC converters (Figure 9). In both cases the tracker module is found compatible using either the SM01C or the STV10 converters when fitted with a copper tape shield.



Column	Reference ENC	ENC with SM01C + painted shield	ENC with SM01C + Cu tape
A	585	645	585
B	591	674	591
C	570	723	595
D	596	716	603

Figure 8



Column	Reference ENC	ENC with STV10 + painted shield	ENC with STV10 + Cu tape
A	590	733	595
B	596	740	603
C	585	648	585
D	591	675	591

Figure 9: system noise of the ATLAS tracker modules using a linear power supply, the DC-DC converter with a painted shield, and the DC-DC converter with a copper tape shield.

Given these results, the preparation of a short stave structure with four modules is now in progress (Figure 10). This structure will be equipped in its DC-DC powered variant with STV10 converter modules (Figure 11).

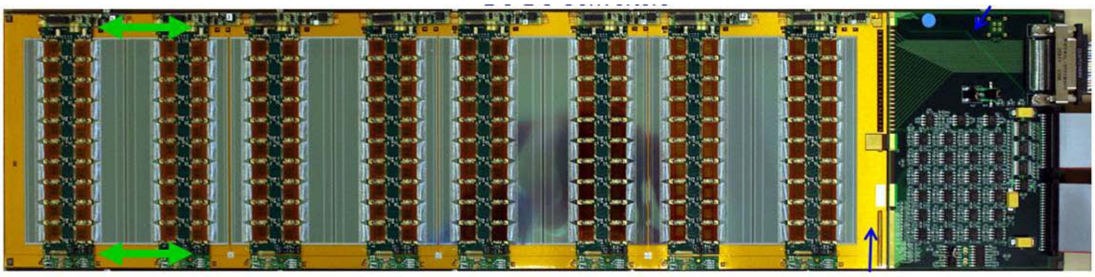


Figure 10: stavelet implementation of the ATLAS tracker.

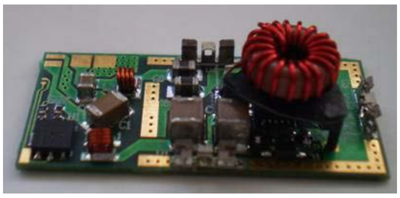


Figure 11: STV10 DC-DC converter for the ATLAS stavelet.

Very similar noise results were obtained with the system tests carried out with the tracker modules of the University of Geneva (supermodules). Here also, a full supermodule is now in preparation, that will be powered with 32 SM01C converter modules (Figure 12).

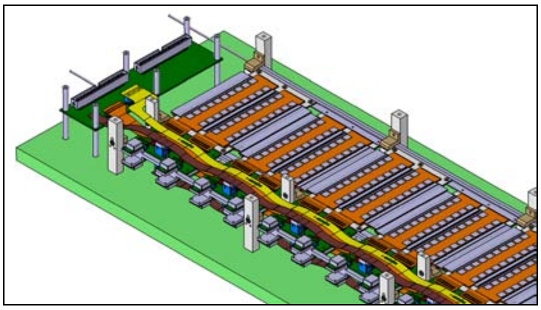


Figure 12: supermodule implementation of the ATLAS tracker using the SM01C converters.

System tests were also carried out on the CMS HCAL front-end electronics using two SM01C converters sitting 25 mm away of the front-end ASICs (Figure 13). The noise is estimated here in terms of RMS ADC counts for different equivalent detector capacitances: no noise degradation is observed in comparison with the noise observed using a linear power supply, irrespectively of the capacitor value used.

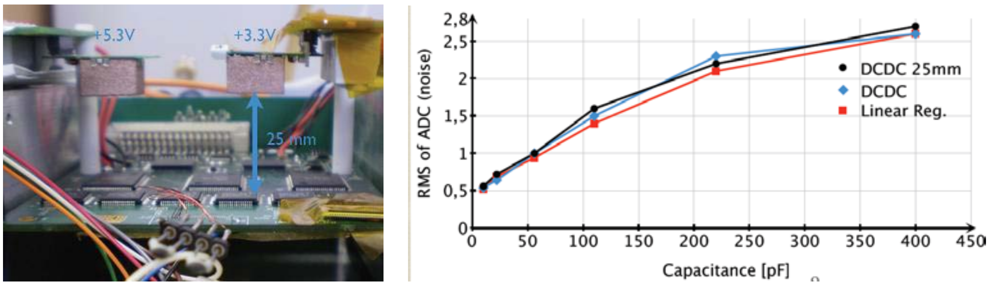


Figure 13: noise performance of the CMS HCAL front-end system using a linear power supply and the SM01C converters.

The full integration of DC-DC converters is also studied at the RWTH Aachen University for the CMS Pixels Detector upgrade (Figure 14) [9][10][11]. The mechanical integration studies are now well advanced, with the converters located on the outermost area of the pixel detector cylinder. The converters are interfaced with the cooling circuit, with a geometry that enables the layout of all the services required by this system. The noise performance of pixel modules powered by the PIX_V7 converters were compared to the one obtained using the reference linear power supply, without any noticeable degradation (Figure 15).

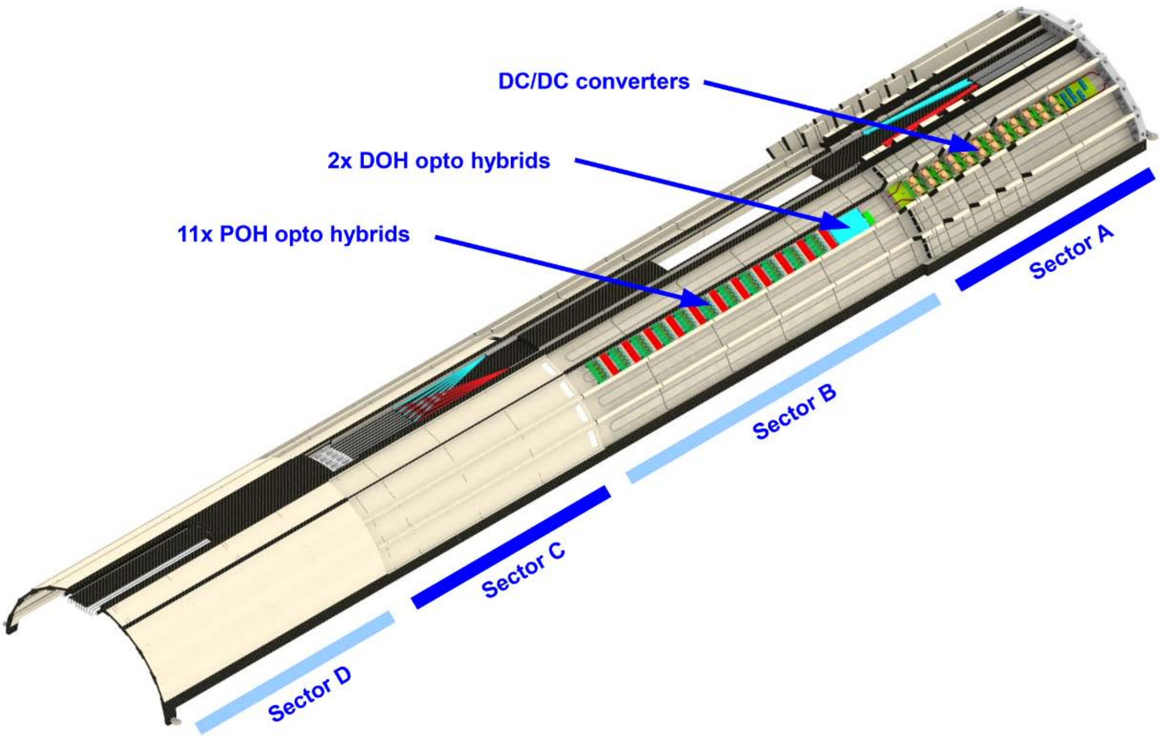


Figure 14: the supply tube of the CMS pixel detector as planned for the Phase-1 Upgrade. DC-DC converters will be integrated at the far end, in sector A, at a distance of about 2m from the pixel modules.

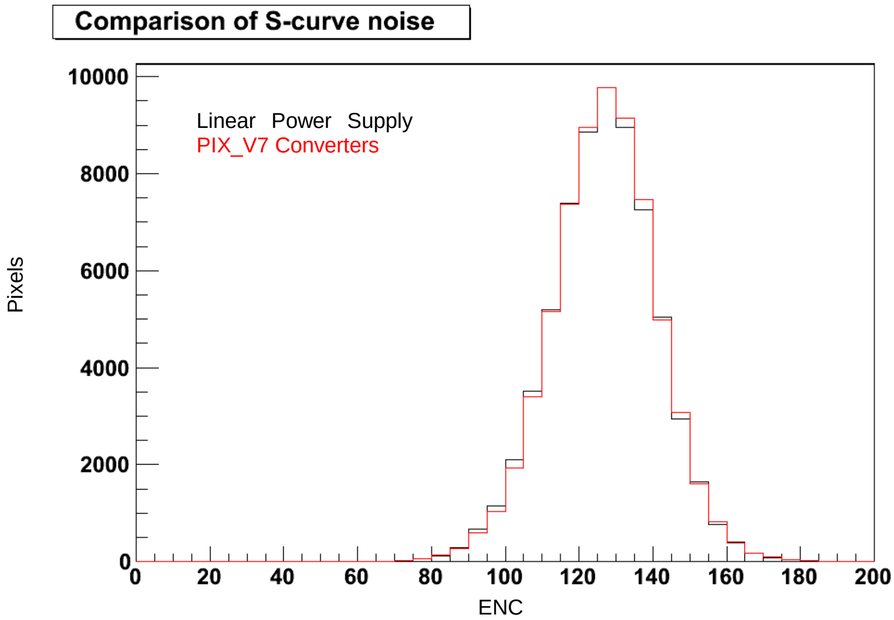


Figure 15: Measured noise distribution (width of the S-curve) for a current pixel module when powered with a linear lab power supply (black) or with two PIX_V7 DC-DC converters.

5. CONCLUSIONS

The radiation tolerance of the AMIS2 ASIC from On Semiconductor has been fully qualified, enabling it for its integration into front-end systems. Prior to this, the integration of this ASIC into a power module capable of delivering the required voltages and currents while minimizing the conducted and radiated noise emissions was carried out. An optimization method has been established and several power modules have been produced for both ATLAS and CMS experiments, all of them leading to very low levels of emitted noise.

The compatibility of existing modules with these converters was explored with currently available detector modules. In some cases the current required by these modules (i.e. the ATLAS tracker modules) exceed the rating of the AMIS2 chip and for those an equivalent counterpart was developed using a commercial ASIC, achieving comparable levels of noise performance. In other cases the AMIS2 based converter could be directly used (i.e. CMS Pixel modules). The sensitivity to radiated noise varies for every system, however the addition of a shield was found to be effective enough to mitigate almost entirely the remaining coupling effects in all cases between converters and modules.

The front-end systems for the experiments upgrade are now under development and the study for the integration of converters on them has been successfully carried out. In the case of the ATLAS tracker, a stavelet structure is now being produced at the UK housing 4 modules and 8 converters that were specially produced to be glued and bonded. Similarly a supermodule structure with 8 double sided modules is being assembled now at the University of Geneva, and the SM01C converter was designed and produced for it. At the

RWTH Aachen University, the PIX_V7 converter has been developed for the upgrade of CMS pixel detector that is now under development.

Although the technology is now getting available to end users for the implementation of the described powering systems, the development isn't finalized yet. New generations of the AMIS power ASIC are already in production now, implementing new features that will help increasing the functionality and the reliability of those devices. Similarly developments with the IHP technology are kept ongoing in order to obtain another fully qualified supplier that would allow the design of even more power efficient ASICs. On the integration side, efforts are now slowly moving towards the mass reduction of the power modules to mitigate the impact on the material budget of the innermost detectors.

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