DC-DC Converters With Reduced Mass for Trackers at the HL-LHC

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Abstract

The development at CERN of low noise DC-DC converters for the powering of front-end systems enables the implementation of efficient powering schemes for the physics experiments at the HL-LHC. Recent tests made on the ATLAS short strip tracker modules confirm the full electromagnetic compatibility of the DC-DC converter prototypes with front-end detectors. The integration of the converters in the trackers front-ends needs to address also the material budget constraints. The impact of the DC-DC converters onto the material budget of the ATLAS tracker modules is discussed and mass reduction techniques are explored, leading to a compromise between electromagnetic compatibility and mass. Low mass shield implementations and Aluminum core inductors are proposed. Also, the impact on emitted noise due to a size reduction of critical components is discussed. Finally, material reduction techniques are discussed at the board layout and manufacturing levels.

Using DC-DC Converters at the HL-LHC

- The upgrade of front-end systems at the HL-LHC will result in an increase of the required power, that forces the development of new, more efficient powering schemes.
- The DC-DC converters bring an efficient low voltage and high current regulation technique for front-end systems.
- The DC-DC converters help to reduce the power losses in the cabling infrastructure, hence reducing the material overhead and the cooling needs.

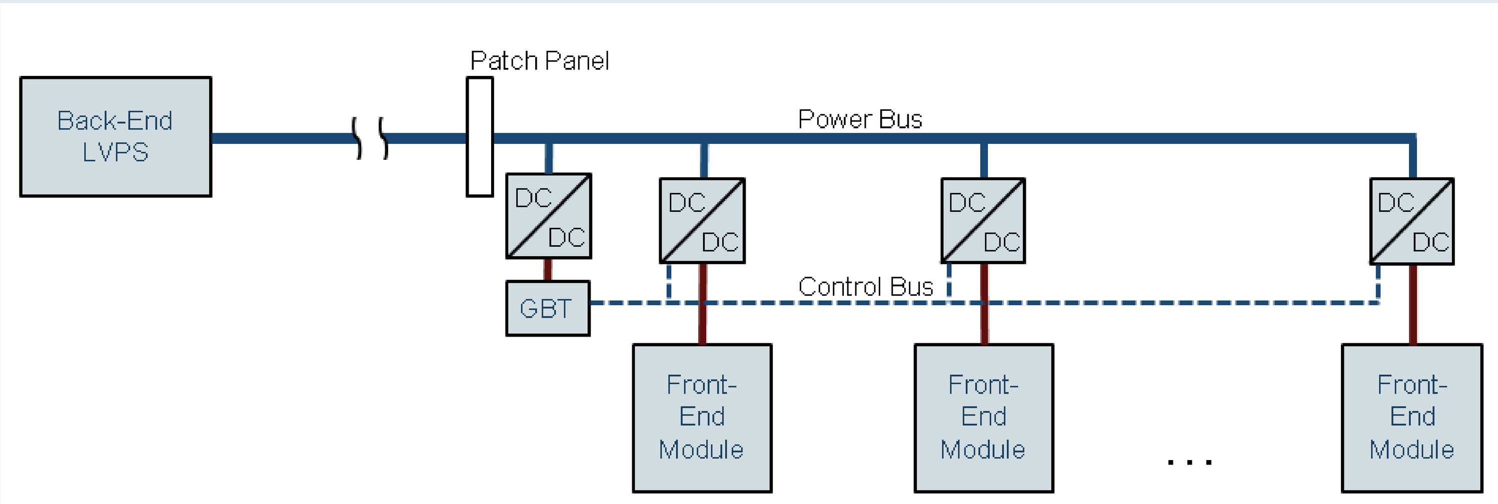
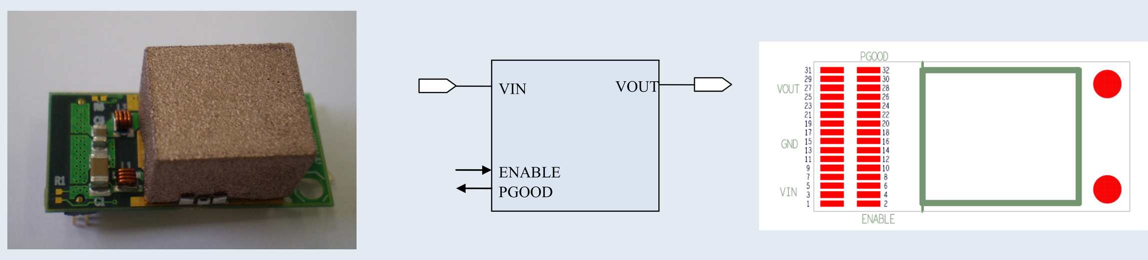


Fig.1: typical powering scheme based on front-end DC-DC converters. A dedicated converter powers a GBT interface that is used to control and monitor the other front-end converters.

- DC-DC converters specifically developed at CERN to withstand high radiation and high magnetic field levels have been produced. The noise emitted by those has been controlled in order to enable their use in close proximity of sensitive front-end ASICs.

Low Noise DC-DC Converters

- Low noise plug-in converter module based on Linear Technology LTC3605 controller.



Input Voltage	**7V to 12V**
Output Voltage	2.5V (trimmable)
Output Current	0 to 5A
Nominal Efficiency	82%

Fig.2: SM01C module, block diagram and board geometry. The module size is 28.4mm x 13.5mm and uses a 10mm high shield box.

- Low noise plug-in converter module based on the radiation hard AMIS2 controller ASIC.

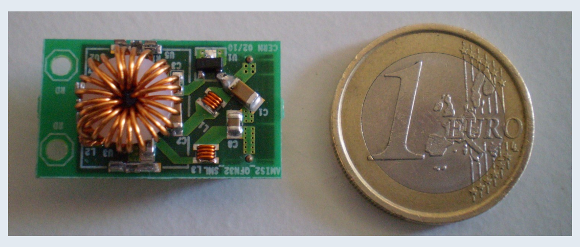
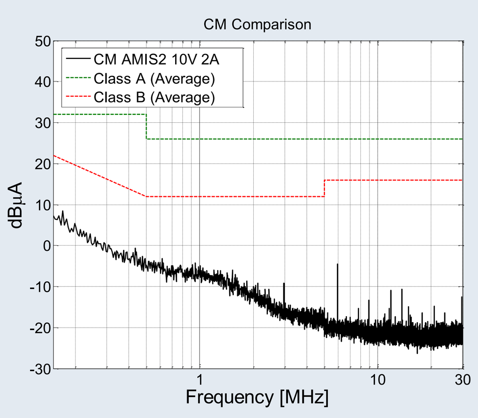


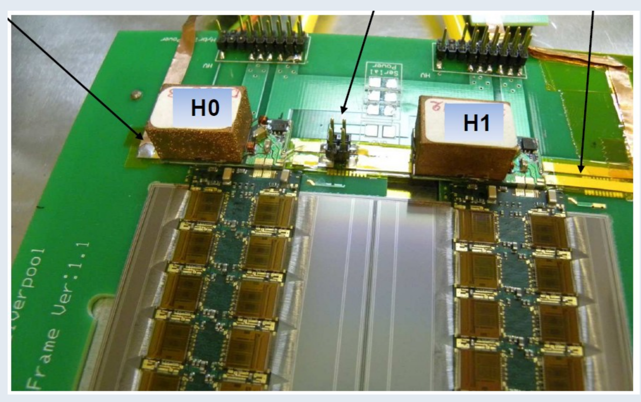
Fig.3: AMIS2 module, same geometry and interface as for SM01C. Shield is removed for visibility of the



Input Voltage	**7V to 10V**
Output Voltage	2.5V (trimmable)
Output Current	0 to 3A
Nominal Efficiency	80%

Fig.4 (left): common mode current of low noise AMIS2 module is below the 0 dBuA level, and is largely below the CISPR11 Class B standard limit line.

- DC-DC modules are being tested with ATLAS stave prototypes.



Configuration	Average ENC
Reference setup (individual powering)	620 … 640 electrons
Module powered by two wire-bonded converters.	660 … 680 electrons

Fig.5: To save in material budget, the STV10 module is a connector-less version of the SM01C module. It is glued 10mm away of the ATLAS short strips sensor prototypes and the power connections are wirebonded. Noise tests have shown the compatibility of the converter with the front-end module.

DC-DC Modules Contribution to Material Budget

The material content of a converter module is split in PCB material, main coil copper and plastic, shield copper and plastic, and passive components:

- PCB: 28.4 mm X 13.5 mm FR4, 2 layers of 35µm thick copper, copper coverage = 85%.
- Main Coil: 220 mm long copper wire, 380 µm diameter.
- Shield: 17 mm X 11.9 mm X 9 mm, 0.5 mm thick PE box, 35 µm copper coated.
- Passives: SMD ceramic capacitors (2 of size 1210, 1 of size 0805, 3 of size 0402).

The material contribution of the 12 converters of a stave is weighted with the overall stave area, resulting in equivalent material thicknesses, on which the fraction of radiation length is estimated.

Part Name	Material	X0 (mm)	Volume (mm3)	Num.	% X0	% of total	*CLASS*
AMIS 2 ASIC	Silicon	93.6	2.187	12	0.0002	0.20	***ASIC***
Shield Copper	Copper	14.3	21.6	12	0.0157	13.24	***SHIELD***
Shield Plastic	Polyethylene	479	360	12	0.0078	6.59	***SHIELD***
PCB (FR4)	FR4	159.2	228	12	0.0149	12.55	***PCB***
PCB (copper)	Copper	14.3	22.61	12	0.0165	13.86	***PCB***
Main Coil	Copper	14.3	27.64	12	0.0201	16.94	***COIL***
Plastic coil standoff	Polyethylene	479	196.8	12	0.0043	3.60	***COIL***
SMD inductor	Copper	14.3	3.08	12	0.0022	1.89	***PASSIVES***
Resistors 0402	86% Al_2O_3, 8% Ni, 6% Sn	39	0.15	60	0.0002	0.17	***PASSIVES***
Caps 1210	86% $BaTiO_3$, 8% Ni, 6% Sn	18.4	22	24	0.0249	20.96	***PASSIVES***
Caps 1206	86% $BaTiO_3$, 8% Ni, 6% Sn	18.4	9.1136	12	0.0052	4.34	***PASSIVES***
Caps 0805	86% $BaTiO_3$, 8% Ni, 6% Sn	18.4	3.8	36	0.0064	5.43	***PASSIVES***
Caps 0402	*86% $BaTiO_3$, 8% Ni, 6% Sn*	*18.4*	*0.25*	*24*	*0.0003*	*0.24*	***PASSIVES***

DC-DC Mass Reduction Strategies

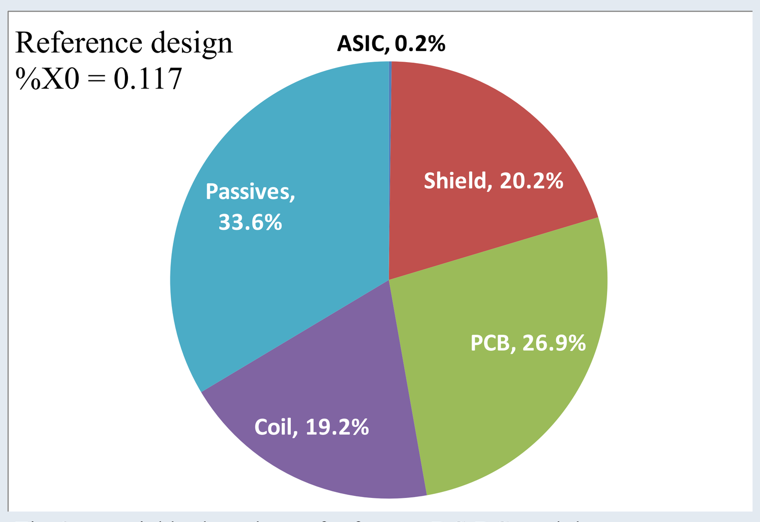


Fig.6: material budget share of reference DC-DC module.

Reference DC-DC construction:

- %X0(DCDC) = 0.12% scaled to full stave.
- %X0(Modules)= 0.53% scaled to full stave.
- DCDC contribution to stave radiation length:

0.12/(0.53+0.12) * 100 = 18.5%.

The material is mainly shared equally between the PCB, the coil, the shield and the passive components. The contribution of the ASIC is negligible.

ECCA inductor wire

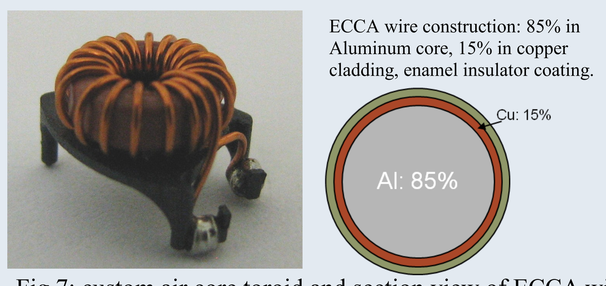


Fig.7: custom air core toroid and section view of ECCA wire.

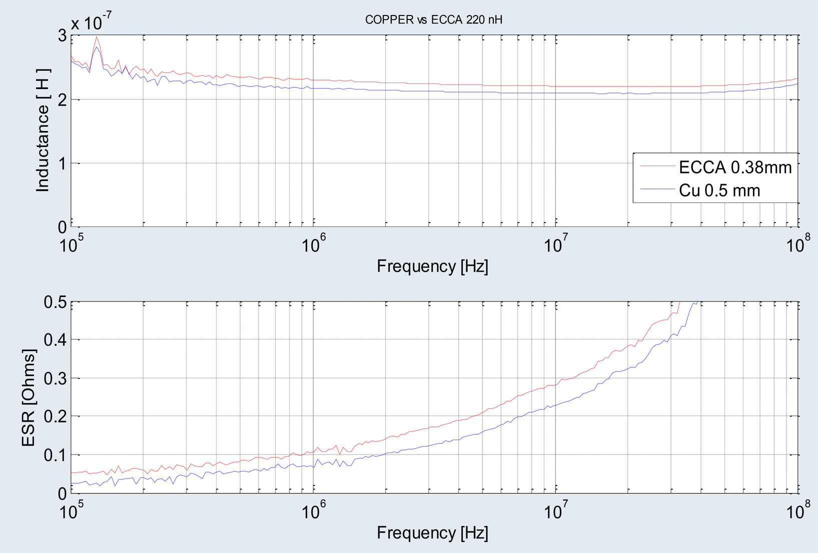


Fig.8: inductance and series resistance of copper coil and equivalent ECCA wired inductor.

- L = 220 nH, made of 220mm long wire of 380 µm diameter.
- Copper wire results in %X0 (Cu) = 0.022.
- Enamelled copper cladded aluminum wire is an alternative to reduce material budget contribution of the main coil: %X0 (ECCA15) = 0.0095.
- DCR(Cu) = 33 mΩ, DCR(ECCA15) = 49 mΩ.

Shields

- Shielding effectiveness is limited by material resistivity and by skin depth. Attenuations were estimated at 10 MHz.
- A 35 µm copper foil box is used as reference with an attenuation of 36dB .
- A 10 µm copper coated PE box provides an attenuation equivalent to the PE reference box: 36 dB.
- A 100 µm Aluminum box brings 28 dB attenuation.
- A thin copper coated box is a more effective shield and adds less material:

%X0(Cu foil)=0.024
%X0(PE box)=0.0068
%X0(Al box)=0.0084.

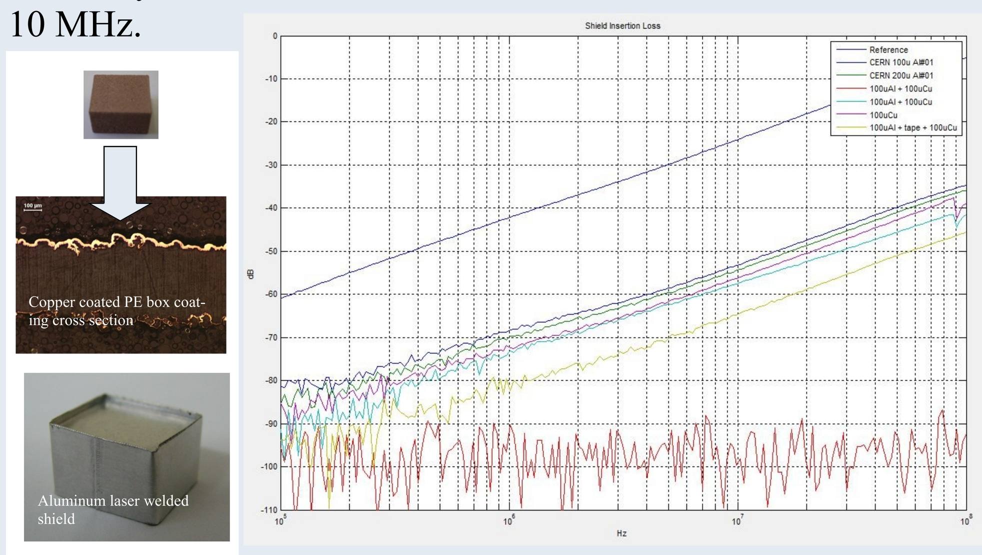


Fig.9: copper coated PE shield and coating cross section view (top left), aluminum welded shield (bottom left), and shielding effectiveness results of various shield constructions.

Capacitors

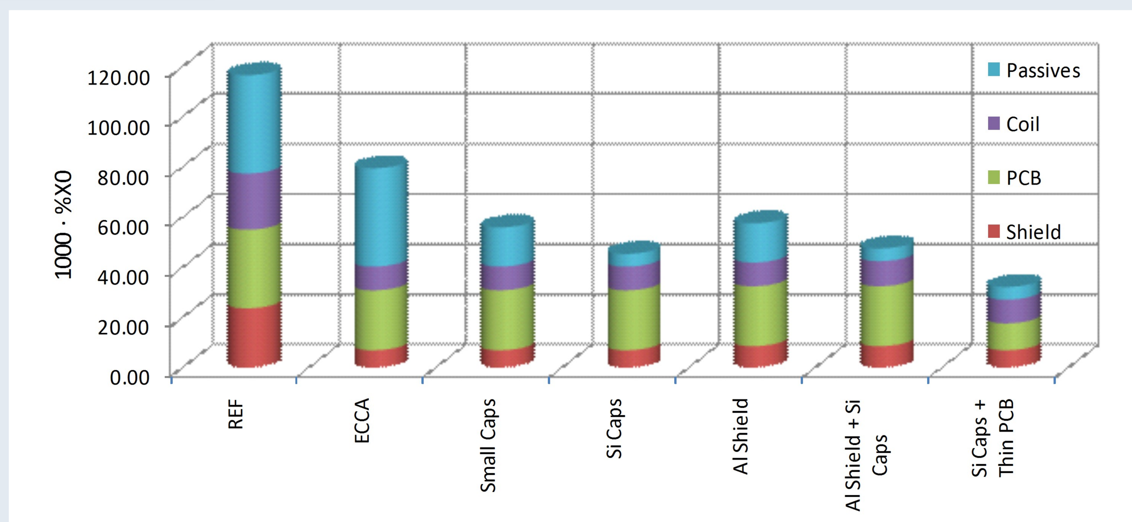
The ceramic capacitors contribute in one third of the reference converter material budget.
At expense of slightly higher emitted noise (few dB only), the size reduction of the 1206 and 1210 ceramic capacitors with 0805 sizes allows to decrease their equivalent fraction of radiation length from %X0 = 0.039 down to %X0 = 0.016.
More recently, silicon bulk capacitances are now available on the market. The replacement of the ceramic capacitances with those would allow achieving a %X0 = 0.005 only.

PCB

The reference design assumes a double layer circuit 600 µm thick with 35 µm copper cladding on both sides, resulting in a %X0 = 0.031. A thickness reduction down to 300 µm with a copper cladding of 17 µm instead would result in a %X0 = 0.0156, and a further thickness decrease down to 100 µm would allow reaching a %X0 = 0.0107. Replacing the FR4 with Kapton would bring a further reduction on this front too.

Summary Chart

	REF	ECCA	Small Caps	Si Caps	Al Shield	Al Shield + Si Caps	Si Caps + Thin PCB
Reference	☑	☐	☐	☐	☐	☐	☐
ECCA inductor	☐	☑	☑	☑	☑	☑	☑
10µm coated shield	☐	☑	☑	☑	☐	☐	☑
Al foil shield	☐	☐	☐	☐	☑	☑	☐
Small capacitors	☐	☐	☑	☐	☐	☐	☐
Silicon capacitors	☐	☐	☐	☑	☐	☑	☑
300um thin PCB	☐	☑	☑	☑	☑	☑	☐
100um thin PCB	☐	☐	☐	☐	☐	☐	☑



Conclusions

A low noise DC-DC converter design has been used for a mass reduction exercise, applied to the staves design of the ATLAS upgraded tracker. At expense of small increase of noise and thermal losses, the material budget contribution of the DC-DC converters can be divided by two using ECCA wire for the main coil, smaller passives and a thinner printed circuit board. The use of bare aluminum for the shield or for the PCB clad does not bring any significant improvement of the overall fraction of radiation length contributed by the DCDCs on the stave.

A compromise configuration (ECCA wire, small capacitors and thin copper PCB) combined with 10 µm copper coated PE shield boxes would result in a fraction of radiation length of 0.056% equivalent to 10% of the modules mass. Ultimately, silicon capacitors combined with a PCB thinned down to 100 µm of FR4 would result in a fraction of radiation length of 0.032% only.