Board-to-Board Interconnections for High Data Rate
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1 INTRODUCTION

Today there is a growing need to develop a board-to-board Interconnections for High Data Rate applications, fully compliant with the compact PCI Serial Space (cPCI SS) standard. These interconnections must efficiently route data and distribute power between processing modules in on-board equipment. Currently, there are no European solutions able to reach 25 Gbit/s and higher, a requirement for next-generation systems. This activity did trade-off connection techniques, including the use of press-fit technology.
The CompactPCI Serial Space standard is a benchmark for critical applications, including aerospace, defense, telecommunications and industrial applications. This standard enables flexible and scalable interconnection while ensuring high bandwidth and optimized power management.
The core of this work is the integration of a CompactPCI Serial architecture that lies in the design of the connectors, and more specifically in the daughterboard-motherboard assembly. These components, often underestimated, play a key role in High Data Rate data transmission and efficient power delivery, while meeting strict constraints of compactness, mechanical robustness and electromagnetic compatibility (EMC).

This article explores the technical issues, innovations and best practices related to the design of the board-to-Board Interconnections for High Data Rate.

From survey we did, we gathered lessons learn and we tried to apply them as much as possible in our design.
If we dig deeper into backplane connectors' technology, the two main solutions used to create transmission lines interconnection between daughter and motherboard are: overmolded leadframe and PCB microstrip technology.

PCB microstrip:

- When direct contact is used on PCB, fretting corrosion on PCB tracks could be a problem (micromotion of Plug-In Module is a potential cause of connector fretting wear/corrosion.)
- As the section of tracks are generally low, DC resistance could be quite high and limits the ampacity creating joules effects and thermal overheating.

Lead frame:

- Terminations are usually made with Flat shape contact created discontinuity during mechanical vibrations and shocks.
- As it is not easy to compensate the length differences between 2 tracks, skew is created by the T-lines shapes.

The bonding method is generalised with press-fit termination which is a solderless solution extensively used in consumer electronics. For low frequency signals, there is no signal disturbance but for high frequency, stub effect with long press-fit shape could be a source of trouble.

Technology choice:
We decided to develop 2 kinds of connectors: one dedicated to HDR (High-Data-Rate) signals and the other more efficient regarding power supply and low frequency bandwidth signals. A lot of common parts will be shared with the both variants and the backplane connector will remain the same.

2 DESIGN AND MANUFACTURING PHASES

As presented in the introduction, modules could be made with PCB or with lead frame inserted and locked into a main housing.
We concentrated the study on the HDR PCB frame in a first time. Two module types are used: “A” & “B” to be compatible with Compact PCI serial Spec routing. On each module, 12 male contacts ensure the bonding with backplane while 12 press-fit ones perform it with daughter card.

With a view to standardisation to facilitate the industrial production of HDR and power connectors, we have designed standard components for backplane connector and for daughter connector. The housing is a common part and HDR or power frame can be selected and integrated according to the required configuration.

AXON’s design leverages press-fit PCB terminations to ensure robust mechanical and electrical connections, while maintaining full compatibility with the CompactPCI Serial Space standard, thus eliminating any impact on existing customer boards. The shape of the press-fit terminations was design to minimize the degradation of the electrical signal (e.g.: reduction of the heigh of the EON (Eye Of the Needle) shape to reduce HF stub effect).
Interconnection between daughter and backplane connectors is ensured with round contact in order to improve reliability in vibrations.

3 HDR CONNECTOR

In the fig. 1 are represented the backplane and daughter connectors on a HDR 8-column connector with 96 positions.

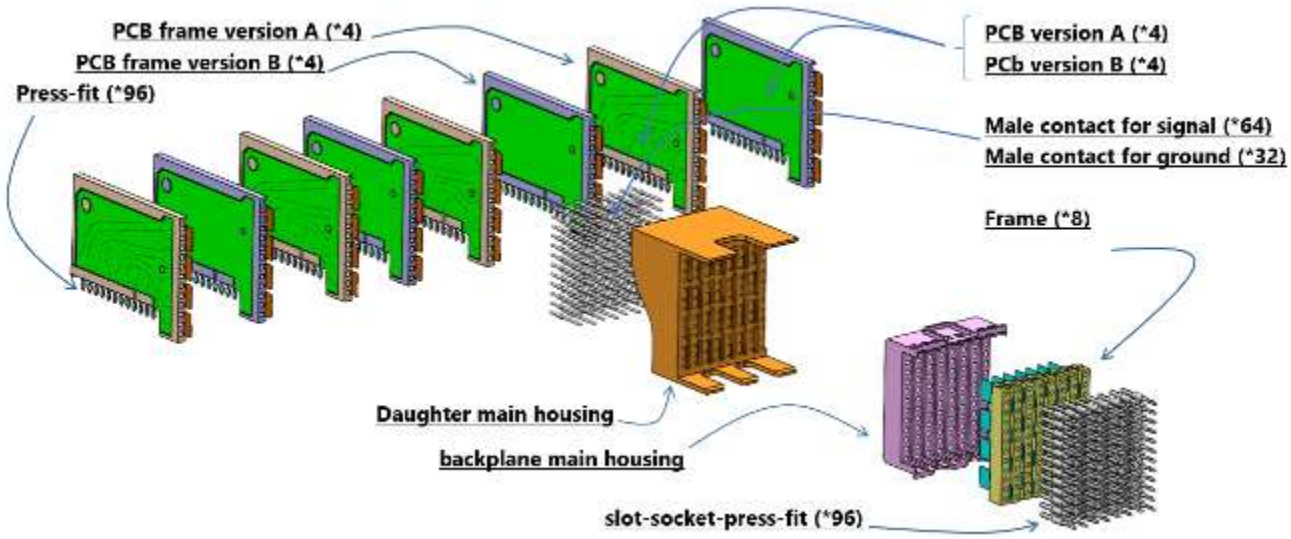


Fig. 1 overview of the components of the two connectors: daughter and backplane.

3.1 Transmission lines

On HDR connectors, transmission lines are made with differential coplanar waveguides to insure a good compromise between signal integrity, size and weight. For first prototypes, low cost substrate was used to speed up the manufacturing. Today MEGTRON7 procurement is on going to improve electrical features and to be in line with ADHA recommendations.

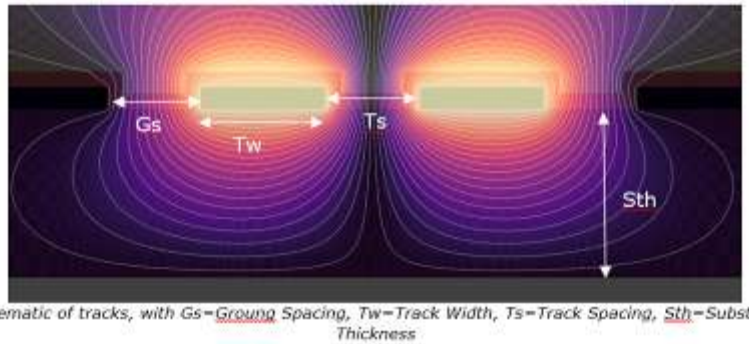


Fig. 2 coplanar waveguide used in daughter connectors PCBs

Zero intrapair Skew: PCB are design to remove intra pair skew in the PCB: same lengths for the 2 conductors of each transmission line.

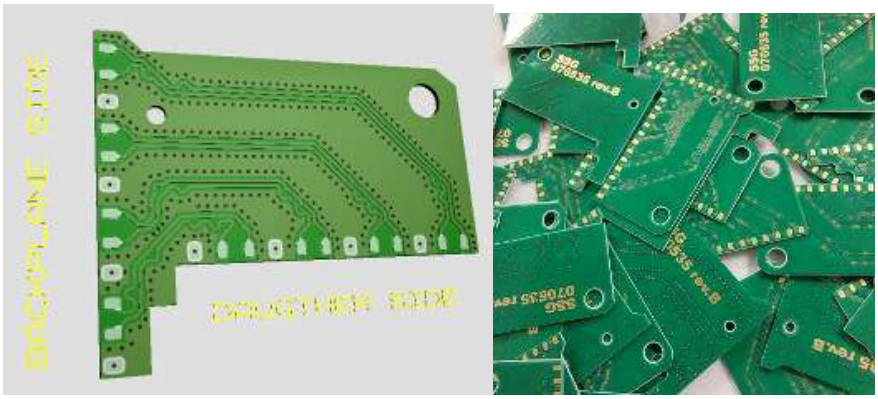


Fig. 3 From left to right: backplane contact, daughter press-fit contact

3.2 Interconnections

Interconnection to backplane & Daughter card PCBs are performed thanks to press-fit technology with an extensive heritage in a lot of application and well mastered by Axon' Mechatronics. For first manufacturing, daughter press-fit is made using chemical machining based on foil material. EON shape has been selected.
On the other side, for backplane connector, we have selected a machined EON Press-Fit with a small height, to minimize signal perturbation caused by electrical stub behavior at hight frequency. This contact part present one side with a press-fit EON and a slots side for interconnection with daughter male part (see fig.4 for 3D illustration and Fig.5 for real products pictures).



Fig. 4 From left to right: backplane contact, daughter press-fit contact



Fig. 5 From left to right: backplane contacts, daughter press-fit contact on a foil after chemical machining before plating, plated contacts.

We launched different sizes and different shapes of press-fit to evaluate the mechanical behaviour mainly the insertion force into the PTH (Plated Through All): press-fit insertion in different holes diameters were carried out to assess their performances regarding the PTH diameter tolerances.

Evaluation made on the two terminations showed the following information:
The flat EON press-fit connectors have been optimised with a range of leg dimensions to achieve an insertion force of 22 N and a retention force about 6 N per press-fit. Mechanical tests were carried out to assess the quality of the press-fit in accordance with the IPC 9797 and IEC 60352-5 standards, which are consistent with the ADHA standard [ref]. Daughter press-fit contact reveals a good behaviour.

On the other side machined press-fit have been evaluated following the same test sequences; insertion (21 N) and extraction (9N) values are compliant, nonetheless uncompliant cracks have been observed for the plated holes within the lower tolerance range of 0.45 to 0.49 mm in diameter. An optimised design is currently being manufactured and will be characterised shortly in order to address this risk.

Mating Interconnection between daughter and backplane connector is achieved using circular contacts for better mechanical behaviour. Termination of the male is shaped to offer a low force mating (see fig. 6).
GND (ground) contacts are not mated in the same time than signal contact to reduce the overall insertion force peak at the beginning of the couple mating.



Fig. 6 daughter male contact

Moreover, we worked on the female shape to reduce the reaction force during the mating phase. As it is not easy to simulate the reaction force, we launched 2 female terminations: one with 4 slots and the other one with 2 slots as described in Fig.7. The measurement force will be done on the manufacturing batch.

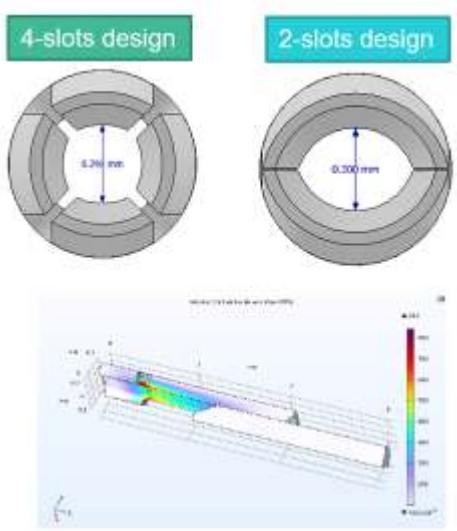


Fig. 7 FEM simulation with 2 & 4 slots designed contacts

3.3 Housing and frames

Initially, for prototypes, we planned to use only 3D printed parts for all the plastic one but it was not safe w.r.t. the poor mechanical behaviour of the material: very often, the guide walls broke during insertion or manipulation. Nevertheless, printing materials offer good dielectric constant (some around 2.5) and high service temperature (up to 150°C and more)

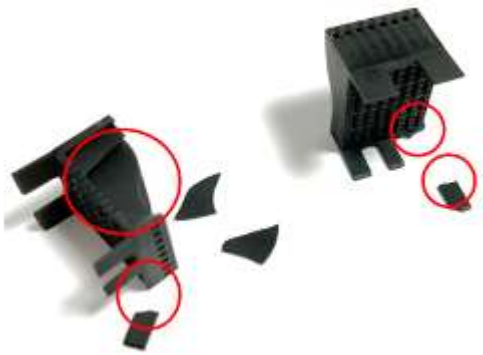


Fig. 8 housing breaks during manipulation

To be more confident with mechanical behaviour and to ensure a safe insertion in PCB, we decided to launch machined frames with PEEK material as we need to push on the frames to insert press-fit in the PCB which needs an important force. Nevertheless 3D printed plastic material will stay for housings only as it is impossible to machine these complex parts as illustrated in Fig9. Fig.10 show the manufactured parts used for connectors.

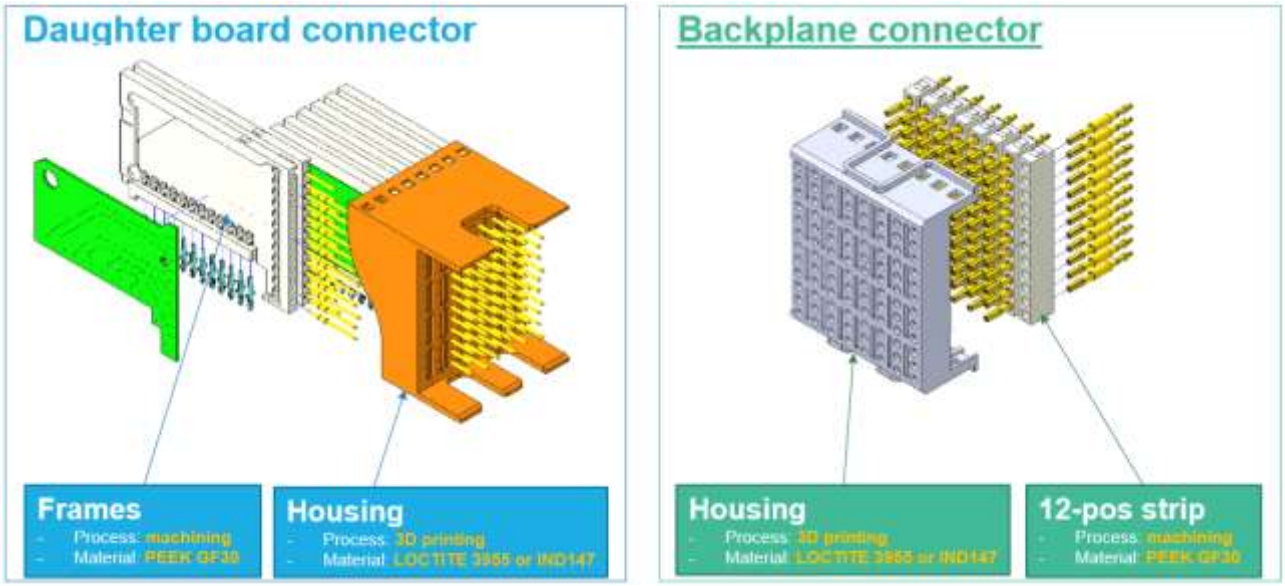


Fig. 9 From left to right: PEEK daughter connector, backplane connector

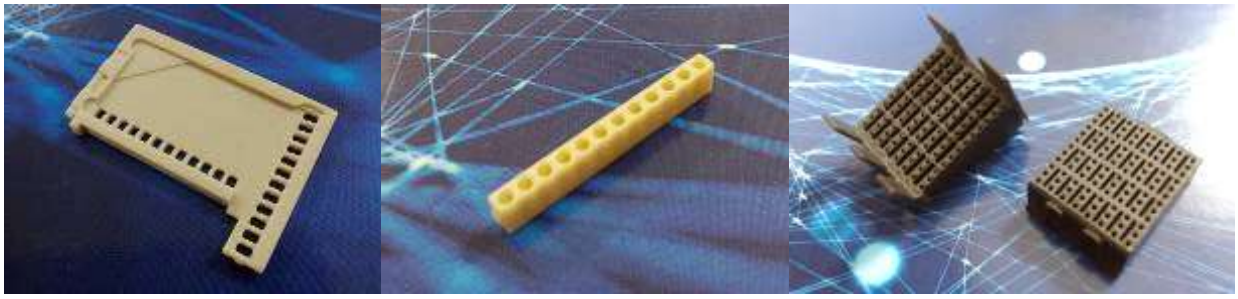


Fig. 10 From left to right: PEEK daughter machined frame, PEEK backplane machined part, daughter & backplane housings.

Plastic parts injection for series:

For series phase, all plastic connector parts will be made of high pressure moulded LCP material extensively used in axon' in a lot of components (e.g.: connector inserts, connector housings, lead frames, shells)

These parts need to be mould in cavities with dedicated design rules to be sure the filling will doing well and the warpage of the parts will be minimum. This is an important on-going activity funded by ESA.

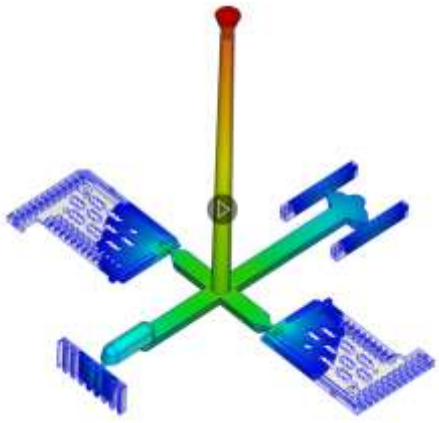


Fig. 11 Simulation of plastic injection in moulds (housings and frames)

Parts assembly:
On daughter connector, male contacts and press-fit terminations are soldered together on the PCB thanks to the PEEK plastic frame (grey parts in Fig.12). On backplane connector, contacts are inserted in housing and locked with PEEK parts
For series, vapor phase reflow soldering will be implemented to speed up the process.

Then frames are gathered in the 3D printed housing and locked by various clipping shapes like presented in Fig.12

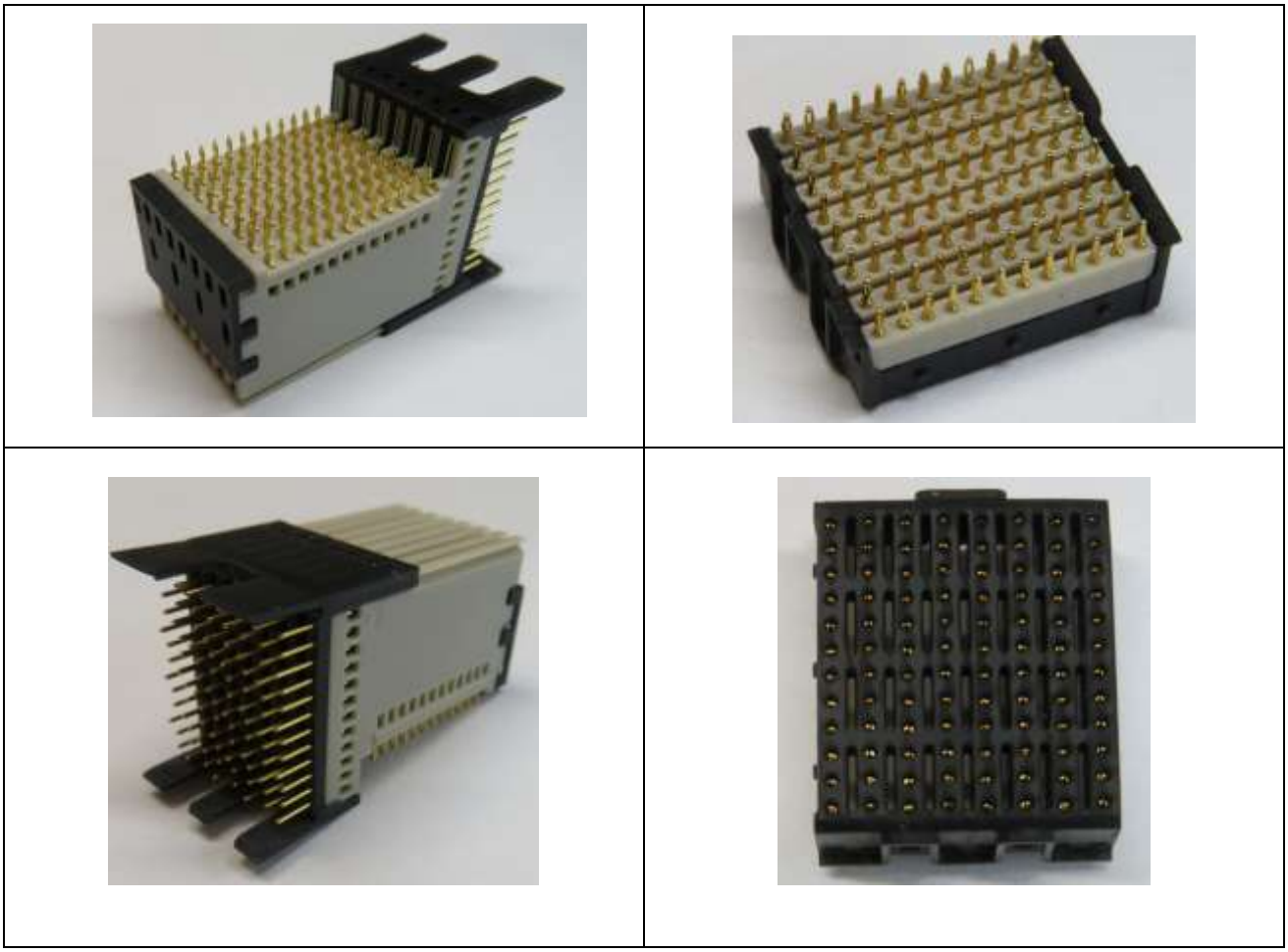


Fig. 12 From left to right: daughter connector & backplane connector prototype

3.4 Control and manufacture tooling:

Tooling test for full connectors assembly is designed and manufactured, it is used to validate each connector manufacturing ensuring an electrical connection on all connector's contacts (press-fit and male terminations) Continuity and insulation test are achieved thanks to an automatic test bench like in Fig.13.



Fig. 13 Tooling jig for automatic electrical test on an assembled connector.

Press-fit insertion device is also designed and manufactured by axon' for internal tests and customer integration. An insertion example is present in Fig.14. In Fig.15, the tooling list for both daughterboard & backplane with 72 to 96 contacts.

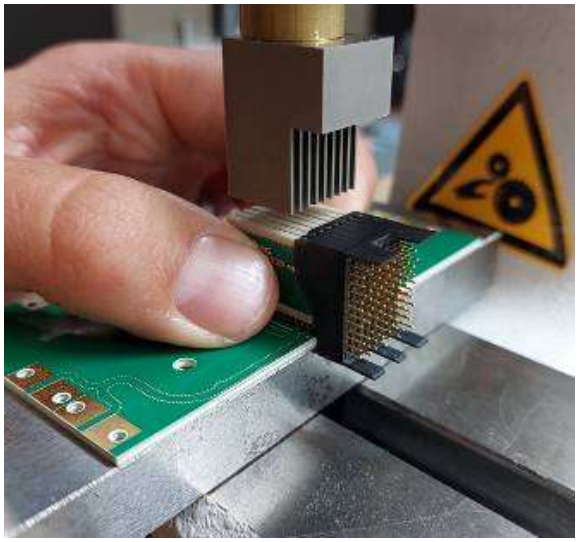


Fig. 14 daughter connector press-fit insertion jig in operation

Connector type Size	Daughterboard 6-COL / 72-POS	Daughterboard 8-COL / 96-POS
Tooling P/N	CTR177	CTR175
Picture		

Connector type Size	Backplane 6-COL / 72-POS	Backplane 8-COL / 96-POS
Tooling P/N	CTR176	CTR174
Picture		

Fig. 15 Tooling list

3.5 Electrical evaluation in time and frequency domain

Electrical evaluation was performed in time domain to asses Eye pattern transmission and TDR characteristic impedance and in frequency domain to measure losses and Xtalk.
For Eye pattern measurement, we took the setup and the sanction mask of the SpaceFibre validate the Digital signal integrity. Long and short lines were tested. Illustration of the setup is available in Fig.16.

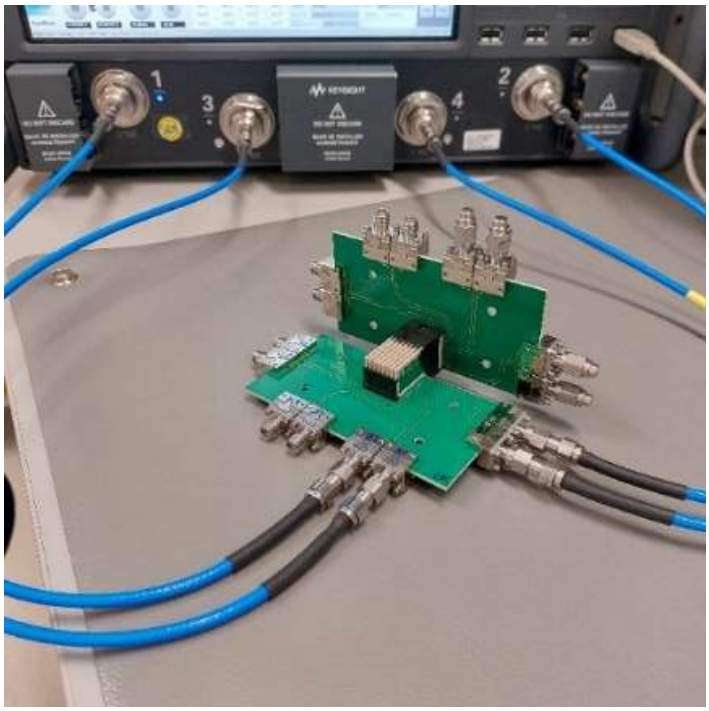


Fig. 16 Daughter & backplane connector mounted on the test jigs

Static tests:
At first, we performed static tests (continuity, voltage proof test & insulation):
These tests are important to verify the cabling of the connectors.

Continuity measurement results:

PCB Daughter	PCB Backplane	R0 (mOhms)
A1	A1	63.3
B1	B1	61.8
B2	B2	52.4
C2	C2	52.7
J1	J1	107
K1	K1	109
K2	K2	119
L2	L2	121

With A1… L2, the line (A, B...) and frame (1, 2…) numbers as describe in the CompactPCI Serial specification.

DWV & Insulation test results:

Measured poles	DWV under 600Vrms	Insulation under 500Vdc
A1 & B1	<2mA	>1000MΩ
A1+B1 & GND	<2mA	>1000MΩ
B2 & C2	<2mA	>1000MΩ
B2+C2 & GND	<2mA	>1000MΩ
J1 & K1	<2mA	>1000MΩ
J1+K1 & GND	<2mA	>1000MΩ
K2 & L2	<2mA	>1000MΩ
K2+L2 & GND	<2mA	>1000MΩ

A four ports VNA N5227B (67GHz) is used to perform frequency & time domain measurement.
A Fourier transformation gives the possibility to work from frequency domain to time domain and a special function to get the eye pattern. The following tables gives us the results of the measurements.

Insertion Losses results are available in the following table:

Insertion losses	**3.125GHz**	**6.25GHz**	**12.5GHz**
limits	<- 1dB	<- 1.5dB	<- 2dB
A1-B1 measurement	- 0.71	- 2.74	- 3.37
K1-J1 measurement	- 0.73	- 2	- 3.88
B2-C2 measurement	- 0.68	- 2.09	- 3.81
K2-L2 measurement	- 1.05	- 2.91	- 3.02

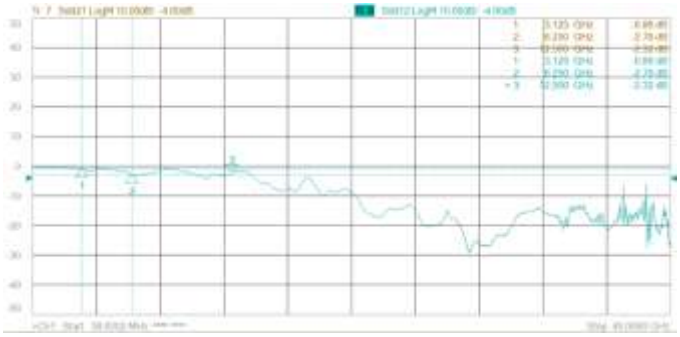


Fig. 17 Example of insertion losses measurement

Near end and far end signal crosstalk measurement results are available in the following tables:

Near end signal crosstalk	**0 to 3.125GHz**	**3.125GHz to 6.25GHz**	**6.25GHz to 12.5GHz**
limits	<-39dB	<-34dB	<-29dB
A1-B1 / B2-C2 measurement	-45	-49.3	-39
K1-J1 / K2-L2 measurement	-45.2	-56.1	-41.9

Far end signal crosstalk	**0 to 3.125GHz**	**3.125GHz to 6.25GHz**	**6.25GHz to 12.5GHz**
limits	<-42dB	<-34dB	<-26dB
A1-B1 / B2-C2 measurement	-45	-49.3	-39
K1-J1 / K2-L2 measurement	-45.2	-56.1	-41.9

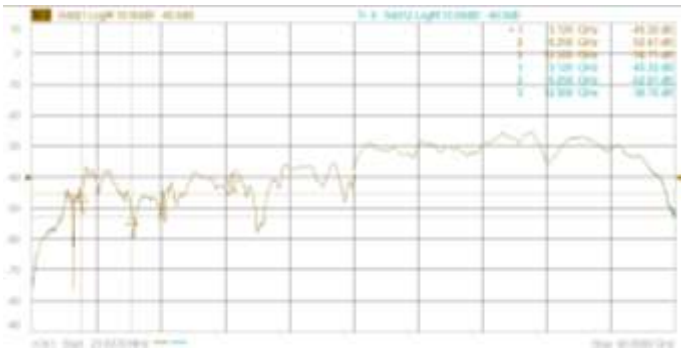


Fig. 18 Example of crosstalk measurement

Characteristic Impedance measurement results are available in the following tables:

Differential characteristic impedance TDR (Rise/fall time ≤ **17.5 ps**)		
limits	>90Ω	<100Ω
A1-B1 measurement	83*	124
K1-J1 measurement	84*	117
B2-C2 measurement	85*	115
K2-L2 measurement	81*	120

*linked to PTH Zc of test jig

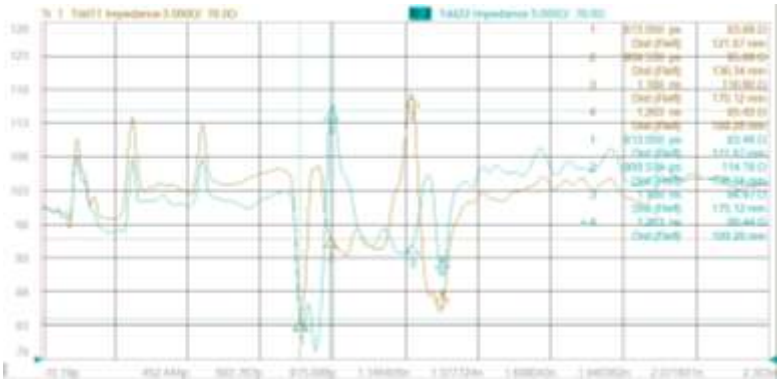


Fig. 19 Example of characteristic impedance measurement

Eye pattern results are available in the following tables:

Eye pattern Pattern generator @12.5Gb/s, 25Gb/s, 32Gb/s output swing= +/-400mV (minimum) SpaceFibre mask: 6.25Gb/s (+/-100mV Threshold)	**12.5Gb/s**	**25Gb/s**	**32Gb/s**
limits	Mask	Mask	Mask
A1-B1 measurement	PASS	PASS	PASS
K1-J1 measurement	PASS	PASS	PASS
B2-C2 measurement	PASS	PASS	PASS
K2-L2 measurement	PASS	PASS	PASS

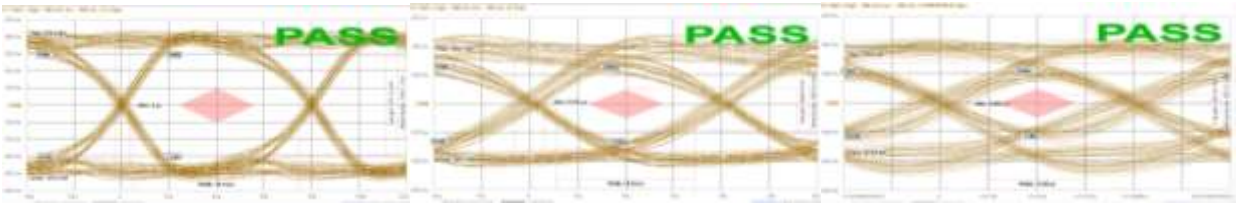


Fig. 20 Example of eye patterns from left to right @12.5Gb/s, 25Gb/s, 32Gb/s

Regarding measurement results on Compact PCI serial space axon' connector prototype, some parameters are above the limits asked by the requirement of the SOW nevertheless, digital transmission is insured with margin over 25Gb/s with a NRZ baseband signal. The non-conformances concern mainly the insertion losses. Axon is thinking of how to improve the losses of the couple of connectors (impedance improvement and PCB material change).

3.6 Mechanical evaluation

Mechanical evaluation was performed following internal evaluation plan N° 22029-ETP-0001-AXON on connector couples. This evaluation was made to validate the implementation and the robustness of the flat shape & circular pressfit on PCB and validation of 500 mate/de-mate cycles.

The evaluated samples are listed in the table below:

SAMPLE TYPE	DESCRIPTION	QTY (P)
Pin contact	Male contact diam. 0.4mm PCB variant L=6.85mm	**20**
Socket contact	4-slot socket contact for pin 0.4 machined closed pressfit	**10**
Socket contact	2-slot socket contact for pin 0.4 machined open press fit	**10**
Connector receptacle	96-POS/8-COL Backplane connector receptacle, with 4-slot SKT contacts, closed pressfit variant	**3**
Connector receptacle	96-POS/8-COL Backplane connector receptacle, with 2-slot SKT contacts, open pressfit variant	**3**
Connector plug	96-POS/8-COL Daughterboard connector plug	**6**

The following test in Fig.21 were performed on the contacts themselves & on the mated connector pairs:

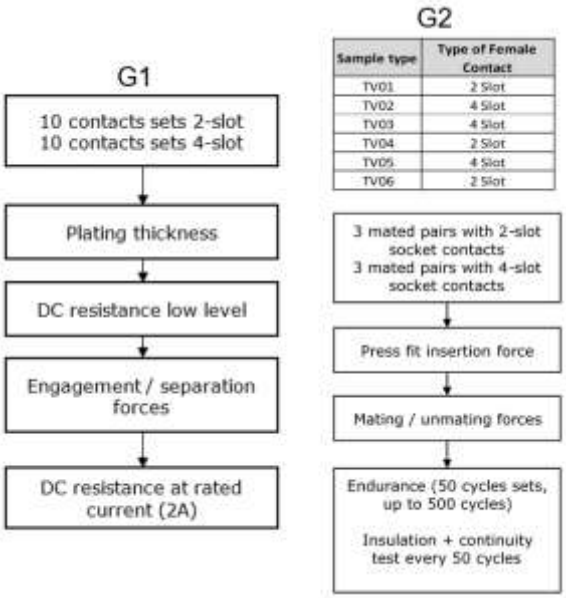


Fig. 21 test sequence for Group1 (contacts only) and Group2 (96p connectors)

Pull test machine was used to measure the resulting force of mechanical tests on contact alone, press-fit insertion and mating/unmating as illustrated in Fig.22.

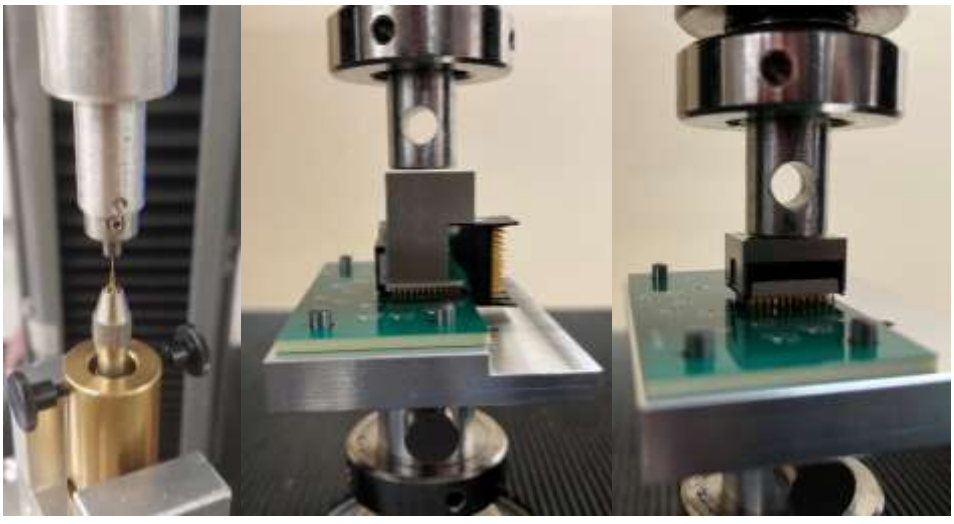


Fig. 22 From left to right, Engagement & Separation Forces on contact, Press Fit Insertion Forces on daughter connector then on backplane connectors with manufactured tooling installed on a pull test machine.

Test results of the 20 contacts alone (Group1):
The electrical results on the 20 contacts show a DC contact resistance <6mΩ (low level) & <5mΩ (2A rated current)
The Engagement & Separation Forces shows us a lower insertion force for the 2 slots contact and a better demate force for the 4 slots contact (Goal: Mate force target <0.4N, Demate force target >0.15N)

- **2 slots contacts results:**
  F_{mate}=0.27 to 0.37N : 100% PASS
  F_{demate} >0.09 to 0.2N : 40% PASS, 60% FAIL

- **4 slots contacts results:**
  $F_{insertion}$ =0.37 to 0.51N : 90% FAIL, 10% PASS
  F_{demate} =0.12 to 0.21N : 90% PASS, 10% FAIL

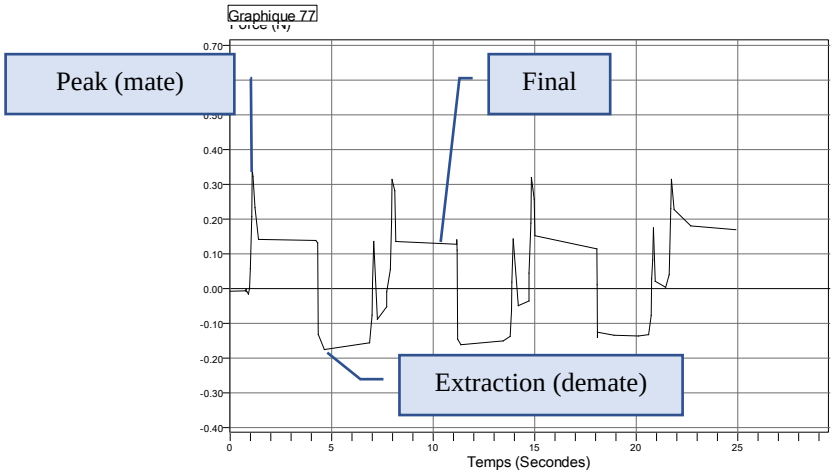


Fig. 23 Engagement & Separation Forces results example

Test results of the 6 connectors pairs (Group2):

Press-fit insertion force on 6 daughter & 6 backplane connectors:
The connectors were inserted on test PCB using a pull test machine as illustrated previously in Fig. 22.

Connector Ref	Max Insertion Forces (N)	Criteria	Compliance
TV - Daughter	2266 N	< 2400 N*	PASS
TV -Backplane EON	2265N	< 2400 N*	PASS

*Meaning less than 25N per press-fit contact for 96p connector

After connectors press-fit insertion on test PCB, cabling is done on all TVs to allow continuity and dielectric test. (Continuity test is performed by 4wires method)

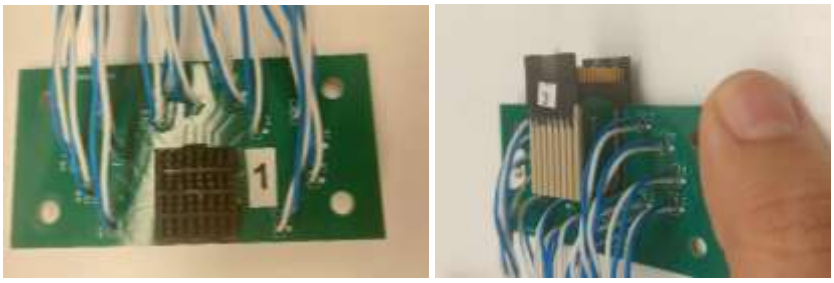


Fig. 24. From left to right, backplane connector TV, Daughter connector TV

Mating/unmating cycles were performed using the setup presented in Fig.25 on the left and show us a very low variation of the force values on the right before and after 500 mating cycle as illustrated in Fig. 25.

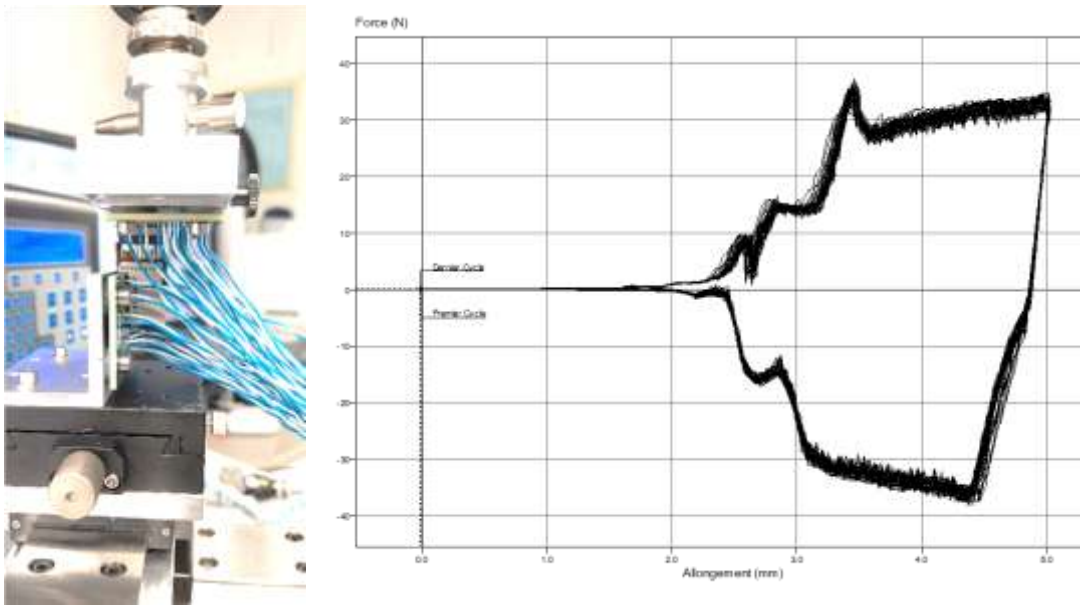


Fig. 25 . From left to right, Push/Pull test setup on connectors couples, measurement after 50 cycles.

The results available in the table below, show us a fully compliance with the 500 mating cycles regarding the electrical and mechanical forces values for mating and un-mating operations.

Tests Before and after 500 matings cycles	Criteria	Compliance Before mating/unmating	Compliance After 500 mating/unmating cycles
Continuity	<200 mΩ	PASS	PASS
Insulation Resistance	>100GΩ / 500V	PASS	PASS
DWV	<2mA / 600V	PASS*	PASS*
Maximum mating forces	<43N	PASS	PASS
Minimum unmating forces	>14.5N	PASS	PASS

*One failure detected due to a bad PCB manufacturing on a track before mechanical tests

Regarding first mechanical evaluation on machined contacts alone, we identified one deviation on press-fit side, as previously presented, cracks have been observed for the plated holes within the lower tolerance range. At the date of this publication, an optimised design is currently being manufactured and will be characterised shortly in order to address this risk. This deviation was not met during mechanical tests on the fully populated connectors.

4 POWER FRAME DESIGN

The Idea is to develop an injection moulded lead frame, with impedance matching, and cross section area adapted for power supply, to be compatible with daughter housing and backplane connector. Press-fit terminations are already developed and will be machined in the same time as the tracks.
The main target is to allow a 2A max supply current per track while consents a low voltage drop of 40mV maximum meaning an insertion resistance of 20mΩ maximum. This will be achieved using a good compromise copper alloy between electrical conductivity and spring properties.
Moreover, we want to respect as much as possible a differential characteristic impedance of 100Ω to stay compatible with low-speed digital communication standards.

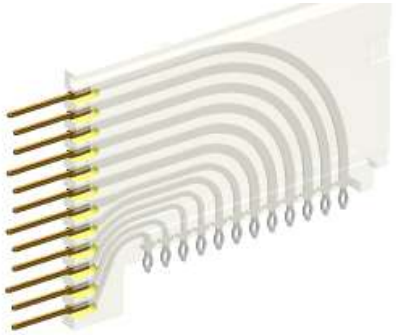


Fig. 26 power frame design (injection moulded on stamped shapes tracks)

4.1 The contacts

The contacts are already developed (and tested) with the max current target in mind but we need to customize the termination to lead frame. This concept is taken from another development, for size 16 power contacts for flat conductors. As illustrated in Fig. 27, the contact will be slotted at the rear, to be inserted on a flat conductor (the lead frame termination side).

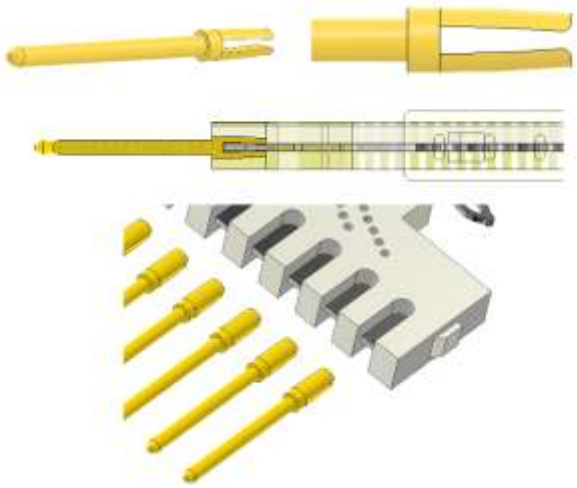


Fig. 27 contact presentation with dedicated termination to coop with lead frame

There will be no impact on backplane connector design, nor in daughter connector housing design and we will have the possibility to mix HDR or Power layer within the same connector.

4.2 FEM simulation

This design was settled and adjusted using FEM simulation for both behaviours electrical and Thermal in order to be compatible as much as possible with 100 Ω transmission lines and to allow 2A current with low voltage drop meaning low power losses. Thanks to CST used for Electro Magnetic FEM simulation and COMSOL for thermal calculation we designed a frame with a limited space constraint.

4.2.1 The Electrical simulation

The design of this frame is mainly motivated by thermal behaviour but we considered it also to be compatible with “low speed” digital link. This is the reason why we keep as much a possible the structure of multiway transmission lines with a differential characteristic impedance fixed to 100Ω.

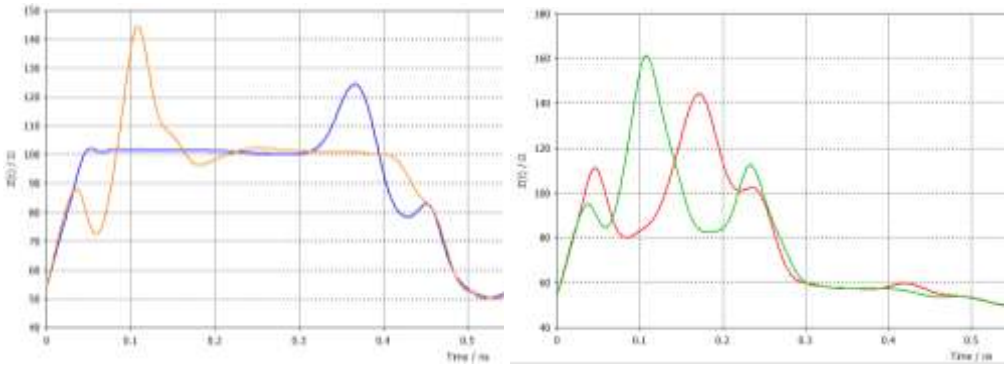


Fig. 28 differential characteristic impedance of long and short lines

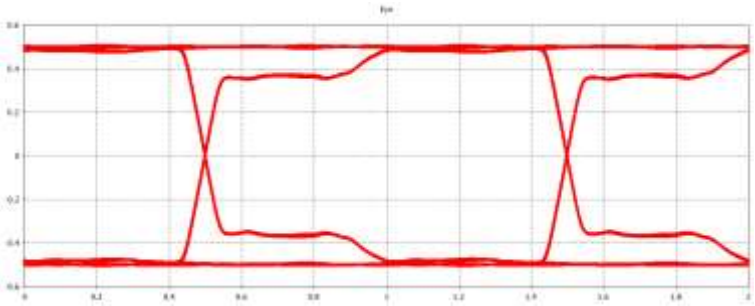


Fig. 29 eye pattern simulation @1Gb/s

4.2.2 The Thermal simulation

In Fig. 28 is presented the result of a simulation of the mated couple frame (Power daughter and backplane) with PCB. This simulation was made assuming a current of 2A in each conductor, an ambient temperature of 20°C with only surface to ambient radiation and conduction between elements.

The first results show a conductor temperature elevation of around +50°C for the short lengths and around +25°C for the long ones. These temperatures are compatible with the materials and the connectors designs with a big margin (e.g. Temperature of deflection under load for the LCP material = 255°C)

This simulation needs to be improved taking into consideration the thermal behaviour of the daughter card and the Backplane.

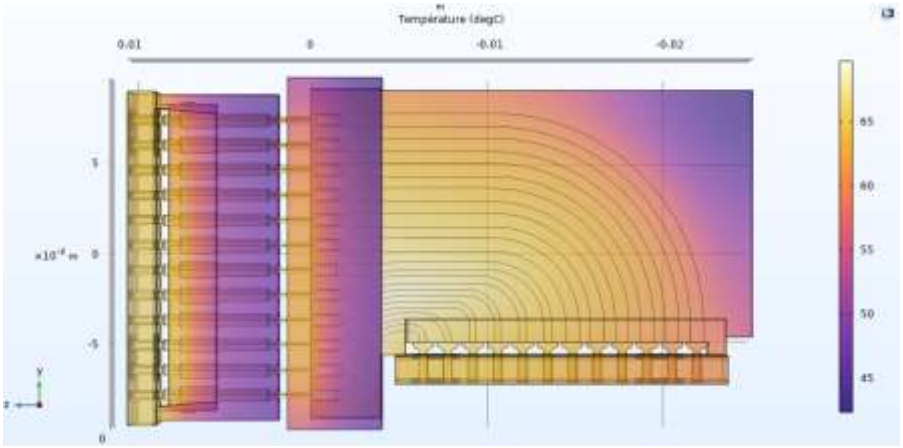


Fig. 30 FEM thermal simulation for the full mated connectors

5 CONCLUSION

Regarding evaluation results on Compact PCI serial space Axon' connector prototype, some electrical parameters are above the limits asked by the requirement of the SOW nevertheless, digital transmission is insured with margin over 25Gb/s with a good confidence against mechanical constraints: PCB press-fit bonding were achieved in a good way on PCB jigs and 500 mated/unmated cycles were performed without any mechanical and electrical degradation.

The next steps are:

- Integrate new PCB in MEGTRON7 to improve electrical performances:
  - A new batch procurement is ongoing.

- Test new backplane press-fit to eliminate the risk of cracks:
  - This will need the procurement of another contacts batch.
  - This procurement is conditioned to the evaluation test currently on-going on the new designed contact prototype.

- Launch moulds machining to manufacture injected plastic parts. The mould will be divided into cavities:
  - 2 cavities for housing.
  - 5 cavities for frames and retainer.

- Make the assembly and test the connector with new injected parts.

- Make a complementary evaluation on electrical and mechanical aspects:
  - Electrical signal integrity.
  - Vibrations and shock tests (with nanosecond discontinuity monitoring).

- Launch power frame prototype manufacturing:
  - Contacts are already developed (and tested) with the max current target and the procurement of parts is on-going.
  - Machined plastic frame and chemical machining tracks is under investigation to manufacture a prototype.