Radiation hard TwinAx for ATLAS ITk pixel electrical data transmission

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ABSTRACT

The high radiation dose and the cold environment at the HL-LHC pixel detector regions presents serious challenges for the survival of optical components. Radiation hard twinax cables are developed for the ATLAS ITk pixel data transmission within the pixel detector volume for up to 6m before transitioning to optical links at larger radius where radiation dose is reduced to acceptable level for optical components. We will present the design, qualification and industrialization process of the ATLAS ITk pixel electrical links using such twinax cables.

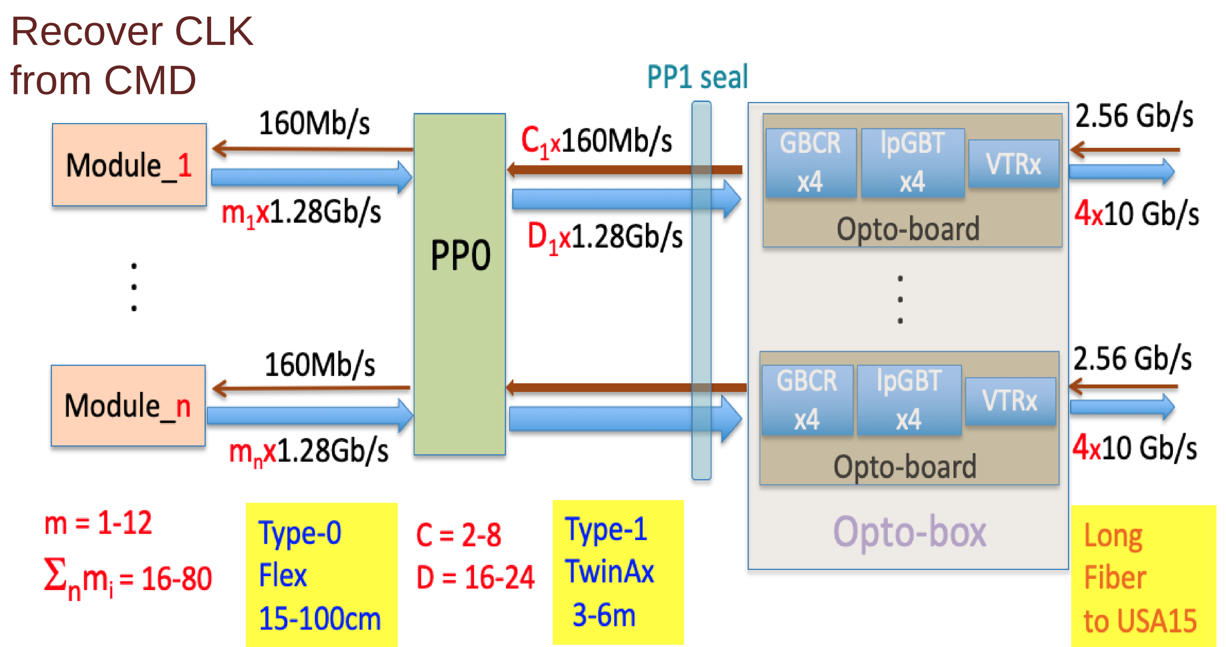
INTRODUCTION

The need for radiation hard electrical links operating in the cold volume of the ATLAS upgrade tracker led to the original custom TwinAx R&D in 2008. Most commercial twinax cables use PTFE as dielectric medium, but it is unfortunately radiation soft. The systematic evaluation of the transmission loss and radiation hardness of components led to the key conclusion that Low Density Polyethylene (LDPE) is the optimal choice of dielectric medium, balancing data transmission quality and radiation hardness. The original TwinAx prototype from Temp-Flex (now a subsidiary of Molex) from 2009 with AWG30 Cu-clad Al signal wires and LDPE dielectric achieved 6.2Gb/s over 6m once applied pre-emphasis and 8b/10b DC-balance. With the RD53 pixel readout chip for HL-LHC settled to1.28 Gb/s data links, a more compact version of the TwinAx with AWG34 Cu signal wires became the nominal baseline for both the command links and data links in the ATLAS ITk pixel system. Although the command links are operating at only 160 Mb/s, it also carries the clock to be recovered by the front-end chip so that it also requires Gb/s transmission quality.

In this presentation, we will describe the ATLAS ITk pixel TwinAx design philosophy with a drain wire to reduce shield material and manage termination heating. The thin jack further ensures the dimensions are minimized so that the high multiplicity of links can still fit into the very constrained service volumes. The design insertion loss is up to ~14 dB after irradiation for a maximum length of 6m. The S-parameter measurements before and after irradiation, as well as performance and mechanical integrity checks at low temperature will be presented. To comply with CERN/EU fire retardancy requirements, a series of fire propagation, smoke and acidity certification tests are also performed.

The ITk pixel TwinAx are organized into various types of E-link bundles depending on the detector region. The outer end of the bundles connecting to Optoboards are terminated with a rigid-flex for up to 8 command + 24 data links per Optoboard. The inner ends are terminated to the on detector Patch Panel 0 (PP0) with Samtec FireFly connectors with up to 12 links for the Outer pixel subsystem, or directly soldered to a densely packed PP0 with up to 100 TwinAxes in the Inner pixel system. We will present the termination PCB designs, TwinAx ribbonization and bundle termination process bundle electrical test results. We will also describe the Inner system PP0 design and bundle packing test.

Simplified Block Diagram of Data Transmission



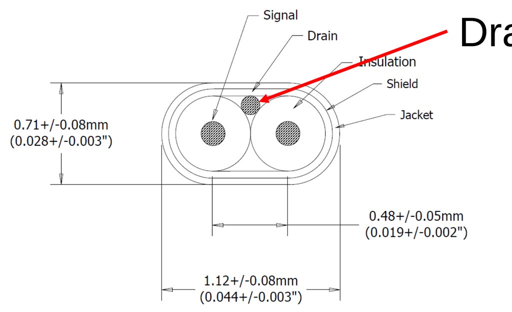
Focus of this Poster

CMD carrying low jitter clock also needs Gb/s transmission quality

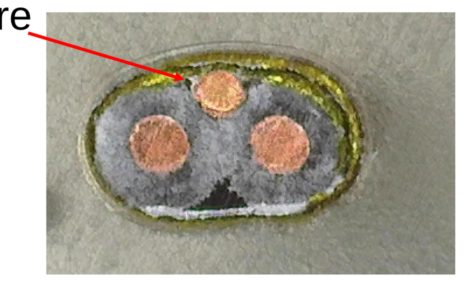
Twinax History

- Custom twinax R&D with TempFlex (now part of Molex) since 2008
  - –https://indico.cern.ch/event/47853/contributions/1988426/attachments/955614/1356172/ACES_Martin_Kocian.pdf
- Low Density Polyethylene (LDPE) as dielectric
  - Balance of loss properties and radiation hardness.
  - FEP more common in commercial cables. Good transmission properties but radiation soft.
  - PEEK very radiation hard, but not as good transmission properties and not as compact.
- Design Chronology
  - Original focus on 5.1Gb/s with aggregator favored 30AWG Cu-clad Al wires
  - 2015-2017 explored more compact versions with reduced jacket material
  - Passive data transmission at 1.28 Gb/s with higher twinax multiplicity favored more compact choice of 100 W cable with 34AWG Cu signal wires
  - Improvements in shield with Al+polyimide foil for better fire retardance and radiation resistance.
  - Adding Nomex cable weave to improve routing, fire retardance, and packing factor.

Design of a 100-ohm differential transmission system that reduces mass and has the volume that can be used for the inner system of the Atlas detector is possible using a drain wire configuration as show in the following pictures.



Drain Wire



The 36-gauge drain wire provides a common mode ground connection without the solid mass as a solid sheet of copper. The disadvantages of a drain wire is that it has inductance to ground. However, in the data rates 1Gb/s of the ATLAS detector the results will illustrate that the eye scan and impedance measurements are very good.

For any cable to be used in the ATLAS detector if has to pass a rigorous fire and Smoke test. These test were done at LS Fire in Italy. The results are illustrated in the following tables. The Twinax cable passed on smoke, droplet and, and Acidity test. The Twinax passed on the small-scale flammability test performed by Underwriters Laboratory (UL) but, did not passed on the large-scale flammability which was not required by CERN.

	CPR	IEEE 1202 FT-4	UL 1685
Fire burner [kW]	20.5	20.6	20.6
Air flow [m3/s]	0.13	0.65	0.65
Test duration [min]	40	20	20
Criteria (Fire reaction)	C_{ca} EN 50399 IEC 60332-1-2	IEEE 1202 FT-4	UL 1685
Fire spread	≤ 2m	≤ 1.5 m	≤ 0.2 m
Peak Heat Release rate (HRR)	≤ 60 kW	not measured	not measured
Fire growth rate	≤ 300 W/s	not measured	not measured
Total HRR @ 20 min	≤ 30 MJ	not measured	not measured
Flame propagation	≤ 425 mm	not measured	not measured
Criteria (smoke)	s2 EN 50399 IEC 61034	IEEE 1202 FT-4	UL 1685
Peak smoke production rate	≤ 1.5 m^2/s	≤ 0.4 m^2/s	≤ 0.25 m^2/s
Total smoke production (at 20min)	≤ 400 m^2	≤ 150 m^2	≤ 95 m^2
Criteria (halogen)	a2 IEC 60754-2	UL 2885	IEC 60754
Acidity [pH]	pH ≥ 4.3	pH ≥ 4.3	pH ≥ 4.3
Conductivity [µS/mm]	k ≤ 10	k ≤ 10	k ≤ 10
		Or	
Mass HCl [mg/g]	-	HCl < 5	HCl < 5
Criteria (droplets)	d1 EN 50399	n/a	n/a
Duration of burning droplets [s]	t ≤ 10	no standard	no standard

1000680052 - d: 1,12x0,74 mm	
FS (m)	2,90
THR1200s (MJ)	51
Peak HRR (kW)	733
FIGRA0,4MJ (W/s)	5271
Peak SPR (m^2/s)	0,54
TSP1200s (m^2)	57
Flaming droplets/particles	no
CLASS (general)	nc
CLASS (smoke)	s2
CLASS (dripping)	d0

B1: ≤ 1.75 m B2: ≤ 1.5 m; C: ≤ 2.0 m
B1: THR ≤ 10 MJ B2: THR ≤ 15 MJ; C: THR ≤ 30 MJ; D: THR ≤ 70 MJ
B1: HRR ≤ 20 kW B2: HRR ≤ 30 kW; C: HRR ≤ 60 kW; D: HRR ≤ 400 kW
B1: FIGRA ≤ 120 W/s B2: FIGRA ≤ 150 W/s; C: FIGRA ≤ 300 W/s: D: FIGRA ≤ 1300 W/s
s1: ≤ 0.25 m^2/s; s2: ≤ 1.5 m^2/s; s3: no s1 o s2
s1: ≤ 50 m^2; s2: ≤ 400 m^2; s3: > no s1 o s2
d0: no; d1: <10s; d2: >10s

PASSING is Green Circles
FAILING is RED Circles

Results

To make a differential measurement using a Vector Network Analyzer (VNA), you need a 4-port analyzer. Using a four port VNA, allows one to drive the input of the twinax cable and measure the response. (see the figure below).

Twinax Cable

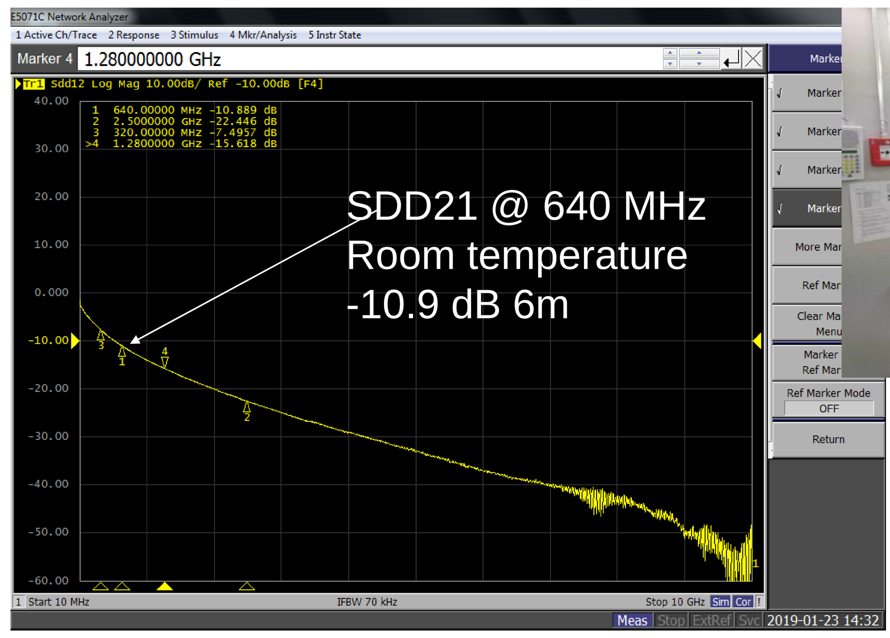
The scattering Matrix for the single ended system and a differential system are illustrated in the following equations:

Single-ended 50ohms

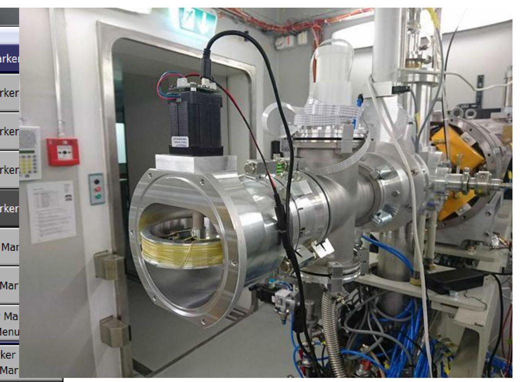
$$S_{\mathrm{SE}} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix}$$

Differential 100ohms

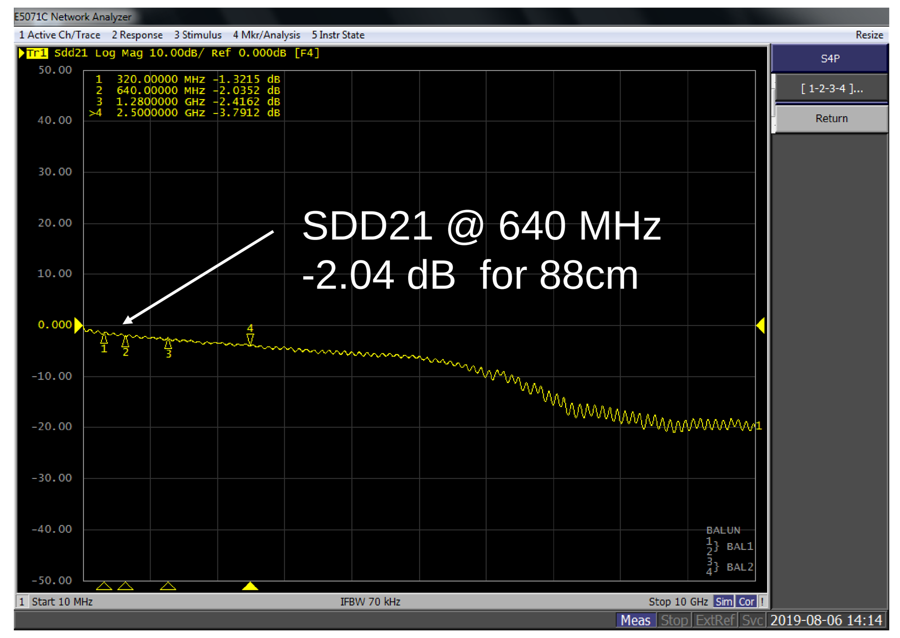
$$S_{\mathrm{mixed}} = \begin{bmatrix} S_{dd11} & S_{dd12} & S_{dc11} & S_{dc12} \\ S_{dd21} & S_{dd22} & S_{dc21} & S_{dc22} \\ S_{cd11} & S_{cd12} & S_{cc11} & S_{cc12} \\ S_{cd21} & S_{cd22} & S_{cc21} & S_{cc22} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} (S_{11}-S_{12}-S_{21}+S_{22}) & (S_{13}-S_{14}-S_{23}+S_{24}) & (S_{11}+S_{12}-S_{21}-S_{22}) & (S_{13}+S_{14}-S_{23}-S_{24}) \\ (S_{31}-S_{32}-S_{41}+S_{42}) & (S_{33}-S_{34}-S_{43}+S_{44}) & (S_{31}+S_{32}-S_{41}-S_{42}) & (S_{33}+S_{34}-S_{43}-S_{44}) \\ (S_{11}-S_{12}+S_{21}-S_{22}) & (S_{13}-S_{14}+S_{23}-S_{24}) & (S_{11}+S_{12}+S_{21}+S_{22}) & (S_{13}+S_{14}+S_{23}+S_{24}) \\ (S_{31}-S_{32}+S_{41}-S_{42}) & (S_{33}-S_{34}+S_{43}-S_{44}) & (S_{31}+S_{32}+S_{41}+S_{42}) & (S_{33}+S_{34}+S_{43}+S_{44}) \end{bmatrix}$$



Before Radiation

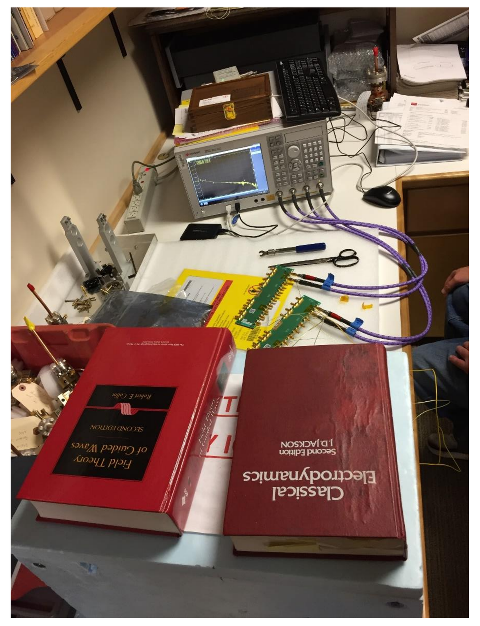


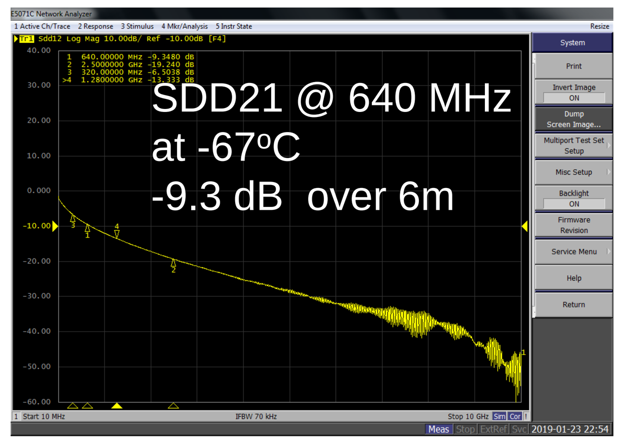
BERN radiation test setup Single layer of 6m twinax on rotating spool to accumulate dose uniformly



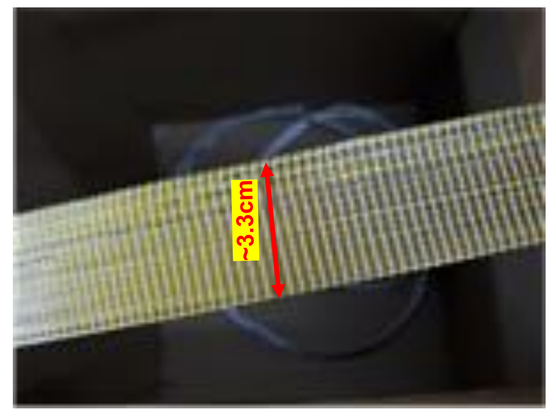
After 800Mev protons ~500MRad Radiation at Los Alamos National Laboratory

Low Temperature measurements



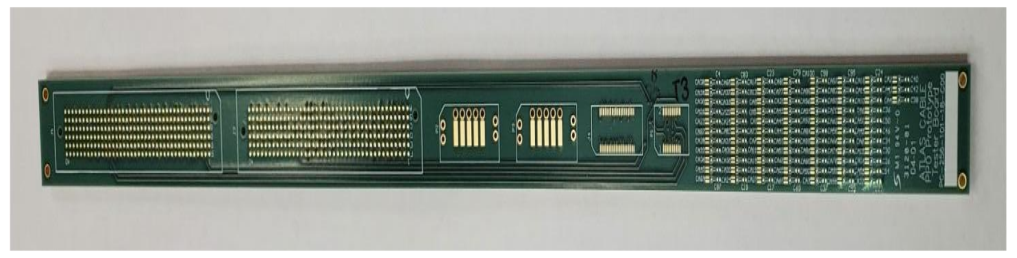


- 6m twinax: 70cm outside and >5m inside dry ice cold bath.
- 3 cycles to below -55°C
- Using four port analyzer as a differential driver.
- The return loss improved by 1.5dB at cold temperatures

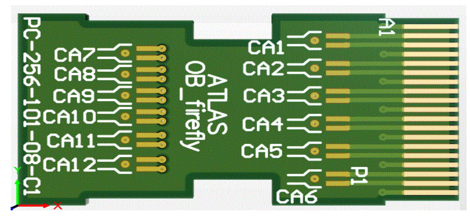


Tekdata (UK) designed a Nomex weave that provides an extra layer of fire protection and mechanical support. This section is 30 cables wide. Not shown in this picture is one can specify unwoven section required for termination on PCBs. The weaving does not affect the performance of the cable.

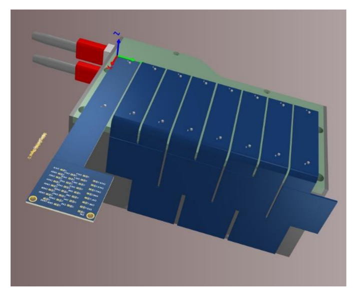
Several PCBs have been designed to use the e-links; PP0s for Inner system, an interface board for the for the Optobox, firefly connector for the Outer barrel and the Outer End-cap, and finally a cable tester pcb.

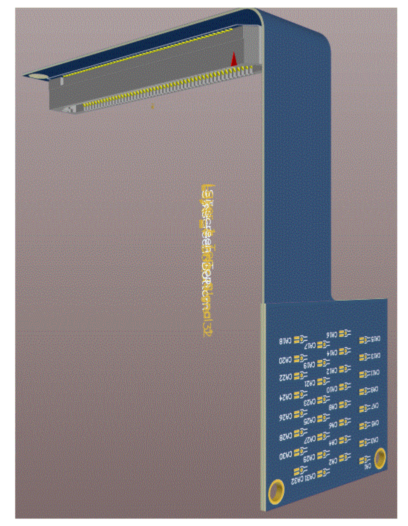


Coupled Ring PCB

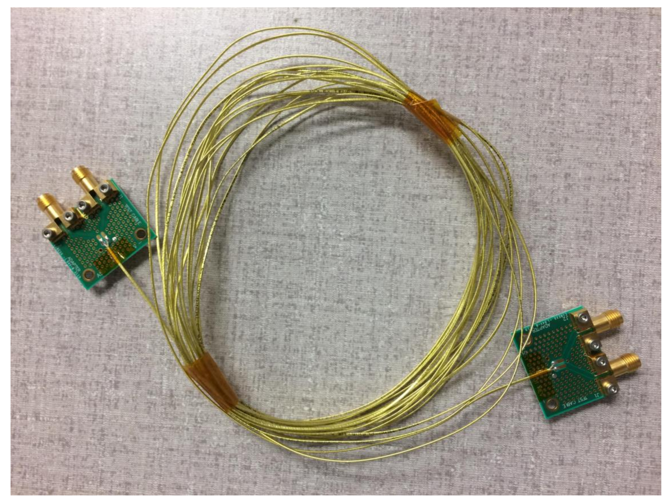


Firefly Twinax PCB





Optobox interface PCB



Twinax cable test interface PCB

CONCLUSIONS

We have successfully demonstrated that data transmission over twinax is a good for Data Transmission at 1Gb/s. Many printed circuit boards have been designed for the Inner System, Outer barrel, and Outer End Cap.

FUTURE WORK

The remaining work for Data transmission is in radiation characterization. We also need to find industrial partners to help assemble these pcbs. Finally, we need to design a strain relief for the PCBs.