Twinax Cables and Data Transmission

Andrew Young

TWEEP 2022

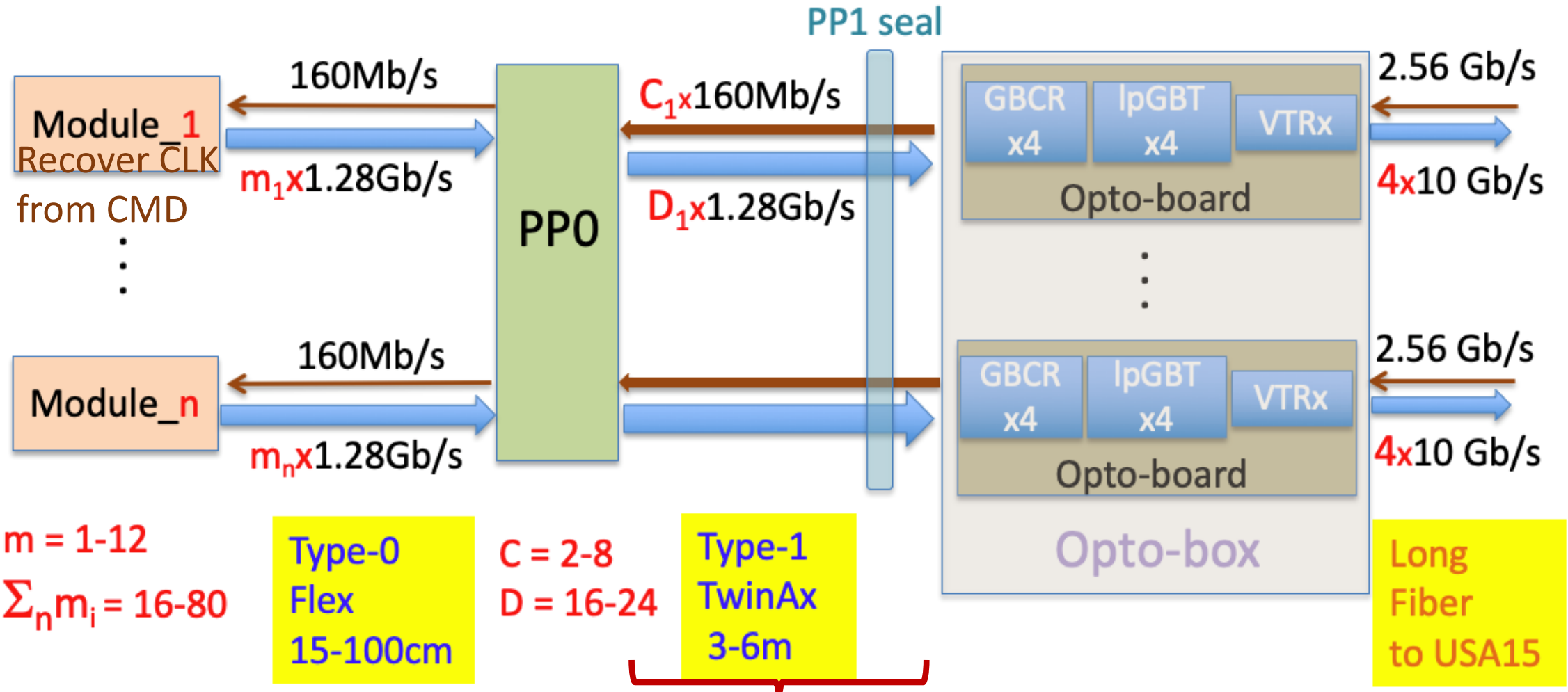
23 September 2022

ATLAS ITk

Outline

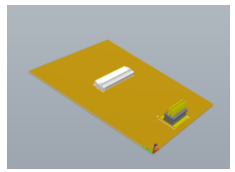
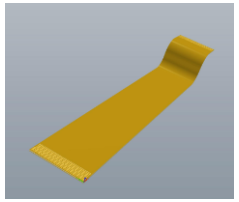
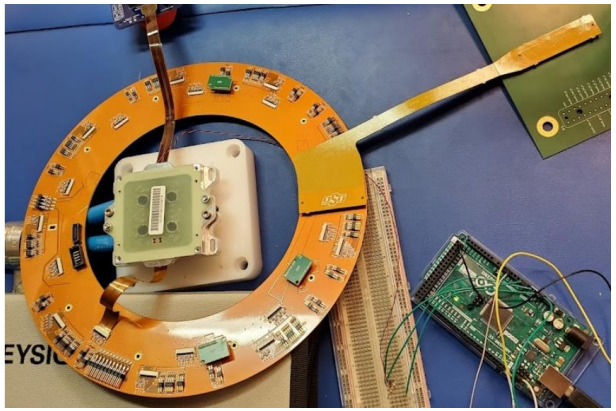
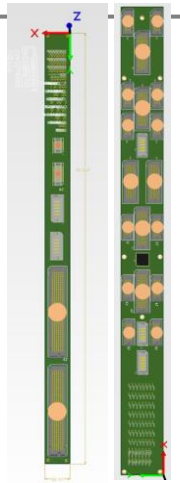
- Data transmission overview
- Twinax design
- Twinax performance measurements
  - Specifications
  - Radiation hardness
- Twinax bundle ribbonization and packing
- Bundle termination
- Bundle QC
- Data Transmission on Coupled Ring Demonstrator

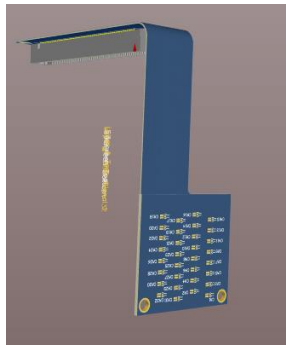
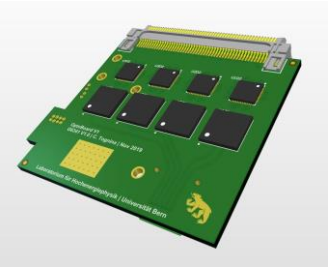
Block Diagram of Data Transmission



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

Data Transmission Chain Block Diagram

Module flex | Module pigtail | Ring PCB | Ring to PP0 FLEX | PP0s | Twinax | Termination board | Optoboard

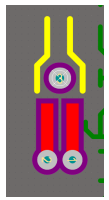
Molex FFC/FPC

Molex FFC/FPC

LPAF/LPAM /Zray

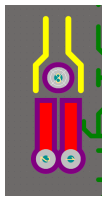
LPAF/LPAM

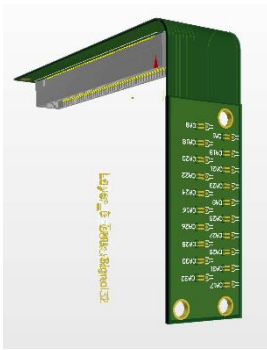
solder



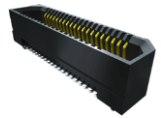
Today's Talk

solder





ERM8/ERF8



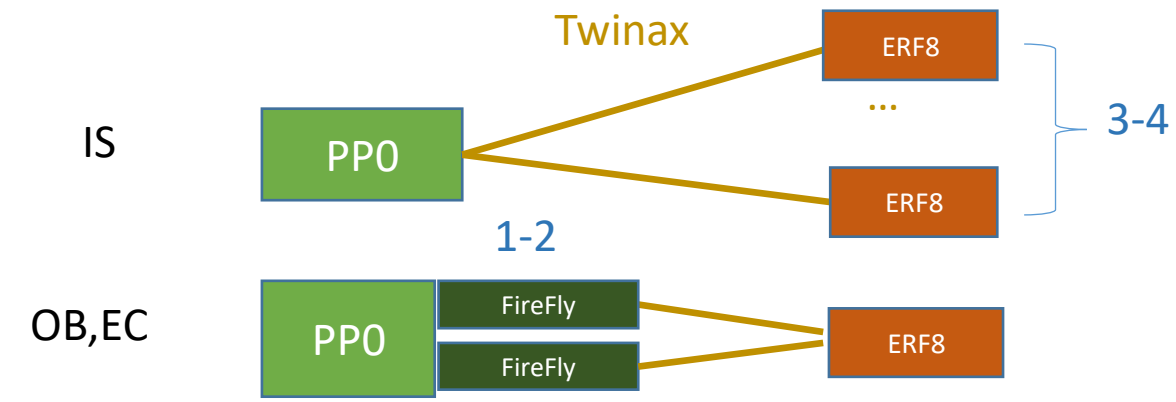
E-Links Topology

Sub-system	PP0 end		Optoboard end		Total E-links
	Termination	#E-links	Termination	#E-links	
Inner System (IS)	Direct solder to PP0 board	70-104	Samtec ERF8 connector	32 (24 data + 8 cmd)	9208
Outer Barrel (OB)	Samtec FireFly ECU5	8-12			9904
Outer Endcap (EC)	Samtec FireFly ECU5	8-12			7072

Interface update since Nov/2020:

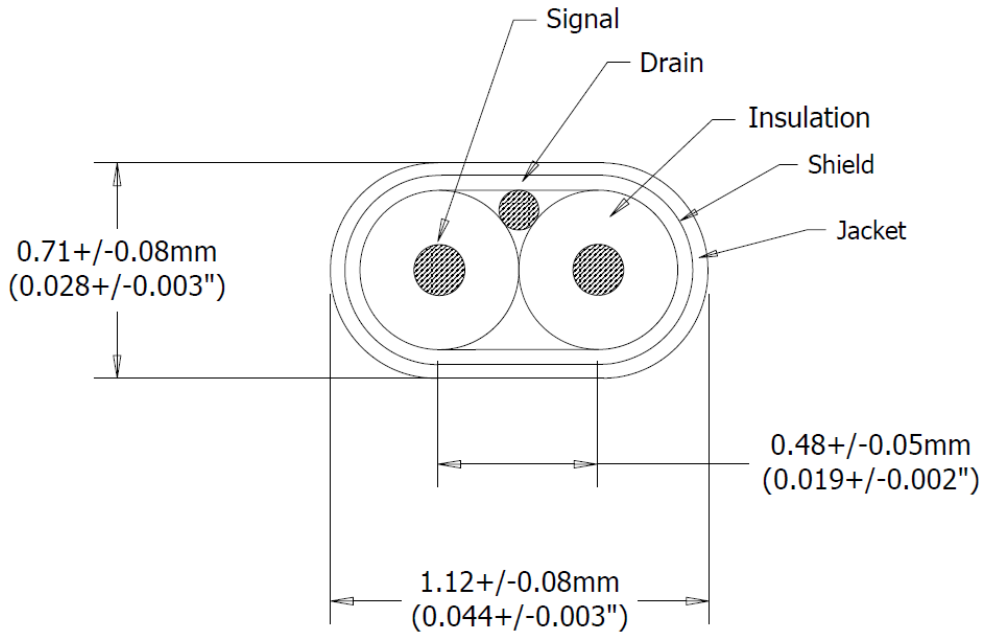
- EC also adopted Samtec FireFly PP0 termination like OB
- Added ‘Slim’ 12 data + 8 cmd ERF8 Opto-termination

Bundle topology



Molex cable

CONSTRUCTION
- Conductor: 34 AWG, 0.16MM (0.0063") Bare Copper
- Insulation: Polyolefin, 0.5mm (0.020") Diameter
- Drain Wire: 36 AWG, 0.13mm (0.005") Bare Copper
- Shield: Aluminum/Polyimide Foil, 0.023mm (0.0009") Thickness Ref.
- Jacket: Polyester, Heat Sealed, 0.018mm (0.0007") Thickness Ref.



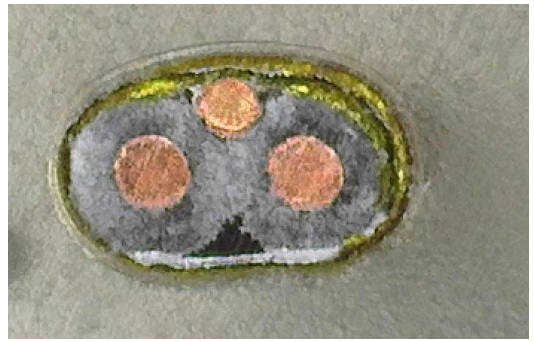
ELECTRICAL CHARACTERISTICS
(Based on a 2m Length)
- Differential Impedance: 100+/-10 ohms
- Propagation Delay: 5.0ns/m Ref.
- Intra-Pair Skew: 20ps/2m Max.

SCD21
- f < 20 GHz: 20 dB Min.

SCD21-SDD21
- 0.01 ≤ f < 12.89: 12 dB Min.
- 12.89 ≤ f < 15.7: (29-(29/22)f) dB Min.
- 15.7 ≤ f < 19: 8.3 dB Min.

Based on 2m Test Length		
	SDD21	
Freq (GHz)	Nom.	Max.
	dB	dB
0.64	3.6	4.0
1.28	5.2	5.7
2.50	7.3	8.0
5.00	10.8	11.9
7.50	13.9	15.3
10.00	17.5	19.3

GENERAL
- Weight: 1.1 kg/km (0.72 lb/kft)
- Min. Bend Radius: 5X OD - Minor Axis



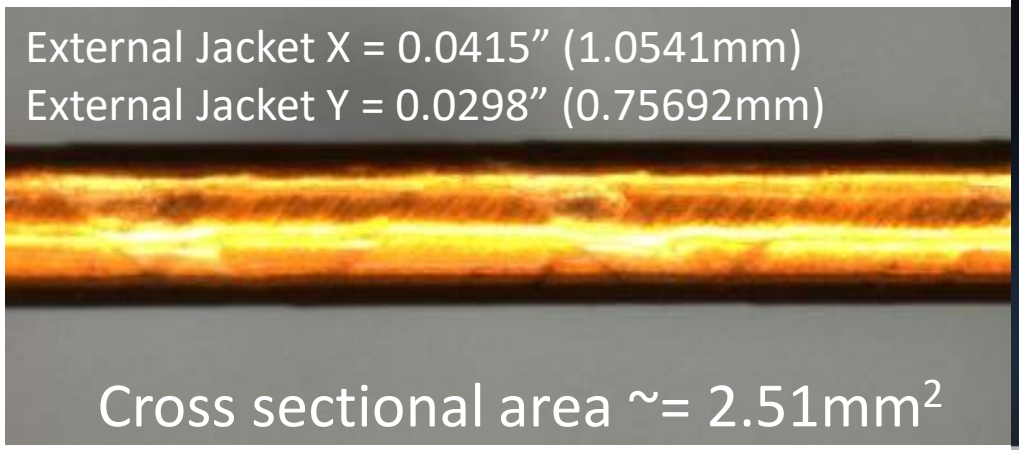
Spec: Combined Type 0+1 loss <20dB @ 640MHz
Type-1 stage budget ~13 dB

Samtec Cable Design

LPDE 34awg 95Ω Twin-Ax: Optimized Design Concept

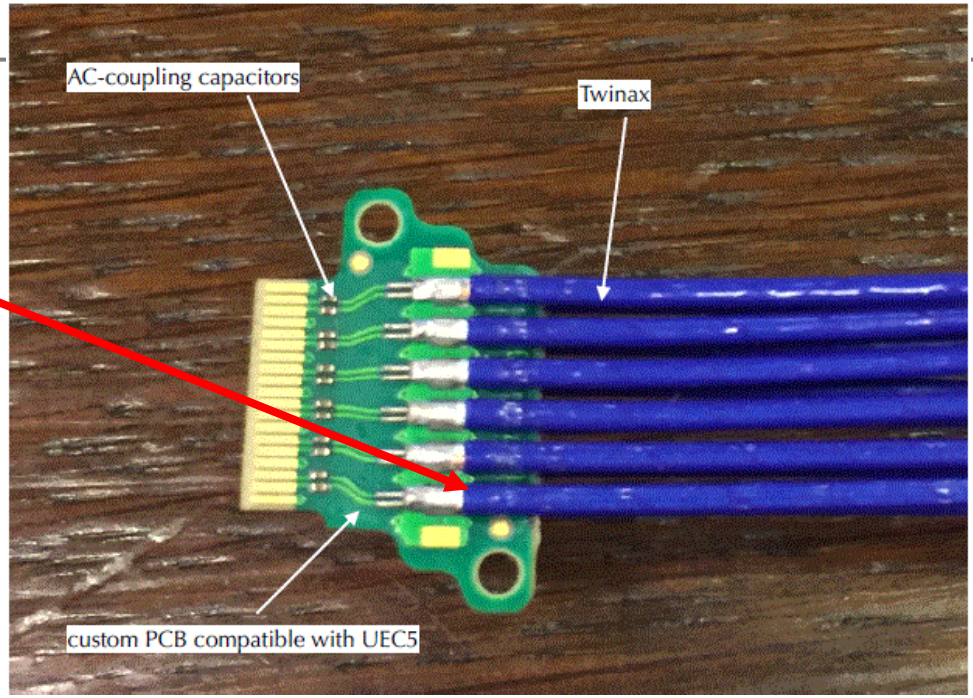
Dielectric Key Dimensions & Values
LPDE Dk, Df = **2.28, 0.005**
Conductor Diameter = .0063" [0.160mm]
Pitch = .0144" [0.365mm]
Height = .0246" [0.625mm]
Height/2= .0123" [0.312mm]

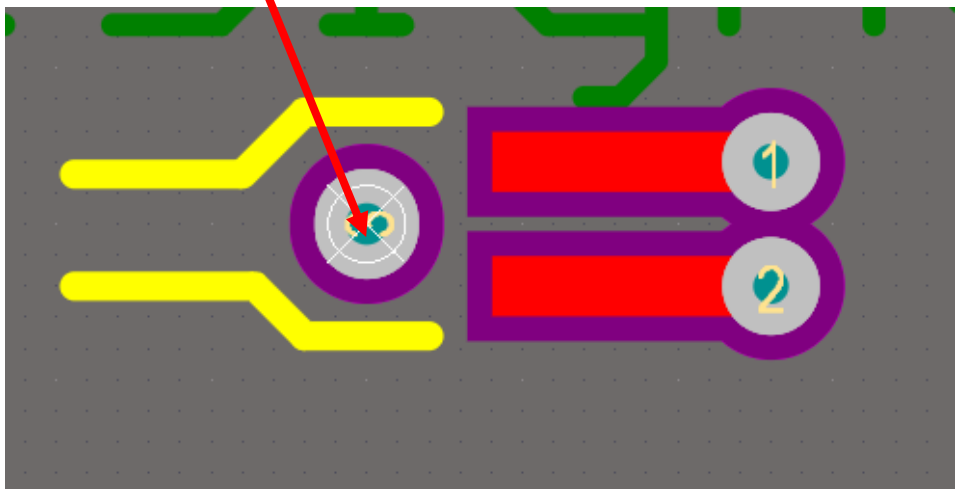
Outer "Taped" Jacket Dimensions
Major X Dim (Width) = .0429 ± .0010" [1.09±0.025mm]
Major Y Dim (Height+ = .0285 ± .0020 [0.724 ± 0.05mm]

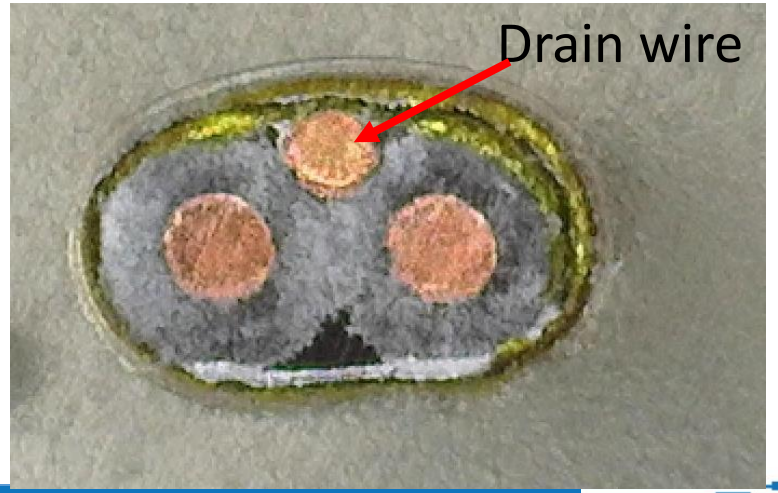


Drain wire vs. solid shield

- Mass of drain wire is less than braid shield over outer circumference
- Drain wire has an easier connection to “ground” to enable thin Al foil shield
- Avoided high heat connection of braid shield that could cause melting of the dielectric material







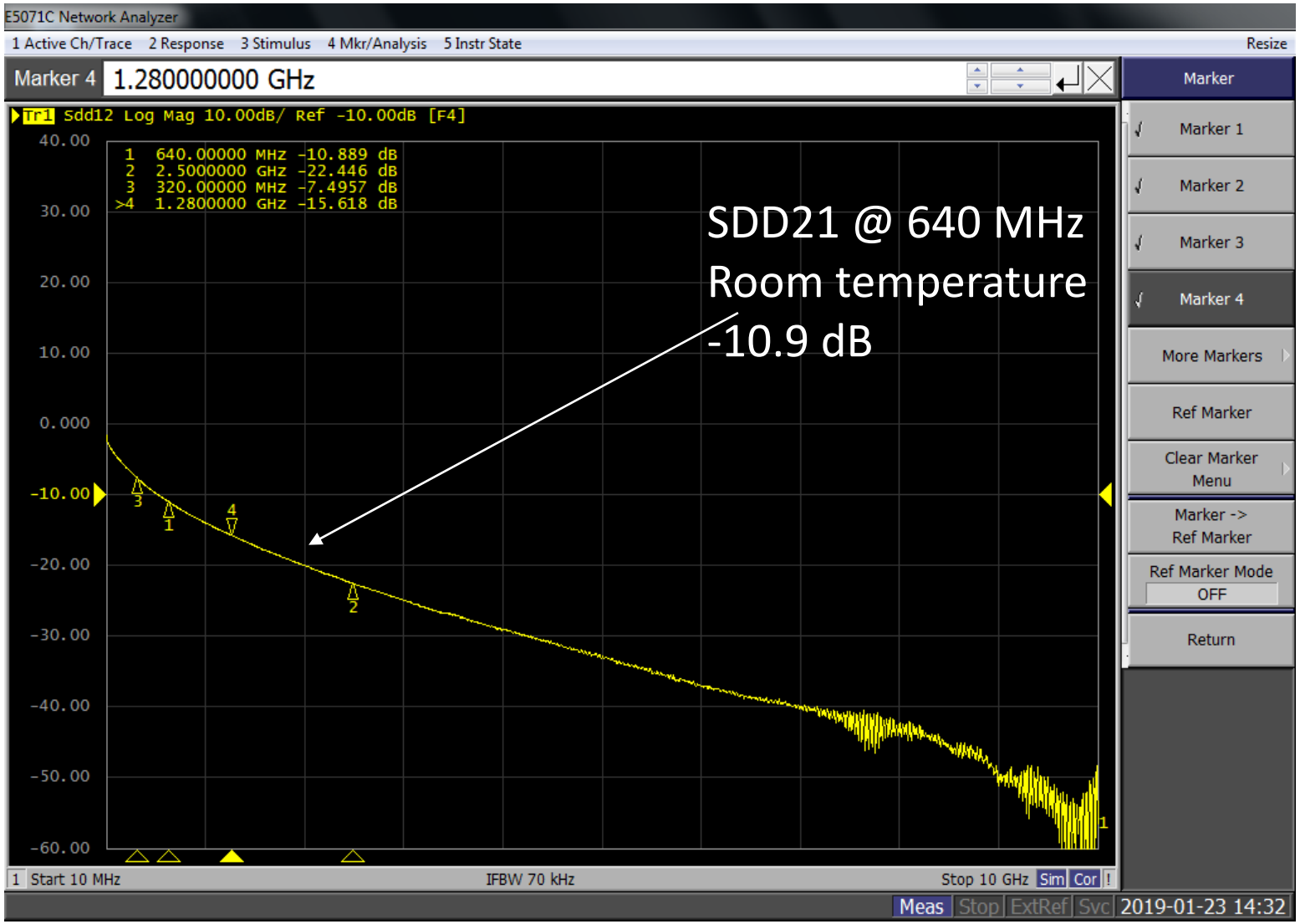
Twinax Material Radiation Length

AWG34 Cu (100Ω) TwinAx material radiation length smeared over 1cm width

Component	X/X0 (%)
Signal wires	0.0281
Drain wire	0.0088
Dielectric	0.0066
Shield	0.0072
Jacket	0.0016
Total	**0.0523**

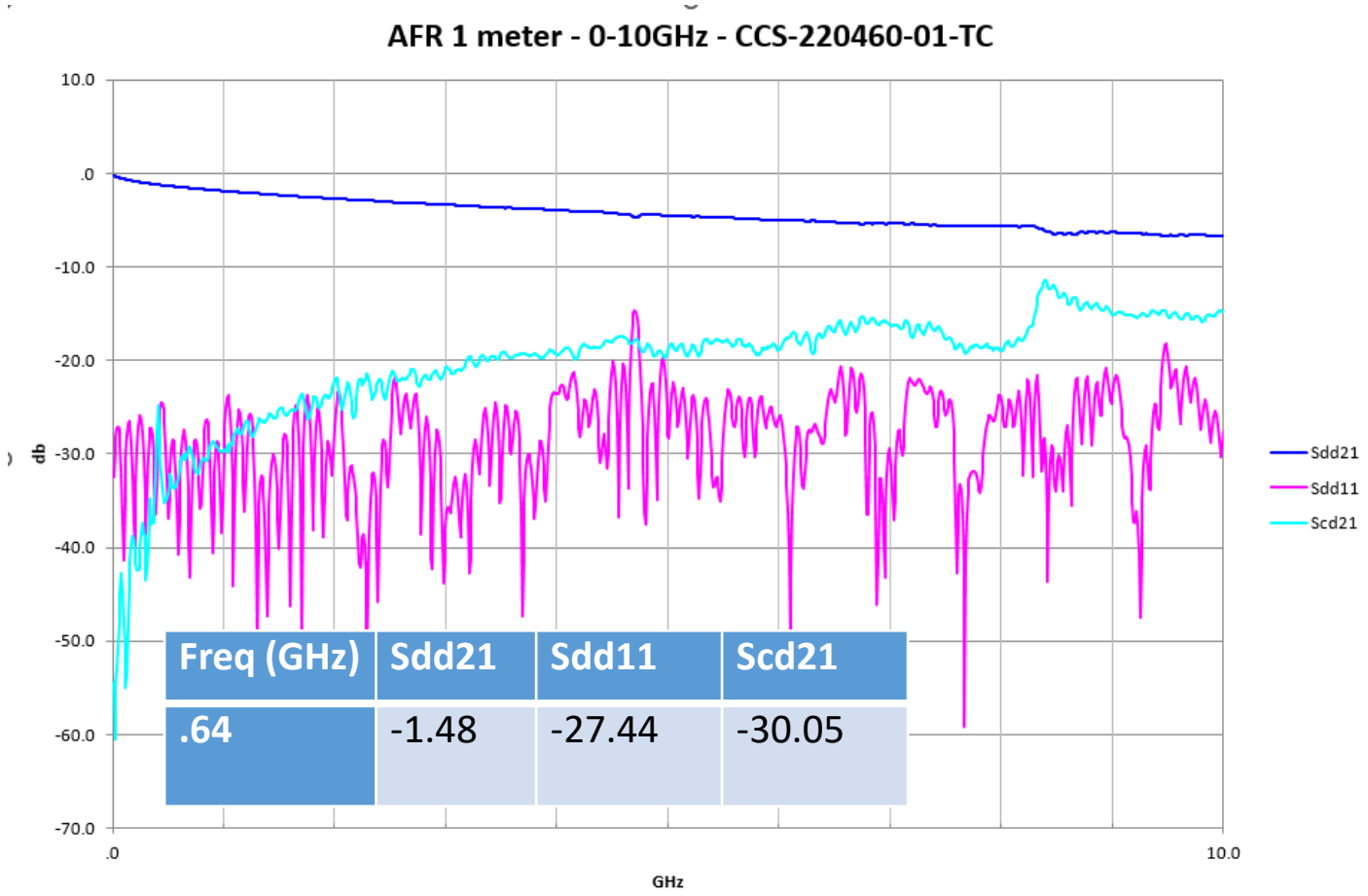
Component	**Material**	**Element Composition**	**Density (g/cm^3)**	**Area (mm^2)**
All wires: Cu	Copper	Cu	8.96	0.053
Dielectric	Polyethylene (LDPE)	C:H=2:4	0.925	0.322
Shield	Al/polyimide	Al	2.70	0.064
Jacket	Fusible Polyester (approx. = mylar)	C:H:O=10:8:4	1.40	0.046

Measured transmission loss of the Twinax 6m



Samtec Losses

- New cable design has >95 ohms characteristic impedance
- Lower loss per meter than Molex (1.48dB/m)
- Good return Loss
- Good crosstalk between +/- terminals (~30dB)
- SLAC will be getting cable to test at SLAC.



Freq (GHz)	Sdd21	Sdd11	Scd21
.64	-1.48	-27.44	-30.05

2021 **Molex** Irradiated Results (FNAL and BERN)

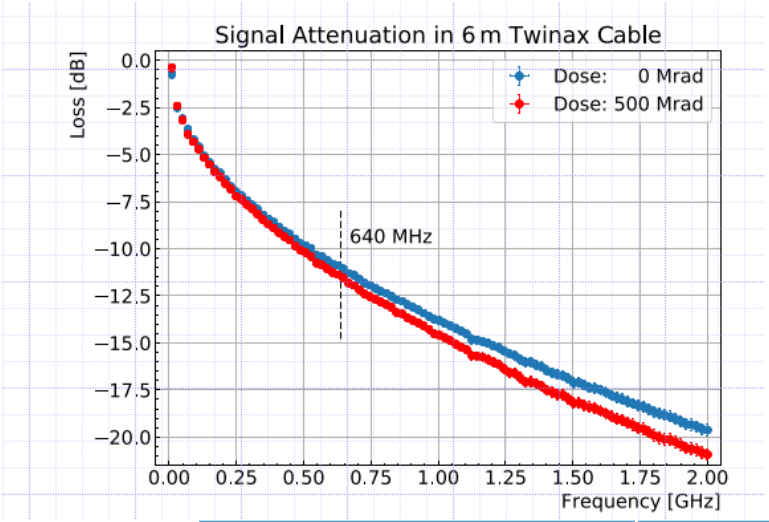
- Radiated at FNAL
- Calculate change in dB/m
  - Notice the loss per foot is consistent within 1%
- The numbers in Red are for the FNAL irradiated sample.
- Bern results in the Table below

		Losses at freq					
		80	160	320	640	1280	2500
Cable	cable distance (TDR measured)						
Pre-Rad C1	3.0443	1.7711	2.4403		5.1165	7.3306	
	Loss/m	0.5818	0.801596		1.680682	2.407976	
Post-rad C1	3.0443			3.7532	5.5497	8.1336	12.044
	Loss/m			1.2329	1.8230	2.6717	3.9562
Pre-Rad C2	3.1358			3.6504	5.3194	7.6075	11.152
	Loss/m			1.1641	1.6963	2.4260	3.5563
Pre-Rad C3	3.3505			3.9124	5.6949	8.178	11.797
				1.1677	1.6997	2.4408	3.5210

Frequency [GHz]

	Length [m]	80 MHz	160 MHz	320 MHz	640 MHz	1280 MHz
Pre-Irrad.	6.00	-3.60	-4.92	-7.13	-10.39	-14.91
	1.00 (p/meter)	-0.60	-0.82	-1.19	-1.73	-2.48
Post-Irrad	6.00	-3.80 (-3.82)	-5.33 (-5.33)	-7.85 (-7.84)	-11.74 (-11.69)	-17.35m (-17.19)
(500 Mrad)	1.00 (p/meter)	-0.63 (-0.64)	-0.89 (-0.89)	-1.31 (-1.31)	-1.96 (-1.95)	-2.89 (-2.87)

2021 Bern **Samtec** Results

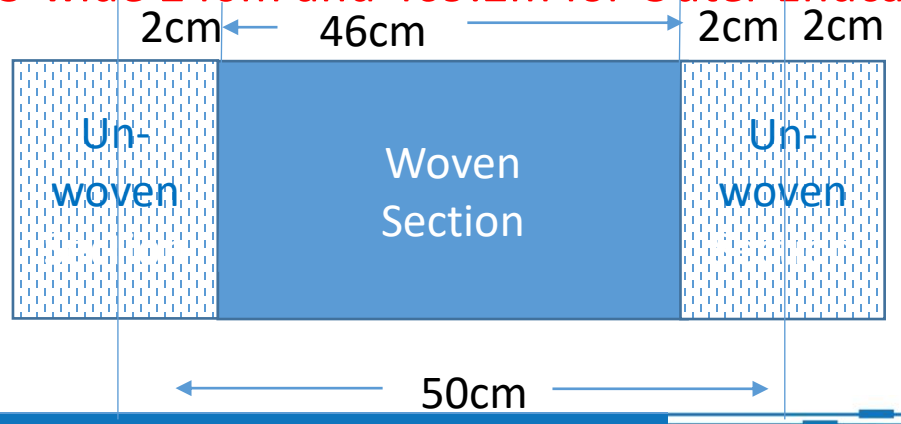


- It was originally reported that the activity of the Samtec was higher; however, this is due to the metal spool.
- The Non-irradiated losses are compatible (Samtec-1.83dB/m vs Molex-1.82dB/m)

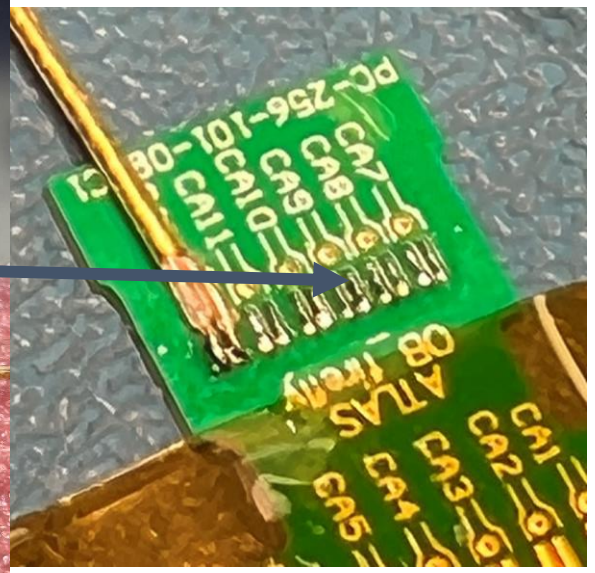
	Length (m)	80 MHz	160MHz	320MHz	640MHz	1280MHz
Non-irradiated	6	-3.92	-5.54	-7.77	-11.00	-15.66
	1	-0.65	-0.92	-1.30	-1.83	-2.61
Post-irradiation	6	-3.94	-5.66	-8.05	-11.51	-16.60
	1	-0.66	-0.94	-1.34	-1.92	-2.77

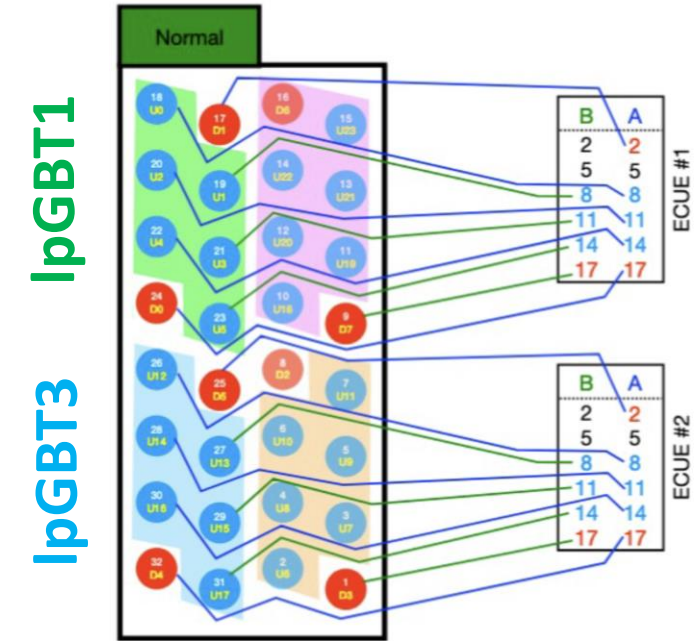
Prototype Bundle Status

- Using the Outer system FireFly-FireFly (8-12 twinax) bundle as a proof of principle sample for fabrication and strain-relief, before attempting the 80-100 twinax Inner System bundles.
- TekData has ribbonized:
  - 6-wide bundle (with breaks every 50cm)
  - Continuous 6-wide 117m long with breaks every 30m because of the weaving restrictions
  - 5-wide and 4-wide ribbons (with breaks every 50cm)
  - 10-wide 6m for the inner system
- Waiting for continuous 5-wide 240m and 469.2m for Outer Endcap (Italy, UK)



OB L2-Flat Proposed cable type “L-S-1” OptoTerm-FireFly Connectivity

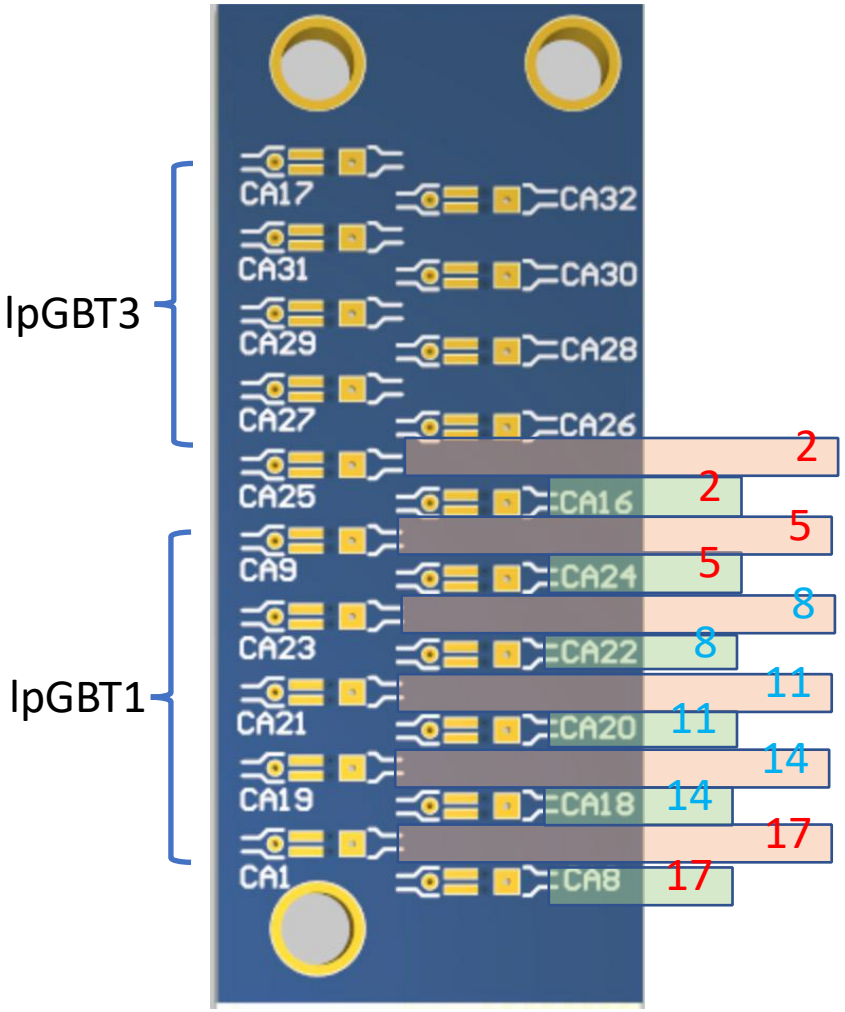




First L2 OB bundle as proposed in EDMS document https://edms.cern.ch/document/2467737/ (6m- two layers of (5/4) cables), we formed a prototype bundle.

- TDR of new optoboard test are GOOD
- Due to handling the pads tore off the opto-termination PCB
  - Solution Design strain relief enclosure

OB R-S-2 as Generic Test Bundle

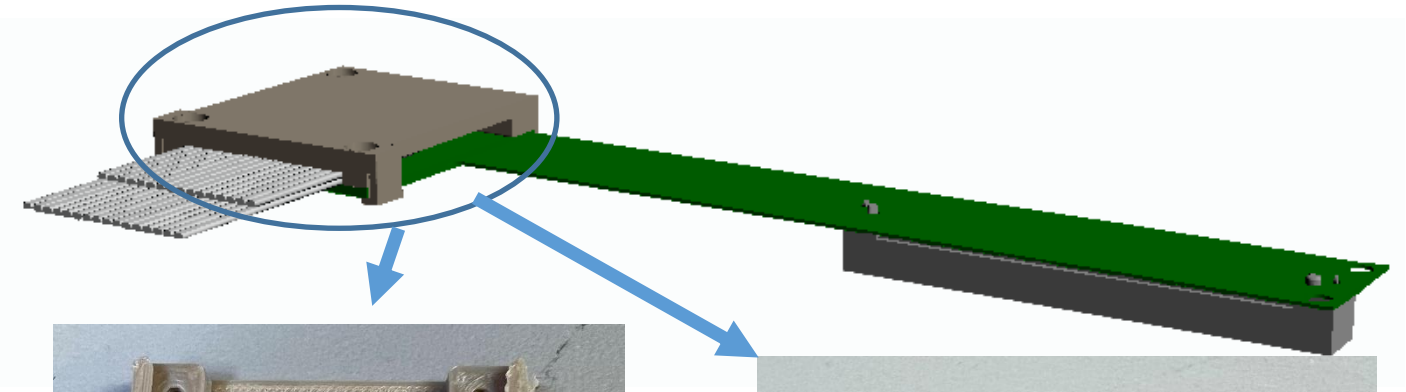


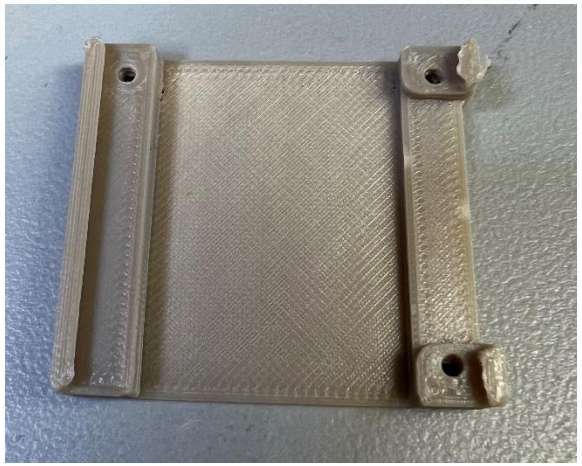
Firefly

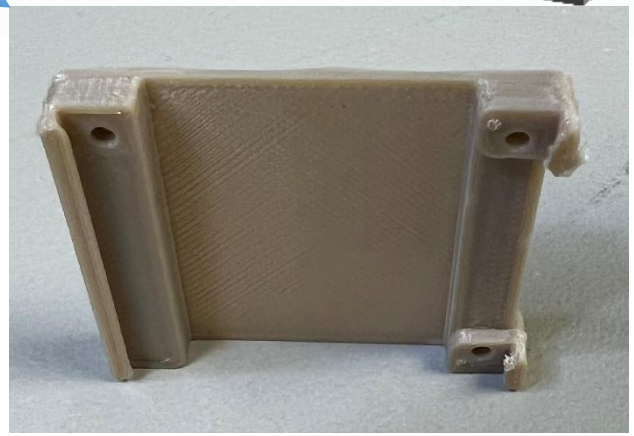
B	A
2	2
5	5
8	8
11	11
14	14
17	17

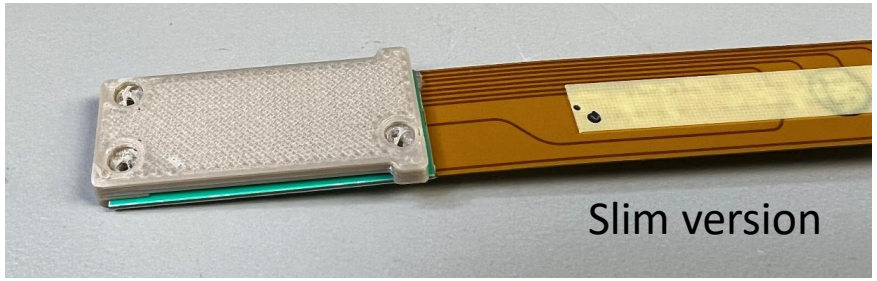
- Now that we have the 6-wide ribbon we can make this flavor of test bundles.
- OB R-S-2 6+6 with Firefly that is fully populated can also server as a generic test bundle.
- Much easier to accommodate to lpGBT1 only connectivity with Slim OptoTerm.
- Slim termination can go with either Left or Right.

L-shape OptoTerm Cover/Strain-relief



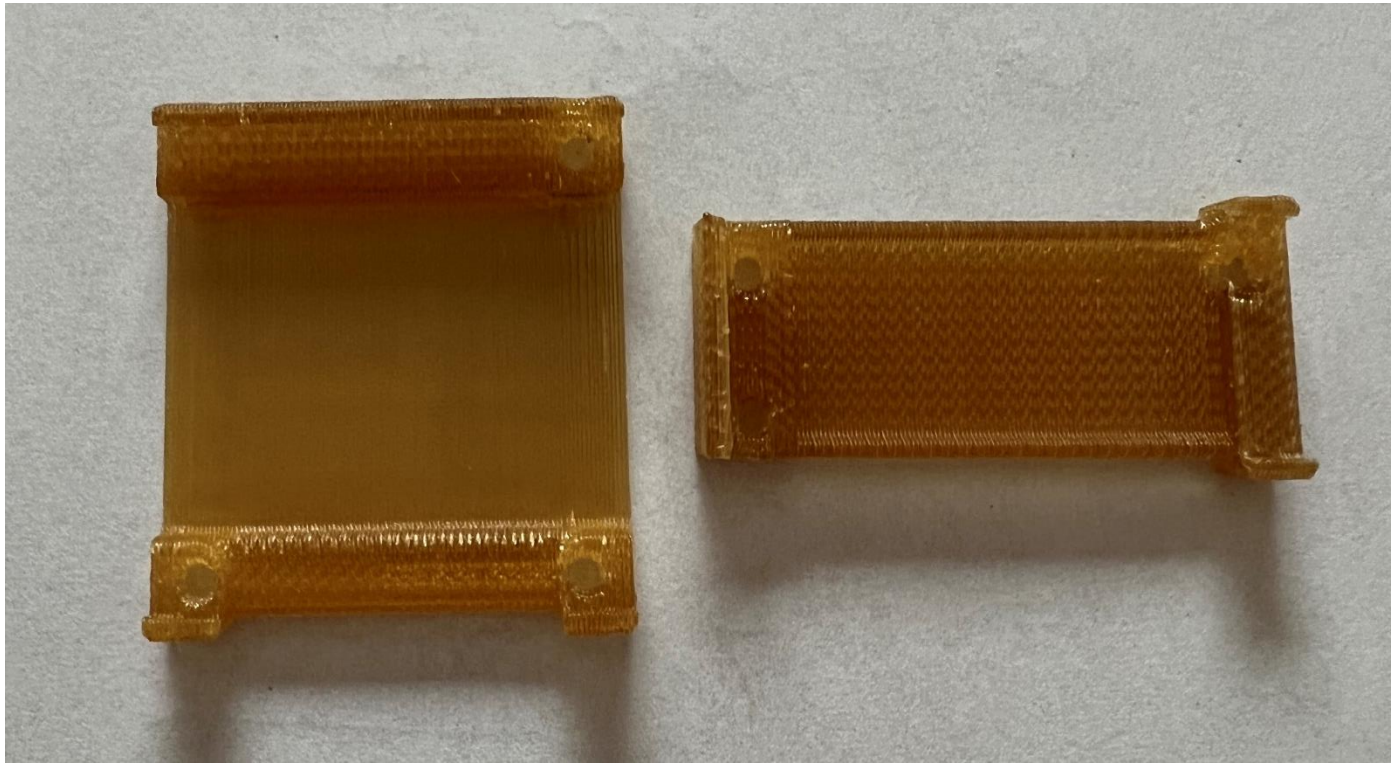






- 3D print PEEK cover design by SLAC Mech. Eng. Mike Hoganson
- Low profile cover to meet very limited Optopanel space to stack many bundles side by side
- Only 2-layers of twinax routing space over pads (0.75mm clearance from cover)
- Interleaving 2-layers of FireFly ribbons into single layer at pad edge for straight run to destination pads – no side wiggle or vertical excursion.
- 3D PEEK prototypes printed
  - Issue resolving some features
    - Soln: More engineering time needed
- Printing cost $30-$50 each small quantities

Possible solution ULTEM material



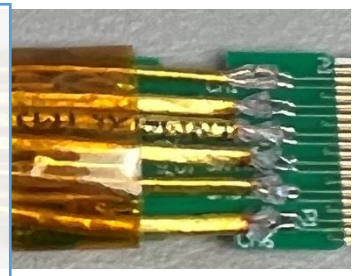
https://edms.cern.ch/document/2510035/1

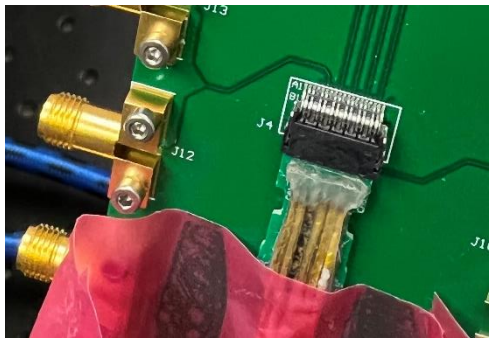
- Material is not as Radhard as PEEK (see edms report ~50Mrad)
  - Ok for Optobox not for Inner System PP0s
- Better printing
  - Some features printed with no problems.
  - Board clips resolved into a guide
- Still needs tweaking

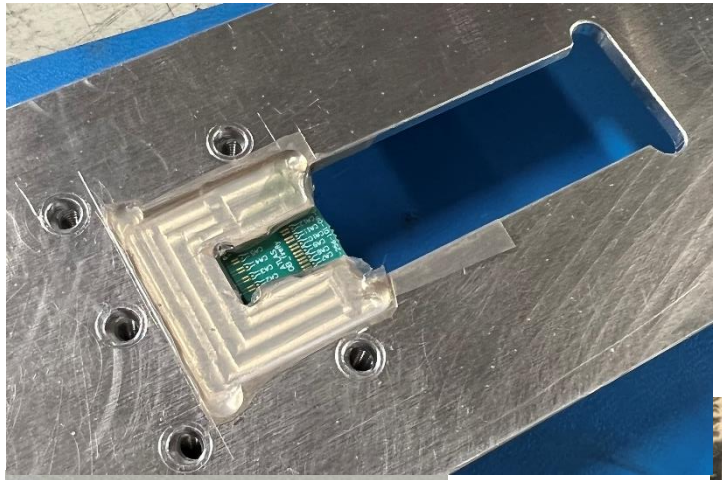
Firefly Strain relief

Epoxy based (Loctite 9396)

- At SLAC we made an Epoxy template mold (see picture)
  - Twinax cable can be epoxied after they have been soldered. This has been fixed!!
  - https://maxrad.web.cern.ch/maxrad/, 1.5Grad
  - Possible alternative Araldite 2021 (viscosity is different)
  - Measured the change impedance due to epoxy ~90ohm instead of 100ohms for a length of ~5mm
  - Note this was our first attempt to use epoxy as a strain relief and we did not have any specification on envelope or needs from other Subsystems.







Kapton Tape prototype has been made and provides adequate protection for engineering samples.

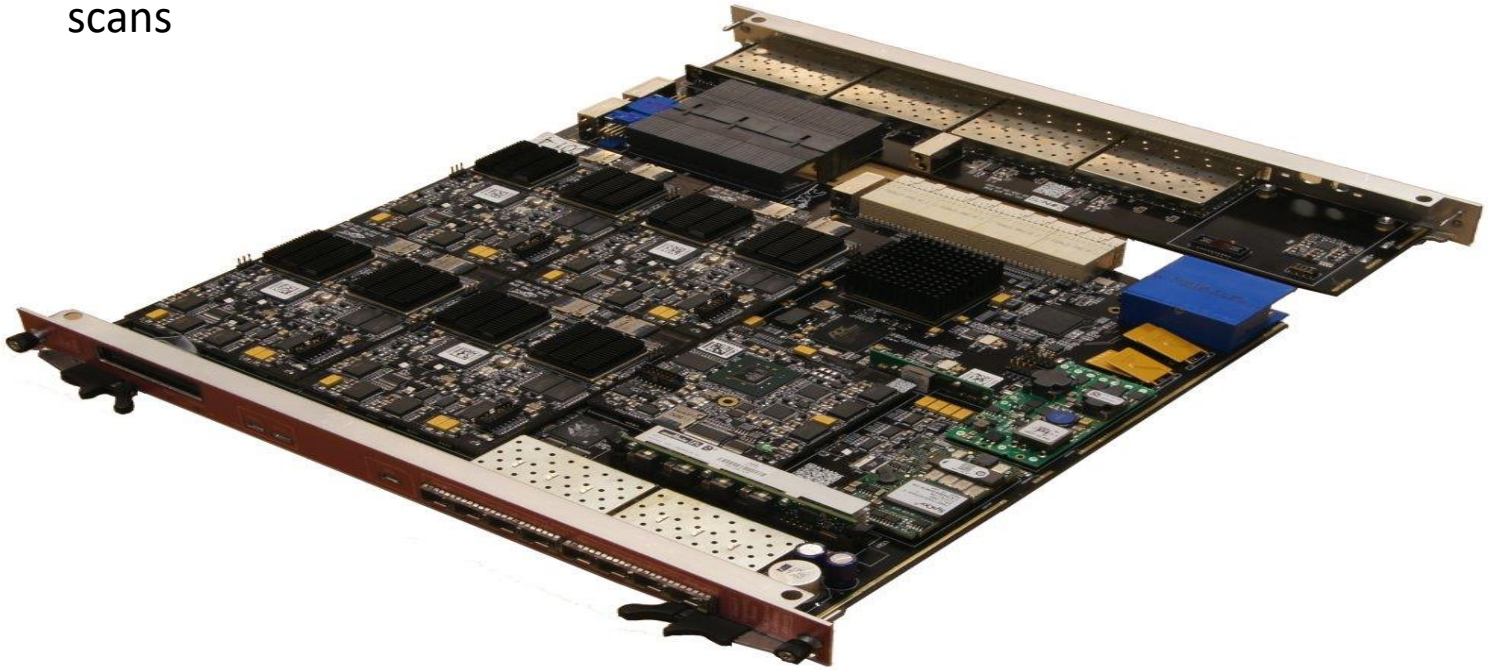
Modifying Samtec Strain relief for Firefly connection Future goal no progress lately

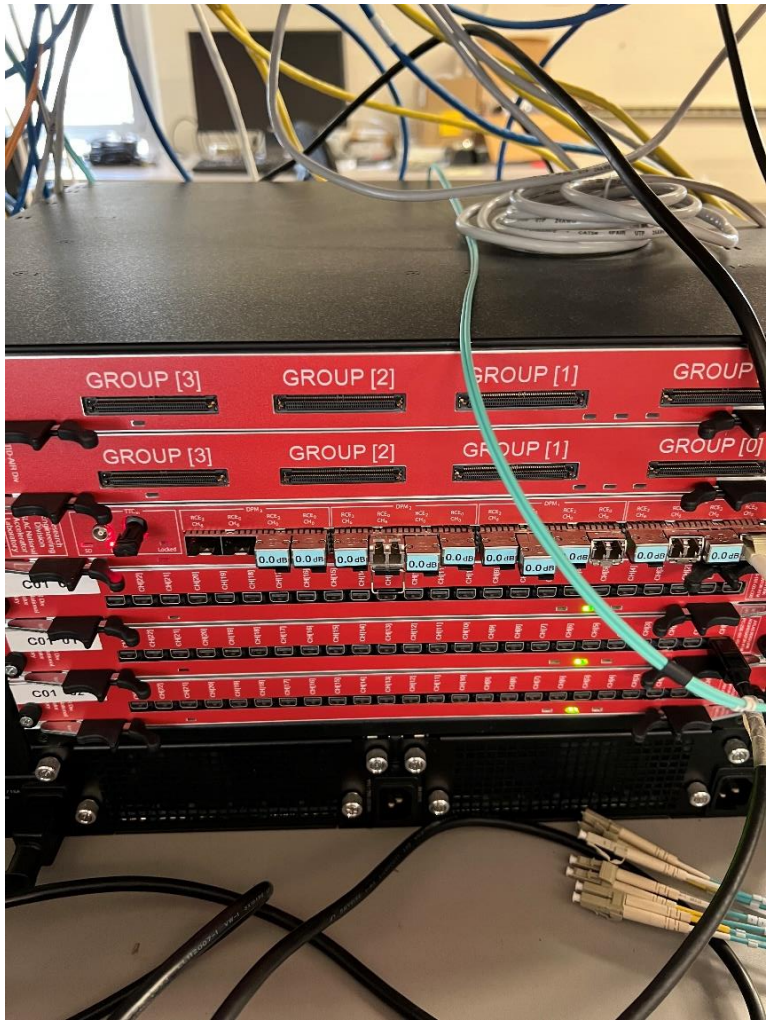
- Using the UCC8 and a new lever arm that will not allow the firefly to pull to the left.
  - The Lever arm will lock into PCB via slots. This has been discussed with Samtec and I will work with them to make a first prototype.
- In discussions with Samtec, Samtec is sending us the drawing and three prototypes are being to SLAC

UCC8
strain relief

Testing Cable Bundles using COB ATCA and RTM

- We need large number of MGTs with advanced data transmission utilities such as Pre-emphasis, BER and Eye scans.
- We can capitalize on the retiring COB RCE/ATCA from muon CSC readout replaced by New Small Wheels (NSW).
- We have designed a new RTM with ERM8 interface for BER and Eye-scans

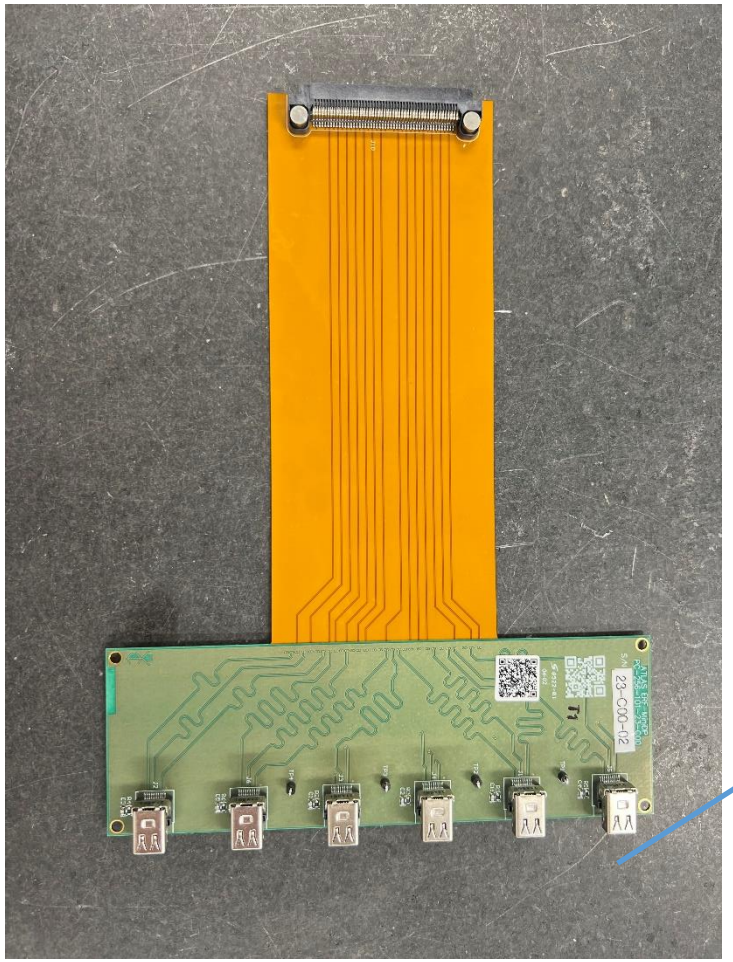




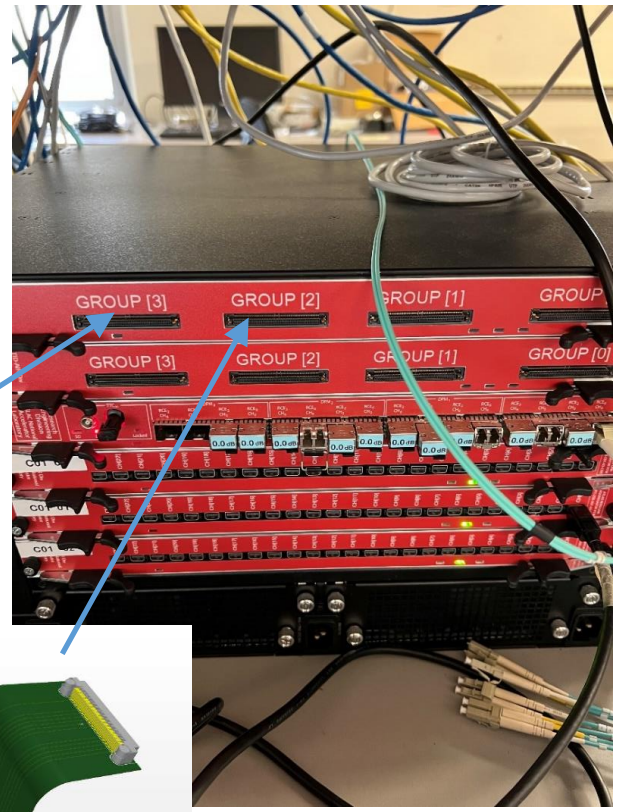
Note: If one COB drives through 2 DPMs and readout through 2 DPMs, you can have 4 channels running in parallel. (Need to check on software and firmware resource loading)

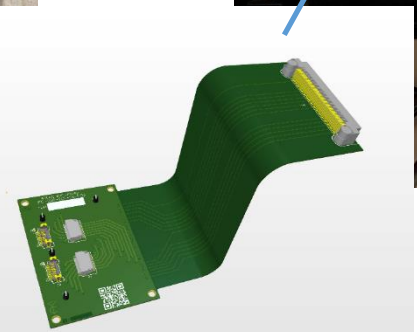
QC Tester PCBs

ERF8-LPAM Adaptor (Assembled)



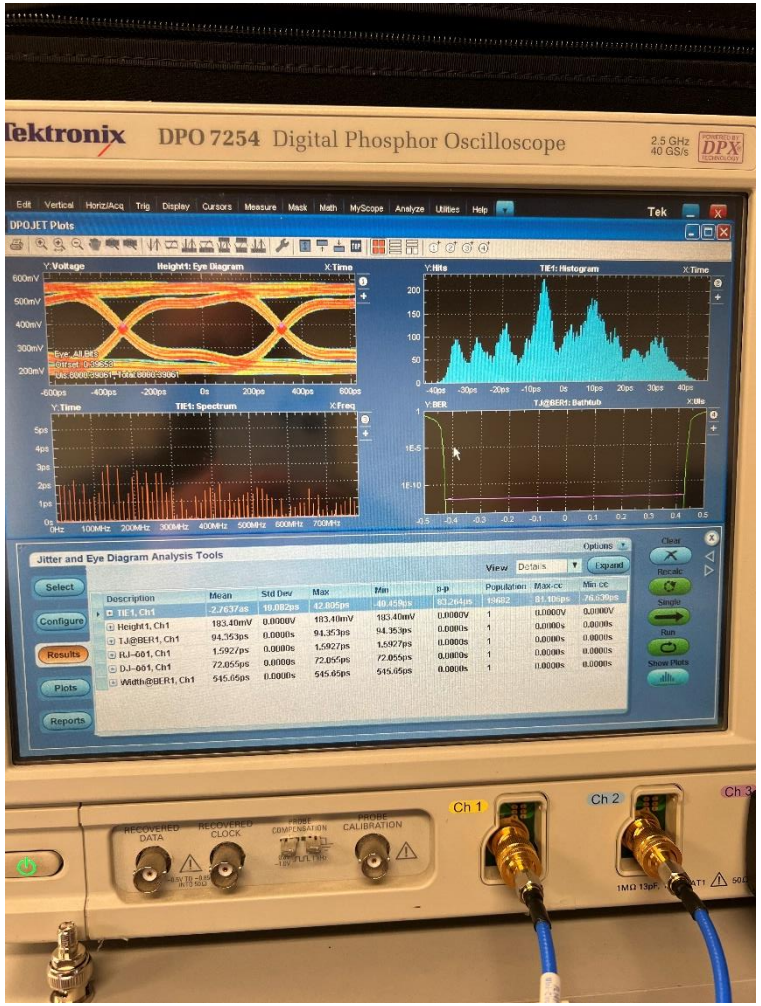
ERF8-miniDP Adaptor (Assembled)



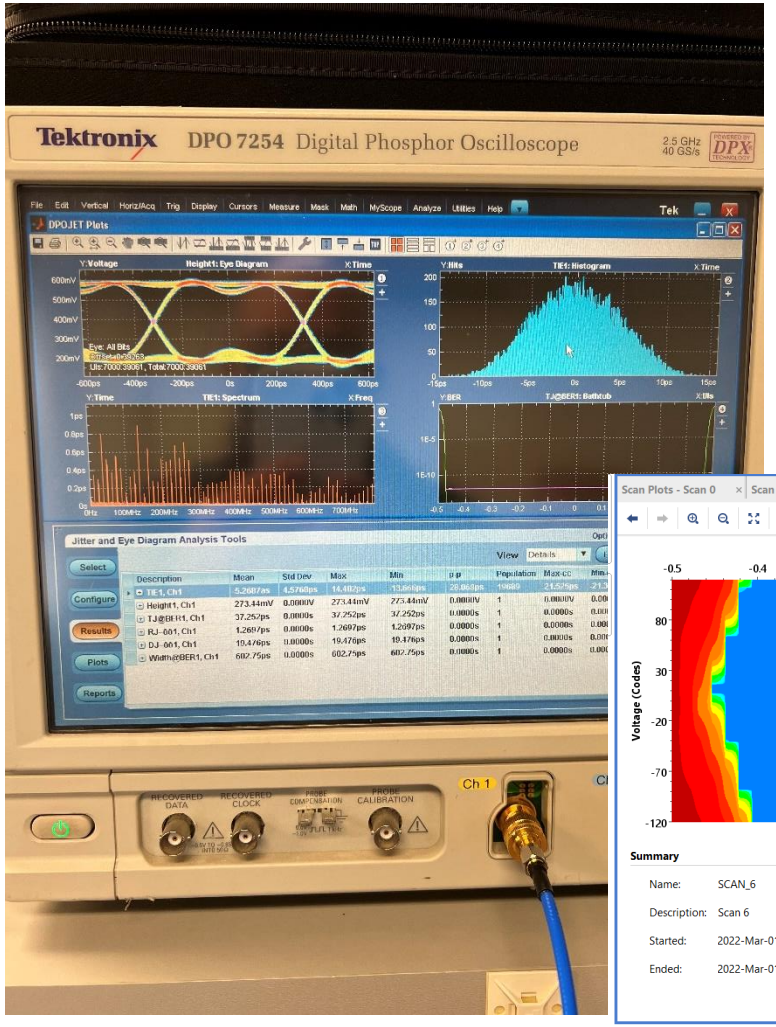


ERF8-FireFly Adaptor (assembled)

Eyescan Scope vs Xilinx

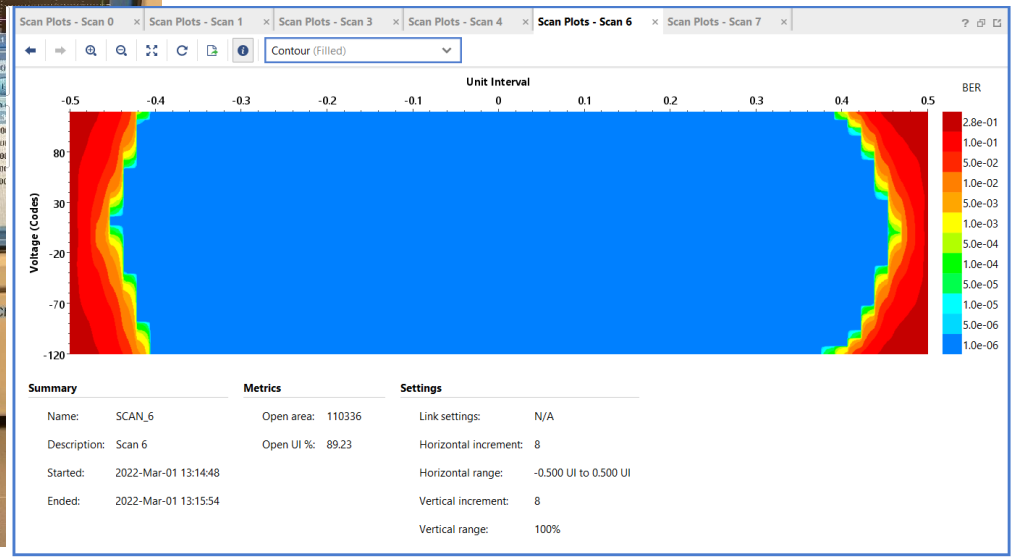


Eye-Scan Twinax

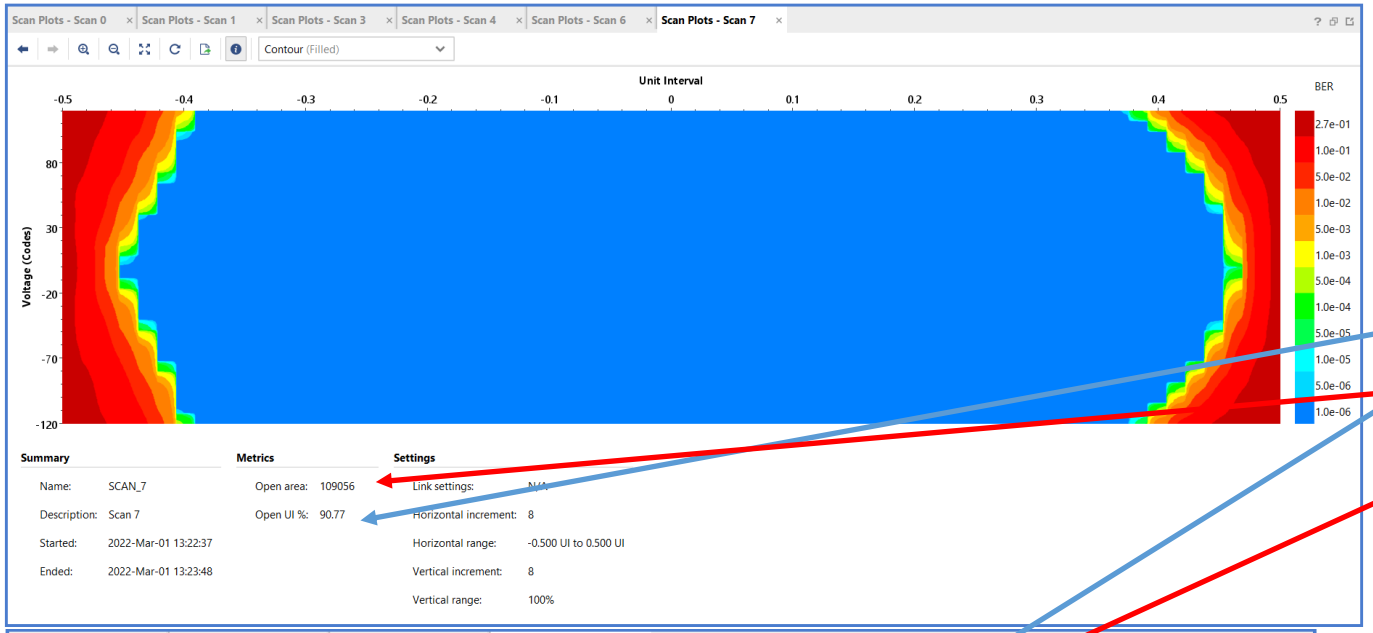


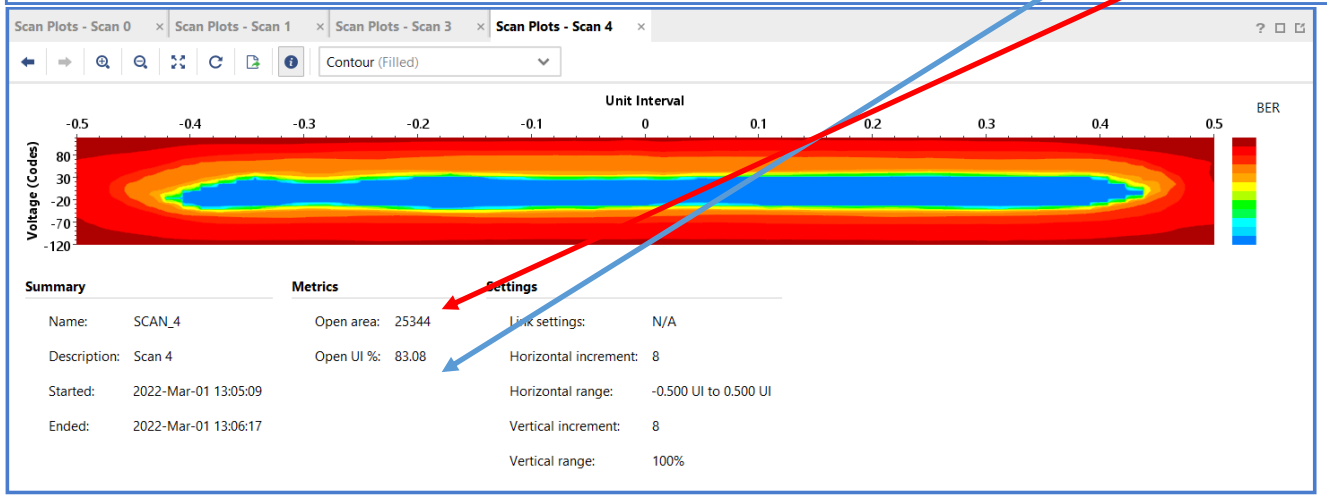
Eye-Scan KCU105

- The eye scan on the measured eye opening on the scope is 90.5%
- The eye opening measured by Xilinx is 89.23%
- The time to do this measurement is only ~1min
- Thus, a coupled ring data transmission can be done in 80min/PP0 or 160min/ring



Detecting bad data transmission chains



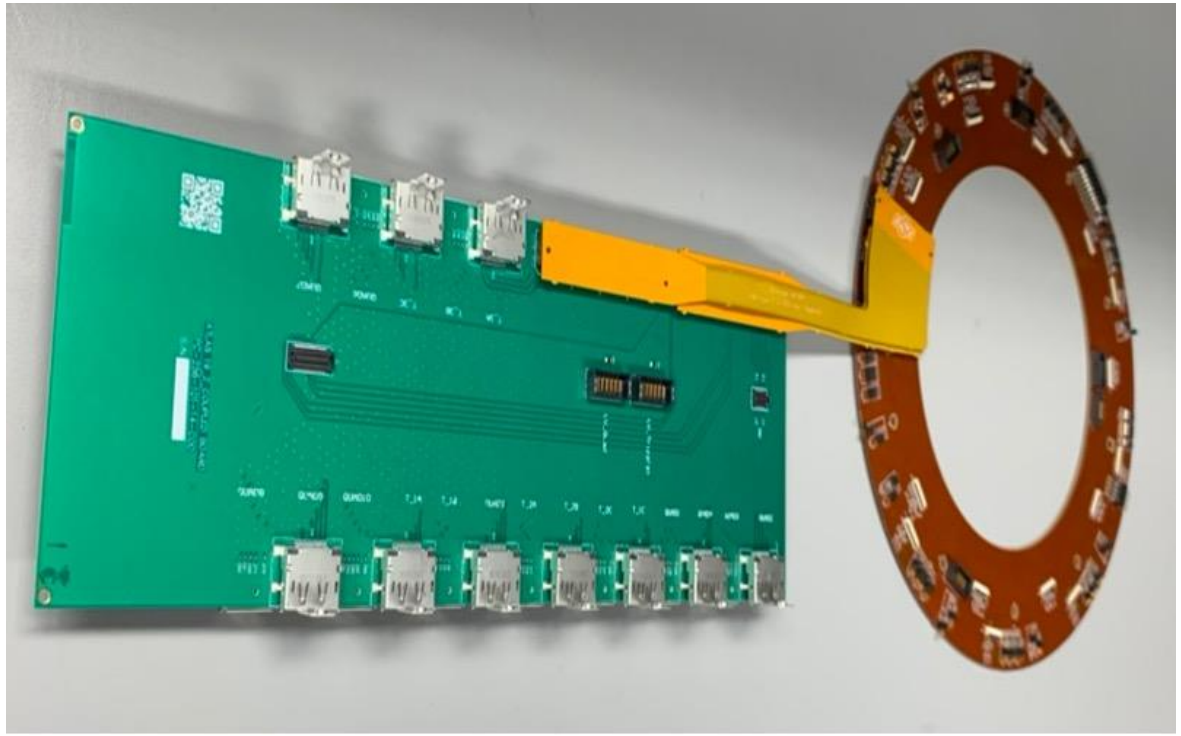


Can we predict a bad chain?

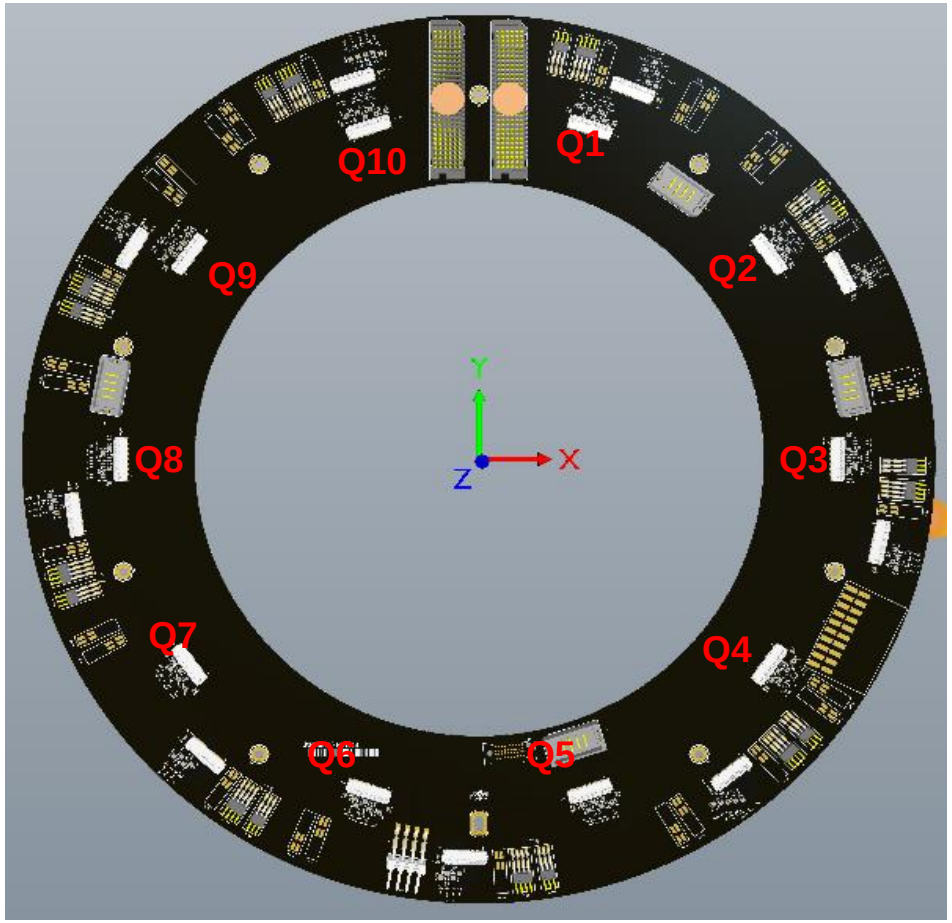
- Here we have two links one is good, and one is bad
- Eye opening is less 90% vs 83%
- Eye Area and Amplitude is different by factor of 4
  - Clearly a broke twinax wire
- We will be able to detect if there is a jitter problem with a driver or receiver because either the x opening will close, or the amplitude will close

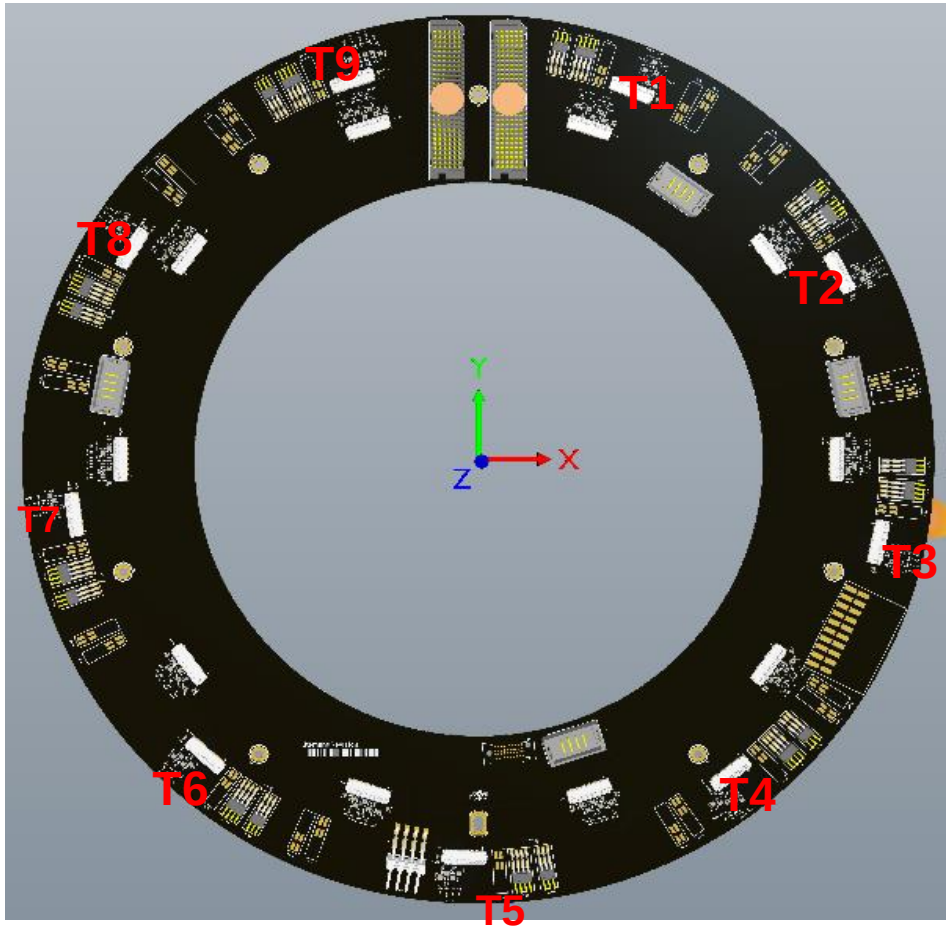
Data Transmission test on Demonstrator components

- The demonstrator Inner system contains a PP0, PP0-ring flex, Ring Flex, Module Flex, (RD53 Quad or RD53 Linear Triplet) and a few other PCB (next slide)
  - PP0 has full type-0 and type 1 services except for the twinax, DP cables used instead
  - PP0-ring flex is the first prototype and uses the LPAM/LPAF connectors (Only the connector will change to a zray connector on the ring side. This eliminates the large mating force of the LPAM on the ring.
  - The module connection uses the Molex connector that will be used on the real module connection



Ring Configuration

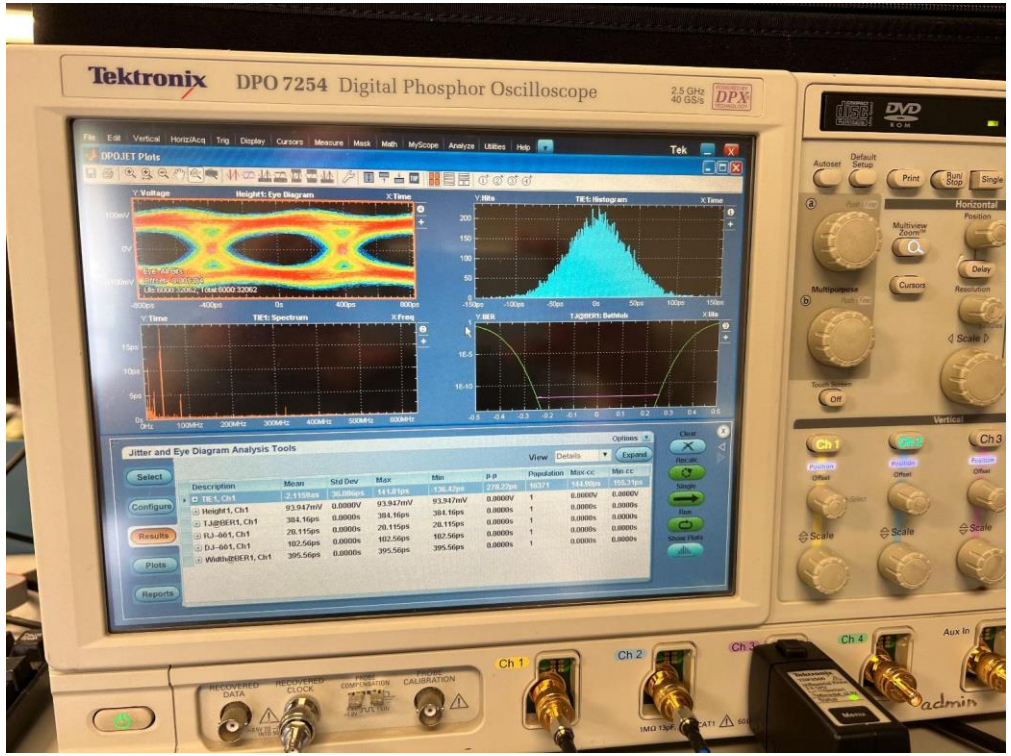




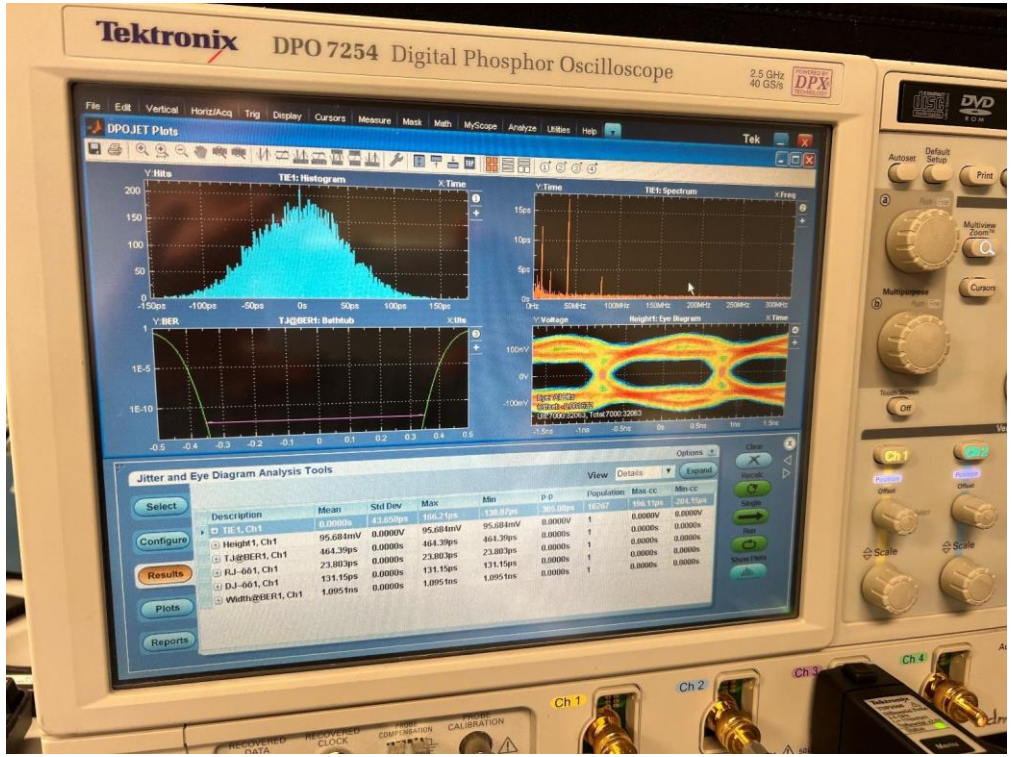
Data Transmission test on Demonstrator components

The measurements are from the module ZIF connection to the DP connector on the PP0. Both ends have a DP-mDP-sma adapter pcb which are included from the loss measurement (~2.4dB). (~5dB loss from module through PP0)

Eye Scans of the Coupled Ring (FULL SPEED)



- We were able to measure the Eyes and perform digital scans on all QUADS except Q3, Q5, Q6.
- Q10 is unique because it is covered by the PP0-Ring flex and we have not tried to connect a module.



- We were able to measure the Eyes and perform digital scans on most TRIPLETS except T1.
- T9 is unique because it is covered by the PP0-Ring flex and we have not tried to connect a module.

Summary

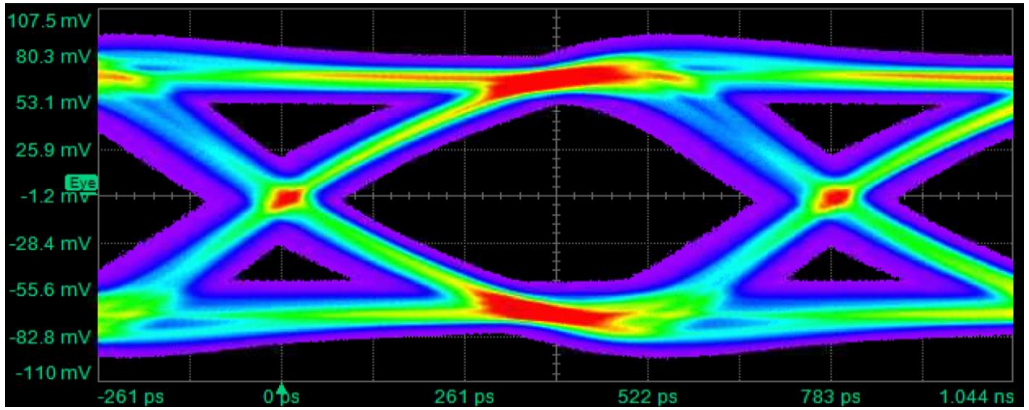
- Joint Molex twinax fab for all subsystems complete. 26km cable at SLAC.
  - Ribbonization is almost complete (missing 5-wide continuous) Tekdata is fabricating these.
  - OB slim optotermination PCBs with twinax bundles ready for assembley, (trying to solve strain relief issues (could use epoxy for quick fix).
- New irradiation results showed better consistency.
  - Further tests at FNAL and Bern to check minor differences.
  - New Samtec cable meets 95ohm specifications:
    - losses are 0.4dB lower,
    - Y-dimension bigger,
    - X-dimension smaller,
    - Cross sectional area slightly bigger
- Strain relief using PEEK and ULTEM shows promise working on better printability
- US vendor lined up for joint prototype bundle fab termination
  - Vendor busy with making many PCB and Pandemic issues
- In-house bundle tested and verified Eye scan theory
  - All QC PCBs fabricated.
  - Developing software and firmware with mDP-ERF interface.
- Data Transmission test suggest we will have ~17dB of loss from module to Optoboard.

BACKUP

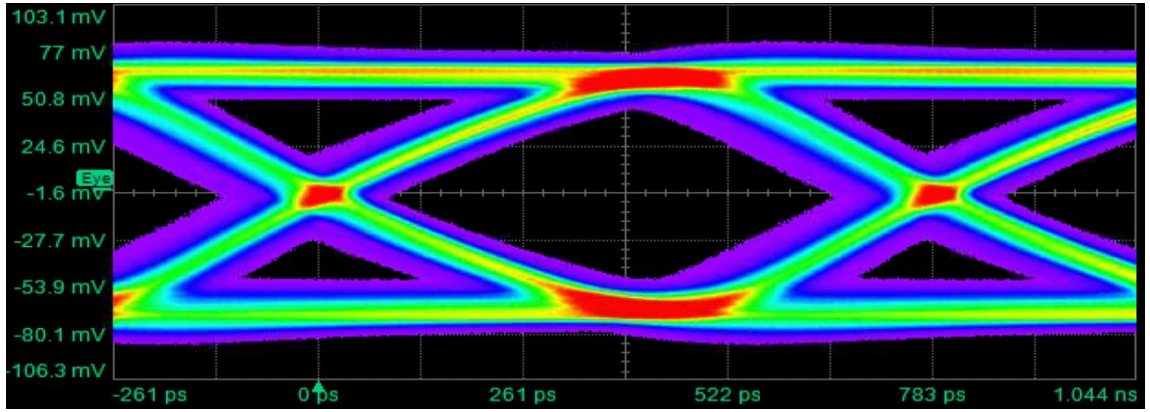
Radiation Hard Twinax Cable

- 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 Ω 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.

Eye Scan before and After radiation



Pre-irradiation eye, Total Jitter: 313 ps
RJ: 12.53 ps, DJ: 137.04 ps

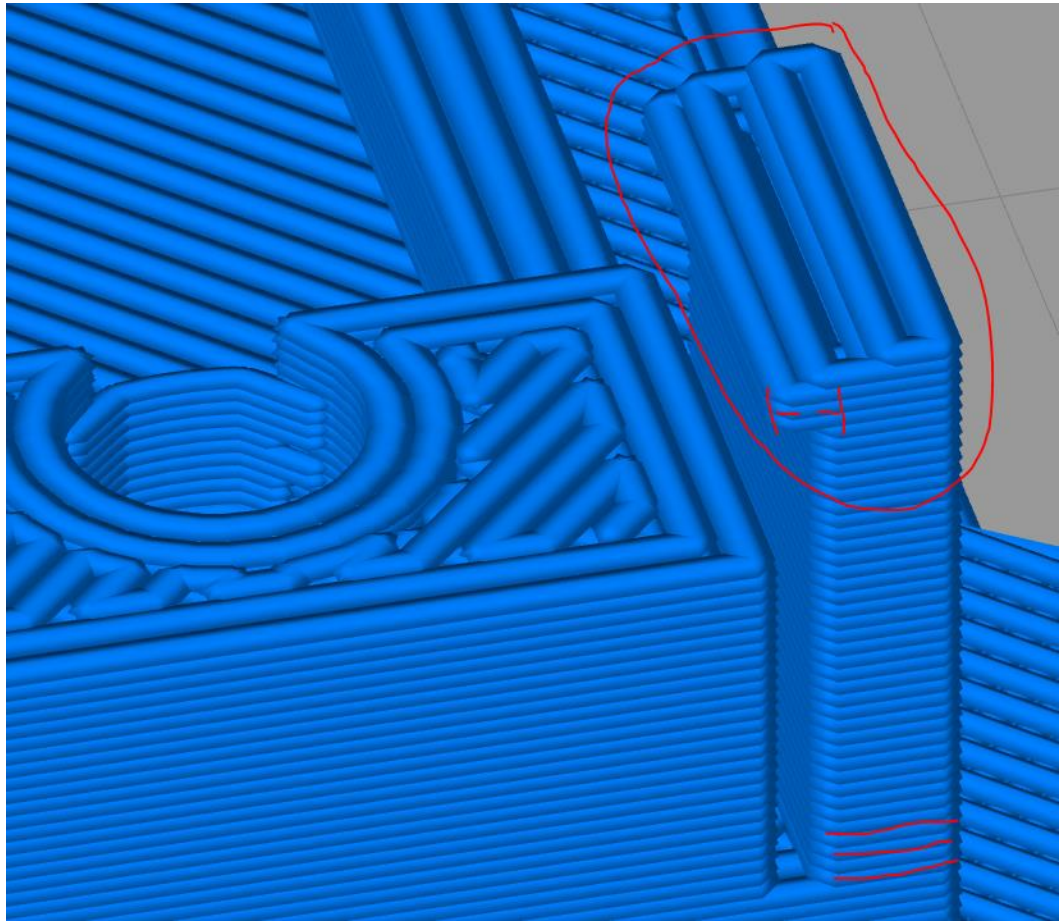


Post-irradiation (500Mrad) eye, Total Jitter: 342 ps
RJ: 13.42 ps, DJ: 154.05 ps

- PRBS7 uplink signal (1.28 Gbps), generated with ITkPixv1 (cmd via BDAQ)
- TJ(1e-12) measured with Teledyne Lecroy Waverunner 16GHz

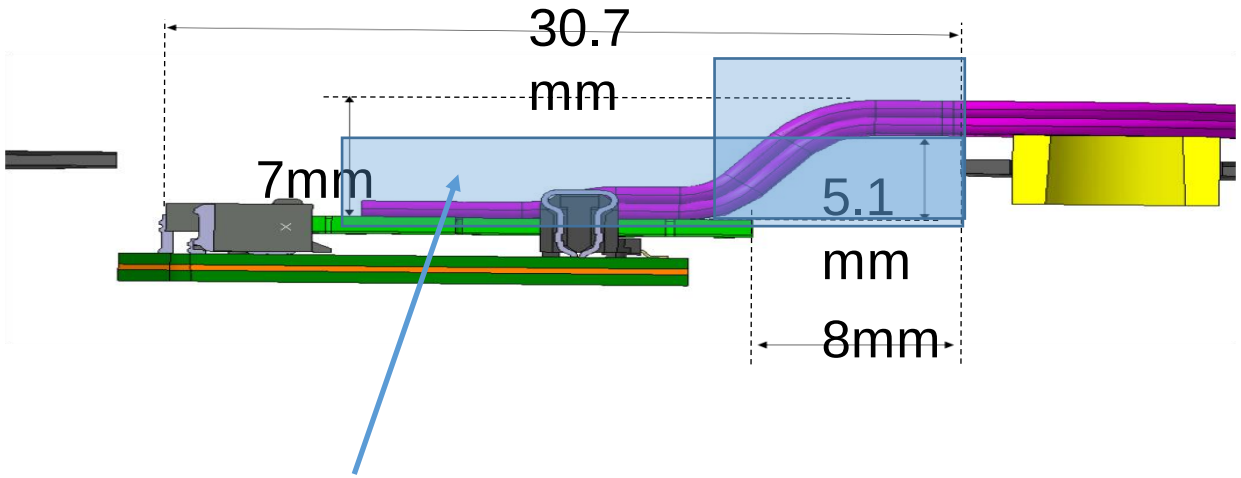
Problems Encountered: Design for Fused Depositioning Modeling (FDM)

- Overall Clip size right at minimum feature size for FDM
- “ledge” of the clip is less than 0.5mm. This small detail is mostly lost while printing. (General tolerance +/- 0.2mm)- similar result on longer clip feature thought not as bad
- Only one orientation was logical for printing, but results in the clips being printed vertically. This is not ideal as leveraging the clip will pull directly on adhered layers.
- Gap between clip and part body is too close and often becomes fused together (This is ok)



Issue with OB Epoxy prototypes

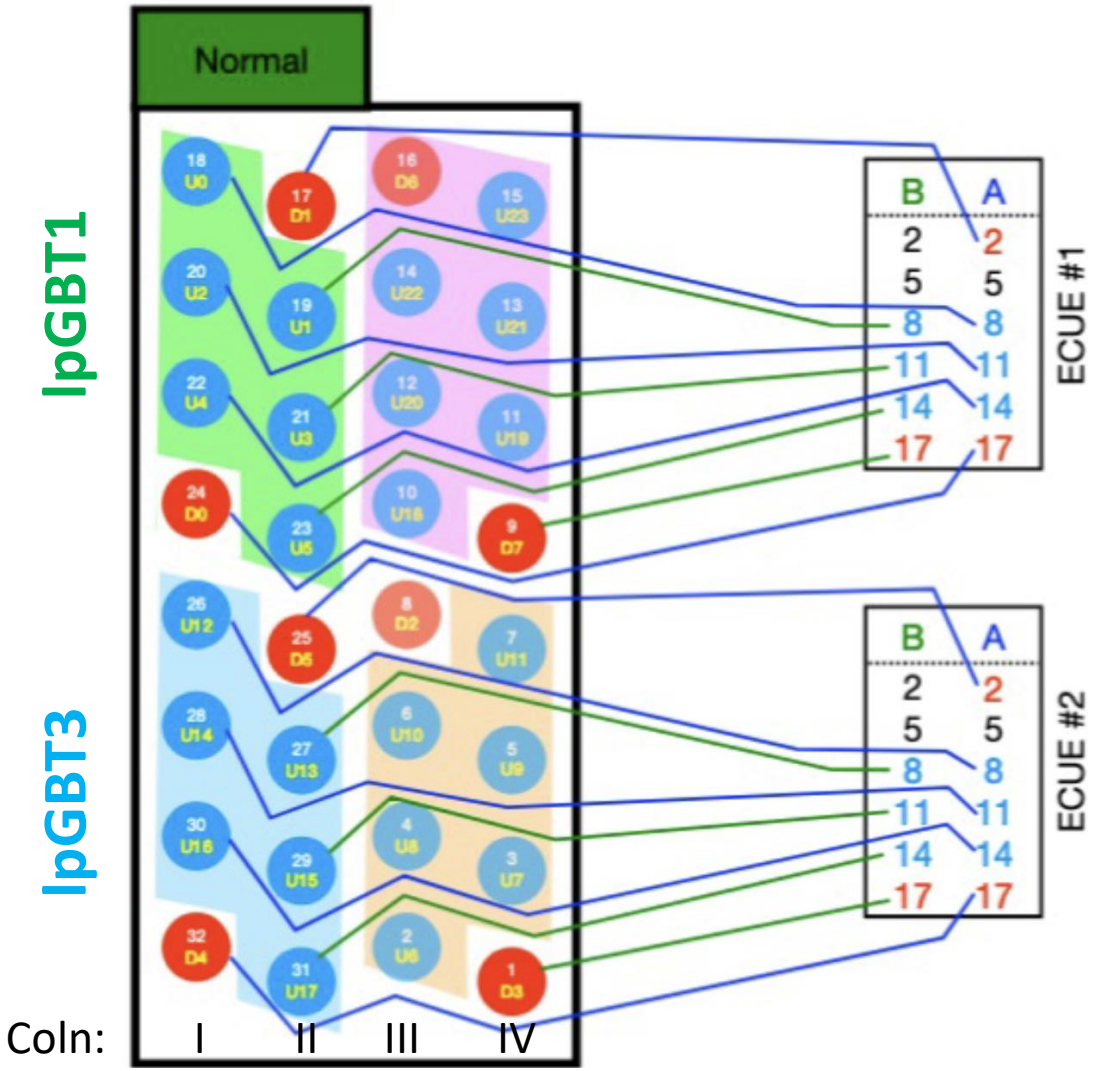
- Epoxy can't extrude from PCB to allow for bending in phi on top of the PP0
- Routing to PP0s of inclined half-rings has to pass through half-shells of inclined units. There is a step down according to drawings in following slides.
- All openings in the inclined unit half-shells will have the bent type-1 cables (power and Data

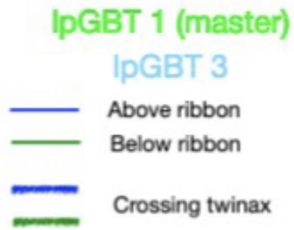


Based on the first prototype bundles, this section of the bundle termination could be potted with epoxy

Diego Alvarez Feito design

OB L2-Flat Proposed cable type “L-S-1” OptoTerm-FireFly Connectivity





- Termination need to proceed column by column:
  - Ribbon B column IV,III
  - Ribbon B column II
  - Ribbon A column II
  - Ribbon A column I

TDR measurements of Samtec cable