Electrical Data Transmission

ACES Workshop

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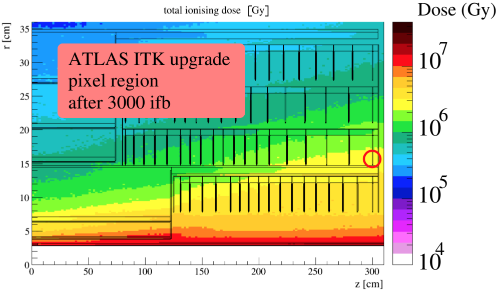
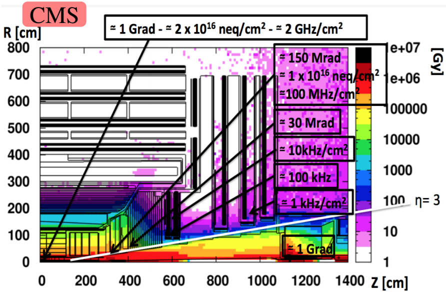
Why copper links?

- **High levels of radiation close to the beam line.** Optical components (laser, fibers) would not survive long in this environment.
- **Size.** Optical modules can be too bulky in the very limited space inside the detector.
- **Accessibility.** Placing optical components deep inside the detector means they cannot be replaced during a normal shutdown if they break.

$\Longrightarrow$ Electrical data transmission between the detector frontends and the optical components over several meters.





Applications

Phase 0 Upgrade:

- ATLAS Pixel nSQP twisted pair.
- ATLAS Pixel IBL twisted pair.

Phase 1 Upgrade:

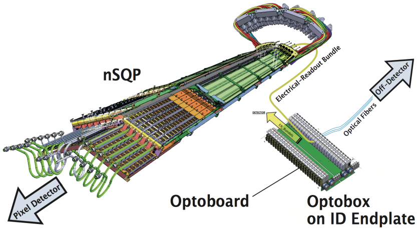
- CMS Pixel twisted pair.

Phase 2 Upgrade:

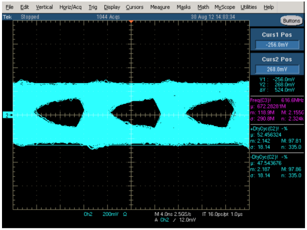
- ATLAS pixel twisted pair.
- ATLAS pixel twinax.
- CMS pixel flex.
- ATLAS pixel flex.
- CMS calorimeter PC board.

ATLAS Pixel nSQP (new service quarter panels)

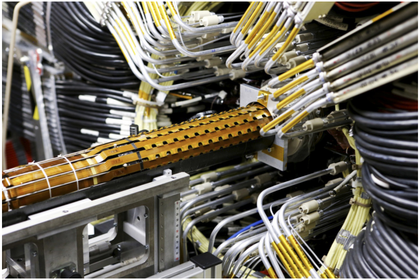
SLAC

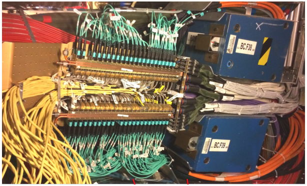


- Originally the optoboards were inside the inner detector.
- Fear of dying VCSELs.
- In 2014 the optical links were moved to the outside of the ID endplate to allow for access during a shutdown.
- Connection between the frontends and the optical components is done over 6.6 m of twisted pair cable.
- 28 AWG CCAl TWP with Kapton insulation for data readout at 80 Mbps.
- 36 AWG Cu TWP with Kapton insulation for clock and command (40 Mbps).



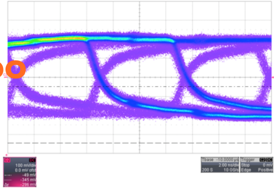
ATLAS Pixel IBL (Insertable B-Layer)



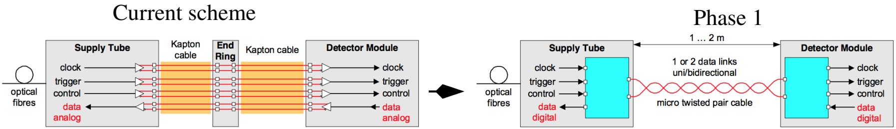


- New innermost pixel layer installed in 2014.
- Transmission over 5.4 m.
- 28 AWG Cu TWP w/ Kapton insulation for data at 160 Mbps.
- Originally we wanted to use CCAI like for nSQP but the wire was too springy which did not allow for the proper number of twists. As a consequence impedance control was not optimal and there was large cross-talk.
- 36 AWG Cu TWP with Kapton insulation for clock and command (40 Mbps).
- Great transmission but more material.

DO

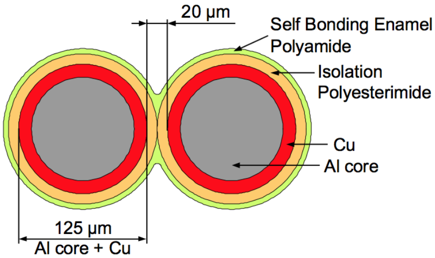


CMS Pixel Phase 1



- Current scheme uses multi-level readout over flat ribbon cables.
- Patch-panel between frontends and optical readout.
- For phase 1 digital readout at 160 or 320 Mbps is envisaged.
- Distance between 1 and 2 m without patch panel.
- Unidirectional or bidirectional link.
- Low current drivers.
- Twisted pair wire.

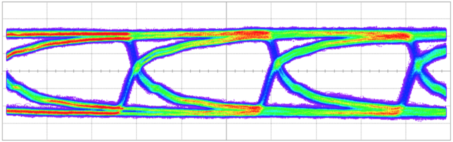
CMS Pixel Phase 1



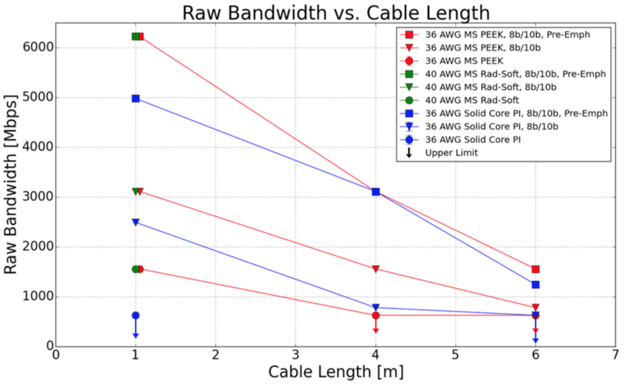
- 125 μm twisted pair cable (ca. AWG36).
- Polyesterimide insulation.
- Self-bonding enamel polyamide cover.
- R&D done on copper clad Aluminum.
  - + Similar transmission properties as Cu wire because of the skin effect.
  - + Lower mass.
  - - Very brittle.

$\Longrightarrow$ Now favoring Cu wire.

Eye diagram at 160 Mbps over 2 m:

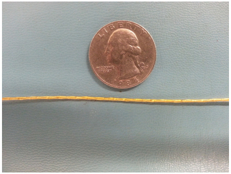


ATLAS Pixel Phase 2 - on-detector



- For phase 2 rates of up to 5 Gbps are expected for the pixel detector.
- The distance between the FEs and the favored location for the optobox is 6 - 7 m.
- Can twisted pair cables be used for data transmission at these rates?
- Tests show that this is only feasible over short distances of about 1 - 2 m so twisted pair cable can only be used for on-detector transmission at these rates.

ATLAS Phase 2 - Twisted Pair



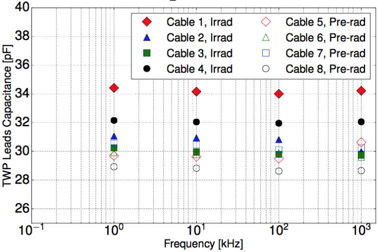
- A radiation hard twisted pair cable was developed and tested.
- 36 AWG stranded copper wires.
- PEEK insulation.
- Kapton jacket as mechanical and cross-talk protection.
- Bit Error Rates Tests (BERT) were performed on a 1.15 m long cable.
- Maximum rates for different transmission options are given in the table below.

8b/10b	Pre-emphasis	BW [Gbps]
No	No	1.555
Yes	No	3.110
No	Yes	4,976
Yes	Yes	6.220

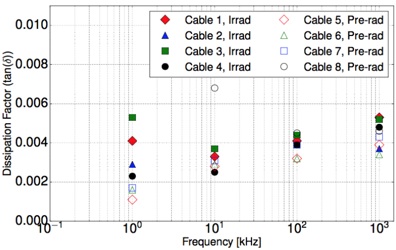
ATLAS Pixel Phase 2 - Twisted Pair Irradiation

- An irradiation test at a fluence of $1.86 \cdot 10^{16}$ n_{eq}/cm^2 was done on the cable at Sandia National Lab.
- Impedance, capacitance, and dissipation factor of the cable were measured and compared to the values before irradiation.
- Some change in capacitance and dissipation factor was observed.
- The maximum rate as measured in a BERT, however, did not change.
- A direct measurement of the dielectric constant of PEEK after irradiation is in planning.

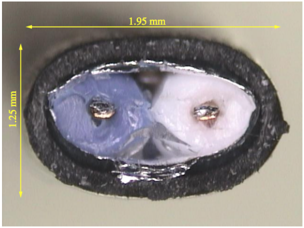
Capacitance

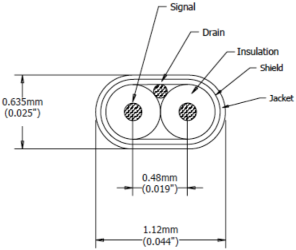


Dissipation factor



ATLAS Pixel Phase 2 - Twinax





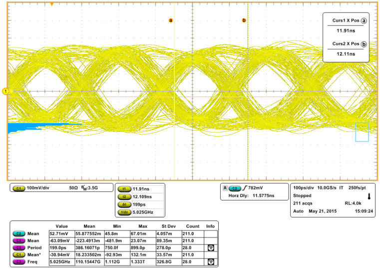
- A Twinax is a dual coaxial cable with a common shield ("Extension" of TWP).
- More material (compare to ca. 0.25 kg/km for a Cu/Kapton AWG36 TWP) but superior transmission properties.
- 3 custom prototypes were produced for R&D purposes.
- Currently Cu wire (later CCAl), low density polyethylene dielectric, Al foil shield, PU or polyester jacket.

AWG	Width/mm	Height/mm	Mass (kg/km)
28	2.39	1.32	5.2
30	1.75	0.97	2.55
34	1.12	0.64	1.1

ATLAS Pixel Phase 2 - Twinax

- Used a bit error rate tester with a number of fixed rates to determine the maximum rates at which the transmission is error-free.
- The table shows the max rates in Mbps.
- The eye pattern is for 6 m of AWG 28 at 5 Gbps.
- An earlier, similar prototype was irradiated at a fluence of 10^{16} protons/cm^2.
- No change in transmision quality was observed.

AWG	length(m)	Raw	DC bal./preem.
28	6	3110	8000
30	6	1555	6220
34	4	1555	6220



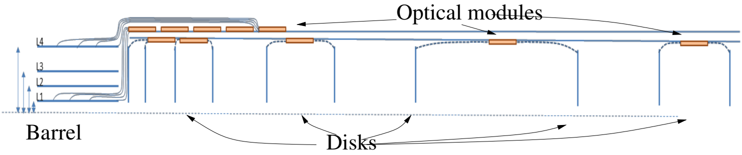
ATLAS Pixel Phase 2 - Hybrid

SLAC

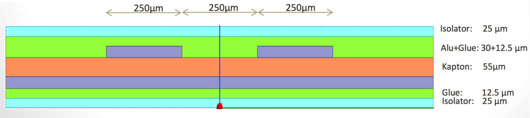
- Since TWP cannot be used to transmit at 5 Gbps over 6 m and twinax has too much mass to be used directly on the detector a *hybrid solution* is being investigated.
- 1 m of twisted pair soldered directly to 6 m of twinax.
- BERT test done on the hybrid: Result for AWG 28 twinax + TWP:

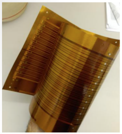
8b/10b	Pre-Emph.	Raw Rate (Gbps)	Errors	BER	Run Time
✗	✗	0.622	4.57×10^{4}	1.93×10^{-8}	1 hour
✓	✗	2.488	0	1.46×10^{-13}	1 hour
✗	✓	3.110	0	4.50×10^{-15}	20 hours
✓	✓	6.220	0	5.67×10^{-14}	1 hour

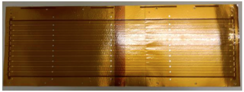
CMS Pixel Phase 2 - Flex



- Place optoboards at a distance of 1 - 2 meters away from the frontend modules.
- Use a flex cable with differential transmission lines to make the connection.
- Kapton flex with Aluminum traces for low mass.
- Transmission rate 1.25 Gbps for compatibility with LPGBT (multiple lines per FE for innermost layer.)

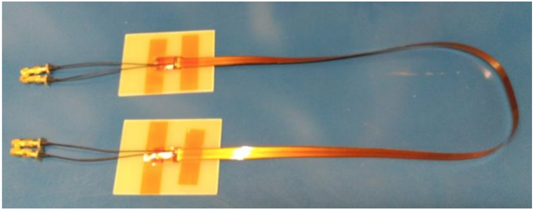


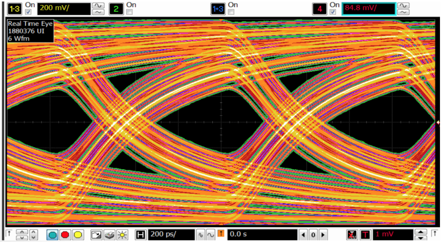




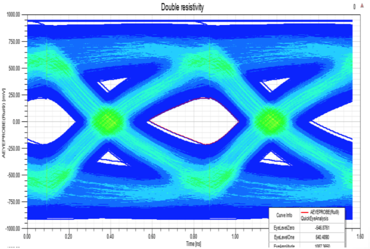
CMS Pixel Phase 2 - Flex Prototype

- A prototype was of 75 cm length was produced and tested.
- Tricky to atttach to Al traces.
- Good agreement with simulation after adjusting DC resistance.
- Eye patterns at 1.25 Gbps:





MEASUREMENTS



SIMULATIONS

CMS Pixel Phase 2 - Alternatives

SLAC

Flex:

- A number of variations of the flex cable is being investigated.
- Cu traces instead of Al traces.
- Different ground plane options.
- With and without soldermask.
- *Total mass varies between 0.62 kg and 2.56 kg.*

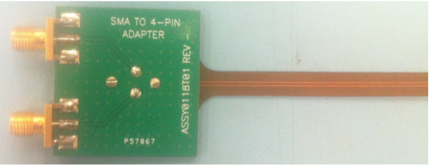
Twisted Pair:

- In addition twisted pair cable is being considered.
- 36 AWG.
- Cu or CCAl.
- With and without shield.
- *Total mass varies between 0.46 kg and 3.7 kg*.

ATLAS Pixel Phase 2 - Flex

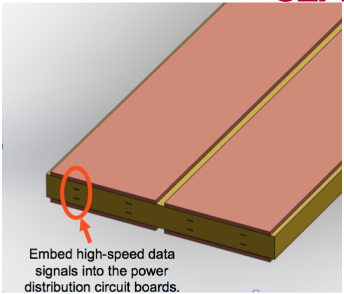
- Flex for on-detector data transmission.
- Length 1 m.
- Kapton flex with copper traces.
- Rate requirement 5 Gbps.
- Irradiation at $2 \cdot 10^{16}$ neq showed no degradation.
- A hybrid cable with flex and twinax is in preparation.
- Bit error rate results can be found in the table below.

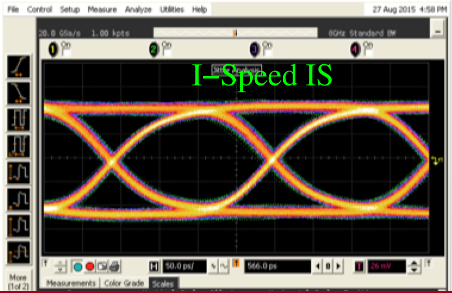
1.0m Flex Cable					
8b/10b	Pre-Emph.	Raw Rate (Gbps)	Errors	BER	Run Time
✗	✗	2.488	0	1.20×10^{-13}	1 hour
✓	✗	3.110	0	9.52×10^{-14}	1 hour
✗	✓	3.110	0	1.14×10^{-13}	1 hour
✓	✓	6.220	0	2.63×10^{-15}	21 hours



CMS HGCAL - PC board

- High speed data lines in power distribution PC board.
- Two 1.05 m long prototypes were produced:
  - Isola Terra Green material.
  - Isola I-speed IS.
- Tested at 4.8 Gbps.
- Pre-emphasis and equalization tested.
- Eye patterns with pre-emphasis:

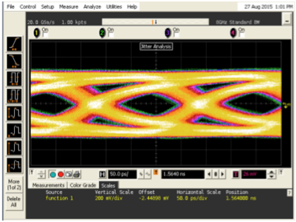


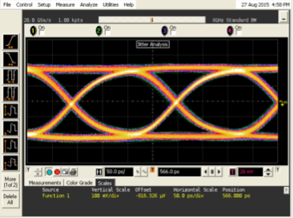


Pre-emphasis (and de-emphasis)

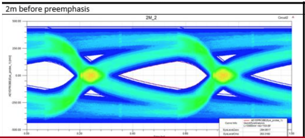
- Pre-emphasis and de-emphasis are techniques to distort the transmitted signal in order to counteract frequency-dependent losses in the transmission line.
- This is an important tool for Gb rate transmission.
- Left: without pre-emphasis   Right: With pre-emphasis.

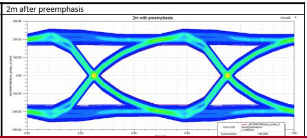
Example from the CMS HGCAL:





Example from the CMS pixel upgrade:

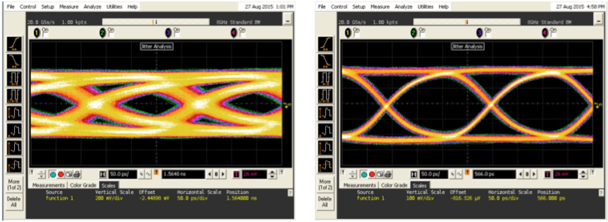




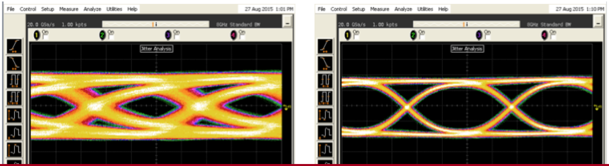
Equalization

- Equalization achieves a similar effect at the receiving end by applying a high pass filter to the incoming signal.
- Example from the CMS HGCAL comparing both techniques:

Pre-emphasis: (left: raw right: pre-emphasis)



Equalization: (left: raw right: equalization)



Data Encoding

SLAC

- DC balancing of the signal results in major improvement of the transmission quality.
- This is achieved by encoding the data.
- Typical codes are:
  - 8b/10b.
  - 64b/66b.
  - Scrambling.
  - Biphasemark-encoding.
  - Manchester-encoding.
- Depending on the encoding scheme part of the bandwidth is lost.

$\Longrightarrow$ Optimization needed.

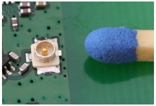
- An additional benefit of DC balancing is the possibility of AC coupling the signal.
- Serial powering of the detector requires AC coupling.
- Commercial optical receivers are AC coupled so DC balancing is required for their use.

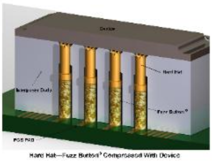
Connections

- The most straightforward way to attach a cable to a PC board is by soldering.
- For the detector installation this solution is not necessarily very practical.
- *Connectors are needed.* Small and suitable for Gb rate transmission.

Example for coaxial cables:

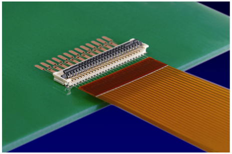
- U-FL: Standard connector for single micro coax.
- Fuzz buttons: Multi-channel high frequency.





Example for flex cables:

- Zero Insertion Force (ZIF).
- Clamps down on cable.
- Rad hard?
- Sufficiently reliable?



$\Longrightarrow$ **Connectors are a crucial element for electrical data transmission.**

Summary

- R&D on electrical data transmission is ongoing for
  - Twisted pair cables.
  - Flex cables.
  - PC boards.
  - Twinax cables.
- The distance ranges from 1 m to 7 m.
- The rates vary between 160 Mbps to 5 Gbps.
- Copper or Aluminum conductors.
- Techniques like DC balancing, pre-emphasis, and equalization are important.
- Solutions for connecting the cables have to be found.

$\Longrightarrow$ Finding the right cable is an optimization between reliable transmission on the one hand and minimizing the amount of material and space on the other hand.

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