HIGH SPEED ELECTRICAL TRANSMISSION LINE DESIGN AND CHARACTERISATION

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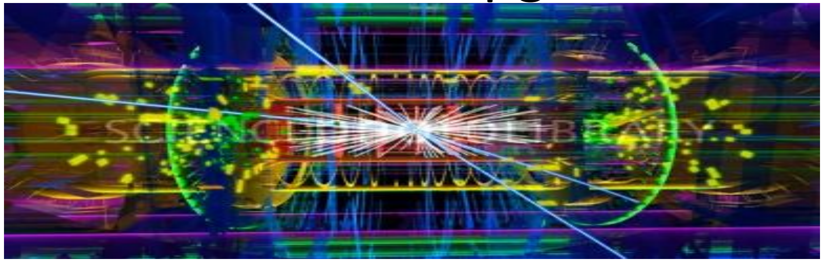
Leyre Flores, Richard Bates, Craig Buttar, Jan Buytaert, Lars Eklund, Iain Longstaff, Sneha Naik, Stephanie Sullivan, Kenneth Wraight

OUTLINE

- INTRODUCTION
- TRANSMISSION LINE DESIGN
- CHARACTERIZATION TECHNIQUES
- SIMULATIONS
- EQUALIZATION

INTRODUCTION

- Vertexing and tracking subdetectors of HEP experiments deliver huge data rates, requiring many multi-Gigabit/s transmission links
- Commercial solution: Data transmitted optically
- Physics solution: Due to the high radiation environment and low radiation length requirements electrical transmission with custom designs are needed
  - In lower radiation regions (strips detector) the transmission is done optically
- This presentation will focus on flex cables (it can be extrapolated to PCB design) and wire cables transmission lines
- Examples from LHCb and ATLAS upgrades will be shown



INTRODUCTION

There are many ways a signal can be disrupted as it crosses a transmission line

Radiative loss

- Energy is lost via EM radiation
- Control through shielding

Resistive loss

- Energy is lost inside the transmission line
  - Skin effect and dielectric losses
- Control through good conductors (low surface roughness) and low-loss dielectrics.

Cross-talk

- Signal line becomes antenna and neighbouring lines collect energy
- Control through ‘guards’ to isolate lines.

Reflection

- Discontinuities in dielectric (Z_0) return fraction of signal to source
- Control through geometry and dielectric

- When designing high speed differential lines there are many important rules to follow:
  - Using tightly coupled differential traces to minimises EM radiation
  - Match the lengths of the traces for the LVDS pairs
  - Have a continuous reference plane for the differential traces, giving a small return line impedance
  - Match the impedance to the rest of the system in order to avoid reflections
  - Use guarding traces between signal traces in order to reduce cross-talk

- Transmission can be deteriorated mainly by two problems:
  - Skin effect: the tendency of a high-frequency alternating current to flow through only the outer layer of a conductor. It is F(√f)

$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}}$$

Where:

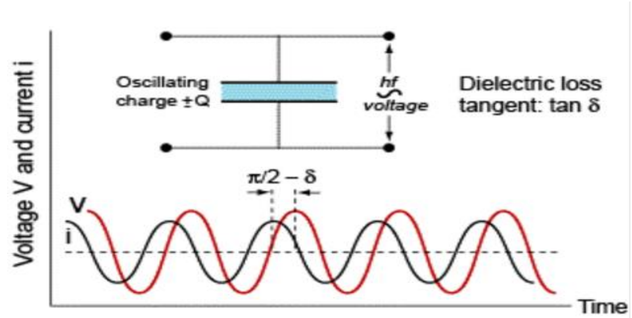
δ = skin-depth in meters;

f = sine-wave frequency in Hz;

μ_0 = permeability of free space =1.256E-6 Wb/A-m;

σ = conductivity in S/m. For annealed copper σ = 5.80E7 S/m.

  - Dielectric losses: The varying electric field causes small realignment of weakly bonded molecules, which lead to the production of heat. It is F(f)



- Choosing the appropriate materials for the conductors, shield and dielectric is a key point
  - Teflon has a very low loss tangent but it is not radiation hard
  - Smooth conductors : silver is the smoothest but it activates causing background radiation

Signal reflections and can be limited through choice of geometry & dielectric material
→ Characteristic Impedance, Z_0

Discontinuities in Z_0 introduce partially reflective boundaries, cf optical analogy

- Usually 50Ω single line used (100Ω differential)

Hence, importance of understanding geometry and dielectric properties: dielectric constant & loss tangent

Simple calculators available online

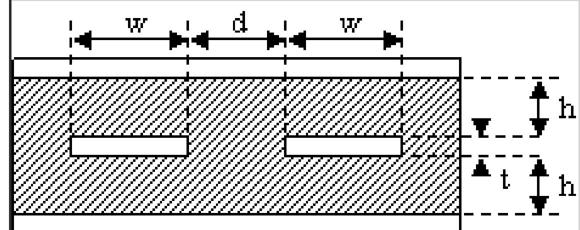
NB Dielectric properties may vary with signal frequency, i.e. causal

Differential Stripline Impedance Calculator

$$Z_d = \frac{120}{\sqrt{\varepsilon_r}} \ln\left(\frac{1.9(2h+t)}{(0.8w+t)}\right)\left(1 - 0.347 \exp\left(-2.9\frac{d}{2h+t}\right)\right)$$

Note: valid for (w/h) from 0.1 to 2.0 and (t/h) less than 0.25

Dimensional units: ◉ mm ○ mils

w (trace width) =	4
d (trace separation) =	6
t (trace thickness) =	1.4
h (dielectric thickness) =	6
er (relative dielectric constant) =	4.2
	Calculate
Zd (Impedance, Ohms) =	90.700

Note: 1oz = 1.4mils = 0.03556mm

Cable impedance calculation:
Z (Ohms) = 120/√ε · ln (2s/d),
where s is the conductor separation and d is the conductor diameter

Any point-to-point transmission lines including flex, cable and PCB can be characterized with this method.

Signal is scattered as it passes through:

- Reflection = signal returned / signal in
- Transmission = signal out / signal in

Any number of ports can be considered in this manner

Differential signals lines are usually better for high speed data transmission

- Noise reduction

Scattering can be calculated for sets of input/output ports

The S-matrix (scattering matrix) is a square matrix of coefficients which describe the signal propagated between any binary coupling of ports

S parameter = response / signal

- Signal defined towards DUT
- Response defines away from DUT

E.g. port 1 **reflection**, S11 = Signal back to port 1 / input to port 1

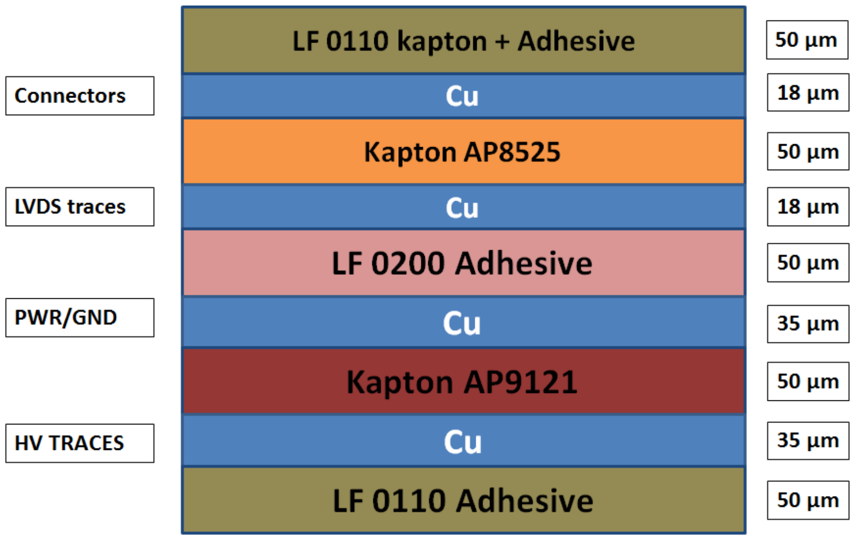
E.g. **transmission** across 1-2, S21 = Signal from port 2 / input to port 1

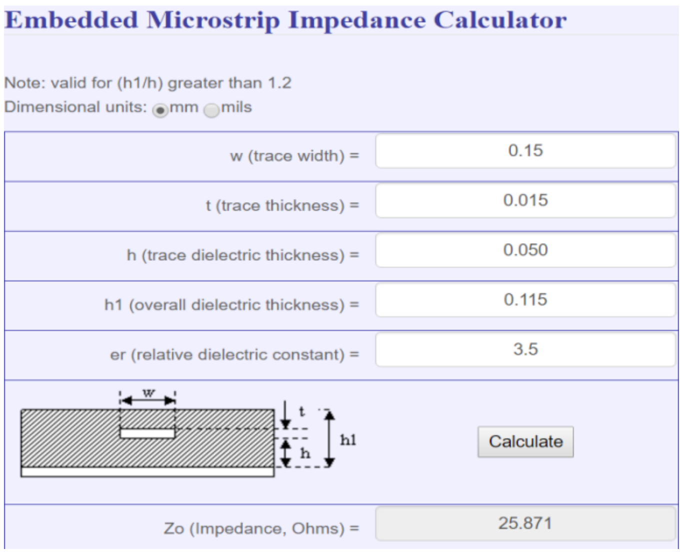
- In order to carry out s-parameters measurements a network analyser is required
- Performing a good calibration before taking a measurement is required in order to obtain accurate results
- Time Domain response can be derived from the s-parameters
- Furthermore the Device Under Test (DUT) should match the impedance of the Network analyser ports so there are no additional losses due to this fact.
- In order to achieve this sometimes adapter boards have to be designed just for this purpose

Note: BER measurements is another way of characterizing transmission lines, however as the transmitter and receiver were not available at this stage, they are not discussed in this presentation

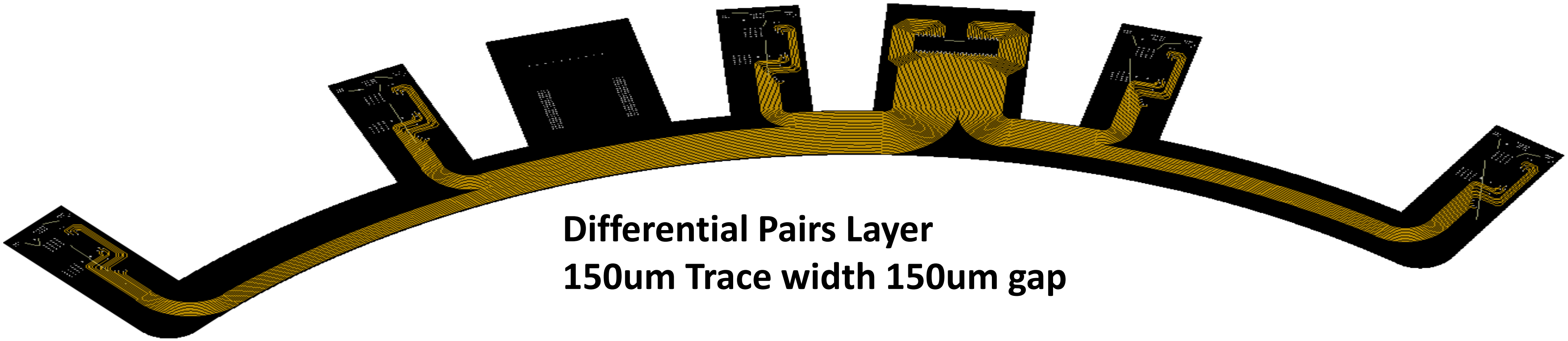
EXAMPLE : FIRST VERSION OF ATLAS RING TAPE

- Basically a curved bus tape
- All data ends at "End of Stave" (EoS)
  - Where a GBTx collects the data
- The design is not optimized for high speed data because when it was designed there was no requirements of high data rates (a few Mbps) and now it should work at 5 Gbps
- The designed trace width and material choices do not result in the desired 100 ohm impedance

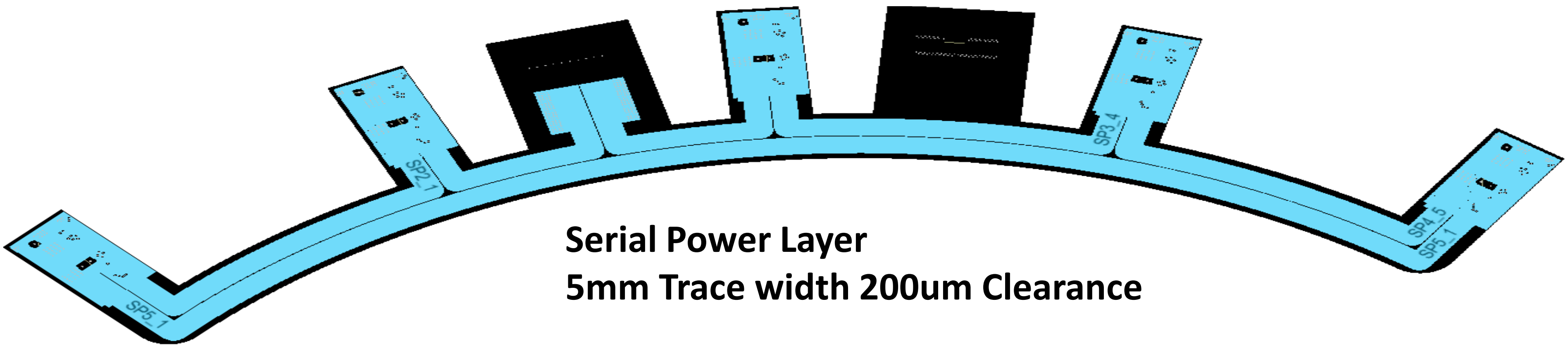




ATLAS RING TAPE V1



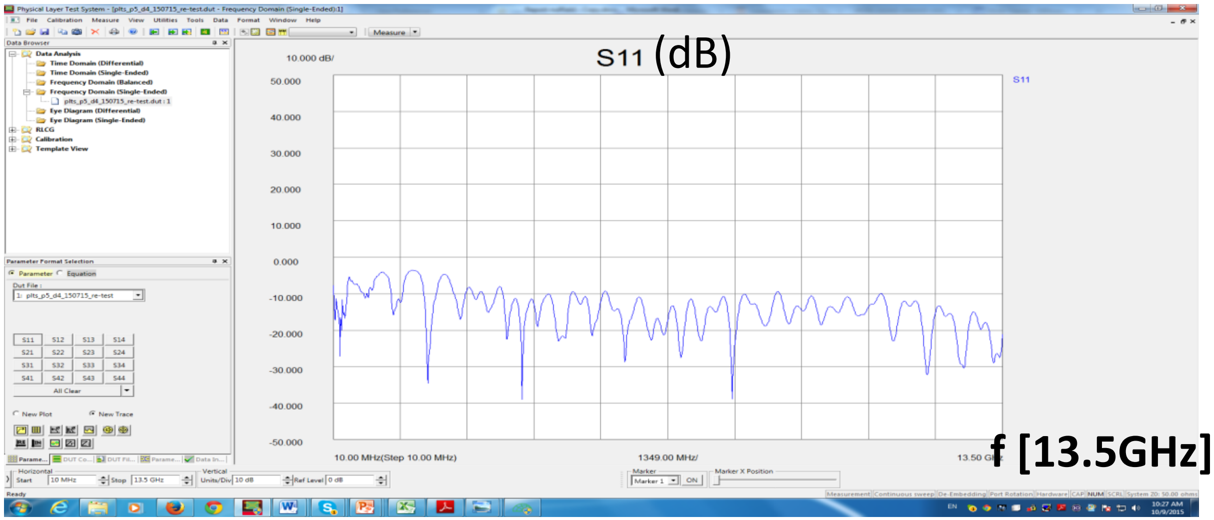
Differential Pairs Layer
150um Trace width 150um gap

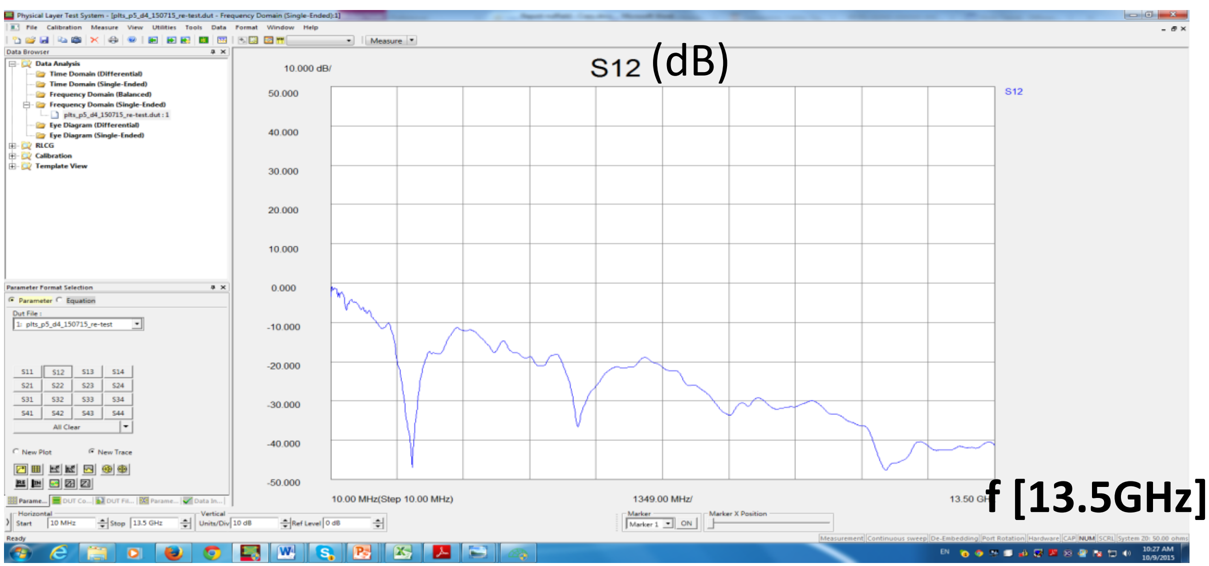


Serial Power Layer
5mm Trace width 200um Clearance

- Data crosses several planes, LVDS traces don’t have a continuous reference
- Results improve by adding copper on top →Having a homogeneous reference

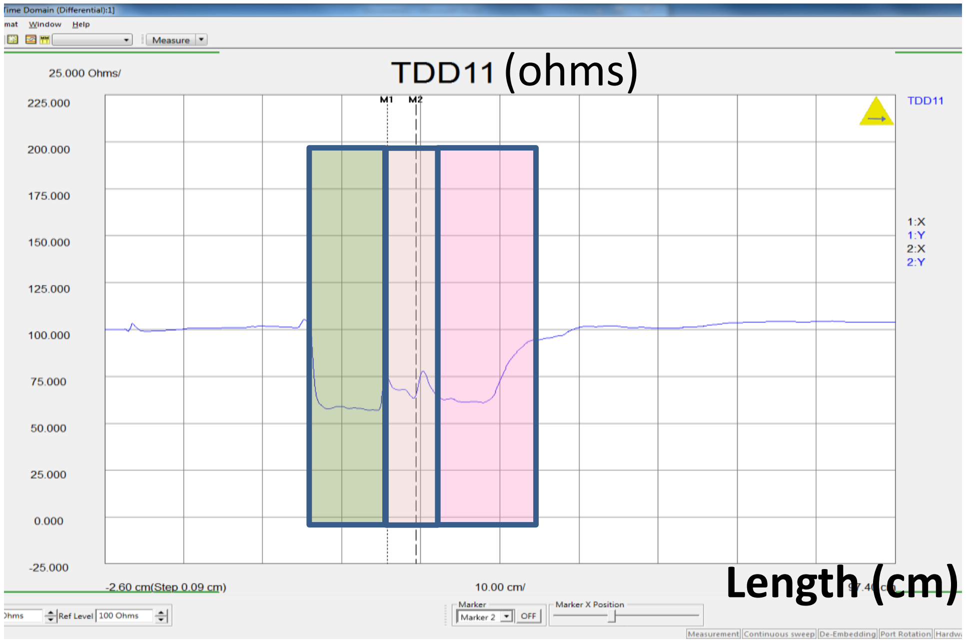
TRANSMISSION AND REFLECTION





- The reflection remains more or less constant at around -10 dB
- The impedance is not matched so the reflection is very high
- The transmission has peaks where signal is almost completely attenuated
- These peaks are due to the lack of a continuous plane
- At 3 Gbps the attenuation is -35 dB

TIME DOMAIN ANALYSIS



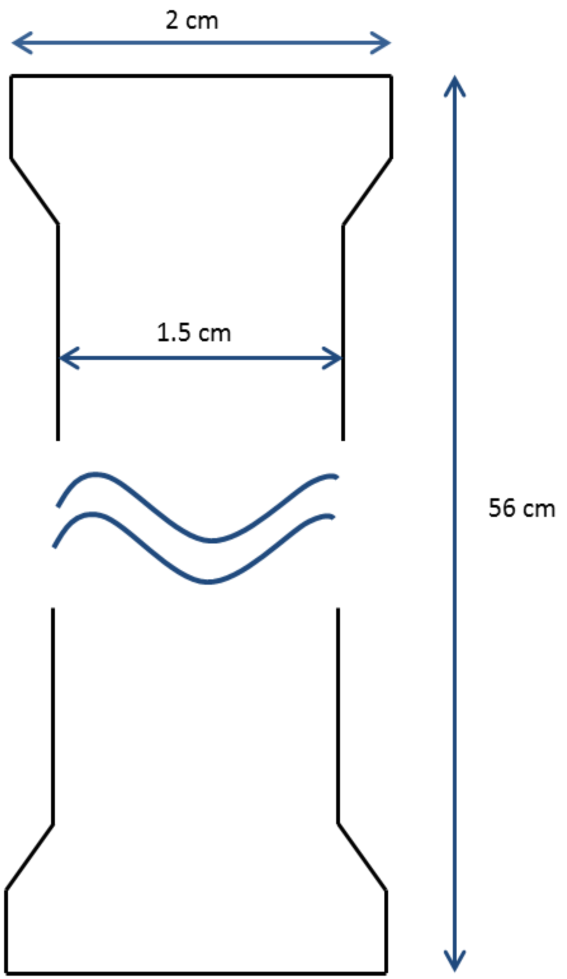
Three regions can be distinguished

- **Green**: It represents the adaptor board. It has an impedance of 60 ohms
- **Orange**: It corresponds to the tape, 70 ohms impedance
- **Pink**: It represents the other PCB, from where the signal is measured, 60 ohms impedance.

CONCLUSSIONS

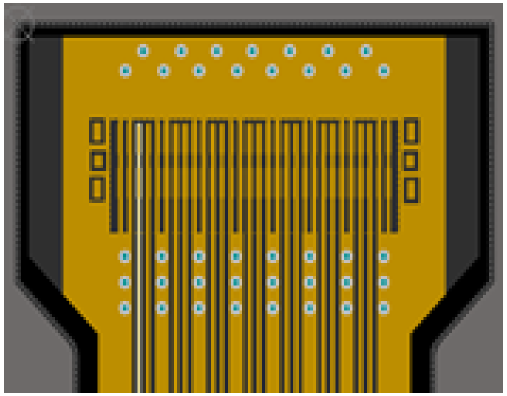
- Design not valid to use it for data transmission → Data will be taken straight from the modules via cables (see example 3) to the opto-box (off detector electronics)
- The tape will be used for HV, DCS lines, clock and command
- Really high reflections and transmission losses
- Impedance mismatched

EXAMPLE: LHCb TAPE

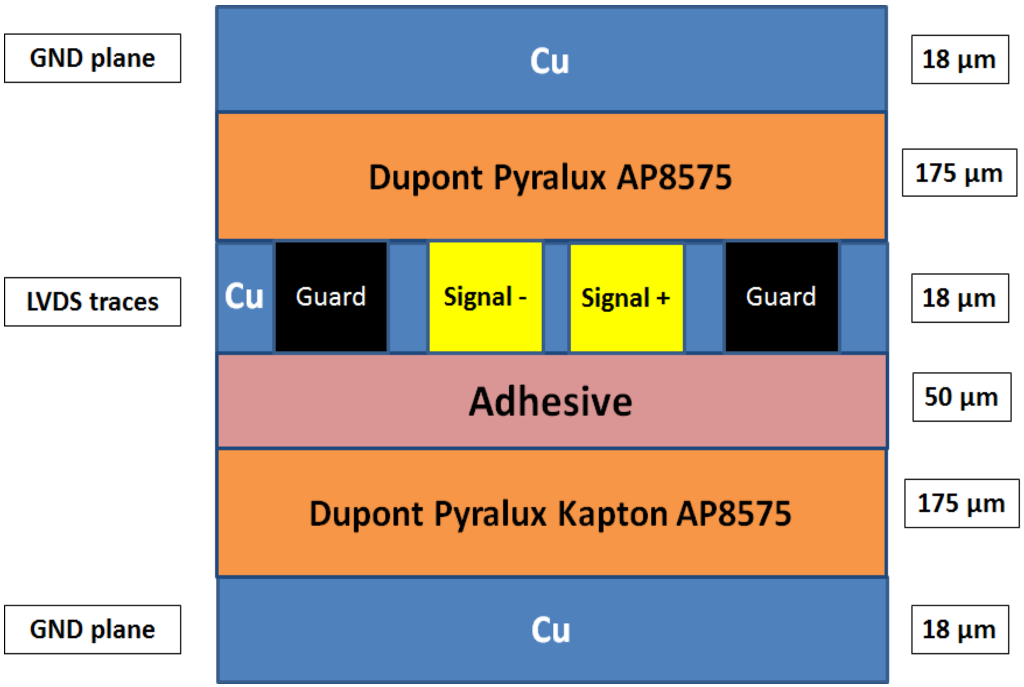


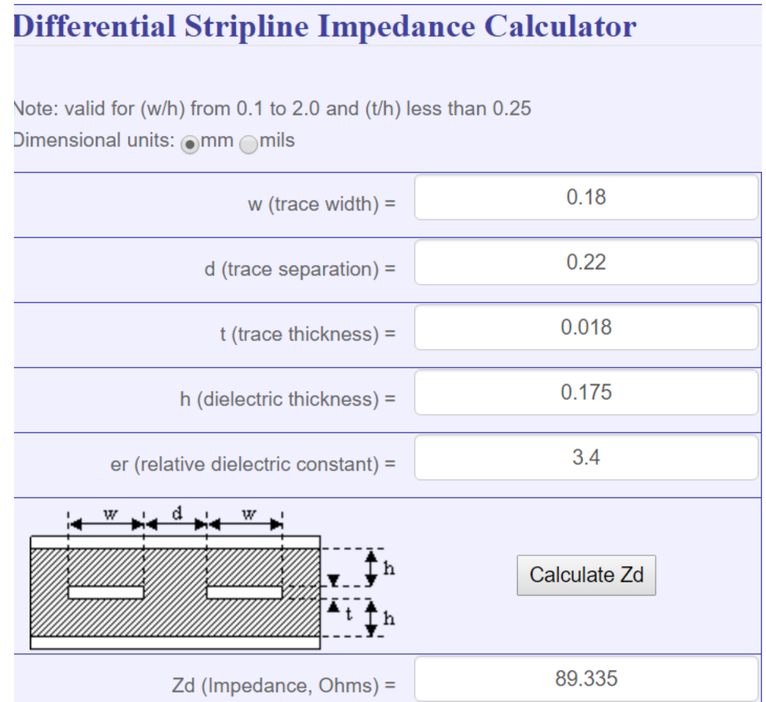
Hybrid tape dimensions

- Design criteria: 5 Gbps data rates and mechanical flexibility
- Carries data from Velo to vacuum interface
- 0.2 mm trace width and spacing
- 100 ohms differential impedance
- Signal Integrity
  - Traces embedded in between two ground planes
  - Every LVDS pair is separated by a ground trace on the signal layers
  - Connectors sitting in the signal layer (Layer 2)
  - No vias required to lay the differential pairs
  - Stitching vias help in tightly coupling the 3 ground planes and provide short return path



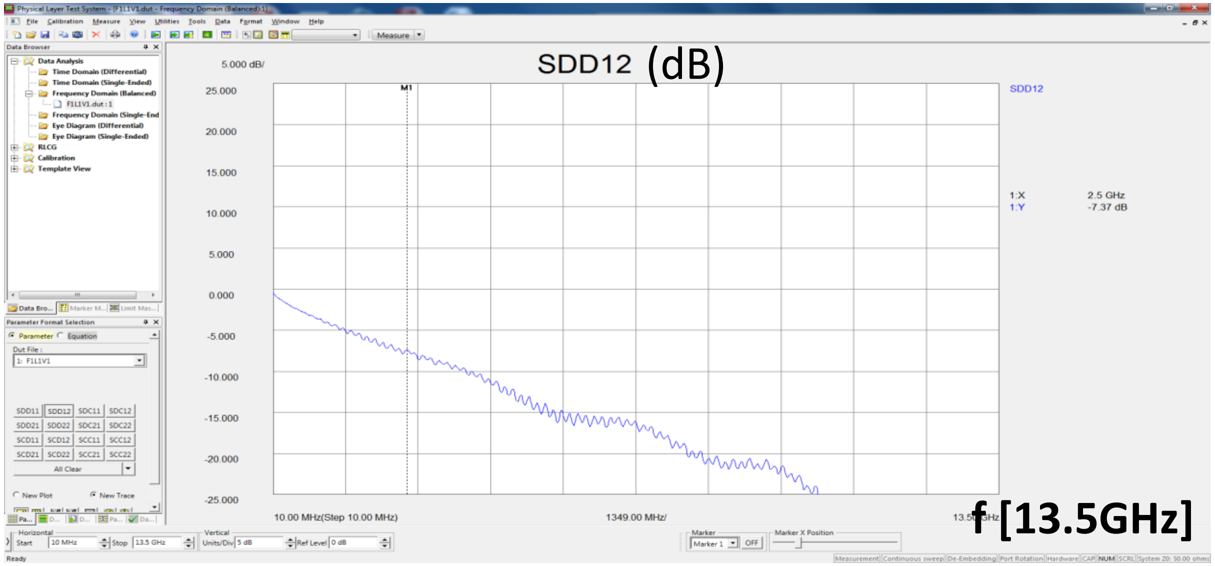
LAYER STACK

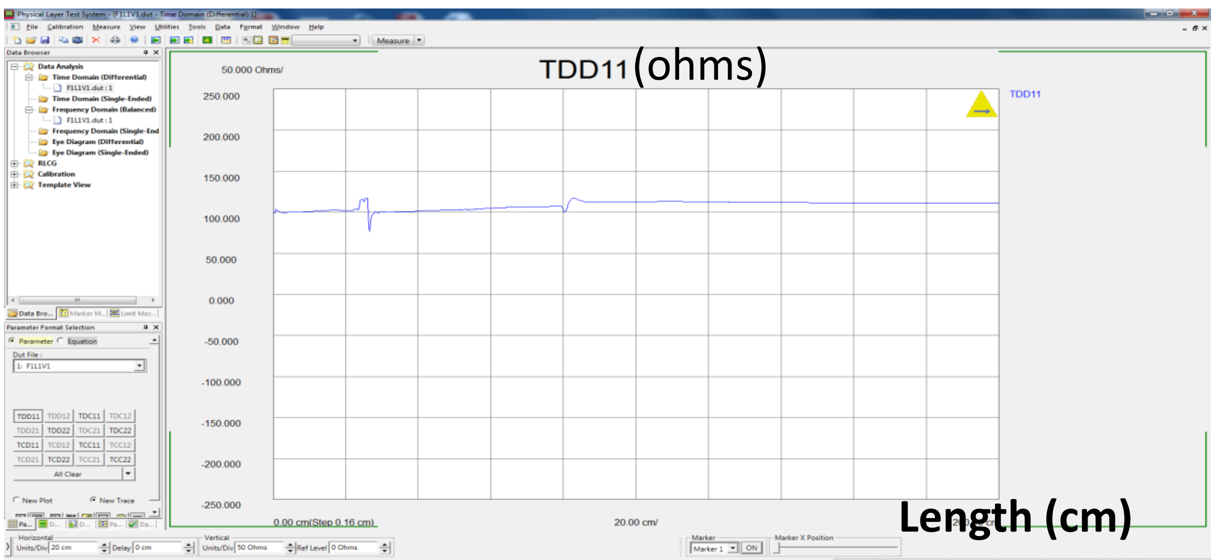




- Dielectric Material: Dupont Pyralux AP8575
  - It has a low loss tangent → Minimizes the dielectric losses
  - It has smoother copper → Minimizes skin effect loss
- Impedance is 90 ohms and not 100 ohms because the adhesive cannot be considered in the online calculators

TRANSMISSION & TIME DOMAIN





TRANSMISSION S21

- Smooth transmission curve
- The loss at Nyquist frequency of 2.5 GHz is -7.37 dB

TIME DOMAIN ANALYSIS

- The impedance is almost constant over the length of the tape
- The bumps at the start and end correspond to the connectors

CONCLUSSION

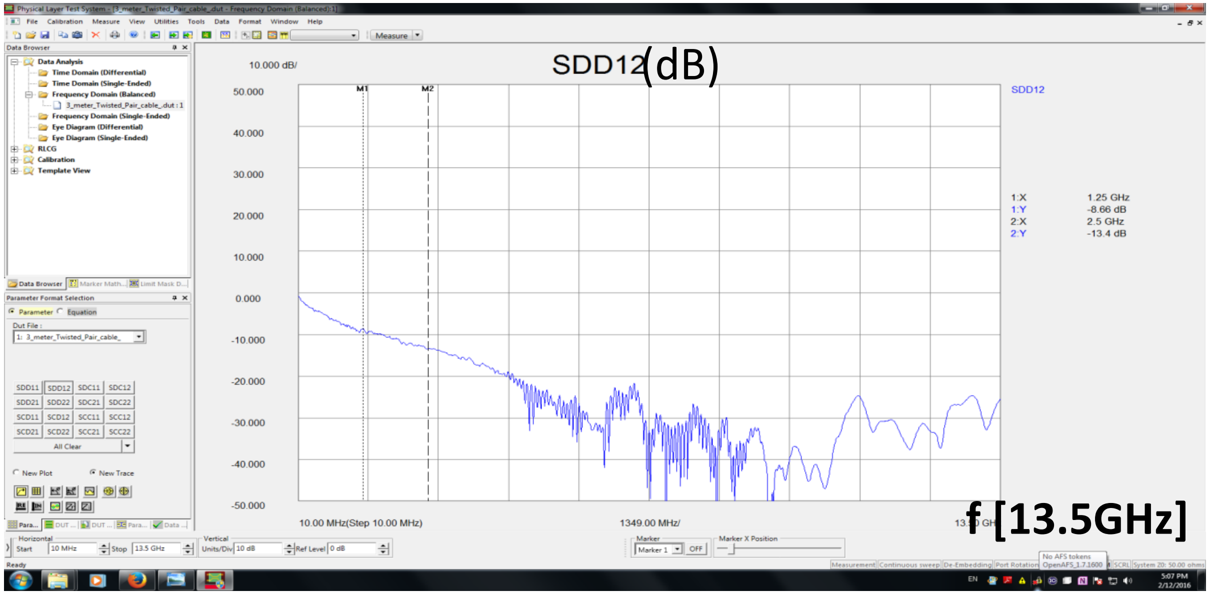
- Low transmission losses achieved
- Very good impedance match

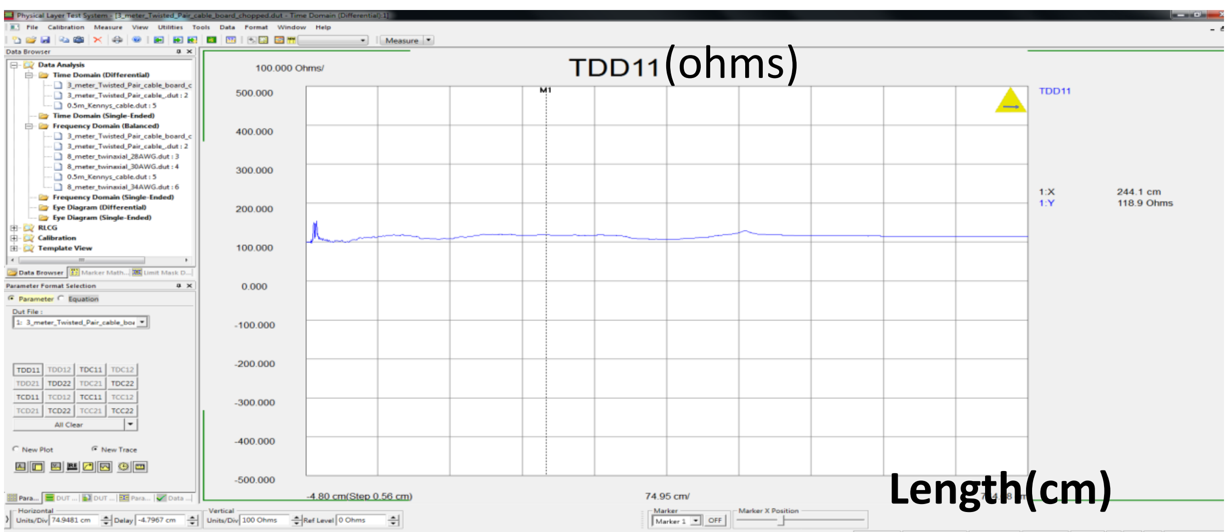
EXAMPLE: ATLAS 36 AWG TWISTED PAIR

- Cable required to take data from the module to the optobox at 2.5-5 Gbps
- Custom made cable with 36 AWG (American Wire Gauge) ≈ 0.127 mm diameter
- Multi-stranded Copper : 7 strands/ cable
- Each conductor is insulated with PEEK (colorless organic thermoplastic polymer, Poly-Ether-Ether-Ketone)

    - Different thicknesses has been measured for this insulator
        - 390 μm for "transparent" PEEK
        - 307 μm for "blue" PEEK
- Both conductors are shielded with 10 μm aluminium foil
- Backed with kapton insulator, 25um thick
- 100 ohm differential impedance

TRANSMISSION AND REFLECTION





Results for 3m twisted pair

TRANSMISSION S21

- 8.66 dB of attenuation at 1.25 GHz (2.5 Gbps)
- 13.4 dB of attenuation at 2.5 GHz (5 Gbps)

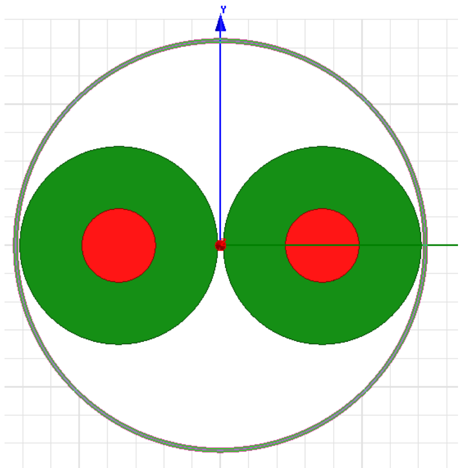
TIME DOMAIN

- Continuous impedance of 115 ohms over the cable

CONCLUSSION

- Good transmission performance of the cable
- Correct impedance match

ANSYS SIMULATIONS



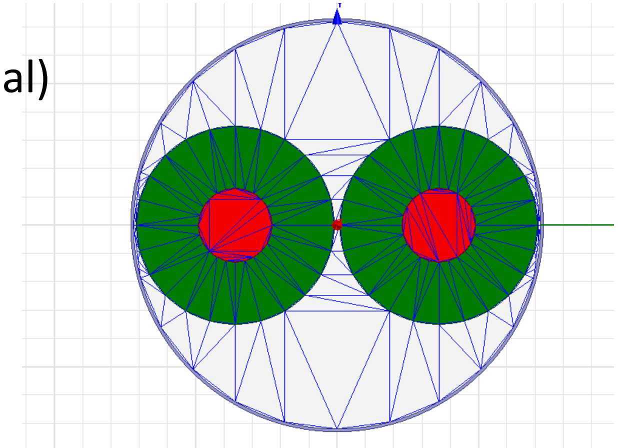
Simulation done using ANSYS Electronics Desktop

- Define 2D cross-section tape geometry & material
- Set Z_0=50Ω per port ($Z0_{diff}$=100Ω)
- 1m cable length

Simple cross-section

- Copper differential signal lines R=130μm (red)
- PEEK dielectric, Dk=3.3, LT=0.003, R=350μm (green)
- Air, Dk=1.0006, LT=0, (white)
- Aluminium reference ground R=730μm (grey)

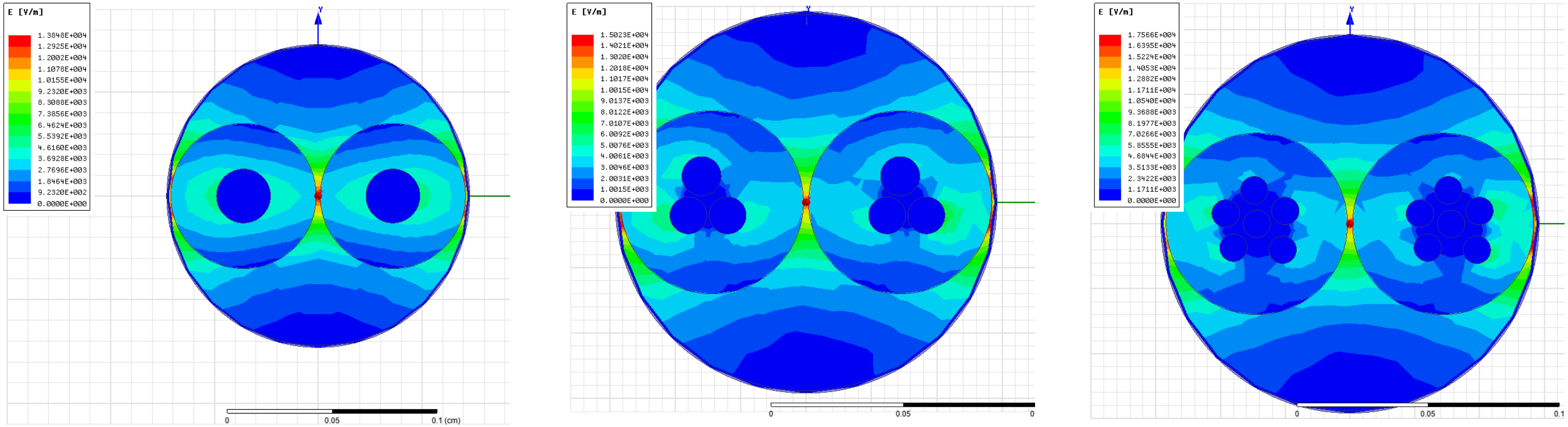
No frequency dependence in dielectric properties used (acausal)



Frequency sweep: 10MHz-10GHz, 10MHz steps

Used coarse mesh used

- quicker calculation time



At high frequencies (~1GHz) skin effects of conducting cores become important

- Charge carried on the surface of conductors

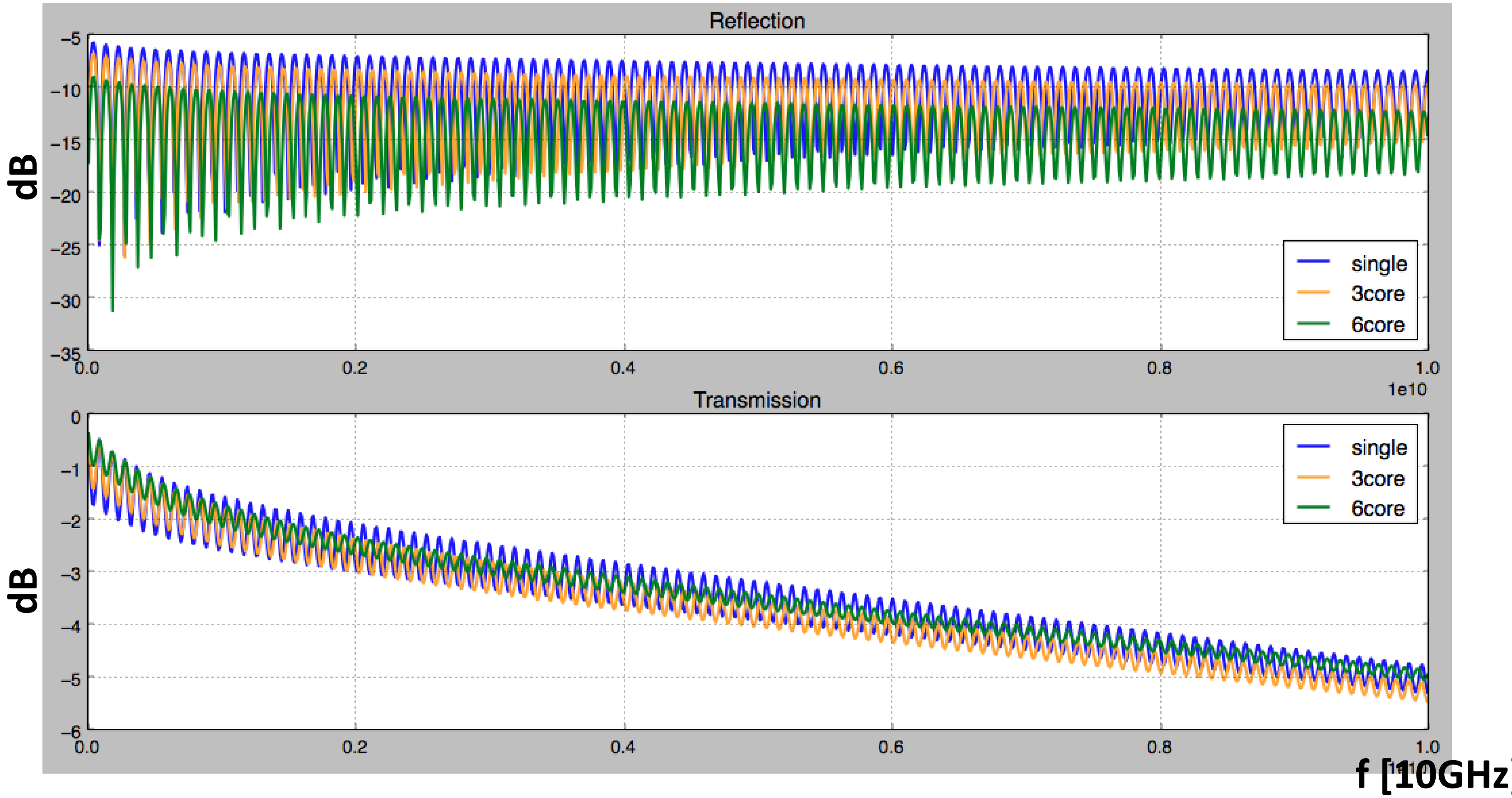
Single, three and six core E-field comparison (same conductor area)

Single core

- See attraction between differential cores, charge focusses at adjacent faces

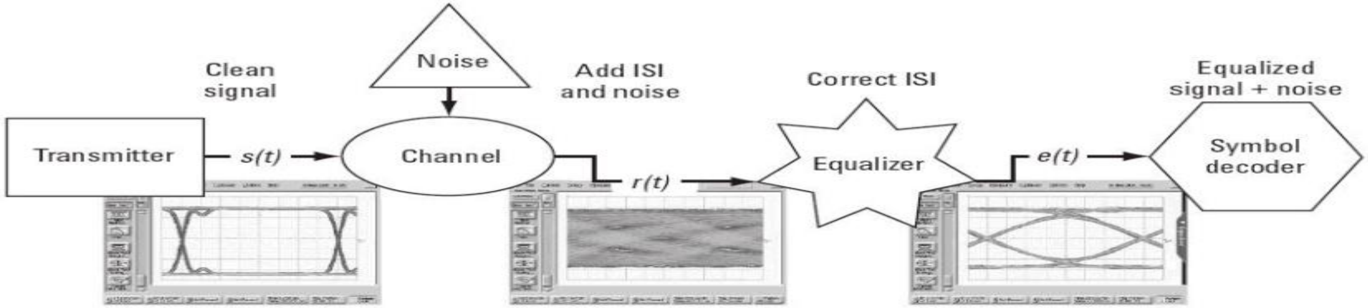
Multi-core

- Still high field from adjacent differential lines
- Low field between individual conductors, charge moves to opposite end of conductor



- Linear distributions (acausal), low transmission loss (few dB) over range
- Little comparative effect seen on reflection and transmission between core variations
- For the same cross-sectional area (→ same mass) multiple conductors per core offer a flexible alternative to single core tapes
- Transmission favoured by large conductor radius

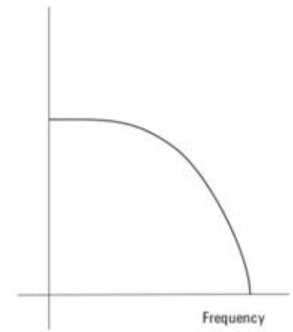
- The problem:



- Random noise cannot be corrected as it is not deterministic
- ISI or inter-symbol interference is caused by a not flat frequency response of the channel and can be corrected → Equalization
- The solution: Equalization
- Its purpose is to correct for the problems caused by the transmission channel
- Various techniques
    - Feed-Forward Equalization (FFE)
    - Continuous Time Linear Equalization (CTLE)
    - Decision Feedback Equalization (DFE)

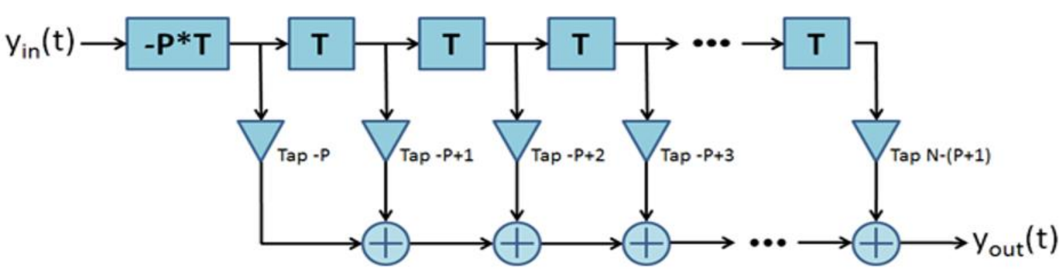
FFE

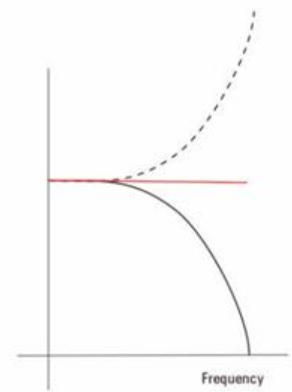
- FFE corrects the received waveform with information about the waveform itself and not information about the logical decisions made on the waveform
- It acts like a FIR (finite impulse response) filter and uses the voltage levels of the received waveform associated with previous and current bits to correct the voltage level of the current bit
- It requires a good level of signal in order to perform clock recovery before filtering
- Mathematical description of FFE (3 taps):



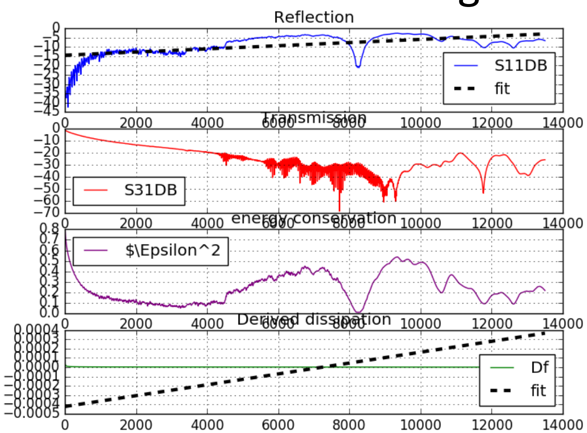
$$e(t) = c_0 r(t-0T_D) + c_1 r(t-1T_D) + c_2 r(t-2T_D)$$

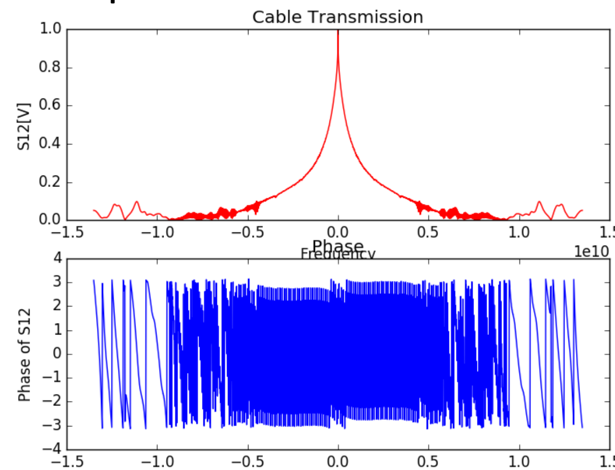
- $e(t)$ is the corrected (or equalized) voltage waveform at time t.
- T_D is the tap delay.
- $r(t-nT_D)$ is the uncorrected input waveform n tap delays before the present time.
- c_n is the correction coefficient (tap) multiplied with the version of the uncorrected waveform that has been time-advanced by n tap delays.

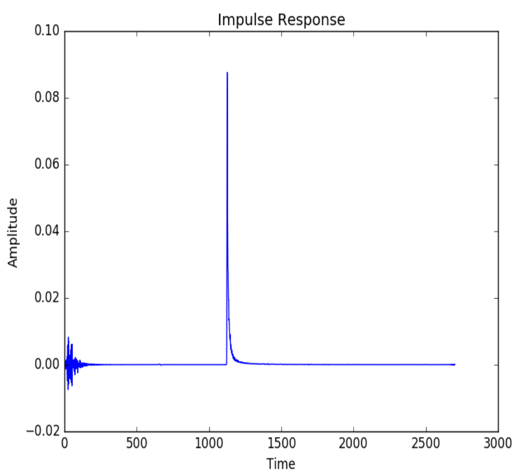


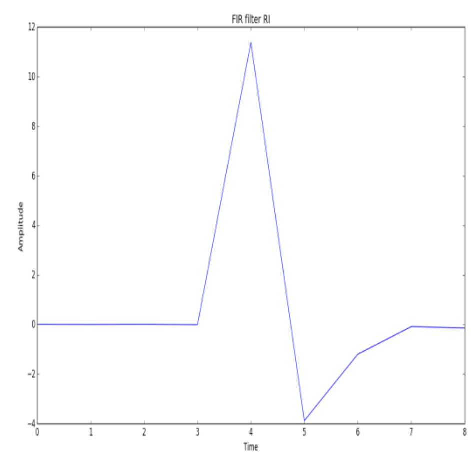


- A python script that calculates the impulse response and the tap coefficients of the FIR filter has been coded.
  - Based in: The algorithm for FIR corrections of the VELO analogue links and its performance



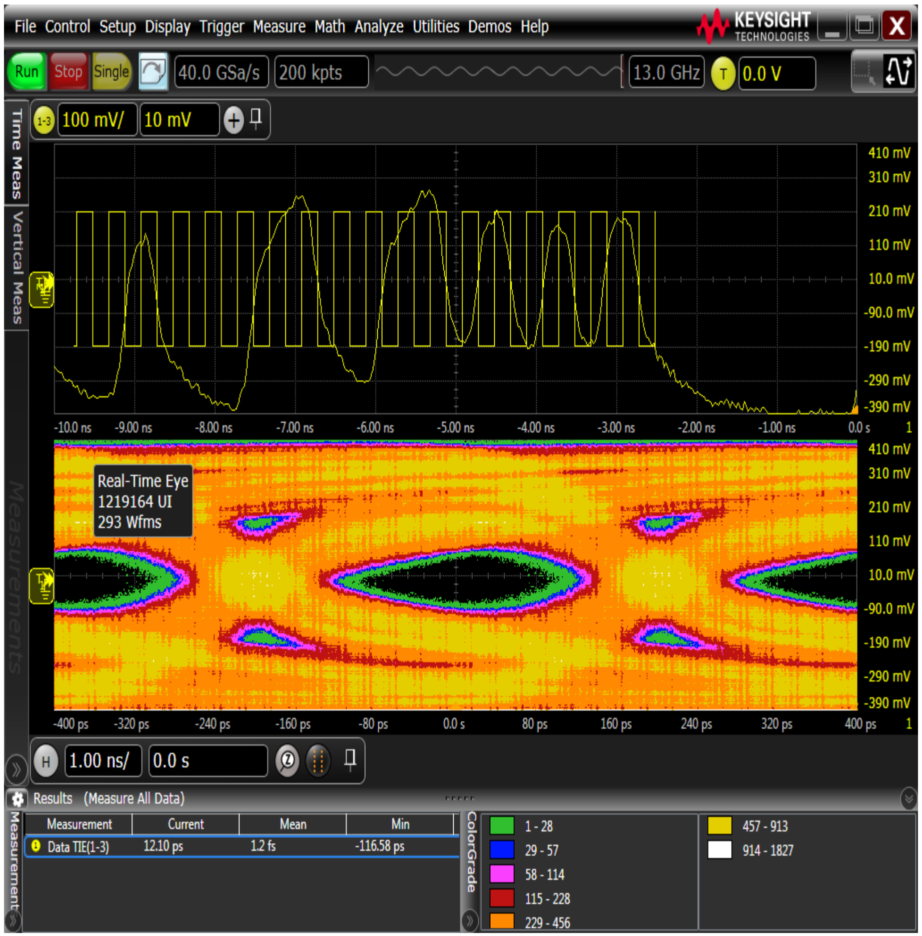


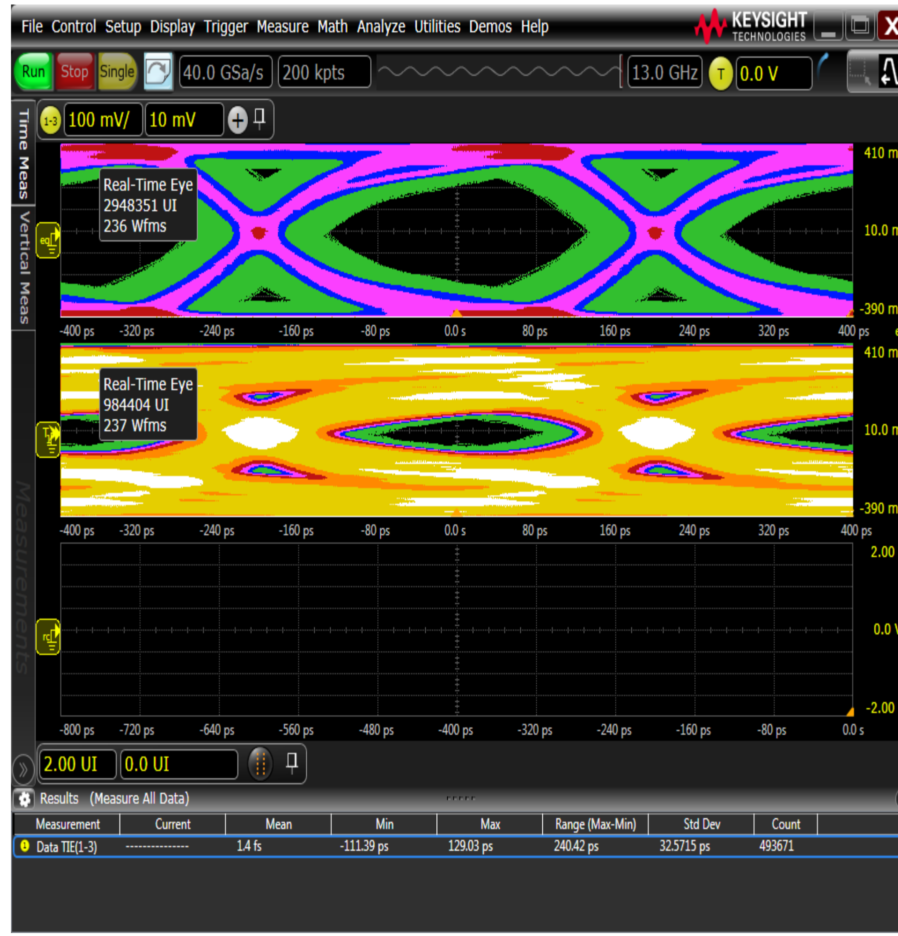




MEASURED DATA RESULTS FOR ATLAS CABLE

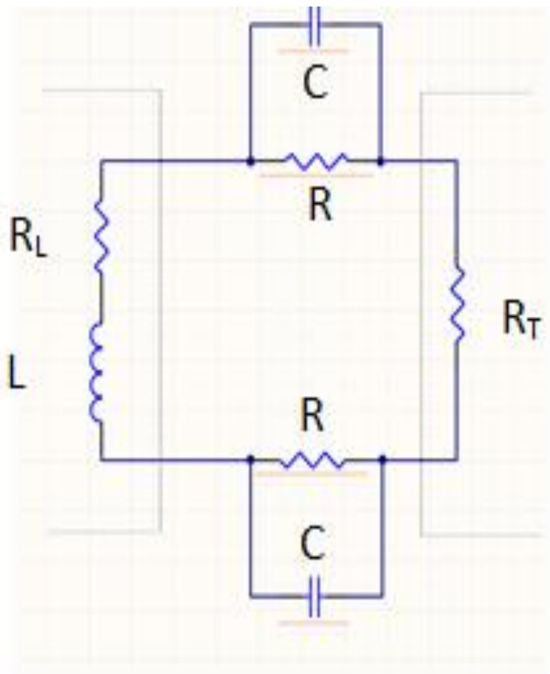
- 3 meters twisted pair cable with 2.5 Gbps data





PASSIVE CTLE

- Normally uses an amplifier but due to design constrains we are investigating in using a purely passive CTLE



R_T: Input impedance of GBLD
R, C: CTLE components to be optimised
L-R_L at the input to compensate for Z_{in} and so it $Z_{in} = R_T$

Transfer function

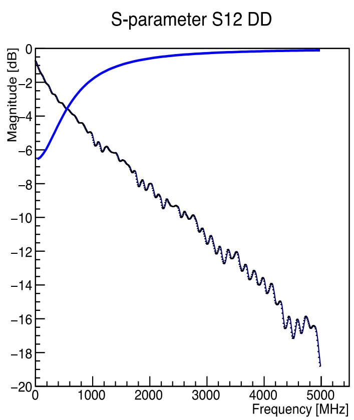
$$H(j\omega, R, C) = \frac{1 + j\omega RC}{1 + \frac{2R}{R_T} + j\omega RC}$$

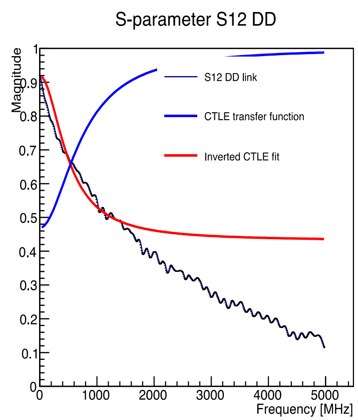
Input Impedance

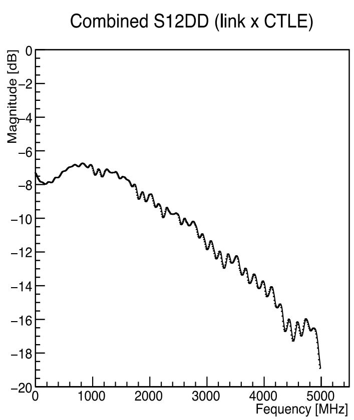
$$Z_{in} = R_T \;\; \forall \;\; \omega$$

MEASURED DATA RESULTS FOR LHCb LINK

- LHCb link: Hybrid + tape + vacuum feed-through with data at 5.12 Gbps







Fit from 10 to 1750 MHz

R_T = 100 Ω

R = 56.6 Ω

C = 42.8 pF

R_L = 188.3 Ω

L = 214.2 nH

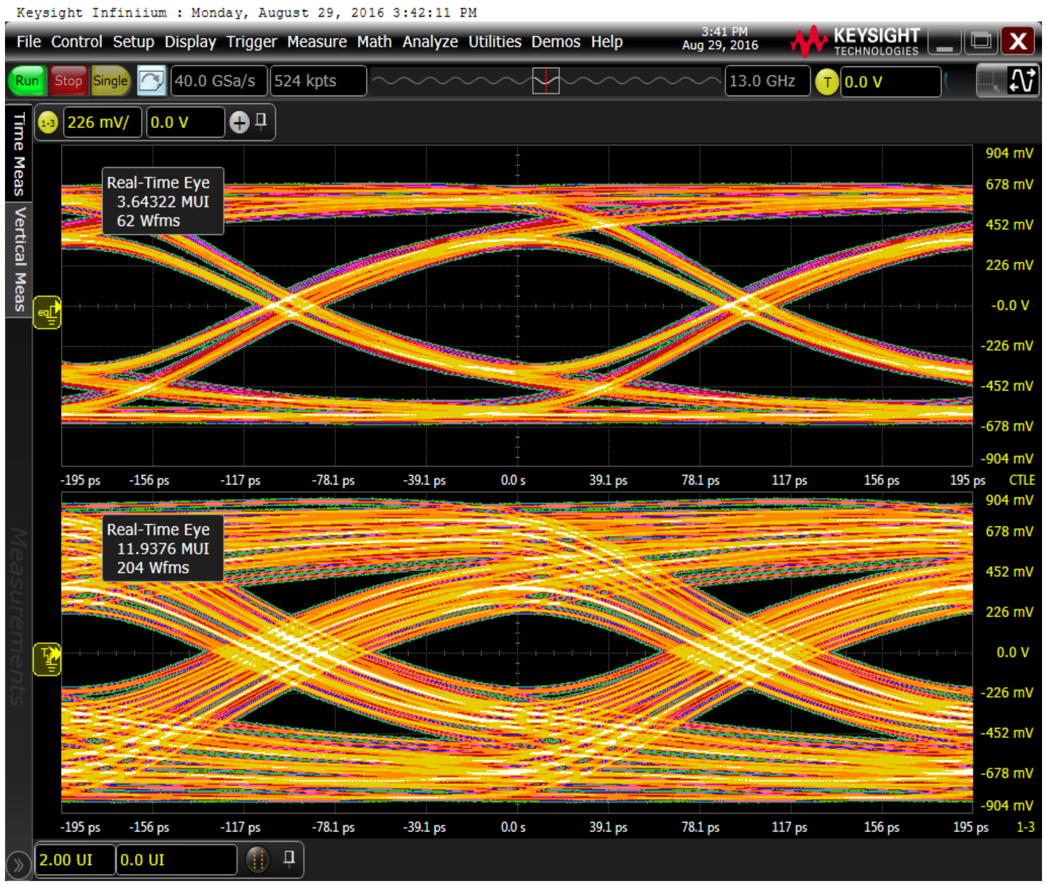
DC Gain A_{DC} = 0.469

Zero f_z = 65.6 MHz

Pole f_p = 139.9 MHz

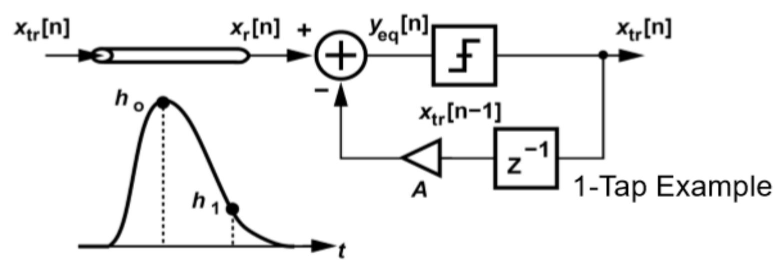
S12DD (link x ctle) @ 10 MHz = -7.3 dB

S12DD (link x ctle) @ 2.5 GHz = -9.8 dB



DFE

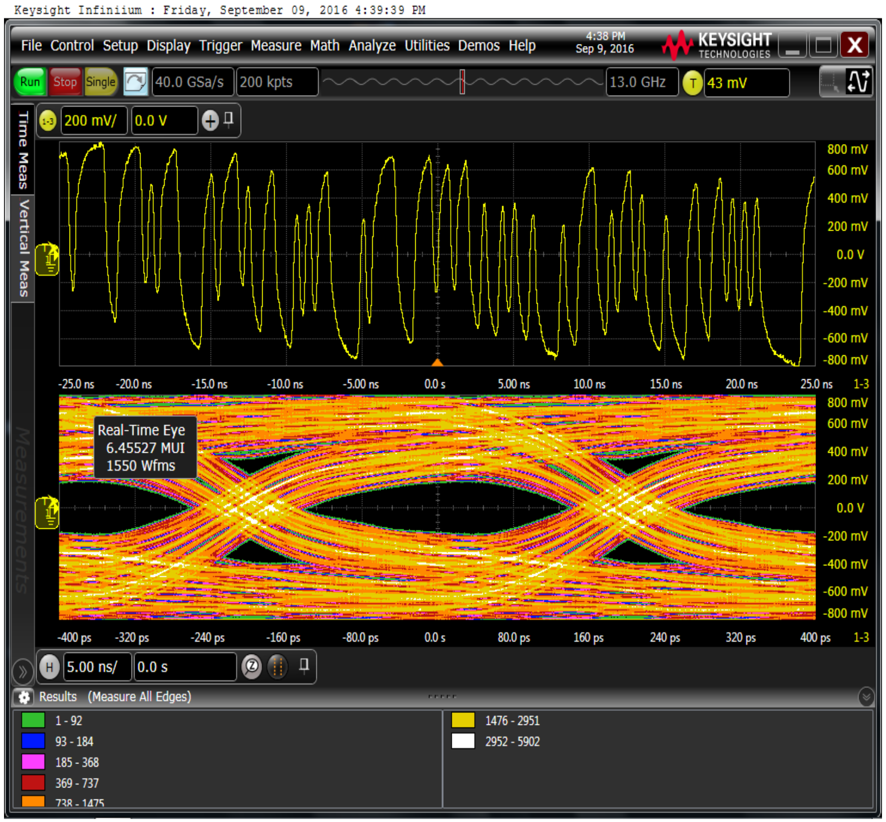
- It is a non-linear equalizer. A slicer makes a symbol decision
- The ISI is then directly subtracted from the incoming signal via a feedback FIR filter.
- If only DFE equalization, DFE tap coefficients should equal the unequalized channel pulse response values [a1 a2 … an].
- With other equalization, DFE tap coefficients should equal the preDFE pulse response values

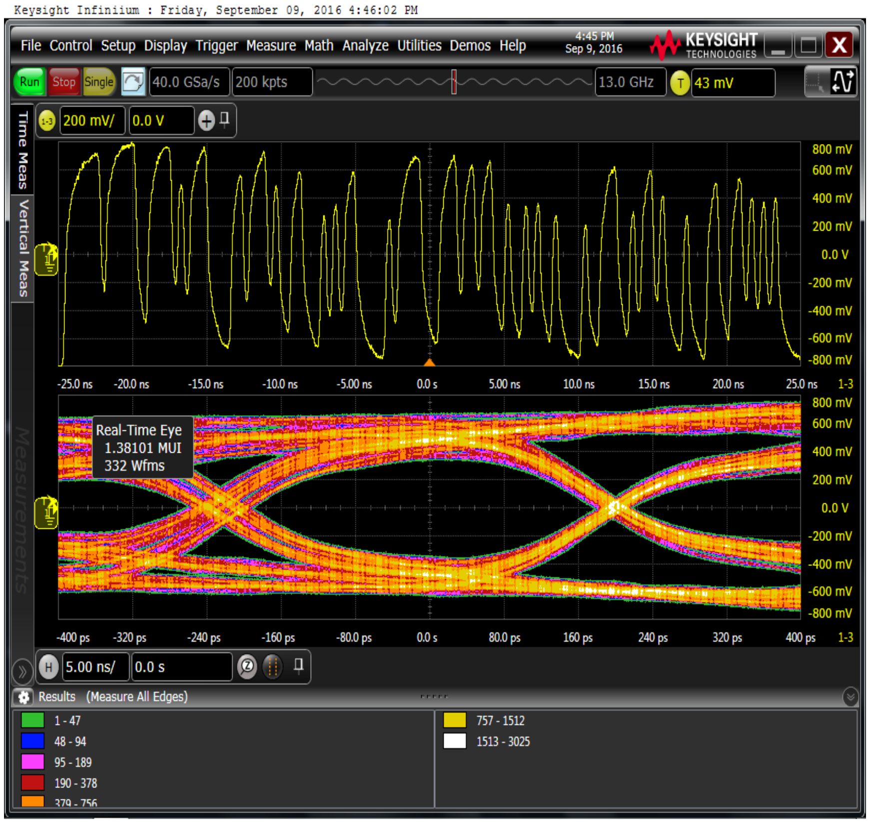


$$
\begin{aligned}
x_r[n] &= h_o x_{tr}[n] + h_1 x_{tr}[n-1] \\
y_{eq}[n] &= x_r[n] - A x_{tr}[n-1] \\
&= h_o x_{tr}[n] + h_1 x_{tr}[n-1] - A x_{tr}[n-1]
\end{aligned}
$$

MEASURED DATA FOR ATLAS TWISTED PAIR

- 3 meters twisted pair cable with 2.5 Gbps data





CONCLUSION

- Transmission lines at high speed require a very careful design
  - Parameters to consider while designing a transmission line:
    - Material choice → In order to avoid skin effect and dielectric losses as well as matching the impedance
    - Geometry of the design → PCBs (stripline, microstrip etc.) or cable
    - Recovering performance → Equalization techniques
- In order to be able to fully characterize a transmission line in the measurements should be included the whole chain: transmitter + channel (tapes and cables) + receiver
- Reducing the number of connectors improves the signal quality as there are less reflections due to impedance mismatches
- Very difficult to design a transmission line with low material requirements (High Energy Physics experiments)
- Final tests will be BER measurements with transmitter and receivers will be performed

THANK YOU

BACK-UP

- The best way of characterising transmission lines working at high frequencies is with the s-parameters
- The scattering matrix is a mathematical construct that quantifies how RF energy propagates through a multi-port network
  - For an RF signal incident on one port, some fraction of that signal gets reflected back out of the incident port, some of it enters *into* the incident port and then exits at (or *scatters* to) some or all of the other ports
- S-parameters are usually displayed in a matrix format, with the number of rows and columns equal to the number of ports
- S_{ij} the j subscript stands for the port that is excited (the input port), and the "i" subscript is for the output port.

- S_{11} refers to the ratio of the amplitude of the signal that reflects from port one to the amplitude of the signal incident on port one

2 Port

$$\begin{vmatrix} S11 & S12 \\ S21 & S22 \end{vmatrix}$$

3 Port

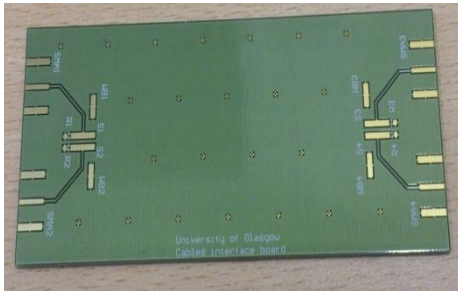
$$\begin{vmatrix} S11 & S12 & S13 \\ S21 & S22 & S23 \\ S31 & S32 & S33 \end{vmatrix}$$

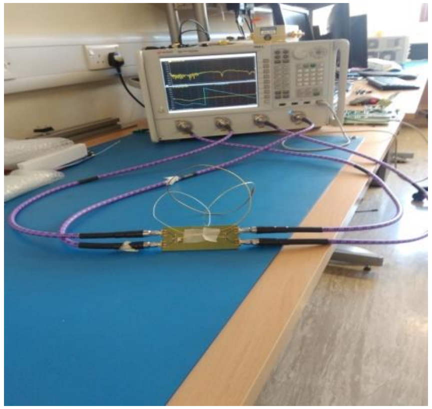
4 Port

$$\begin{vmatrix} S11 & S12 & S13 & S14 \\ S21 & S22 & S23 & S24 \\ S31 & S32 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{vmatrix}$$

S-parameter Matrix of 2, 3 and 4 Port

- An interface board was designed to test the cable:
  - 2 layers: Cover with ground planes
  - Stitching vias
  - 4 SMA connectors
  - Matching impedance pads for resistors (if necessary)
  - Wire-bonding pads to connect the shield
  - 100 ohms differential impedance traces

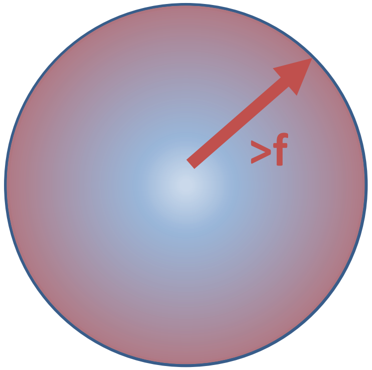




SIMULATIONS

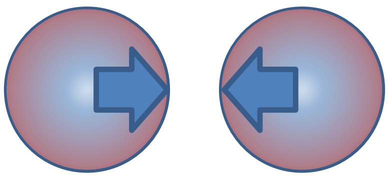
At high frequencies (~1GHz) skin effects of conducting cores become important

- Charge carried on the surface of conductors



For **single** core devices charge distributed **evenly** over cross-sectional surface

For **differential** pairs there is **attraction** between cores which disrupts charge distribution

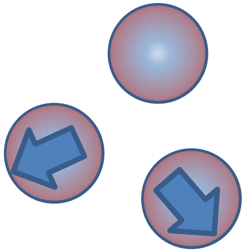


differential

For **multi-core** case there is **repulsion** between individual conductor elements

LHCb and ATLAS tapes use differential signaling

- Increased cable flexibility
- multi-core effect will convolute charge distribution

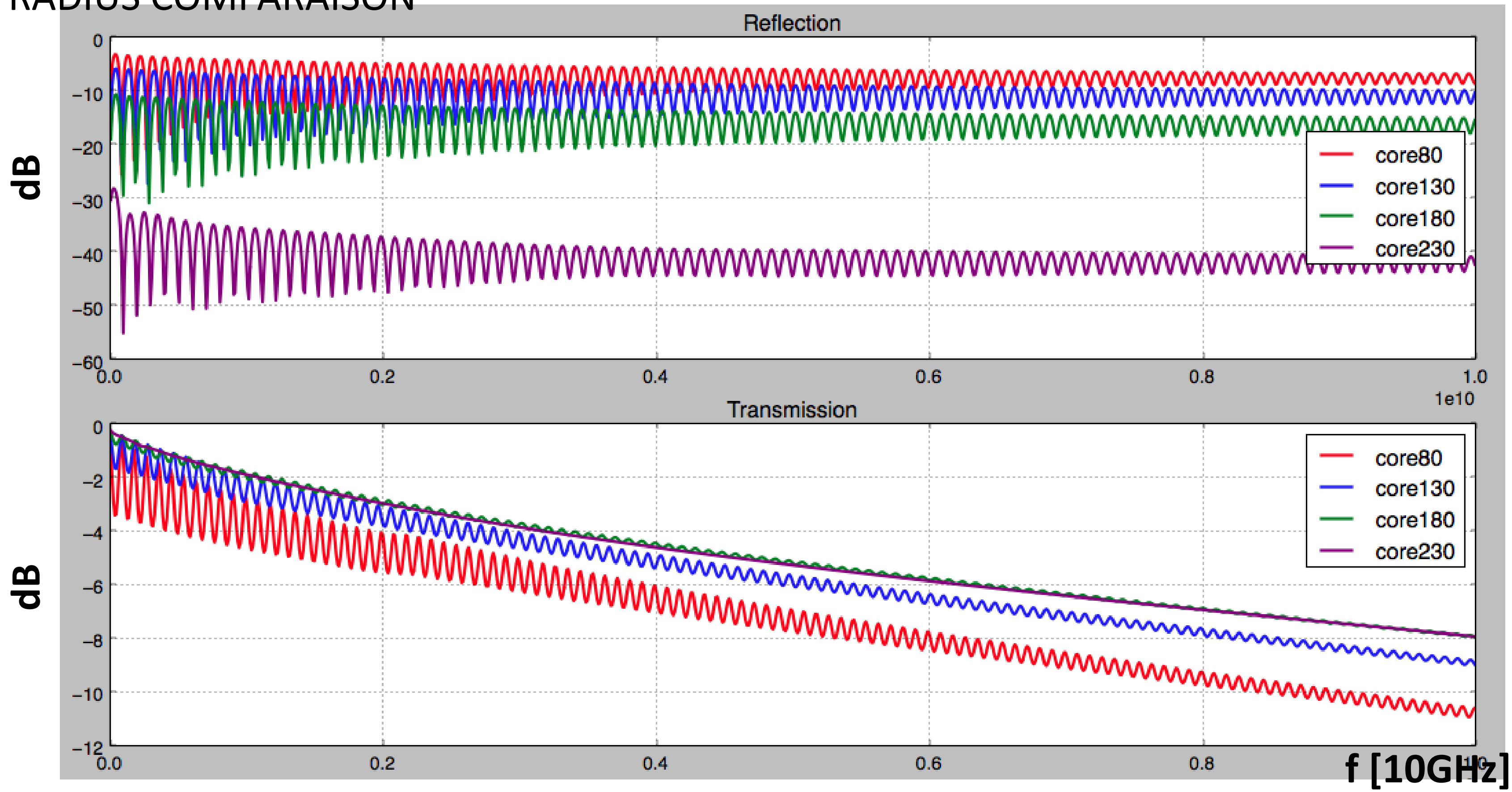


multiple

Here we compare

- Single core, 3 cores & 6 cores per differential line

DIFFERENT CONDUCTOR RADIUS COMPARAISON



Larger radius gives better transmission

- More divergence seen at higher frequencies → skin effect
- Seems to be saturation R > 180µm

Only conductor radius changed so geometry not adapted to Z0 → reflections

FFE VISUAL EXPLANATION