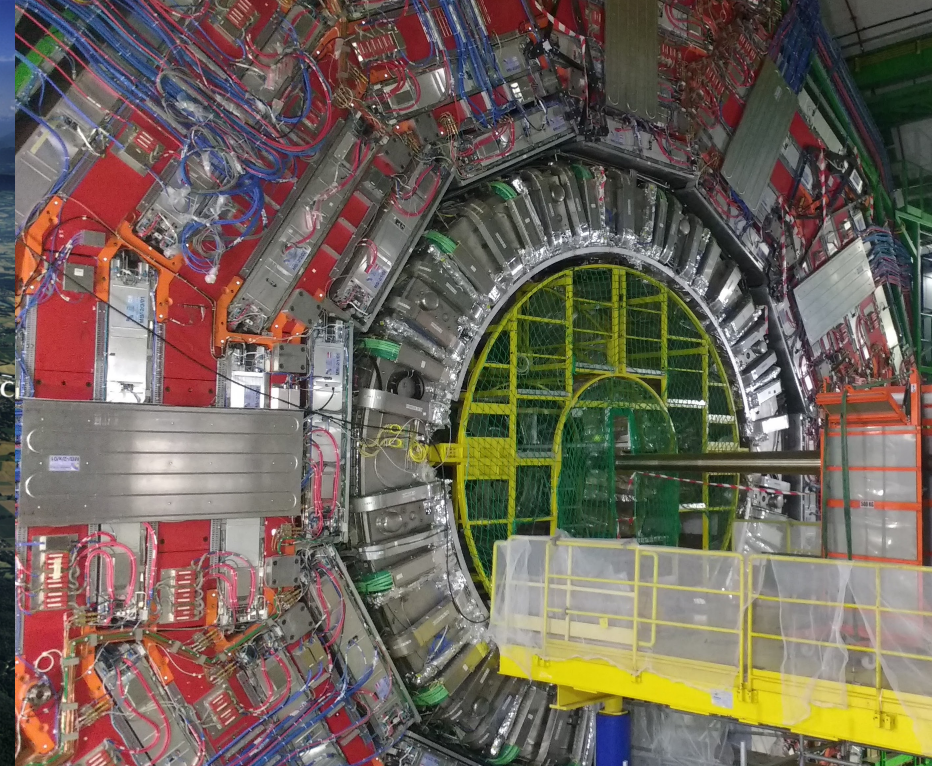


Building a new pixel detector for the CMS experiment at the High Luminosity LHC

Devdatta Majumder

THE UNIVERSITY OF KANSAS

CMS Compact Muon Solenoid

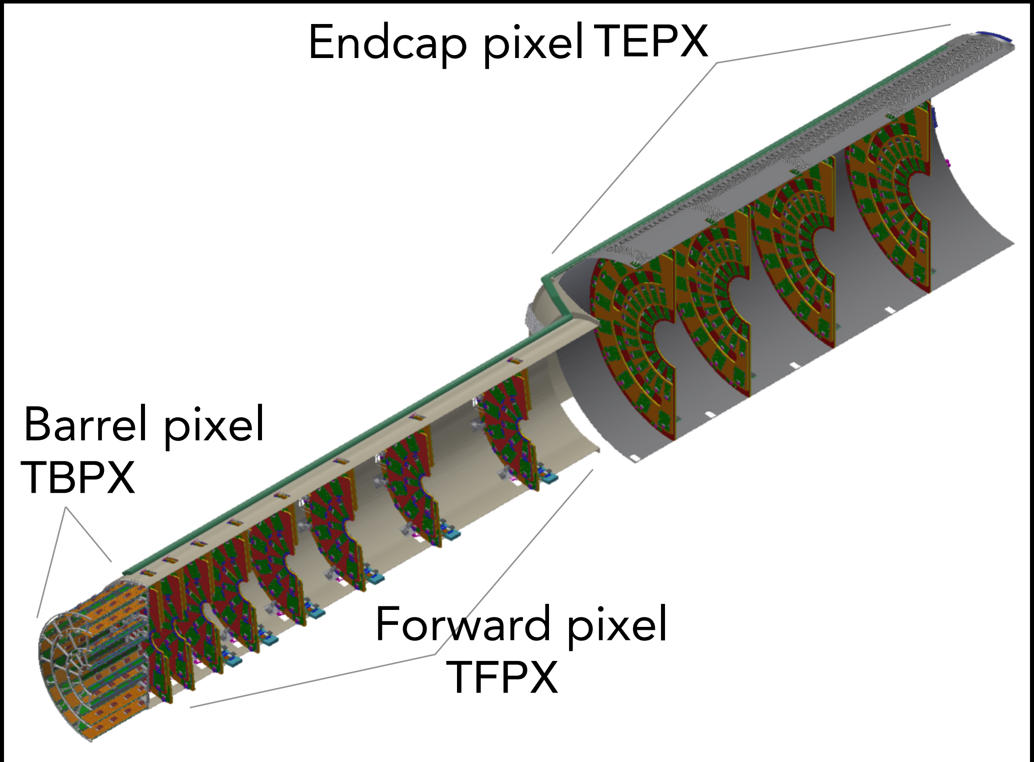
IRB, Zagreb
07 May 2019

The Phase 2 pixel detector

- The HL-LHC poses a challenging environment
  - A factor of 5–7 increase in instantaneous luminosity. Pileup up to 200
  - ~10000 particle tracks per event.
- The new pixel detector:
  - Should be radiation tolerant
  - Have higher granularity and low occupancy
  - Larger fiducial volume: better coverage for physics analysis
- Todays talk:
  - Mainly covering the electronics system
  - Readout: E-links and the performance of the pixel detector prototype chip.

Inner tracker layout

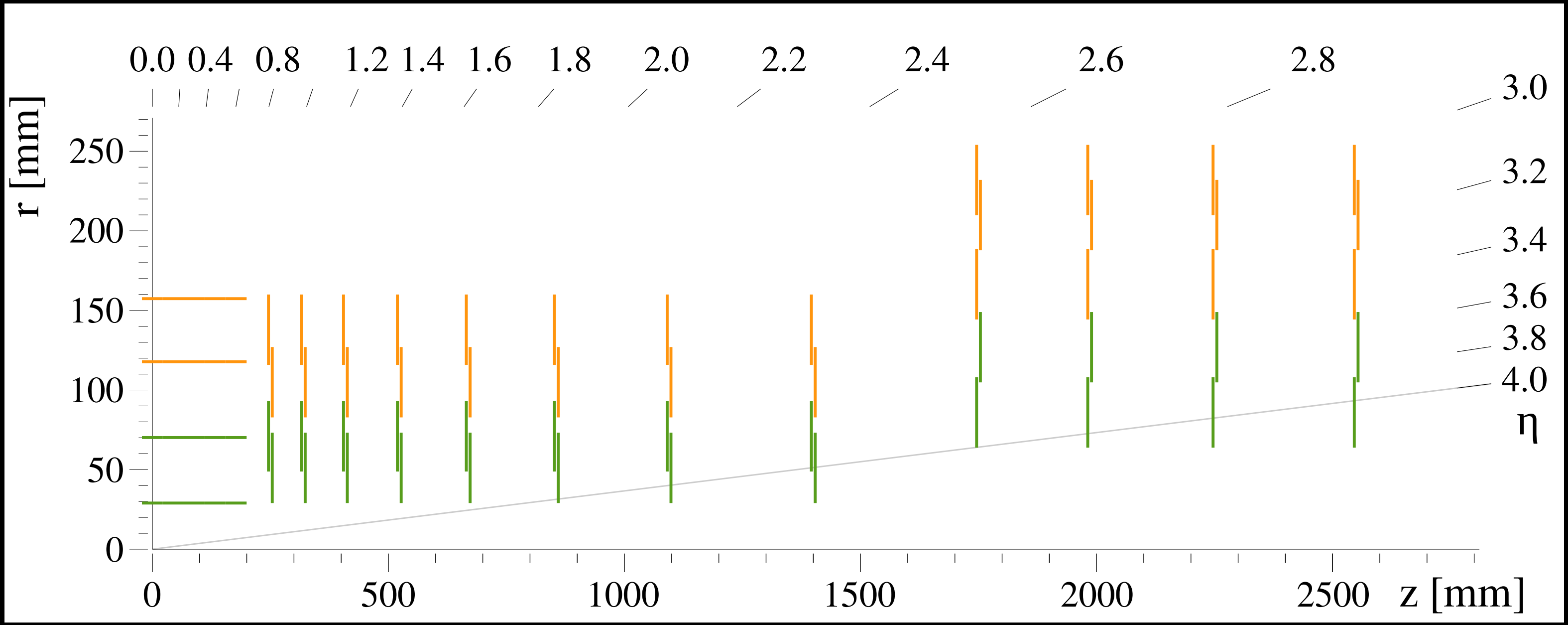
CMS-TDR-014



- One-quarter of the CMS pixel detector layout.

The Phase 2 pixel detector

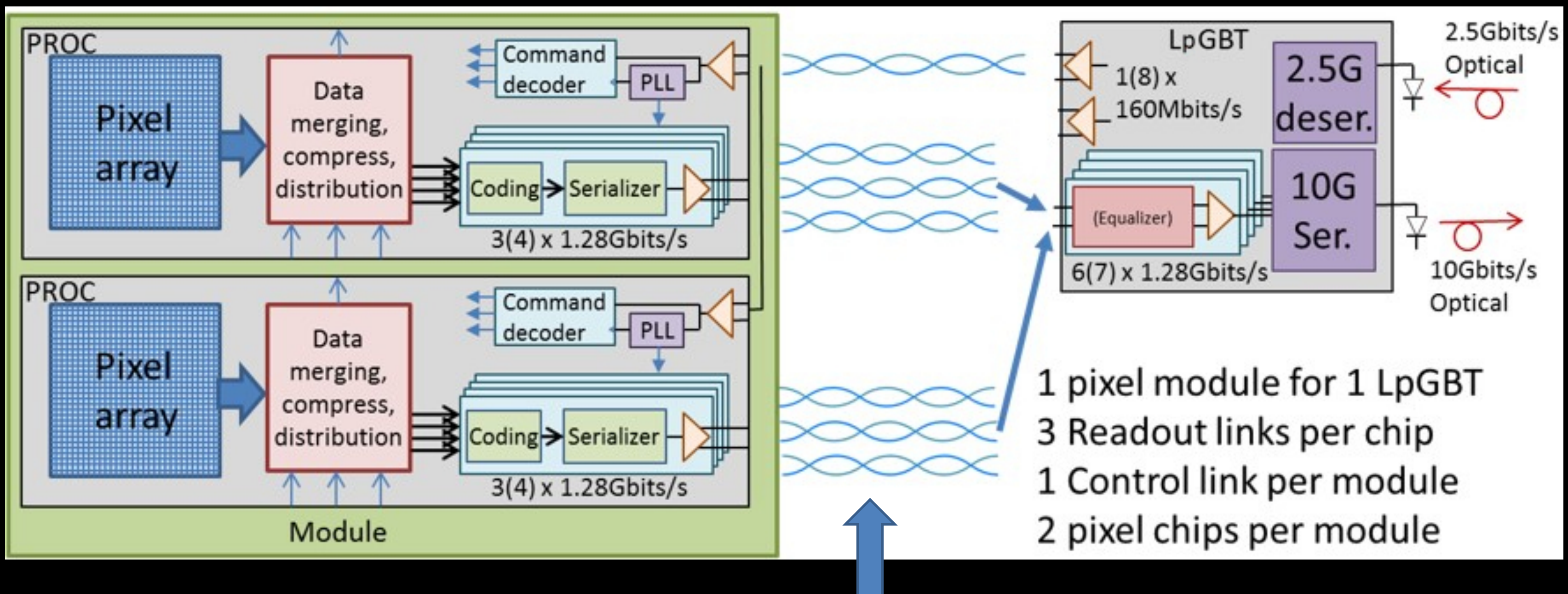
CMS-TDR-014



- 1x2 ROCs modules (inner layers)
- 2x2 ROCs modules (outer layers)
- Total active area of silicon ~4.9 m^2
- Hybrid pixel detector: Sensor with bump-bonded readout chips

The detector components

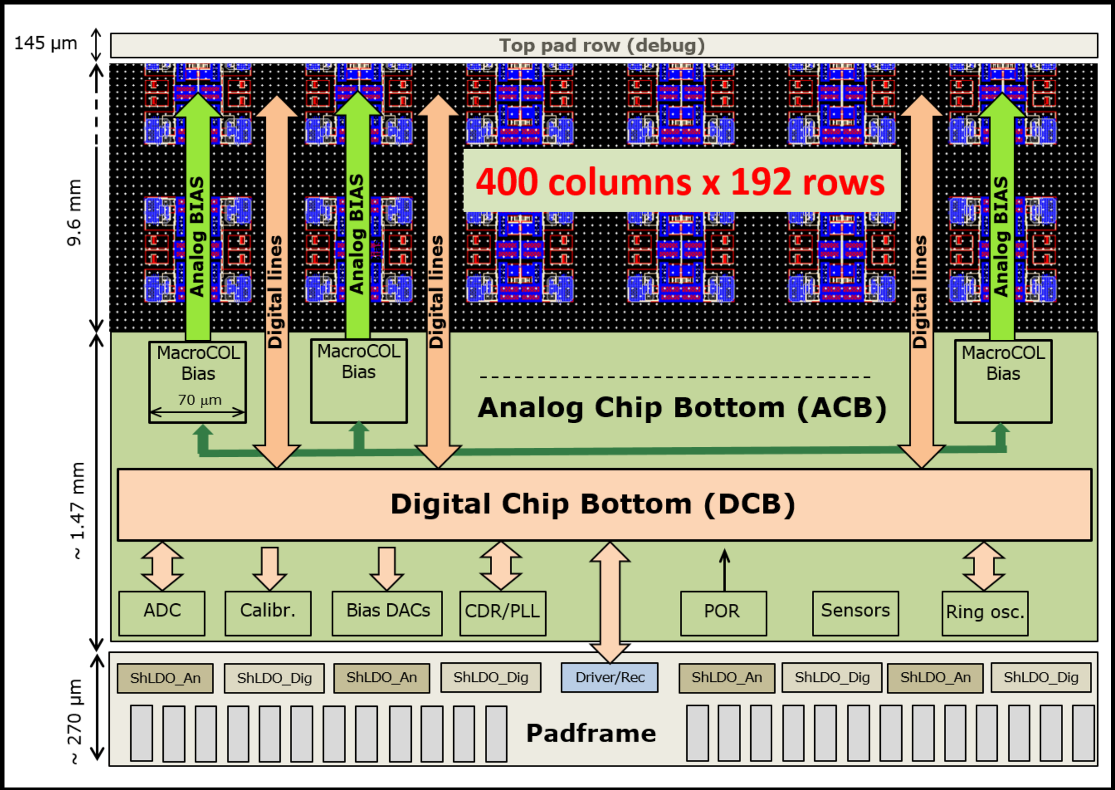
CMS-TDR-014



- This particular layout is for the inner barrel layer:
  - One pixel module, with two chips each, connected to one lpGBT.
- The other layers have seven pixel modules with four chips each, connected to one low power gigabit transceiver (lpGBT).

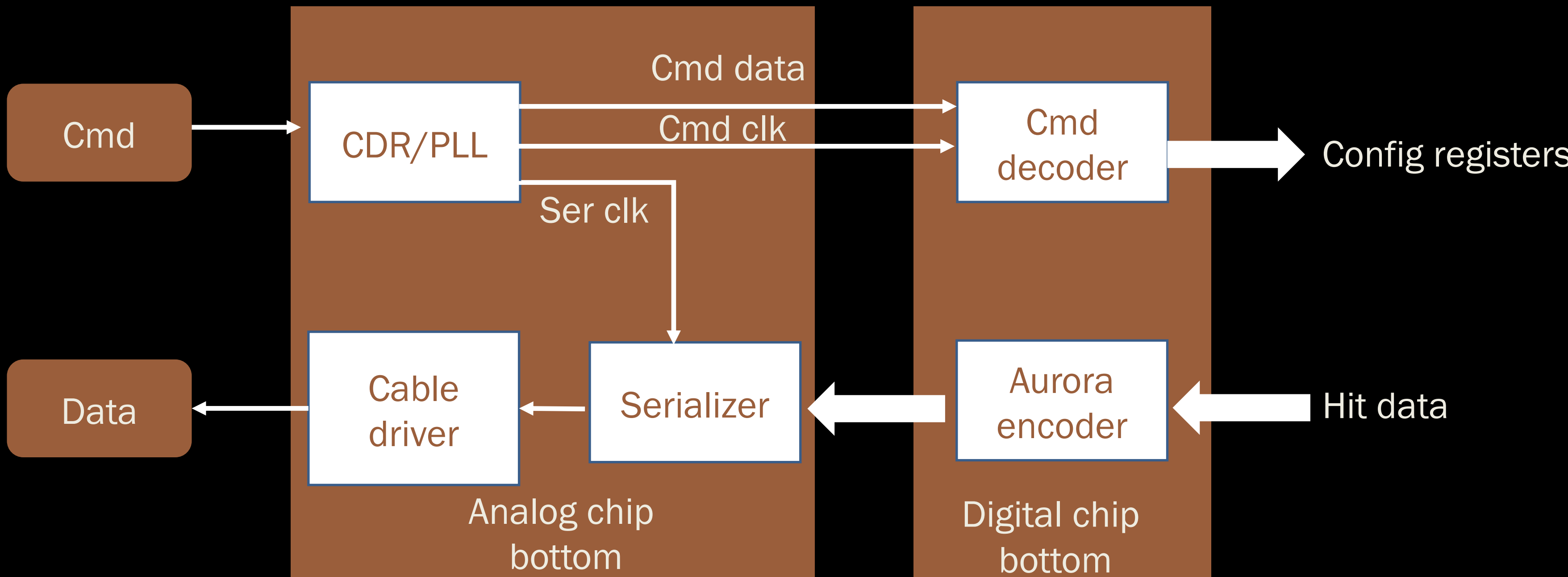
The RD53A chip

CERN-RD53-PUB-17-001



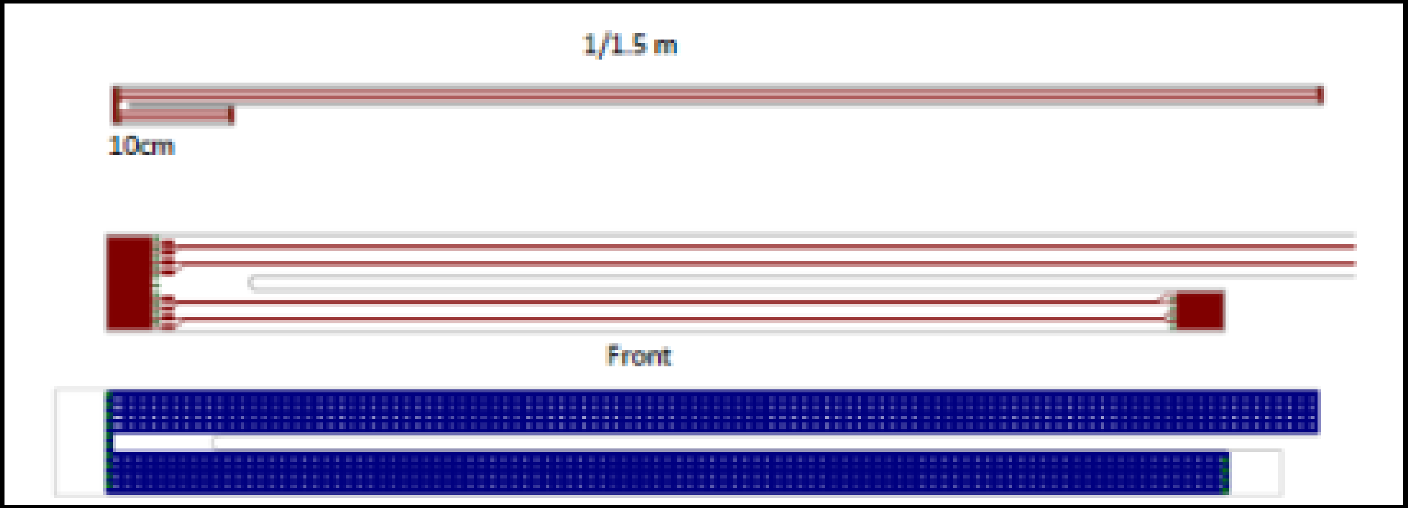
- Prototype for ATLAS/ CMS readout chips
  - 400 columns and 192 rows.
  - Designed to withstand HL-LHC radiation doses (500 Mrad) or 2×10^{16} n_{eq}

Phase 2 chip: The frontend



- Cmd_clk = 160 MHz
- Ser_clk = 640 MHz

E-links



- E-link: 1 control link (160 Mbs^{-1}), 1-3 data link at 1.28 Gbs^{-1}.
- Different prototypes developed:
  - Flat-flex cables
  - Twisted pair cables
- Length: 10 cm to 2m

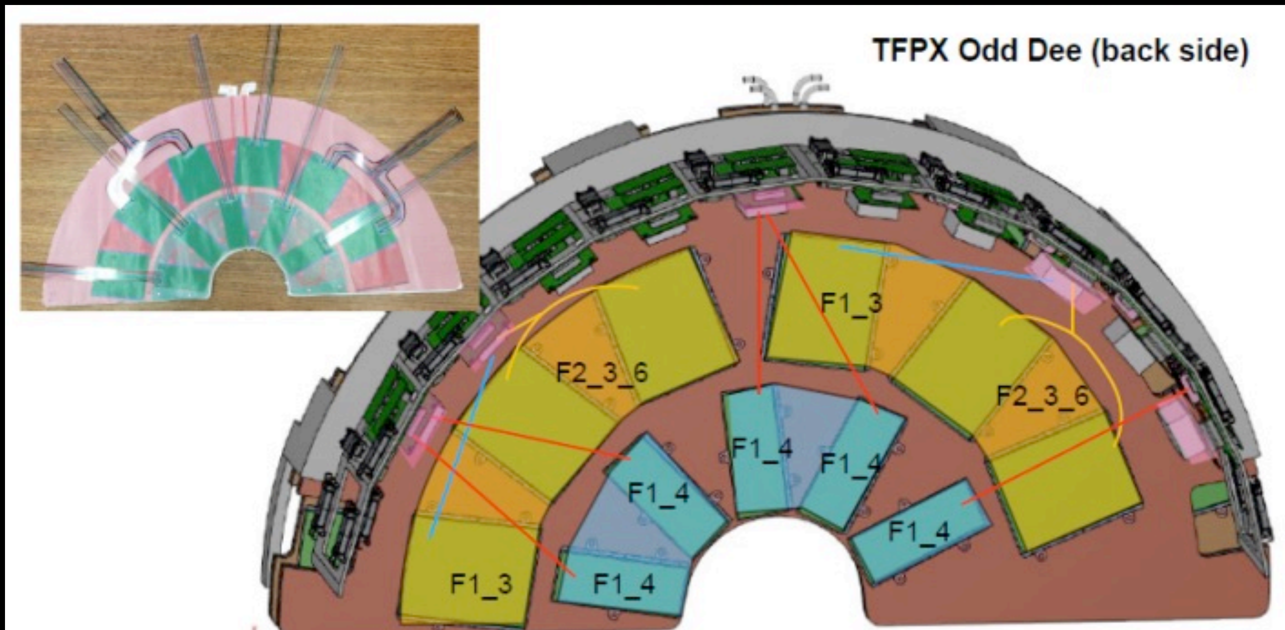
E-link characteristics

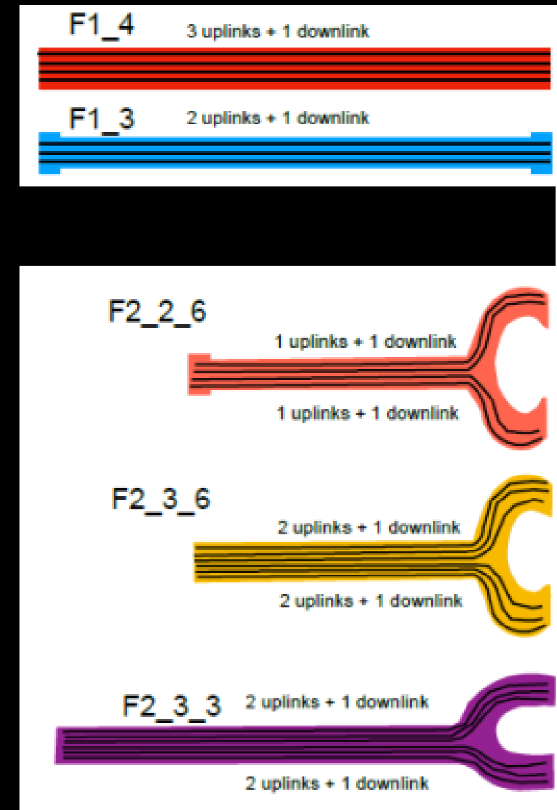
Properties	Labels			
	CFF_L001	CFF_L002	TP_1M_011	TP_2M_111
Mass/ length	1.2 g		0.3 g	
Cross section and materials	0.15 mm Kapton		Cu with 4 twist/inch Cross section 36 AWG (0.127 mm)	
Grounding/ shielding	bottom face split up into three heavy traces to be used as grounds or to power the electronics		Double QML Kapton insulation	
Length	1 m	1 m	1 m	2 m
Connectors	Left side being connected to the 20 pin AMP connector and the two right hand sides being connected to two 8 pin AMP		SMK	

Several e-link prototypes designed by KU.

Measurement of impedance and performance in signal transmission studied at CERN.

TFPX cable layout study





Flavor	# cable/ disk	#cables	length (cm)	Bifurcation	dist. b/w bifurcated ends (cm)	# diff pairs
F1_3	8	256	25	No	-	3
F1_4	10	320	35	No	-	4
F2_2_6	8	256	25	2	6	4
F2_3_6	4	128	25	2	6	3
F2_3_3	6	192	35	2	3	3

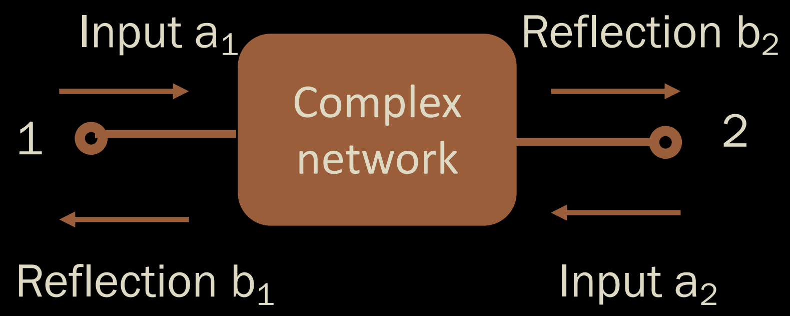
Total of 1152 cables in 5 flavors with lengths from 25-35 cm

Summary of tests on the e-links

- Mass measurements, visual Inspection and thermal cycling
- Radiation tolerance (irradiation at Los Alamos)
- Electrical Properties
  - Continuity/DC Resistance
  - Bit Error Rate
  - S-parameter measurements
  - Eye Diagram
  - Time domain reflectometer studies
  - Cross Talk
- RD53A studies
  - Eye diagram
  - Transmit and receive data and study with different pre-emphasis

The s-parameters

- Scattering matrix quantifying the behaviour of signal in a network.



A two-port network

a_1, a_2, b_1, b_2 are the measured signal strengths √(power).

$$S = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \qquad \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

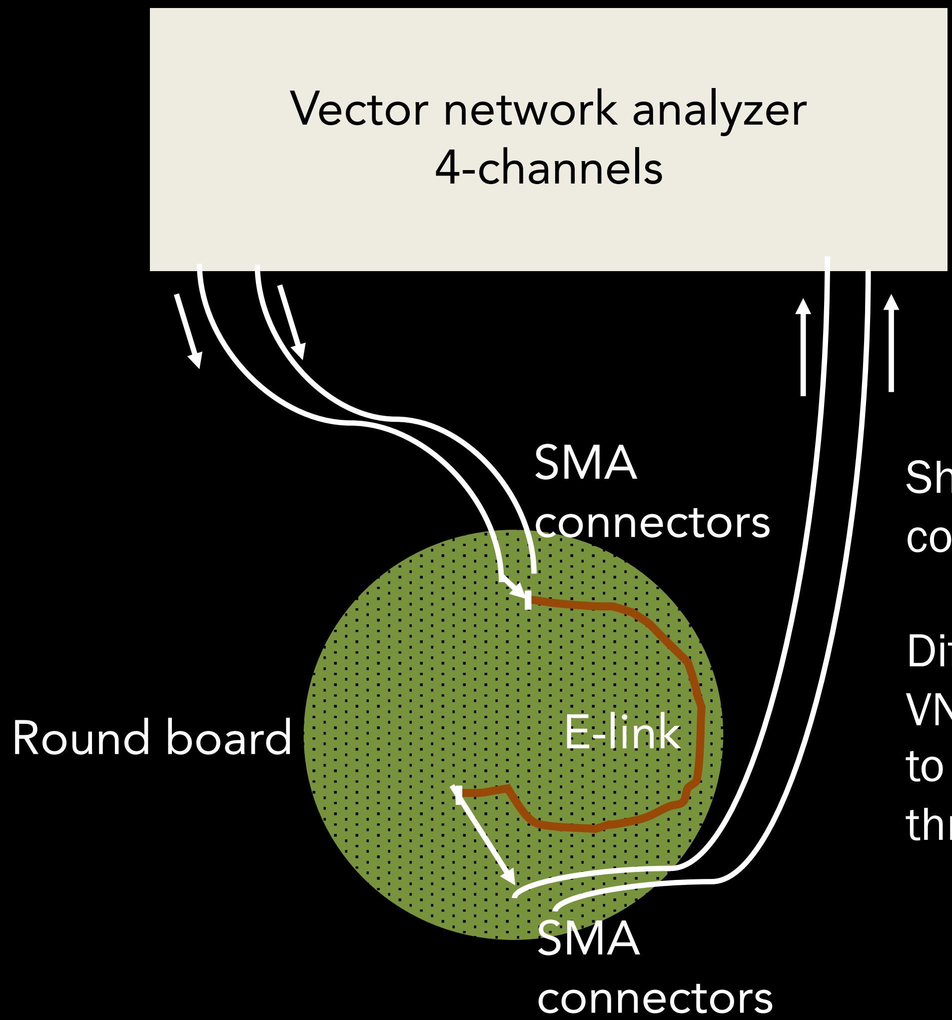
$S_{11} = b_1/a_1$, $S_{21} = b_2/a_1$: $a_2 = 0$

$S_{12} = b_1/a_2$, $S_{22} = b_2/a_2$: $a_1 = 0$

$Z = Z_0 \frac{1+S_{11}}{1-S_{11}}$, Z_0 = characteristic impedance = 100 Ω

Measuring S parameters gives the impedance of the DUT (e-link cables).

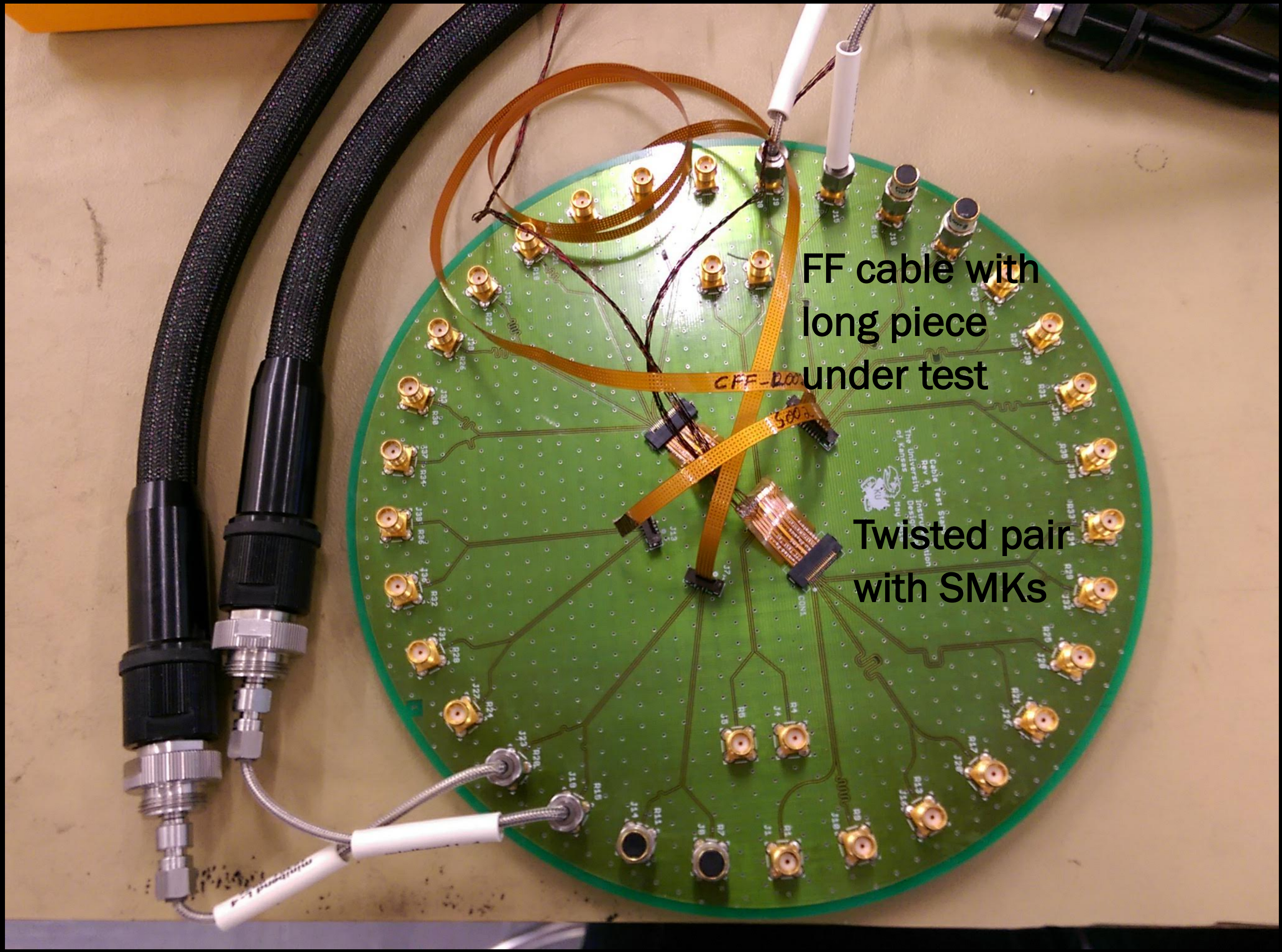
Set-up for s-parameter tests



Shielded cables with SMA connectors.

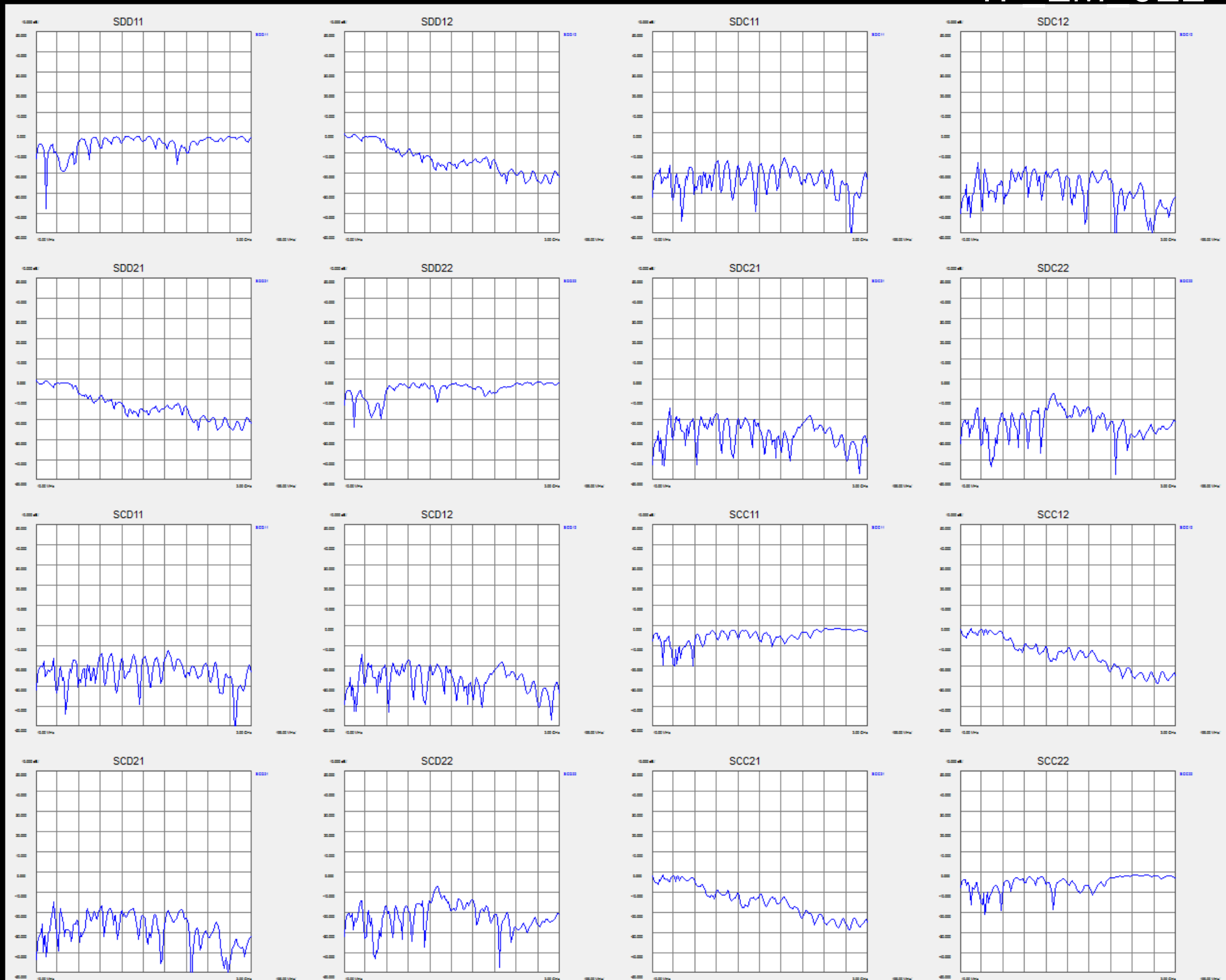
Differential signal sent from VNA output ports
to the VNA input ports
through the e-links.

Set-up for s-parameter tests

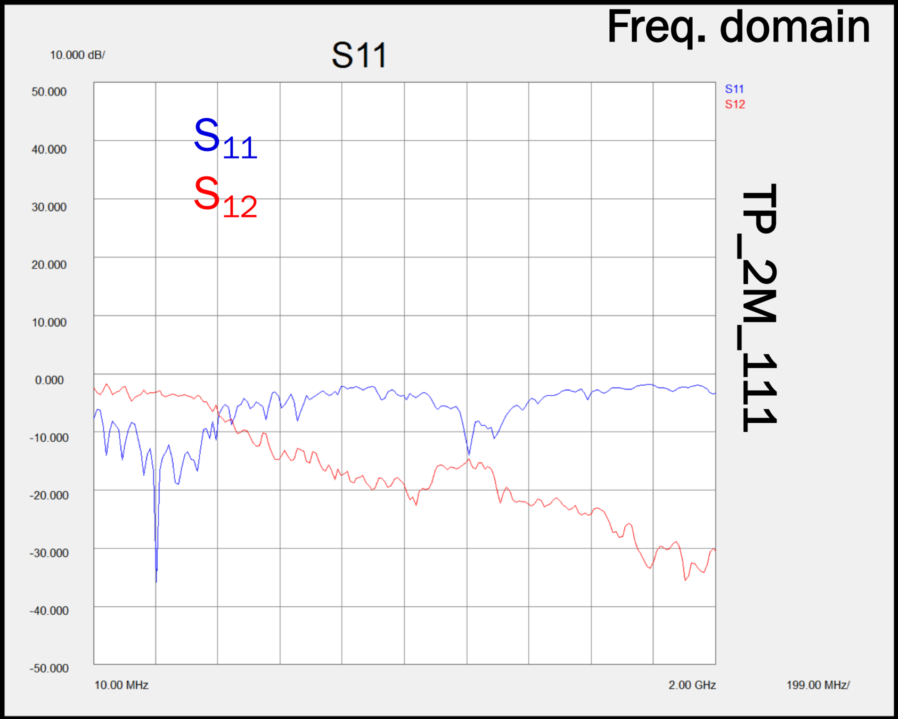


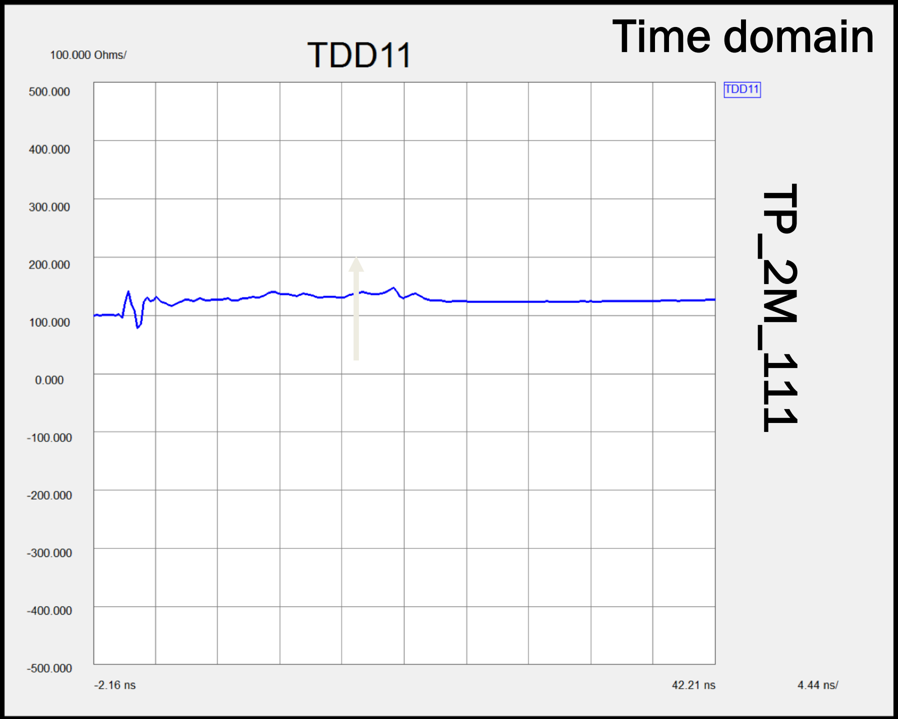
S-parameters

TP_1M_011



Impedance measurement



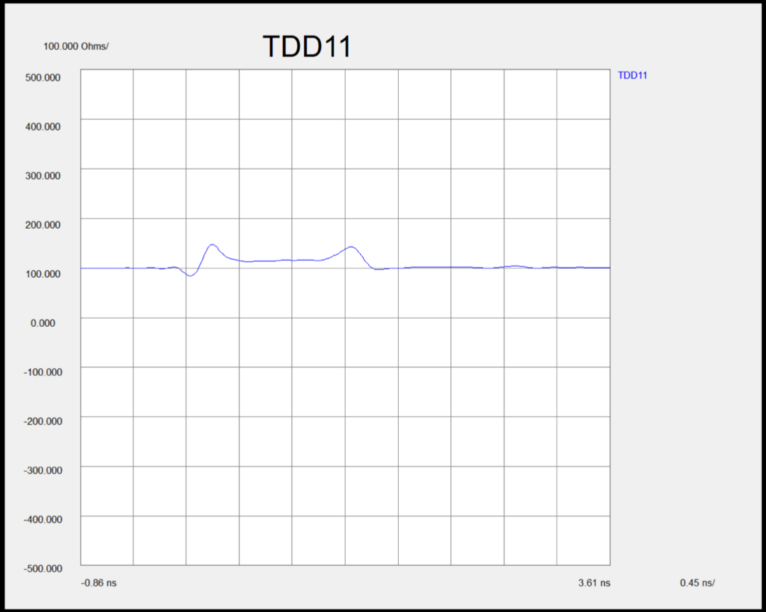


- Comparing S_{11} (reflection) with S_{12} (transmission) gives the bandwidth of the DUT.
- Cross-over point ~500 MHz

- The measured S parameter S_{11} is converted into a measurement on the impedance of the DUT.
- Measured to be 100 Ω.

S-parameters for the round board

- Measured the s-parameters and the impedance of the round board itself.
- Since we interface the cables through the round board, impedance matching here is an important factor.



- Impedance in the expected range ~100 Ω.
- Slightly higher than expected. Potential impedance mismatching.

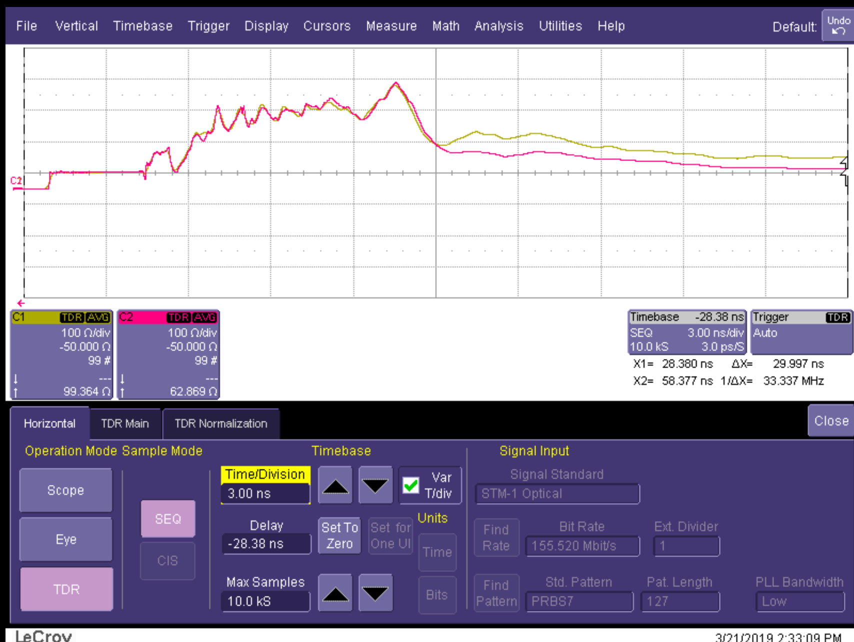
Time domain reflectometer studies

- The round board shows higher impedance than expected/ designed.
- This may lead to the distortions of the signals and the degradation of the quality of the eye diagram.
- Direct measurement of impedances using a time domain reflectometer.

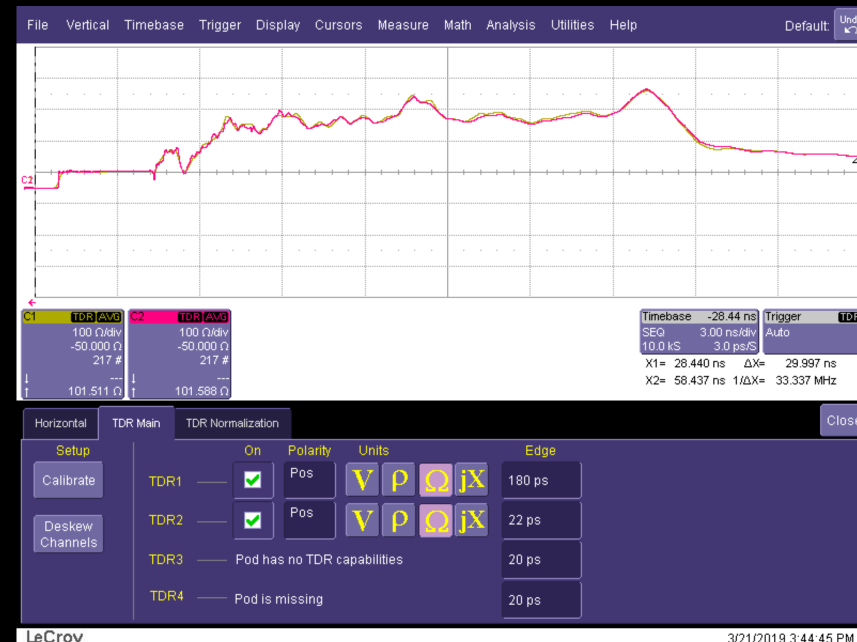
60 Ω
Expected 50 Ω
(single-ended)

TDR with the cables

1m cable

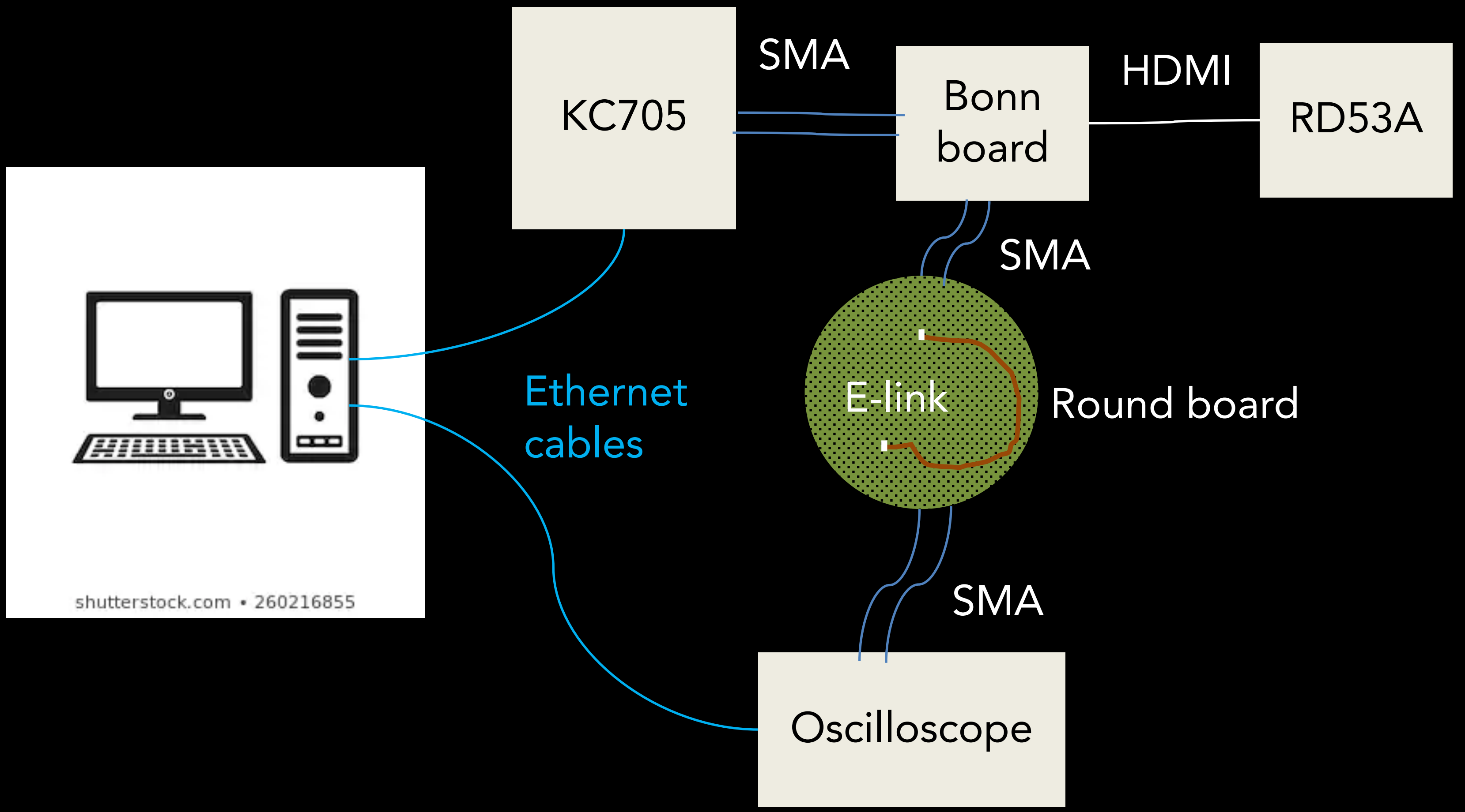


2m cable

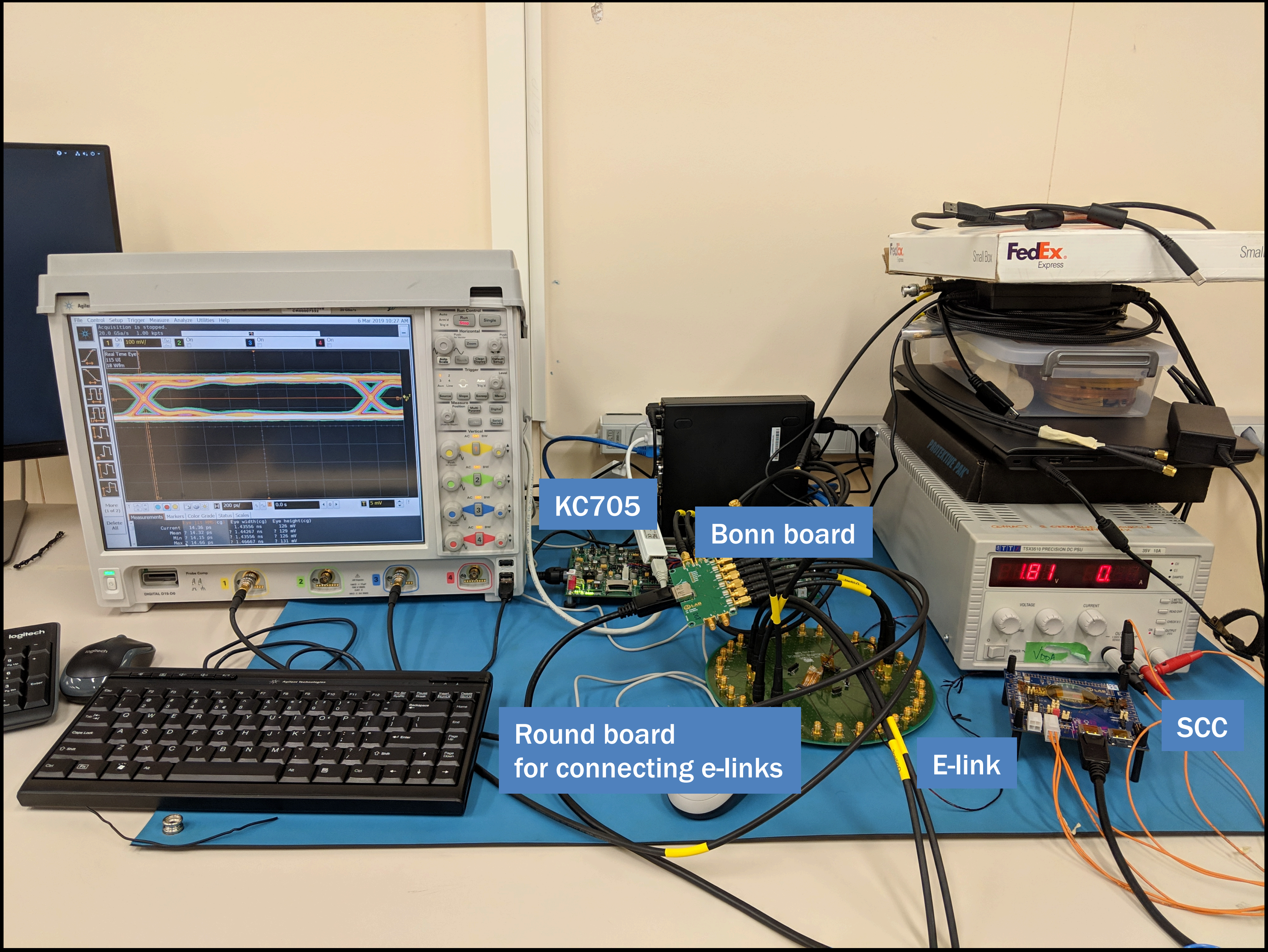


- We also measured the impedances of the twisted pair cables (1m and 2m).
- Showed higher than expected impedance values.
  - Again, see before from the VNA measurements.

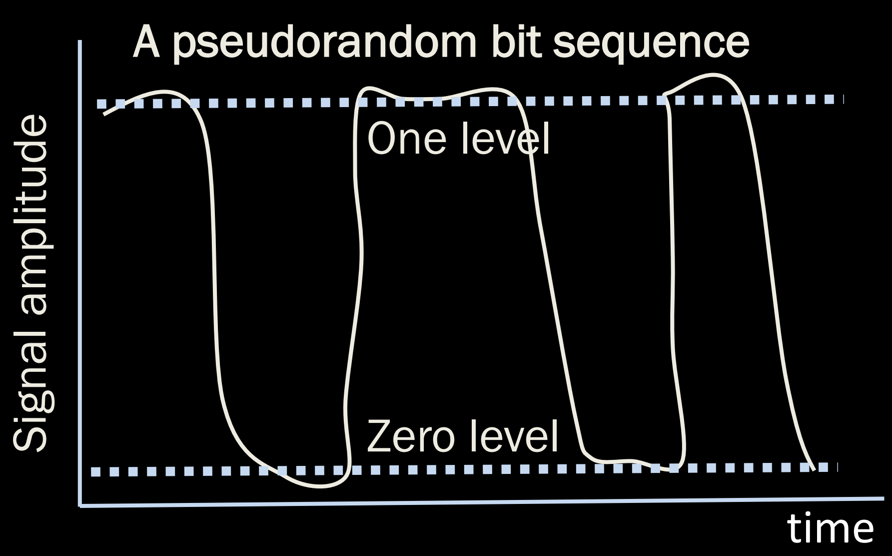
The e-link test set-up

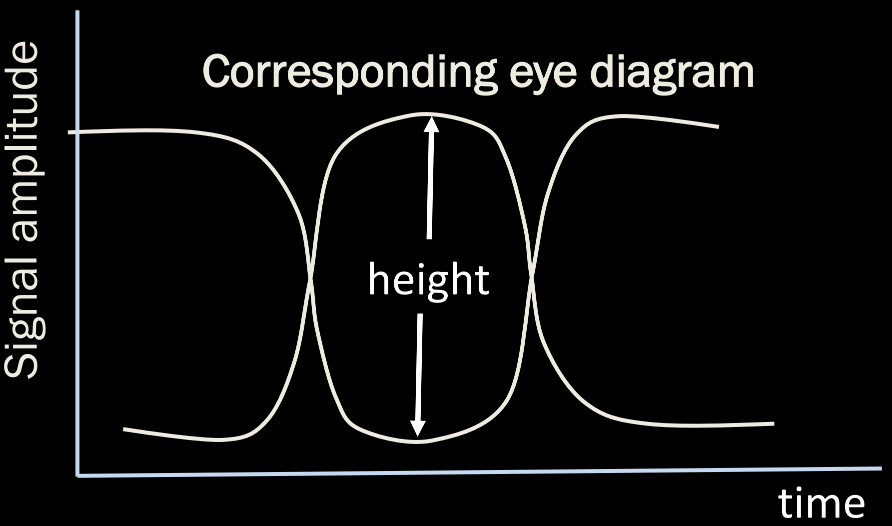


Test set-up with RD53A chip



The eye diagram

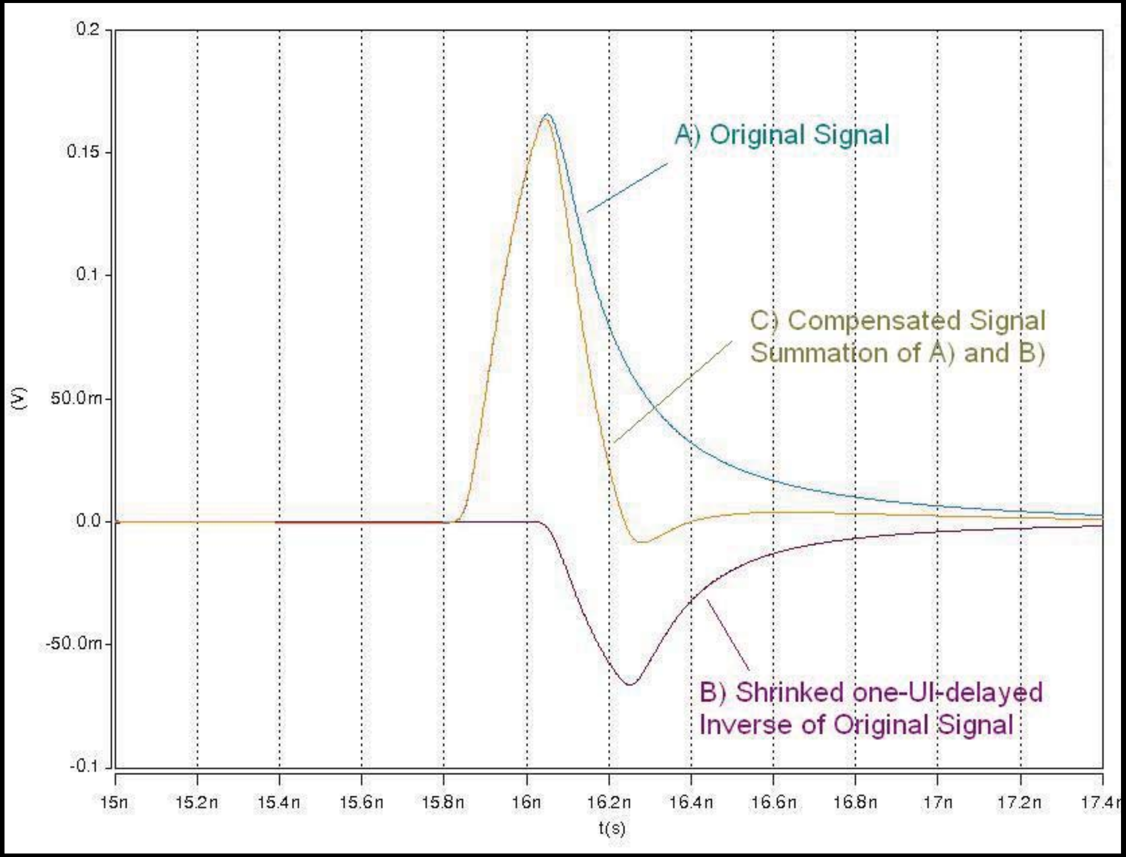




- The eye diagram is a visual method to evaluate signal integrity.
- Th oscilloscope samples the signal at every transition from 0–1 and 1–0 states and overlays all such transitions simultaneously.
- The eye area and height tells how many times the signal successfully transitions from the 0 to 1 state and back.
  - Gives an idea about the signal corruption and information loss.

Pre-emphasis

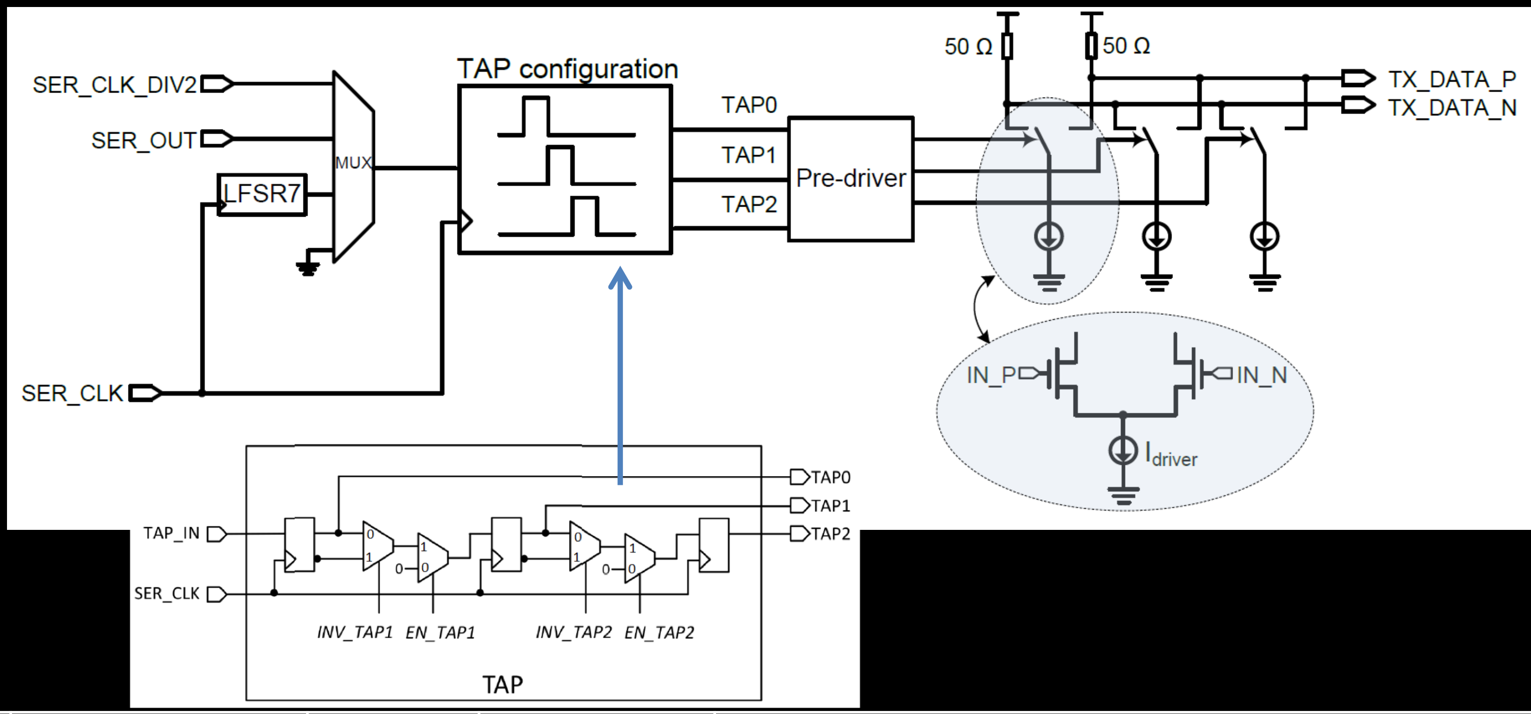
- High frequency signals incur significant losses during transmission.
- Pre-emphasis seeks to mitigate this: apply delay and inversion to the signal and add it back. (reduces signal spread).



The RD53A chip is configured to apply pre-emphasis to the transmitted signal.

Goal: apply pre-emphasis to improve the signal transmission quality.

RD53A pre-emphasis schema

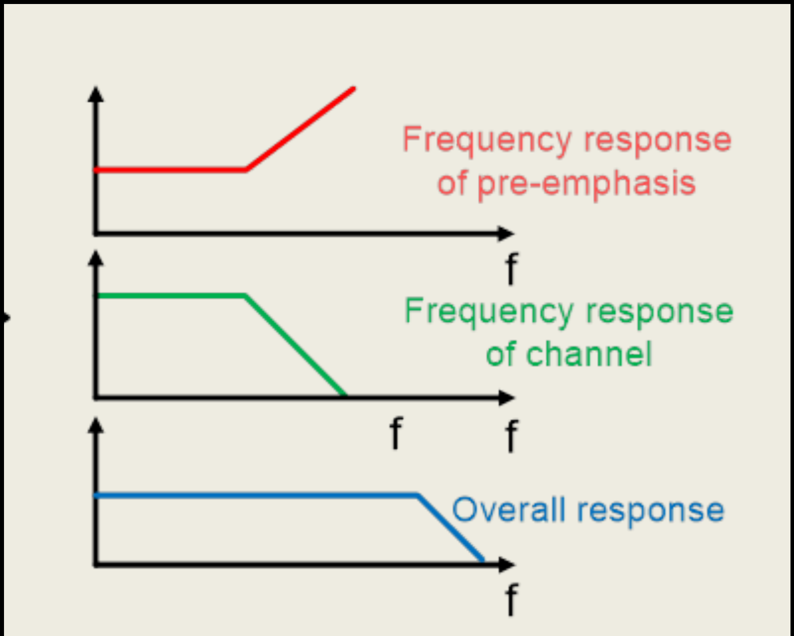


From Piotr Rymaszewski

Reg. Nr.	Name	Nr. Bits	Default value	Bit description
68	SER_SEL_OUT	8	8'b01_01_01_01	{SerSelOut3[1:0],SerSelOut2[1:0],SerSelOut1[1:0],SerSelOut0[1:0]} 00-SER_CLK_DIV2, 01-SER_OUT, 10-LFSR7, 11-GND
69	CML_CONFIG	8	8'b00_11_1111	{SER_INV_TAP[1:0], SER_EN_TAP[1:0], CML_EN_LANE[3:0]}
70	CML_TAP0_BIAS	10	10'd500	Bias current for tap 0 of CML driver (LSB ≈ 14.6μA, MAX ≈ 15mA, same for all tap bias)
71	CML_TAP1_BIAS	10	10'd0	Bias current for tap 1 of CML driver
72	CML_TAP2_BIAS	10	10'd0	Bias current for tap 2 of CML driver

How pre-emphasis works

From RD53A designers

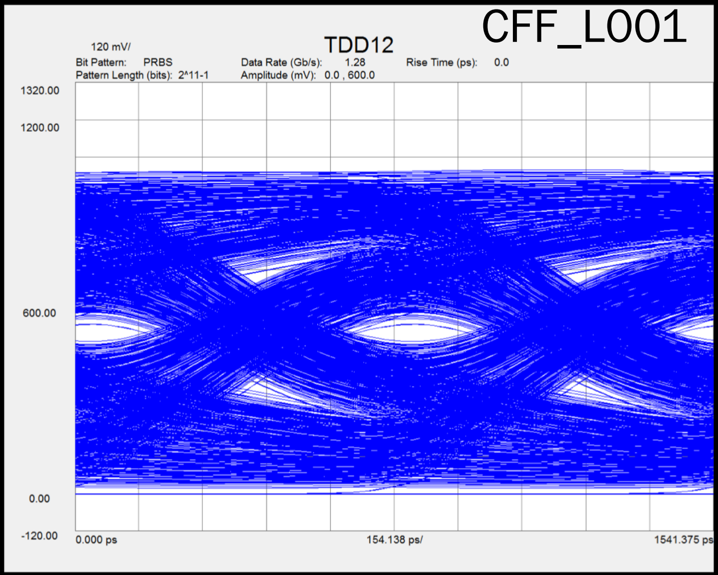


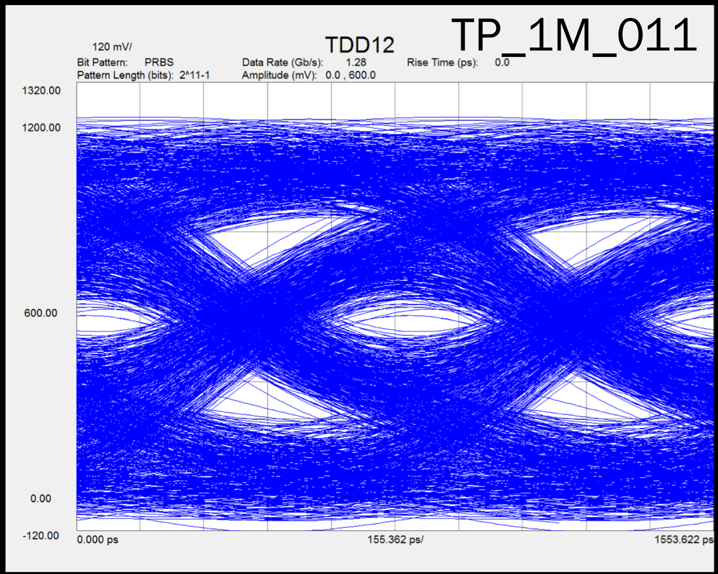
The frequency response of the pre-emphasis filters de-emphasize the low frequency components and boost the high frequency components of a signal.

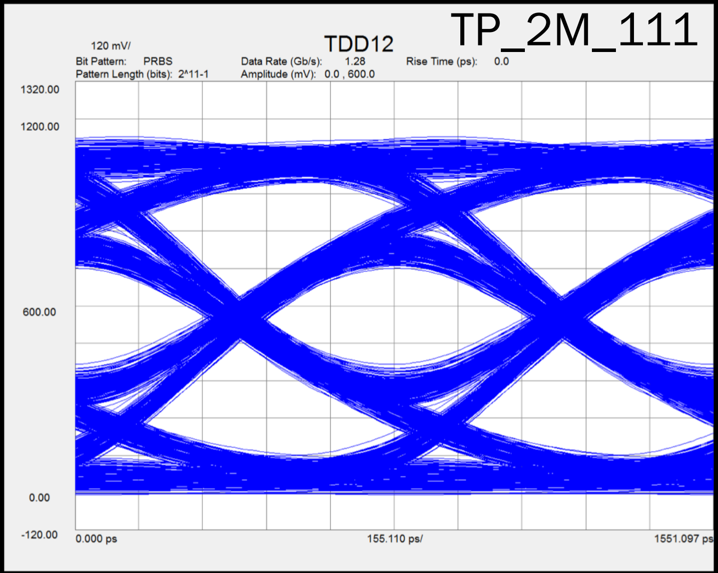
Compensates for low-pass effects (high frequency losses of the transmission media).

Helps achieve a flatter frequency response.

Eye diagrams with VNA

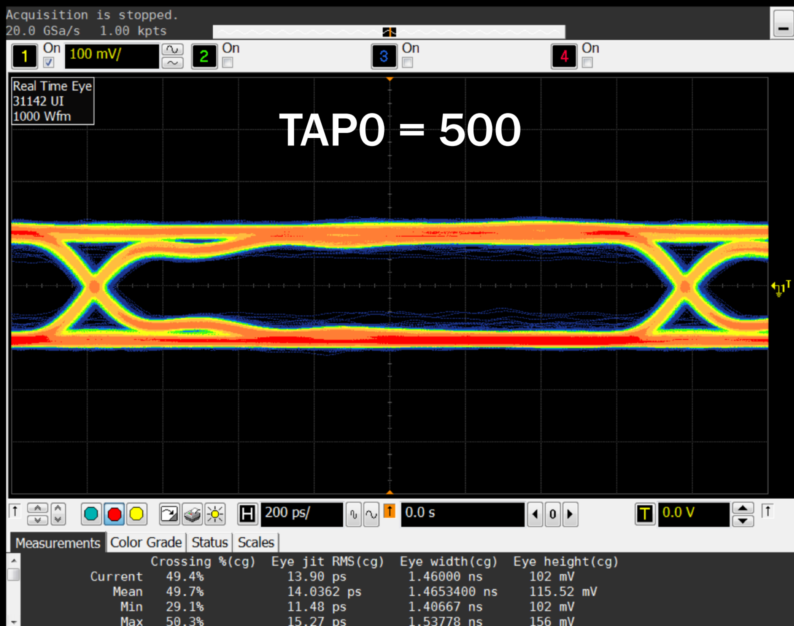


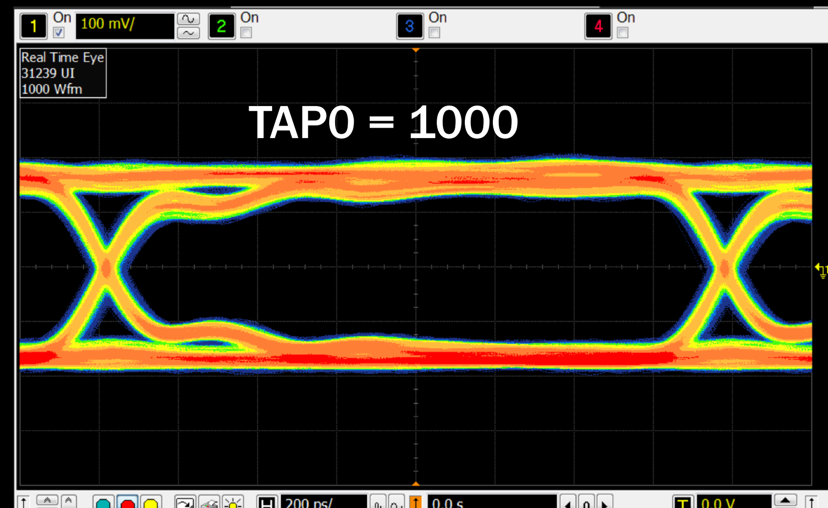




- Eye diagram simulated from s-parameter measurements.
- Tested in the range 10 MHz–5 GHz
- S-parameters measured using PRBS
  - Length: 2^{11}.
  - Rate: 1.28 Gbs^{-1}.
- Without pre-emphasis.

Measured eye diagrams

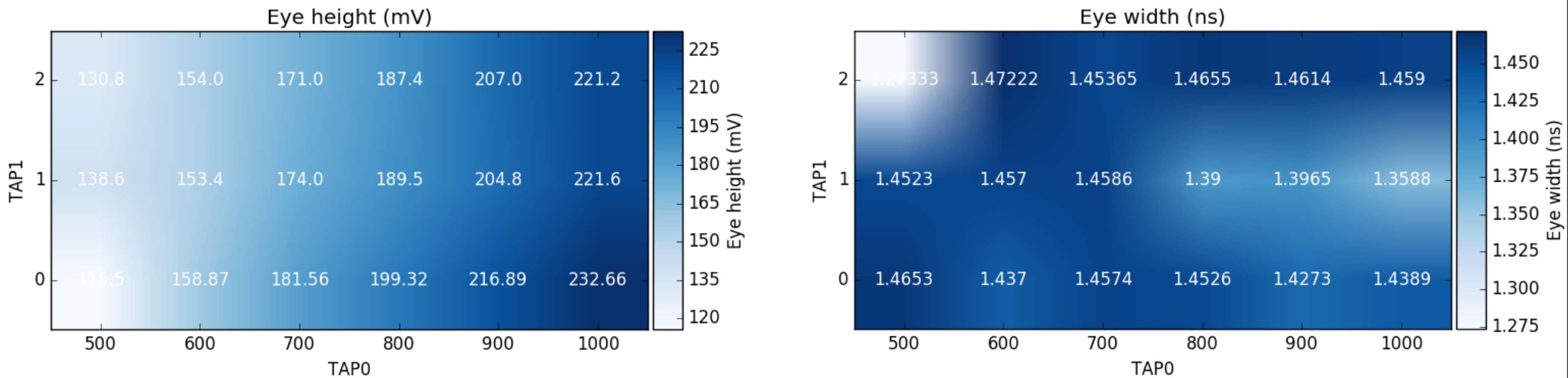




- Here the eye diagrams actually measured using RD53A signal.
  - Pseudorandom bit stream
- Direct connections using SMA connectors (no e-links yet).
- Changed video cable since last time–no transitions between clock cycles. (Was not really due to PLL locking issue).

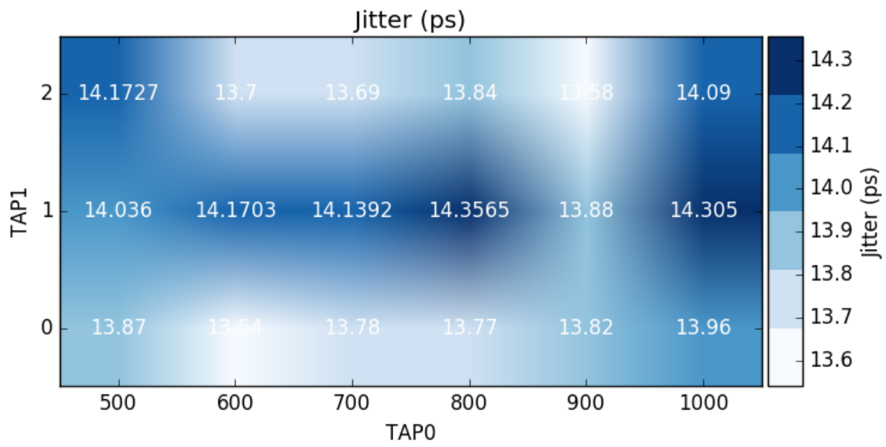
Scanning pre-emphasis taps

- Scan TAP0: 500–1000 in steps of 100
- Scan TAP1: 0, 1, 2



- Change in eye height with TAP0
- Not much change in width
- Not much change with TAP1

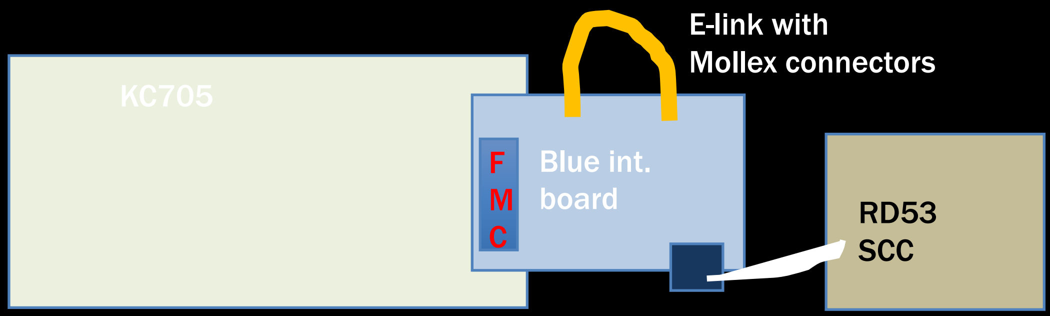
Jitter



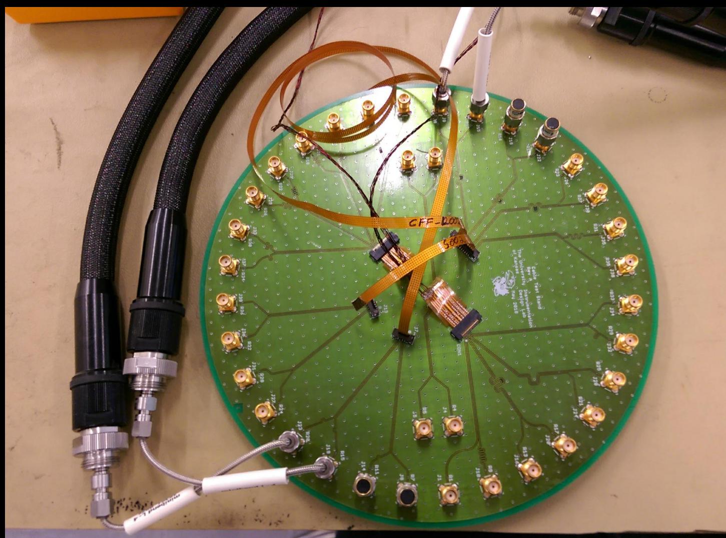
- Jitter remains fairly constant with TAP0 and TAP1.
- Higher when TAP1 = 1 but probably not significantly high.

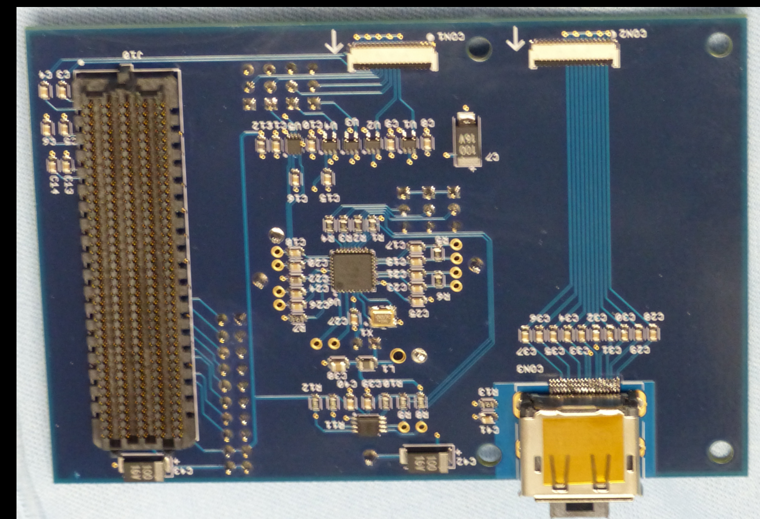
Improvements

- The scanning process of the pre-emphasis taps is now more automatic.
- Can make plots scanning all three taps.
- Redoing measurements increasing the ranges of TAP1 and TAP2.
- New e-links have been designed at KU.
- A new interface "blue board" has been designed: Currently in the process of writing firmware for this.



A new e-link interface





- Less complicated connections.
- Less noise and problems with impedance matching.

Summary and plans

- CMS Phase 2 pixel detector development well under way.
- At CERN several tests on the pixel detector system being undertaken:
    - Powering tests, chip testing, electronic links, lpGBT.
- Covered the tests related to the electronic readout system.
    - Prototypes of cables developed at University of Kanas
    - Testing being done at KU and CERN.
- Plan is to get full testing procedure in place by summer.
- Perform tests with new RD53 chip when available
- Current tests done without the lpGBT drivers.
    - Need to test using the lpGBT in the readout chain
- By the end of the year:
    - Arrive at a baseline choice for the e-link designs.
    - Demonstrate readout chain working with full module, e-links and optoboard.

Contributors: E-link studies

- University of Kansas (KU): Alice Bean, Shayla Bellamy, Sadia Khalil, Devdatta Majumder, Robert Young
- CERN: Luis Miguel Casas, Dominik Koukola, Pedro Leitao, Stella Orfanelli, Csaba Soos
- Rice University: Arun Kumar
- University of Zurich: Sebastien Wertz

Backup

Semiconductor properties

M. Moll Ph.D. thesis

Properties	Si	Ge	Diamond
Bandgap [eV]	1.12	0.66	5.47
e-h creation energy [eV]	3.6	2.9	13
e mobility [$cm^2V^{-1}s^{-1}$]	1450	3900	1800
h mobility [$cm^2V^{-1}s^{-1}$]	450	1900	1200
Radiation length [cm]	9.4	2.3	18.8
Avg. ionization energy loss [MeV cm^2 g^{-1}]	1.66	1.37	1.75
Avg. Signal [e-h pairs/ μm]	110	260	36
Intrinsic carrier density [cm^{-3}]	1.1×10^{10}	2.4×10^{13}	$< 10^3$

- Si has less noise than Ge.
- SiO_2 surface can be used for gates, protects crystal.
- Ge can be fabricated into large crystals.
- Diamond is more radiation hard.

Drift velocity $v_d = \mu E$
CMS pixel operating voltage ~400V.
Sensor thickness = 200 μm (layers 2-4 and FPIX)
= 75 μm (layer 1)

The e-link test set-up

- Fast readout cables from RD53A chip modules to lpGBT module
- E-link: 1 control link (160 Mbs^{-1}), 1-3 data link at 1.28 Gbs^{-1}.

Twisted pair cable

Flat-flex cable