Precision mm-Wave Test Fixture for 400Gbps Serial PHY Characterization

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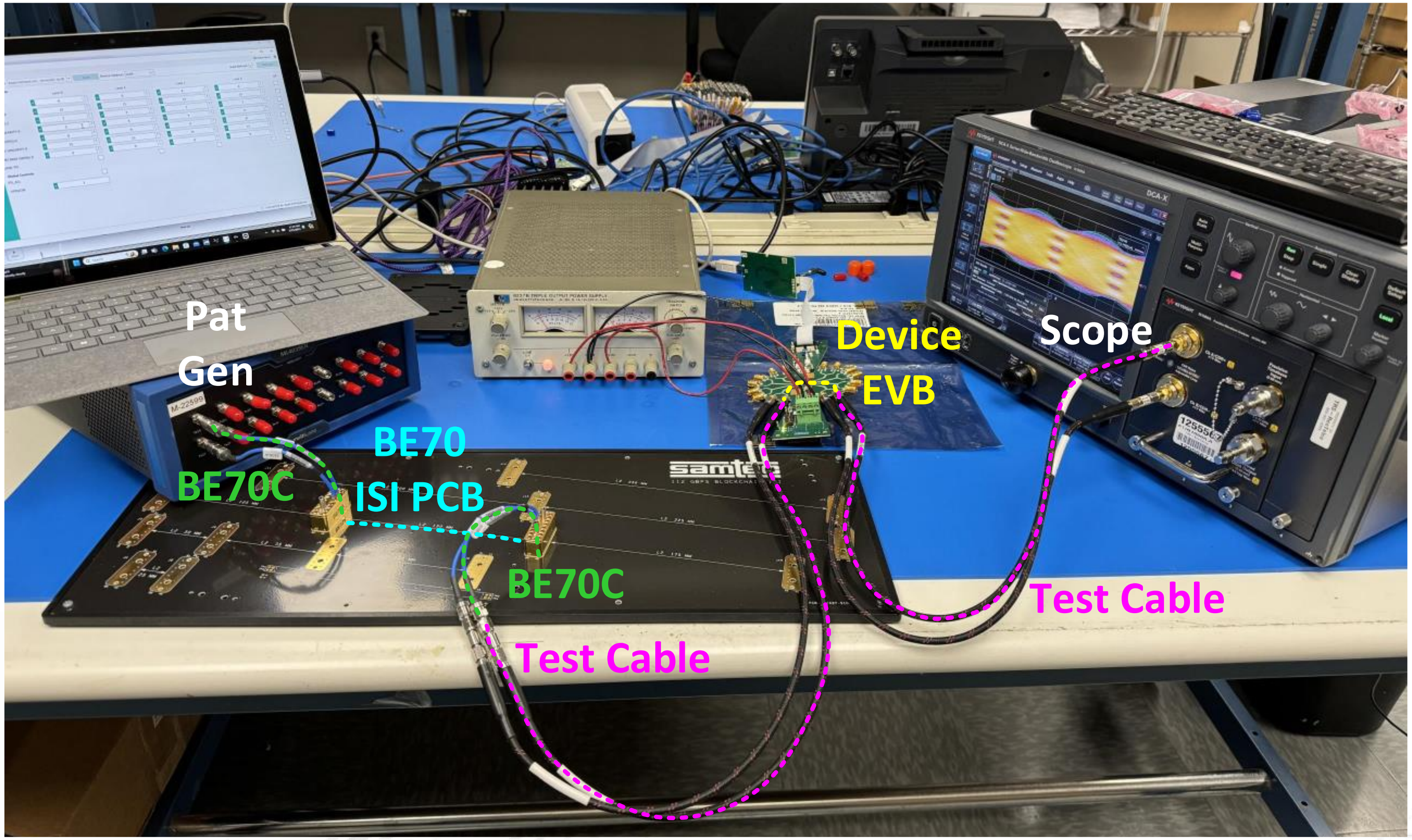
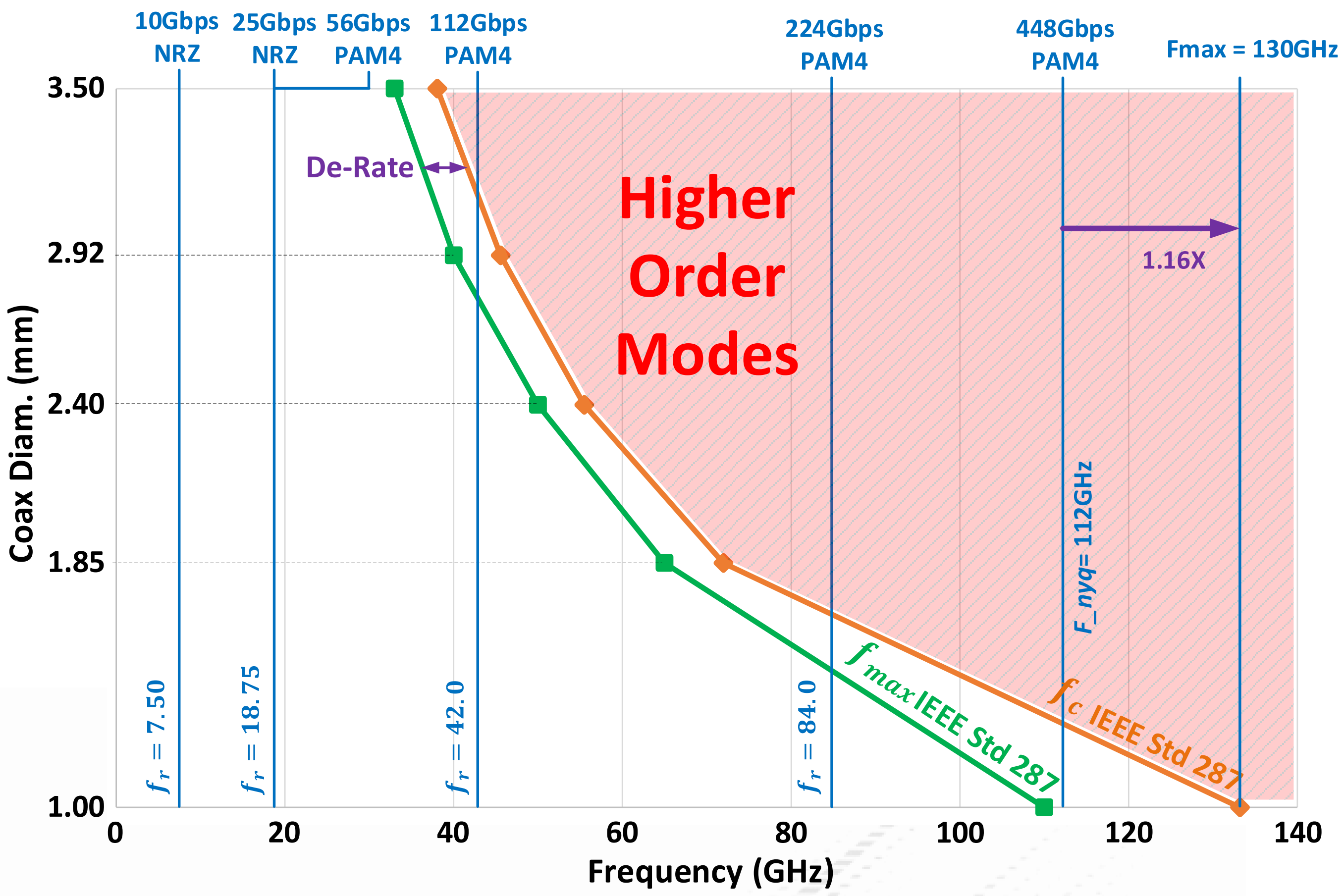
Agenda

- 1.85mm vs. 1.00mm Coax Connectors and Cabling
- BE70 ISI and BE90 ISI Channel Emulators
- BE90 EVB as a C2M Emulator
- Some (non)-Intuitive Pulse Responses
- Coax Cable Moding Revisited
- Conclusions and Summary

Part 1: 1.85mm and 1.00mm Coax Connectors and Cables



1.85mm and 1.00mm Coax Modal BW



- IEEE Std 287 defines expected modal cutoff frequencies (f_c) from mechanical interface specification
- De-rated (f_{max}) for margin and interoperability per Butterworth filter cutoff (f_r) traditionally 1.5x fundamental frequency.
- 448Gbps PAM4 F_Nyq = 112GHz
- Factor of 1.16X to 1.00mm Airline modal BW

Higher Order Modes in Coax - Analytic

- **Higher order modes → non TEM propagation**
- **These modes do not exist below cutoff (f_c)**
- **First higher order coaxial mode TE11**
- **Reducing inner ($2a$) and outer diameter ($2b$) or relative permittivity (ε_r) increase cutoff**

$$J_n'(k_c a)Y_n'(k_c b) = J_n'(k_c b)Y_n'(k_c a)$$

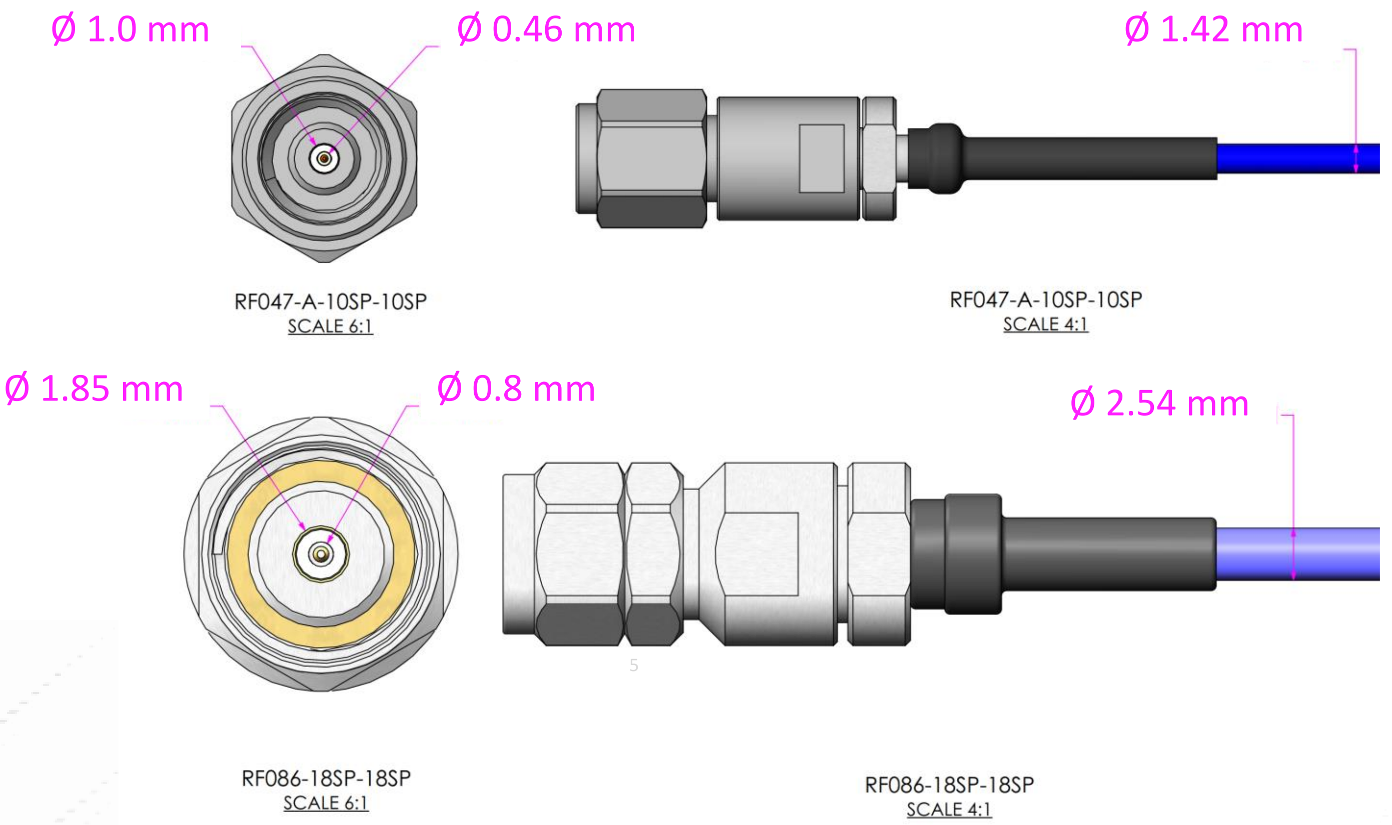
$$f_c = \frac{c_0 k_c}{2\pi\sqrt{\varepsilon_r}}$$

$$k_c = \frac{2}{a + b}$$

Two Areas of an RF Cable Can Mode

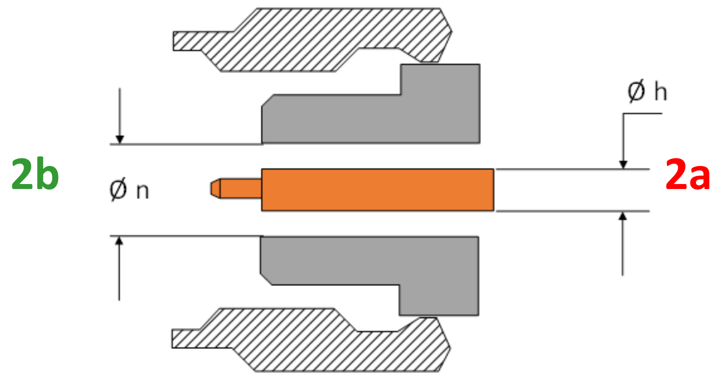
- **Airline region of RF connector**
- **Dielectric support bead complicates**

- **Cable cross-section limited by air/polymer composites (foaming density)**



Tolerance to Bore Relationship

Conductor gap for 1.0 mm shrinks by 46%
Tolerances of 50 um (bore) and 25 um (pin)



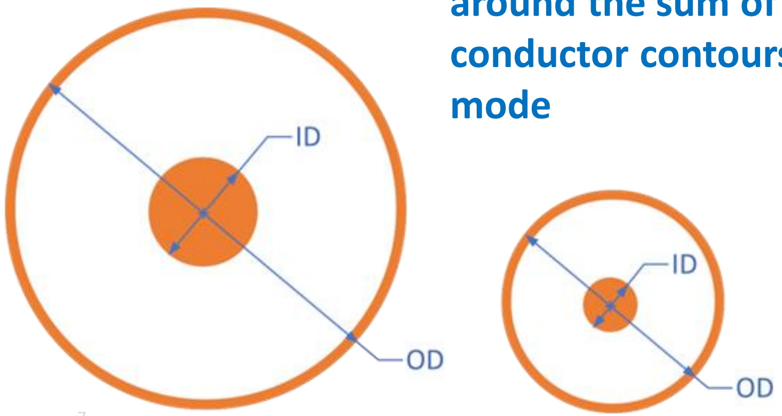
Connector Type	n (mm)		h (mm)	
	nominal	tolerance	nominal	tolerance
1.85	1.85	+/- 0.0127	0.8036	+/- 0.0127
1.0	1.0	+/- 0.0050	0.4340	+/- 0.0025

2.8X Tighter Pin Diam. to Bore Diam. Tolerance

Cable inner conductor shrinks by 52%

$$k_c = \frac{2}{a + b} \qquad 2\lambda_c = \pi * (2a + 2b)$$

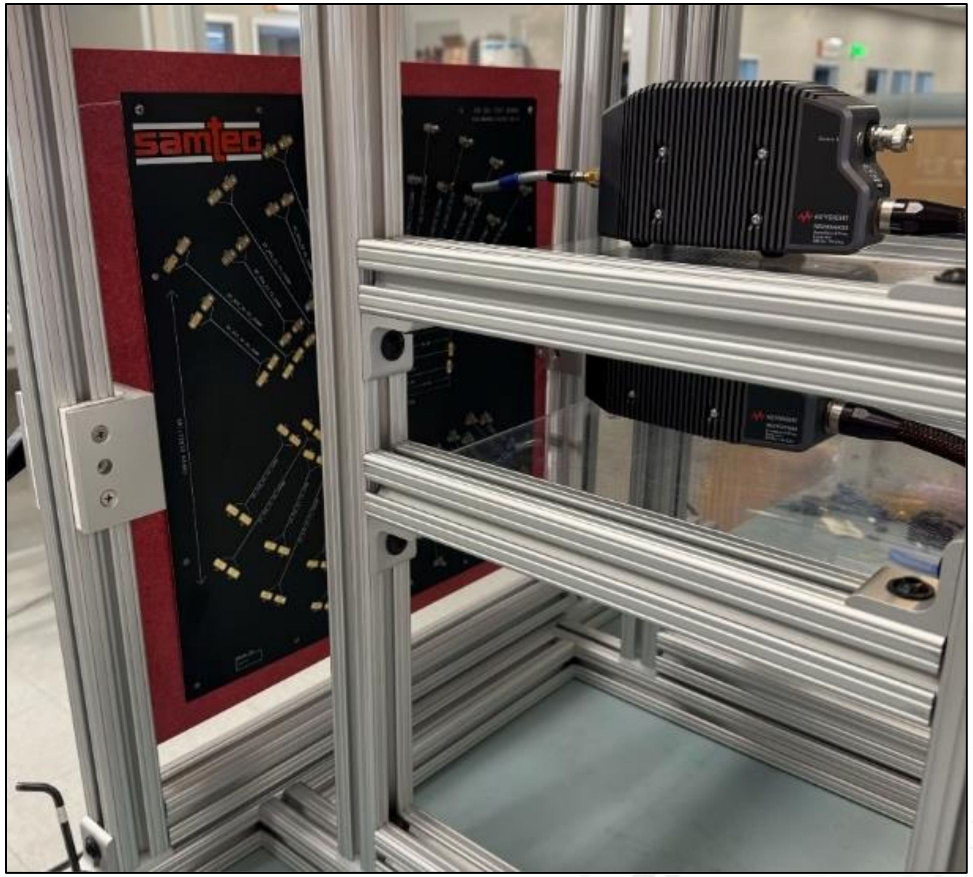
~2 Wavelengths must fit around the sum of the conductor contours to mode



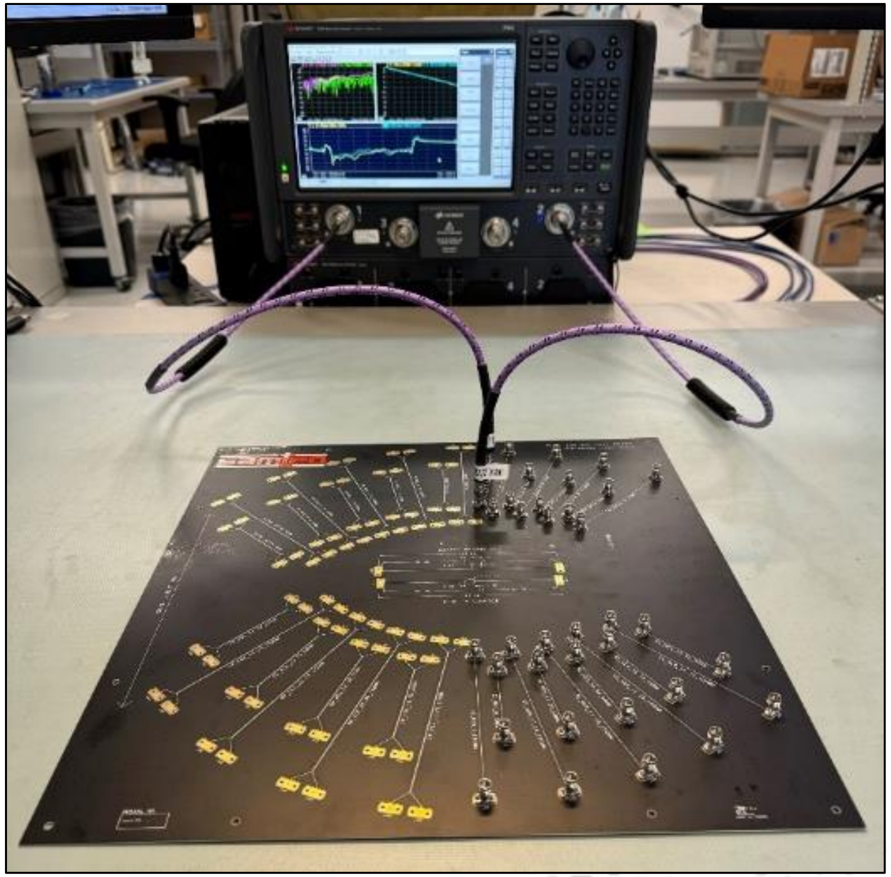
Cable Type	2a ID (in)	2b OD (in)	Cutoff (GHz)
086	0.023	0.086	72
047	0.011	0.047	112

1.85mm vs 1.00mm Compression Connector Comparison

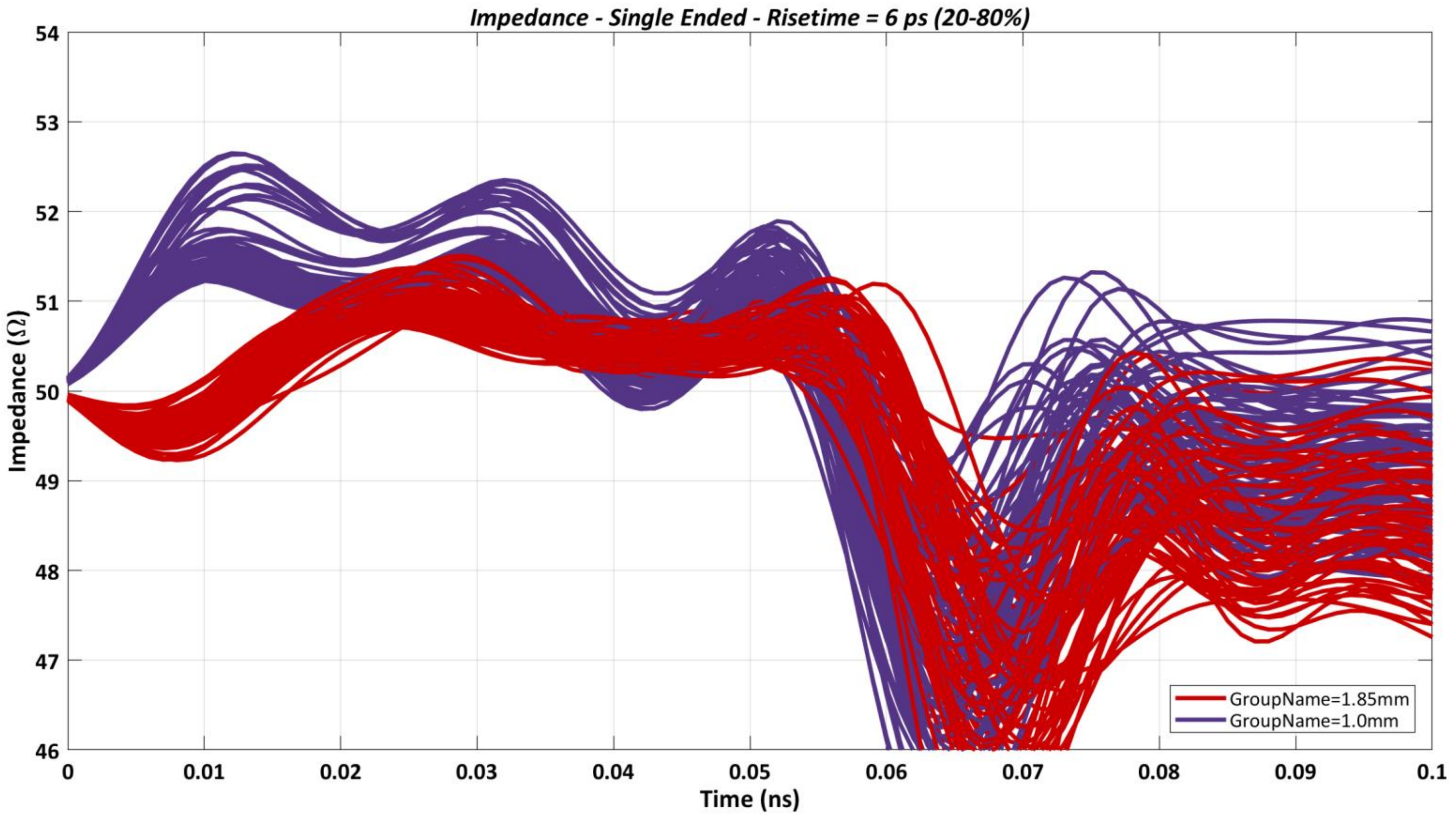
1.00mm Setup

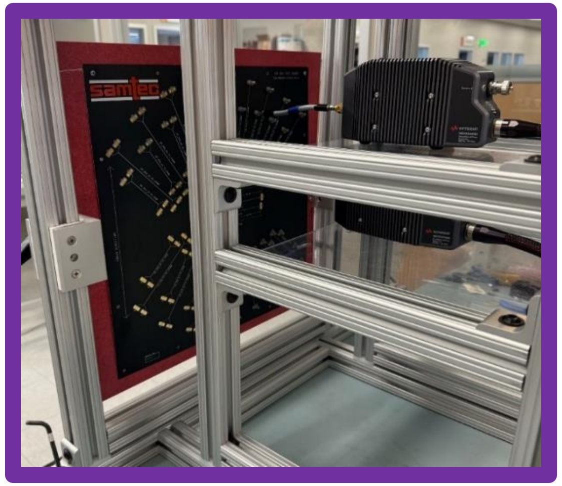


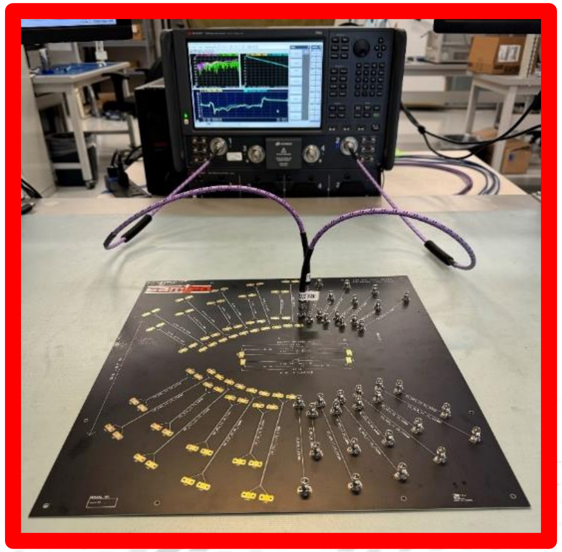
1.85mm Setup



40 TDR Waveforms per Connector Type

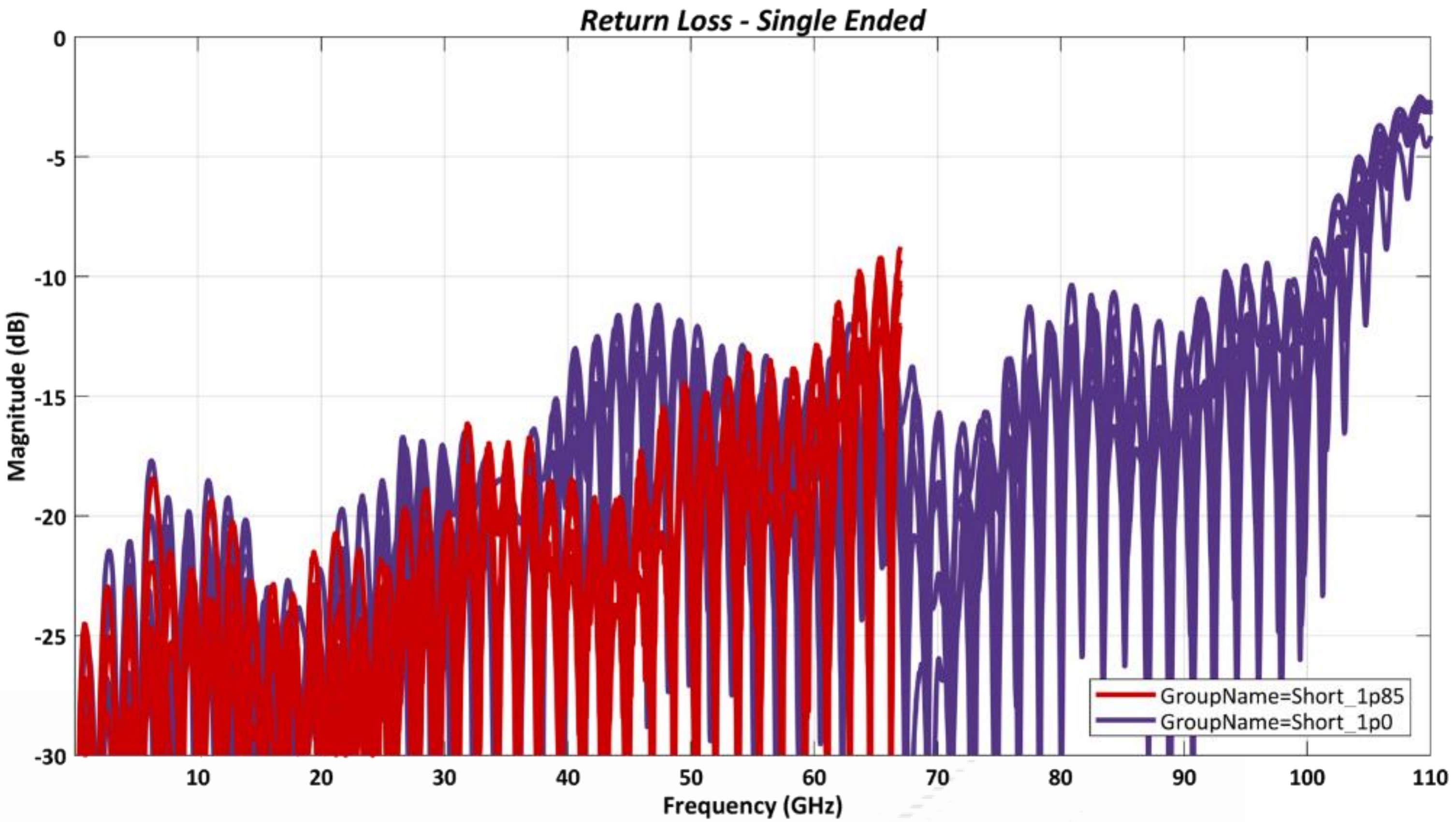


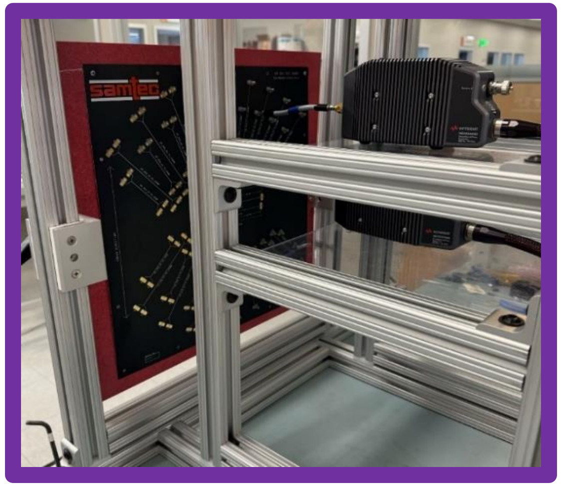


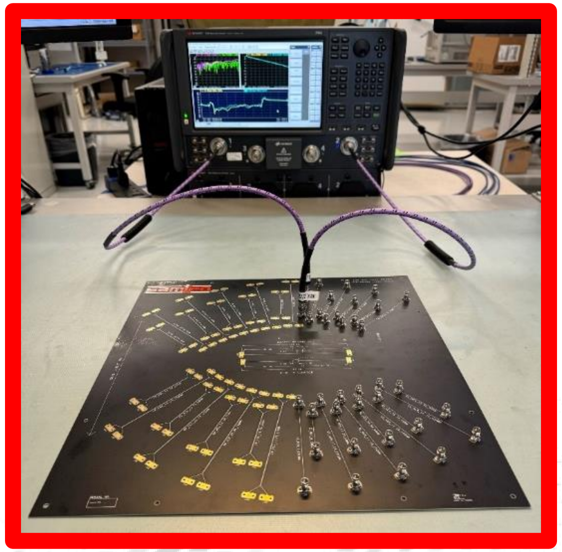


- Larger percent tolerances in the smaller 1.00mm Bore present an in-band VSWR penalty to 50GHz for the extra 60GHz of modal BW.

40 TDR Waveforms per Connector Type







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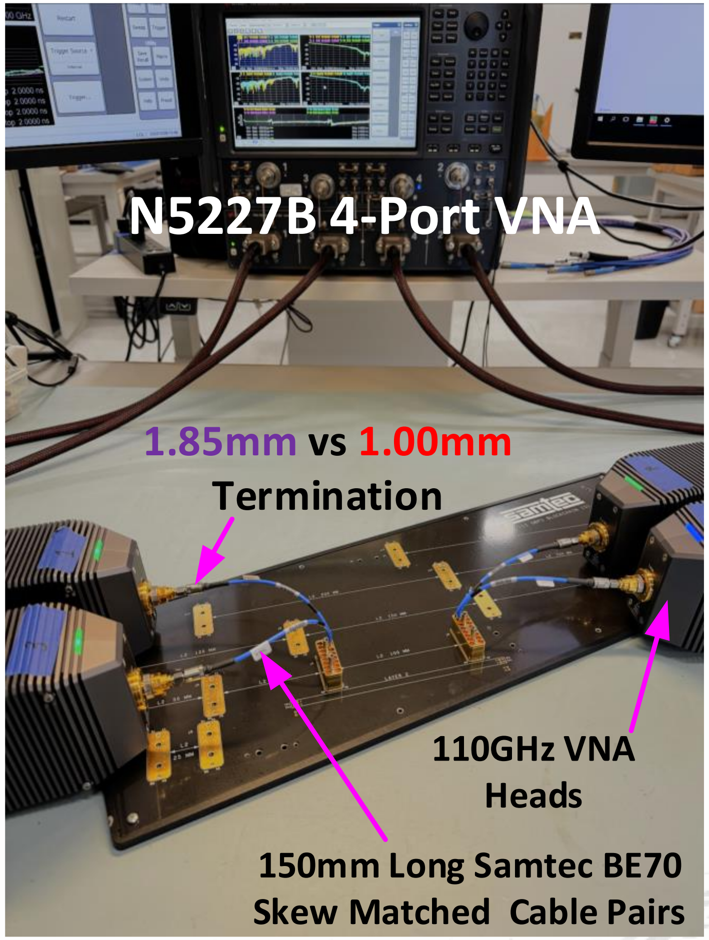
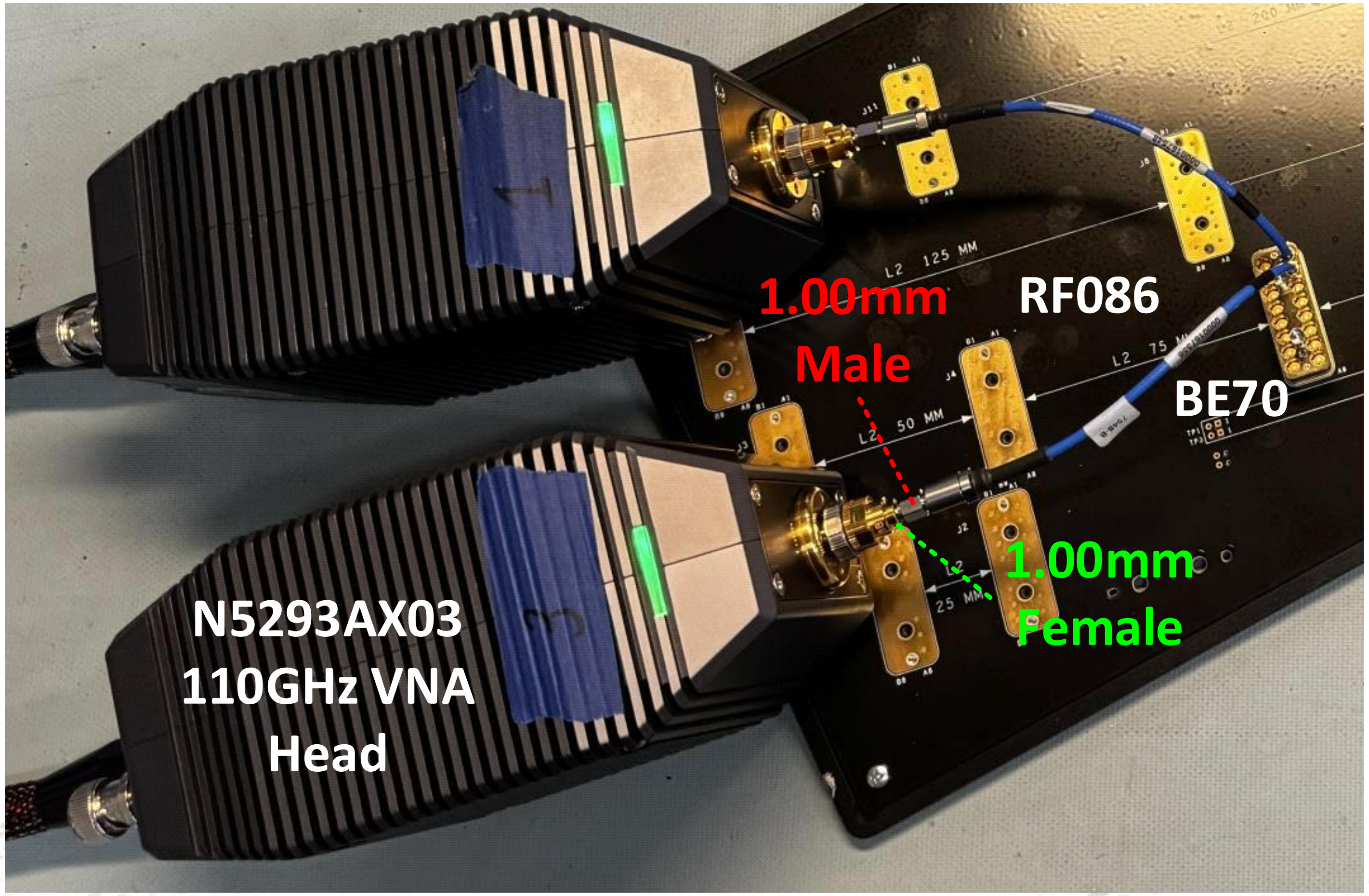
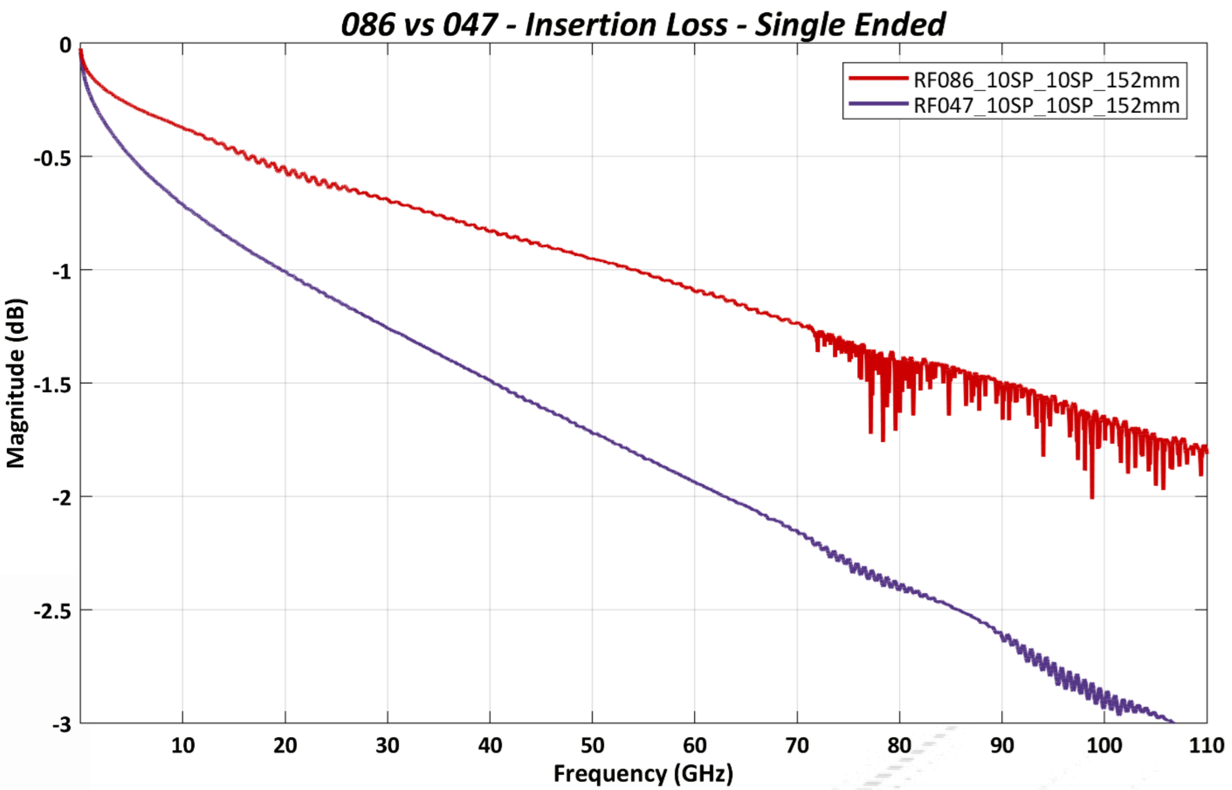
Direct Comparison on Cable Requires Over Moding



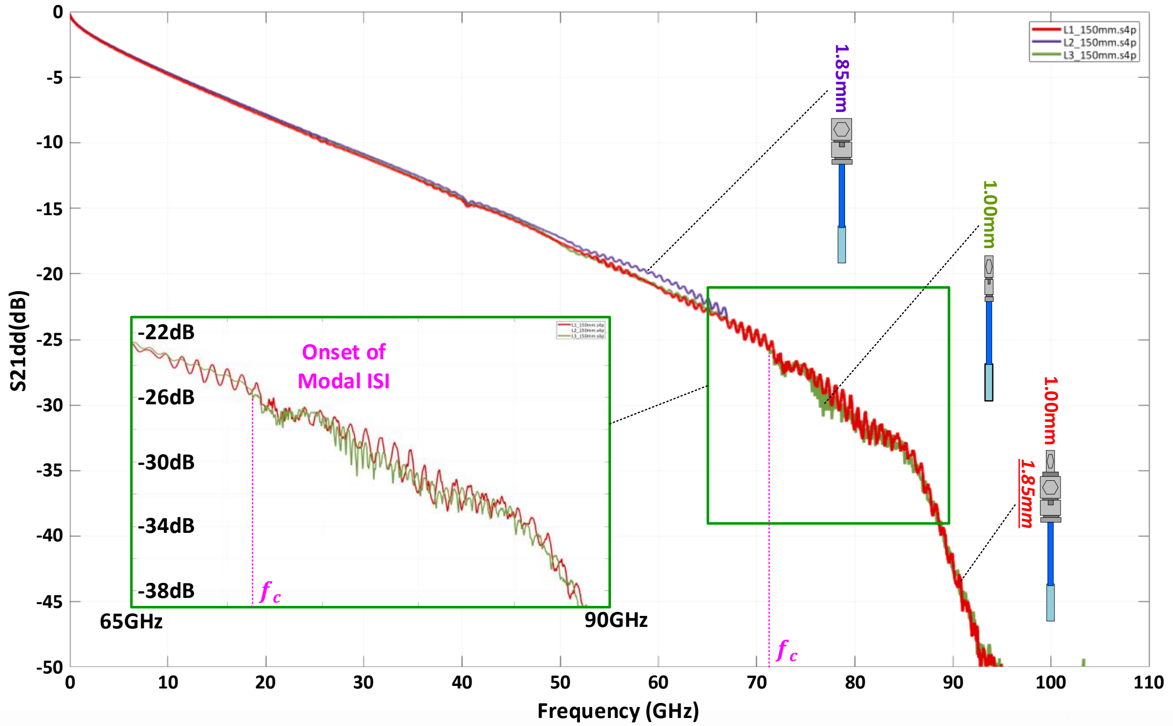


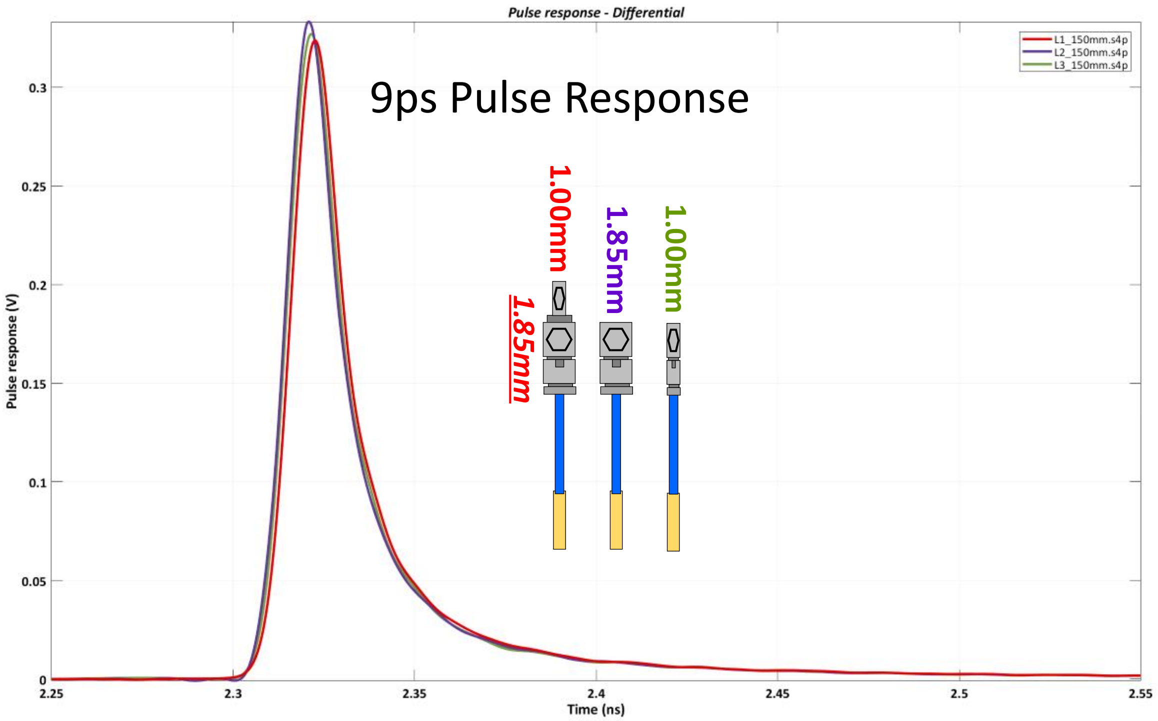
Reducing Coax Diameter to Increase Modal BW

- **Choice 1: Terminate lossier RF047 in both 1.85mm and 1.00mm preserving modal BW at higher IL.**
- **Choice 2: Terminate less lossy RF086 in both 1.85mm and 1.00mm overmoding less lossy cable from Fc to 110GHz.**
- **Same length RF cable assemblies.**
- **Loss increases due to smaller cable cross-section**
- **HOM present in RF086 cable apparent after f_c**



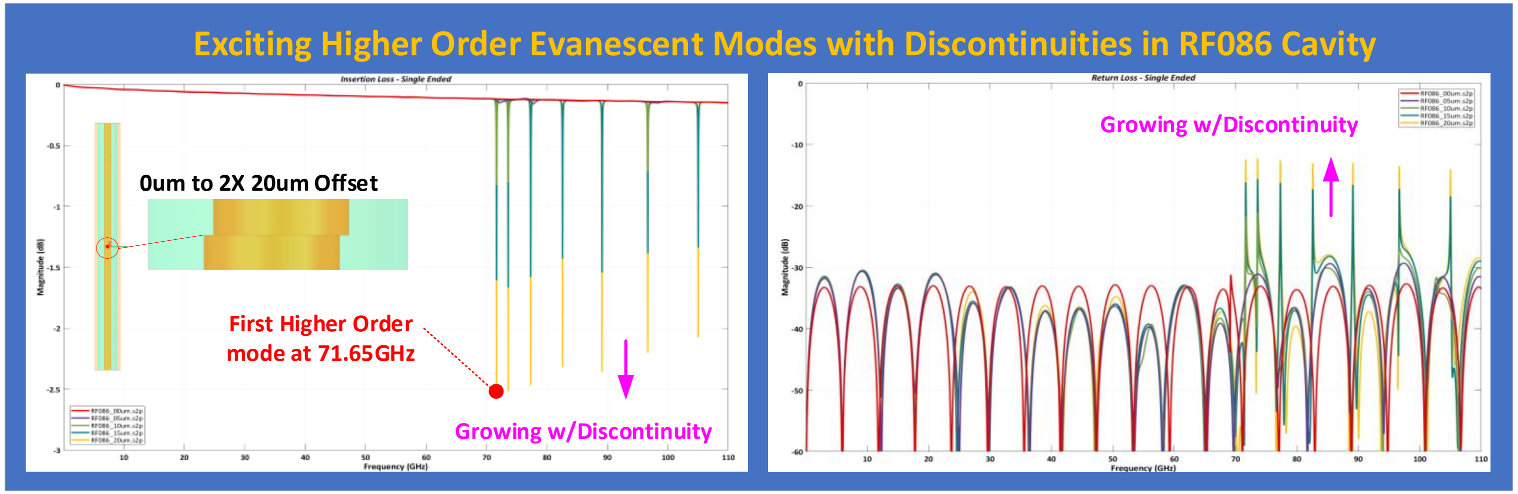
Modal ISI as Insertion Loss Deviation (ILD)

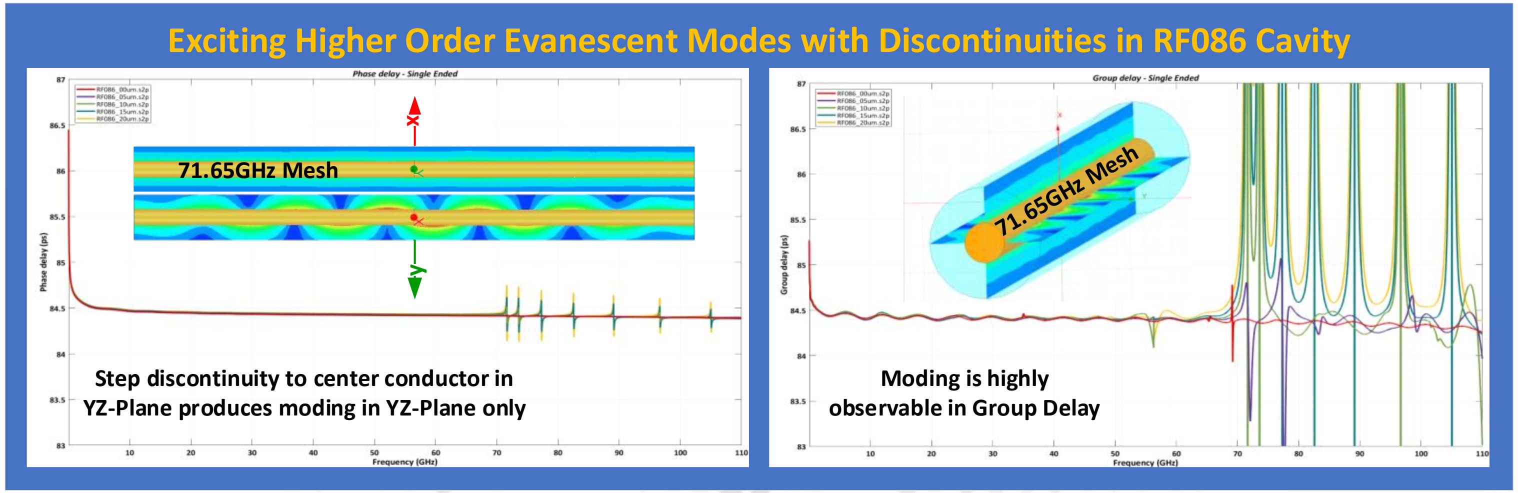




- **Measured 19 dB Loss @ 56 GHz**
- **HOM is more directly observable in 1.00 mm terminated and overmoded RF086 coax**
- **1.85 mm above cutoff is dominated more by impedance mismatch than modal ISI**

Exciting Higher order Modes In Simulation

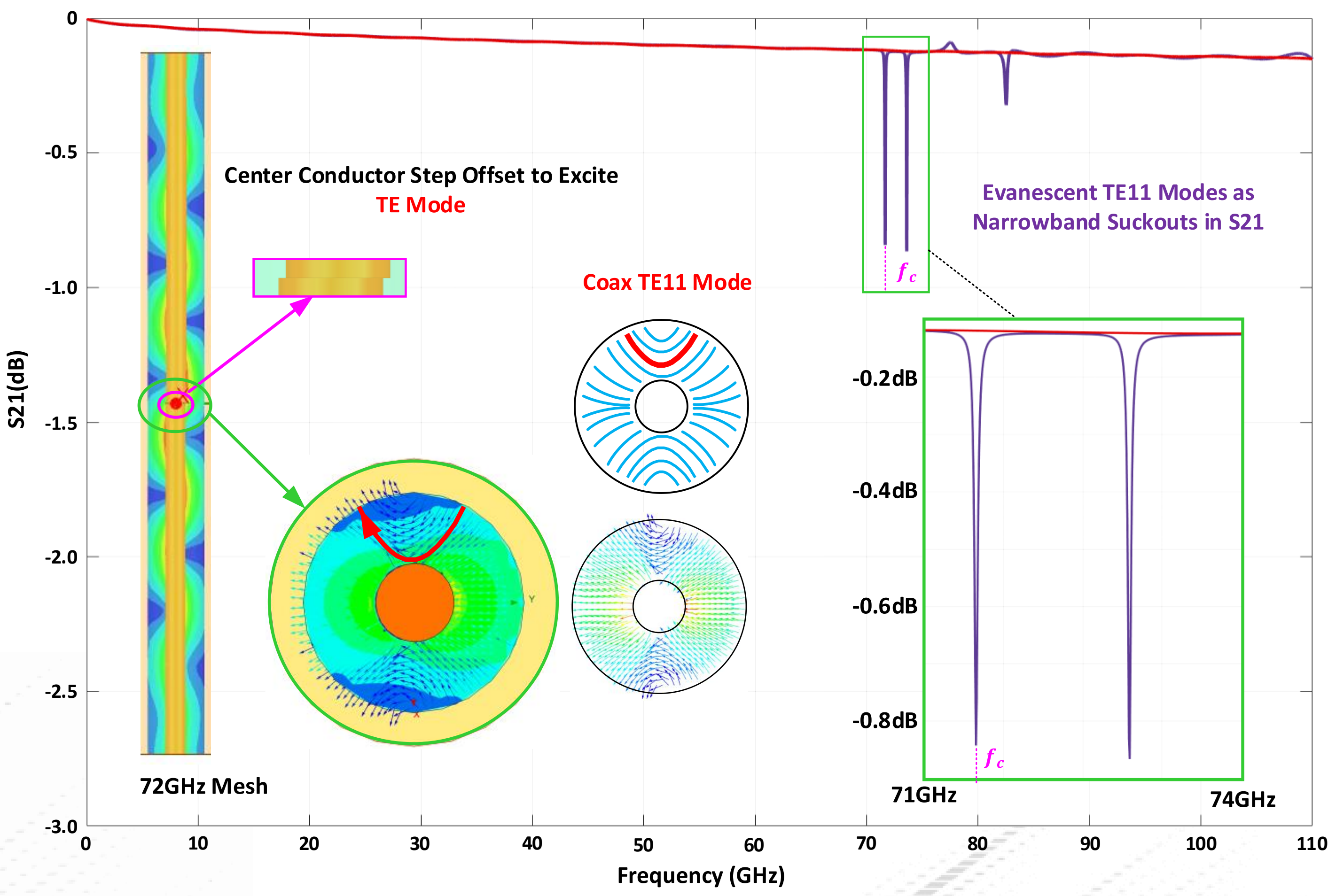




- **Higher Order Modes represent changes in wave momentum wrt to TEM propagation.**
- **Excited with simple center conductor step discontinuity placed inside continuous ground cavities.**
- **'Notch' frequencies in S21 correlate to frequencies from eigen mode solver.**

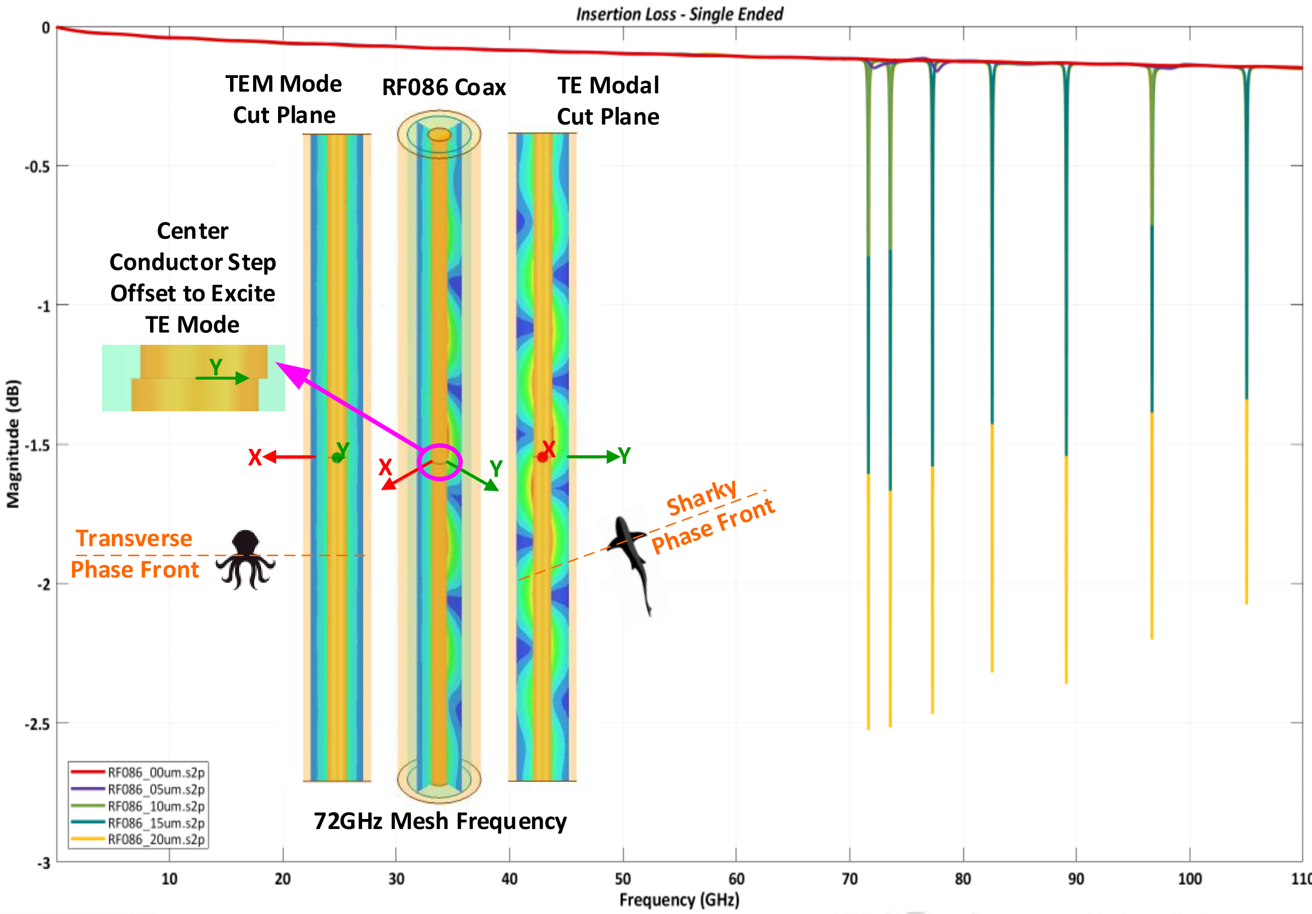
3D EM Model for Cable Moding Signature

- 3D EM model exploring TE11 coaxial mode excitation through center conductor step discontinuities
- Cable cross-section with f_c of 71 GHz
- Evanescent modal excitation present as narrowband suckouts in S21.
- Energy is lost to decay
- Observe TE11 modal cross section signature in wave guide cross section slice

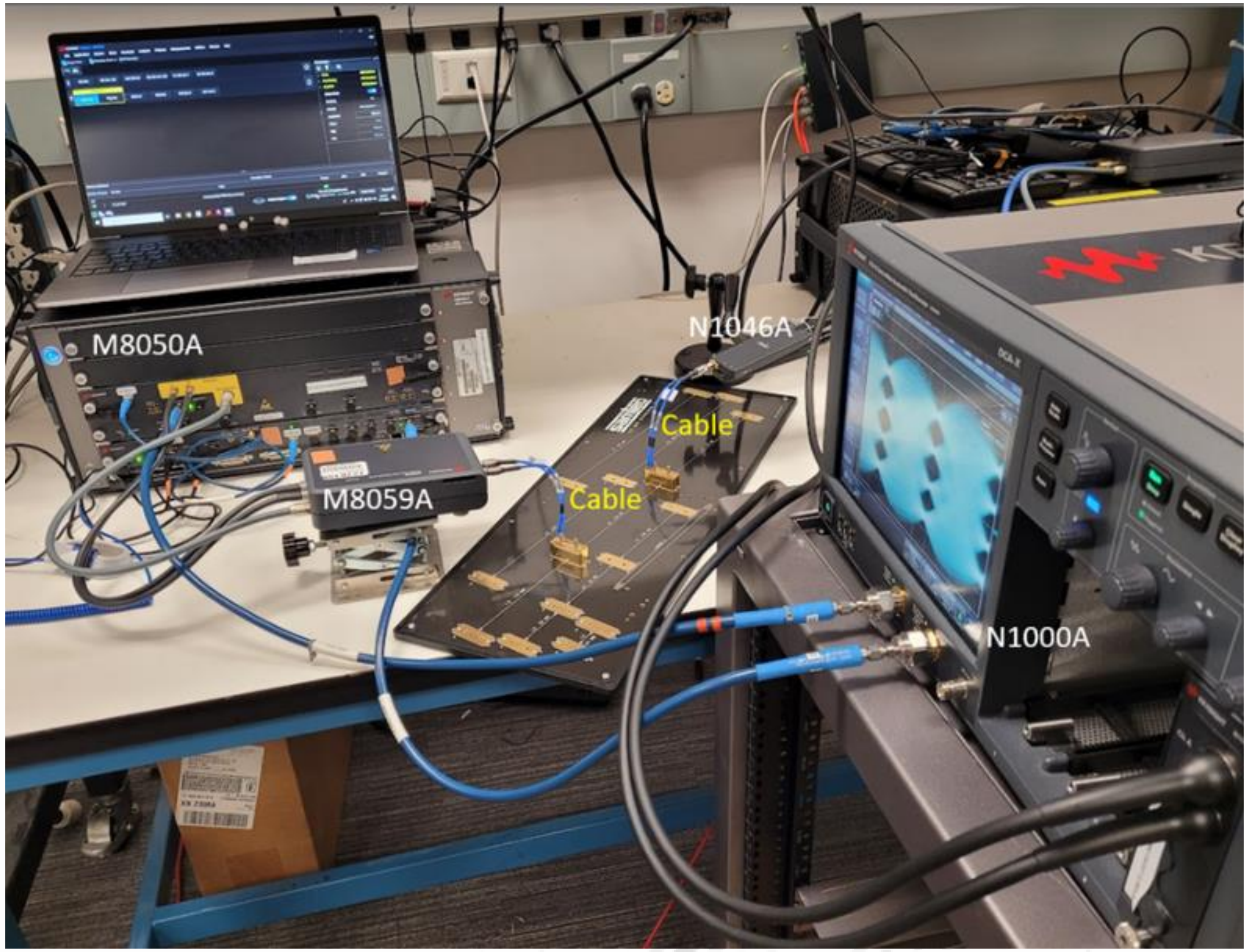


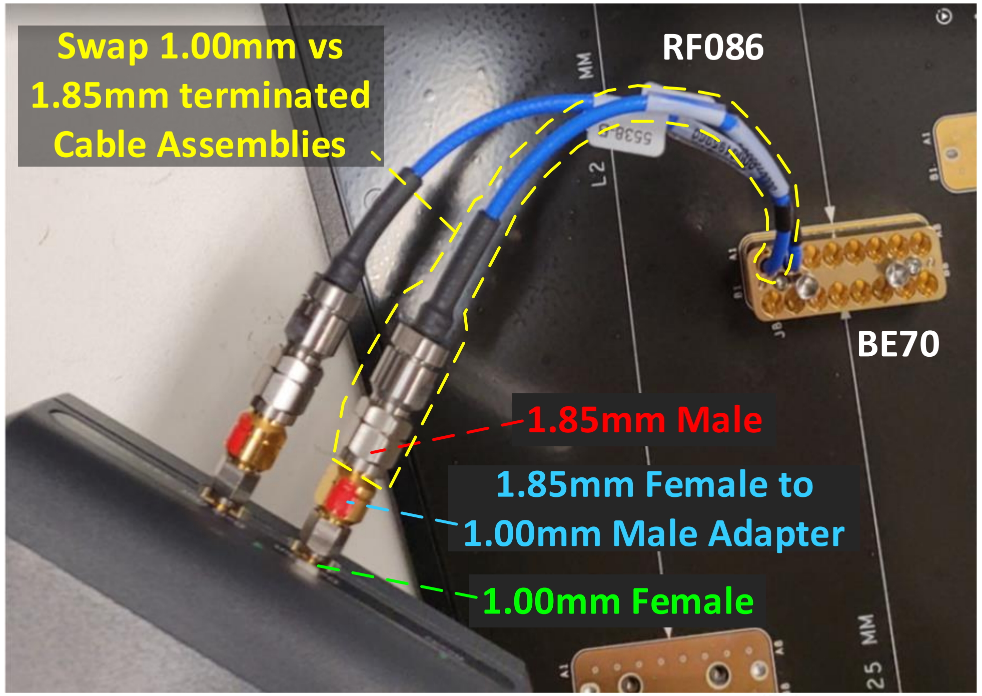
TE and TM Modes as Orthogonal Swimmers

- **Propagation as Swimmers**
  - Assign E-field to Dorsal Fins
  - Assign H-field to Pectoral Fins
  - Assign Pointing Vector to Noise
- **Sharkies swim left to right**
  - Dorsal fin transverse (TE mode swimmer)
- **Porpoises swim up and down**
  - Pectoral fin transverse (TM mode swimmer)
- **Then what swims strait ahead….?**
  - Let Octupus = TEM Mode
- **In practice, the octopus TEM pulse gives birth to an evanescent sharkie at locations where momentum changes. The baby shark TE mode can not swim around the coax center conductor and decays reflectionless. Scarred octopus pulse makes it to far end Rx.**



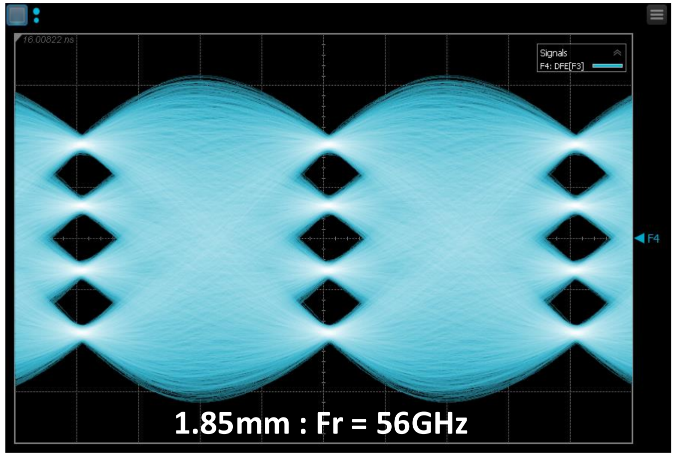
224Gbps Time Domain Test Setup



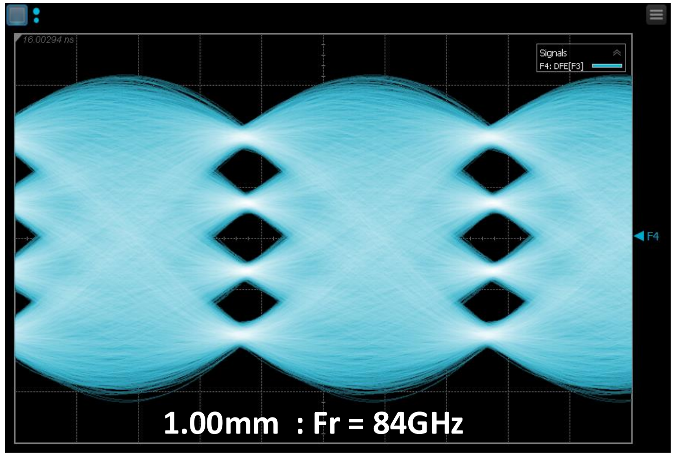


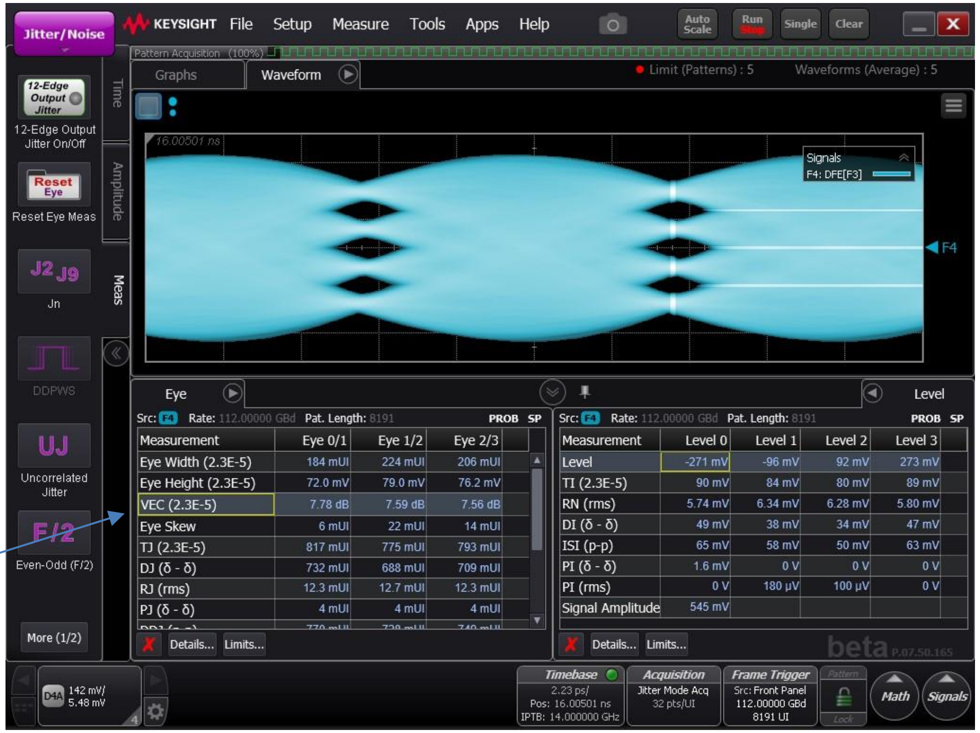
224Gbps Time Domain Results

Min Connector and Rx BW



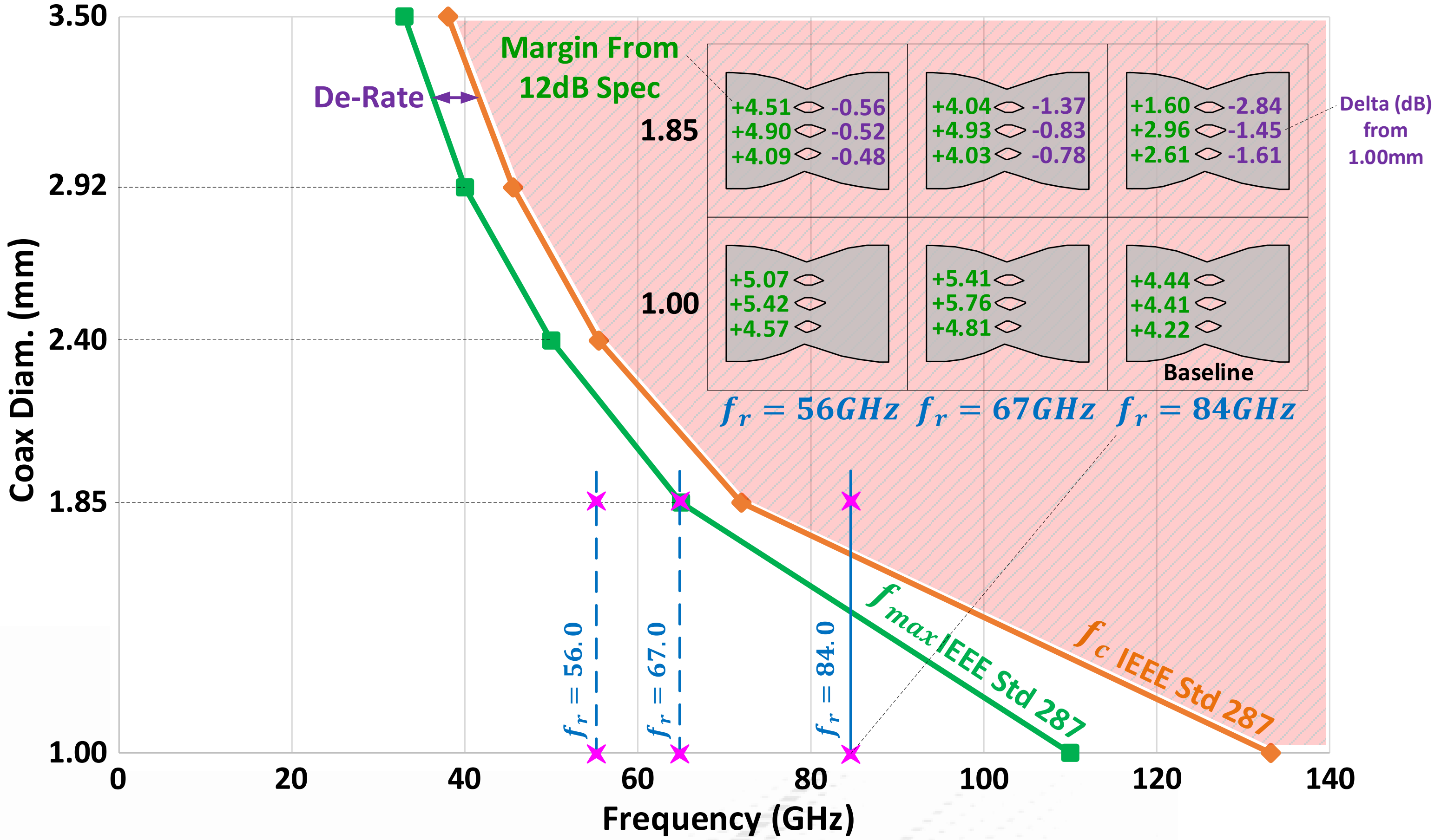
Max Connector and Rx BW





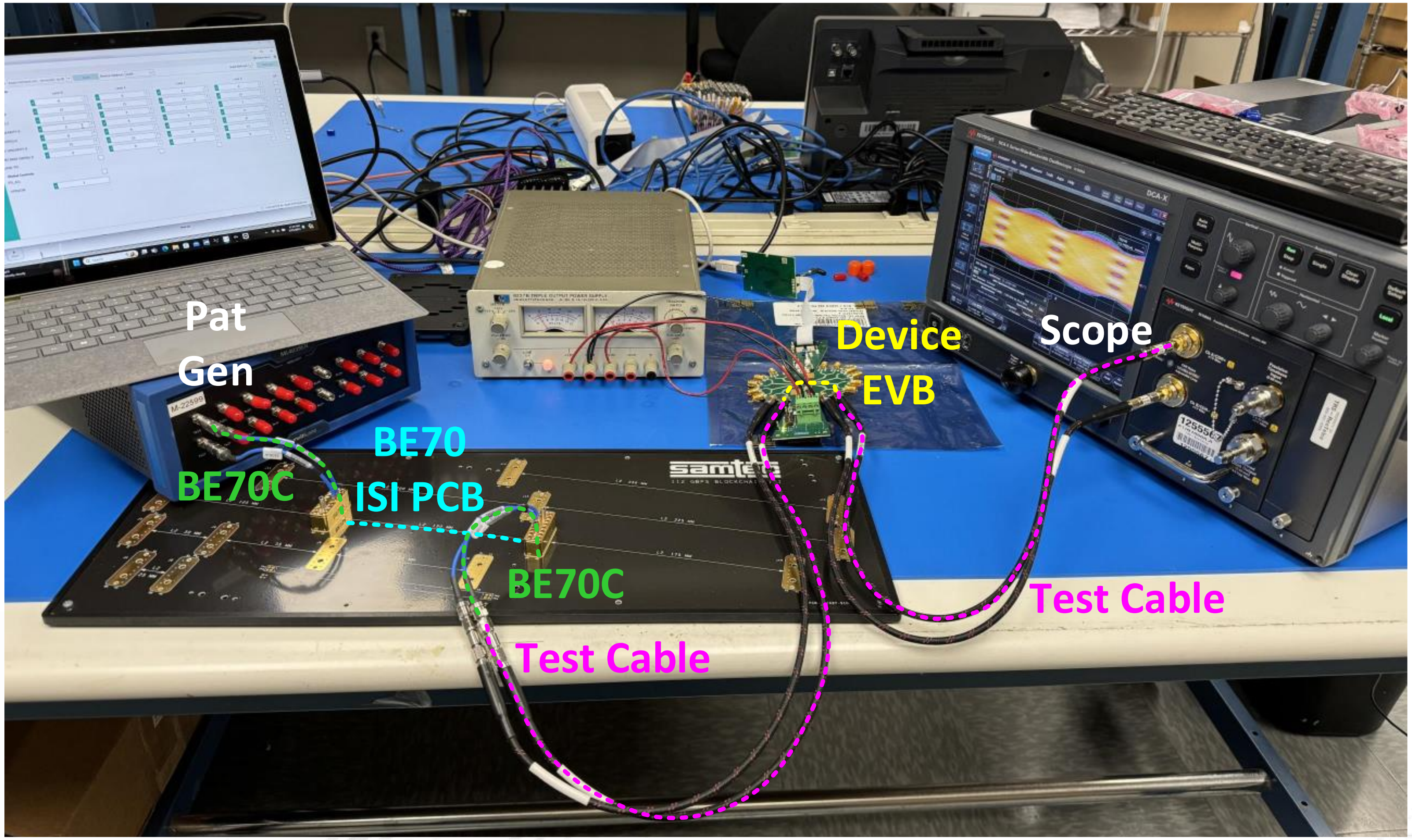
- Quantifying differences requires statistical channel quantities
- Statistical channel metrics requires SerDes equalizer emulation
- Chose to quantify BW differences on VEC

224Gbps VEC Findings

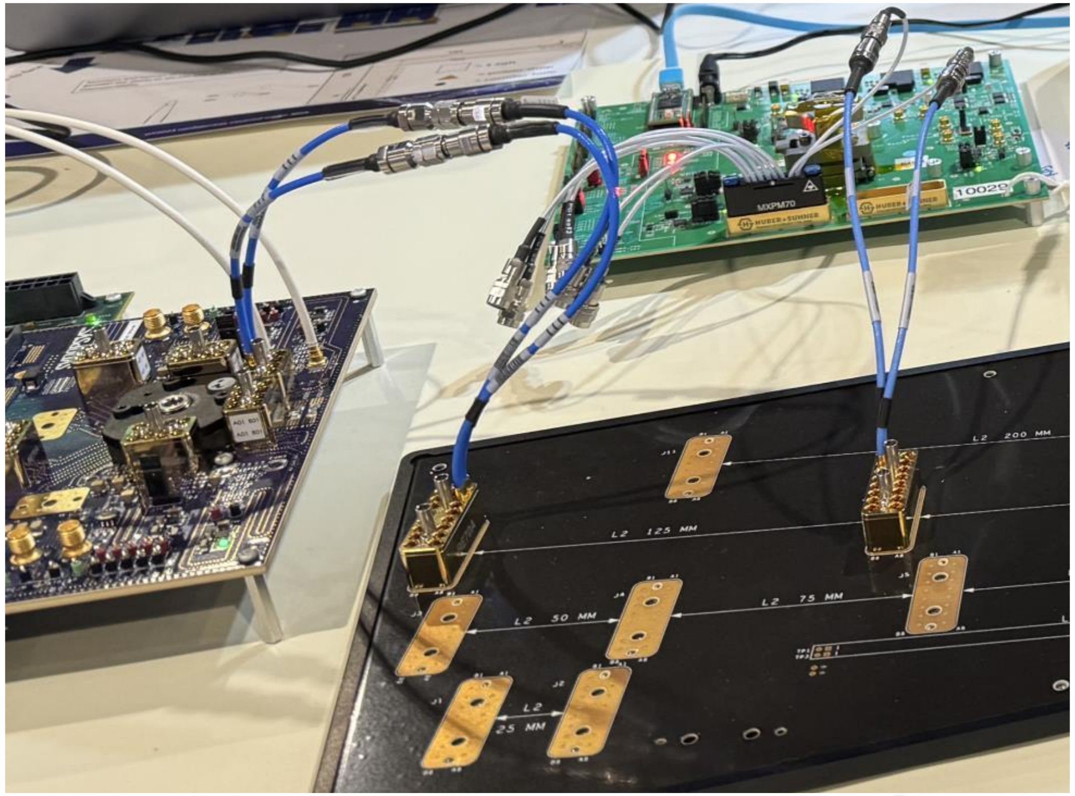


- **VEC01, VEC12, VEC23 penalties (dB) from the 1.00mm Baseline**
- **VEC01, VEC12, VEC23 Margin (dB) to assumed 12dB limit**
- **1.0 mm connector best VEC at f_r= 67 GHz**
- **Lower f_r decreases VEC and Delta (dB) 1.85 mm**

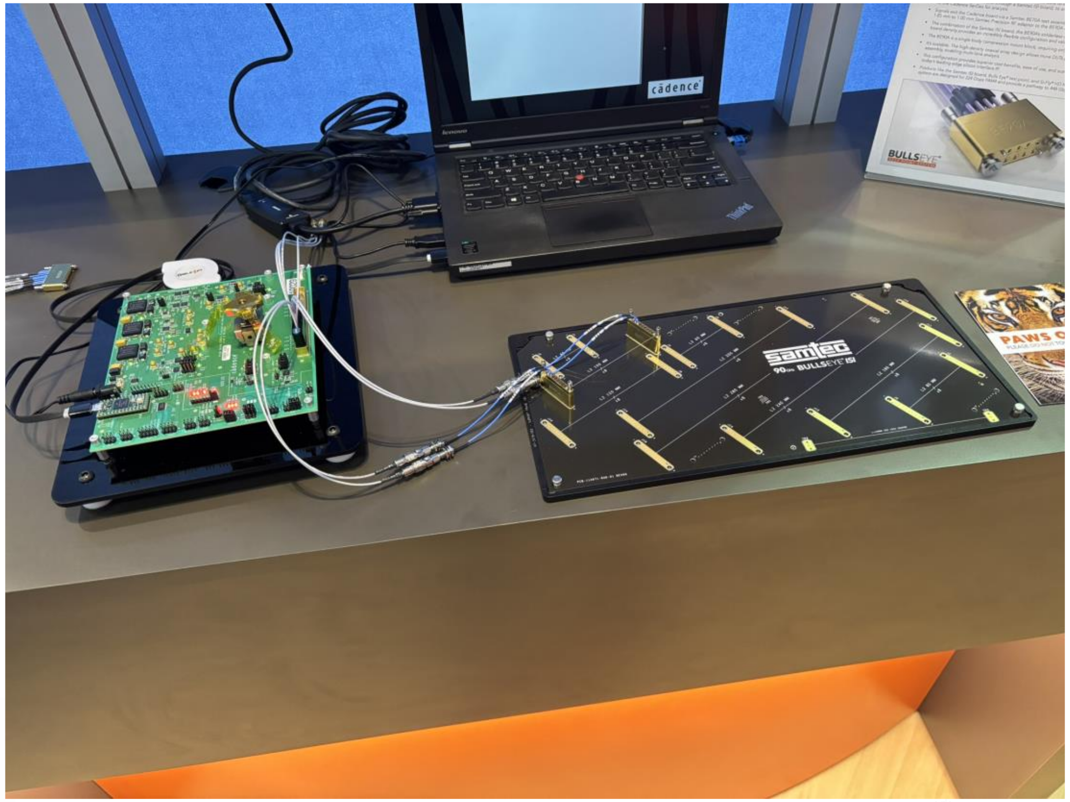
Part 2: Channel Emulators



BE70 ISI and BE90 ISI in Functional Verification



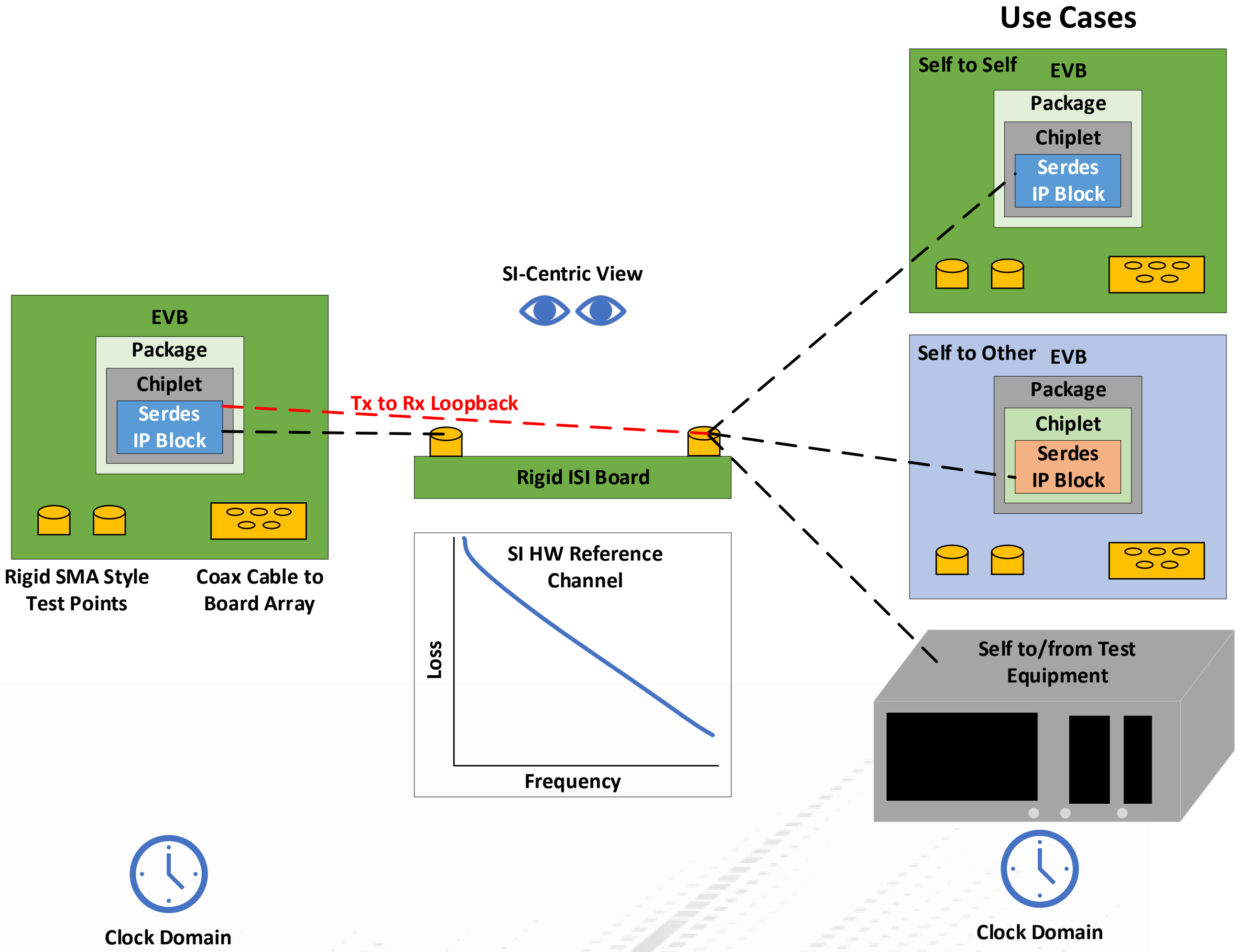
BE70 ISI in 224G SerDes IP Interoperability



BE90 ISI in 224G SerDes IP loopback performance characterization

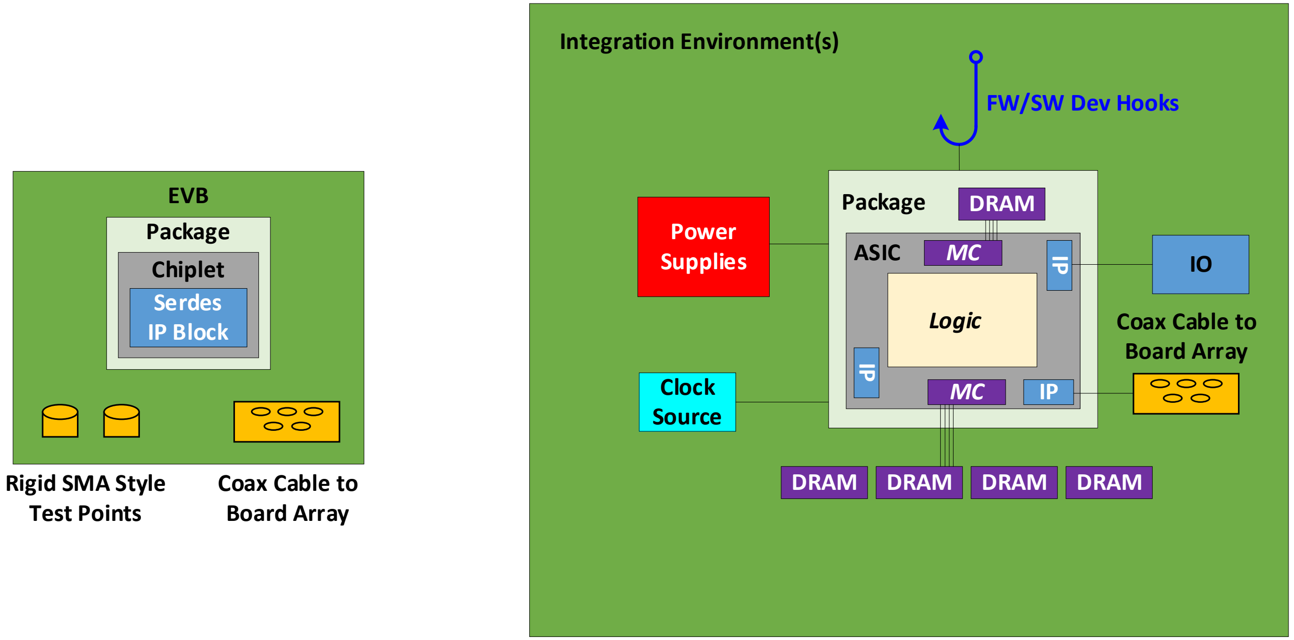
IEEE Webinar: *Precision mm-Wave Test Fixtures for 400Gbps Phys*

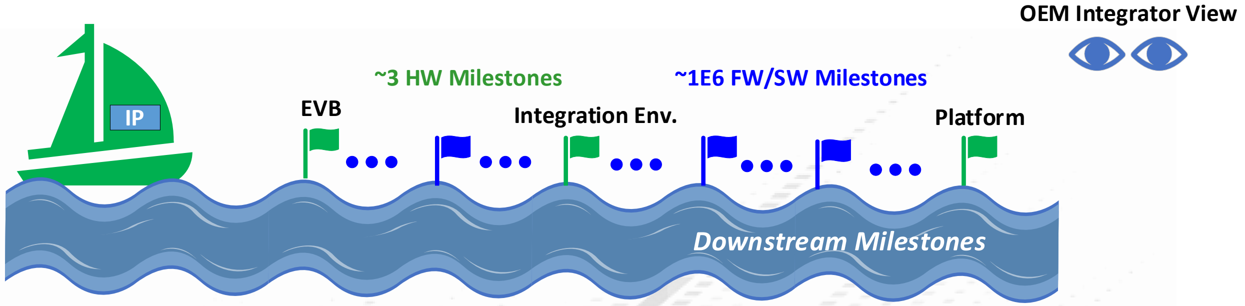
Role of ISI Boards in SerDes Verification: SI View



- **Provide a physical hardware reference for adding (sometimes stepped) and repeatable high speed digital signal distortion.**
- **Relative steps are useful for Phy characterization.**
- **Absolute channel loss is useful for validating dynamic range or demonstrating performance at known compliance points.**
- **Useful in functional performance testing**
  - Self to self in loopback or across clock domains
  - Self to other for interop

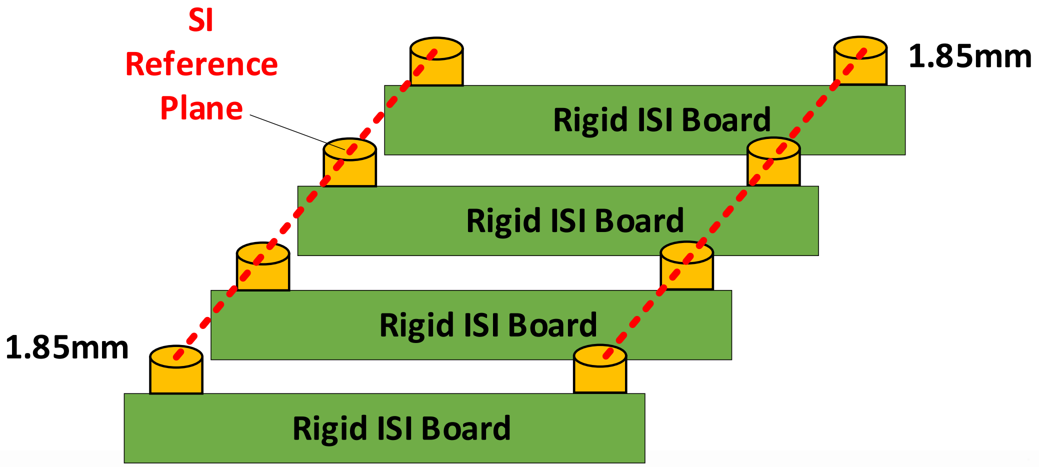
Role of ISI Boards in SerDes Verification: Integrator View



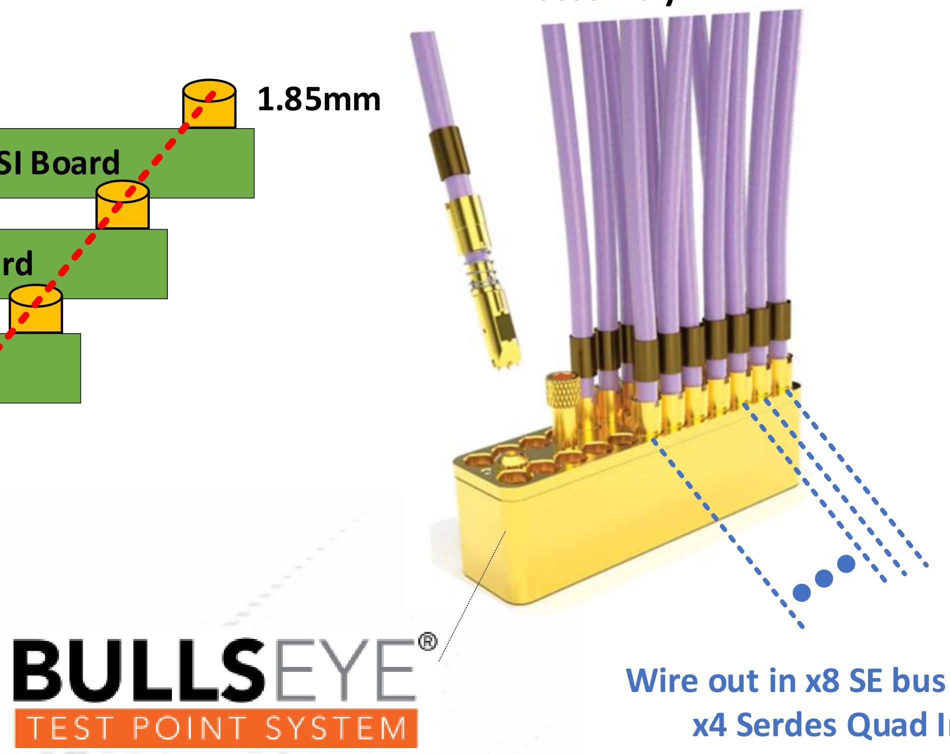


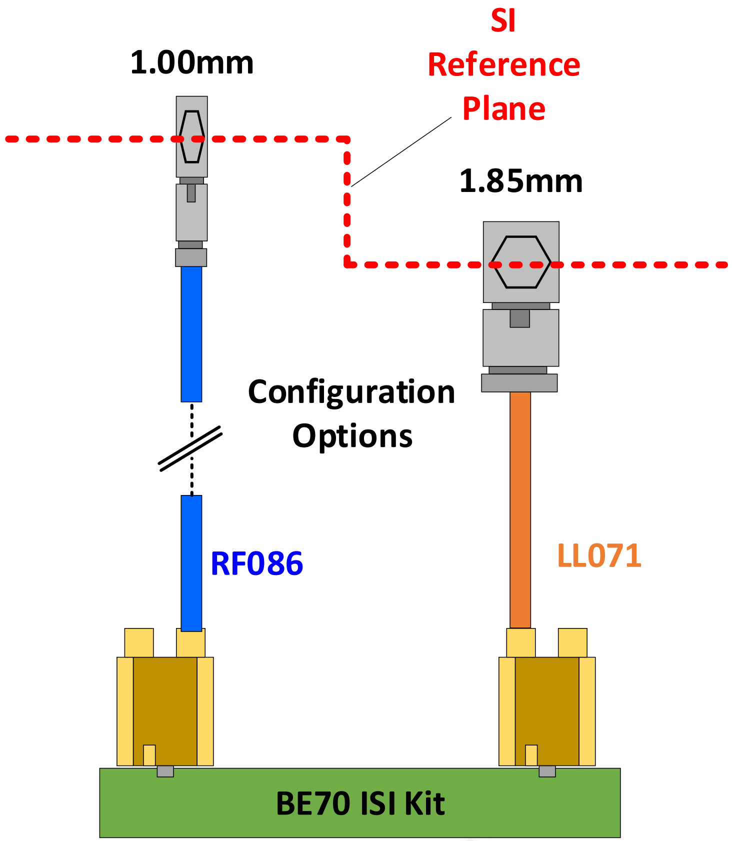
- **Do I have SerDes lane to lane performance penalties due to?**
  - Clock Fanout
  - Power Fanout
  - Logic Step Loads
  - DRAM Interface Activity
- **Can I quantify these through FW/SW/HW development milestones?**
- **Why does FW/SW get to save new text files for revs while HW has to procure real material and tool it?**
- **I think I need a configurable multi-lane ISI channel test asset inside my integration ecosystem.**

Evolution to Parallel ISI Assemblies



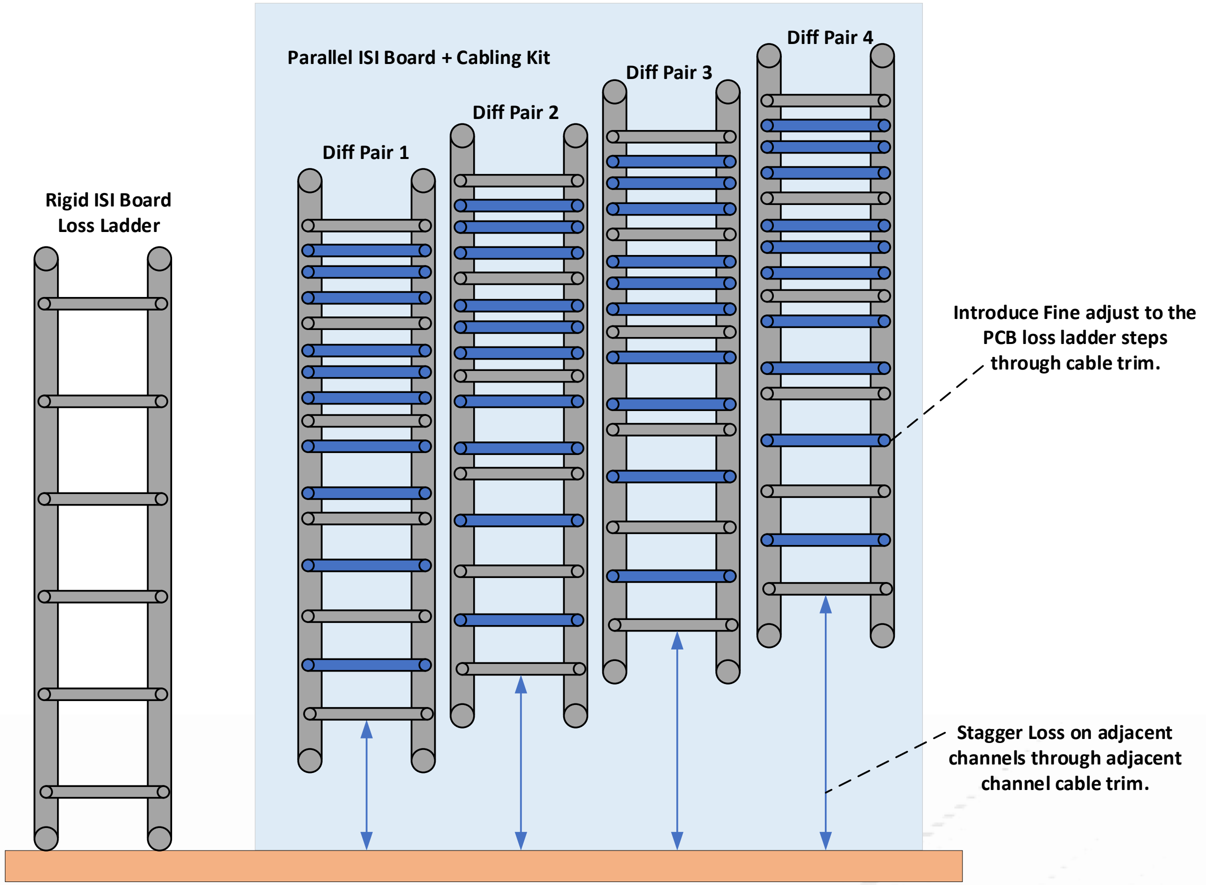
Extend the Rigid ISI Board Channel reference to the far end of a high performance arrayed Microwave Grade test cable assembly

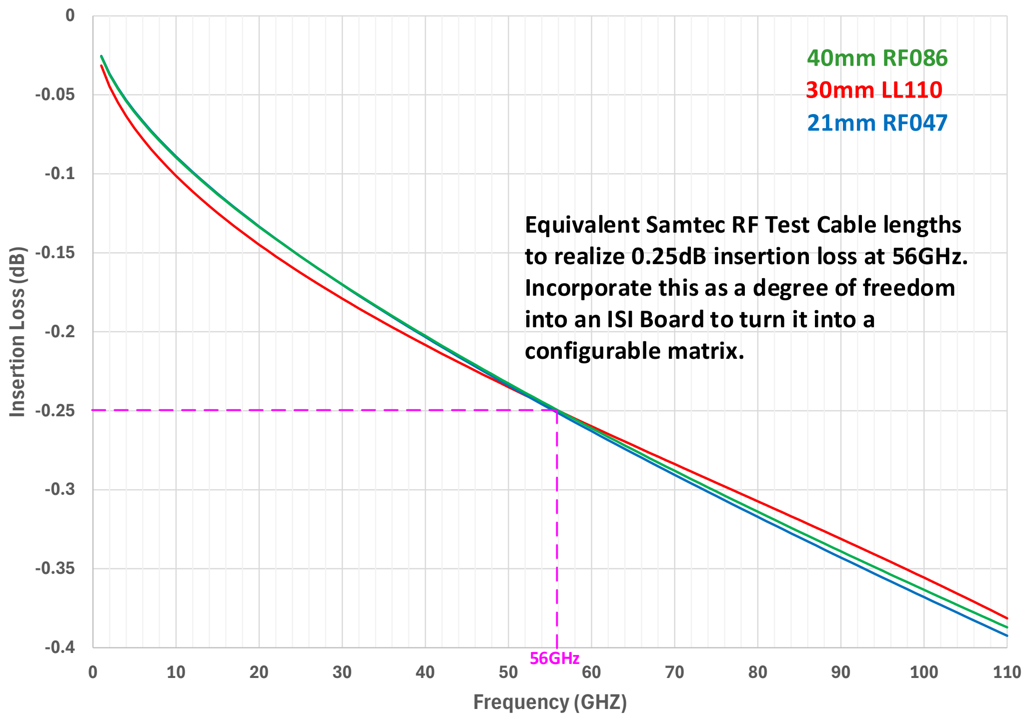




Wire out in x8 SE bus to support a x4 Serdes Quad Interface

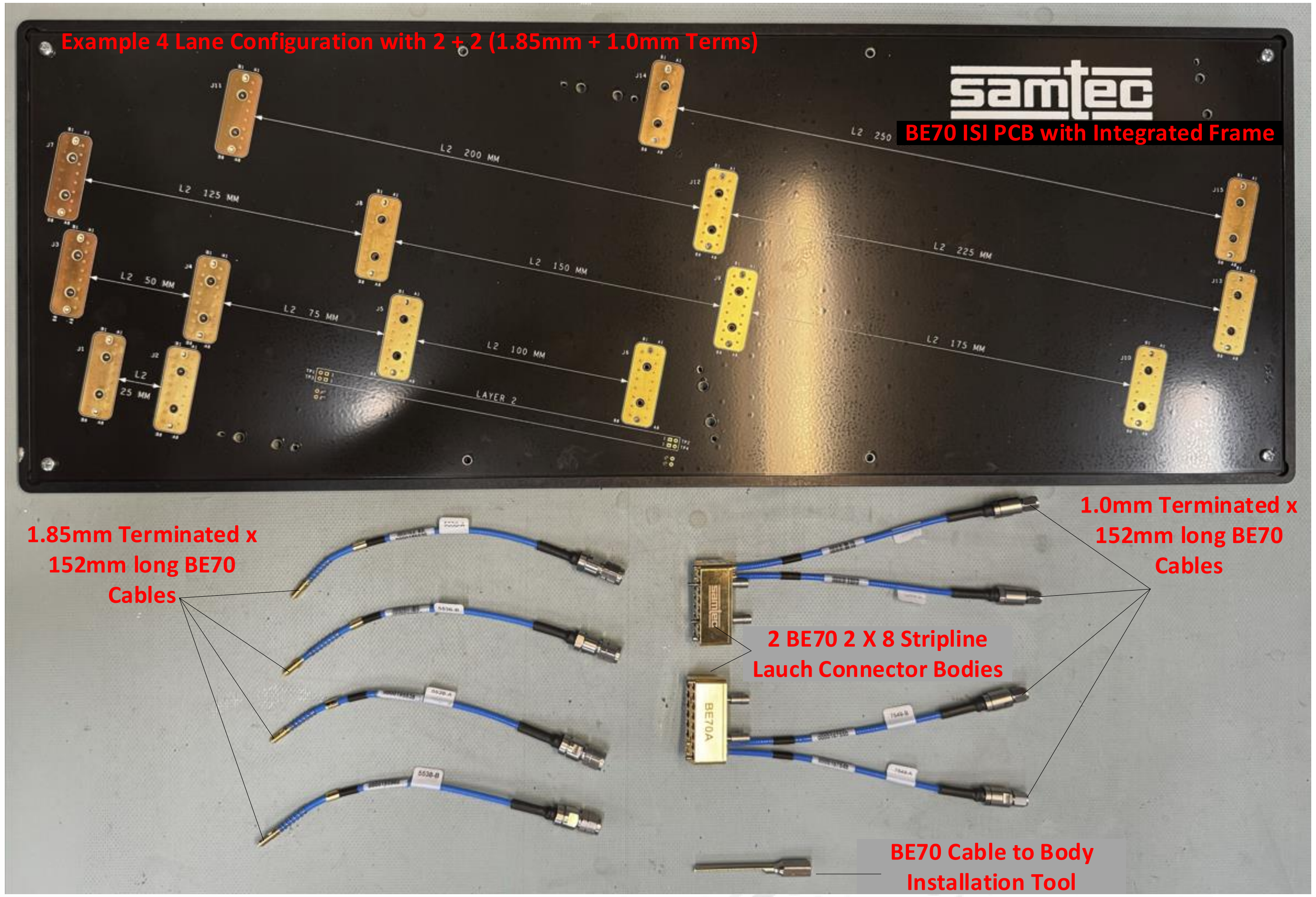
Configurability with SI Performance

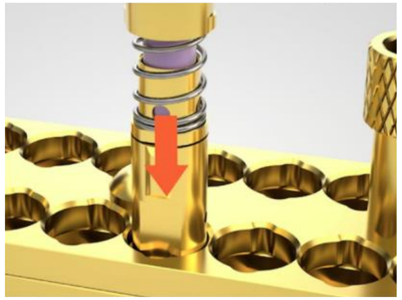


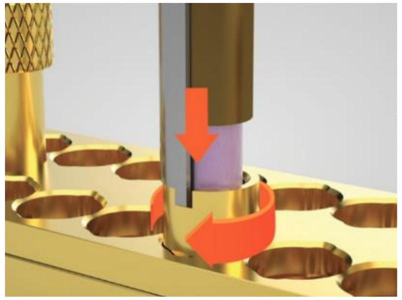


A microwave grade test cable assembly is the only thing that makes practical sense to 'configure' at 90GHz. So stick them inside the channel emulator.

Unlocking Configurability

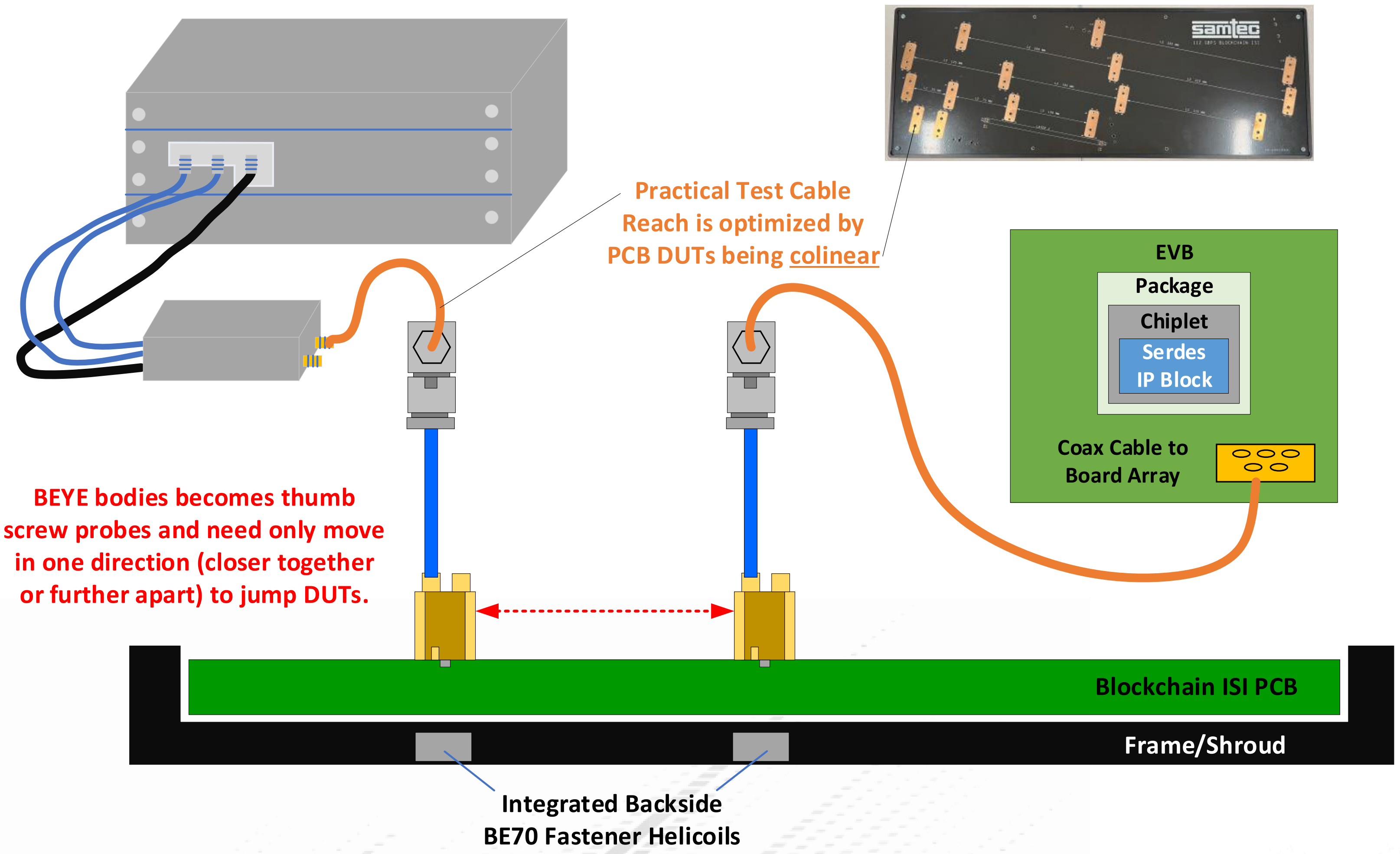






Samtec Bulls Eye® Test Point System supports field serviceable cable installation leveraged as precision test fixture configurability.

Managing External Test Cable Lengths



- Hosting the loss generating PCB in an integrated backplate and frame preserves access to dynamic range with limited test cable reach.
- BEYE bodies become thumb screw probes to move around matrix.
- BEYE bodies only need to move in X direction to open or close the span. All translation in Y direction is handled by sliding the assembly on the backplate like an XY positioning table.

Managing External Test Cable Lengths

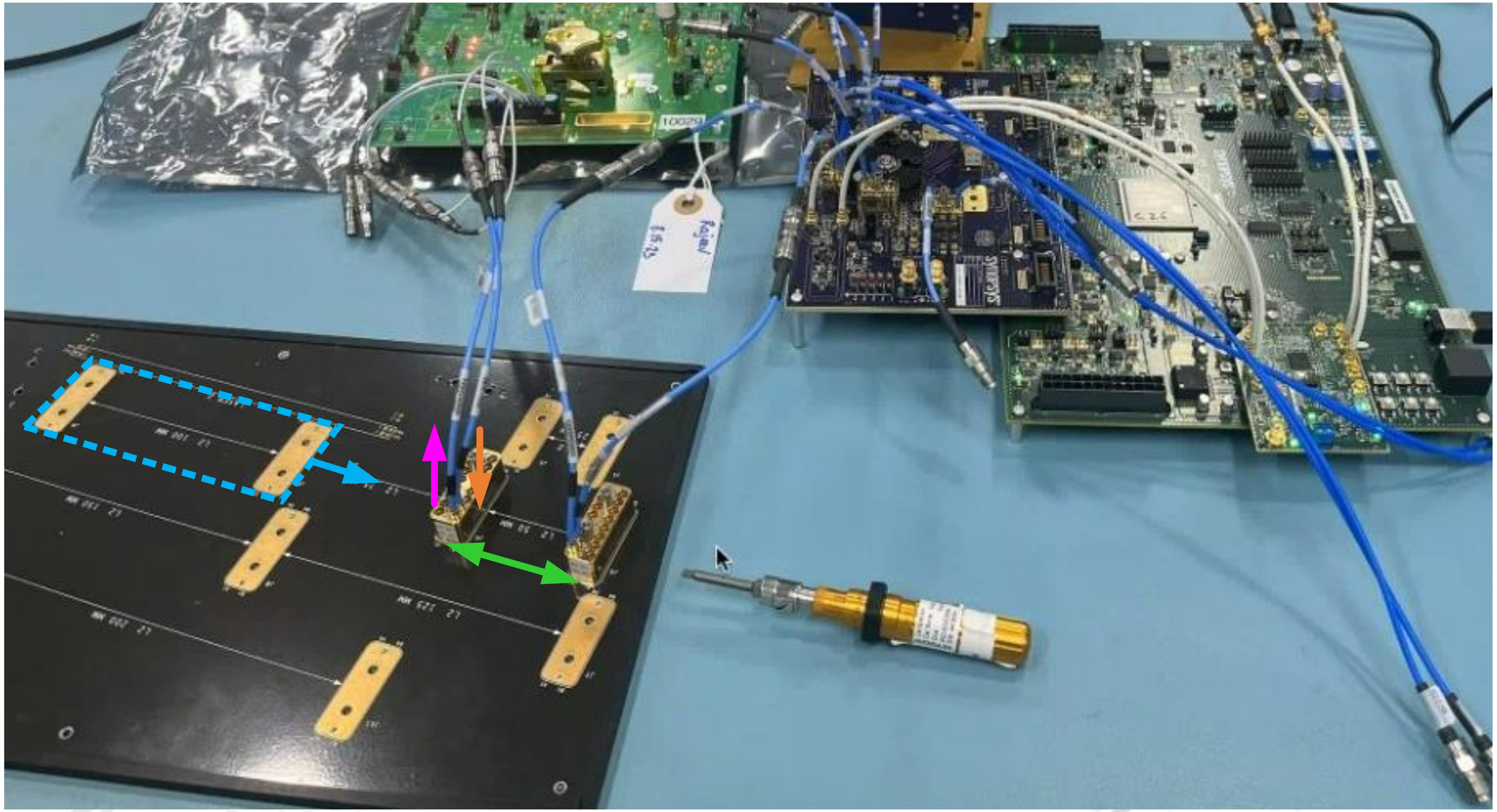
De-mate Bulls Eye Bodies from integrated frame helicoils with 2 thumb screws

Slide PCB in frame to new position

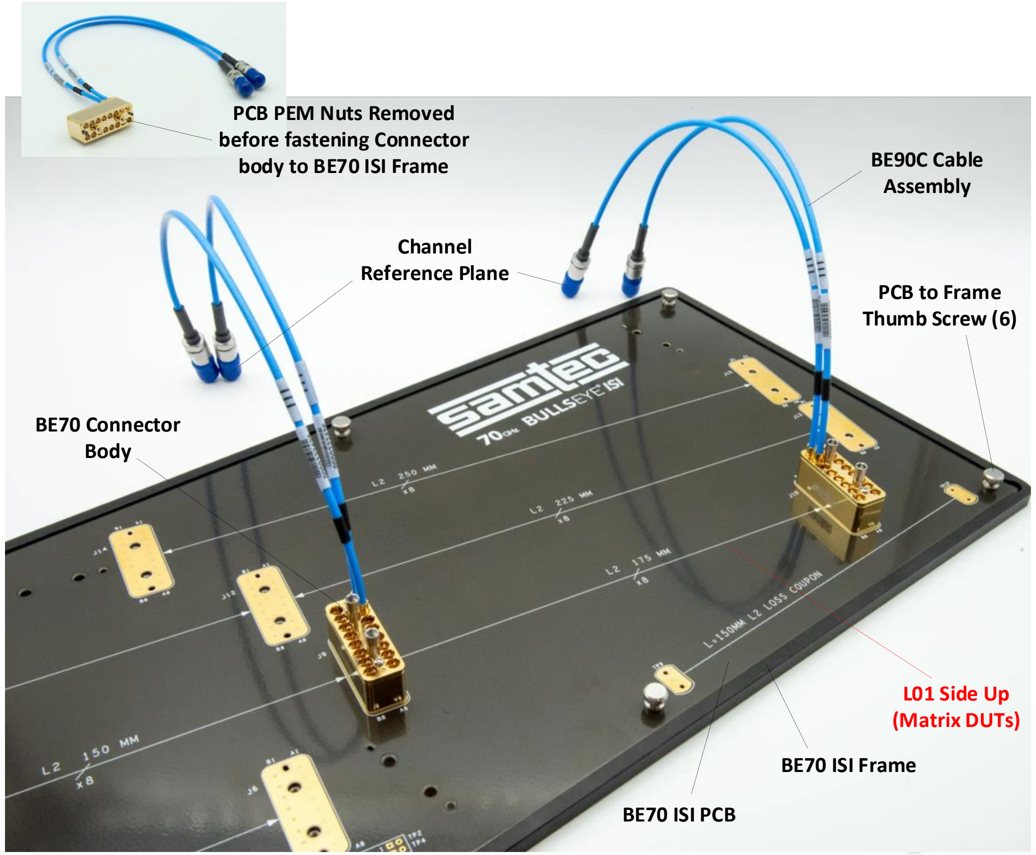
Minimal cable respanning

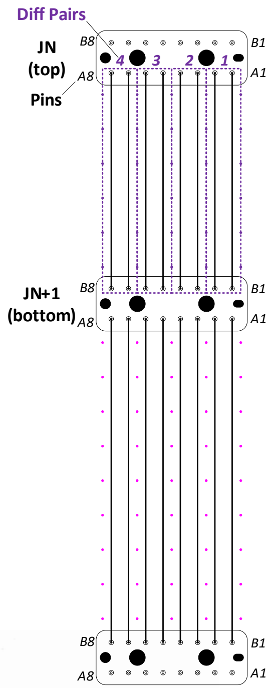
Re-mate Bulls Eye Bodies with 2 thumb screws

Preserved Dynamic Range



BE70 ISI Kit Assembly (50 Ohm SE Bus Routing)



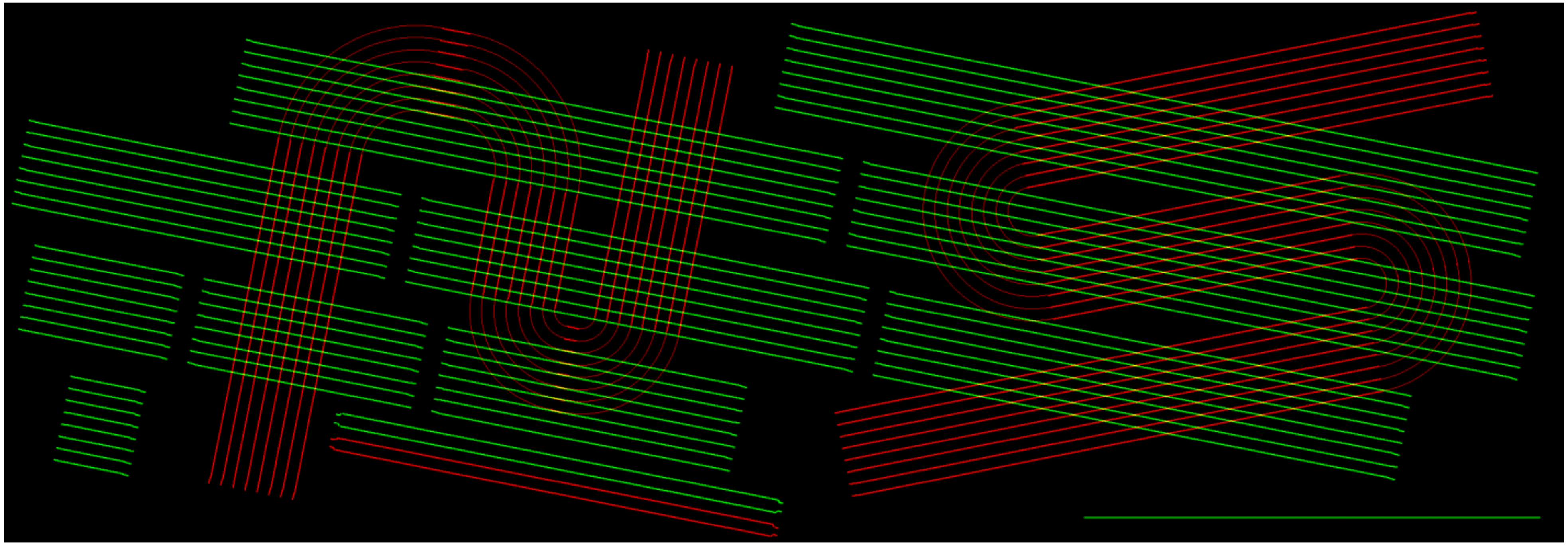


Every DUT Length Has this Relationship logically and spatially

REF_Des	Pin	Net	Pin	REF_Des	Layer	Bit	Byte Lane	Length (mm)
J1	A1	J1A1_J2B1	B1	J2	S02	B000	1	25
J1	A2	J1A2_J2B2	B2	J2	S02	B001	1	25
J1	A3	J1A3_J2B3	B3	J2	S02	B002	1	25
J1	A4	J1A4_J2B4	B4	J2	S02	B003	1	25
J1	A5	J1A5_J2B5	B5	J2	S02	B004	1	25
J1	A6	J1A6_J2B6	B6	J2	S02	B005	1	25
J1	A7	J1A7_J2B7	B7	J2	S02	B006	1	25
J1	A8	J1A8_J2B8	B8	J2	S02	B007	1	25
J3	A1	J3A1_J4B1	B1	J4	S02	B008	2	50
J3	A2	J3A2_J4B2	B2	J4	S02	B009	2	50
J3	A3	J3A3_J4B3	B3	J4	S02	B010	2	50
J3	A4	J3A4_J4B4	B4	J4	S02	B011	2	50
J3	A5	J3A5_J4B5	B5	J4	S02	B012	2	50
J3	A6	J3A6_J4B6	B6	J4	S02	B013	2	50
J3	A7	J3A7_J4B7	B7	J4	S02	B014	2	50
J3	A8	J3A8_J4B8	B8	J4	S02	B015	2	50
J4	A1	J4A1_J5B1	B1	J5	S02	B016	3	75
J4	A2	J4A2_J5B2	B2	J5	S02	B017	3	75
J4	A3	J4A3_J5B3	B3	J5	S02	B018	3	75
J4	A4	J4A4_J5B4	B4	J5	S02	B019	3	75
J4	A5	J4A5_J5B5	B5	J5	S02	B020	3	75
J4	A6	J4A6_J5B6	B6	J5	S02	B021	3	75
J4	A7	J4A7_J5B7	B7	J5	S02	B022	3	75
J4	A8	J4A8_J5B8	B8	J5	S02	B023	3	75

See: BE70_ISI_Netlist_Dist.xlsx

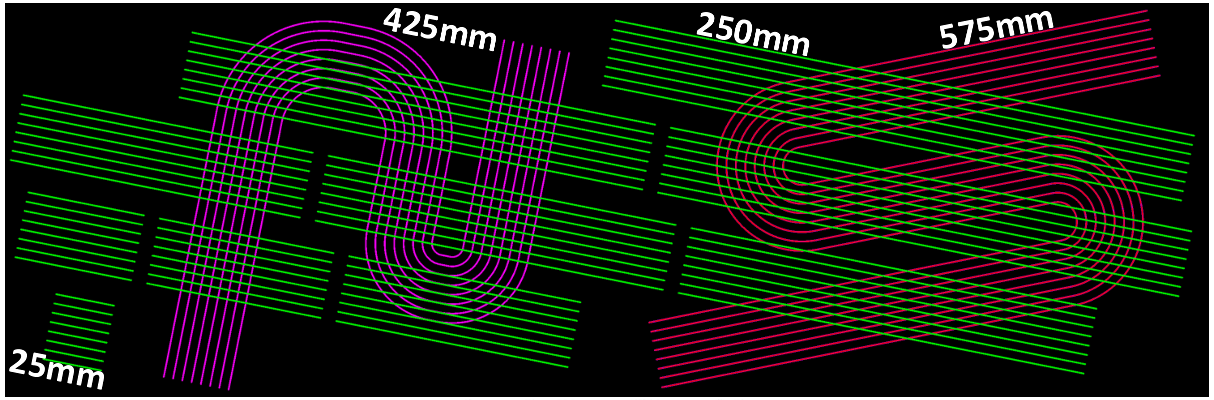
BE70 ISI Kit SE Bus Routing (~2.5 dB/inch @ 56 GHz)

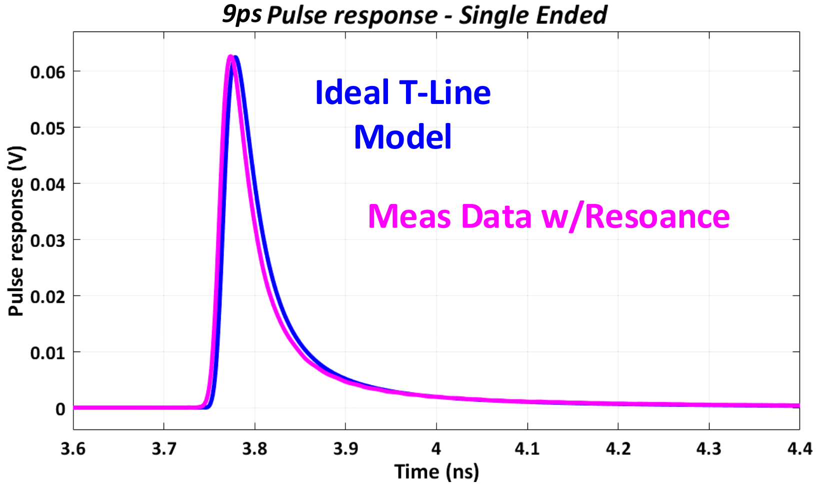


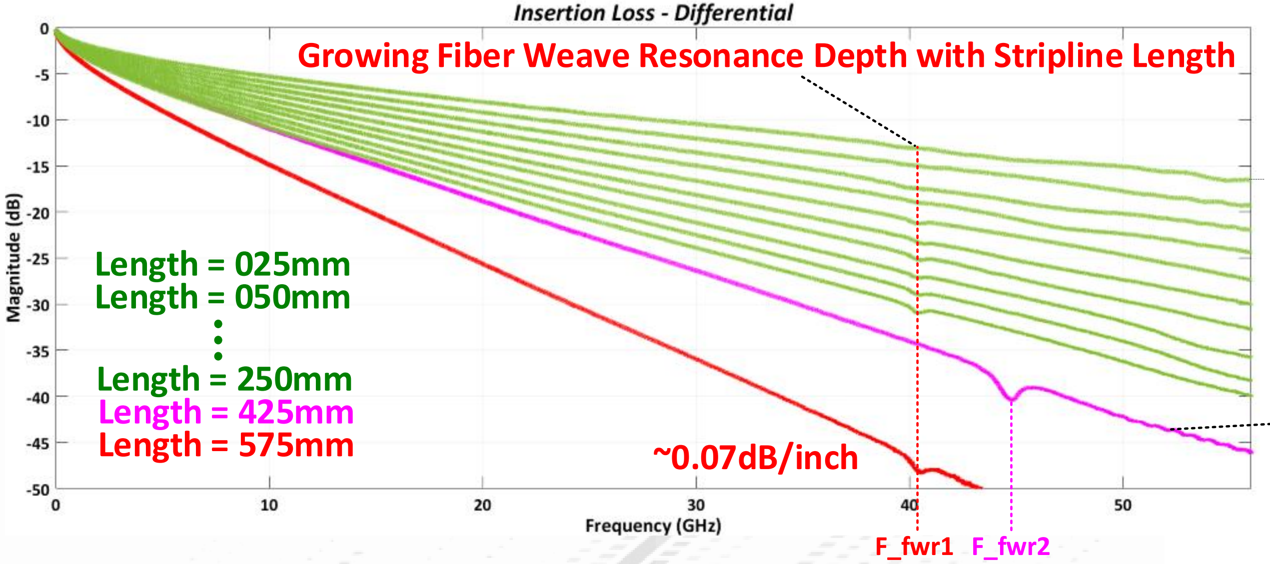
- DUTs: 12 Different x8 lengths each capable of supporting a x4 SerDes quad.
- 10 stepped ladder DUTs on topside. 2 Long S-Bend DUTs for 112 Gbps - 128Gbps LR type channels on backside.
- 540 mm X 190 mm Board Form Factor.

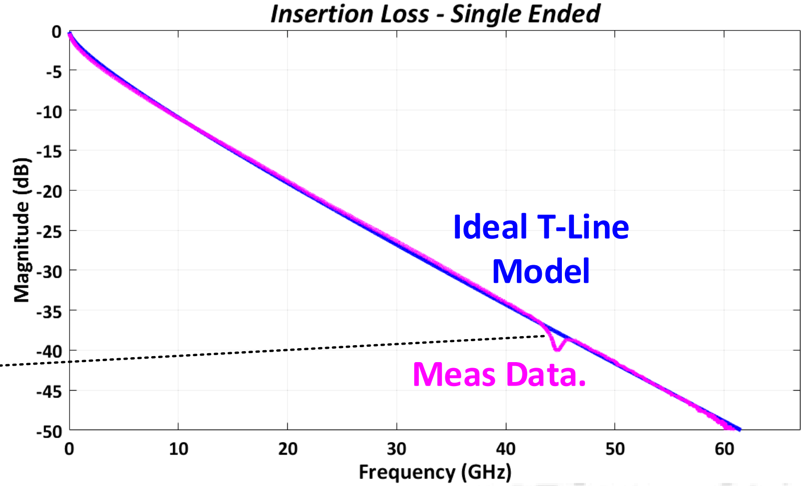
BE70 ISI Fiber Weave Resonance Analysis

Samtec BE70 ISI X4 SerDes Channel Emulator Platform

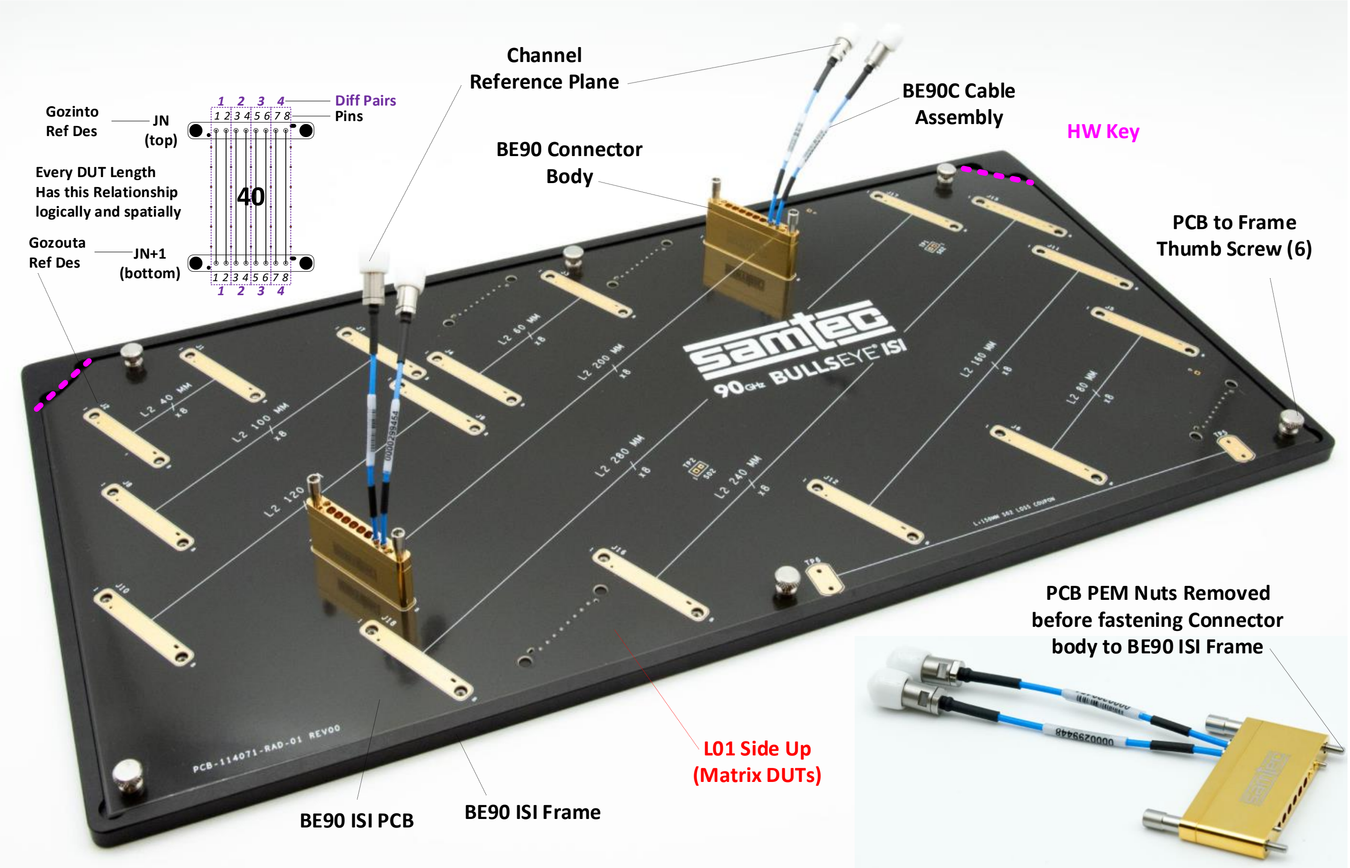








BE90 ISI Kit Assembly (50 Ohm SE Bus Routing)

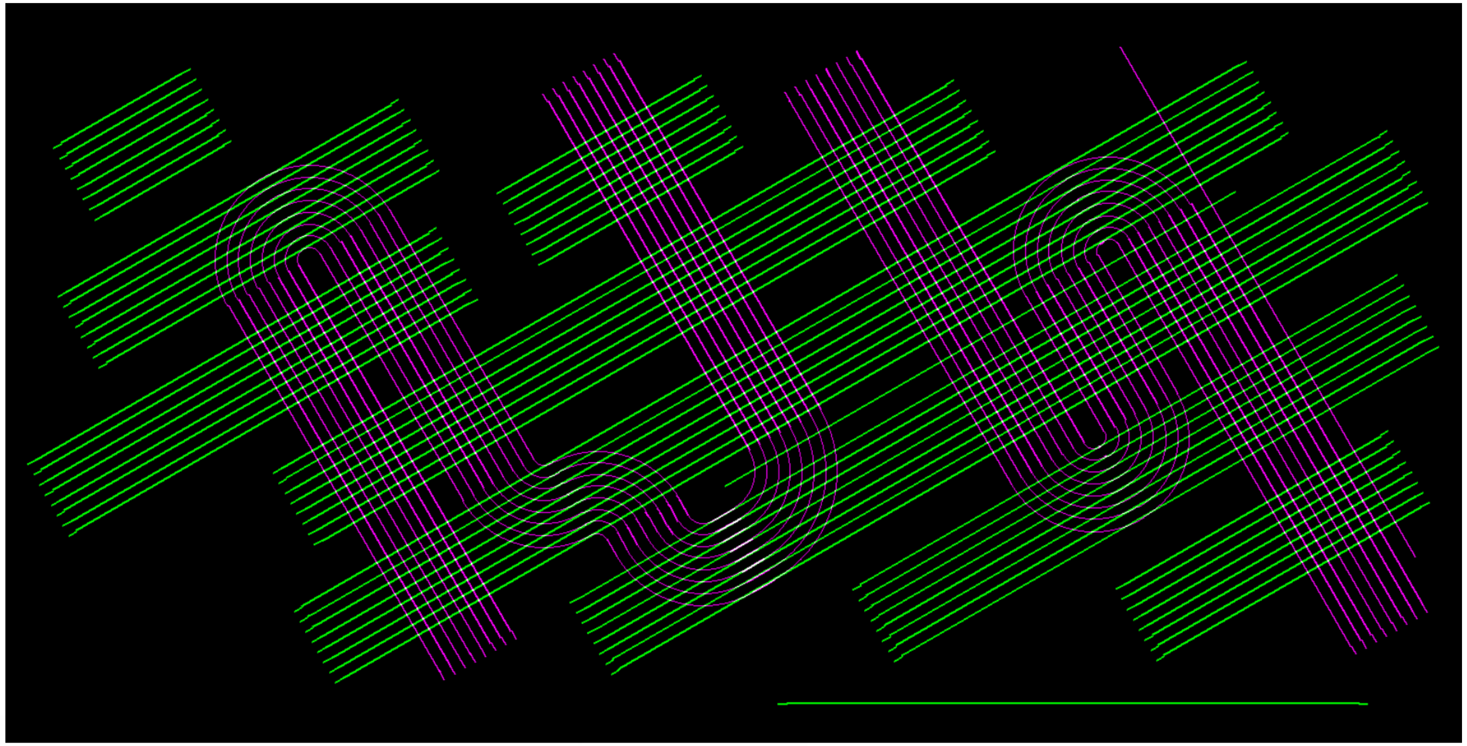


REF_Des	Pin	Net	Pin	REF_Des	Layer	Bit	Byte Lane
J01	A1	SE_040MM_A1	A1	J02	S02	B000	1
J01	A2	SE_040MM_A2	A2	J02	S02	B001	1
J01	A3	SE_040MM_A3	A3	J02	S02	B002	1
J01	A4	SE_040MM_A4	A4	J02	S02	B003	1
J01	A5	SE_040MM_A5	A5	J02	S02	B004	1
J01	A6	SE_040MM_A6	A6	J02	S02	B005	1
J01	A7	SE_040MM_A7	A7	J02	S02	B006	1
J01	A8	SE_040MM_A8	A8	J02	S02	B007	1
J03	A1	SE_060MM_A1	A1	J04	S02	B008	2
J03	A2	SE_060MM_A2	A2	J04	S02	B009	2
J03	A3	SE_060MM_A3	A3	J04	S02	B010	2
J03	A4	SE_060MM_A4	A4	J04	S02	B011	2
J03	A5	SE_060MM_A5	A5	J04	S02	B012	2
J03	A6	SE_060MM_A6	A6	J04	S02	B013	2
J03	A7	SE_060MM_A7	A7	J04	S02	B014	2
J03	A8	SE_060MM_A8	A8	J04	S02	B015	2
J05	A1	SE_080MM_A1	A1	J06	S02	B016	3
J05	A2	SE_080MM_A2	A2	J06	S02	B017	3
J05	A3	SE_080MM_A3	A3	J06	S02	B018	3
J05	A4	SE_080MM_A4	A4	J06	S02	B019	3
J05	A5	SE_080MM_A5	A5	J06	S02	B020	3
J05	A6	SE_080MM_A6	A6	J06	S02	B021	3
J05	A7	SE_080MM_A7	A7	J06	S02	B022	3
J05	A8	SE_080MM_A8	A8	J06	S02	B023	3

⋮ ⋮ ⋮

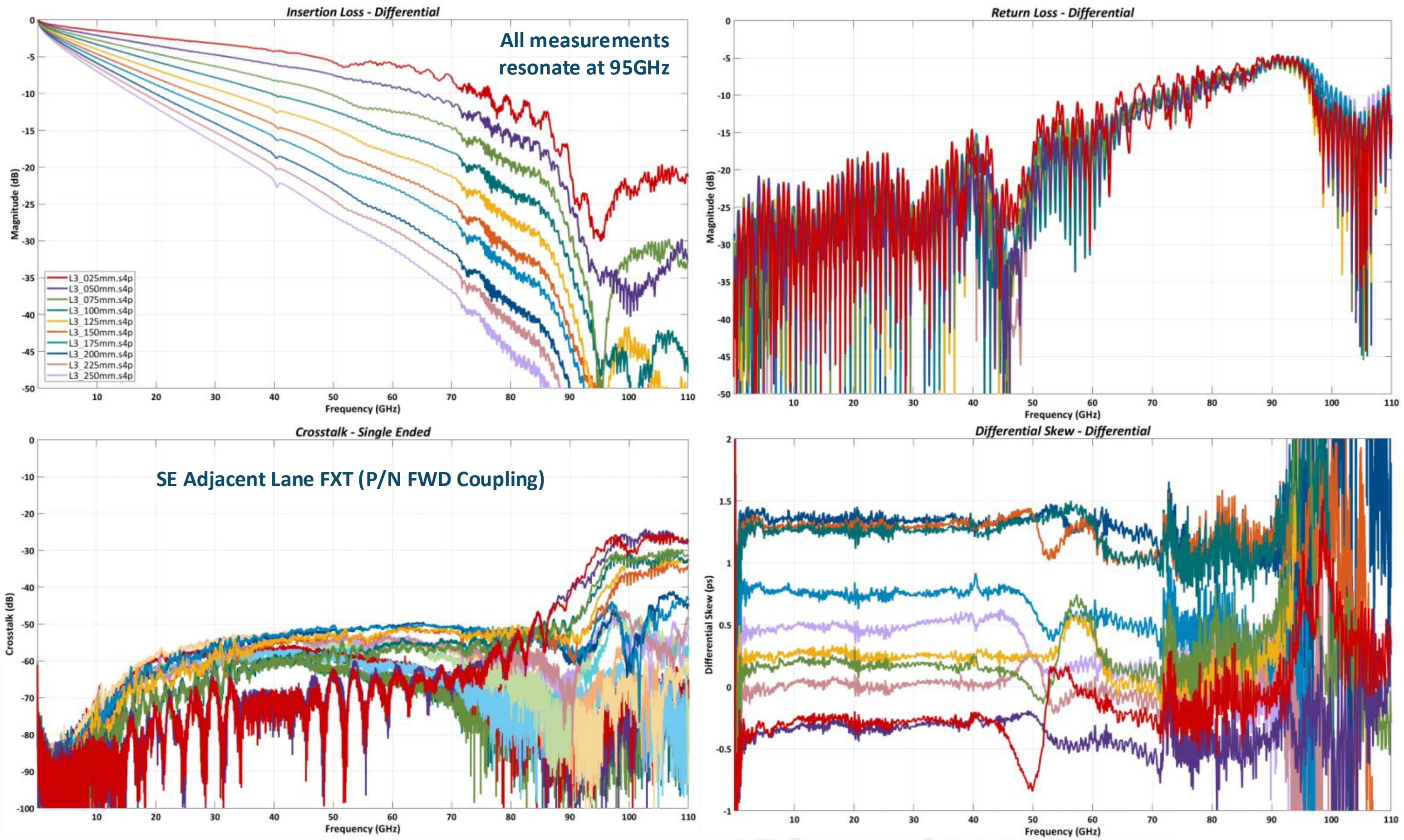
See: BE90_ISI_Netlist_Dist.xlsx

90 GHz Bulls Eye® ISI Buses (Expect 1.5dB/inch @ 56GHz)



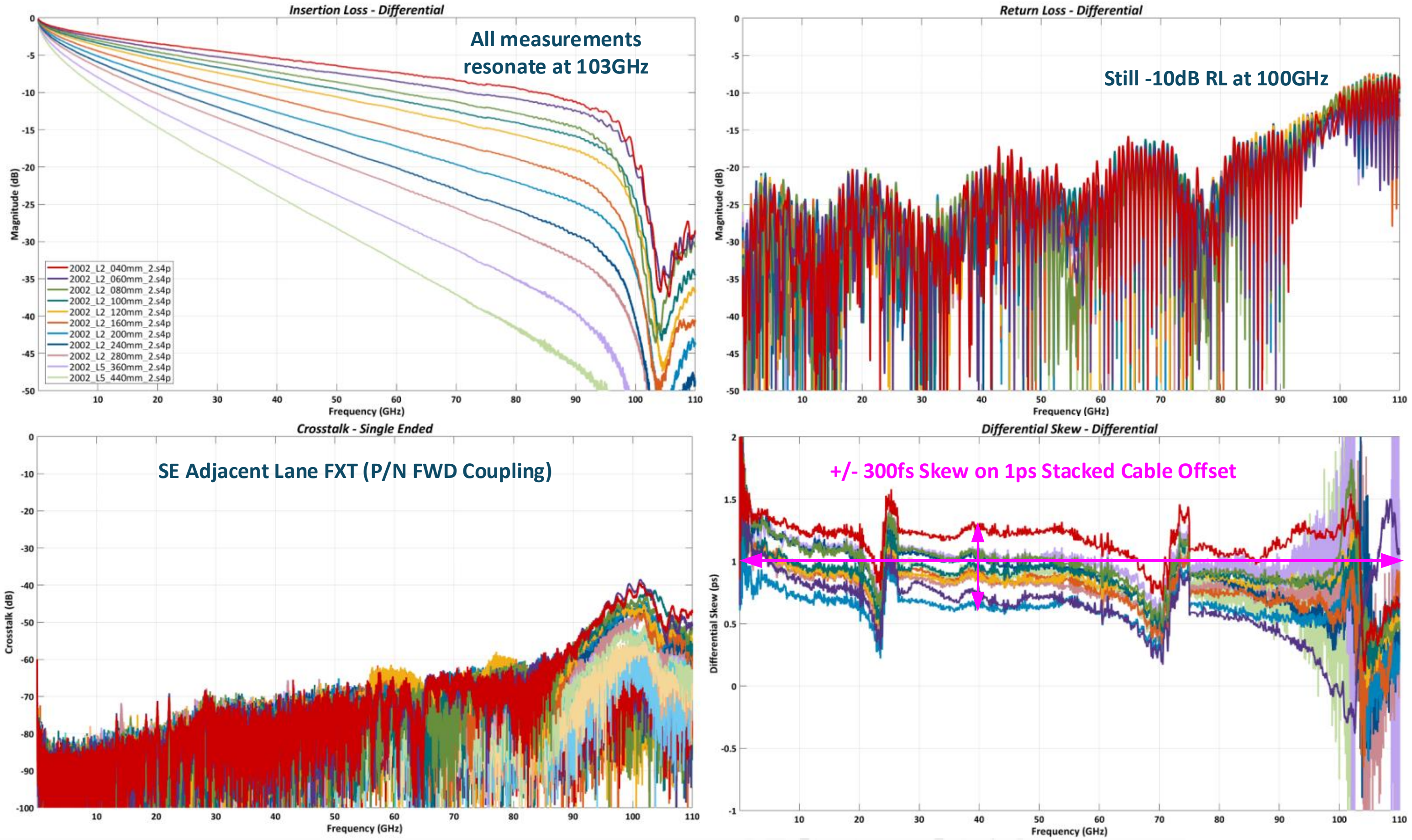
- DUTs : 11 Different x8 lengths each capable of supporting a x4 SerDes quad.
- 9 stepped ladder DUTs on topside. 2 Long S-Bend DUTs for backplane type channels on backside.
- 382 mm X 182 mm Board Form Factor.

BE70 ISI Channel Emulator Performance



- **BE70 ISI is offered with 1.00mm terms on RF086 coax on BE70C cable assemblies.**
  - This coax cable over modes beyond 72GHz
  - The HOM are evanescent and present as ~1dB ILD
- **BE70 ISI PCB in strong resonance at 95GHz (-5dB RL)**
- **Flat uniform 3mm bus route FWD X-talk is 50dB down to 80GHz and picks up at via BOR resonance.**

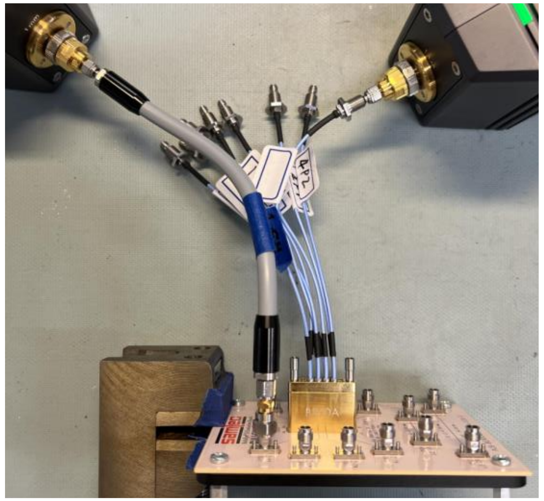
BE90 ISI Channel Emulator Performance



- **BE90 ISI is offered with 1.00mm terms on RF047 coax on BE90C cable assemblies.**
  - This coax cable has 110GHz modal BW
- **BE90 ISI PCB in strong resonance at 103GHz (-8dB RL)**
- **Flat uniform 3mm bus route FWD X-talk is 60dB down to 95GHz and picks up at via BOR resonance.**

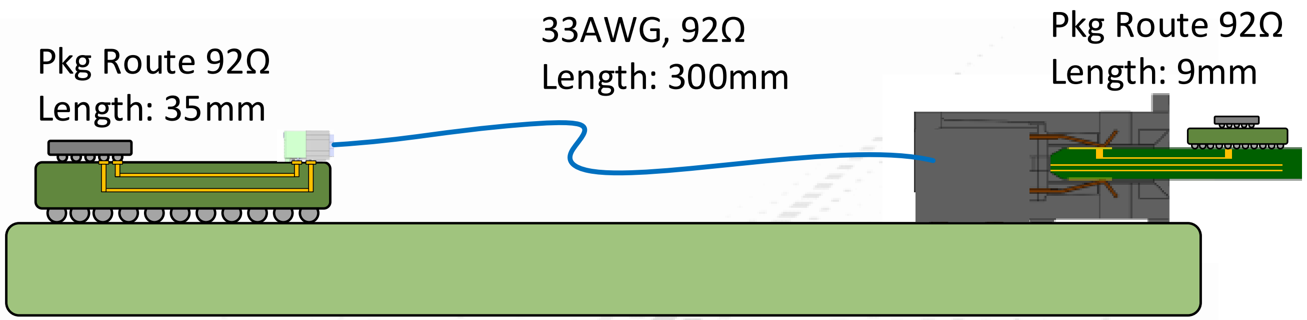
Cabled Host Empirical Upper Bound

- Generalize cabled host interconnect as 35mm of planar routing to cable to front panel connector with 100% implementation freedom.
- The result is very similar to today's precision RF test fixtures with 1.00mm cabling.
- Leverage existing empirical characterization to 110GHz.
- Non-scalable RF fixture design rules

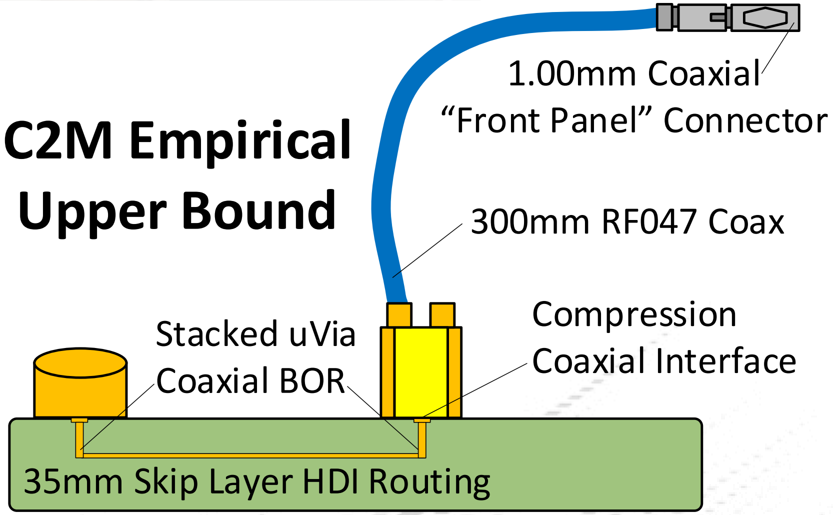


BE90 EVB
Measurement
Setup

Chip to Module (C2M)



C2M Empirical Upper Bound



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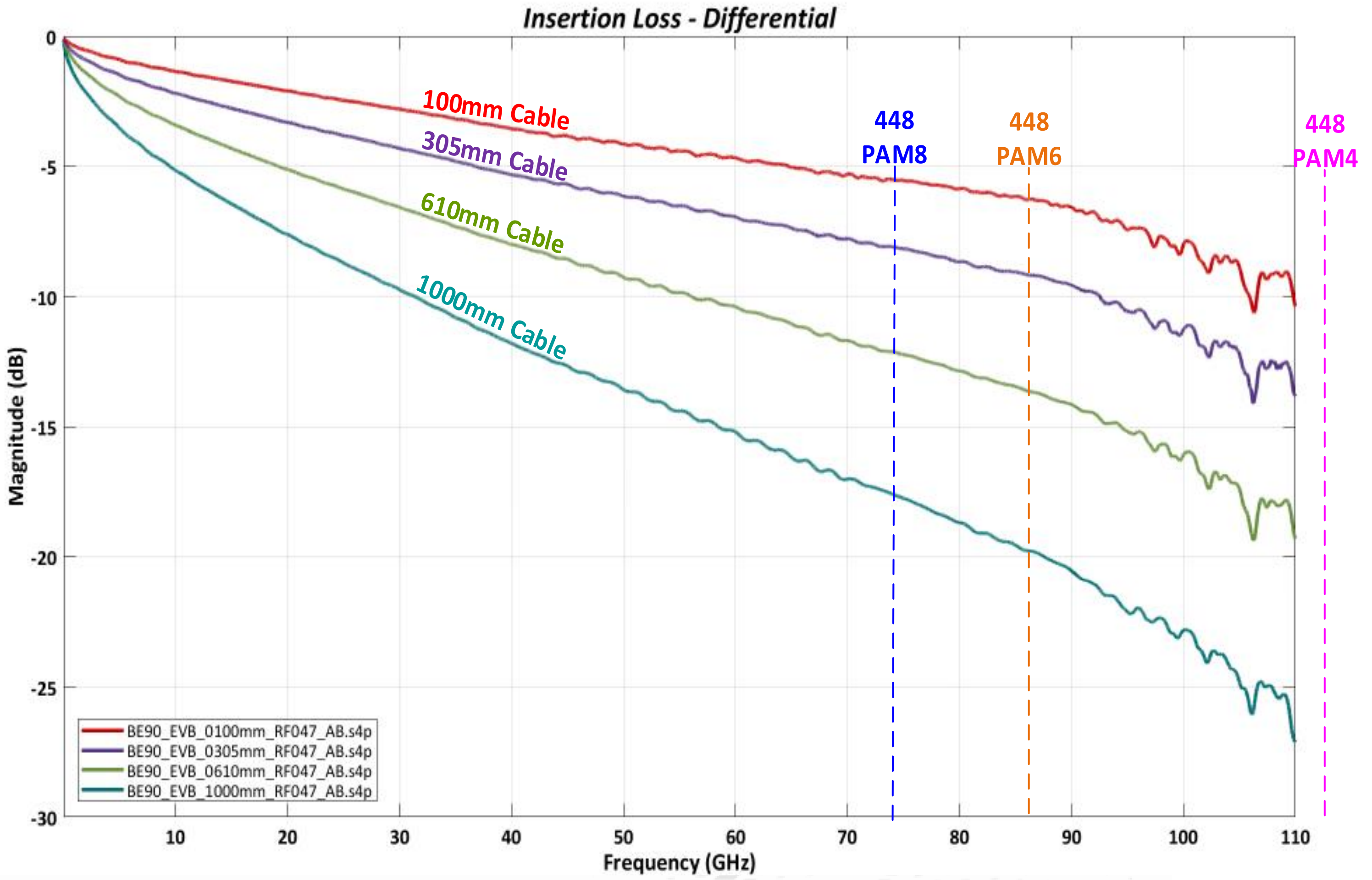
BE90 EVB Measured Performance



- 4.5dB to 14dB 224Gbps Channels
- No resonant notch filter response to 110GHz
- -1dB ILD BW ~ 95GHz
- -15dB RL BW ~ 95GHz
- P/N Skew < 0.5ps
- P/N Coupling <80dB to 90GHz
- 1.65dB/25mm @56GHz PCB Strip lines
- 1.00mm coax termination to RF047 Coax Cable to BE90C ferrule.

Bulls Eye® ISI Assembly DUT Line Up

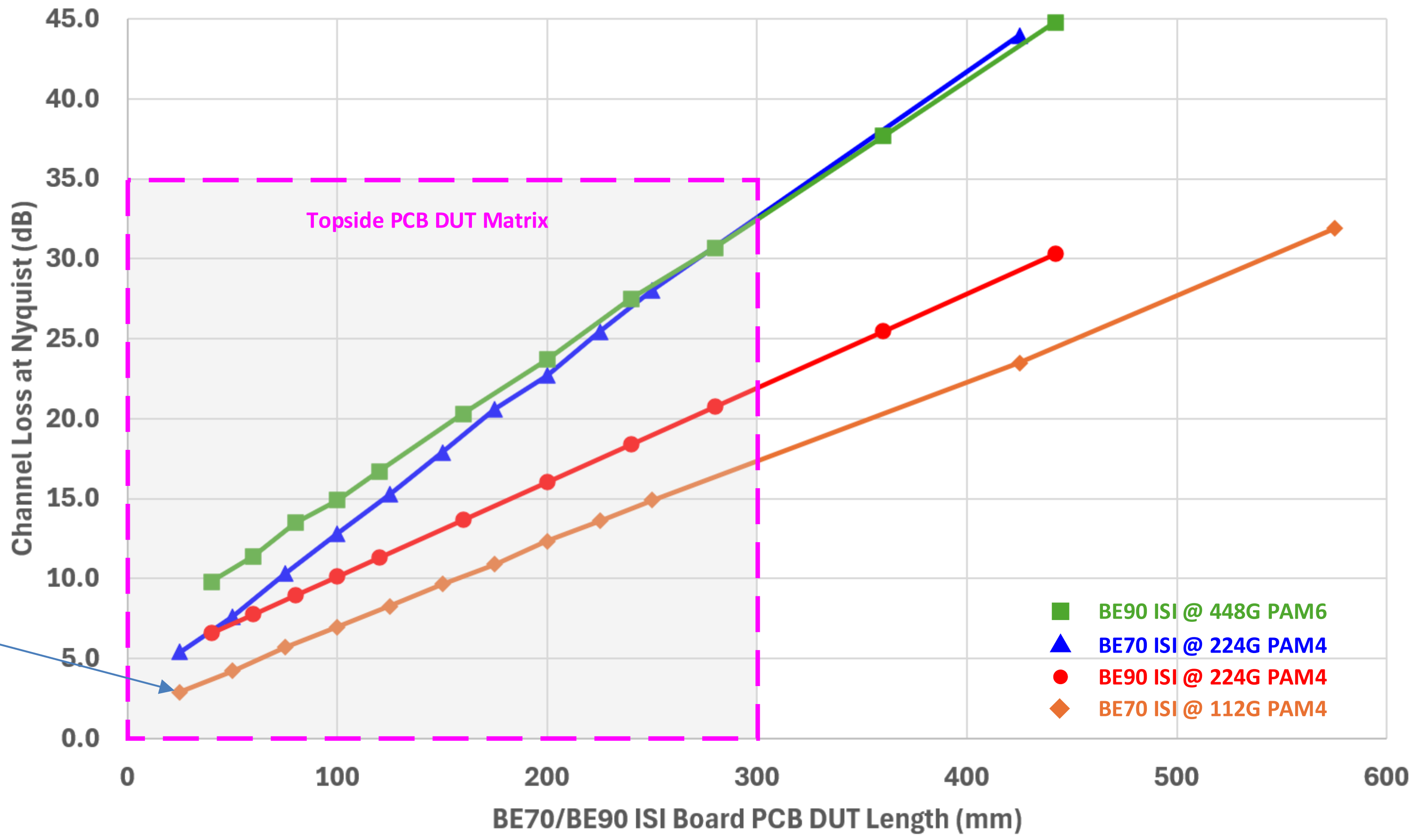
BE70 ISI DUT PCB + 152mm Cables (mm)	Avg. Meas. BE70 ISI Kit Loss at 28GHz (dB)	Avg. Meas. BE70 ISI Kit Loss at 56GHz (dB)	BE90 ISI DUT PCB + 152mm Cables (mm)	Avg. Meas. BE90 ISI Kit Loss at 56GHz (dB)	Avg. Meas. BE90 ISI Kit Loss at 86GHz (dB)
25	2.9	5.4	40	6.6	9.8
50	4.2	7.6	60	7.8	11.4
75	5.7	10.3	80	8.9	13.5
100	7.0	12.8	100	10.1	14.9
125	8.3	15.3	120	11.3	16.7
150	9.7	17.9	160	13.7	20.3
175	10.9	20.6	200	16.0	23.7
200	12.3	22.7	240	18.4	27.5
225	13.6	25.5	280	20.8	30.7
250	14.9	28.0	360	25.5	37.7
425	23.5	44.0	442	30.3	44.8
575	31.9	58.0			

All channels measured with 152mm OAL Cabling

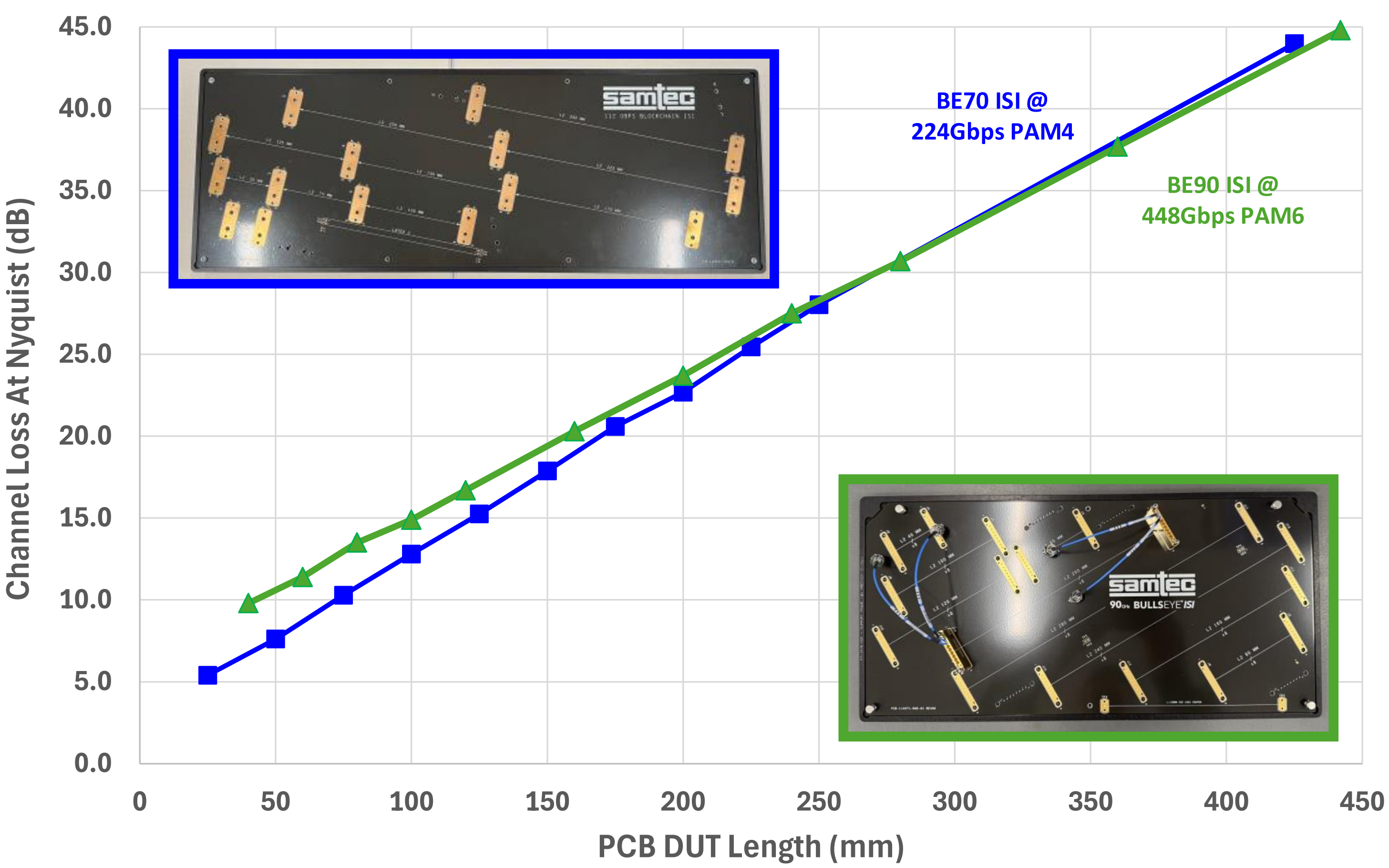
BE70 ISI and BE90 ISI Loss Ladder vs PCB Trace Length

- **BE70 ISI Matrix (Topside)**
  - Targets 224 VSR/MR/LR
- **BE70 ISI S-Bends (Backside)**
  - Targets 112/128 MR/LR/LR+
- **BE90 ISI Matrix (Topside)**
  - Targets 448 PAM6 VSR/MR
- **BE90 ISI S_Bends (Backside)**
  - Targets 224 LR/LR+

- **Note: The DUT removed from the BE90 ISI (11 BE90 vs 12 BE70) count was trimmed from the low end.**

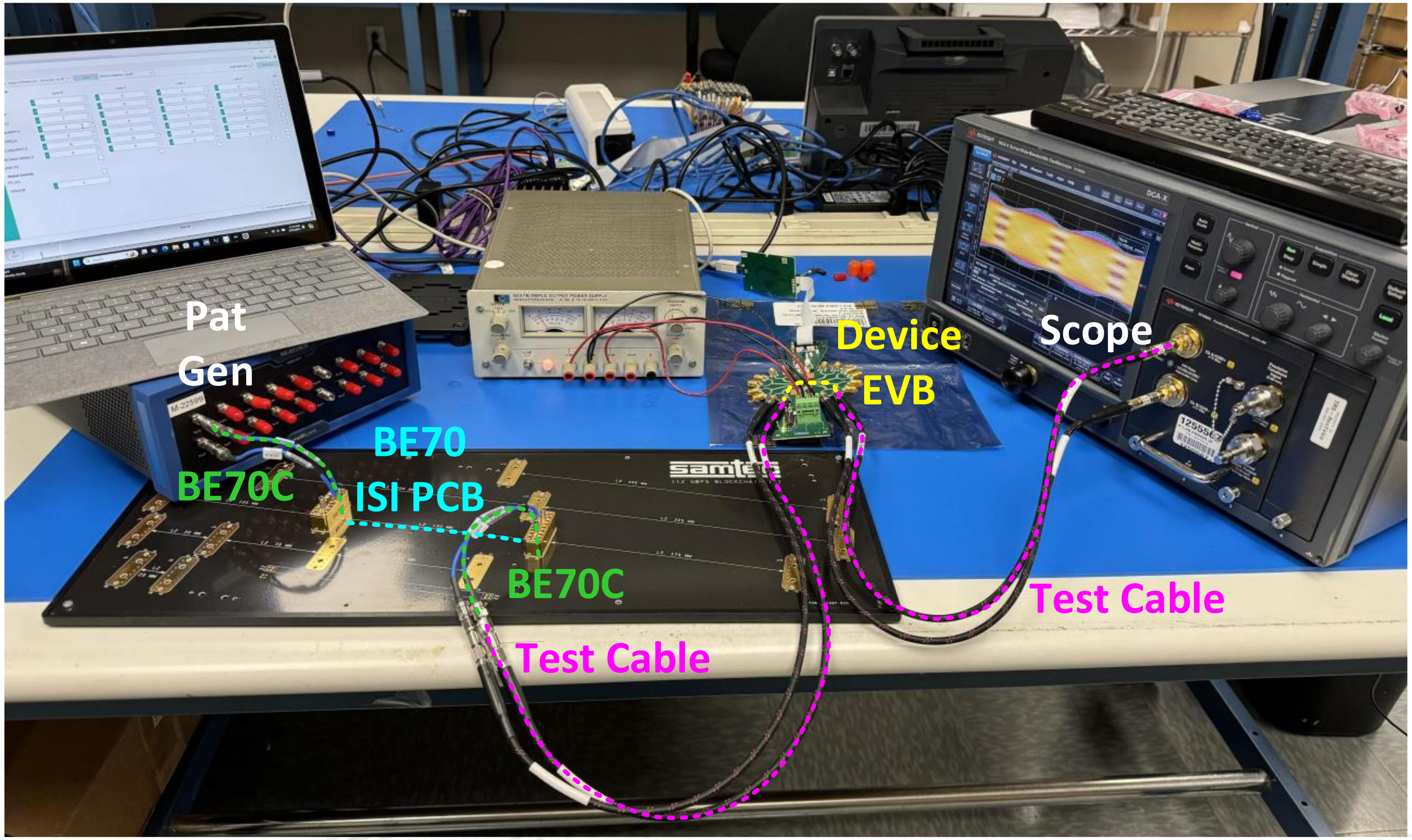


BE70 ISI vs BE90 ISI (224G PAM4 to 448 PAM6)

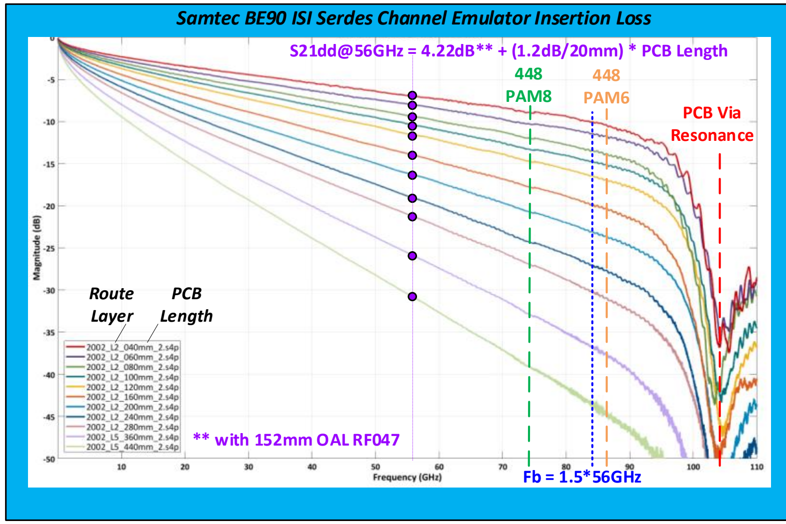


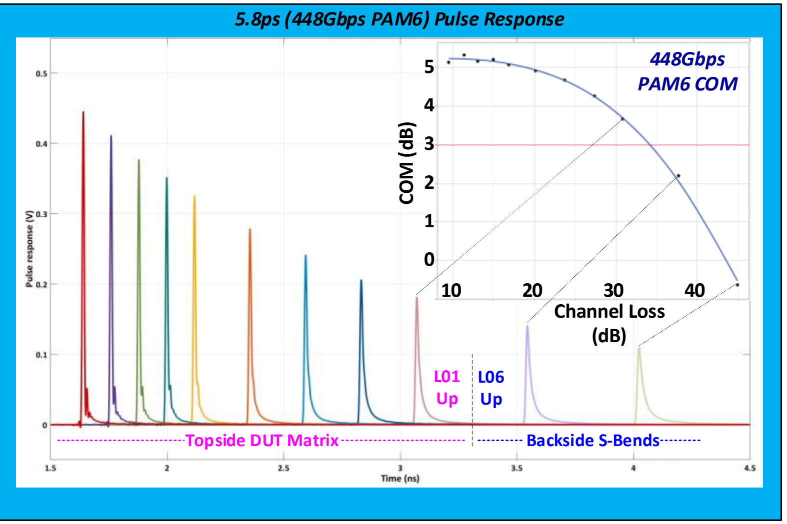
- **BE90 ISI was designed to be the 86GHz analog to the 56GHz Nyquist Channels from BE70 ISI.**
- **PCB Stripline Loss at 56GHz**
  - BE70 ISI : 2.5dB/in
  - BE90 ISI : 1.5dB/in
- **Scalable DUT matrix on topside**
- **Long lossy backplane channels on backside**

Part 3: Pulse Responses



BE90 ISI Channel/Pulse Responses (448G PAM6 COM)



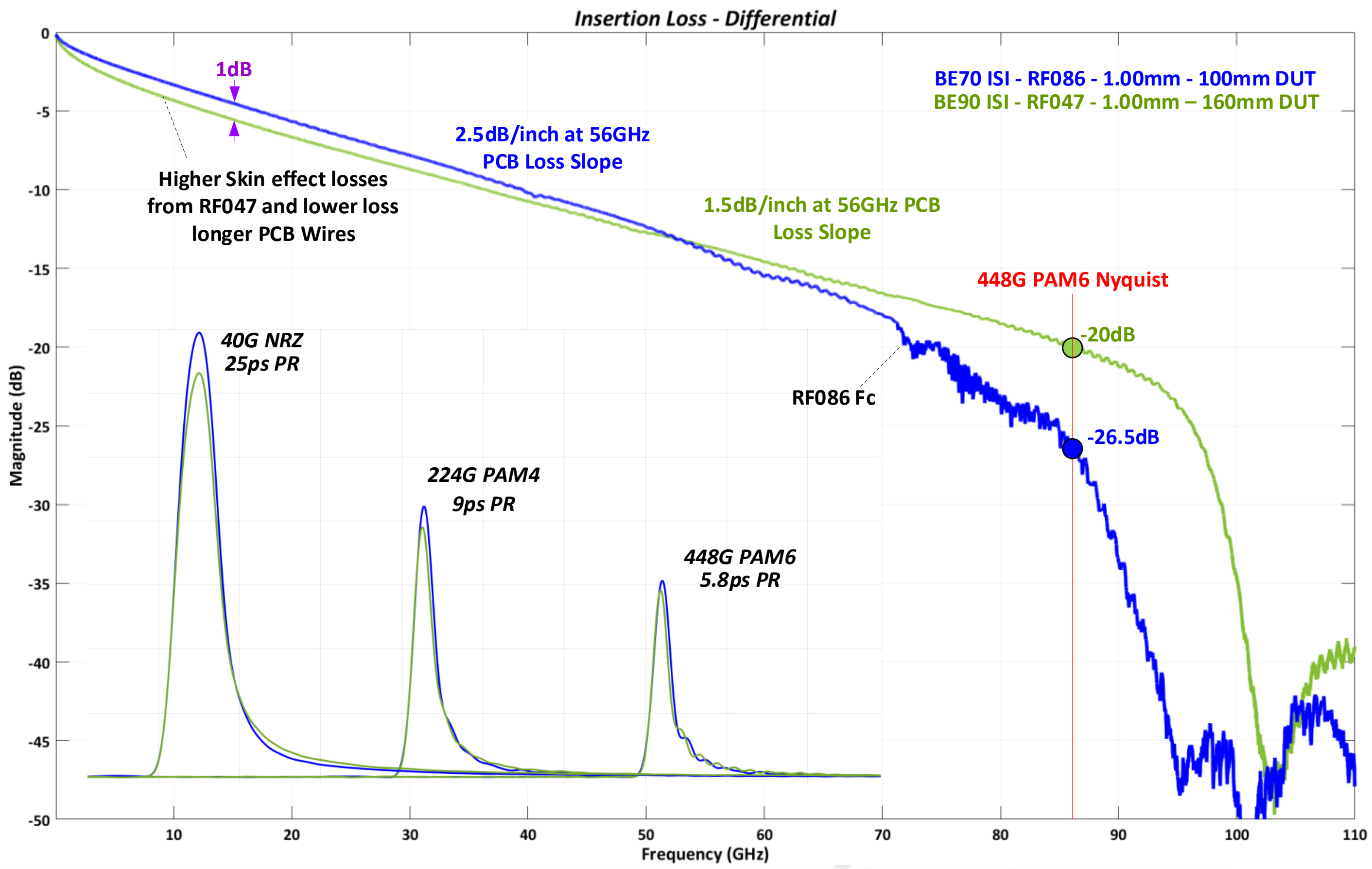


Top Side DUTs

Backside Side DUTs

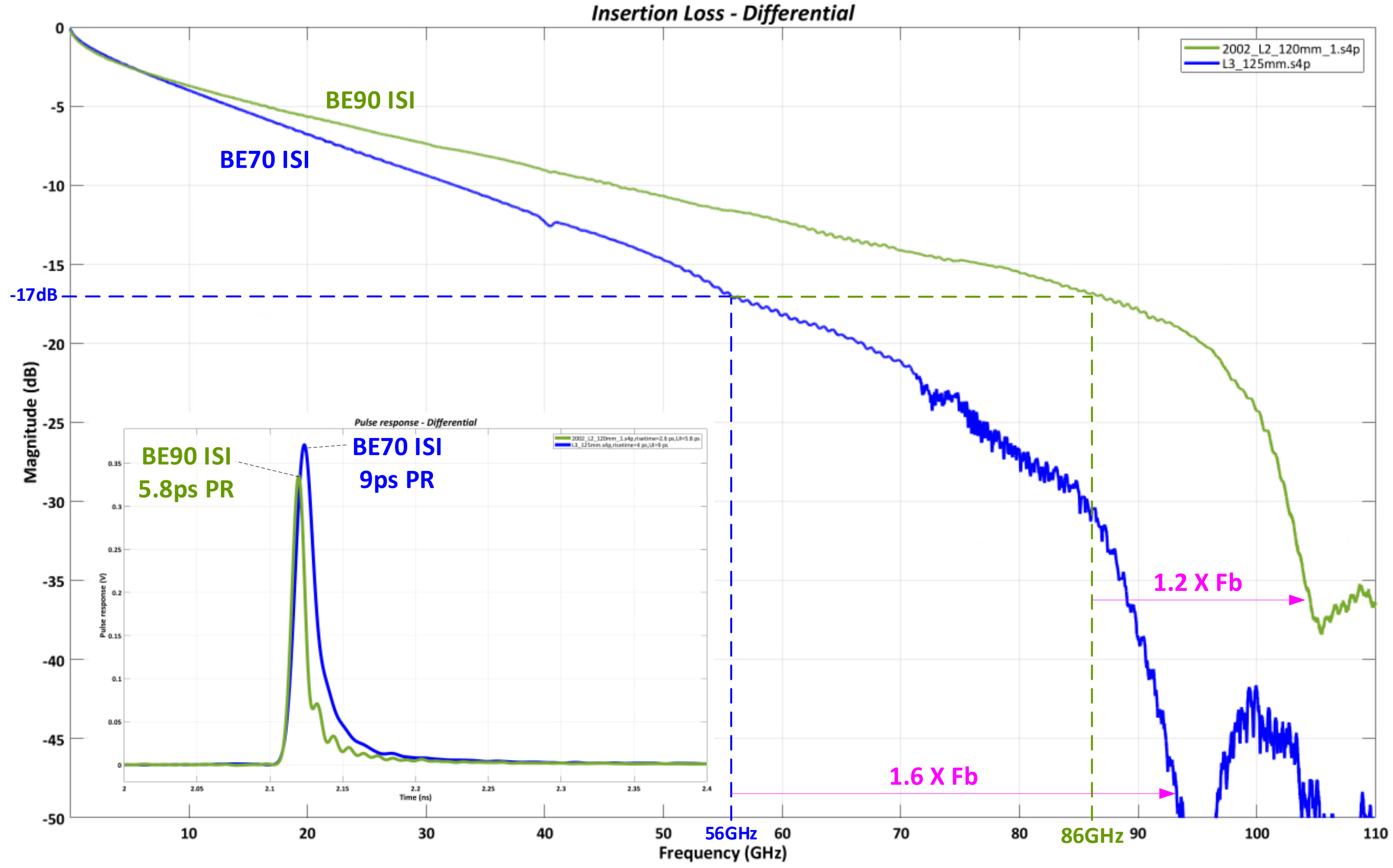
- **BE90 ISI PCB design was based on PAM6 pulse response behavior prior to 400G SerDes pathfinding.**
- **Do to 5.8ps pulses what BE70 ISI does to 9ps pulses.**
- **Design goal was to have all topside DUTs pass 448G PAM6 COM**
  - Anticipating long s-curve DUTs to fail.

BE70 ISI vs BE90 ISI 13dB at 53GHz Channel Comparison



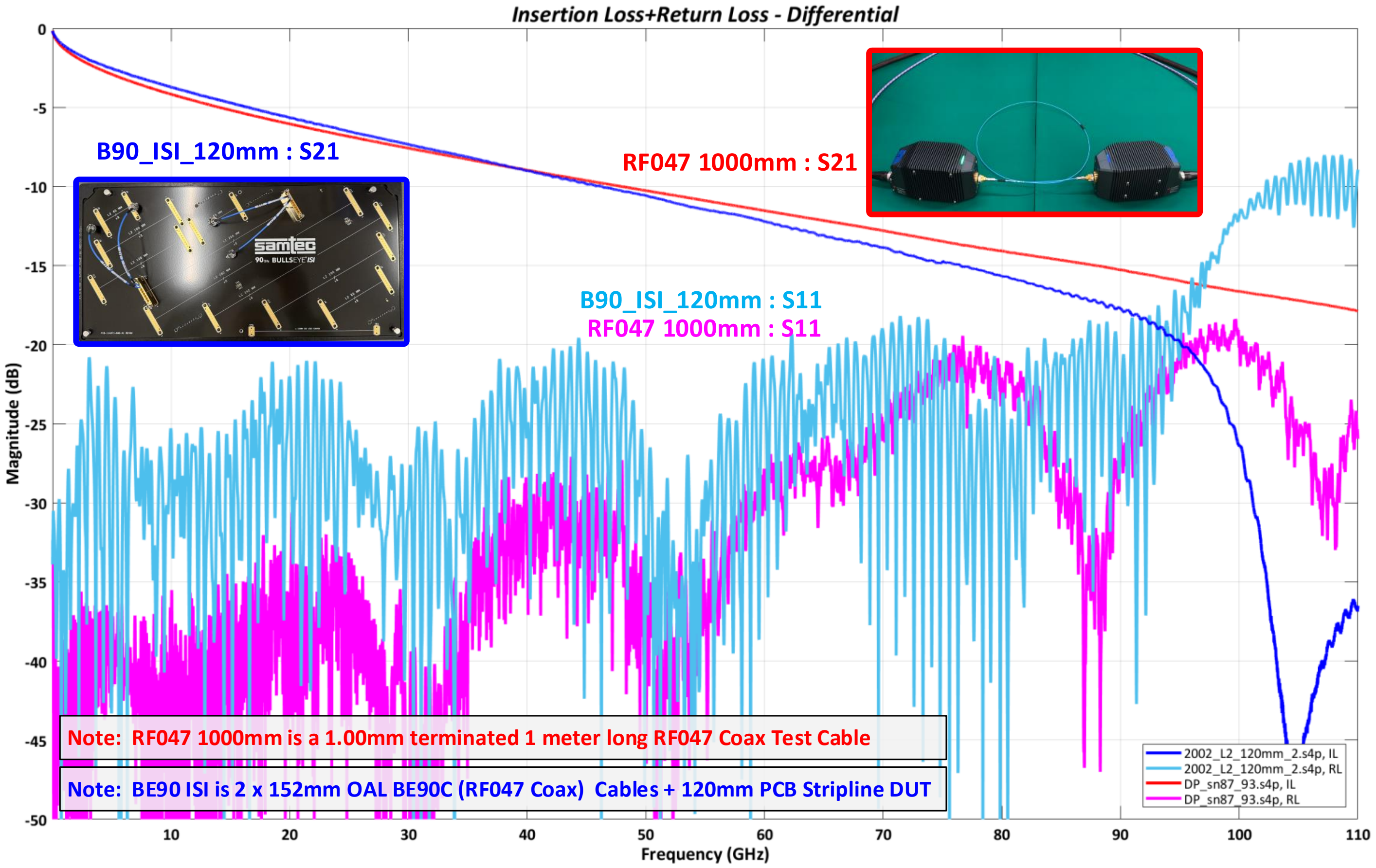
- **What is worth more?**
  - ~1dB less loss to 60% Nyquist (86GHz)
  - 6.5dB less loss at Nyquist (86GHz)
- **It depends on SerDes capability**
- **But…simple pulse response comparisons provide substantially more comparative insight than frequency domain s-parameters**

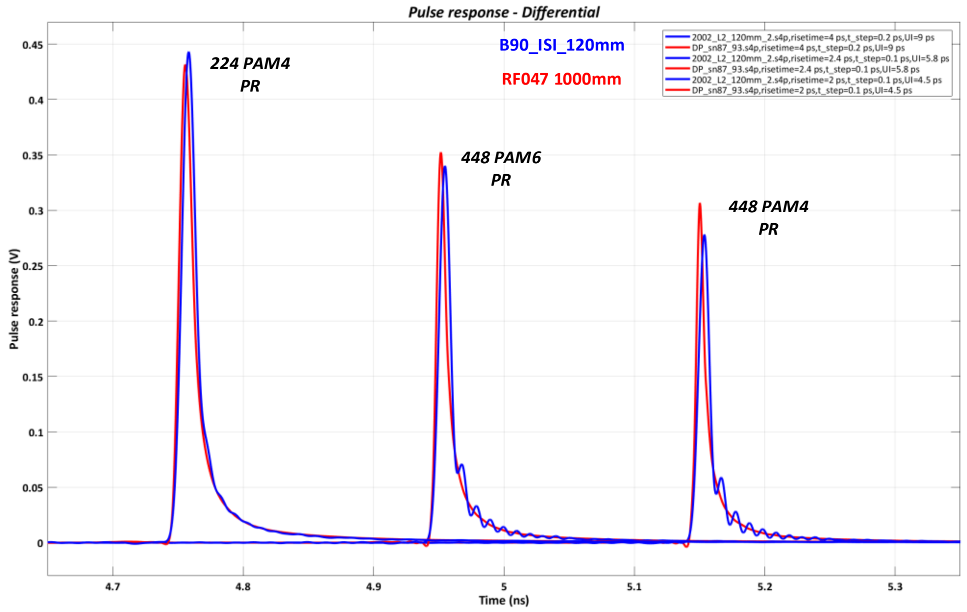
BE70 ISI vs BE90 ISI 17dB Channel Comparison



- **Channel Rolloff to Nyquist Comparisons**
  - 1.6X Channel to 224G PAM4 Nyquist
  - 1.2X Channel to 448G PAM 6 Nyquist
- **It depends on SerDes capability**
- **But…simple pulse response comparisons provide substantially more comparative insight than frequency domain s-parameters**

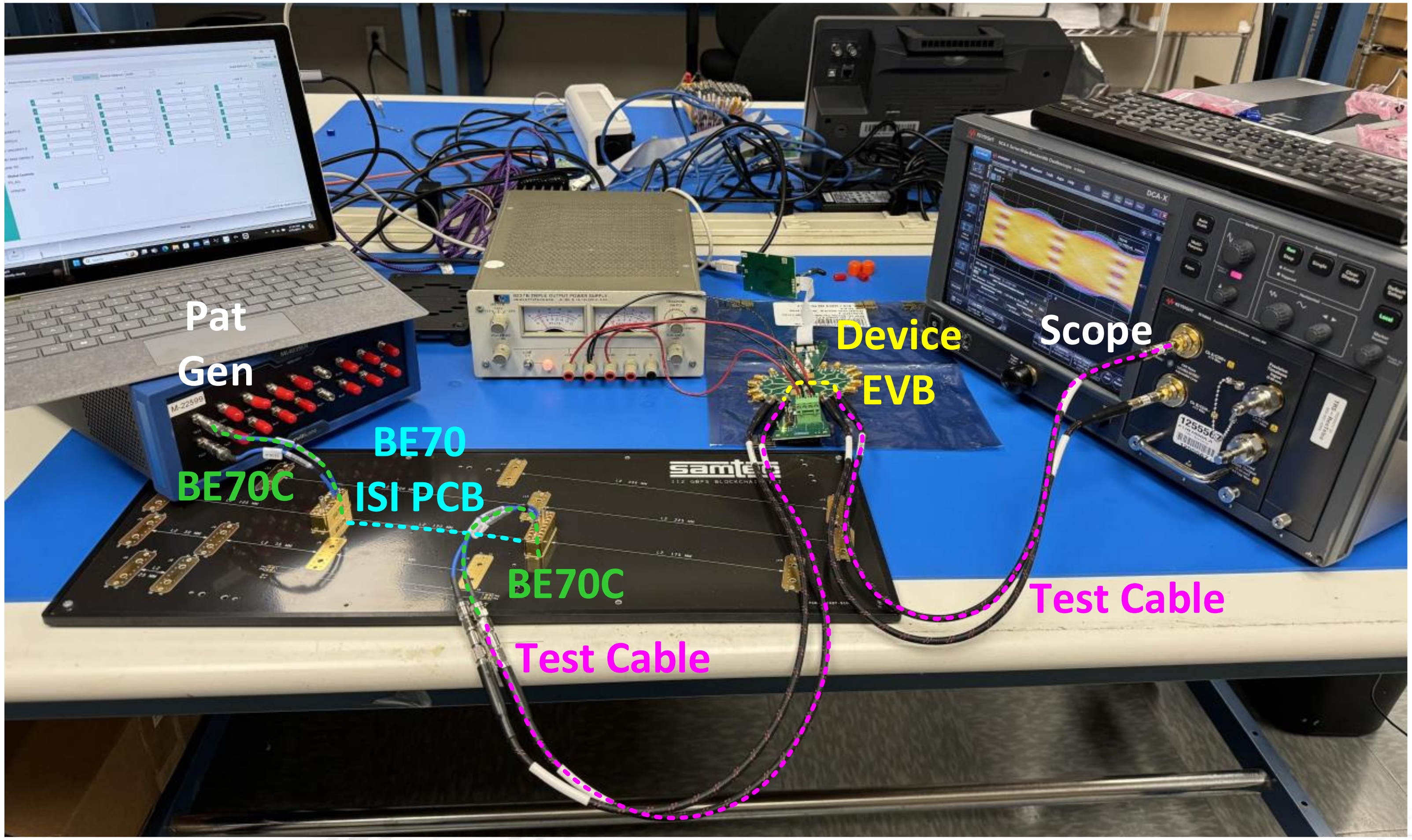
BE90 ISI vs 1000mm RF047 Test Cable Comparison



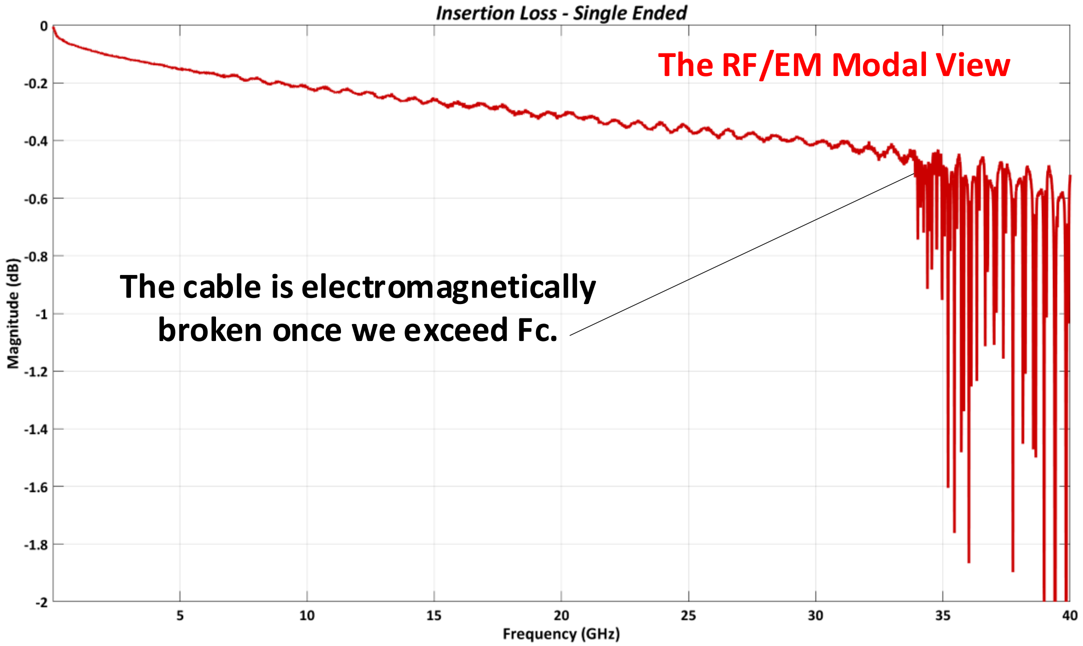


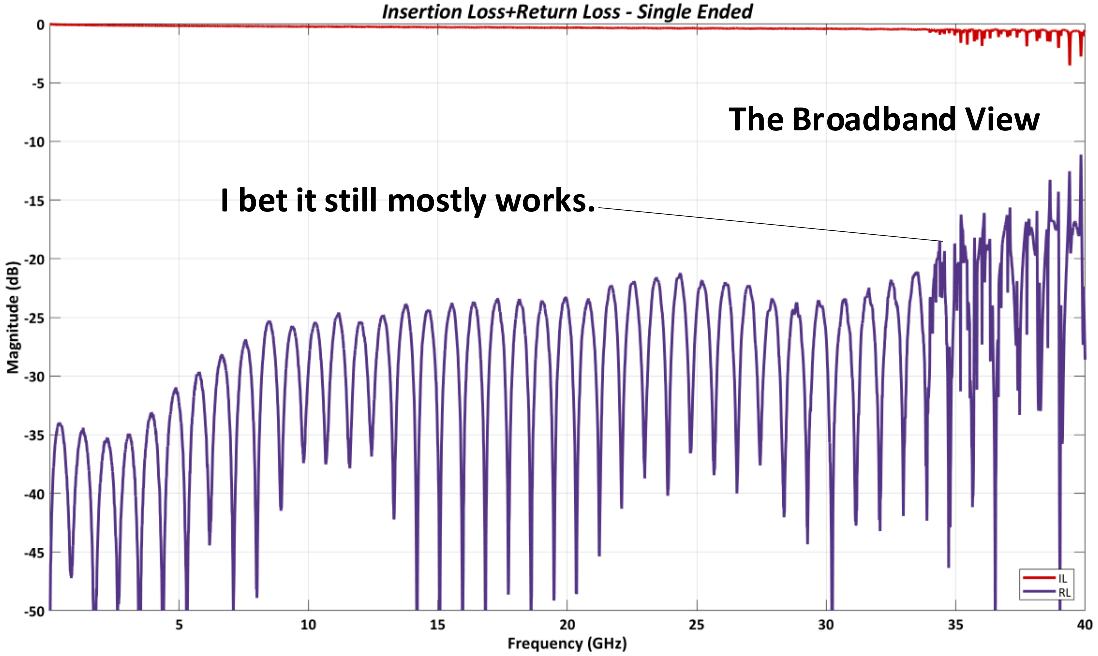
- **1000mm RF047 Test Cable**
- **BE90 ISI 120mm PCB DUT**
- **How far inside Nyquist can we tolerate the resonance?**

Part 4: Over Moded Coax Re-visited



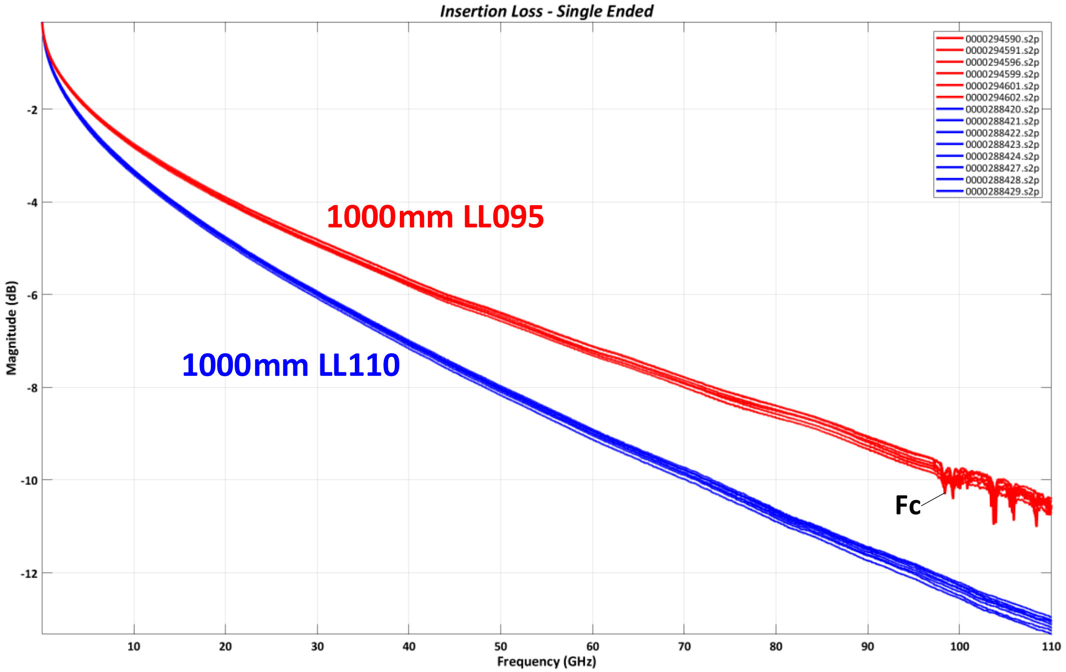
Samtec LL032 Nitrowave Coax

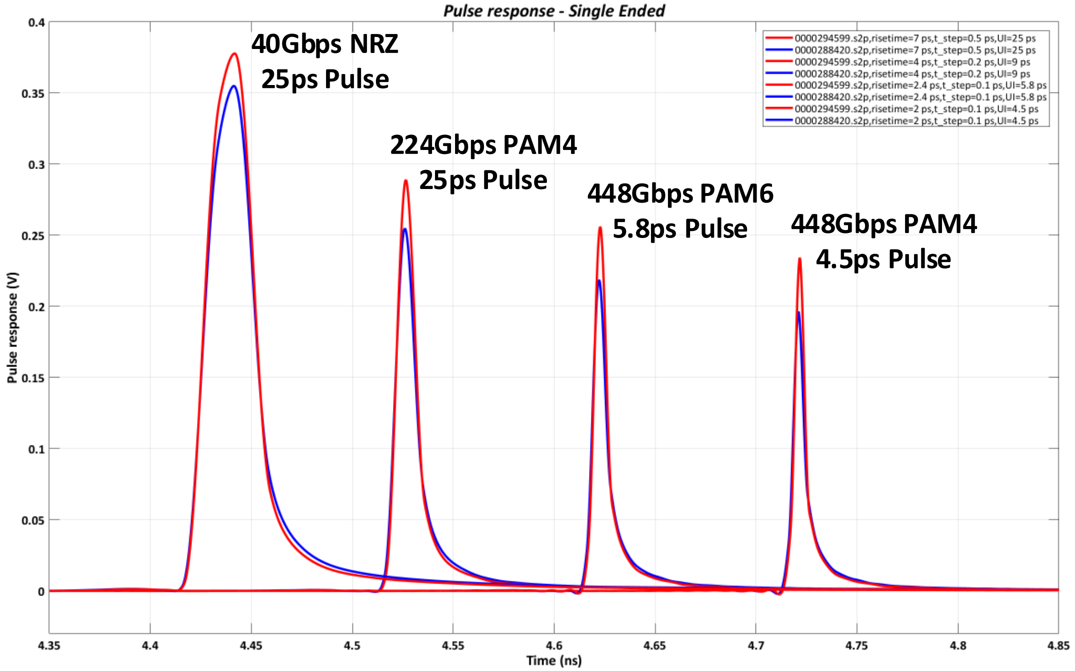




- Cable performance above Fc looks bad for high dynamic range RF performance applications
- A broadband view for high speed digital SerDes test puts higher order moding in different light

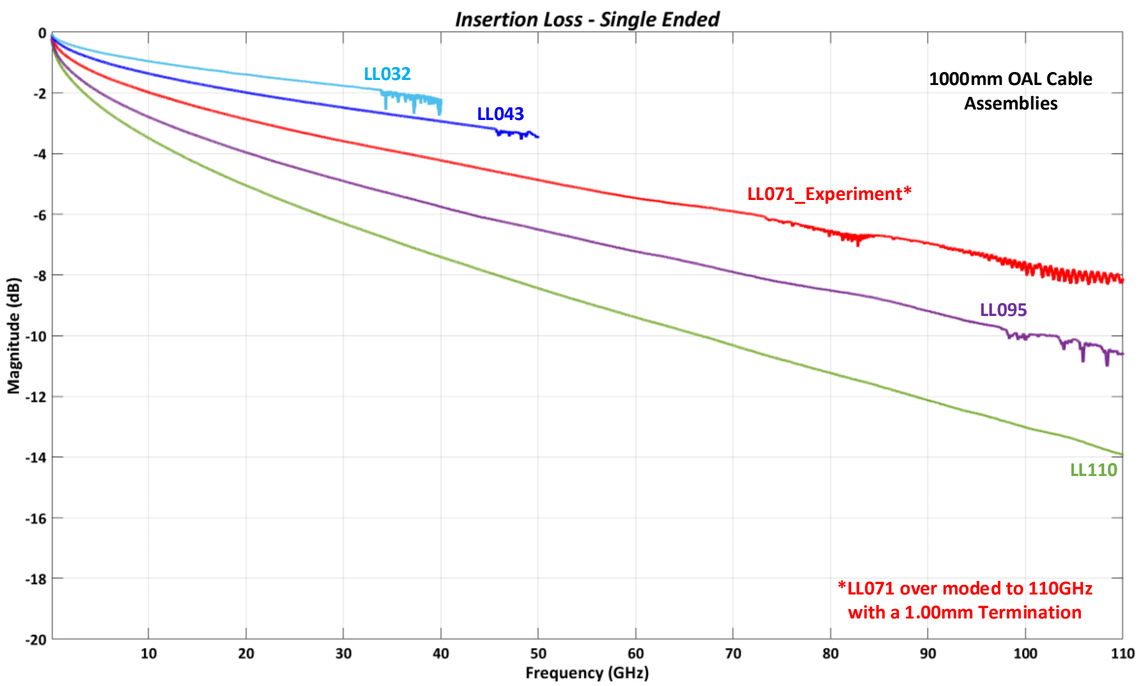
Samtec LL095 Nitrowave Coax

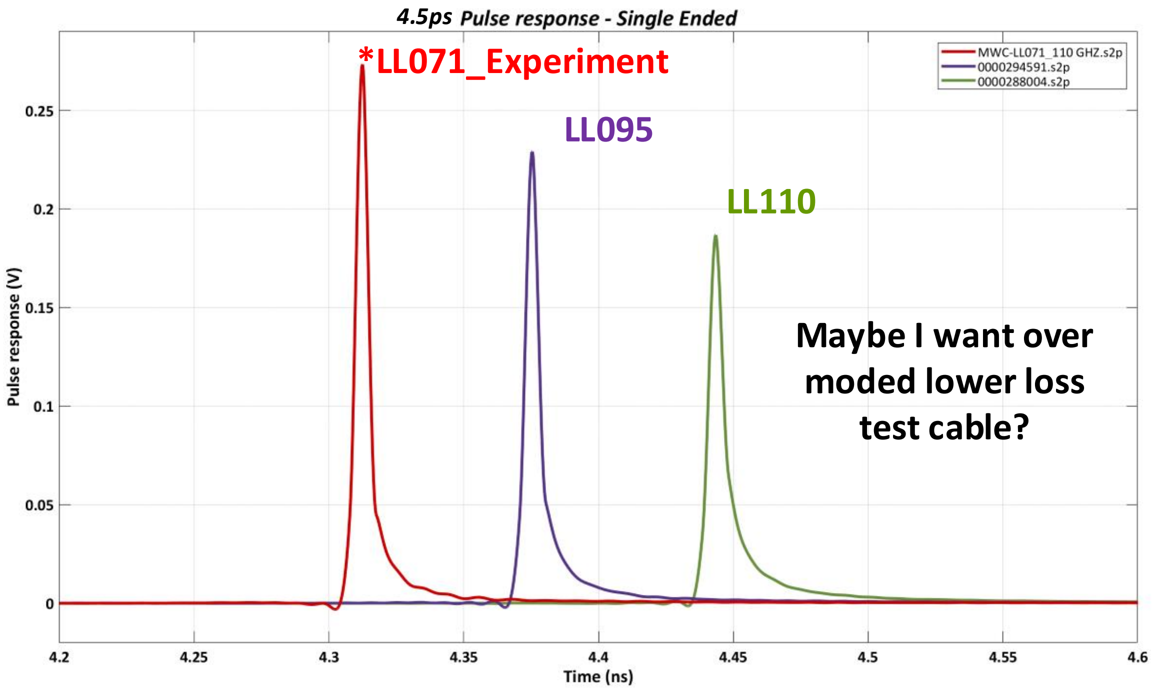




- **Comparison of 12 inches coax cable assemblies with 1.00mm terminations**
  - LL095: 1dB less loss per foot at 95GHz compared to 110GHz modal BW coax matched to the 1.00mm
  - Given higher order modes are evanescent, in a SerDes test application, how much do we care?

Further Opportunities in Over Moded Coax





- **Comparison of 12 inches coax cable assemblies with next largest coax termination.**
- **Over moded LL071 can be ~5dB better per foot than 110GHz modal BW cable in the over moded spectrum with ILD penalty.**

Part 5: Conclusions and Q/A

Conclusions

- **Precision RF test fixtures can be designed for downstream SerDes test configurability by exploiting microwave cable assemblies as the controllable performance knobs.**
- **The resulting assemblies allow lane to lane characterization up to SerDes x4 Quads**
  - Equal to staggered adjacent lane loss profiles
- **The SE BUS topology prevents skew from converting into ISI during channel propagation preserving test equipment and SerDes Tx /Rx de-skew capabilities.**
- **Coax cable design requires trading off loss at Nyquist versus modal BW at some factor beyond Nyquist**
- **A SerDes capabilities continue to develop and sub Nyquist channels become normalized at 400G PAM4, there may be opportunity to trade test cable loss for device margin.**

- **Thank You.**

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