Wireless Communications for FCC-ee

Mainly a summary of the activities of the **WADAPT Collaboration** from the DRD7 Annual workshop presentation and a report of initial tests at UZH

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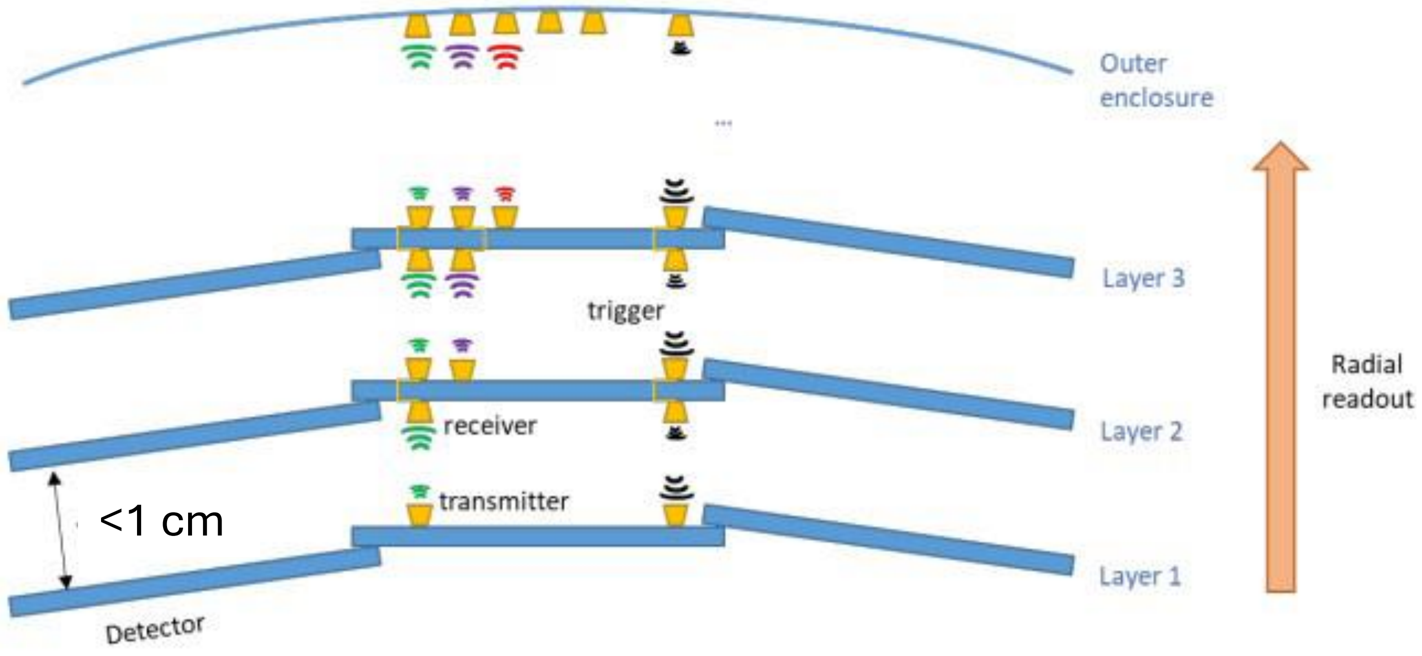
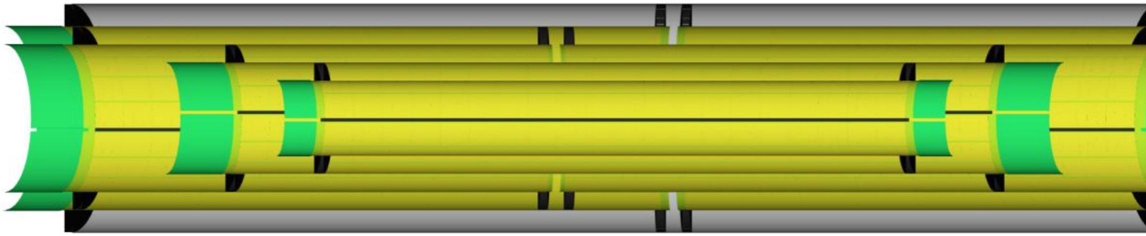
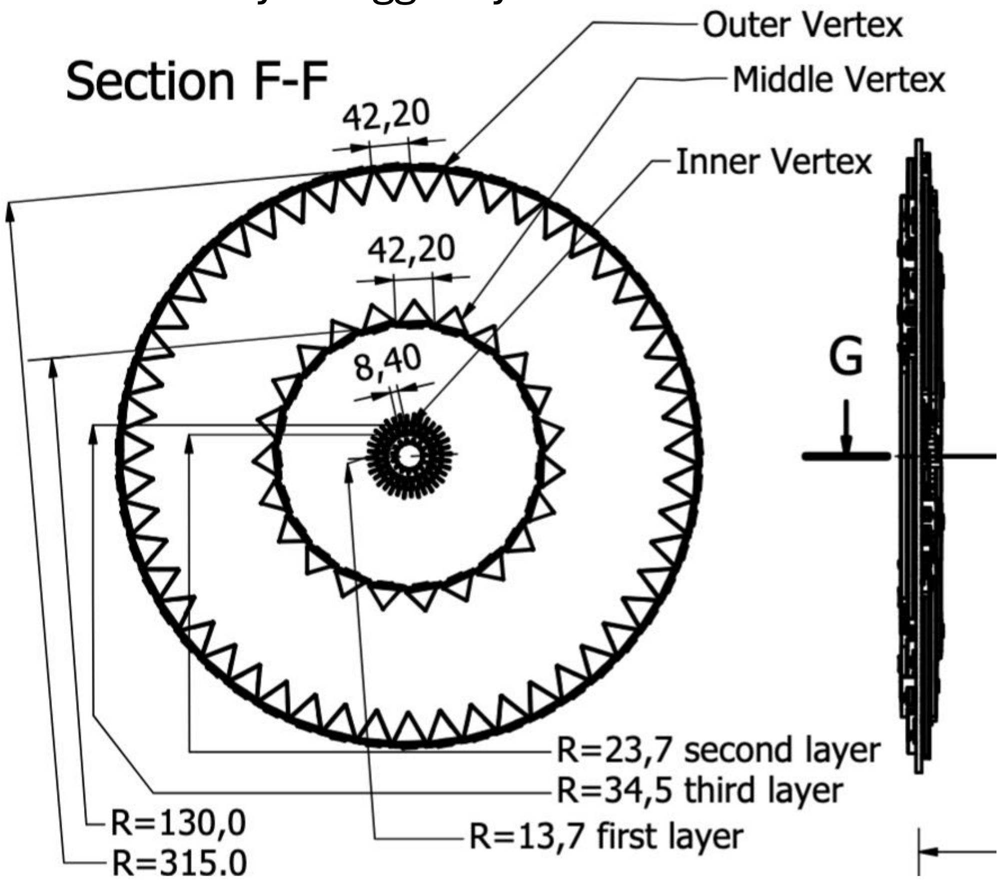
ZHAW group: Luciano Sarperi, Teddy Loeliger, Marc Kuhn

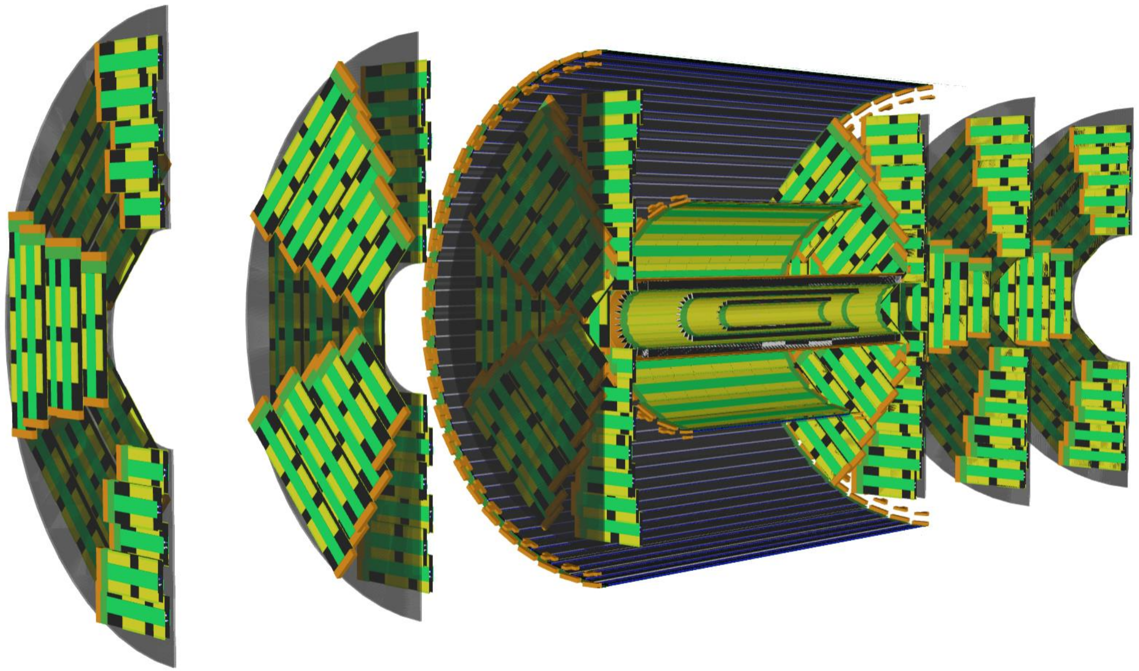


Why wireless?



- Reduction in material budget related to cables and connectors
- Reduced latency: Radial readout instead of axial
- Interlayer intelligence:
  - explore the possibility of identifying hits from ”good physics” tracks in L1 by correlating hits in L1 and L2 if an interlayer trigger system is used





Data rates for a Vertex detector at FCC-ee

Silicon data volume

INFN Istituto Nazionale di Fisica Nucleare

- Pixels to read out for ARCADIA L1 (15 staves x 6 modules x <u>**2 chips x 640 x256 pixels**</u>)

Z	WW	ZH	tt		
7.6	2.7	1.1	0.5	x10^3	in 10 μsec window/2-chip module
23.2	91.8	133.5	380.6		per bunch crossing/2-chip modeule

- Assuming 32 bits/pixel including time stamp/2-chip module

24.4	8.5	3.5	1.6	Gbit/s	Not triggered
149	N/A	N/A	N/A	Mbit/s	triggered

200 kHz trigger rate

  - Total layer 1:
    - 2.2 Tbit/sec (NoTrigger) → 13.4 Gbit/sec (Triggered) at Z pole → port card transmission needs 1.1 Tbit or 7 Gbit/s/side
- Other layers and disks have lower data volumes
  - Layer 2 has ~10x less data volume

Current ARCADIA

- Max readout speed achievable on chip **100** - 200 MHz x 32 bits? → **3.2** - 6.4 Gbit/sec

Untriggered operation looks difficult

For Layer 1:

With 100 MHz/cm^2 incoherent pair hit rate and 32 bits per hit and a double chip module area of 2.05 cm^2:

→ **6.6 Gbit/sec per double module**

In OCTOPUS we consider to sample both the rising and falling edge for offline ToT measurement

→**13.2 Gbit/sec per double module**

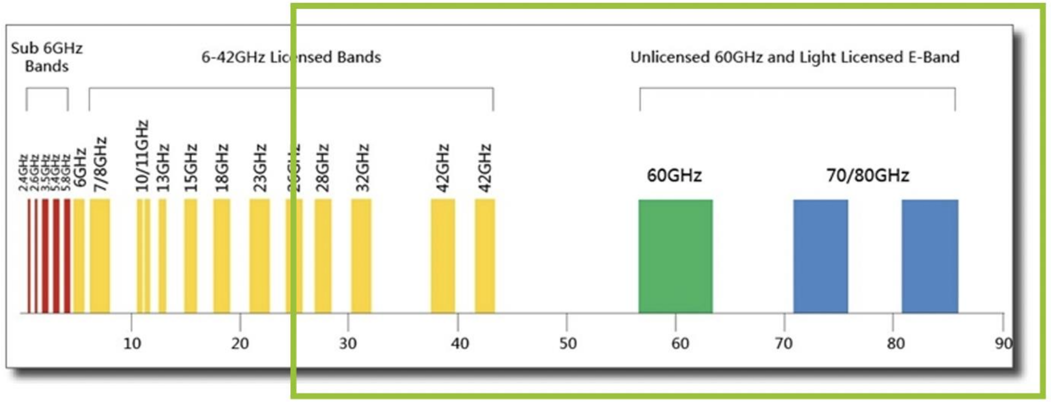
Wireless communications for FCC-ee

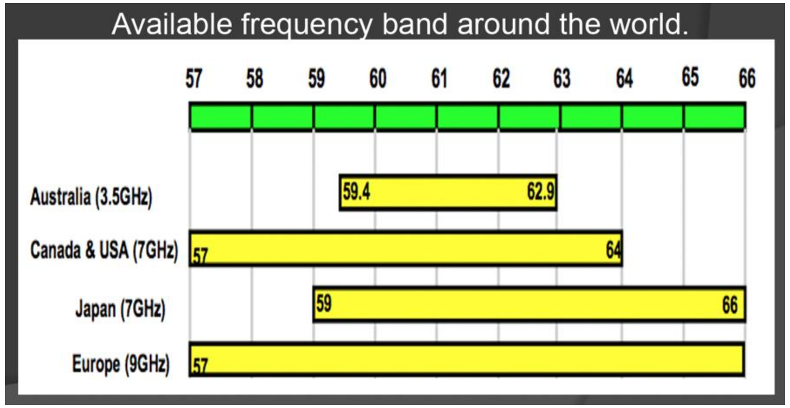
K. Mirbaghestan, UZH

Millimeter Wave

- **1-10 mm wavelength**
- **30-300 GHz Carrier frequency**

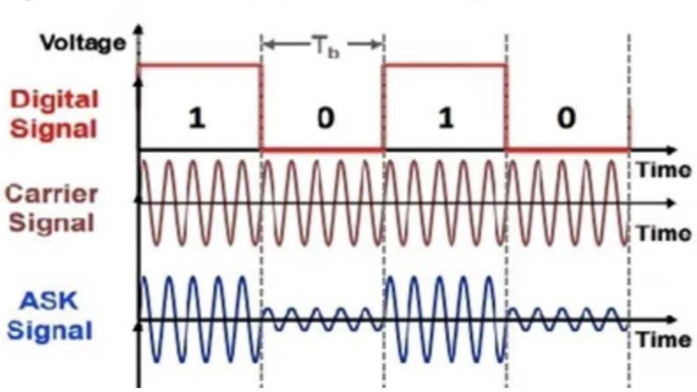
- **60 GHz** band
  - **Unlicensed** spectrum
  - Can send **Gigabits/s** data over short distance
  - Low **Interference**
- **Reliable** low-cost & low-power technology : most transceivers are fabricated in **65 nm or 28 nm RF CMOS**





ASK signal: Amplitude Shift Keying

- The **amplitude of the carrier wave changes** according to the digital data being transmitted
  - typically a **high amplitude for bit "1"** and a **low or zero amplitude for bit "0"**.
- It is a simple form of **digital modulation**, where information is encoded in the **strength of the signal**, while the carrier **frequency (60 GHz) and phase remain constant**.



Antenna parameters

K. Mirbaghestan, UZH and ZHAW

Key Parameters

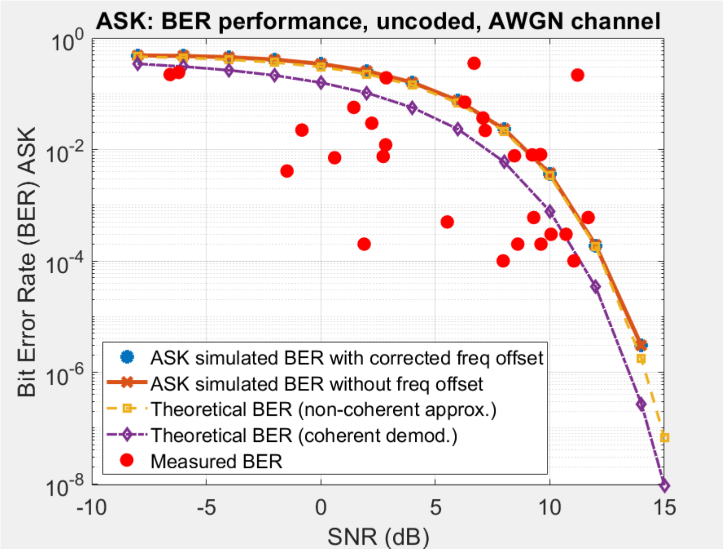
- **Directivity:** Focus of radiated power
- **Gain:** Power output with direction, including efficiency losses
- **Bandwidth:** Range of operating frequencies
- **Max Data Rate without errors:**
- **Shannon–Hartley capacity formula**

$$C = B\log_2\left(1+\frac{S}{N}\right)$$

$C =$ maximum data rate (bits/s)
$B =$ channel bandwidth (Hz)
$\frac{S}{N} =$ signal-to-noise ratio

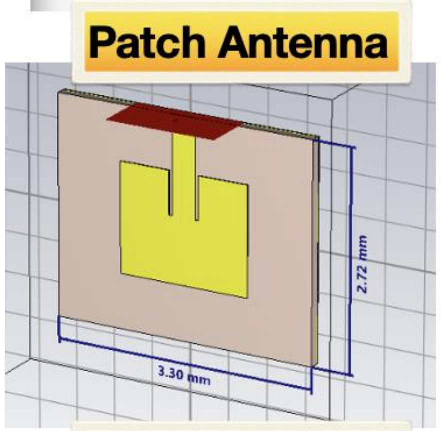
$C =$ maximum data rate (bits/s)

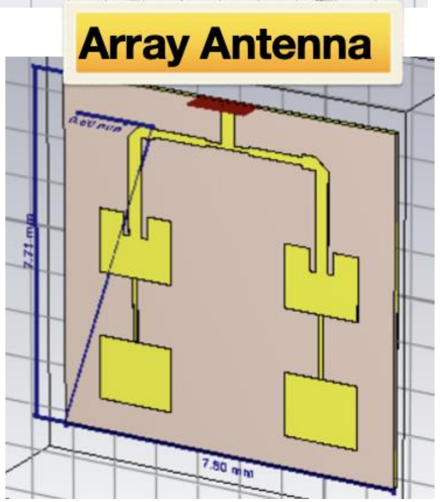
BER comparison



Different Antennas

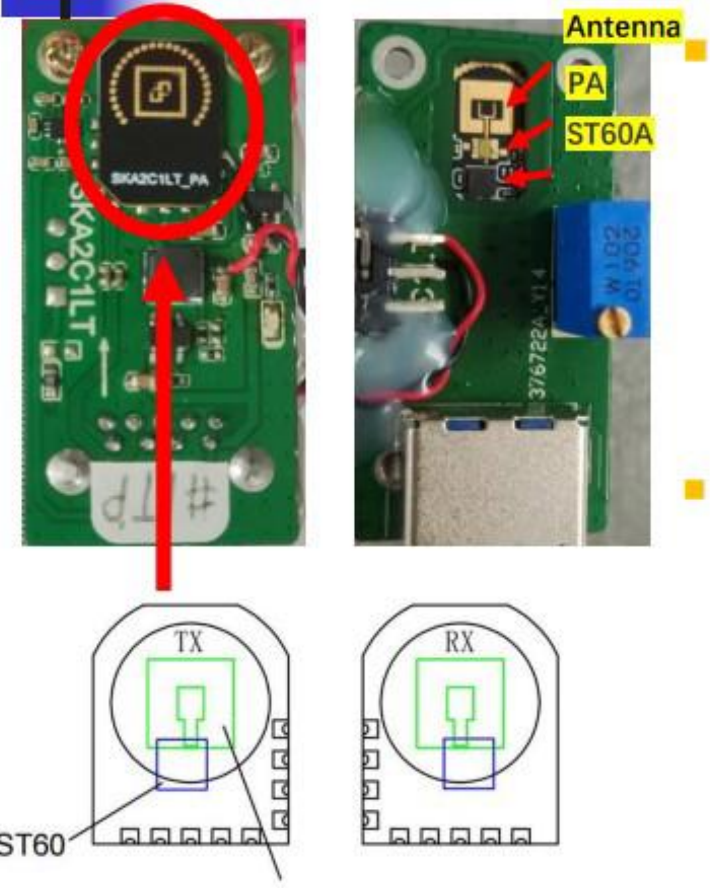
Horn Antenna: Directional, High gain, Big size
Patch Antenna: Compact, Moderate gain, Narrow bandwidth
Array Antenna: High directivity, Compact → multiple radiating elements combine their field constructively in certain direction and destructively in others





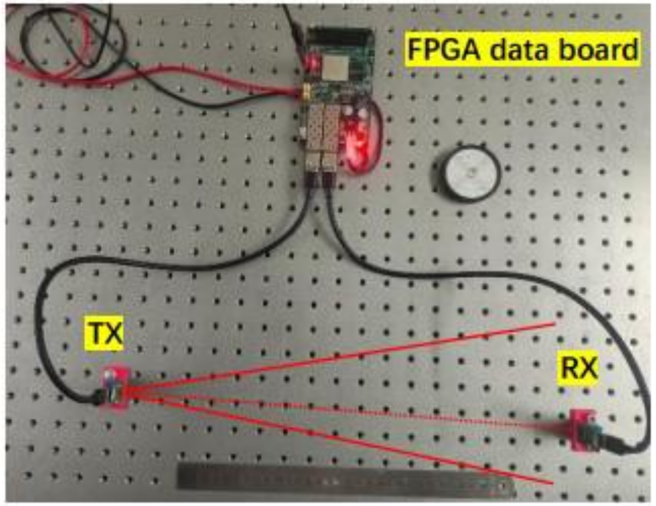
Long-range MMW transceiver design

Results by IHEP CAS



- Long-range millimeter-wave transceiver module
  - Based on ST60A2 with amplifier
  - Utilizing PCB antenna minimizes size and material costs
  - Features stamp-hole interface and simplified peripheral circuit
  - Dimensions: 14mm x 9mm
- Bandwidth test
  - The transmission distance has reached **67.5cm @ 1.25Gbps**
  - The maximum line speed has reached **6.6Gbps @ 22.5cm**

Modulation supports **ASK (Amplitude Shift Keying)**.



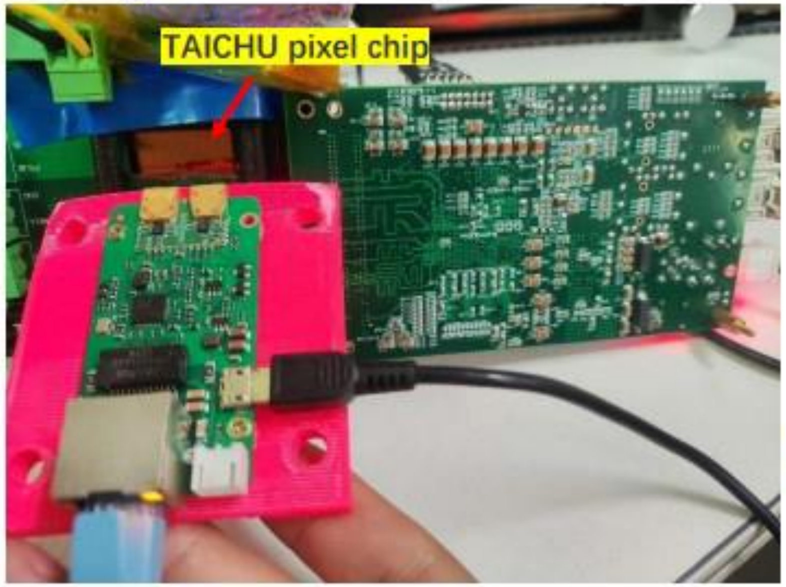
Line rate (Gbps)	Transmit Distance (cm)
1.25	**67.5**
4	50
5	45
6.6	22.5

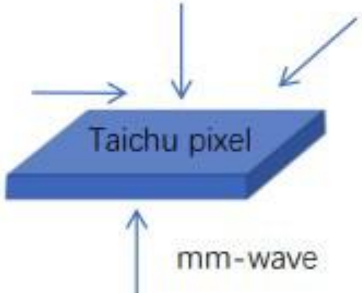
Transmission distance under different line rate

R. Brenner, Summary of WADAPT activities at the DR7 Annual Workshop 2025

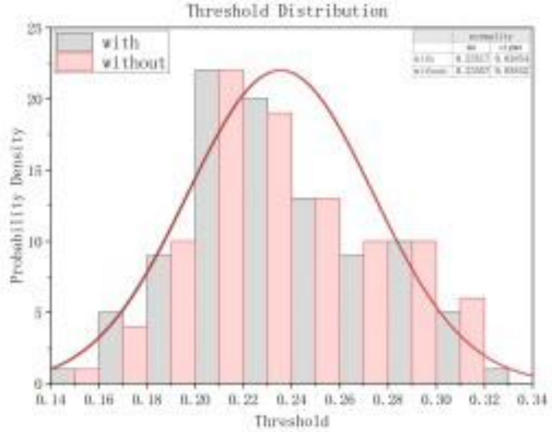
Interference with detectors

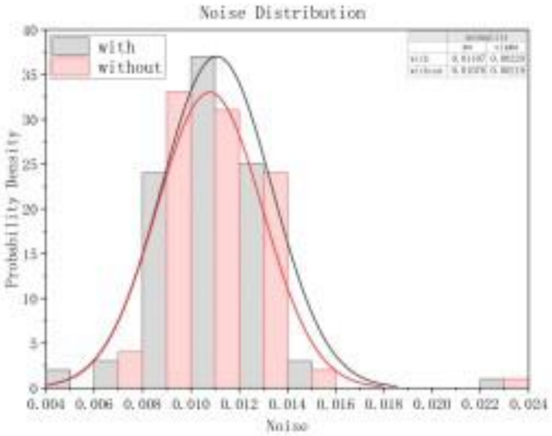
Results by IHEP CAS





- Test with the vertex pixel prototype chip TAICHU3
  - Test two types of modules (short-range and long-range modules).
  - Approach Taichu3 from various directions and distances.
  - Assess the impact on chip threshold and noise levels.
- The test outcomes demonstrate that the influence of 60GHz millimeter waves on the detector signal is minimal.
- Furthermore, the detector signal poses little to no interference with the transmission of millimeter wave signals.





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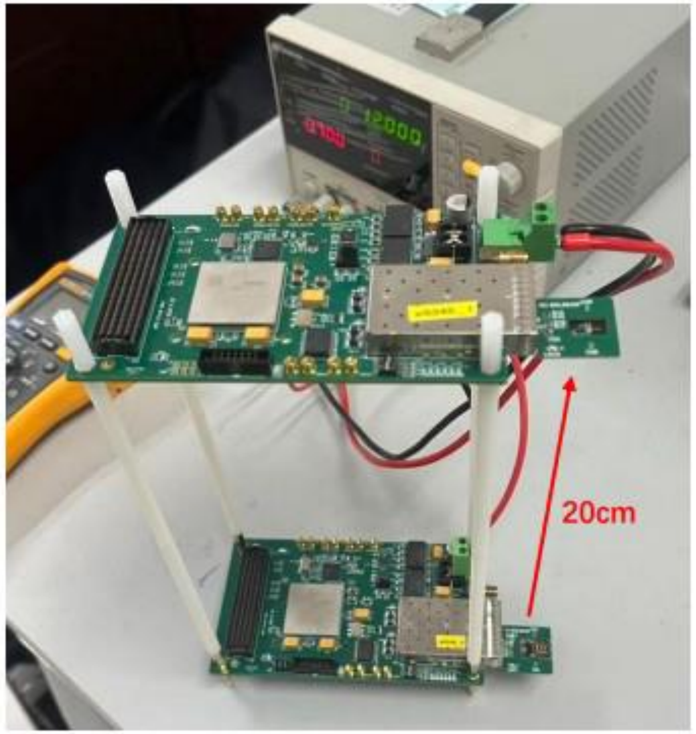
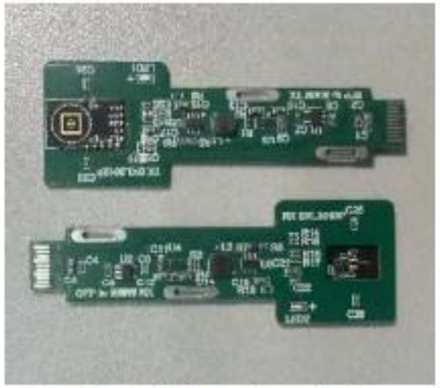
New module test

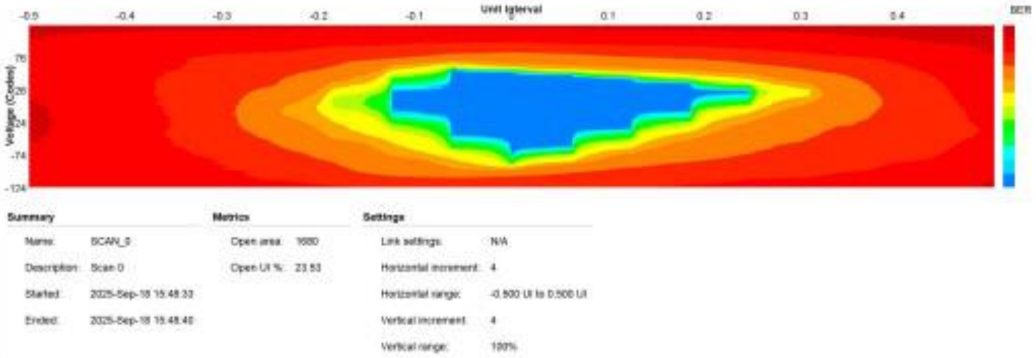
Results by IHEP CAS



Test setup with new designed SFP module



Custom-designed module, SFP-packaging compatible.



Tcl Console | Messages | Serial I/O Links | Serial I/O Scans

Name	TX	RX	Status	Bits	Errors	BER	BERT Reset	TX Pattern	RX Pattern
Ungrouped Links (0)									
Link Group 1 (6)							Reset	PRBS 7-bit	PRBS 7-bit
Link Group 2 (1)							Reset	PRBS 7-bit	PRBS 7-bit
Link 9	MGT_X0Y1/TX	MGT_X0Y1/RX	6.250 Gbps	2.503...	0E0	3.995E-13	Reset	PRBS 7-bit	PRBS 7-bit

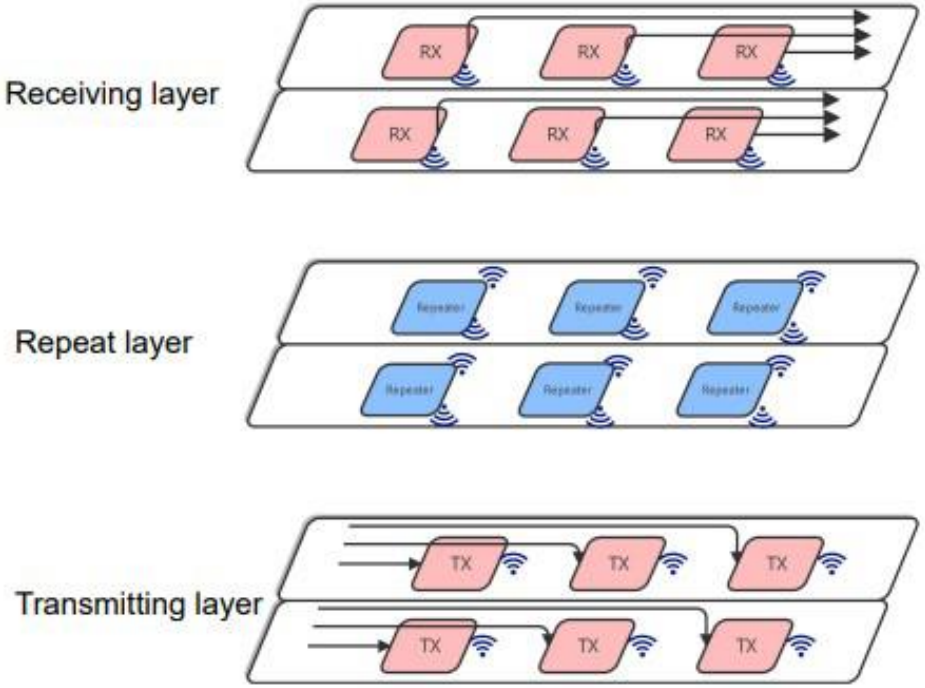
AMD Kintex 7 FPGA ibert test

- Achieve a BER of 4*E-13 at a maximum line rate of **6.25Gbps**.

[R. Brenner, Summary of WADAPT activities at the DR7 Annual Workshop 2025]

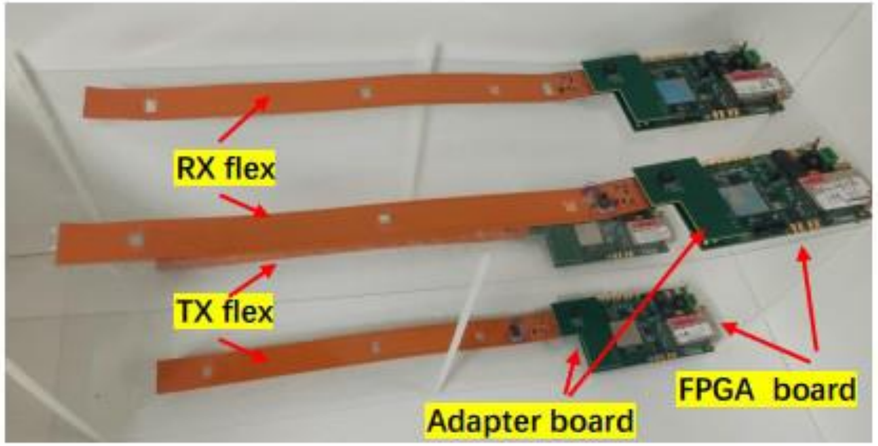
MMW demonstrator

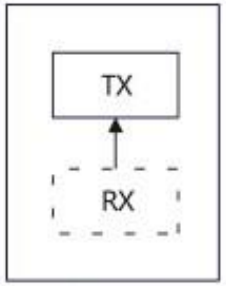
Results by IHEP CAS



mmWave demonstrator schematic

- Two flex PCBs per layer.
- Each flex PCB accommodates 3-channel transceiver modules.





Repeater structure:
RX is at the bottom layer of PCB,
TX is at the top layer of PCB

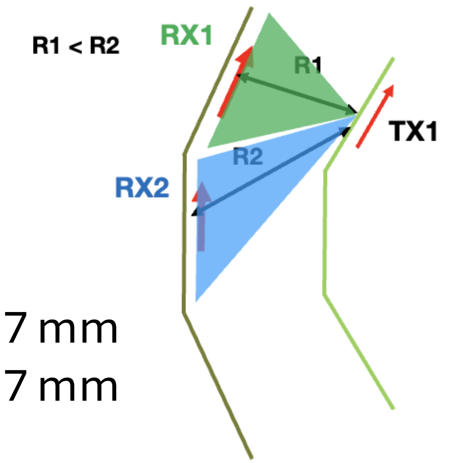
- Most hardware design and production have been completed
  - TX/RX flex PCBs, adapter boards, and FPGA board.
  - Repeater is still under design.
- Prelimilary test with one pair of transceiver module have been completed succesfully.
- This setup mainly focus Multi-channel crosstalk analysis and validation

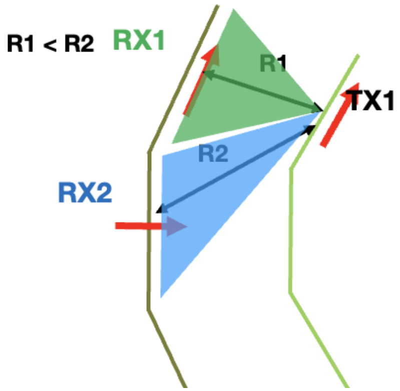
[R. Brenner, Summary of WADAPT activities at the DR7 Annual Workshop 2025]

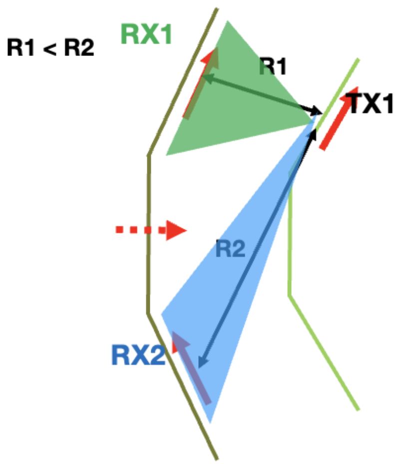
Signal and interference

K. Mirbaghestan, UZH and ZHAW

- Crosstalk is an issue for high link densities.
- Simulation performed including a homogenous metal layer in L1 and L2 to mimic Alu layers in monolithic sensors





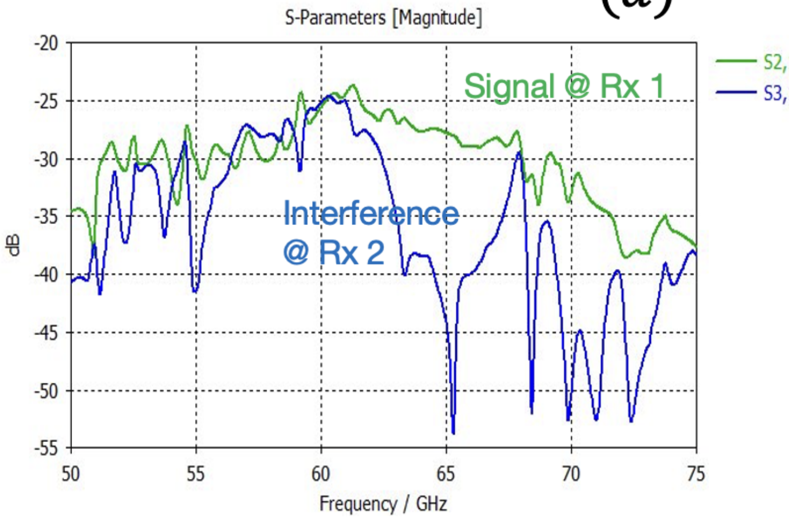


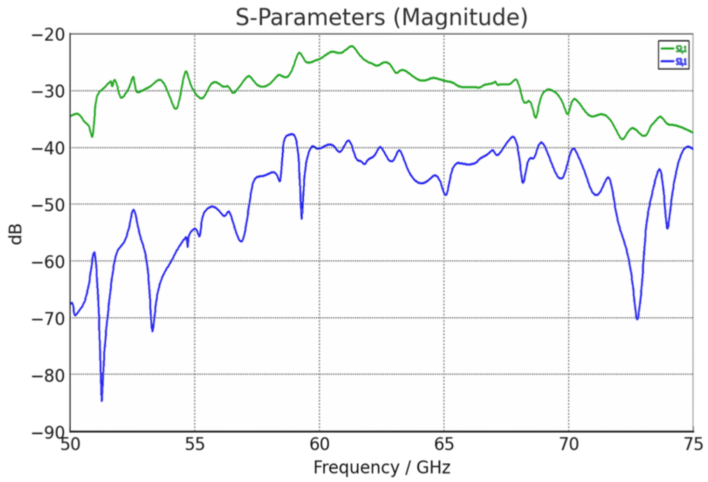
R1=13.7 mm
R2=23.7 mm

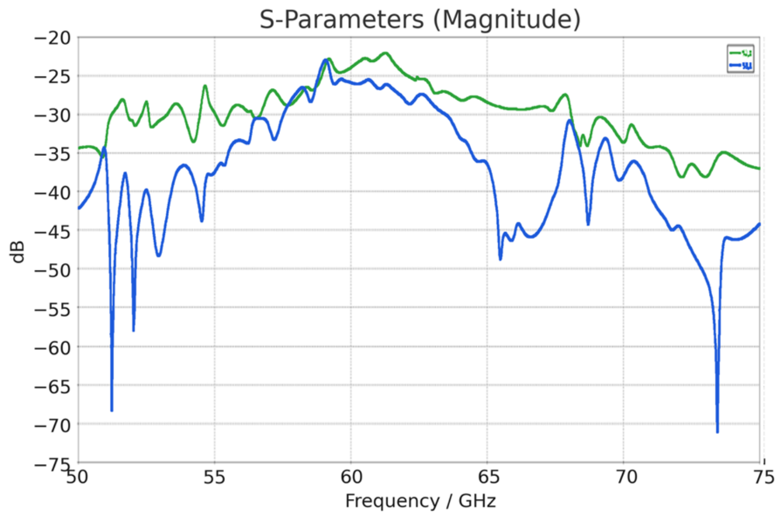
(a)

use **orthogonal linear polarizations**
(e.g. one vertical, one horizontal)

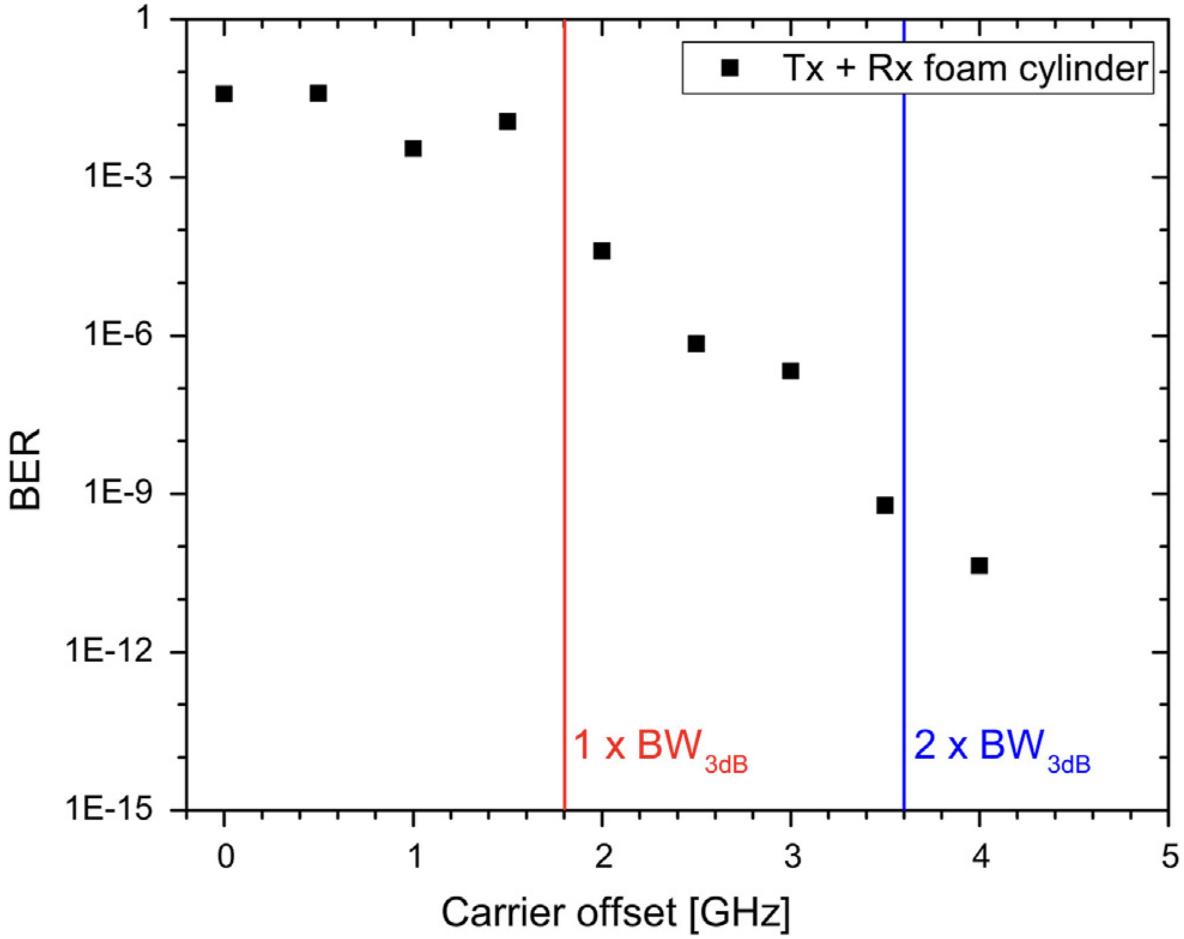
(c)







Signal and interference



WADAPT Collaboration *[Multi Gigabit Wireless Data Transfer in Detectors at Future Colliders]*

- BER has been measured as a function of the carrier offset when two parallel links are positioned at a pitch of 2.6 cm using the same polarization state
- Carrier frequency offset is varied in steps of 500 MHz
- Three frequency channels in parallel within the full 60 GHz band seems possible:
  - Once the offset exceeds roughly one full bandwidth (around ±1.8 GHz), the two channels are effectively isolated, and the BER approaches the single-link baseline (i.e., almost error-free).

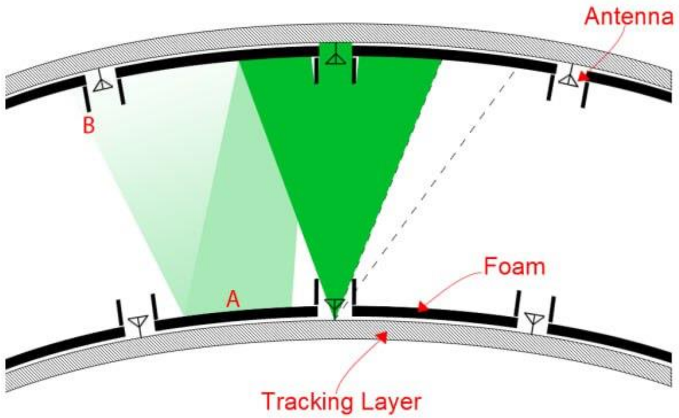
Small carrier offsets may effectively isolate adjacent channels within the 60 GHz band

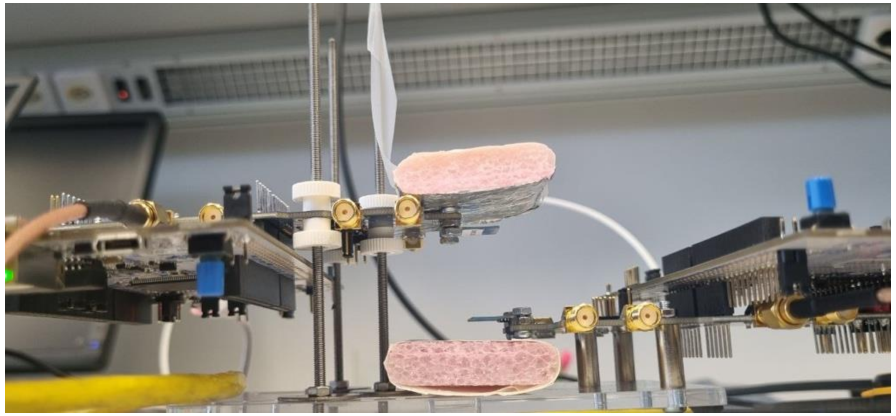
Vertex detector simulation

K. Mirbaghestan, UZH and ZHAW

60 GHz setup with Patch antennas

- Test the new setup with 2 small patch antennas
- Aluminum layer to mimic layers in monolithic sensors
- Added foam to reduce reflections
- Measured the RSSI (Signal Strength)

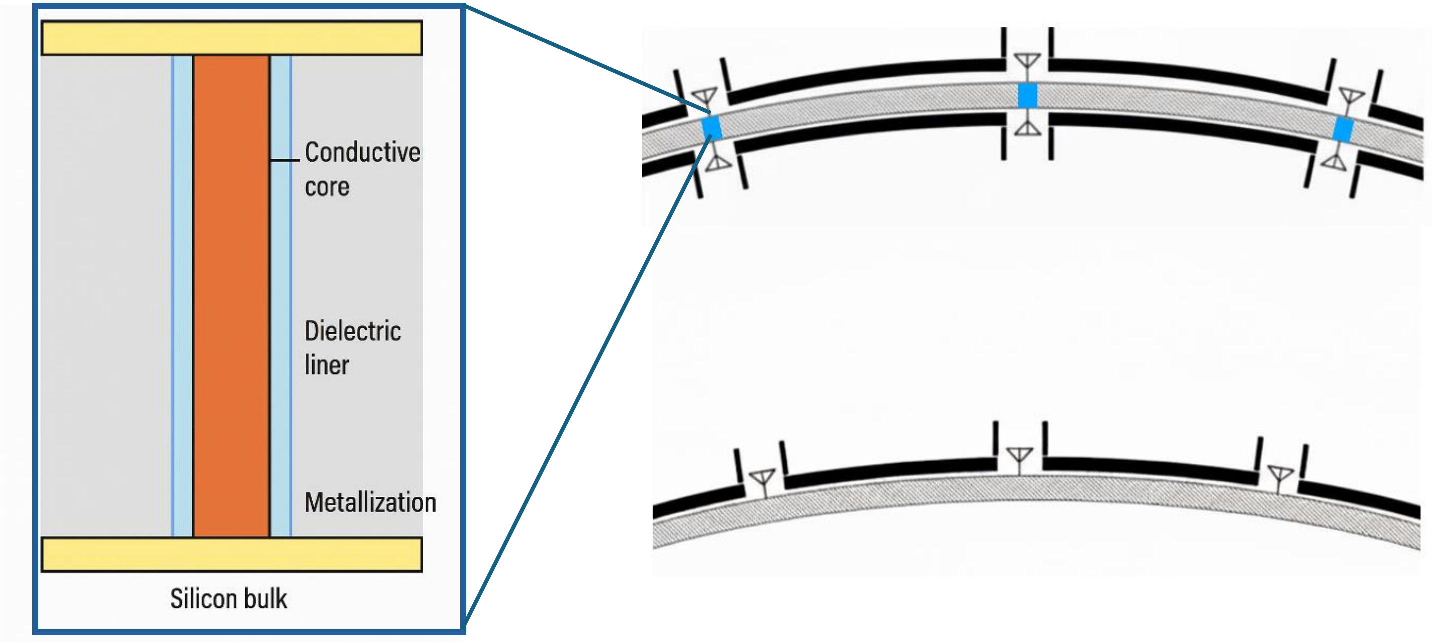




- Need flexes instead of rigid boards to insert the antennas in the Vertex mock-up

Bringing signals across a layer

Through Silicon Vias could be a good solution to get RF from one side of a monolithic sensor to the other **as a matched vertical feed** (signal via + ground fence) that connects transmission lines or an antenna on the far side.



TSV for mm-wave RF

Implementation of transducers and antenna in CMOS requires:

- High resistivity substrates ✓
- **Thick top metals** (2–4 μm Cu or Al) for **low-loss inductors**, transmission lines, and antennas
- Calibrated S-parameter transistor models up to mmWave frequencies

Conclusions and outlook

- **First steps towards a feasibility study**
  - 60 GHz wireless links achieve multi-Gb/s rates over few cm distances
  - compatible with FCC-ee vertex geometry.
- **Crosstalk mitigation**:
  - Orthogonal polarizations and small carrier offsets may effectively isolate adjacent channels within the 60 GHz band.
- **Integration potential**: RF transceivers in 65 nm–28 nm CMOS enable compact, low-power, low-mass data transfer
  - Will it be possible to implement these design feature in the CMOS technology used for MAPs?
- **Next steps**:
  - Extend tests with realistic sensor stack (Al layers + carbon support).
  - Characterize BER stability and timing jitter under varying conditions.
  - Explore TSV-based vertical feedthroughs for signal routing across layers.
  - Estimation of the required power for wireless transmission once embedded in the MAPs
  - Qualify radiation tolerance of RF CMOS front-ends.
  - Full system design and test
- **Goal**:
- Establish feasibility of wireless readout as a viable low-mass interconnect technology for the FCC-ee vertex detector.