Wireless transmission of data and clock for CEPC

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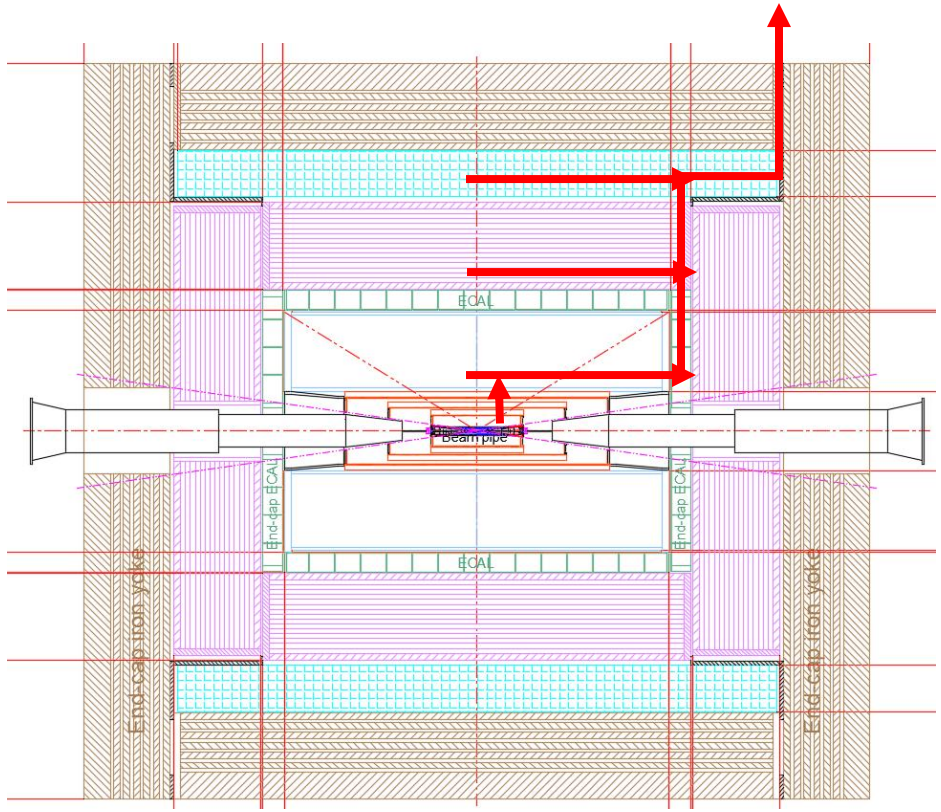
Background

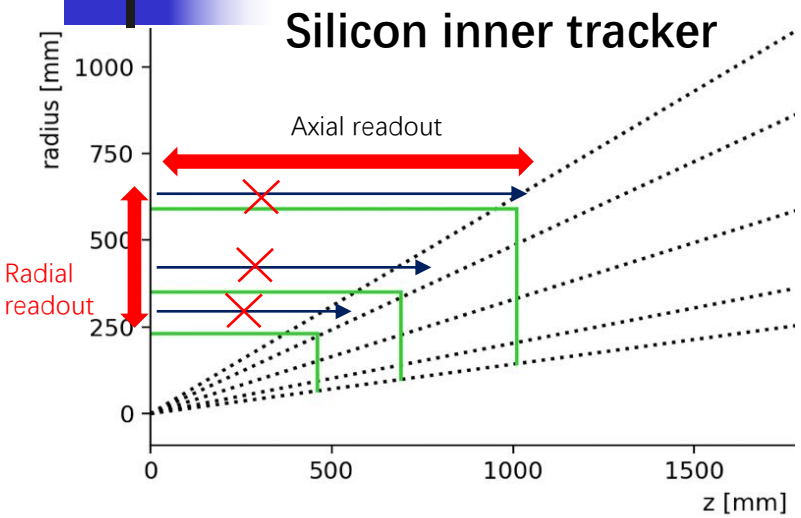
- Wireless transmission advantages include:
  - **Reducing material budget**: Minimize cables, fibers and connectors, while also reducing the dead zone.
    -> Significantly enhance the detection efficiency and resolution!!!
  - **Convenience for installation and maintenance:** Simplify the placement of the transceiver.
  - **Cost Reduction**: Removal of cables, fibers and connectors.

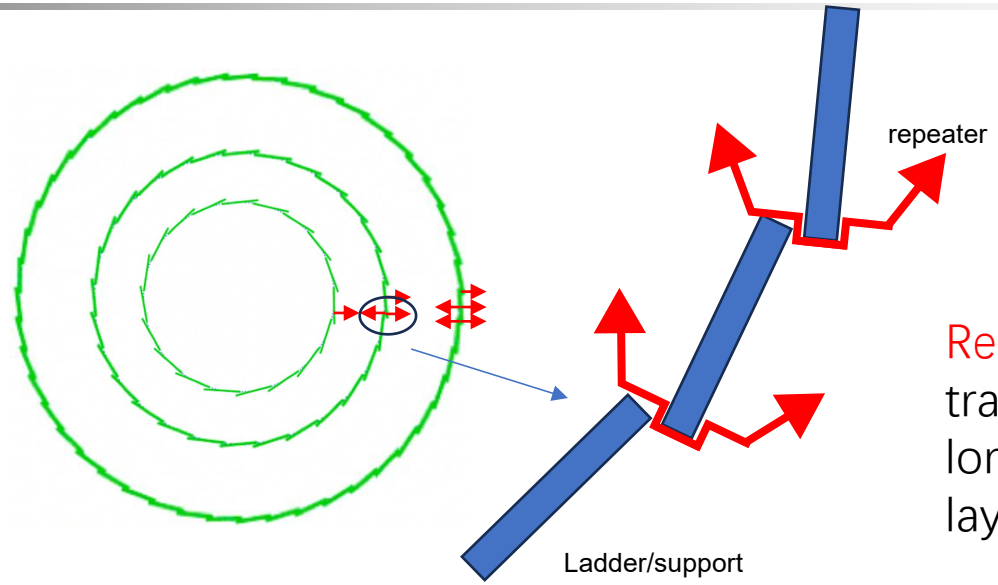
- Application ideas for CEPC detector
  - **Radial data readout between barrel layers:** Provides a new data exchange pathway compared to traditional data readout methods.
  - **Axial data readout from barrel to endcap**: Serve as an alternative to optical fibers, minimizing space and material usage.
  - **Data readout in the endcap:** Concentrates the data at the edge of endcap to simpify the complexities of cables routing



CEPC Detector Geometry

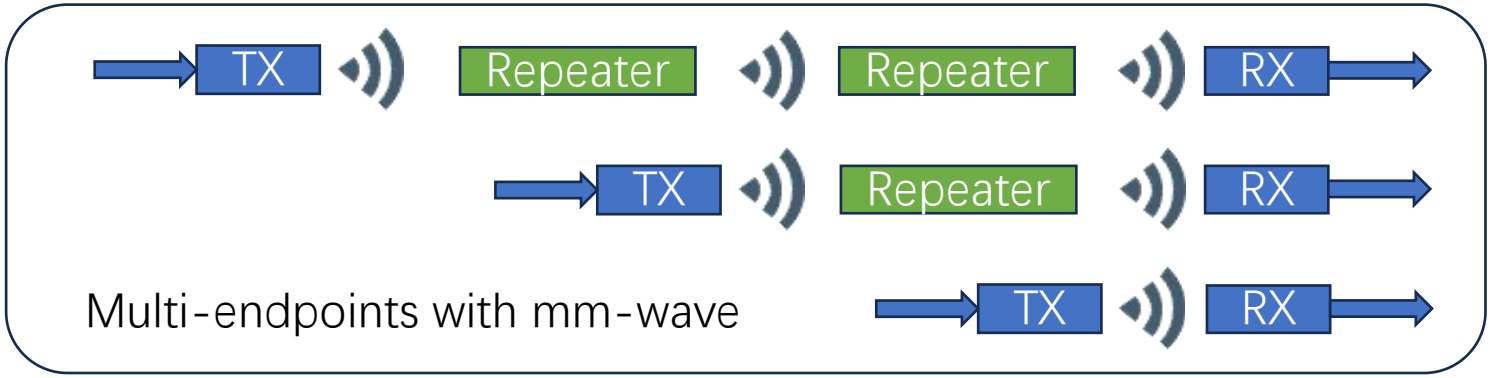
Radial data readout



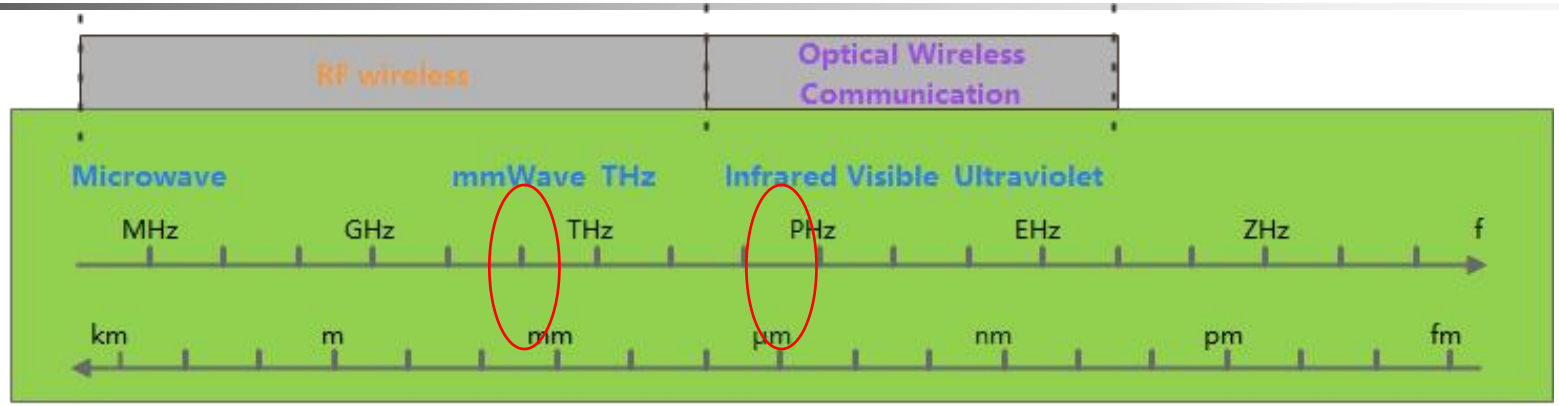


Repeaters: Amplify and re-transmit RF signals over long distances or through layers.

- Radial readout with mm-wave
  - 12- 24 cm transmission distance
- Axial readout to endcap
  - Only at the outermost layer or dedicated aggregation layer.



Research focus

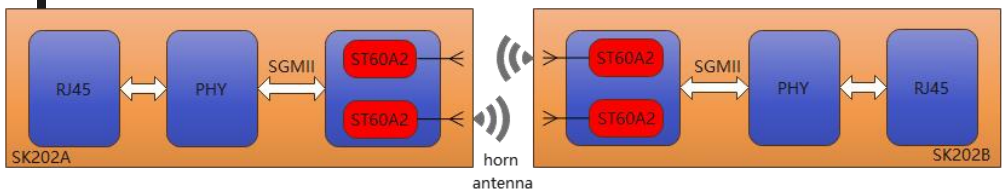


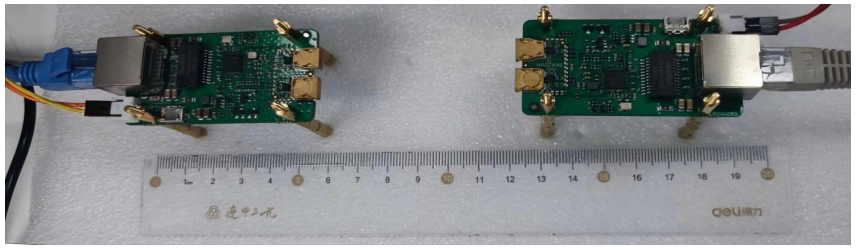
Electromagnetic Spectrum

- **Millimeter Wave (60GHz)**
  - High bandwidth, low power consumption
  - Antenna size miniaturization, can even be integrated into chips
  - Low interference between channels, minimal interference with detectors
  - Medium level of technological maturity

- **Optical Wireless Communication (OWC) / Free Space Optical (FSO)**
  - Extremely high transmission bandwidth
  - High technological maturity
  - Stringent alignment requirements

MM-wave commercial module





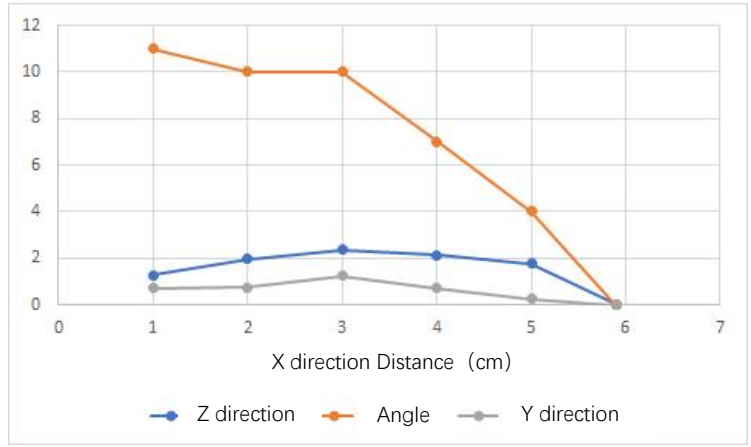
Distance (cm)	Bandwidth (Mbps)	Packet loss rate
1	914	0.031%
3	917	0.061%
5	915	0.05%
6	913	0.13%
>6	No link	No link

Test result at different distances of TX/RX

Material	Thickness	Penetration Ability
Paper	2mm	√
Plastic ruler	2mm	√
FR4 PCB	1.6mm	×
Flex	0.2mm	×

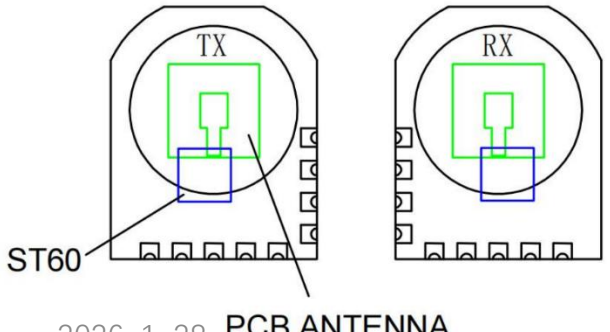
Penetration Test with 3 cm distance

- Test with evaluation boards – SK202 (short-range module)
  - Based on the commercial 60GHz RF chip, **ST60A2G0** transceiver from STMicroelectronics.
  - The transmission speed can exceed 900Mbps when the distance is less than **6 cm**.
  - The 60GHz mm-wave signals can easy penetrate materials such as paper, plastic; but **cannot** pass through FR4 PCBs or Flex cables due to the copper's shielding.
  - Compared to optical communication, mm-wave requires less precise alignment.
  - Power comsuption: Approximately **0.5W** (TX+RX)



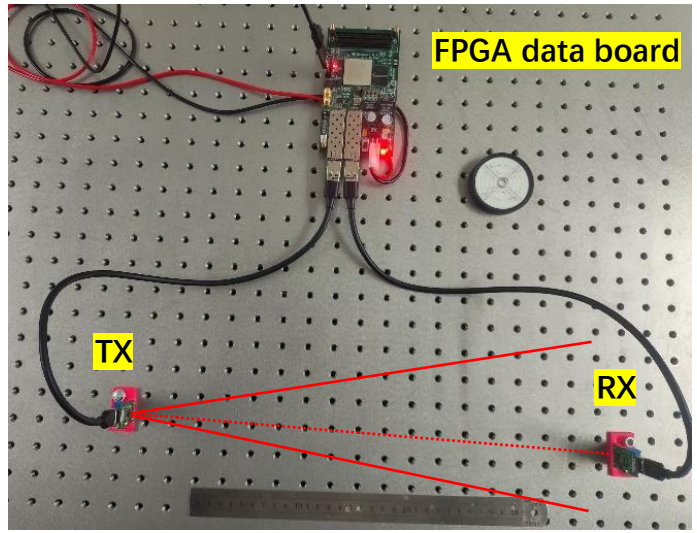
Alignment test

Long-range mm-wave module development



ST60A2 + PA + patch Antenna

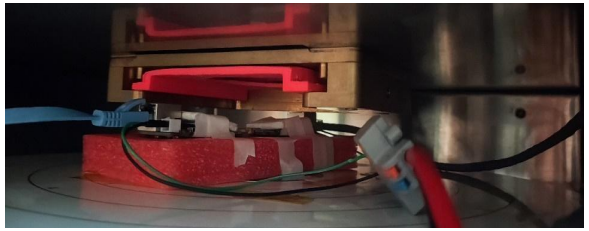
- Long-range mm-wave transceiver module
  - Based on ST60A2 with amplifier
  - Utilizing PCB antenna minimizes size and material costs
  - Features stamp-hole interface and simplified peripheral circuit
  - Dimensions: 14mm x 9mm
- Bandwidth test
  - The transmission distance has reached **67.5cm @ 1.25Gbps**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

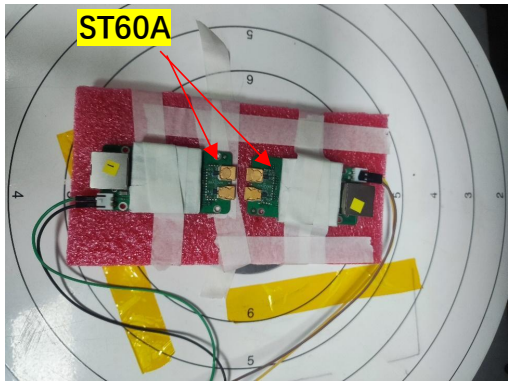


Line rate (Gbps)	Transmit Distance (cm)
1.25	**67.5**
4	50
5	45
6.6	22.5

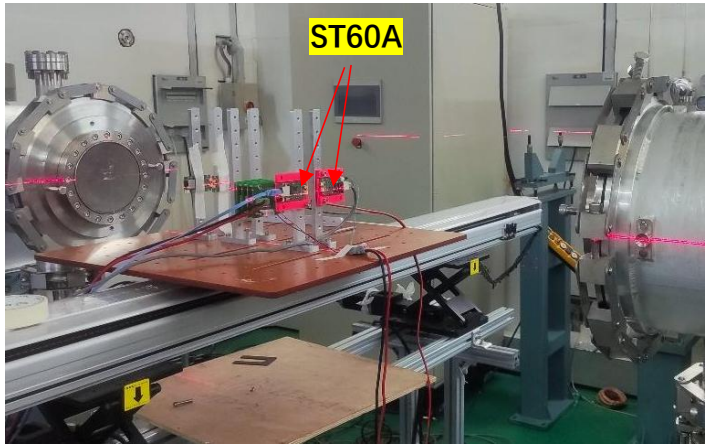
Transmission distance under different line rate

Radiation tolerance

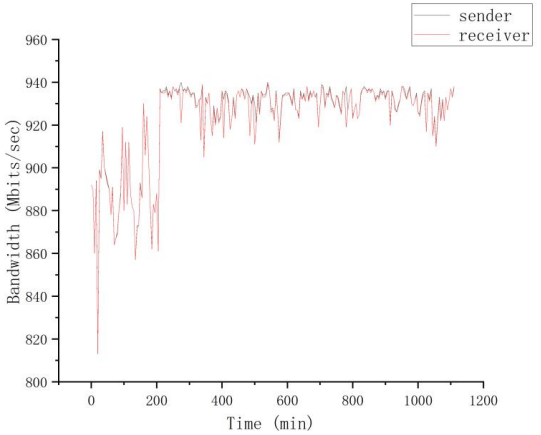




X-ray (20 kV, 40 mA)
Dose rate： 21.2krad/min
Duration： **5.5 hours (7 Mrad)**



CSNS neutron beam



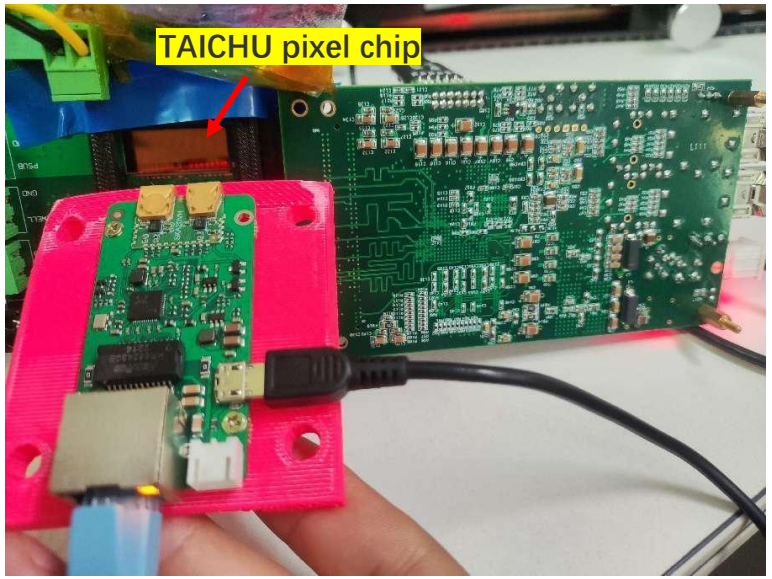
Bandwidth during irradiation

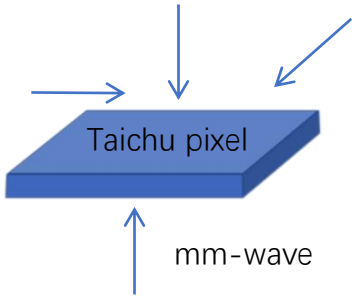
Beam intensity:: $1.65*10^7 n_{eq}/cm^2$
Absorption coefficient: 0.95
Duration: **21 hours (1.2 X 10^{12} n_{eq}/cm)**

- Total dose test
  - Target value: Total dose 5 Mrad (Si).
  - Real-time monitoring during the irradiation process, wireless communication all normal.

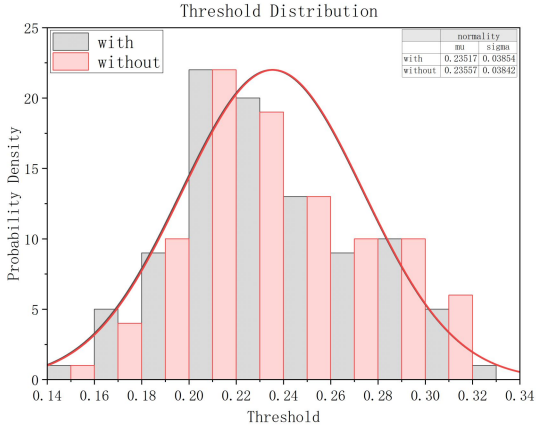
- NIEL test
  - Target value： 0.97 X 10^{12} n_{eq}/cm （1MeV Equivalent Neutron）
  - The real-time test bandwidth during irradiation process, with transmission rate basically unaffected.

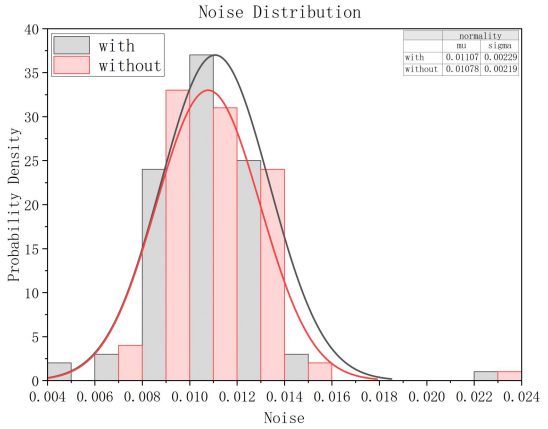
Interference with detectors



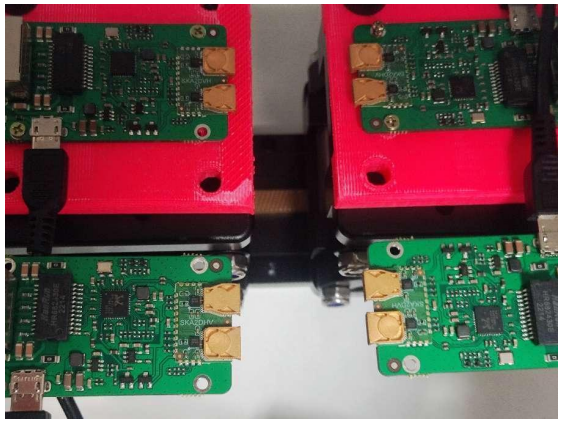


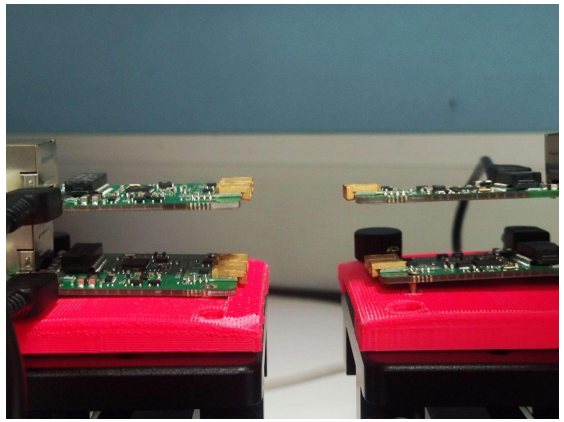
- Test with the vertex pixel prototype chip TAICHU3
  - Test two types of modules (short-range and long-range modules).
  - Approach Taichu3 from various directions and distances.
  - Assess the impact on chip threshold and noise levels.
- The test outcomes demonstrate that the influence of 60GHz millimeter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

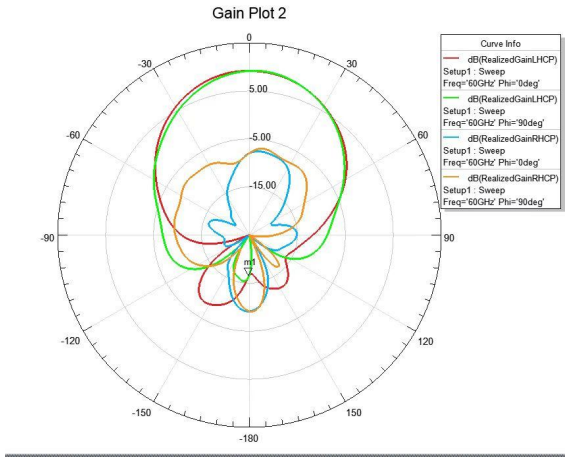


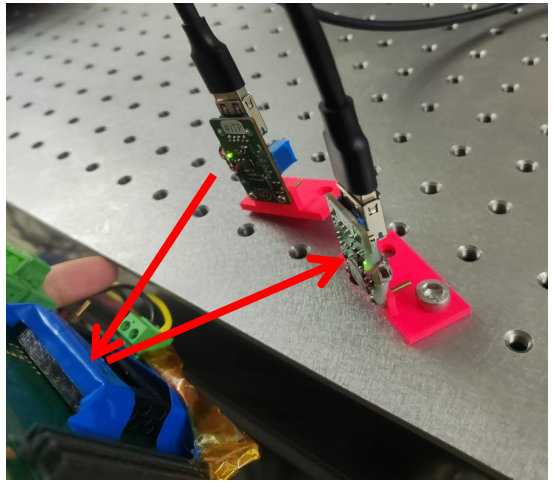


Crosstalk with each other









- For short-range modules with horn antennas, a minimum distance of **3 cm** will not affect transmission, enabling high-density placement.

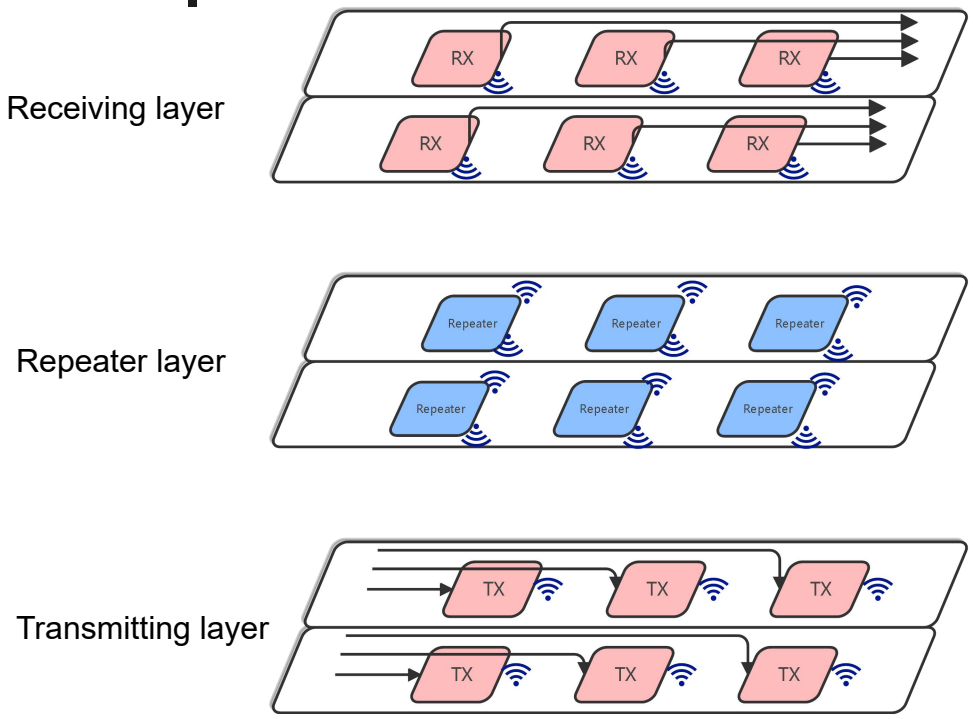
- For long-range modules, the spacing needs to be increased to **15 cm**. Meanwhile, the antenna features a half-power radiation angle of around **90 degrees**.
- It is observed that reflected signals can also affect the interval at specific angles. A balance must be considered by both transmission distance and crosstalk.

Mass production

MMW transmission module

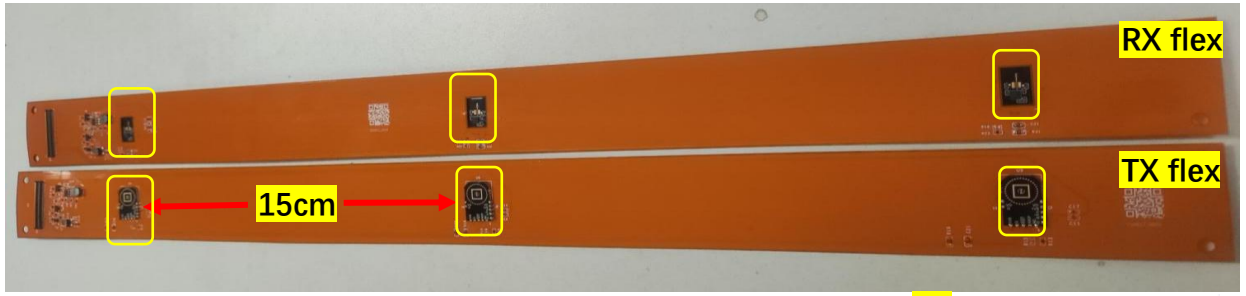
- The assembly process required carefully handling for the bare-die amplifier wire bonding and module soldering.
- Manufactured 200 pairs for subsequent testing and research.

mm-wave demonstrator



mmWave demonstrator schematic

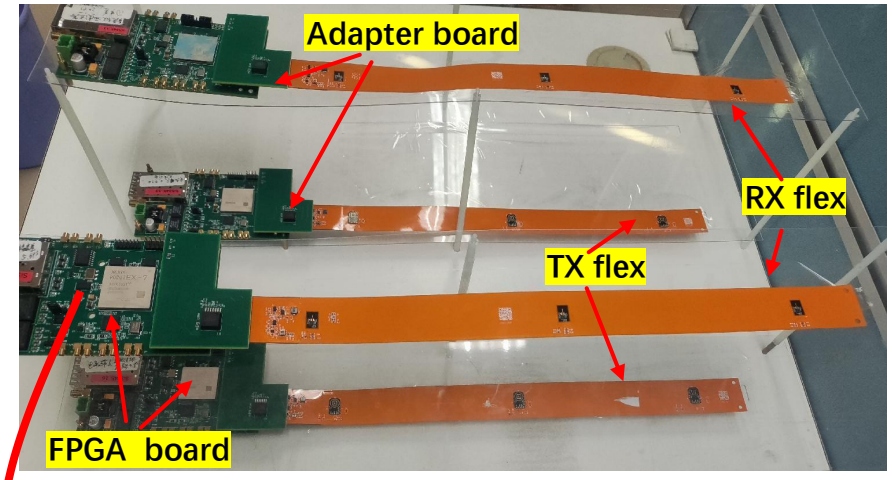
- Two flex PCBs per layer.
- Each flex PCB accommodates 3-channel transceiver modules.

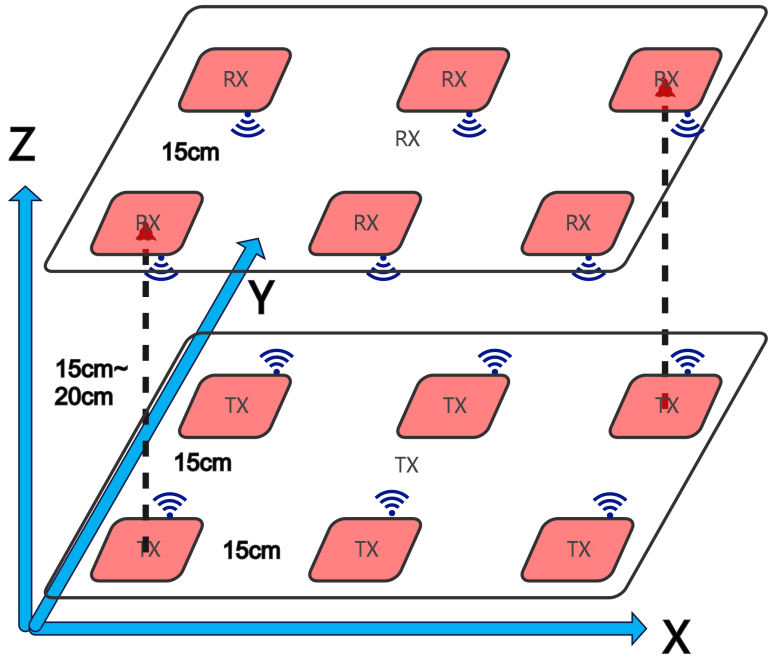


Repeater structure: RX is at the bottom layer of PCB, TX is at the top layer of PCB

- All the hardware design have been completed
  - TX/RX flex, adapter boards, repeater,and FPGA board.
- Multi-channel test with 6 pairs of transceiver module have been completed.

mm-wave demonstrator



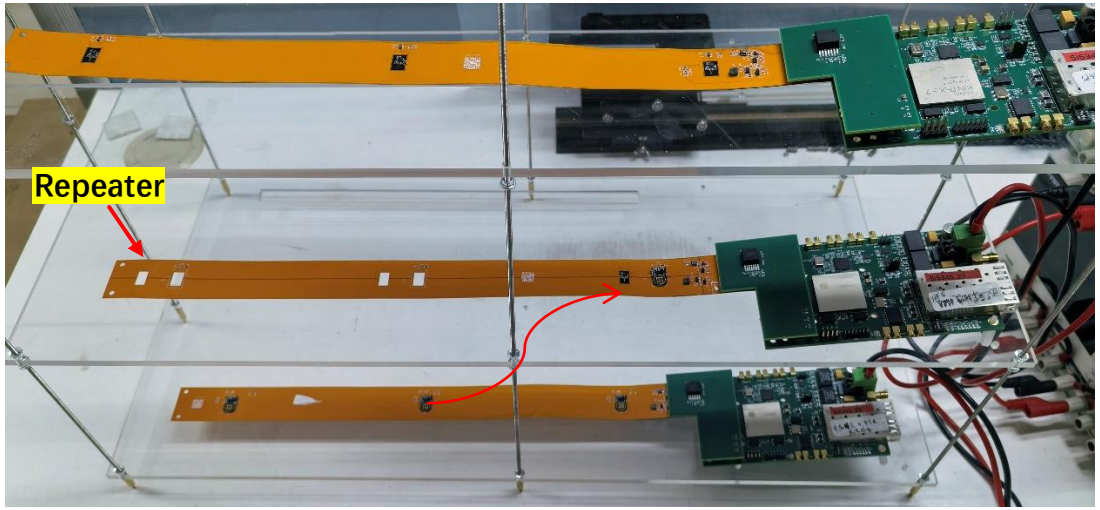


Name	TX	RX	Status	Bits	Errors	BER	BERT Reset	TX Pattern	RX Pattern	TX Pre-Cursor	TX Post-Cursor	TX Diff Swing
Ungrouped Links (0)												
Link Group 0 (3)							Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)
Link 5	Quad_116/MGT_X0Y5/TX (xc7k325t_0)	Quad_116/MGT_X0Y5/RX (xc7k325t_0)	3.125 Gbps	1.005E13	0E0	9.955E-14	Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)
Link 6	Quad_116/MGT_X0Y6/TX (xc7k325t_0)	Quad_116/MGT_X0Y6/RX (xc7k325t_0)	3.125 Gbps	1.005E13	0E0	9.955E-14	Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)
Link 7	Quad_116/MGT_X0Y7/TX (xc7k325t_0)	Quad_116/MGT_X0Y7/RX (xc7k325t_0)	3.125 Gbps	1.005E13	0E0	9.955E-14	Reset	PRBS 7-bit	PRBS 7-bit	1.67 dB (00111)	0.68 dB (00011)	1018 mV (1100)

The IBERT test on 3 pairs of modules within one FPGA (1 hour running): NO error bit

- A stable and crosstalk-free transmission can be achieved.
  - 3D arrangment, **2X3** one direction transmission pairs
  - Line rate: **3.125 Gbps**
  - Reducing the transmit power and increasing the receive power to avoid crosstalk.
  - Spatial constraints: **15 cm** in the XY plane directions and within a range of **15–20 cm** in the transmission direction (Z direction),
  - Power comsuption: 1.5W / pairs

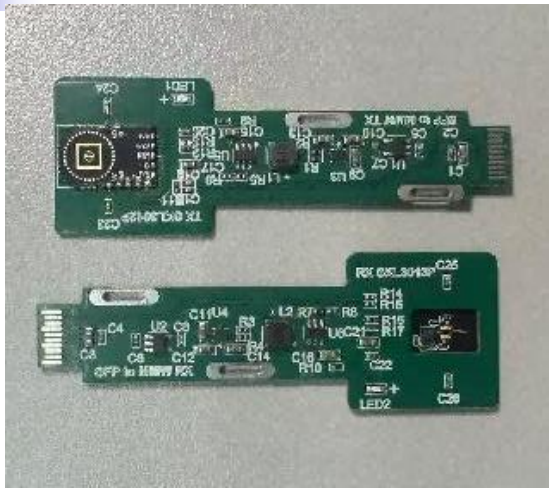
mm-wave demonstrator



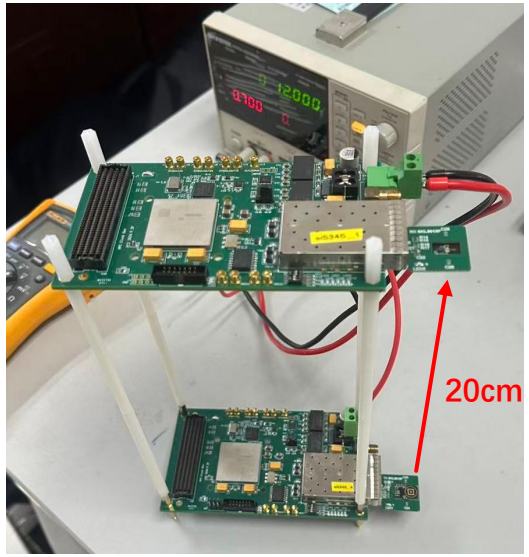
15 cm is a highly critical distance, which causes interference within repeaters. Practical tests show that a larger spacing is required to ensure the normal operation of the repeater layer.

- With the demonstrator, we preliminarily identified the difficulties in controlling crosstalk of mm-wave transmission.
- For actual detectors, customized adaptable power of modules and specific matching of different modules should be employed based on transmission distance demands to mitigate internal signal reflection and interference.

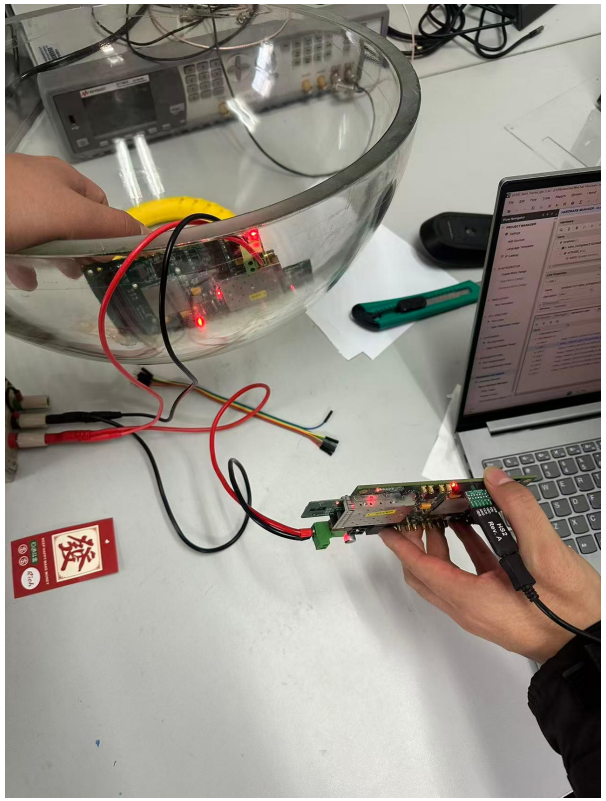
Application to other experiments



Custom-designed module,
SFP-packaging compatible.



Test setup with new designed SFP module



MM-waves penetrate **10 mm glass** easily with almost no transmission impact. This provides a method for data transmission without the need for underwater wall penetration.

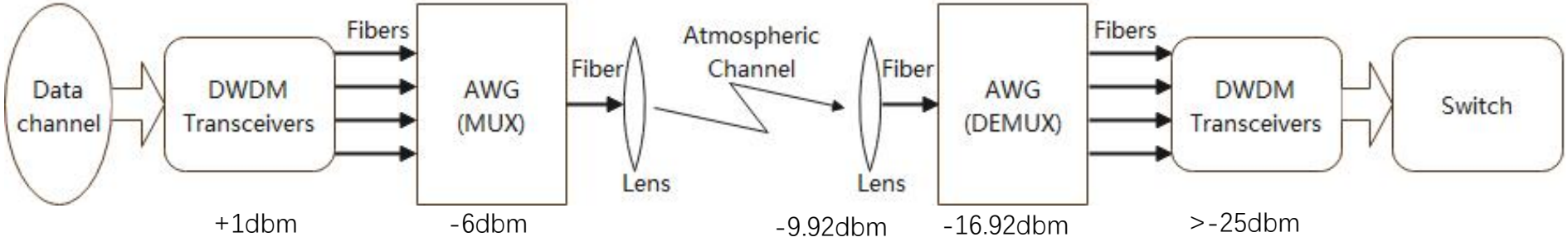
Tcl Console | Messages | **Serial I/O Links** | Serial I/O Scans

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

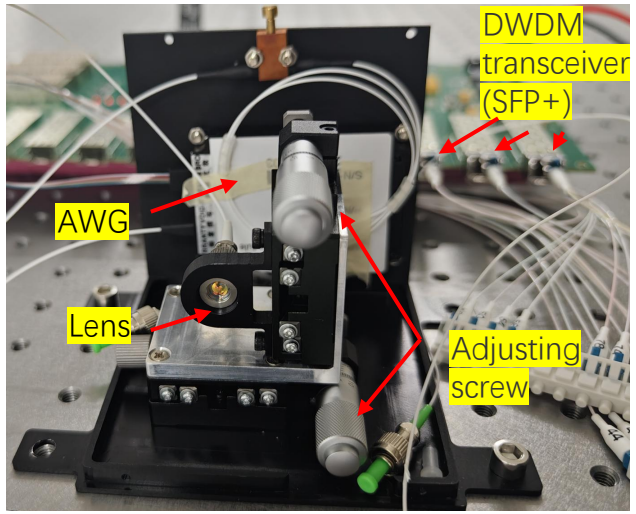
AMD Kintex 7 FPGA ibert test

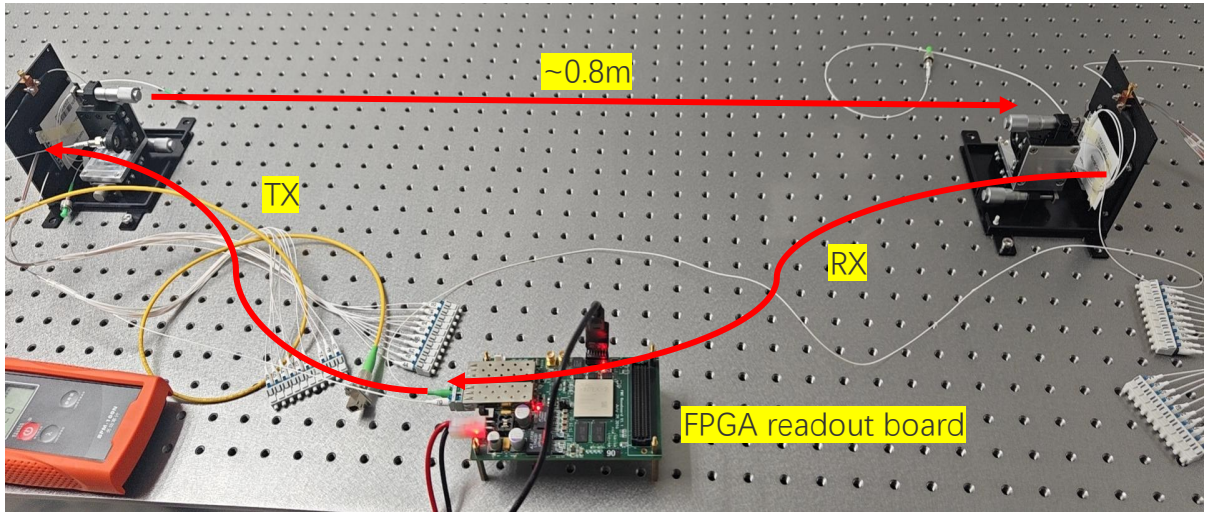
- Achieve a BER of 4*E-13 at a maximum line rate of **6.25Gbps**.

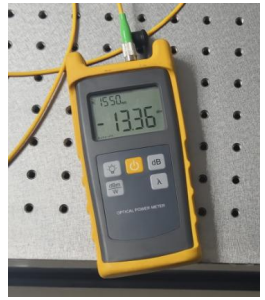
Optical Wireless



Free Space Optical(FSO) test setup structure



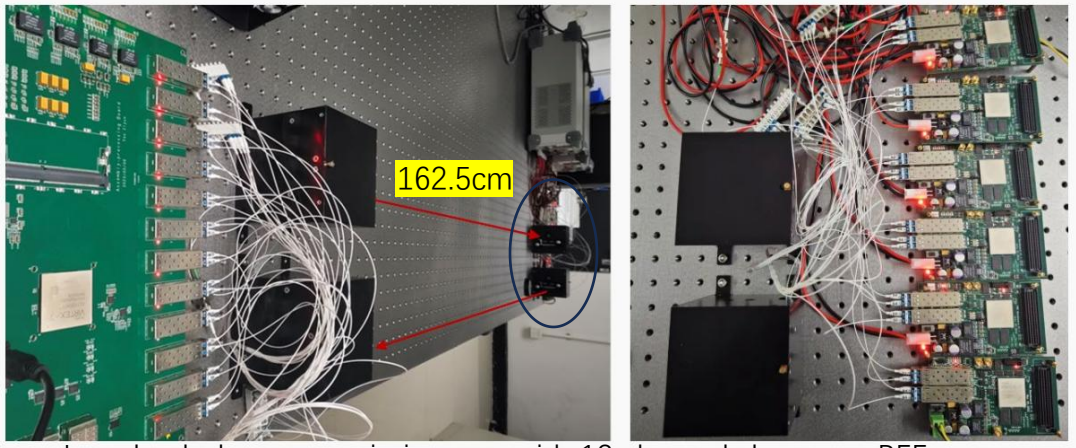




Optical Power received : -13.36dBm

- Mature commercial components (DWDM optical transceivers, optical lens),
- Customized AWG signal generator and mechanical adjustment structure

Performance test



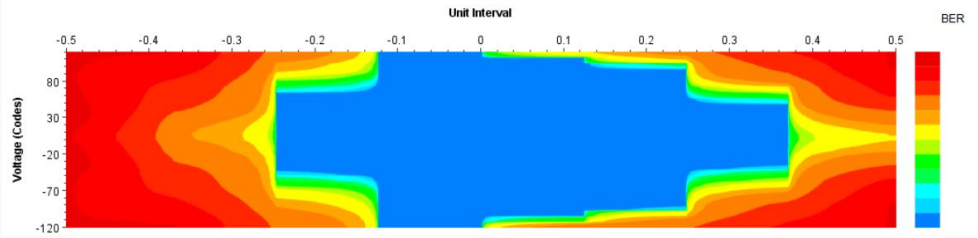
Loopback data transmission test with 12 channels between BEE prototype board(Vertex 7) and MOST2 FEE FPGA board(Kintex 7)

Parameter	λ = 1550.12nm, P = 1.52dB
λ – 0.8nm	-45.54dB
λ	-11.30dB
λ + 0.8nm	-43.57dB

Crosstalk between channels < -34dB
Insertion loss ~ 12.82dB

Name	TX	RX	Status	Bits	Errors	BER	BERT Reset	TX Pattern
Ungrouped Links (0)								
Found Links (12)							Reset	PRBS 31-bit
Found 0	Quad_114/MGT_X1Y16/TX (xc7vx690t_0)	Quad_114/MGT_X1Y16/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	7.43E11	1.79E-3	Reset	PRBS 31-bit
Found 1	Quad_114/MGT_X1Y17/TX (xc7vx690t_0)	Quad_114/MGT_X1Y17/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 2	Quad_114/MGT_X1Y18/TX (xc7vx690t_0)	Quad_114/MGT_X1Y18/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 3	Quad_114/MGT_X1Y19/TX (xc7vx690t_0)	Quad_114/MGT_X1Y19/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 4	Quad_116/MGT_X1Y24/TX (xc7vx690t_0)	Quad_116/MGT_X1Y24/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 5	Quad_116/MGT_X1Y25/TX (xc7vx690t_0)	Quad_116/MGT_X1Y25/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 6	Quad_116/MGT_X1Y26/TX (xc7vx690t_0)	Quad_116/MGT_X1Y26/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 7	Quad_116/MGT_X1Y27/TX (xc7vx690t_0)	Quad_116/MGT_X1Y27/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 8	Quad_118/MGT_X1Y32/TX (xc7vx690t_0)	Quad_118/MGT_X1Y32/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 9	Quad_118/MGT_X1Y33/TX (xc7vx690t_0)	Quad_118/MGT_X1Y33/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 10	Quad_118/MGT_X1Y34/TX (xc7vx690t_0)	Quad_118/MGT_X1Y34/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit
Found 11	Quad_118/MGT_X1Y35/TX (xc7vx690t_0)	Quad_118/MGT_X1Y35/RX (xc7vx690t_0)	10.000 Gbps	4.15E14	0E0	2.41E-15	Reset	PRBS 31-bit

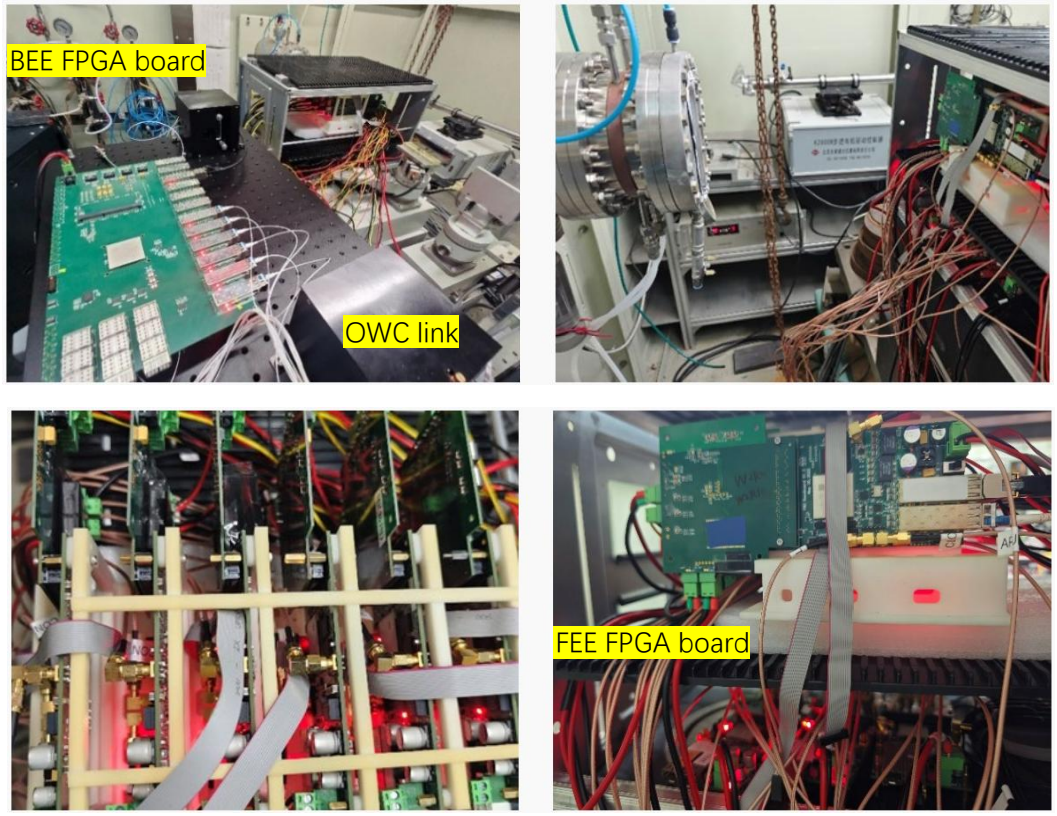
PRBS 31bits error rate < BER-15 @ 8Gbps X 12 channels & 10Gbps X 11 channels



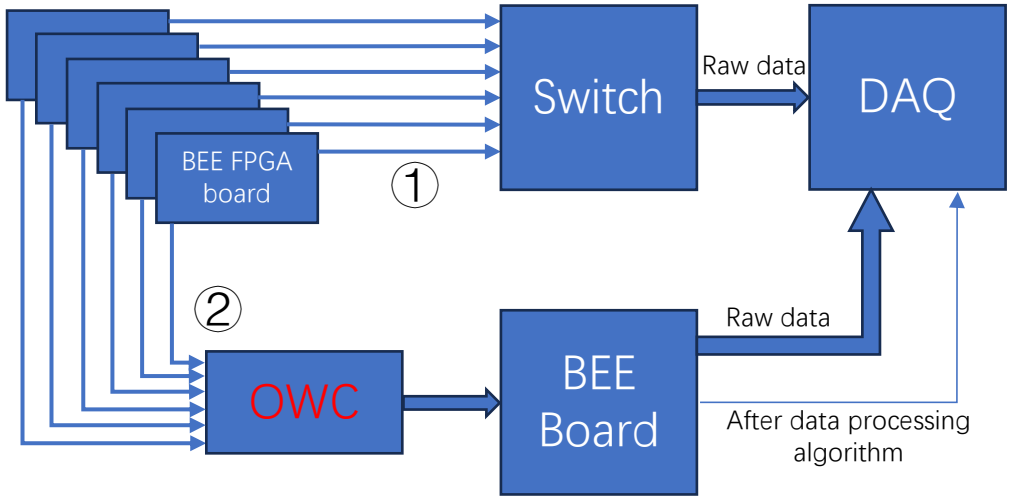
10Gbps eye pattern in loopback test

- The optical wireless system can operate within a distance of **162.5cm,** offering a bandwidth of up to **118Gbps**, and it is capable of supporting 100G Ethernet.

Prototype test



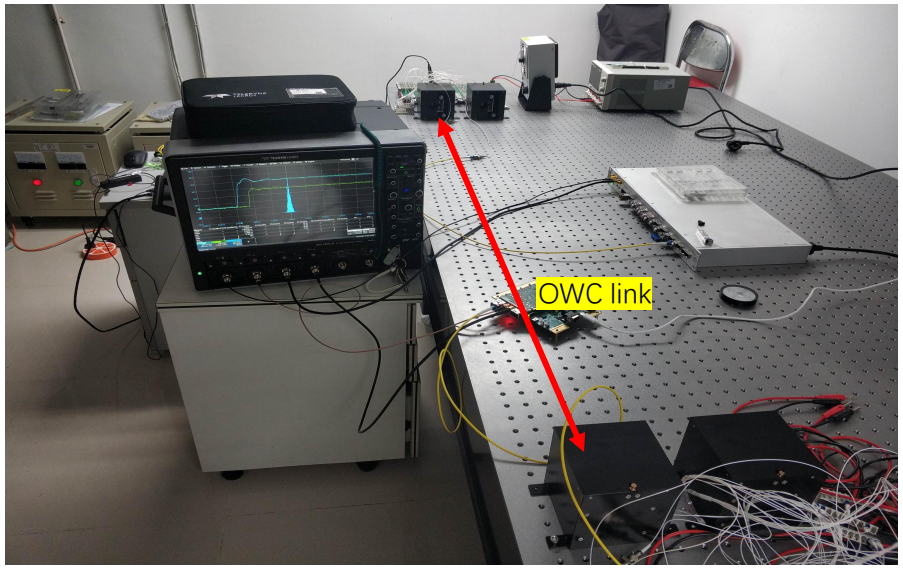
TAICHU3 Telescope prototype test in BSRF



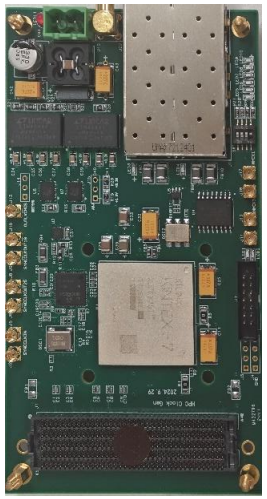
- After running for **2086 minutes** in total, the raw data from optical fiber to switch ① is **100%** matched to the data transmitted through OWC to the BEE board ②.

Clock on OWC

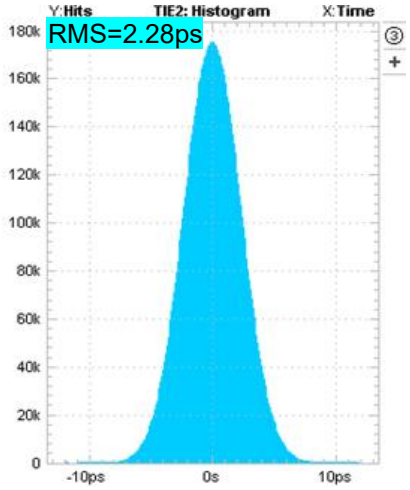
- Introduce WR protocal in OWC transmission
  - Enhance hardware,
  - Resolve reboot uncertainty,
  - Achieve superior performance.



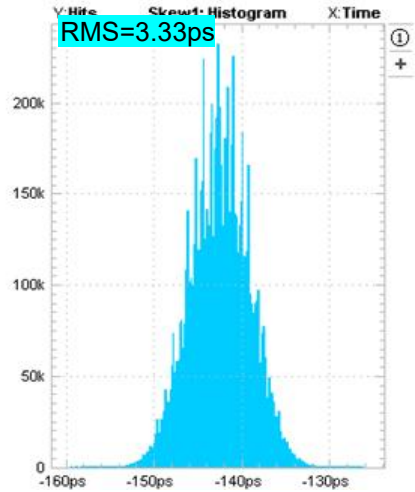
Wireless clock transmission test



new design hardware



TIE jitter of receive clock

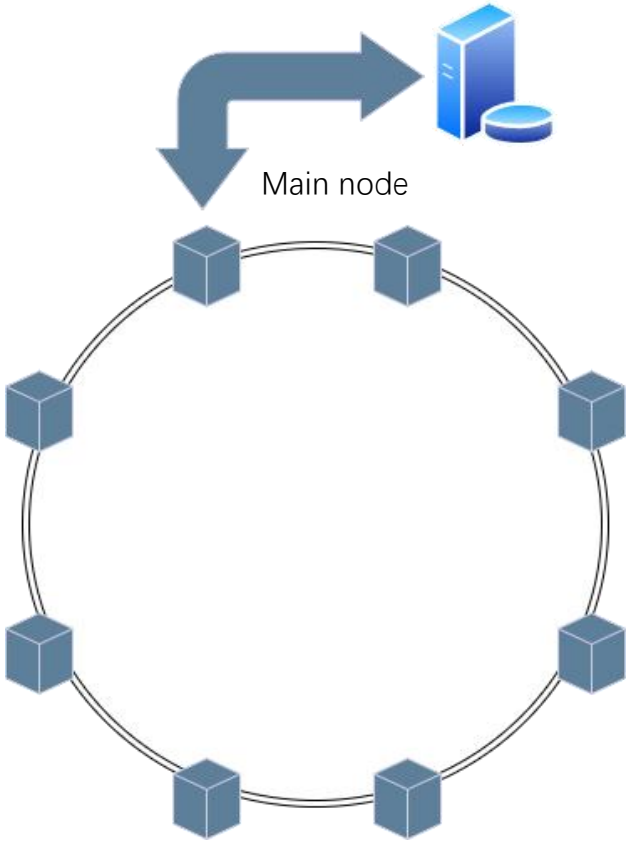


Clock synchronization

- Clock performance
  - TIE jitter : **2.28 ps RMS**
  - Synchronization accuracy: **3.33 ps RMS, 38.6 ps peak to peak**
- A relatively fixed free space optical transmission path will not affect the accuracy of the WR protocol.

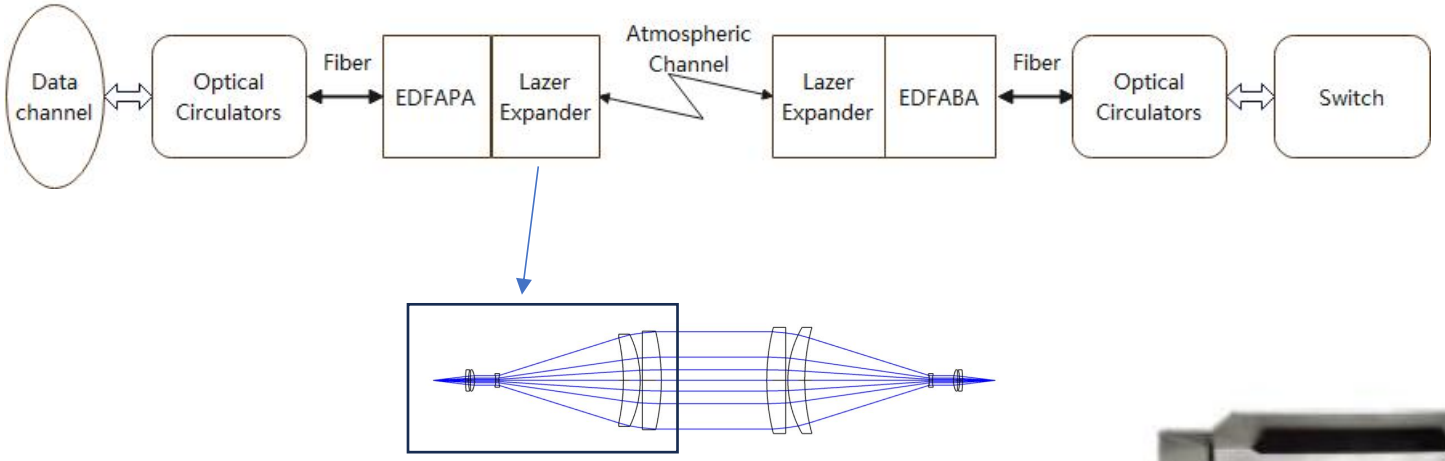
Application in accelerator

- Research on accelerator synchronization timing scheme based on wireless transmission
  - Objective: To achieve high-precision global clock control for various nodes within a 100 km range in accelerator, thereby reducing the installation and deployment of expensive radiation-resistant optical cables.
  - Group： Hu Jun, Jiang Xiaoshan, Zhou Xing, Accelerator Center (Jin Dapeng et al.).
- Technical challenges to be addressed
  - Low-cost long-distance wireless optical transmission (500–1000 meters).
  - Point-to-point data transmission and clock synchronization technology, with synchronization accuracy better than 10 ps.
  - Large-scale, multi-cascaded clock synchronization technology.

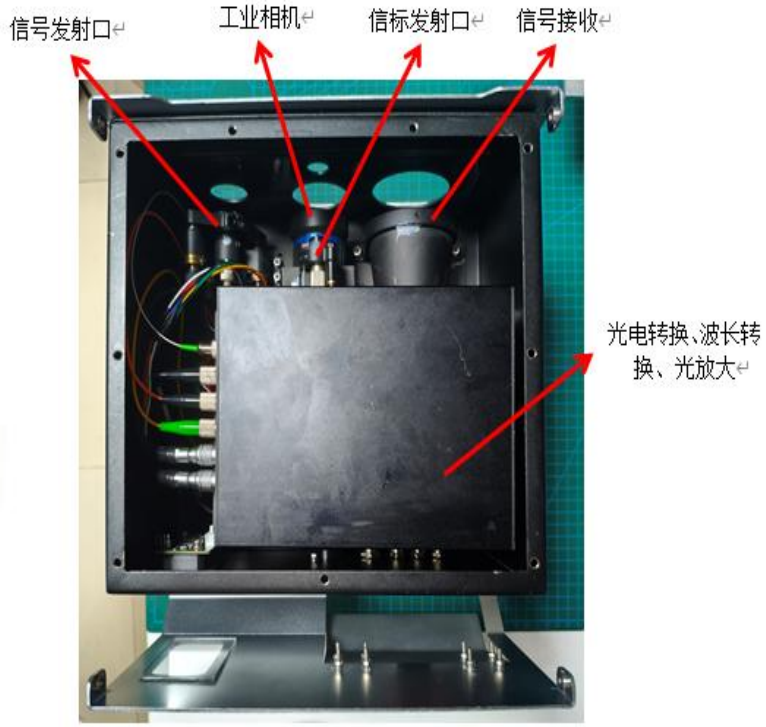


Circular Clock Synchronization

Low-cost long-distance OWC



Long-distance ~1km OWC design

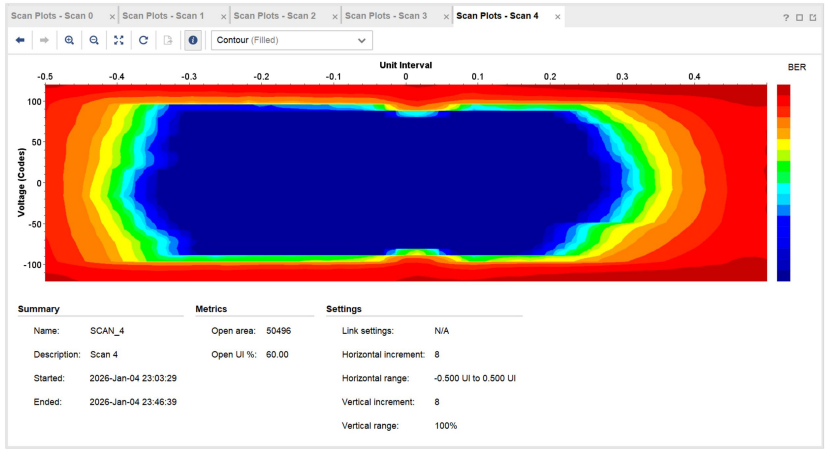


- EDFA + custom design optical Lens structure
  - The price has been reduced to 50,000 yuan per pair.

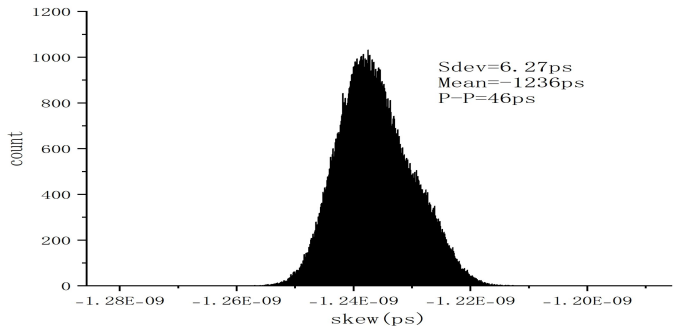
Clock on long distance OWC

- Data transmission and clock synchronization tests succeeded
  - Bit error rate below 1E-13
  - Synchronization accuracy at **6.27ps RMS，46ps peak-to-peak**

500 m Round-Trip Laser Wireless Transmission Test in HEPS campus



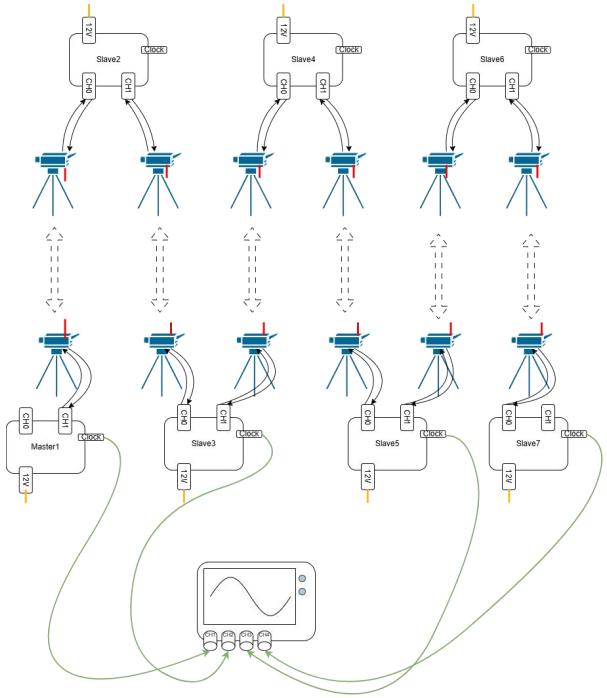
Data transsmission eye diagram

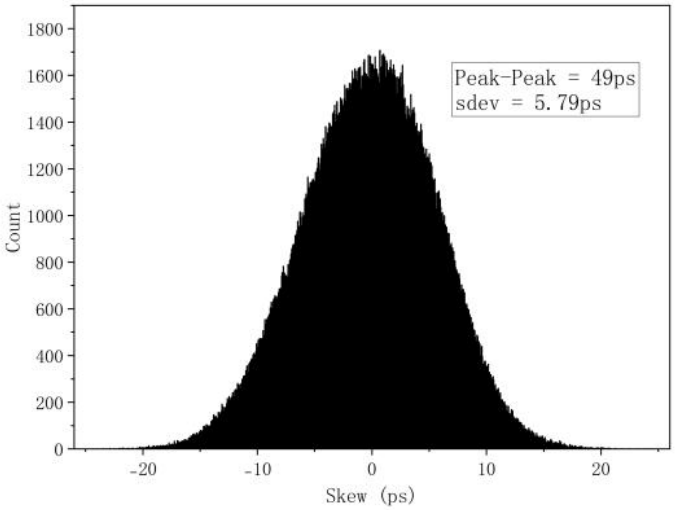


Clock Synchronization Accuracy Results (45 minutes)

Clock on cascade transmission

50m Round-Trip test in IHEP





Clock Synchronization Accuracy Results (60 minutes)

- 7-level cascade clock transmission test
  - L1-L7 synchronization accuracy : **5.79ps RMS，49ps peak-to-peak**
- In the current tests, long-distance and cascading lead to a little of performance degradation, which remains within an acceptable range.

Summary

- **Milimeter wave:**
  - Partnered with the Institute of Microelectronics, ST Technology Co., Ltd., and Huawei to develop a batch-producible system solution for mm-wave technology.
  - Developed a long-range, compact module for CEPC, built a multi-channel demonstrator, and solved key problems in millimeter-wave technology.
  - Future Plan: Expand mm-wave applications to other experiments.
- **Optical Wireless Communication:**
  - Benefited from domestic optoelectronic development, core components like optoelectronic transceivers are readily available.
  - Built a short-distance high-bandwidth optical transmission platform and completed full verification.
  - Applied long-distance OWC solutions to accelerator timing systems, and built a new framework of wireless optical data transmission + high-precision clock timing.

Thanks!