Progress on Wireless Data & Clock Transmission at IHEP

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Outline

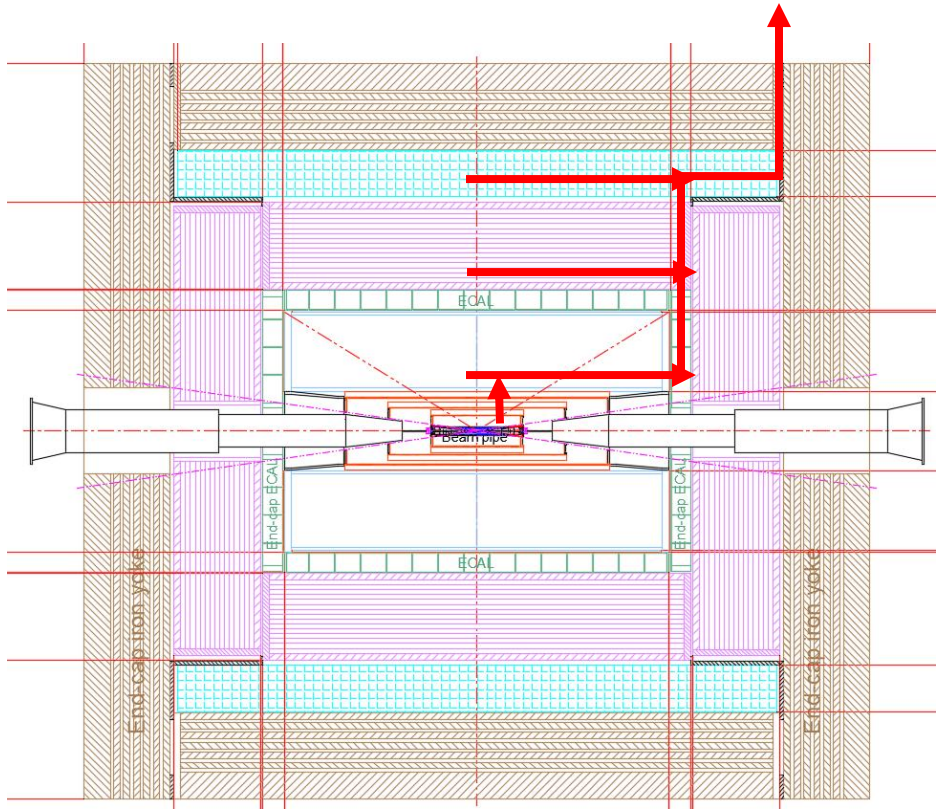


- Background and motivation
- Part 1: 60 GHz mm-wave data link
- Part 2: optical wireless data and clock
- Summary and outlook

Background

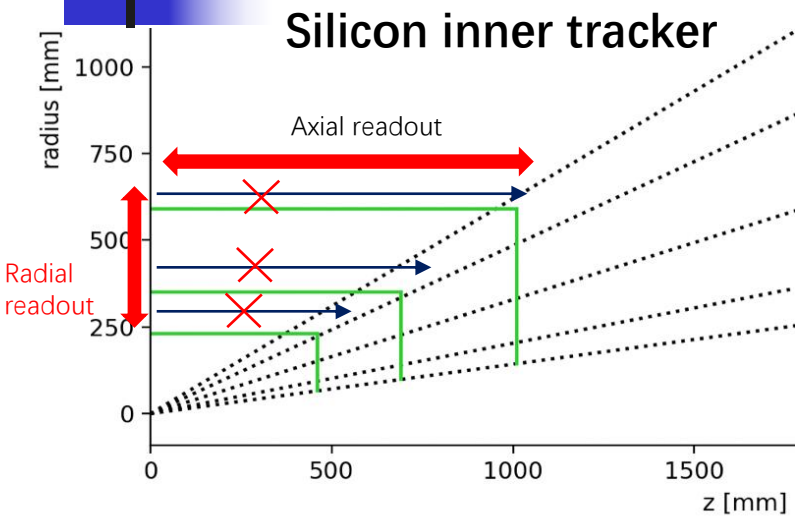
- **Wireless transmission：** WHY
  - **Material budget**: Minimize cables, fibers and connectors, and smaller dead zone.
    -> the largest single gain in detection efficiency and resolution
  - **installation and maintenance:** transceivers are placed, not routed
  - **Cost** : the cables, fibers and connectors are removed

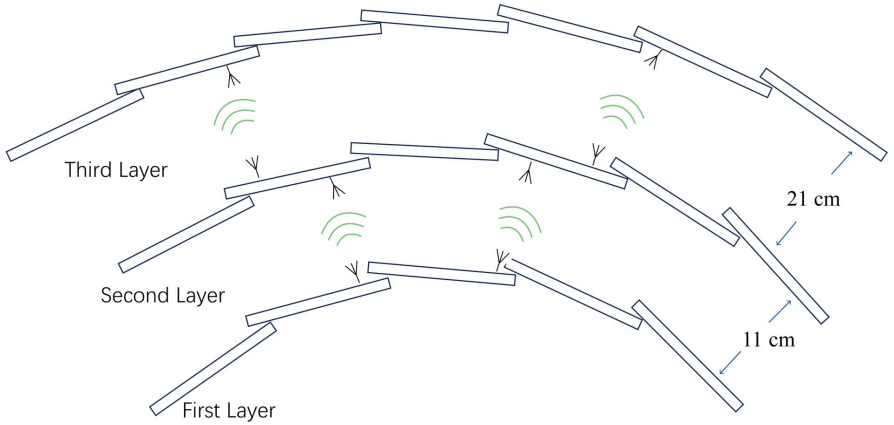
- WHERE **it applies in CEPC**
  - **Radial data readout between barrel layers,** as an alternative to fibre.
  - **Axial data readout from barrel to endcap.**
  - **Endcap readout,** concentrating data at the disc edge.



CEPC Detector Geometry

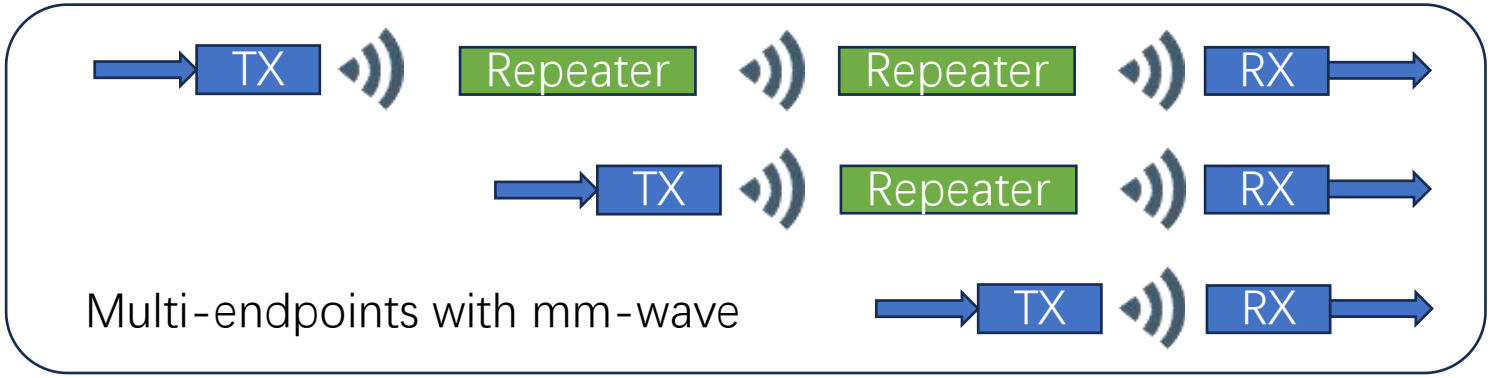
Radial data readout



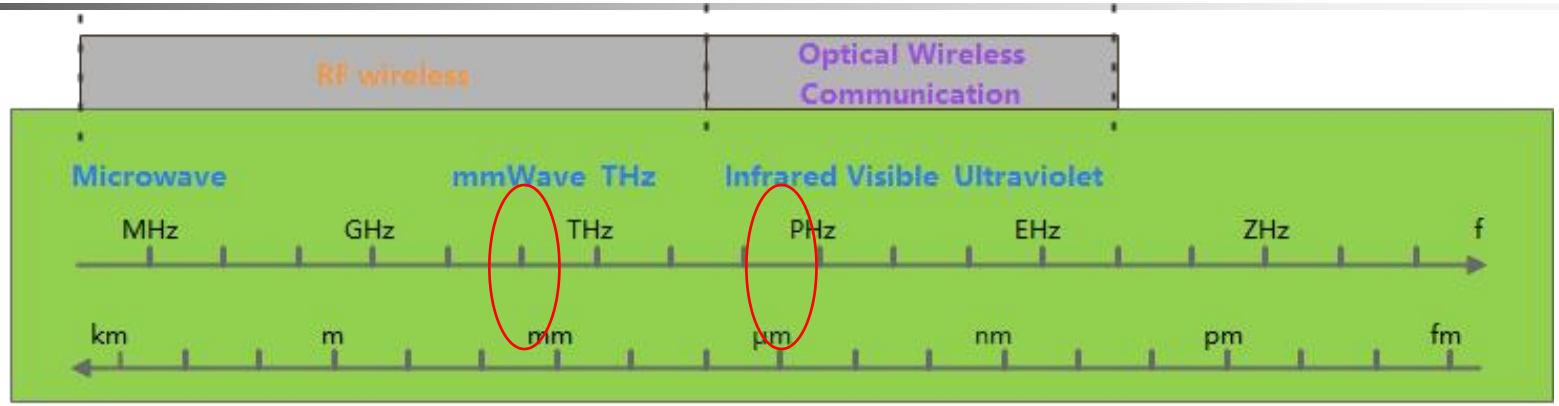


Repeaters: Amplify and re-transmit RF signals over long distances or through layers.

- **Radial readout with mm-wave**
  - 11- 21 cm transmission distance
- **Axial readout to endcap**
  - Outermost layer or dedicated aggregation layer.



Research focus



Electromagnetic Spectrum

- **Millimeter Wave (60GHz)**
  - High bandwidth, low power consumption
  - Antenna small enough to intergrate with the chip
  - Low interference between links and with detectors
  - Medium technological maturity

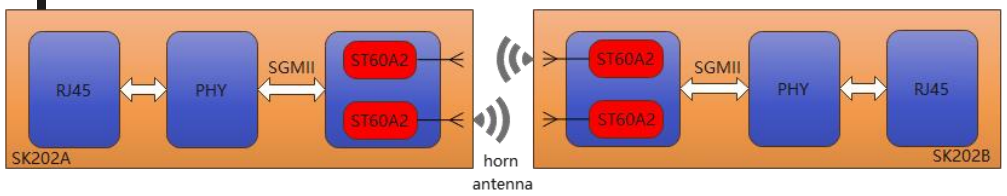
- **Optical Wireless Communication (OWC) / Free Space Optical (FSO)**
  - Extremely high transmission bandwidth
  - High technological maturity
  - Stringent alignment requirements

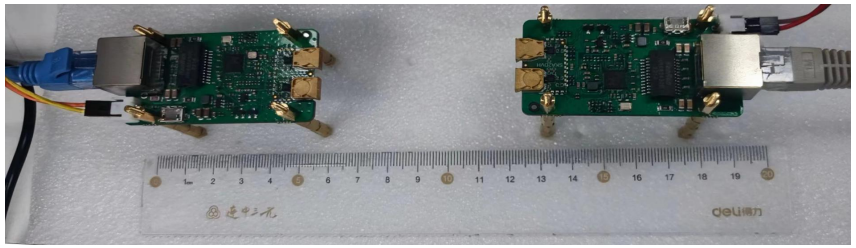
Part 1: 60 GHz mm-wave data link

One link, six links, and what still separates them from a stave

- COTS ST60A2 works, but only over ~6 cm — the V-band module extends it to 45 cm
- 1.25–6.6 Gbps per link, with ≥ 6.6 dB margin at the 21 cm design spacing
- Centimetre-level alignment, 5 Mrad TID, 1.2×10^{12} n/cm² neutron exposure
- Six channels at 18.75 Gbps aggregate — independent links, no downlink yet

MM-wave commercial module





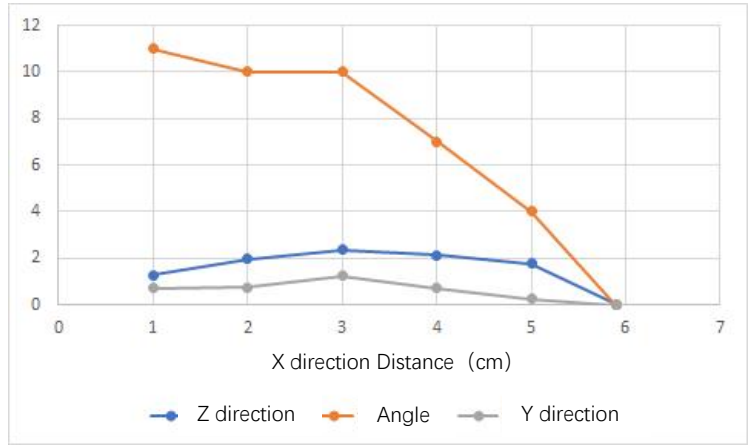
Distance (cm)	Bandwidth (Mbps)
1	914
3	917
5	915
6	913
>6	No link

Test result at different distances of TX/RX

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

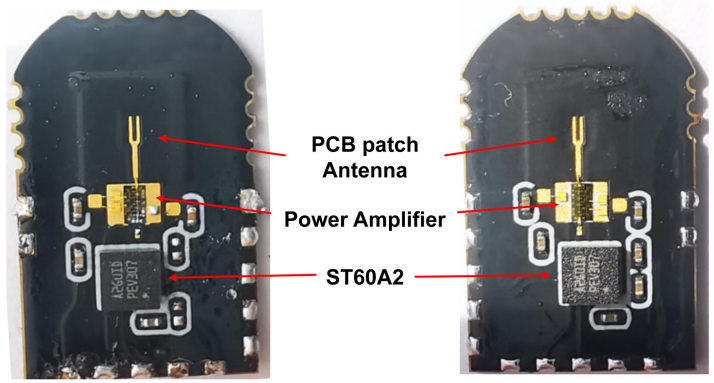
Penetration Test with 3 cm distance

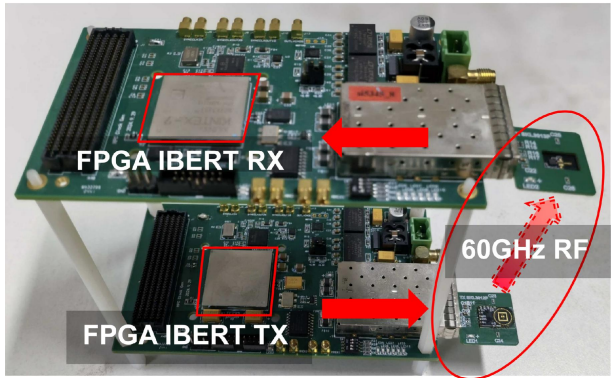
- **Test with evaluation boards – SK202（short-range module)**
  - Core chip: STMicroelectronics ST60A2G0, chosen on bandwidth, power and integration; 44 mW TX / 27 mW RX in a 2.2 × 2.2 mm package
  - >900 Mbps out to 6 cm; the link stops there
  - Passes paper and plastic, blocked by FR4 and flex (copper shield)
  - Needs far less alignment than a fibre coupling
  - Too short, too slow — and the antenna is too large



Alignment test

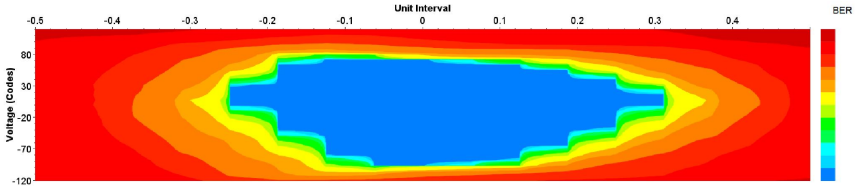
Enhanced mm-wave module development



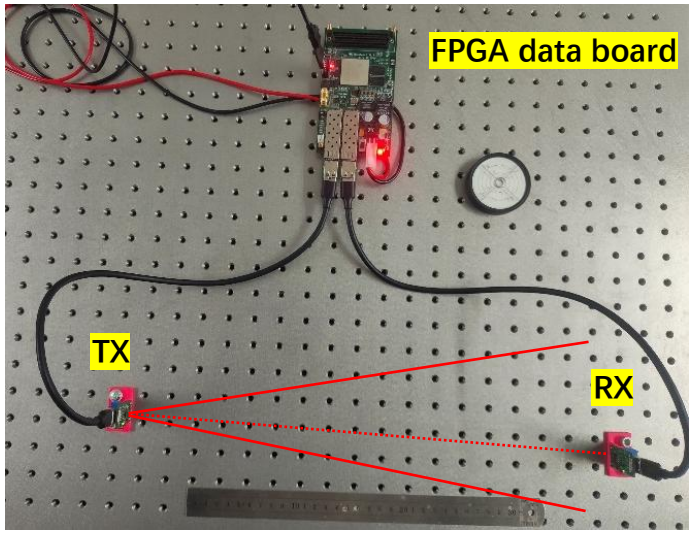


Single link test

- **Enhanced mm-wave transceiver module**
  - ST60A2 + V-band PA chain + PCB patch antenna
  - 14 × 9 mm, ~9 dBi LHCP, 70° HPBW, XPD > 10 dB
  - 444 mW TX / 427 mW RX — 871 mW per link
- **Measured span**
  - **67.5 cm** at 1.25 Gbps, **6.6 Gbps** at 22.5 cm
  - 45 cm error-free at 5 Gbps



5 Gbps, PRBS-7, 20 cm. ~120 mV differential, >0.6 UI at 10-12



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

Transmission distance under different line rate
Each row: 2.5 h continuous, zero errors;

Link budget



- **Budget at the antenna ports**
  - ST60A2 gives 28 dB at 5 Gbps; two patch antennas add 9 + 9 dBi
  - Total 46 dB — enough for only ~8 cm of free space
  - 19 dB of TX-chain gain carries the rest
- **At the built spacing**
  - 54.4 dB path loss at 21 cm against 65 dB available
  - Margin **6.6 dB** at 21 cm, **12.2 dB** at 11 cm

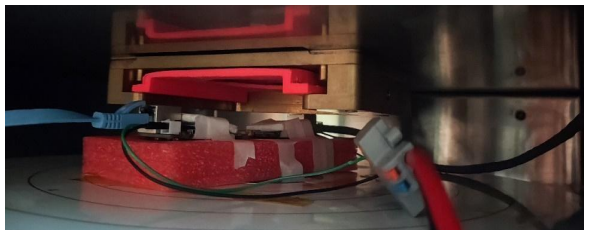
Item	dB
28 dB chip budget + 2 × 9 dBi antenna	46
TX chain gain (19 dB at band centre)	+19
Budget carried into the comparison	65
Path loss at 11 cm	−48.8
Path loss at 21 cm	−54.4
Margin at 11 cm / 21 cm	+12.2 / +6.6

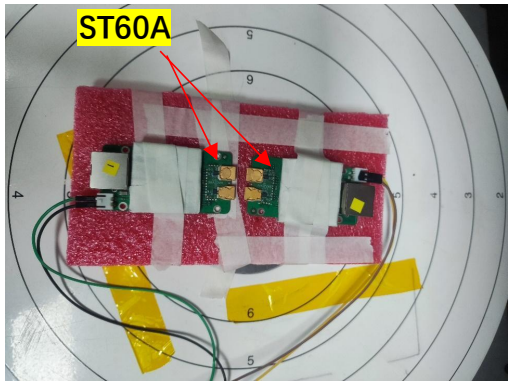
$$FSPL(d) = 128.0 + 20 \log_{10}(d/1000) + 0.015\, d$$

Oxygen absorption contributes 0.003 dB at 20 cm — negligible, contrary to the usual objection to 60 GHz.

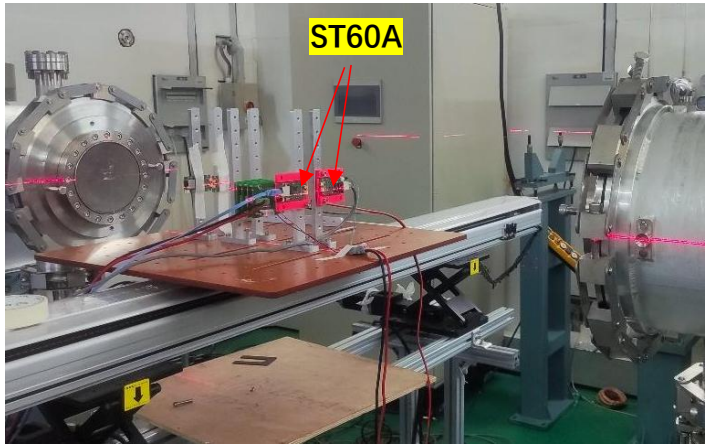
Radiation tolerance



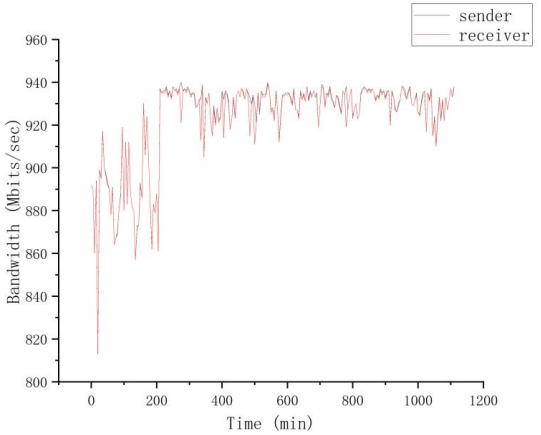




X-ray (20 kV, 40 mA)
Dose rate： 21.2krad/min
Duration： **5.5 hours (7 Mrad)**



CSNS neutron beam



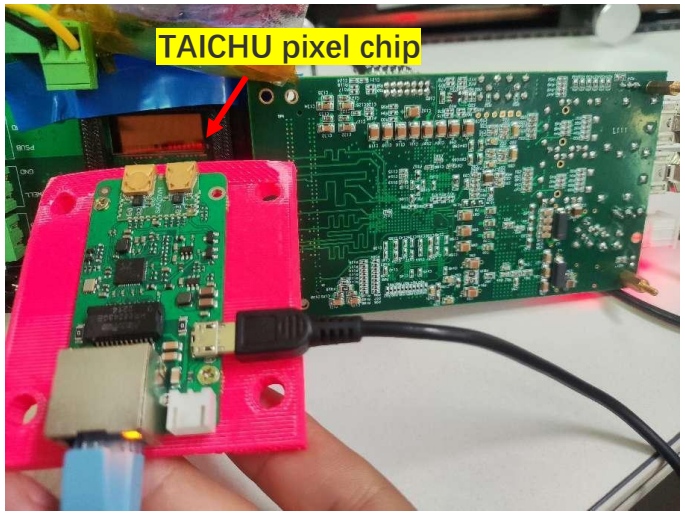
Bandwidth during irradiation

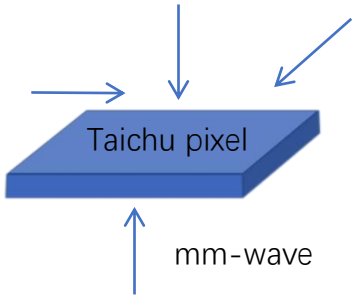
Beam intensity:: $1.65*10^7 n_{eq}/cm^2$
Absorption coefficient: 0.95
Duration: **21 hours (1.2 X 10^{12} n_{eq}/cm)**

- **Total ionizing dose — 5 Mrad survived**
  - MultiRad 160 X-ray: 40 kV, 20 mA, 0.15 mm Al
  - Two devices link live at 1 Gbps throughout, under iperf3
  - No dropout; no parameter moved from pre-irradiation
  - The PA reached 5 Mrad too, but in an equal-duration exposure with no link up

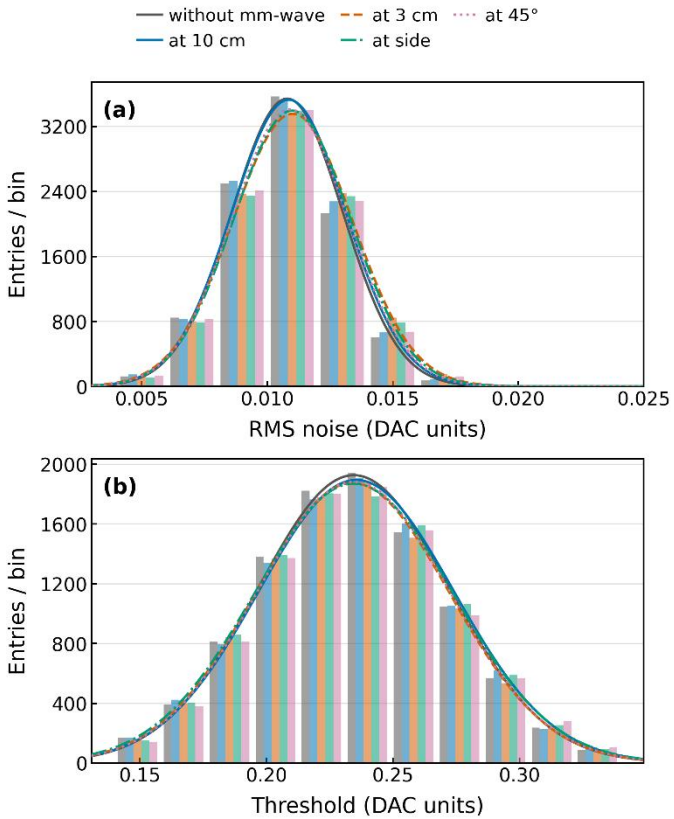
- **NIEL test**
  - CSNS: 80 MeV protons on tungsten, white spectrum
  - 1.65 × 107 neq/cm²/s, 21 h, absorption 0.95
  - Recovered fully after power cycling
  - The PA was not neutron-exposed.

Interference with detectors

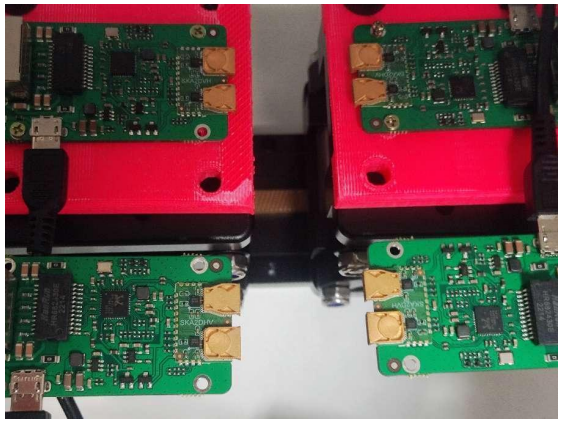


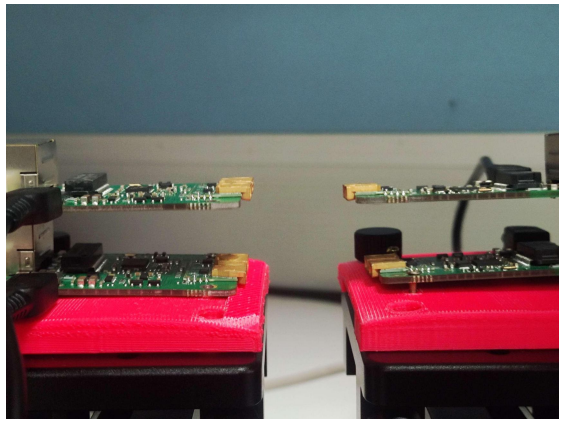


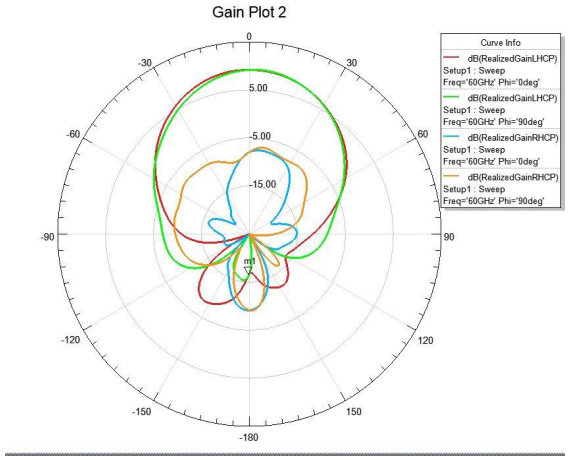
- **Radiated interference with the pixel chip**
  - TAICHU3, five configurations: link off, 10 cm, 3 cm, to the side, 45°
  - Largest noise-mean shift 2.4 % of the mean (0.11 σ)
  - Largest threshold-mean shift 0.26 % (0.017 σ)
  - Standard error of the means: 2.3 × 10−5 and 3.7 × 10−4
- The test outcomes 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.

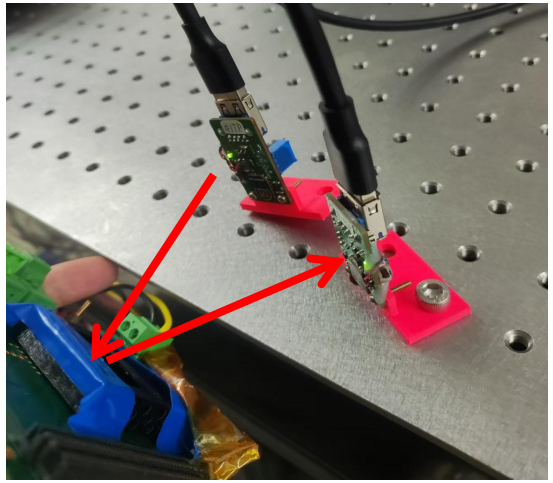


Crosstalk with each other









- **Short-range pair**: 3 cm spacing leaves the link unaffected
  - horn antennas, no reflectors in the path

- **Enhanced pair**: 70° HPBW
  - 70° in both planes, XPD > 10 dB
  - Reflections at specific angles set the practical pitch
  - The ST60A2 is single-carrier — separation must be spatial and polarization, not a frequency plan

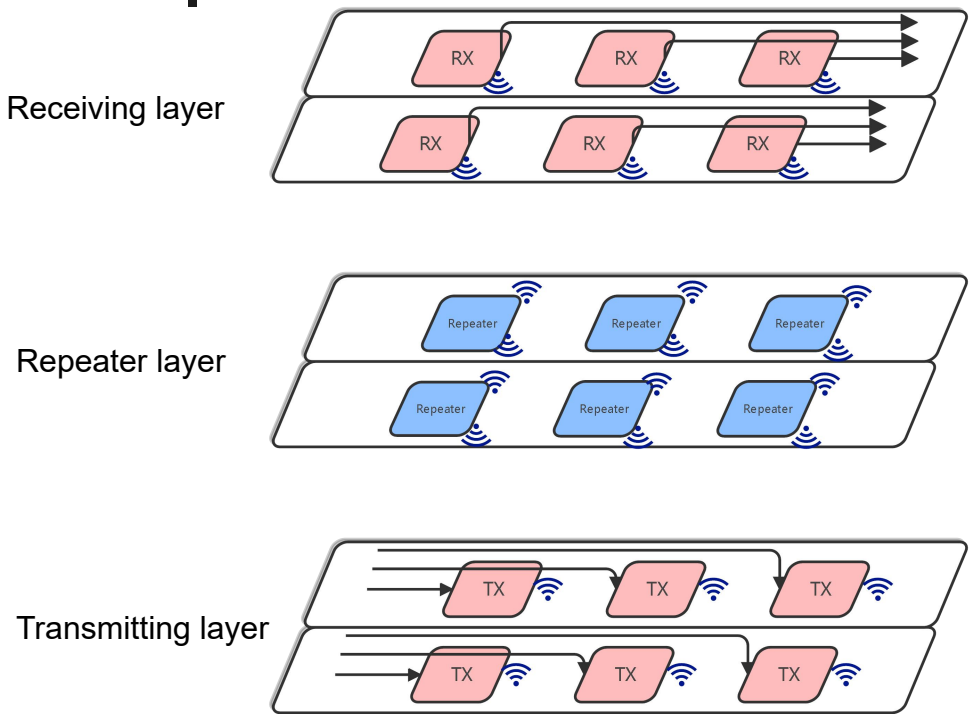
Mass production



MMW transmission module

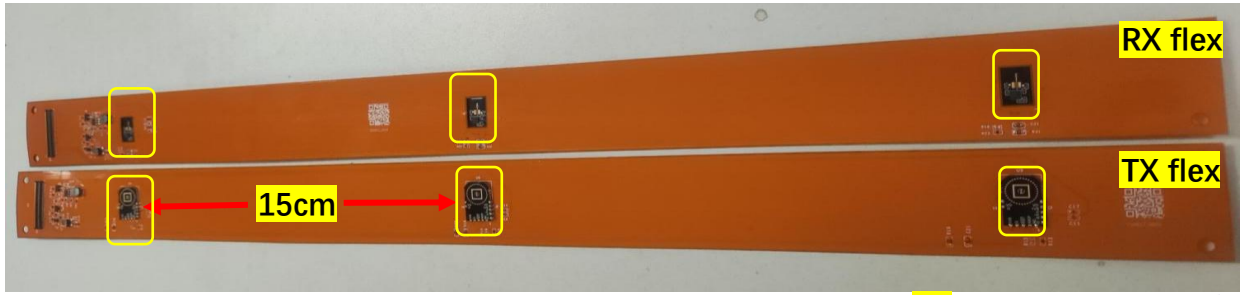
- **Assembly and lifetime**
  - Bare-die PA wire bonding and module soldering are the hard steps
  - 200 pairs manufactured for the test campaign
- **What one pair costs in power and latency**
  - 871 mW per link;
  - 750 ps HDR latency — ~2.3 UI at 3.125 Gbps, manufacturer value

mm-wave demonstrator



mmWave demonstrator schematic

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



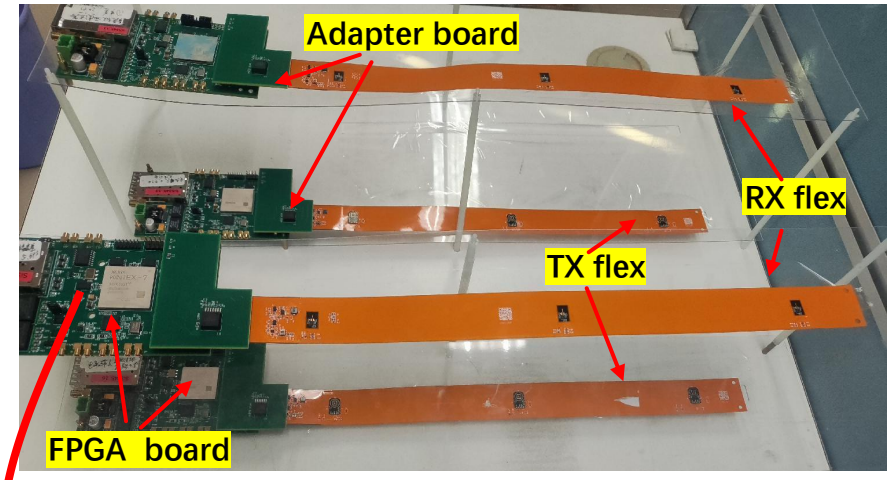


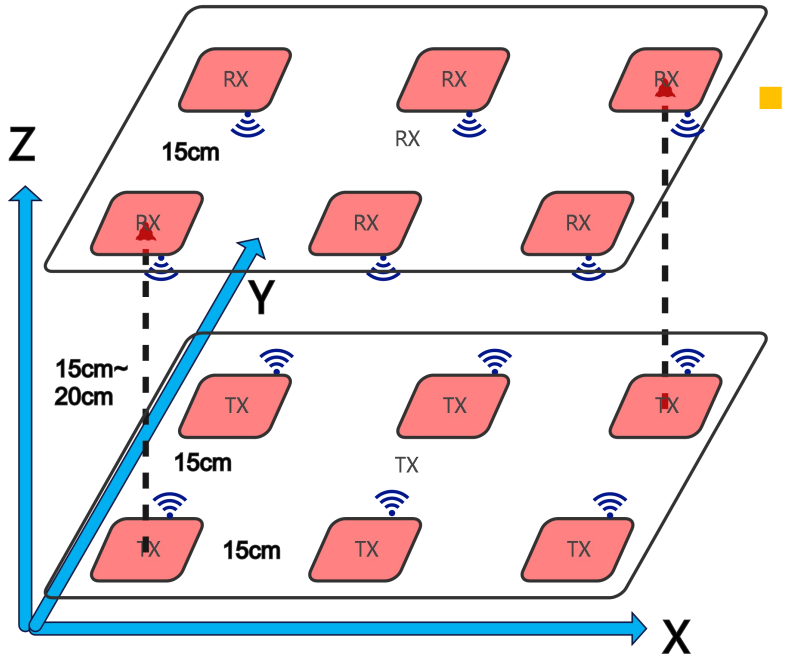
Repeater structure: RX is at the bottom layer of PCB, TX is at the top layer of PCB

Hardware complete

- TX/RX flex, adapter boards, repeater boards, FPGA board
- **0.3 mm FPC, 40 × 3 mm strips, 2 × 3 array**
- **15 cm pitch in XY; 10–30 cm along Z**
- Accepted at 20 cm for the BER runs

mm-wave demonstrator





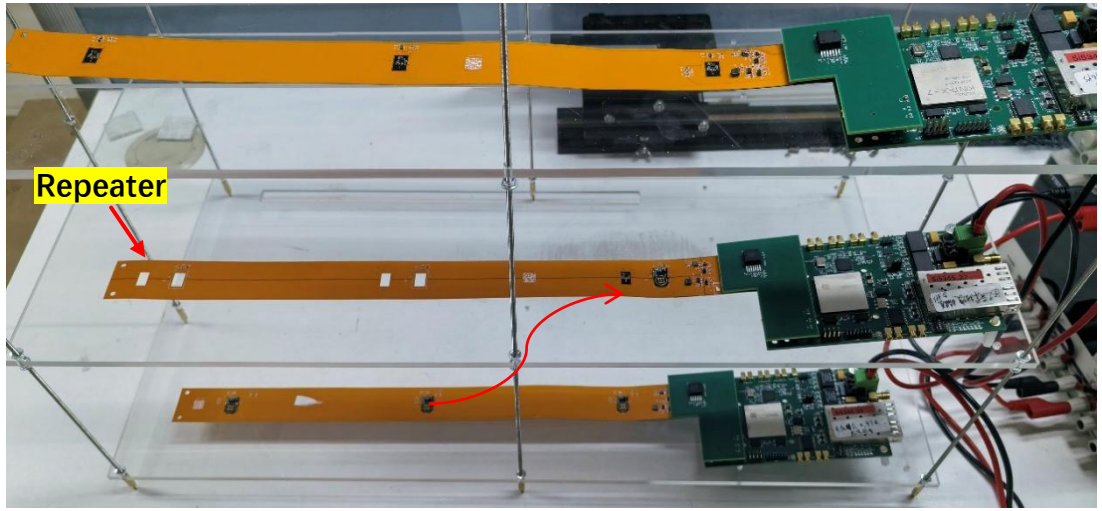
- **Six links, zero errors**
  - 2 × 3 array, one direction
  - **3.125 Gbps per channel → 18.75 Gbps total**
  - 1 h per channel, BER < 1 × 10−13
  - 4 Gbps: four channels; 5 Gbps: two
  - Limit is FPC baseband loss and mismatch, not the radio

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

18.75 Gbps is six independent point-to-point links. There is no aggregation, multiplexing or downlink, and the downlink path is not implemented.

mm-wave demonstrator



Repeater-layer prototype — stacked flex-circuit links with RF modules; 15 cm inter-layer gap proved critical.

- Crosstalk is the bottleneck：The demonstrator surfaced how hard it is to control crosstalk in mm-wave transmission.
- 15 cm is a critical spacing：At 15 cm interference sets in inside the repeaters, so a larger gap is needed for the repeater layer to operate normally.
- Real detectors need tuning. Module power and module-to-module matching must be customized to the transmission distance to suppress internal reflection and interference.

Demonstrator to stave: open items



1 **Isolation measurement,** Reported as the interference a victim link tolerates

2 **Synchronization and downlink demonstration,** the least developed part of the architecture

3 **Trace-length vs rate on the final FPC stack-up,** including the bend radius of a 40 × 3 mm strip

4 **A representative stave mechanical model** multipath, keep-out volume, in-band nulls; today's tests are in an unobstructed lab

5 **Neutron irradiation of the assembled module** , with PA.

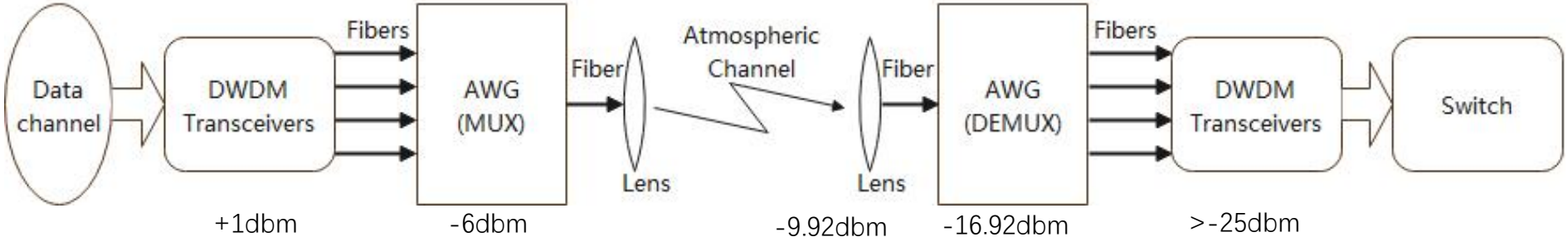
Part 2 : Optical wireless data and clock



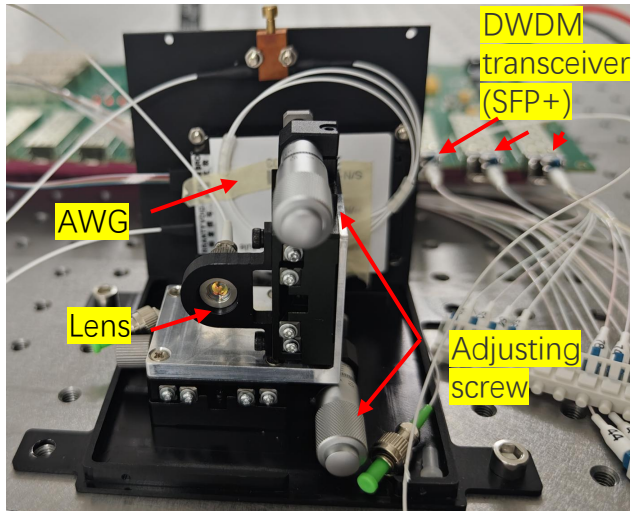
1550 nm free-space links: bench loopback, clock transfer, 500 m outdoor run

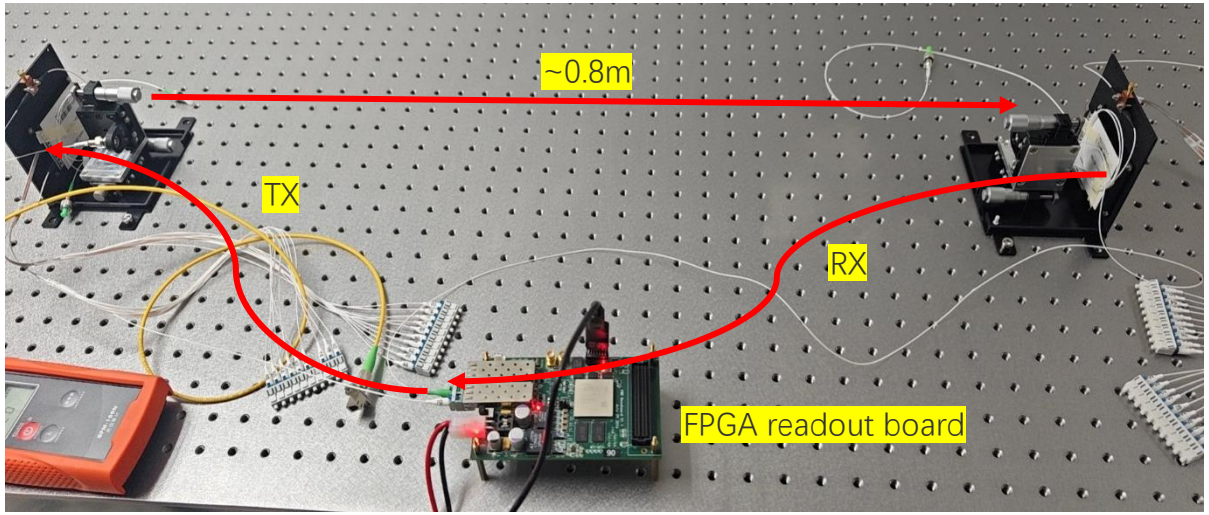
- 12 channels × 8 Gbps or 11 × 10 Gbps over a loopback, BER < 1×10^{-15}
- White Rabbit clock carried on the optical link: TIE 2.28 ps
- 6.27 ps RMS over 500 m outdoor; −4.9 dBm at the APD against a −20 dBm floor

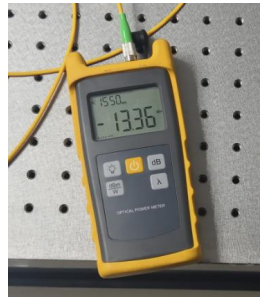
Optical Wireless



Free Space Optical(FSO) test setup structure



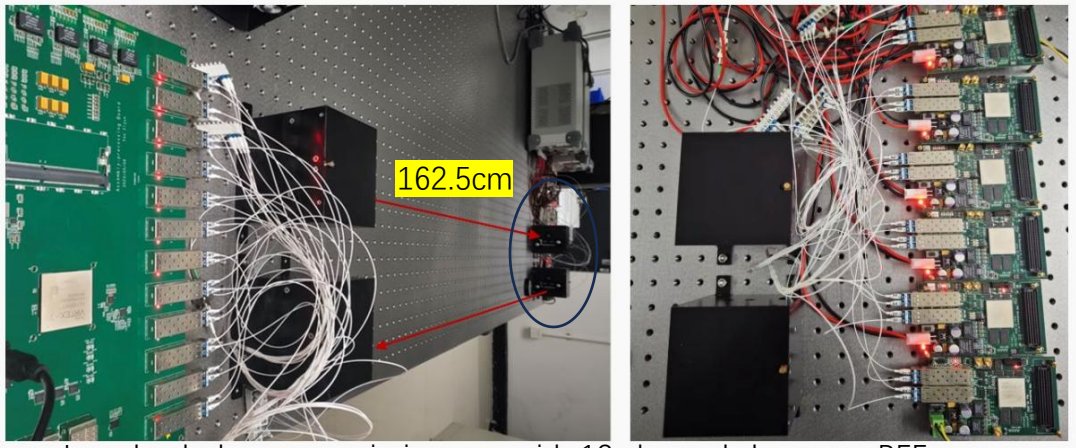




Optical Power received : -13.36dBm

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

Performance test



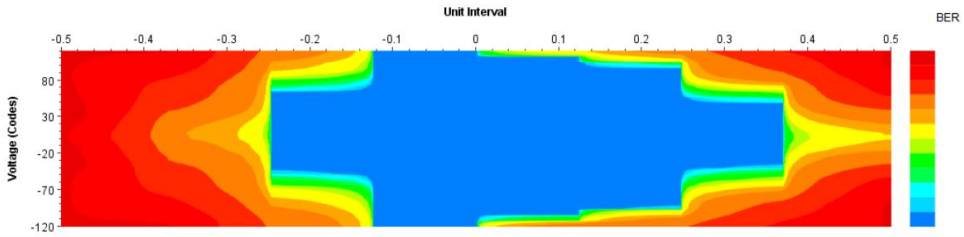
Loopback data transmission test with 12 channels between BEE prototype board(Vertex 7) and MOST2 FEE FPGA board(Kintex 7)

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

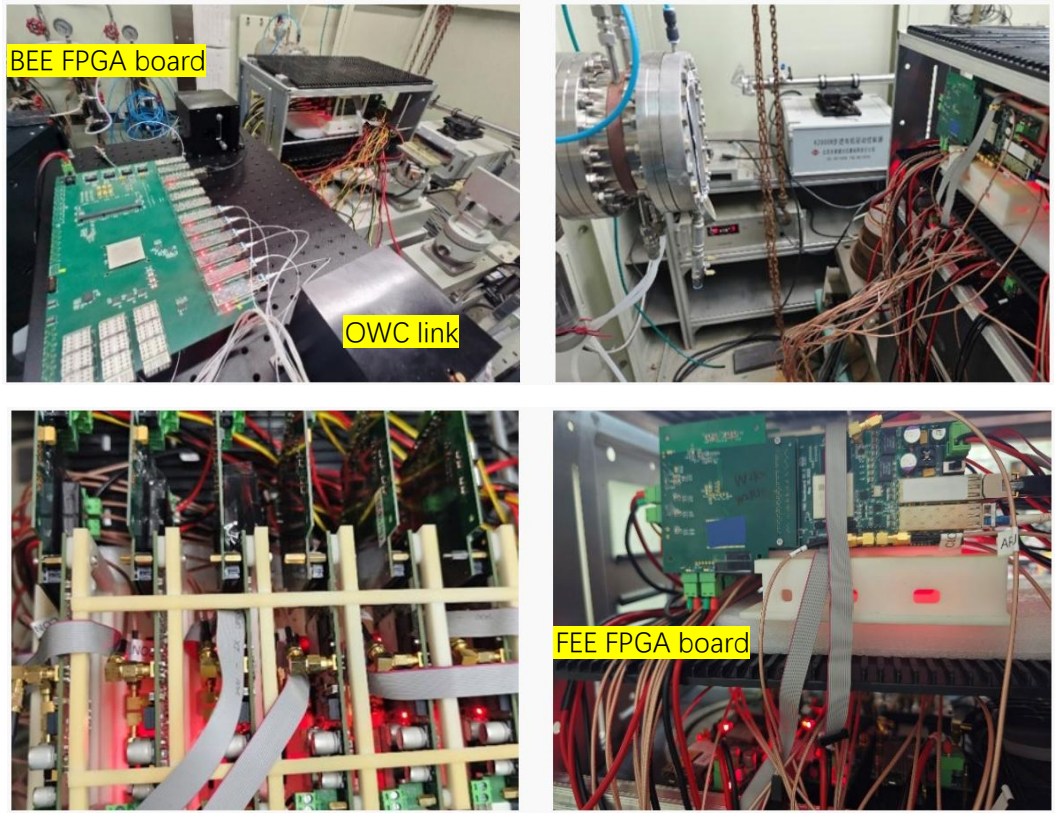


10Gbps eye pattern in loopback test

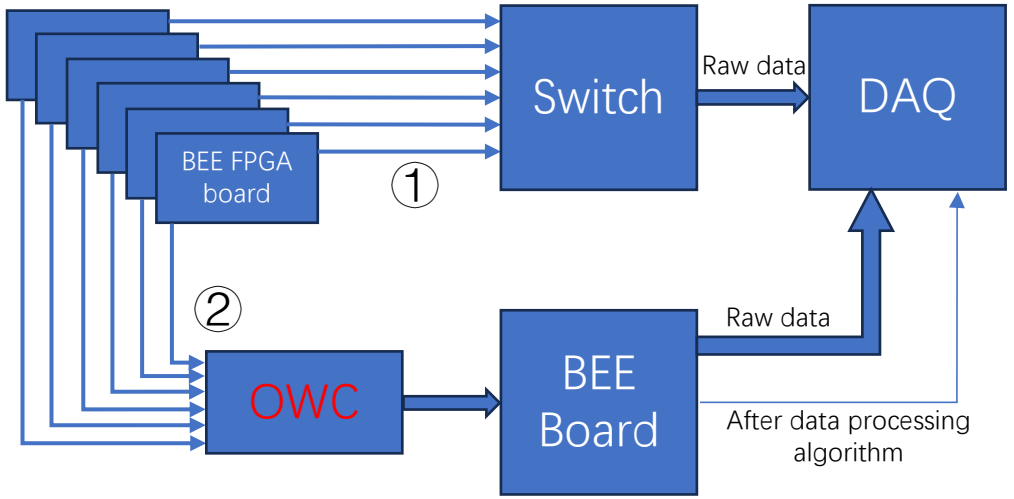
- 162.5 cm span, 118 Gbps aggregate, 100G Ethernet capable

Prototype test

https://iopscience.iop.org/article/10.1088/1748-0221/20/09/T09001



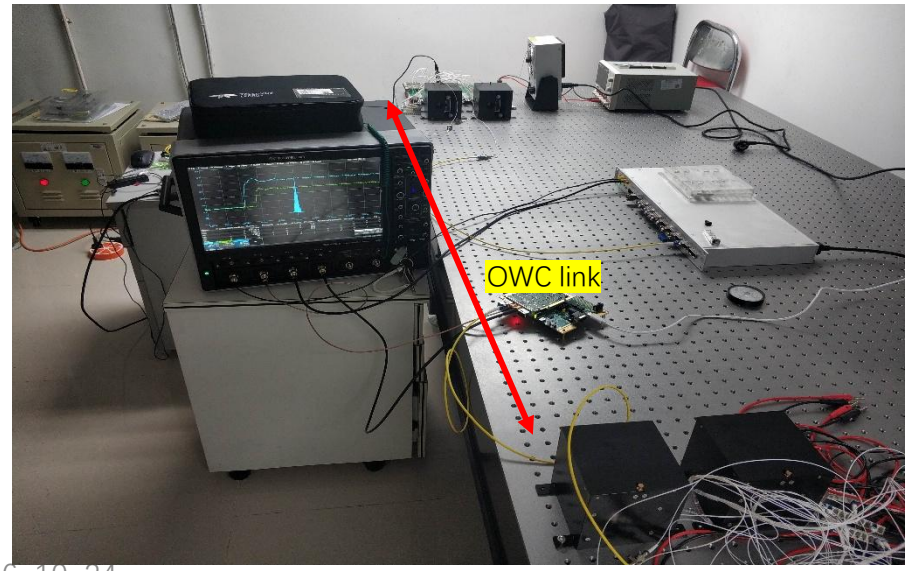
TAICHU3 Telescope prototype test in BSRF



- 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.

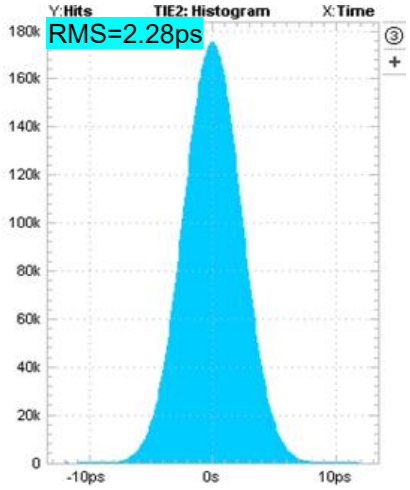
Clock on OWC

- **White Rabbit over OWC link**
  - WR stack unchanged — only the SFP changes: dual-fibre, FC/APC
  - Hardware reworked to remove the WR reboot uncertainty
  - High-frequency noise in the DDMTD loop optimized

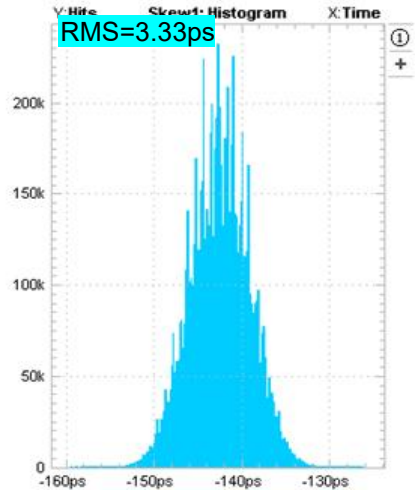


Wireless clock transmission test


new design hardware



TIE jitter of receive clock



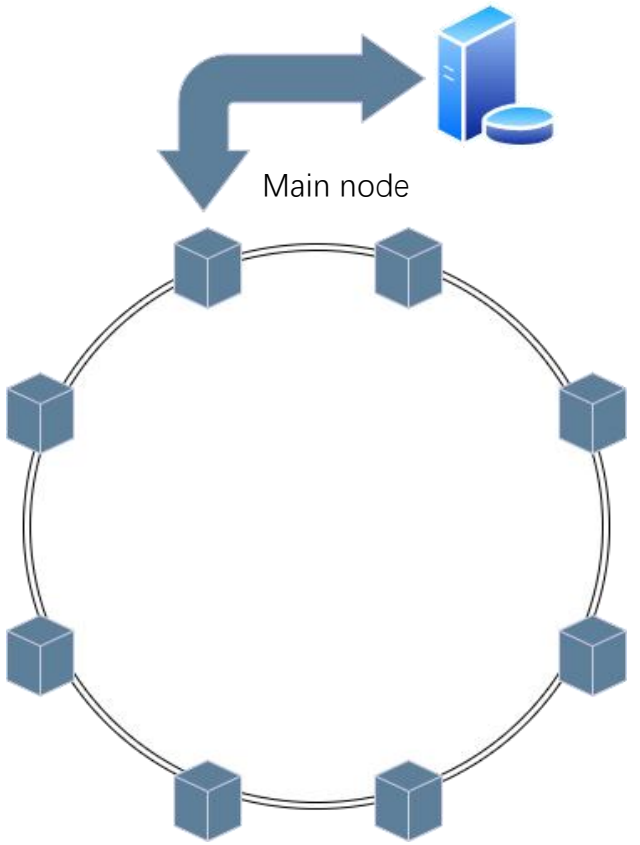
Clock synchronization

- **Clock performance**
  - **Synchronization 3.33 ps RMS at 1 m (right plot)**
  - Receive-clock TIE 2.28 ps RMS on this bench (left plot)
  - Restart uncertainty 88.8 → 12 ps peak-to-peak
  - Restart repeatability 2.82 ps
  - A fixed free-space path does not disturb the WR servo

Application in accelerator

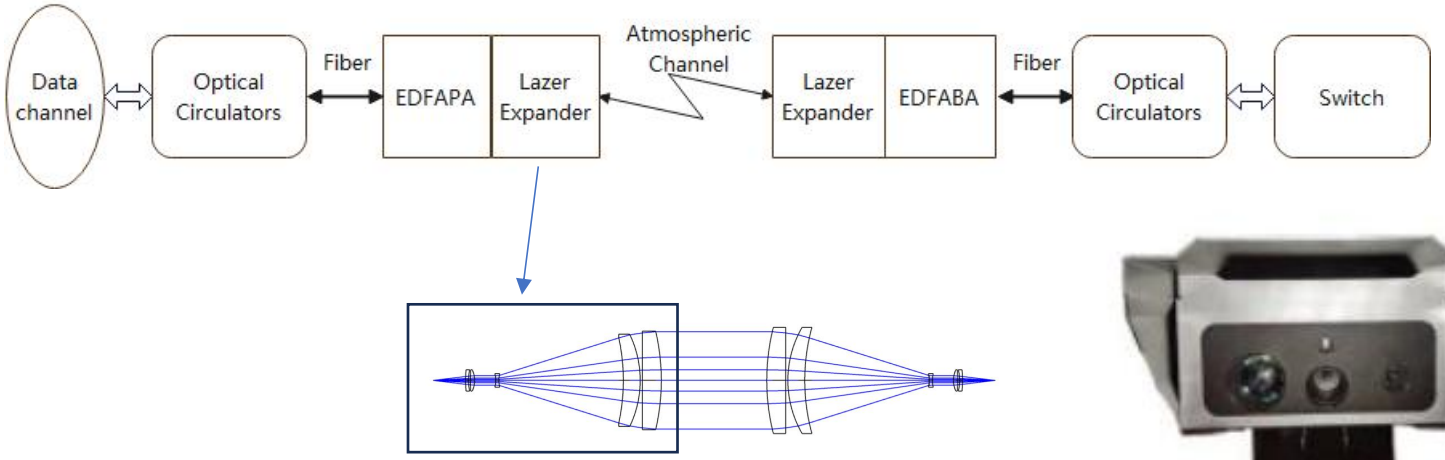
- **CEPC timing: the requirement**
  - 192 control nodes on a 100 km ring, 6.5 m tunnel, 30 ps (1σ)
  - Adjacent nodes 520 m apart; longest chord 643 m
  - 8 shaft masters, 16 subsystems, ~23 slaves each — ~200 transceivers
  - Baseline: SyncE + IEEE 1588 PTPv2 + DDMTD 16385/16384, 800 Hz PLL

- **The idea**
  - Trade 100 km of radiation-hardened fibre for ~200 shielded heads. The hardening problem goes from distributed to local.

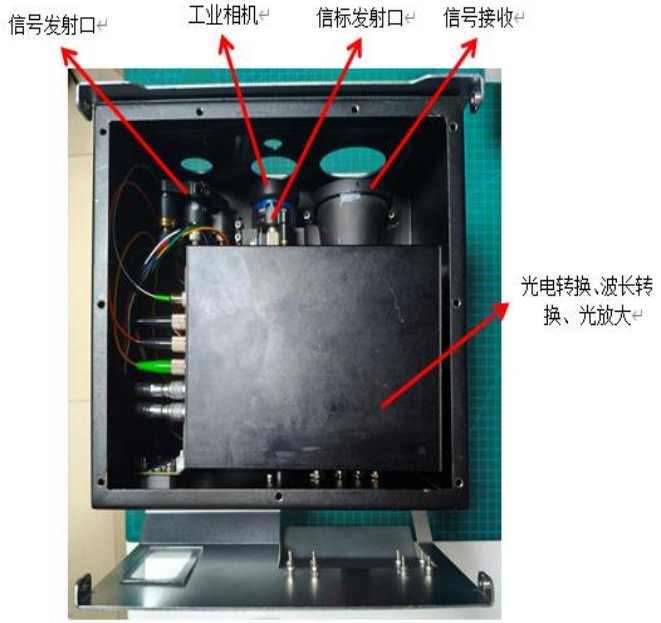


Circular Clock Synchronization

Low-cost long-distance OWC



Long-distance ~1km OWC design



- **1550 nm signal, 650 nm beacon, camera for alignment**
  - +20 dBm launch, 0.5 mrad divergence, 50 mm aperture
  - 50 mm aperture → 200 µm large-core fibre → InGaAs APD (M = 10) → TIA
  - 418 × 272 × 203 mm, 7.7 kg, 8.92 W, −10 to 55 °C
  - Rated 1 km, deployed at 520 m

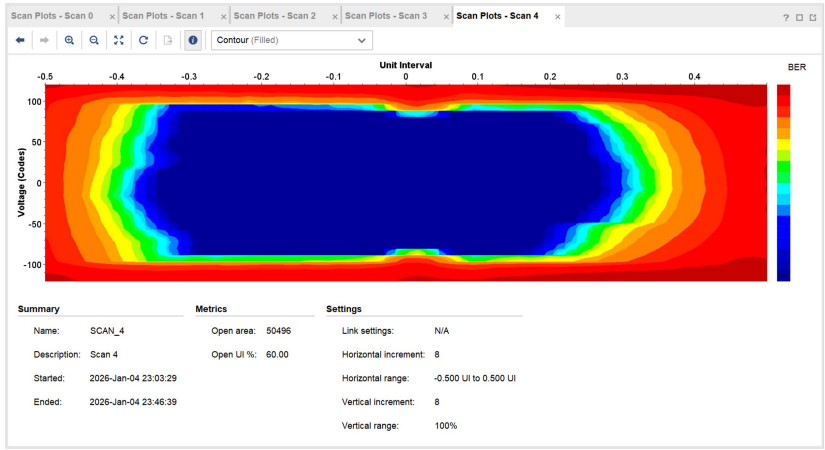
520 m link budget	dB
Launch power	+20
Geometric loss, 50 mm aperture	−17.4
At the receiver aperture	+2.1
Rx train + fibre coupling	−7
At the APD (floor −20 dBm)	−4.9
Cumulative margin	≥ 13

Clock on long distance OWC

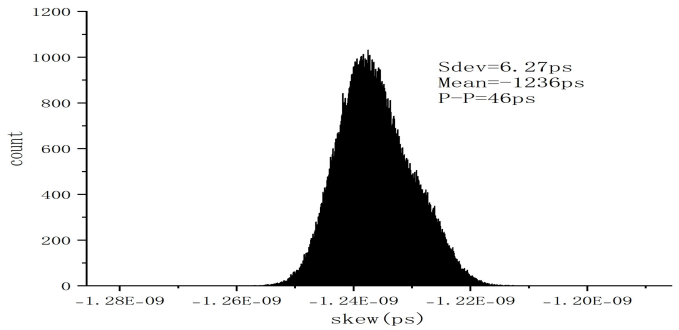
- **Outdoor 500 m, three levels**
  - **6.27 ps RMS, 46 ps peak-to-peak**
  - BER < 1 × 10^{-13} over the 6-hour run



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



Data transsmission eye diagram



Clock Synchronization Accuracy Results (45 minutes)

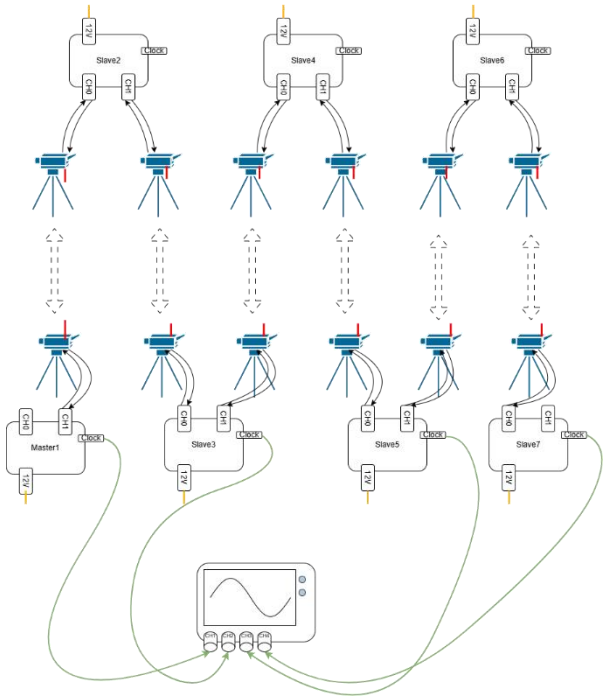
Clock on cascade transmission

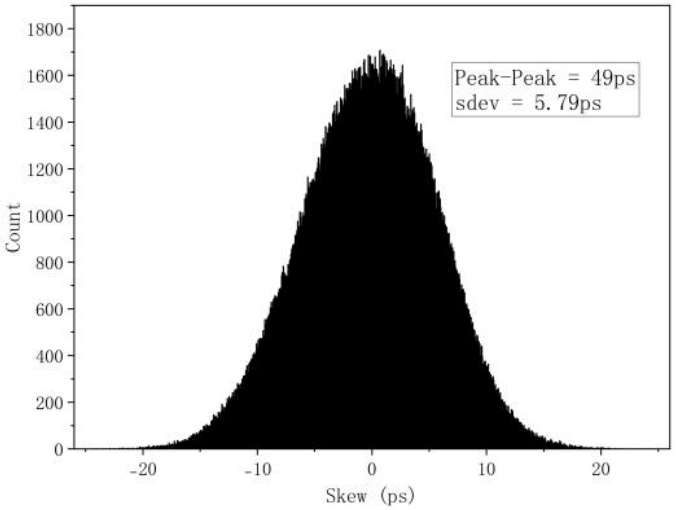
https://doi.org/10.1016/j.nima.2026.172051





50m Round-Trip test in IHEP





Clock Synchronization Accuracy Results (60 minutes)

- **Indoor cascades at 25 m**
  - 3 / 5 / 7 levels → 3.61 / 4.68 / 6.83 ps;
  - Fibre, for contrast: 3.38 ps at 1 m, 6.66 ps over 12 levels

- 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!