Wireless Data Transmission For High Energy Physics Applications

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Connecting the Dots / Workshop on Intelligent Trackers 2017

LAL - Orsay

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

Wireless **A**llowing **D**ata **A**nd **P**ower **T**ransmission

- **WADAPT** group formed to identify specific needs of projects that might **benefit from wireless technologies** with the objective of providing a **common platform for R&D** arXiv:1511.05807

- This talk covers **data transmission** only

  Outline:

  - Motivation
  - Wireless data transmission and the 60 GHz band
  - 60 GHz studies
  - Future prospects
  - Summary and outlook

Motivation

Motivation 1: Bandwidth

- High demands on **bandwidth** in present and future HEP experiments
- Especially true for **highly granular** tracking detectors operated at **high beam luminosities**

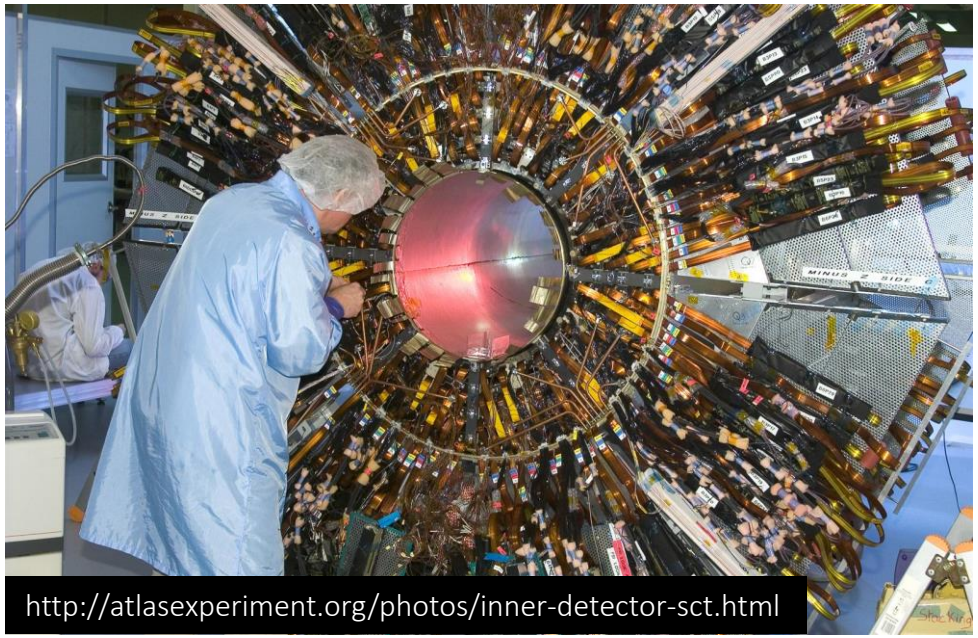
Example: ATLAS ITK Pixel Detector
- Over 10000 links at 5 Gb/s
- Distance between stave and opto-electrical converters: 5-7 m on copper cables (twisted pair, TwinAx or Flex cables)

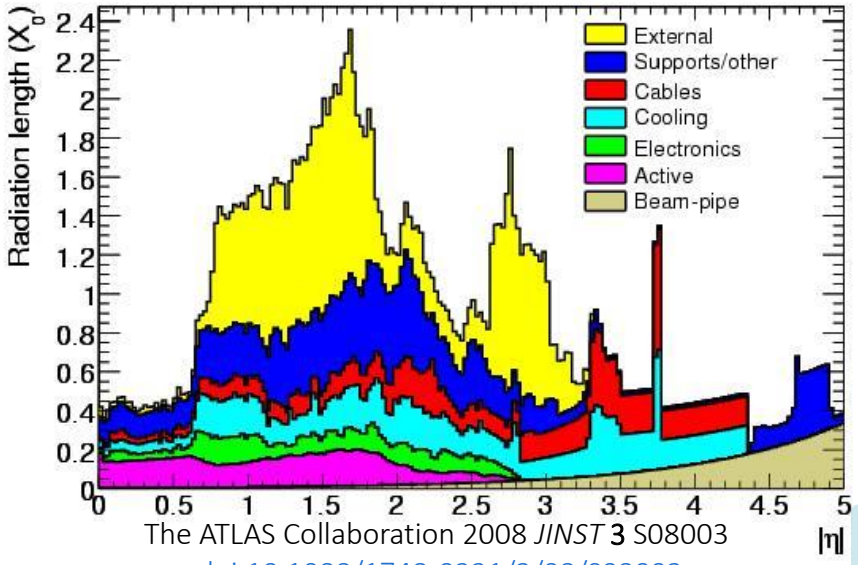
http://cds.cern.ch/record/2217152/files/ATL-ITK-SLIDE-2016-673.pdf

- Readout electronics have to withstand **high radiation doses**
- Copper interconnects: increased impedance at higher frequencies

Motivation 2: Cables

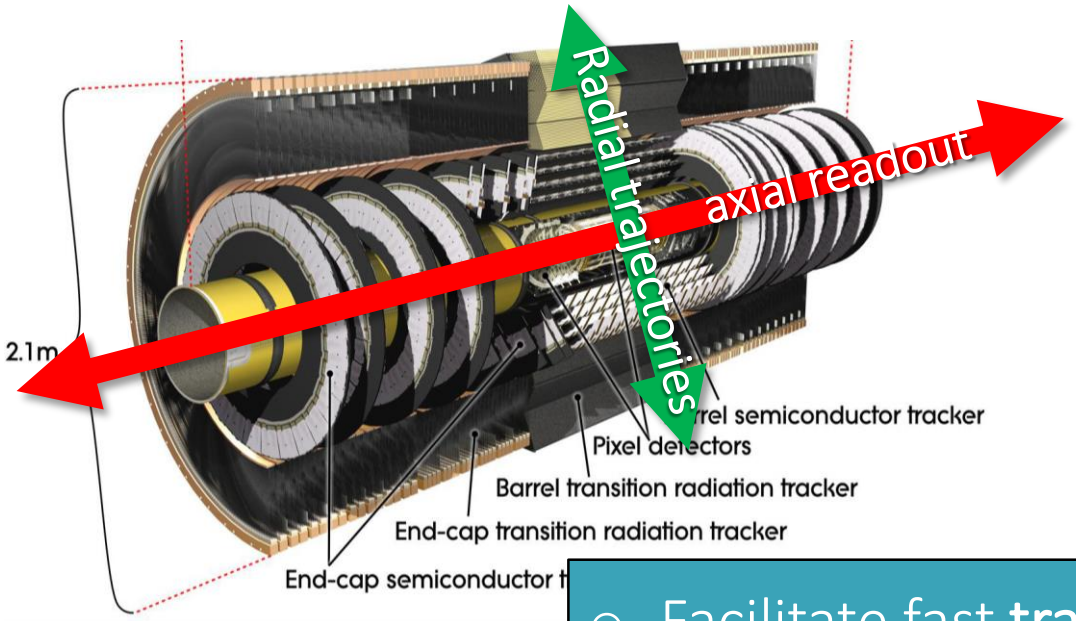
- Significant **cost** contribution
- **Installation** is always a challenge
- Significant contribution to **material** budget
- Dead material: multiple scattering

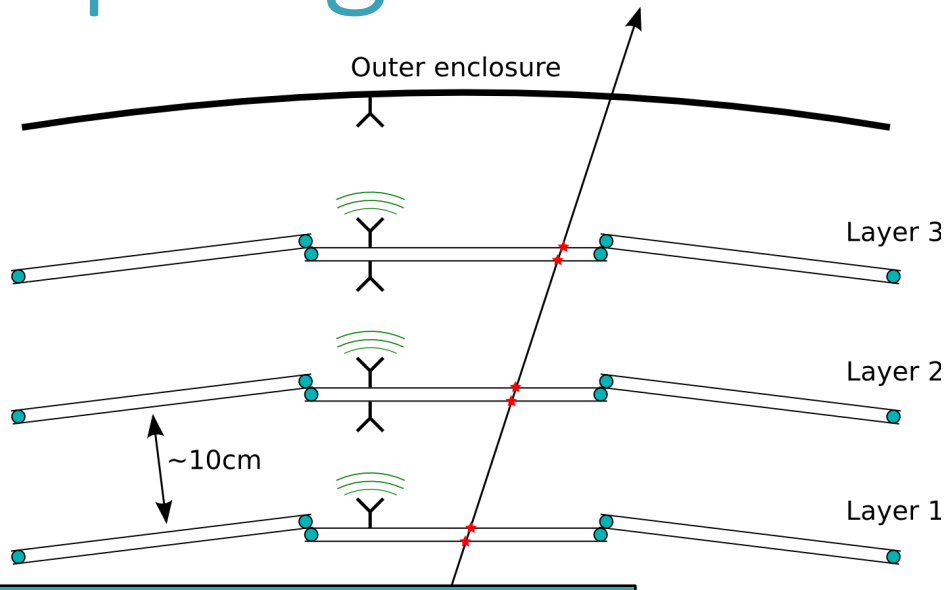

http://atlasexperiment.org/photos/inner-detector-sct.html



The ATLAS Collaboration 2008 *JINST* **3** S08003
doi:10.1088/1748-0221/3/08/S08003

Motivation 3: Readout Topologies

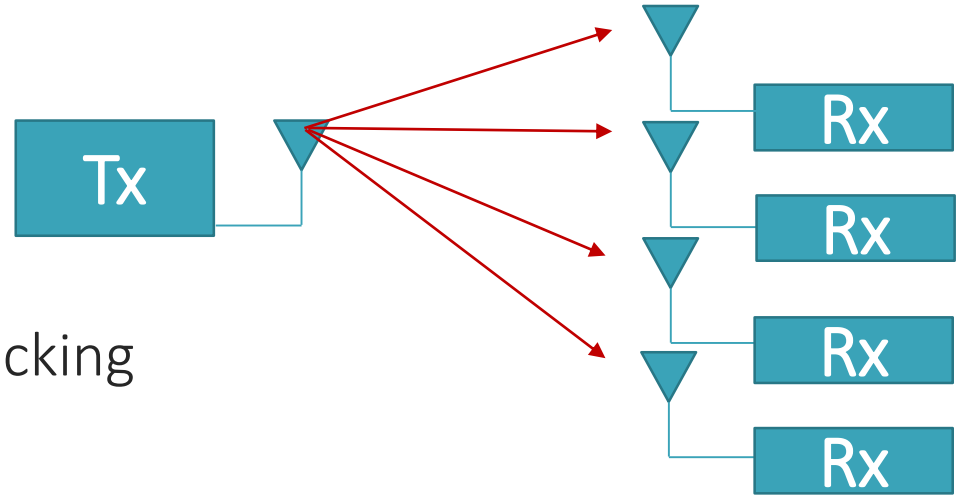




- Facilitate fast **track trigger** decision
- Application specific design considerations required
  - Link density
  - Signal reflection and transmission
  - ...

Motivation 4: Broadcasts

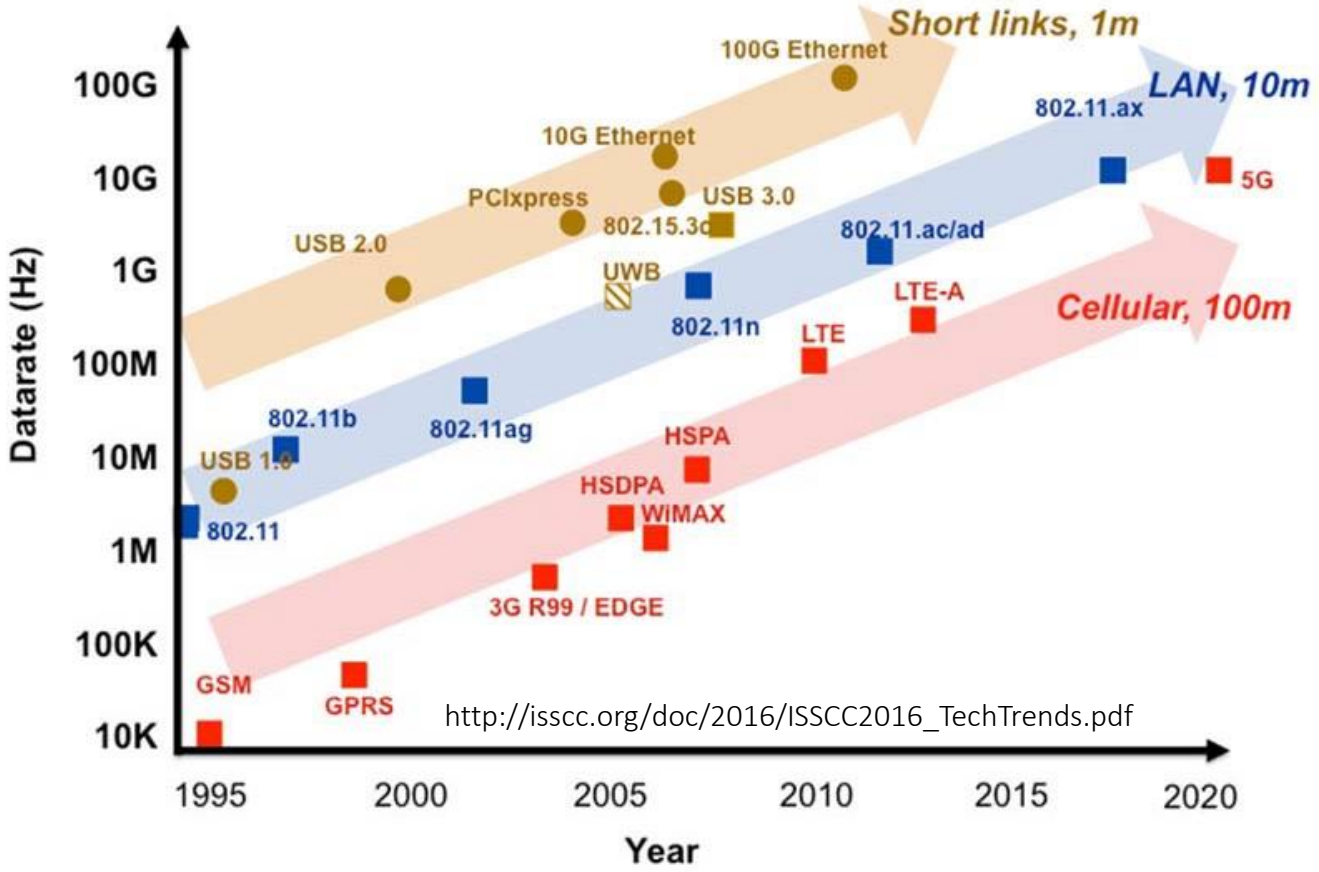
- Multiple receivers for single/multiple transmitters
- Distribution of common signals
- Clock, reset, trigger, ...
- Share hit informations for on-detector tracking



Wireless data transmission and the 60 GHz band

Progress in wireless technologies

Data rate increases by a factor of 10 every 5 years



http://isscc.org/doc/2016/ISSCC2016_TechTrends.pdf

Shannon-Hartley Theorem

$$C_S = B \cdot \log_2(1 + S/N)$$

C_S: upper bound on channel capacity in b/s

B : bandwidth in Hz

S/N: signal to noise ratio

Wireless channel capacity

$$C = \rho \cdot B$$

C : channel capacity in b/s

ρ : spectral efficiency in b/s/Hz

B : bandwidth in Hz

Increase wireless channel capacity

$$C = \rho \cdot B$$

C : channel capacity in b/s
ρ : spectral efficiency in b/s/Hz
B : bandwidth in Hz

- Case: bandwidth limited
- 2.4 GHz and 5 GHz band

$BW_{2.4\,\mathrm{GHz}} = 100\,\mathrm{MHz}$
$BW_{5.0\,\mathrm{GHz}} = 600\,\mathrm{MHz}$

- Improvement in silicon technologies
- Higher frequencies: **mm-waves**

$BW_{60\,\mathrm{GHz}} = 9\,\mathrm{GHz}$

- Improve spectral efficiency

Modulation schemes

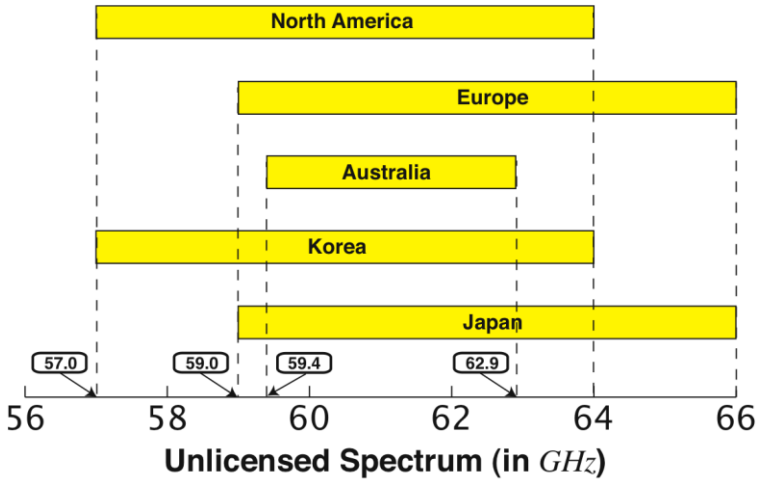
OOK	0.5 b/s/Hz
MSK	1 b/s/Hz
4QAM	2 b/s/Hz
1024QAM	10 b/s/Hz

Increased complexity and power consumption

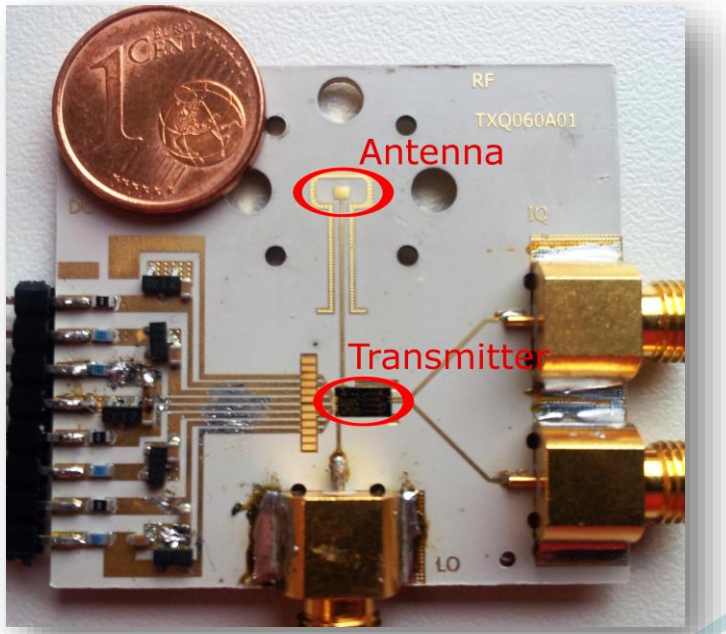
- Spectral efficiency not critical
- **Trade bandwidth for complexity**

The 60 GHz band

- Huge bandwidth:
  Gb/s with less complex modulation schemes
- Wavelength $\lambda \sim 5\ mm$:
  Small form factor
- Free-space path loss: 68 dB @ 1 m
  Secure short range communication
  High channel densities possible



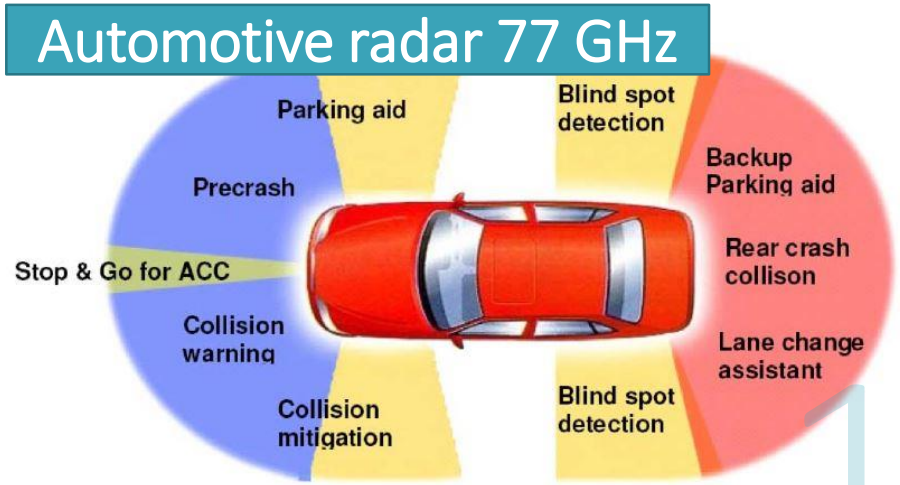
http://windowsil.org/category/wsil-publications/



60 GHz transmitter by Gotmic

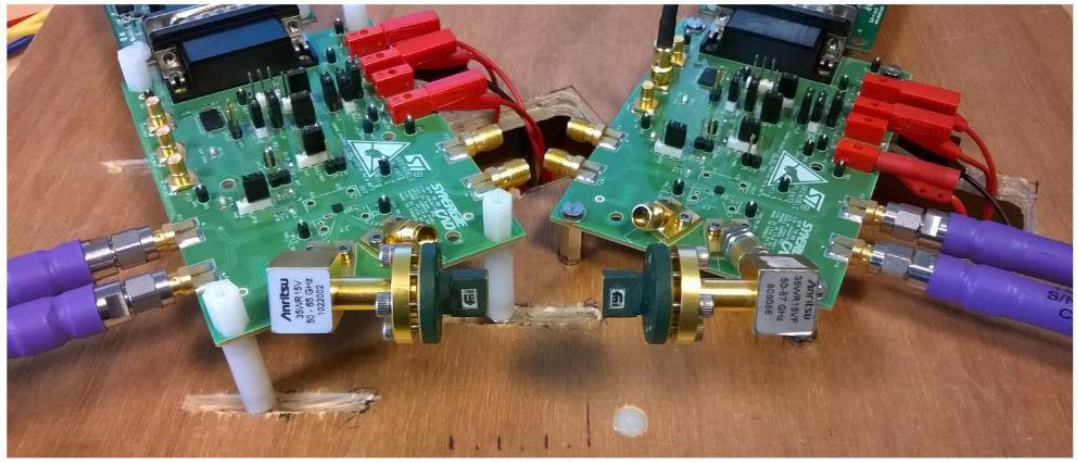
Drivers of mm-wave development

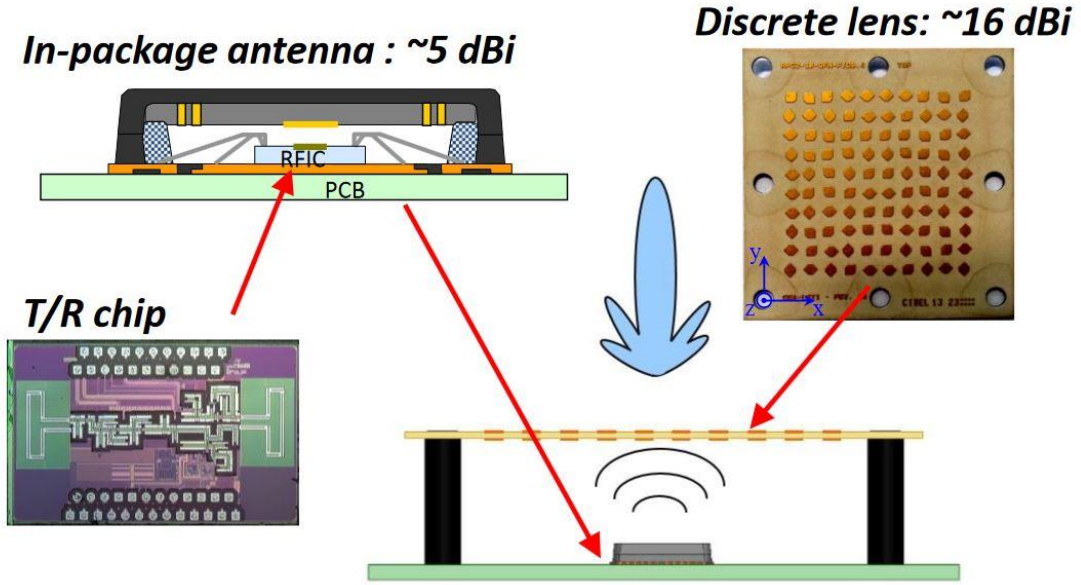
- Multimedia:
  - Increased demand on bandwidth
  - Wireless high definition streaming
- Automotive industry:
  - Radar
  - Intra vehicle communication
- Sub-THz imaging



60 GHz developments (CEA-LETI)

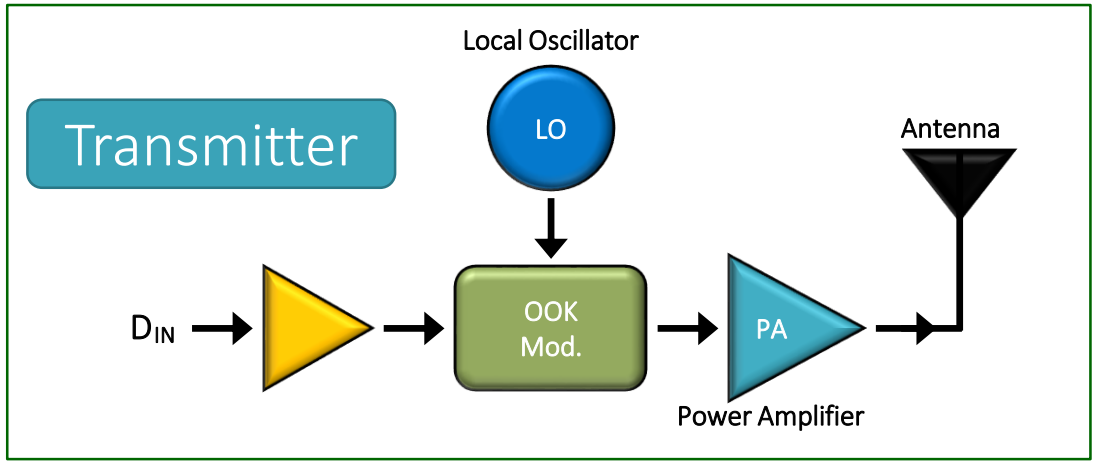
- CMOS 65nm time domain transceiver
- OOK/ASK modulation
- Short range: 2-3 cm ⟶ can be increased with discrete lens
- Power consumption: Tx 40 mW, Rx 20mW
- Data rates 0.5 – 8 Gb/s





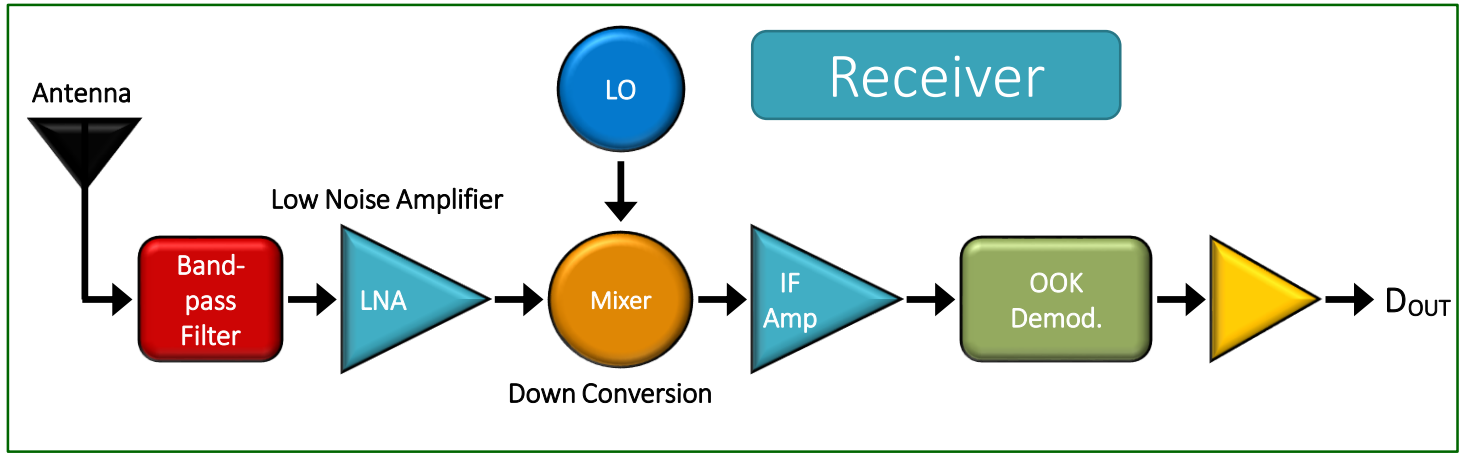
Heidelberg transceiver

Towards a 60 GHz demonstrator for HEP



Specifications of this prototype

- 130 nm SiGe-Bi-CMOS
- Bandwidth: 9 GHz
- Modulation: On-Off-Keying
- Target data rate: 4.5 Gb/s
- Target power consumption: 150 mW
- Transmission distance: 20 cm (1 m)



H K Soltveit et al 2013 IEEE dx.doi.org/10.1109/NSSMIC.2013.6829448

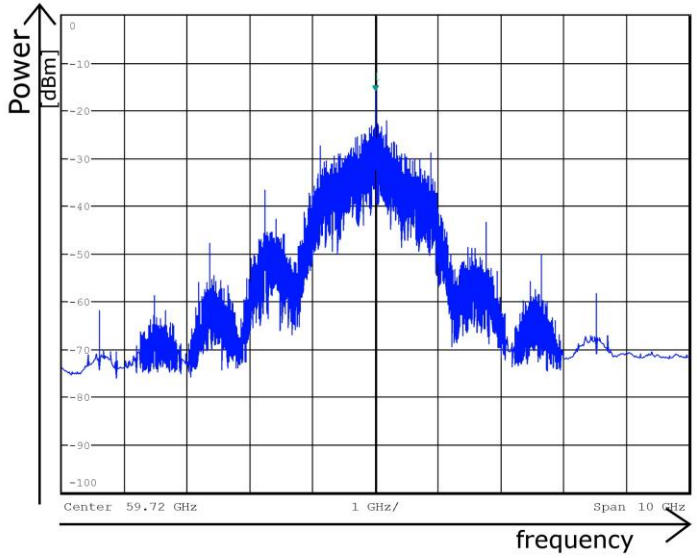
60 GHz Studies

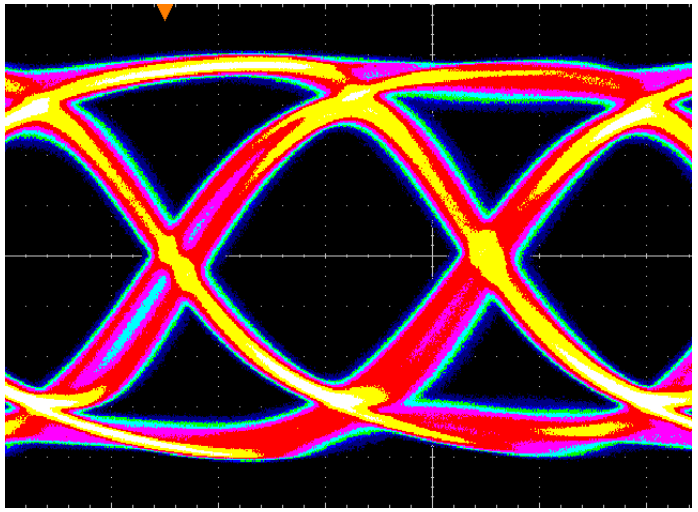
Data transmission and antennas

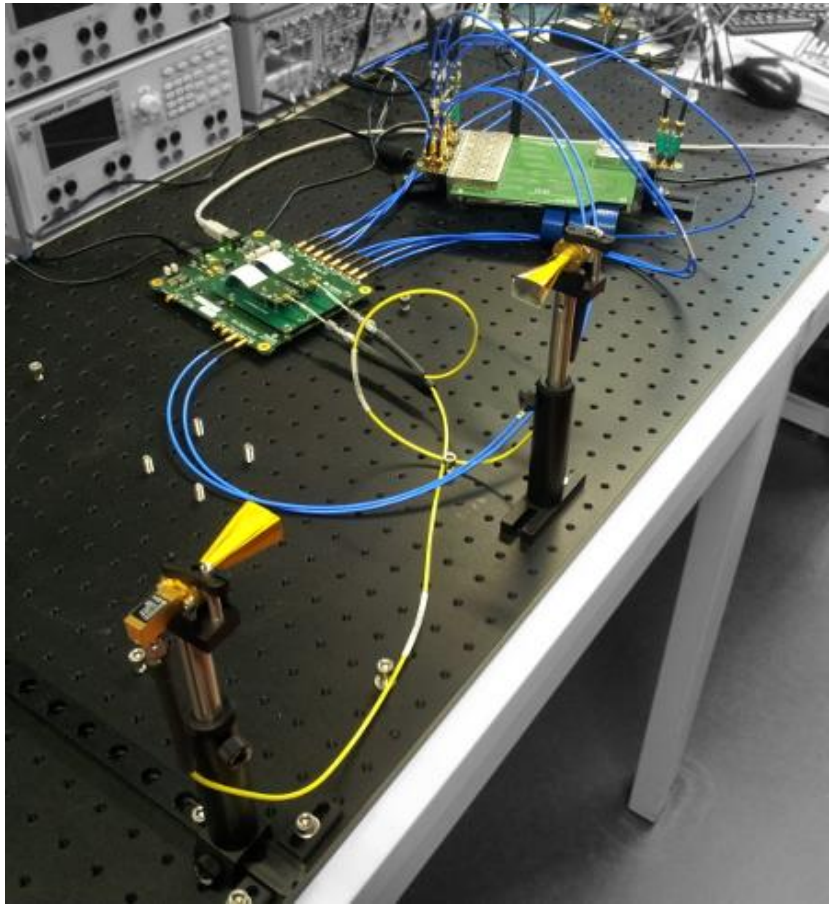
Data transmission (Uni HD)

- Hittite 60 GHz transceiver kit
- 1.76 Gbps @ 22 cm distance with foil horn antennas:

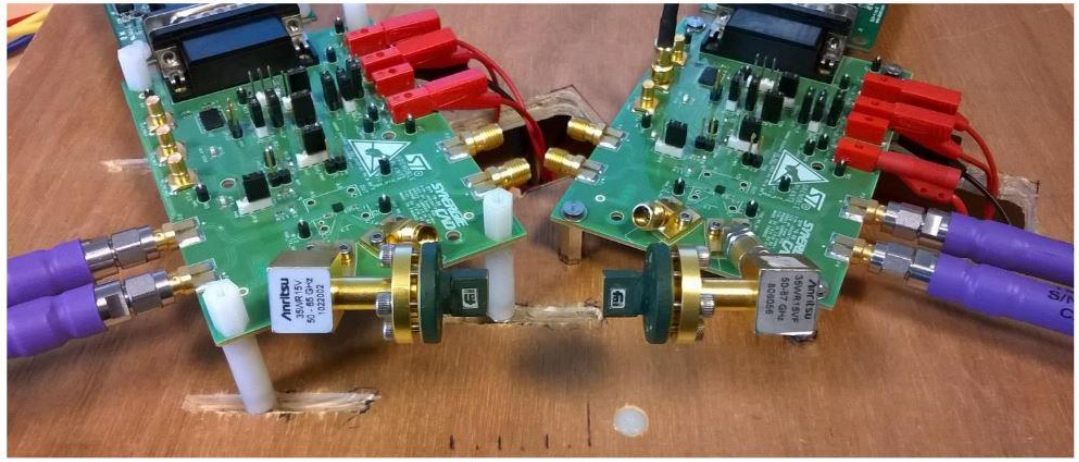
  Error free transmission: $BER < 4.0 \times 10^{-15}$





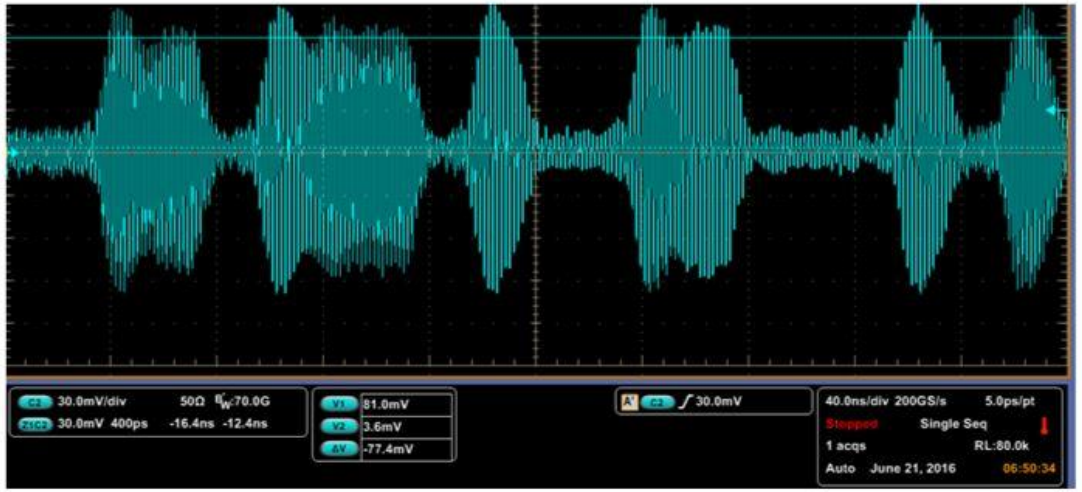


Data transmission (CEA-LETI)



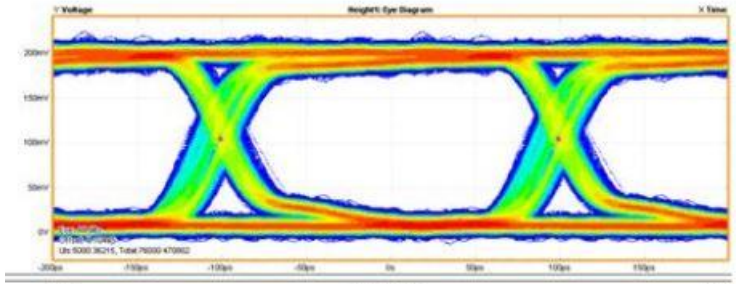
- CMOS 65nm time domain transceiver
- OOK/ASK modulation

Emitted RF wave form

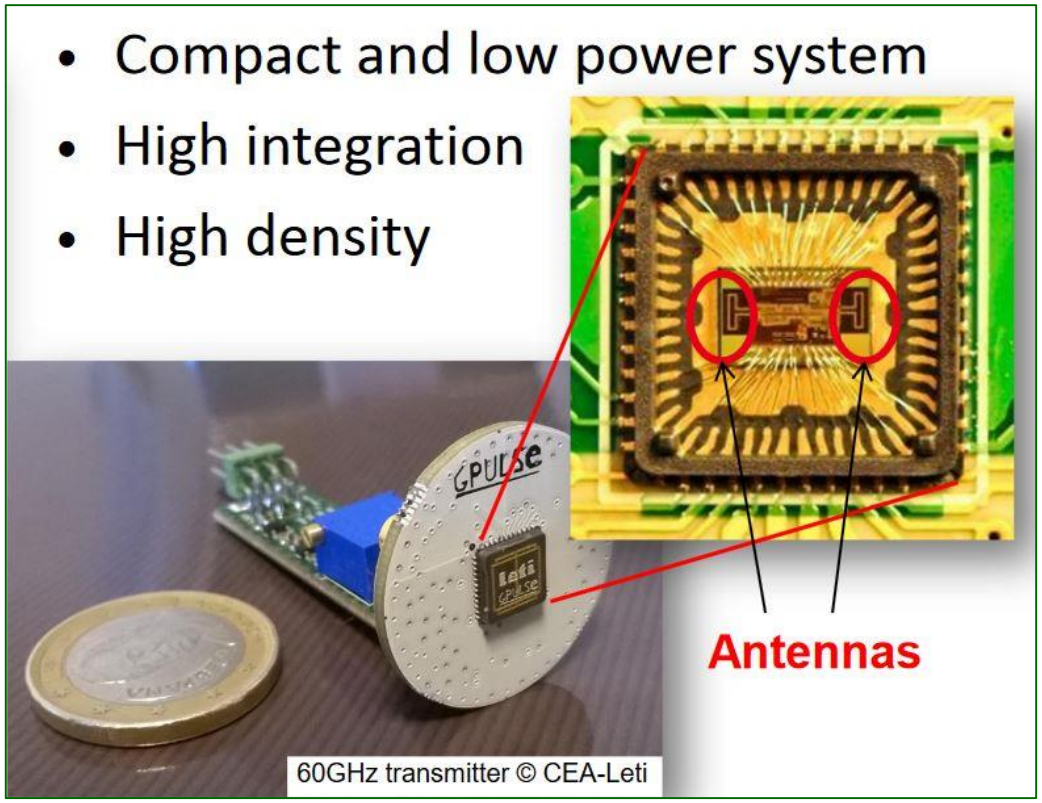


5 Gb/s eye diagram at receiver

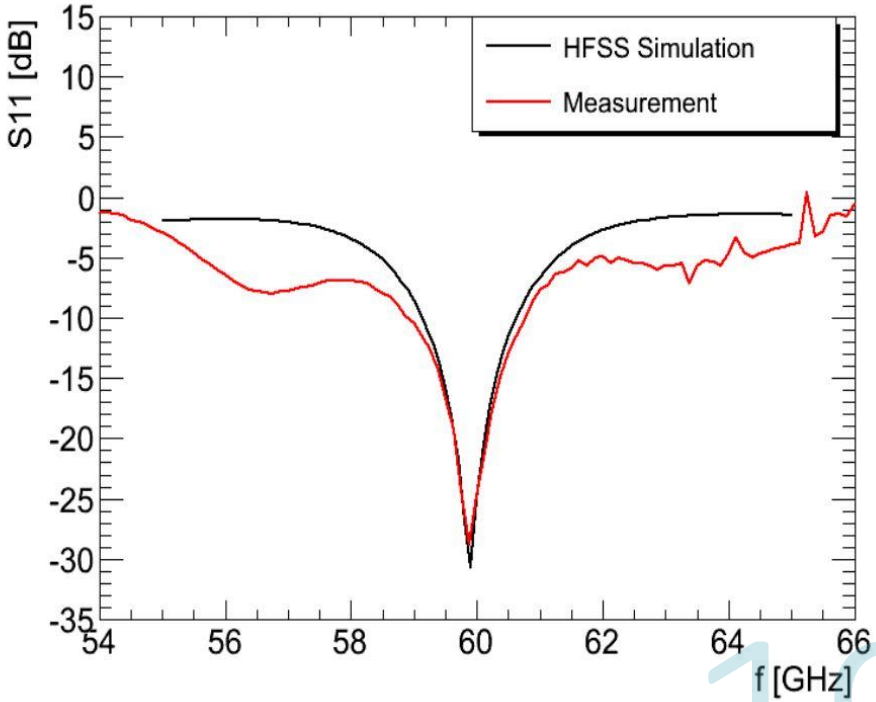
$BER < 10^{-12}$



Antennas (CEA-LETI & Uppsala Uni.)



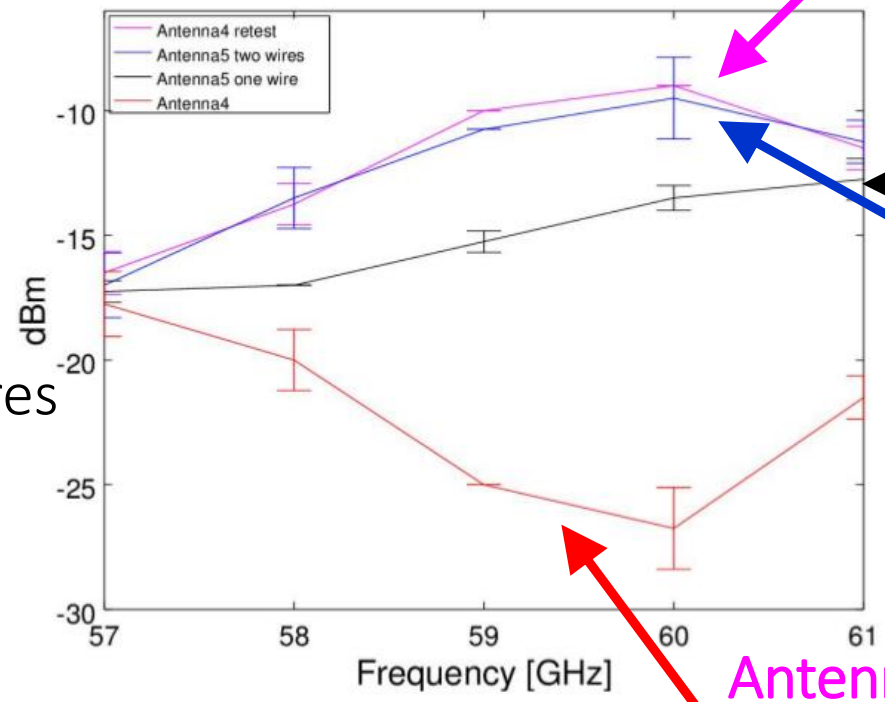
- Small structure sizes
- Multi-patch antenna test

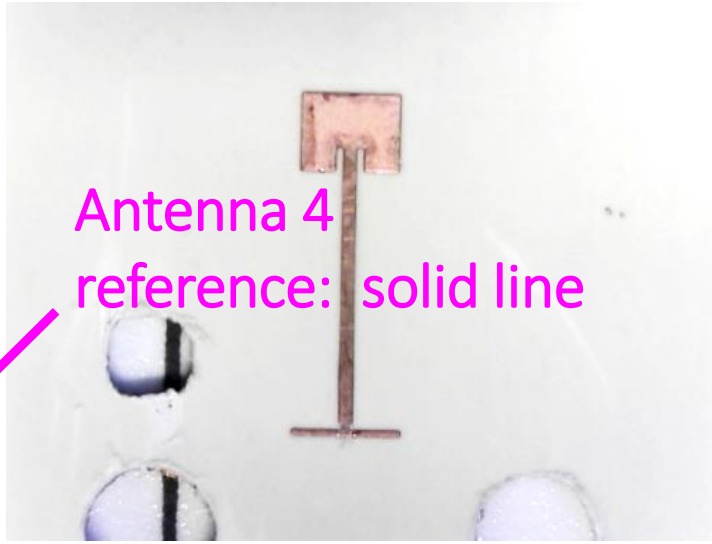


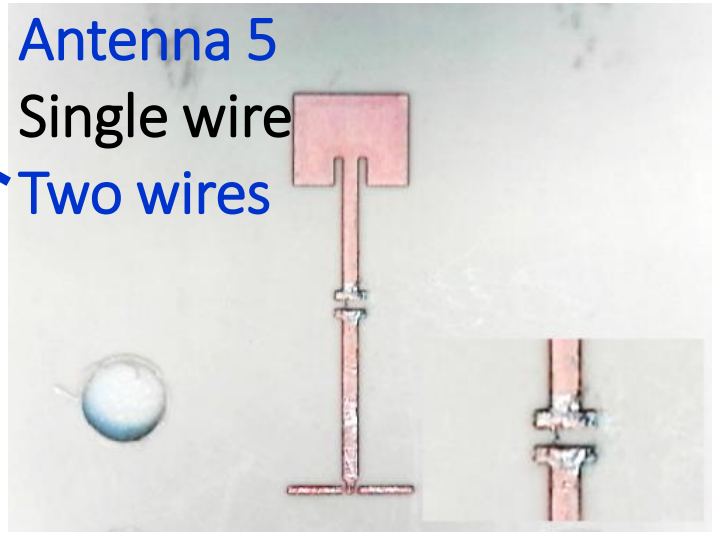
Bonding to antennas (Uppsala Uni.)

Towards a 60 GHz demonstrator for HEP

- Demonstrator with external antenna requires wire bonding
- Impedance of single wire critical
- Solved issue: No signal losses for 2 wires



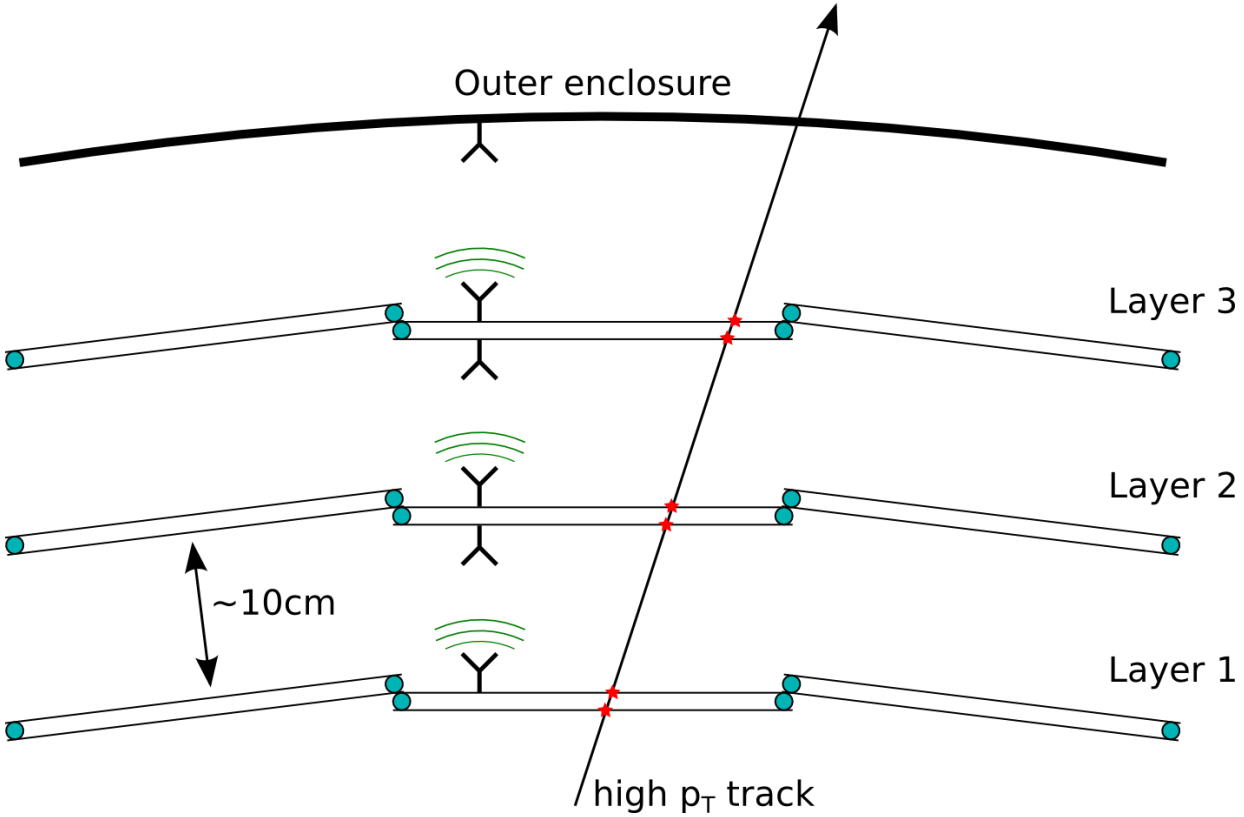




Antenna 4
Etching issue

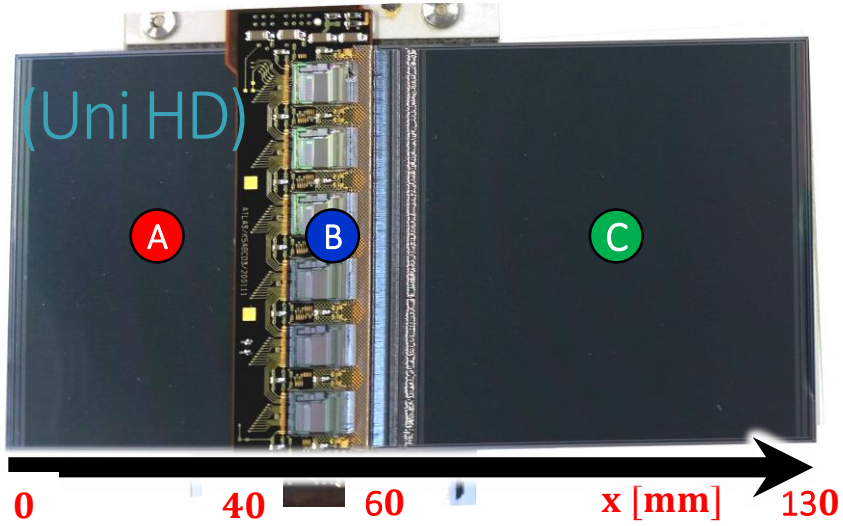
60 GHz Studies

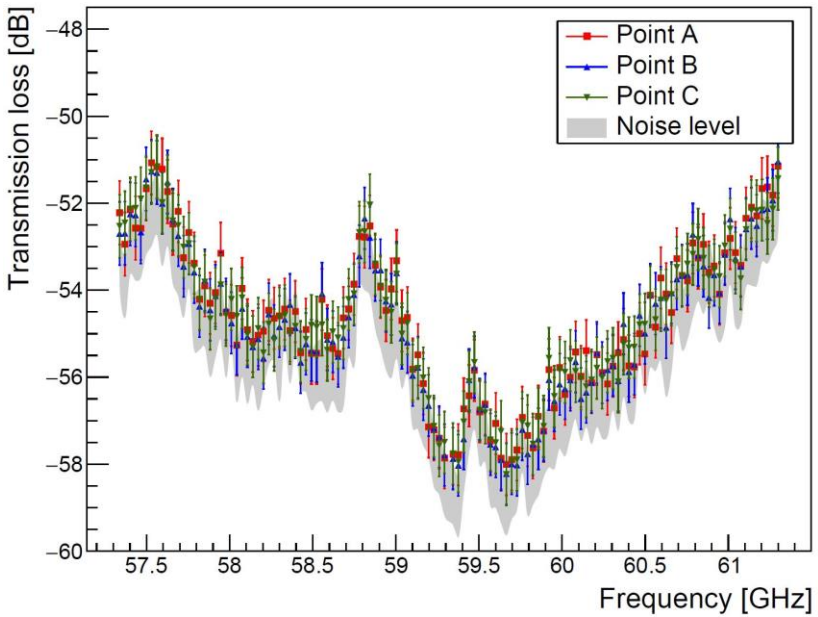
Tracking Detector Scenario

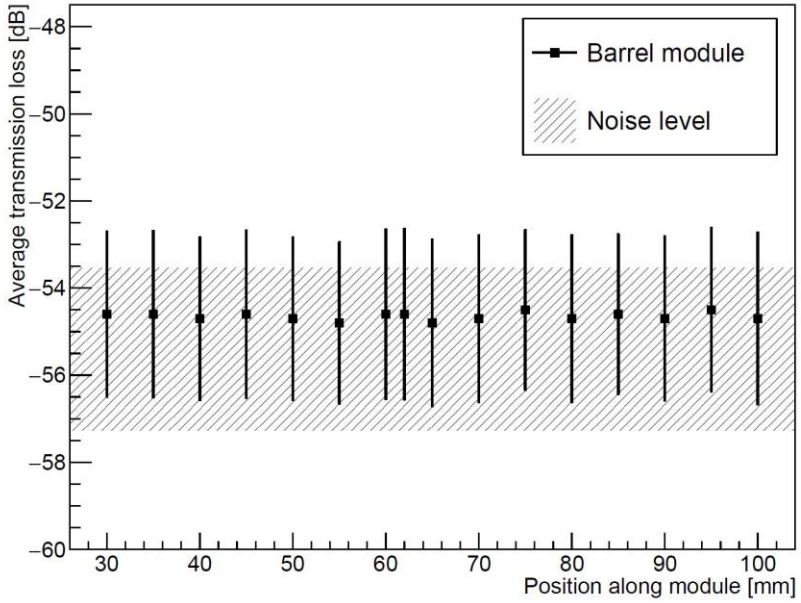


Transmission through layers (Uni HD)

- Transmission through spare ATLAS SCT module tested
- No transmission of 60 GHz signals measured
- 60 GHz signals fully reflected



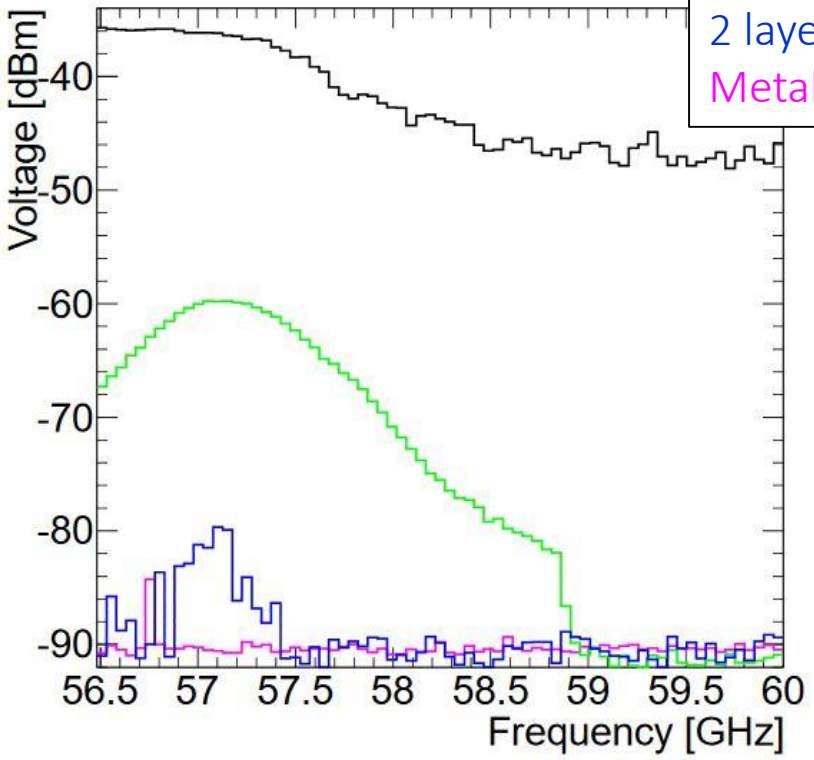




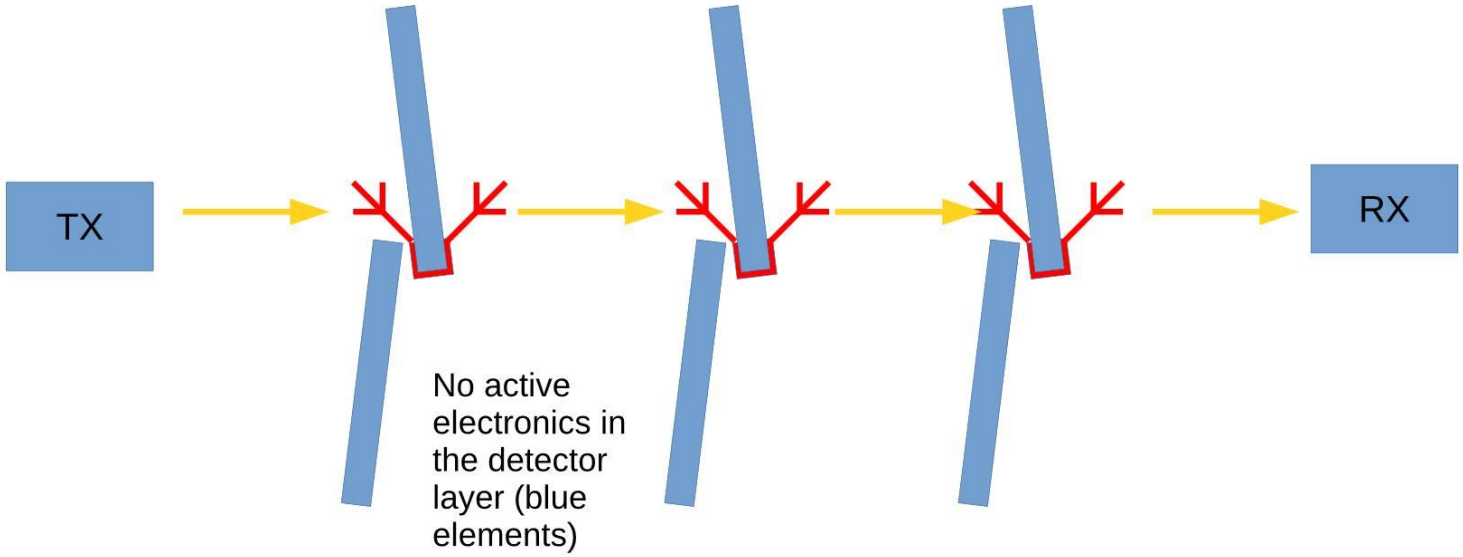
http://dx.doi.org/10.1016/j.nima.2016.06.016

Transmission through layers (Uppsala Uni.)

No layer – no repeater
1 layer with repeater
2 layers with repeaters
Metal layer – no repeater



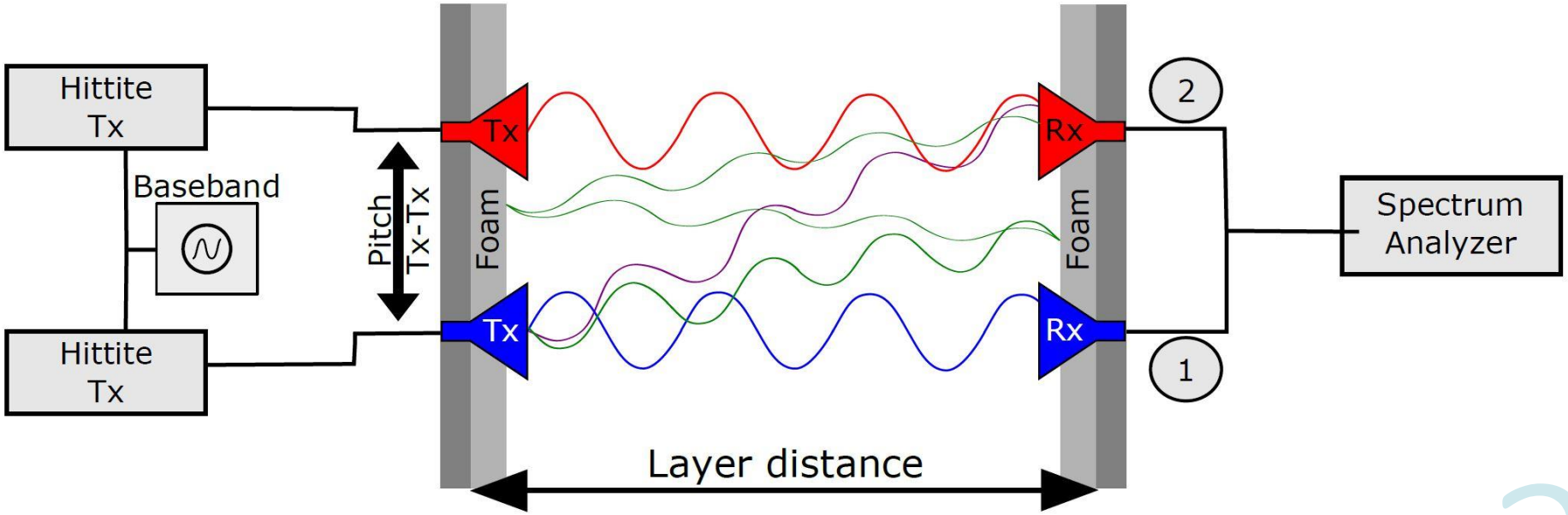
Signals from layer to layer:
Wave guides, holes, repeater, ...?



https://pos.sissa.it/archive/conferences/213/095/TIPP2014_095.pdf

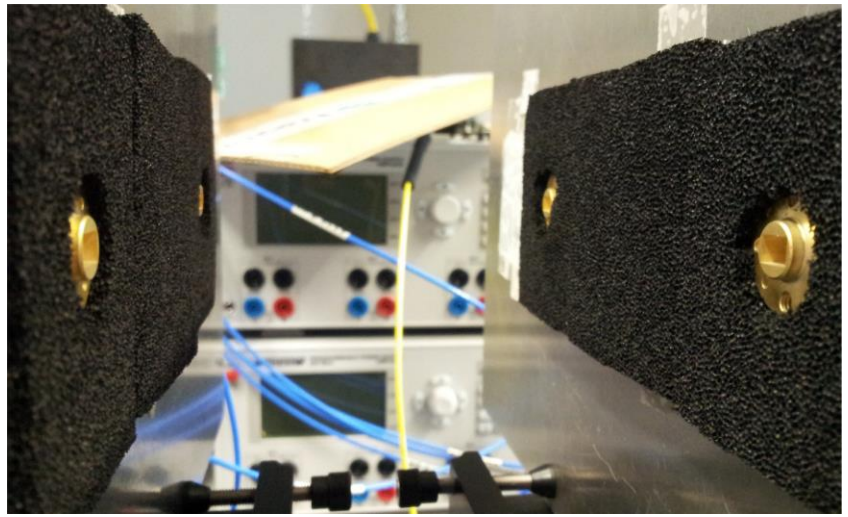
Cross talk studies (Uni HD)

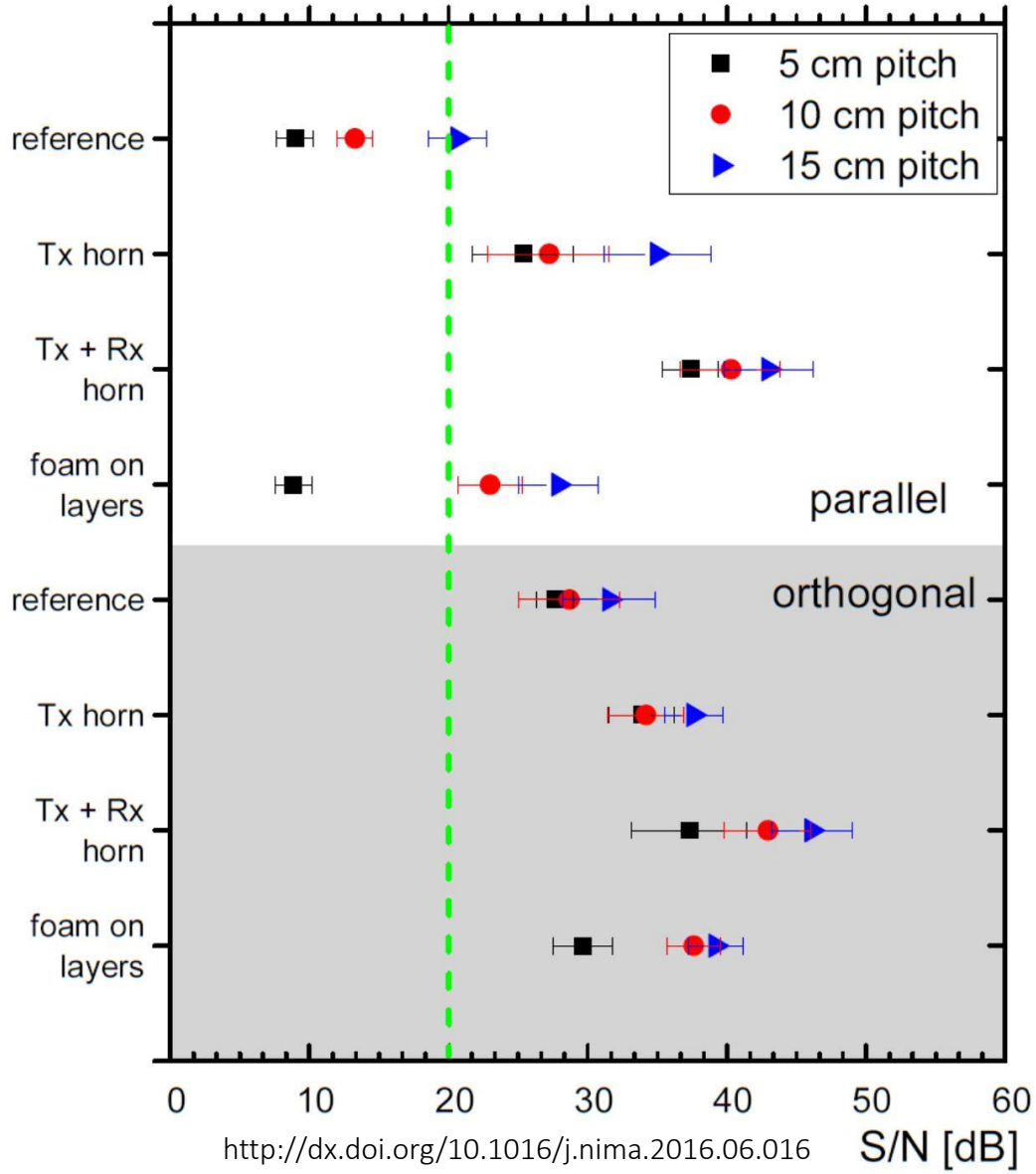
- Study reflections and how to mitigate cross talk in multi-path setup
- Signal to noise in RF for link pitch of 5 cm, 10 cm and 15 cm



Cross talk studies (Uni HD)

- Polarisation excellent option for close-by links
- Highly directive antennas improve S/N strongly
- Additional gain in S/N by graphite foam

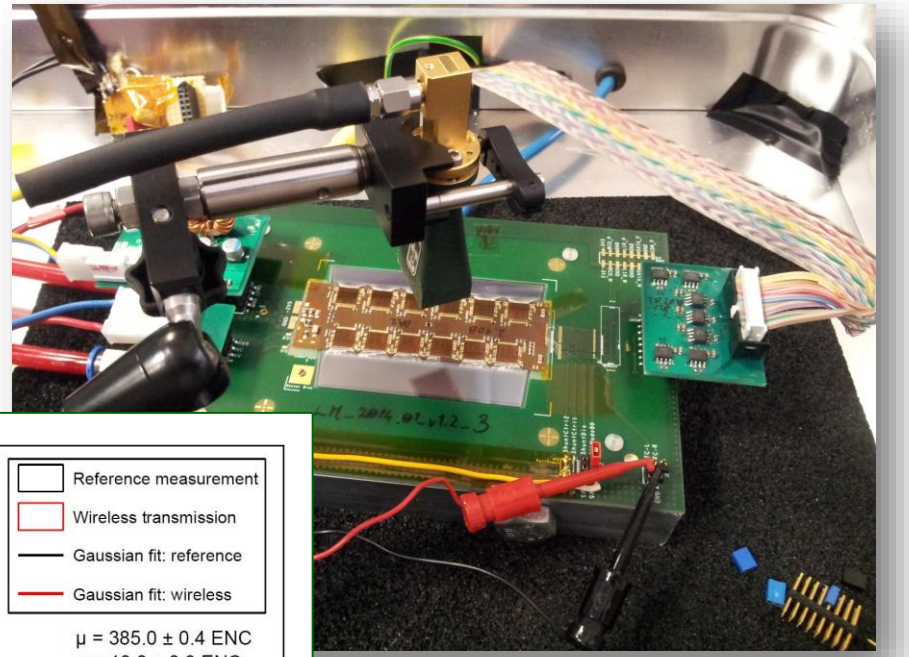


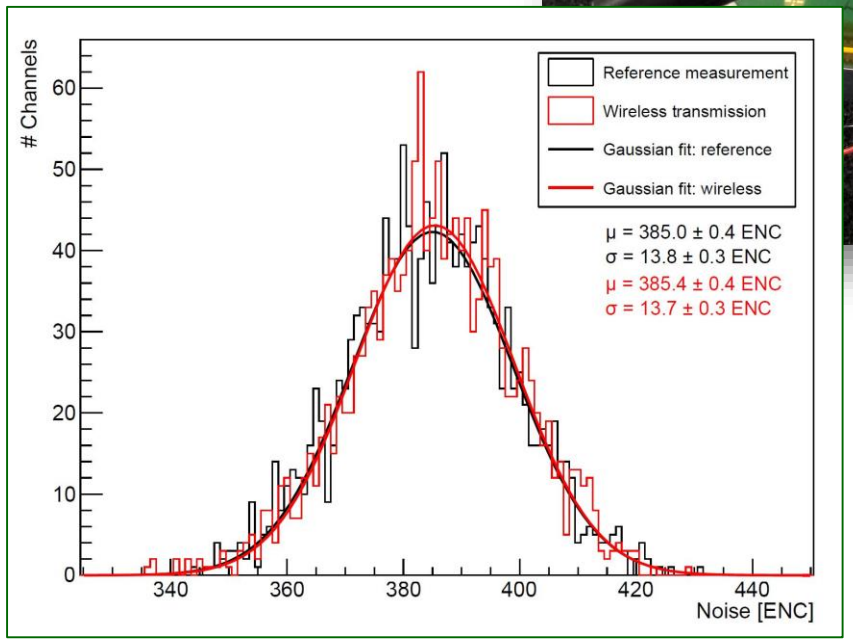


http://dx.doi.org/10.1016/j.nima.2016.06.016

Inteference: 60 GHz vs. detector readout (Uni HD)

- Tests with ITK hybrid with ABCn130 ASICS (Uni Freiburg)
- No increase in noise observed
- Well above cut-off frequency of typical readout electronics

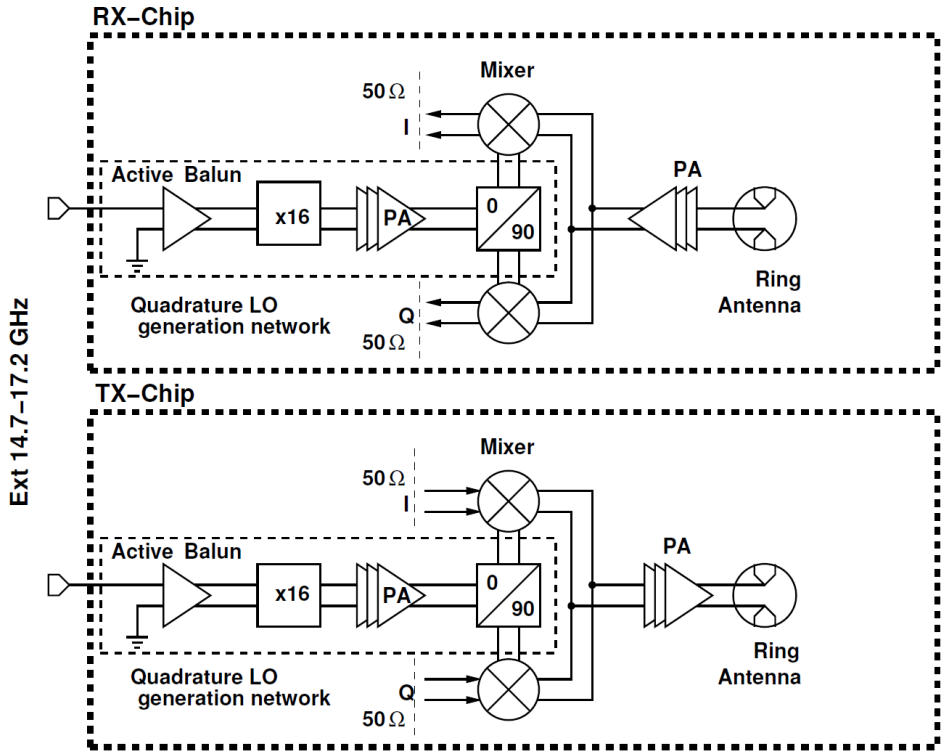




http://dx.doi.org/10.1016/j.nima.2016.06.016

Future prospects

240 GHz wireless transceiver
(IHCT Wuppertal)

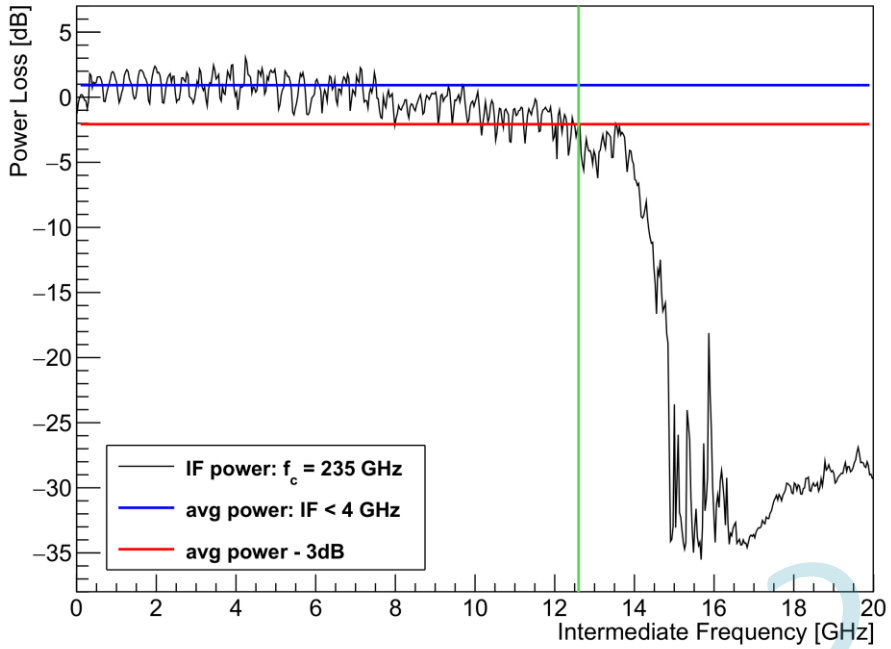


N. Sarmah, P. R Vazquez, J Grzyb, W. Foerster, B. Heinemann, U. R. Pfeiffer
"A Wideband Fully Integrated SiGe Chipset for High Data Rate Communication at 240 GHz"

- 0.13 µm SiGe HBT technology
- Up to 6 dBm of output power
- Power consumption:

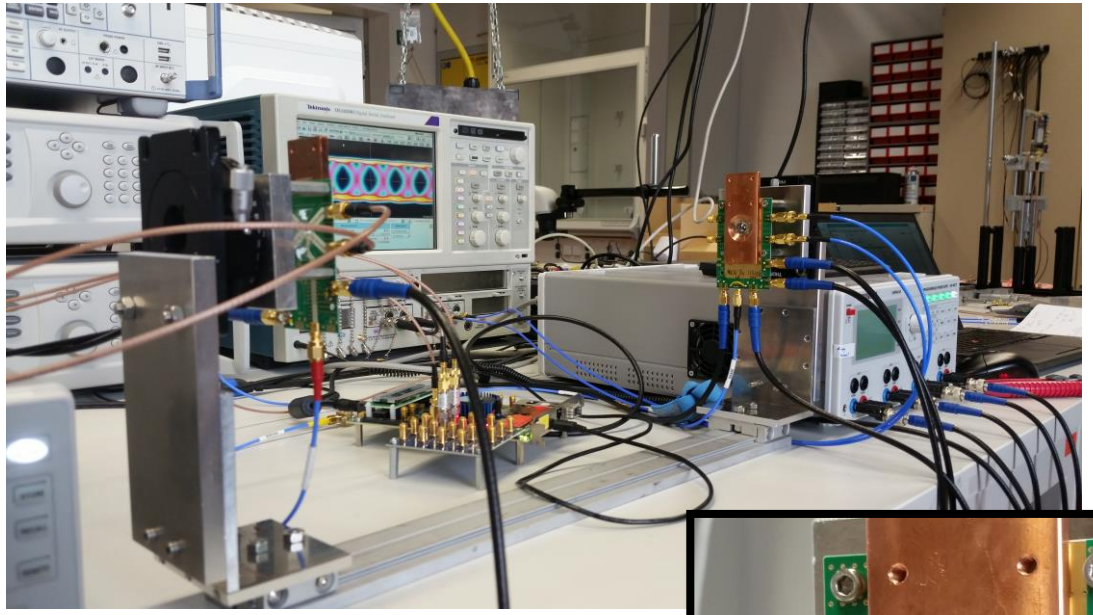
$$P_{Tx} \approx 1.5\ \mathrm{W}$$
$$P_{Rx} \approx 1.3\ \mathrm{W}$$

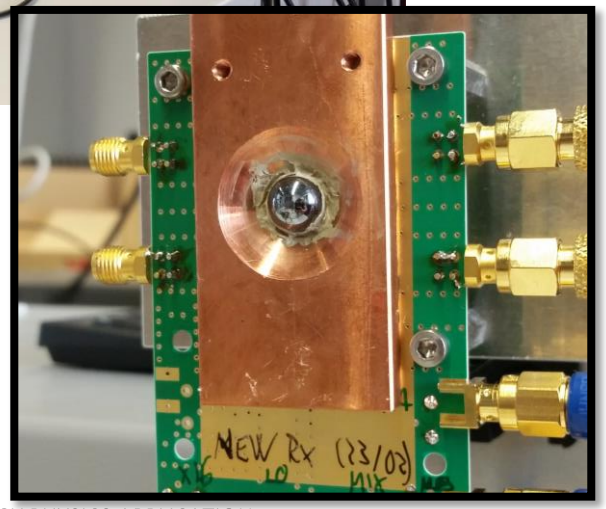
- Measured IF Bandwidth > 12 GHz



240 GHz wireless data transmission studies

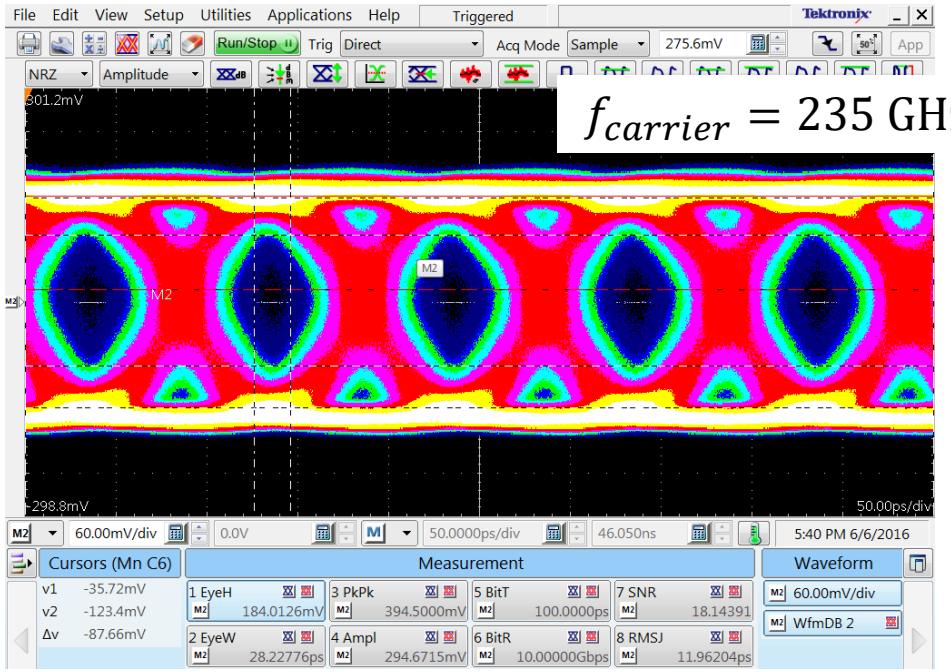
Setup in the laboratory at PI Heidelberg





- Transmission distance ≈ 40 cm
- Silicon lenses G ≥ 25 dBi
- Binary Phase Shift Keying

10 Gb/s pseudo random data stream (PRBS7)



$f_{carrier} = 235\ \mathrm{GHz}$

Data rate [Gb/s]	Bit error rate
8.0	$\leq 5 \cdot 10^{-13}$
10.0	$3 \cdot 10^{-14}$
12.0	$5 \cdot 10^{-10}$

Conclusions

- Huge progress in the field of mm-waves over the last years
- Wireless data transmission is an attractive option for HEP experiments
- Potential benefits:
    - Reduce cabling issues for high bandwidth readout systems
    - Radial readout topologies could facilitate fast track trigger implementation

Summary and Outlook

- Error-free high speed data transfer demonstrated
- Demonstrated that detector performance is not degraded by mm-waves
- High link densities possible:

  Cross talk can be mitigated by means of antennas, polarization, …
- Carrier frequencies above 60 GHz will allow for even higher data rates
- WADAPT: Technical proposal for CERN R&D in preparation for May LHCC
- WADAPT: Potential support through ATTRACT initiative

Backup

60 GHz transceivers

- Mature technology:
  many transceiver ASICs published

- Energy efficiencies down to 6.3 pJ/bit for 10.7 Gb/s

  C. W. Byeon, C. H. Yoon, and C. S. Park
  A 67-mW 10.7-Gb/s 60-GHz OOK CMOS transceiver for short-range wireless communications
  IEEE Trans. Microw. Theory Techn., vol. 61, no. 9, Sep. 2013