60 GHz Wireless in High Energy Physics

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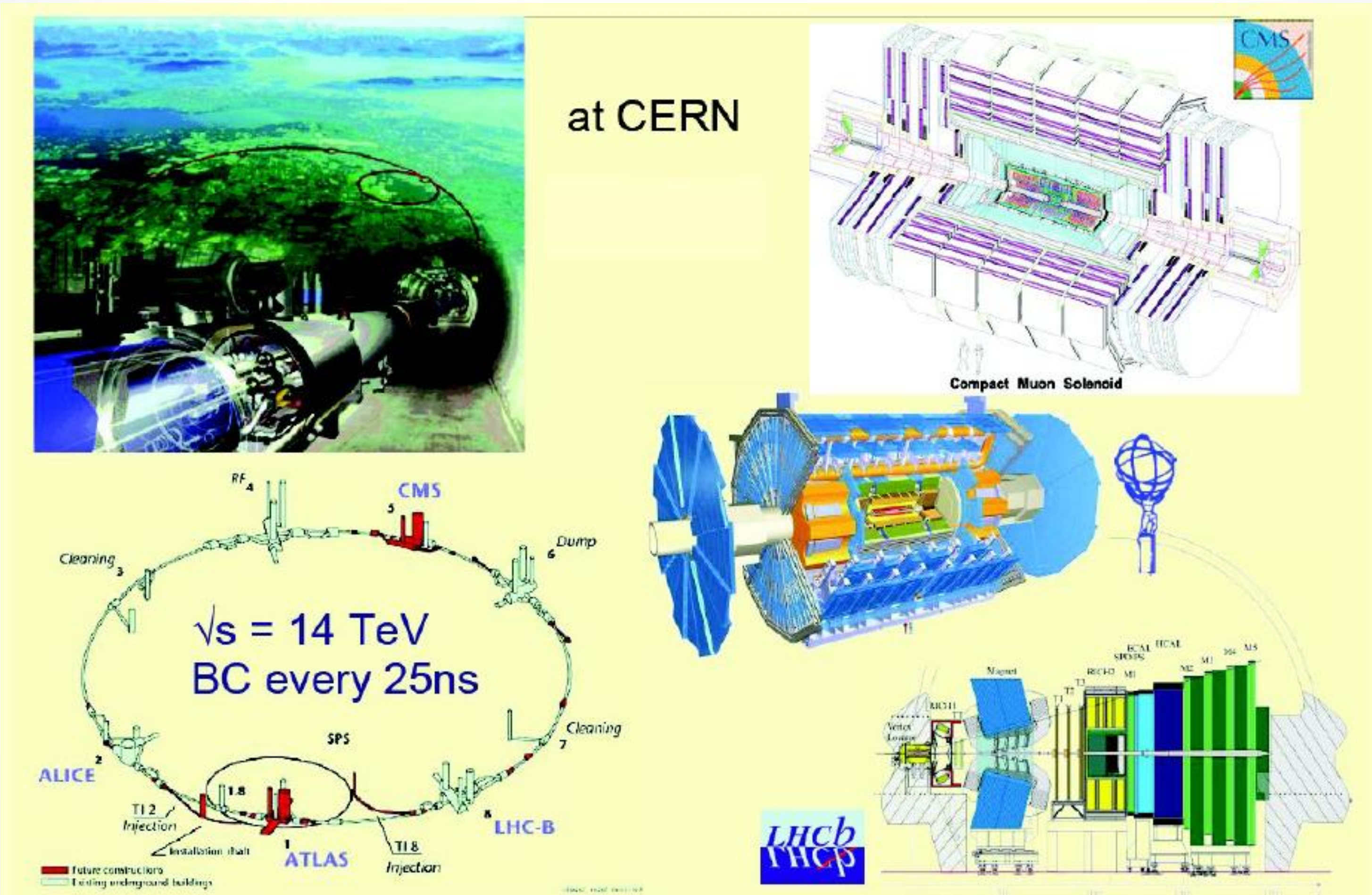
Outline

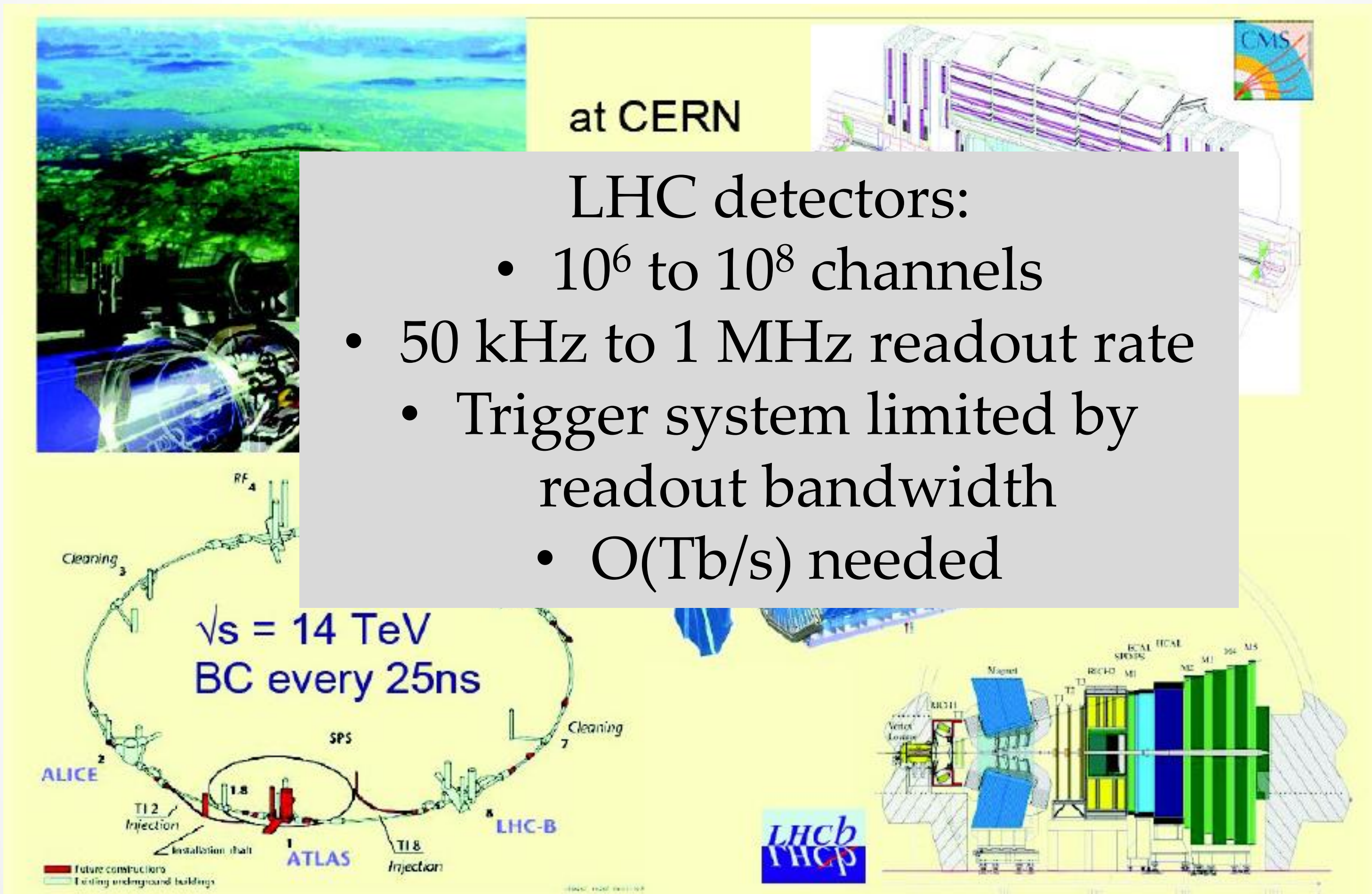
- Readout Challenges in HEP
- Wireless Data Transmission for HEP
- 60 GHz ASIC
- 3D chip Advantages
- First Experience
- Summary and Outlook

Readout Challenges in HEP

Readout Challenges in HEP



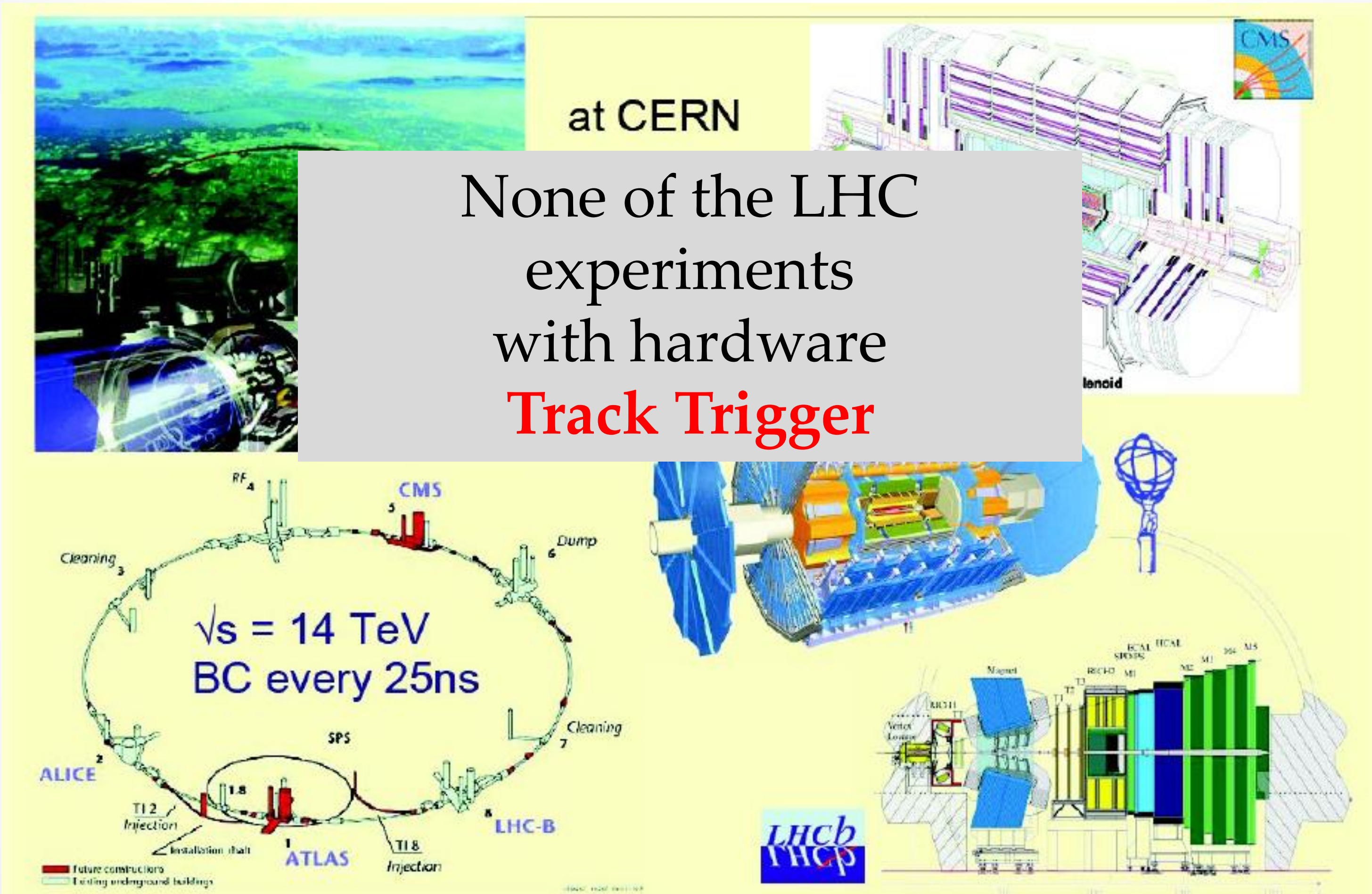
Readout Challenges in HEP



LHC detectors:

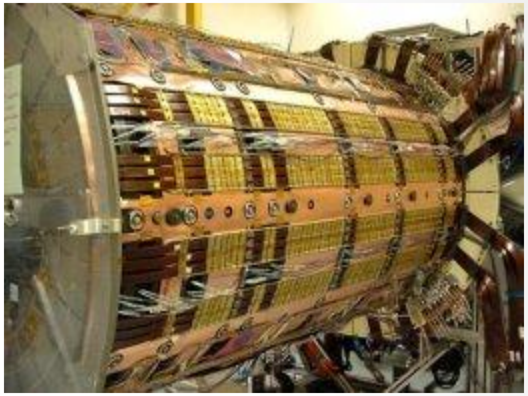
- 10^6 to 10^8 channels
- 50 kHz to 1 MHz readout rate
- Trigger system limited by readout bandwidth
- O(Tb/s) needed

Readout Challenges in HEP



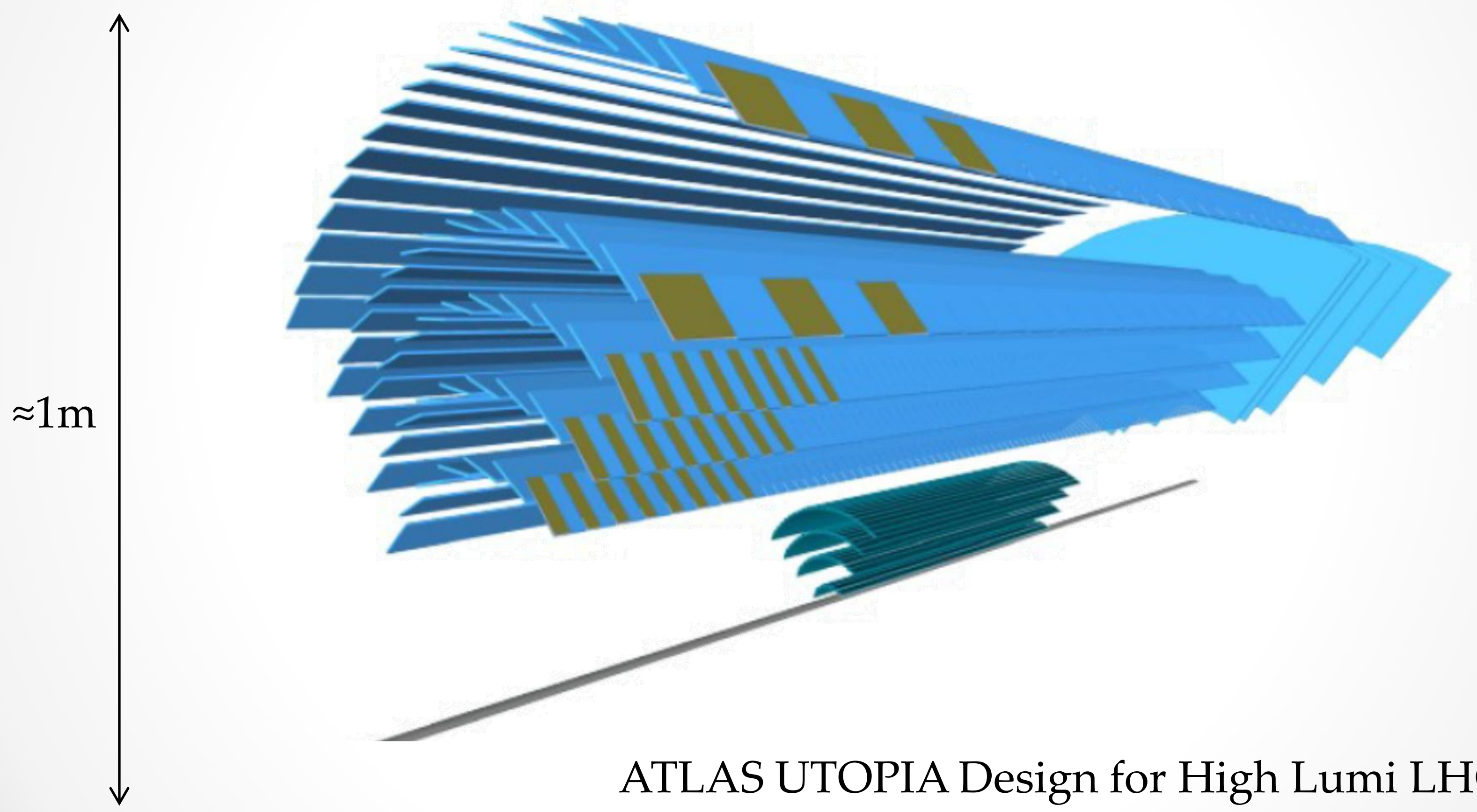
High Precision Tracking Detectors

- Innermost silicon layers
  - High event rates: f=O(100) MHz
  - High particle fluxes
  - ➢ Data rate/area of 10^{10} signals/second/cm^2



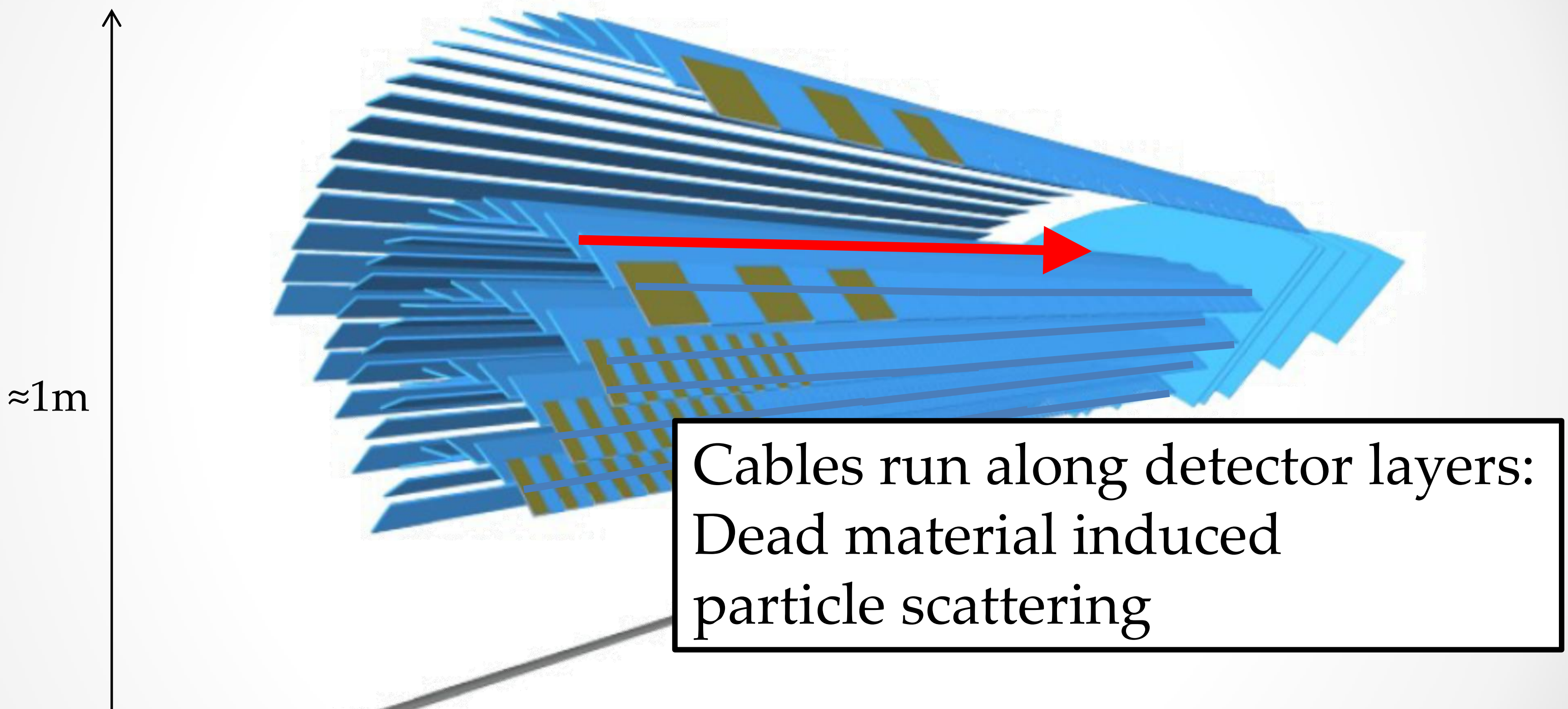
- Outer silicon layers
  - Factor 10-100 smaller particle flux!
  - Data rate/area 10^8 signals/ second /cm^2
  - ➢ Wireless multi Gbit/s readout?

Bandwidth Limitations in Inner Detectors



ATLAS UTOPIA Design for High Lumi LHC

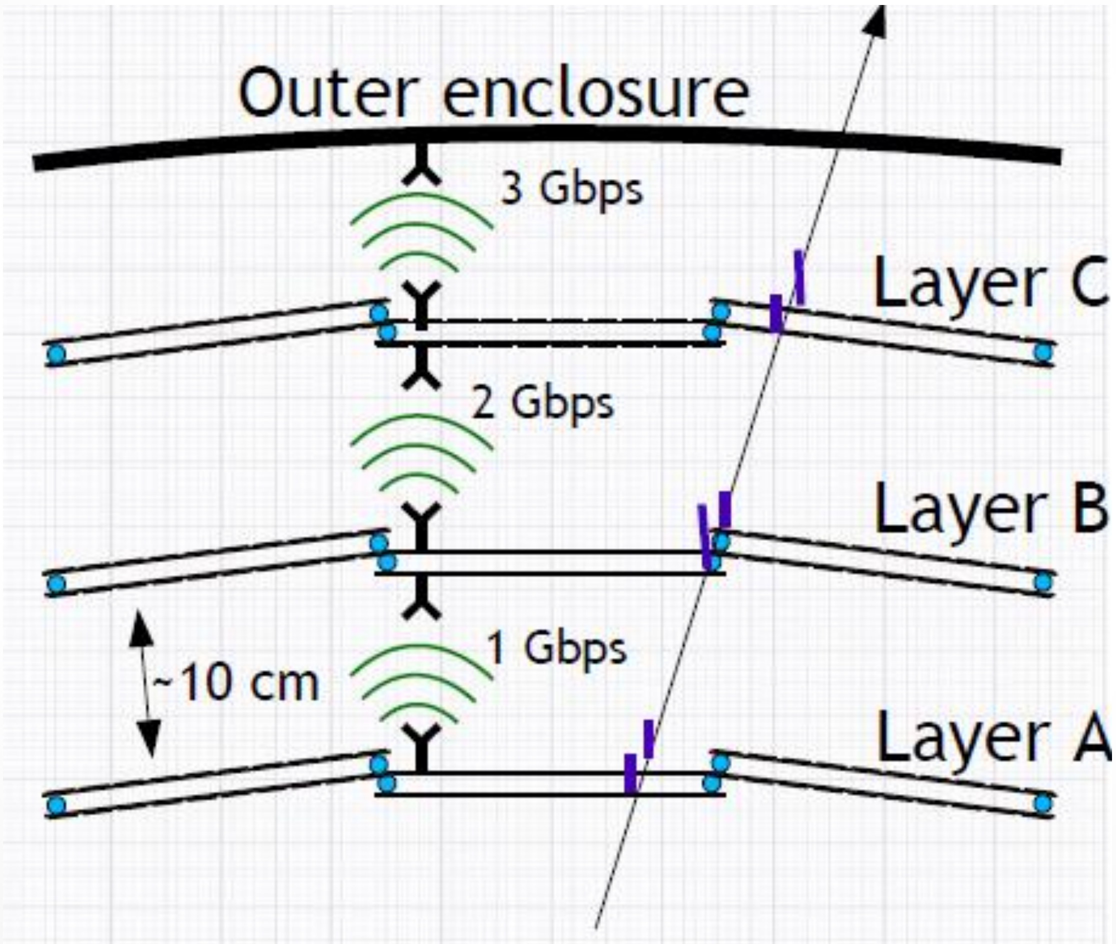
Extra Material from optical / electrical RO



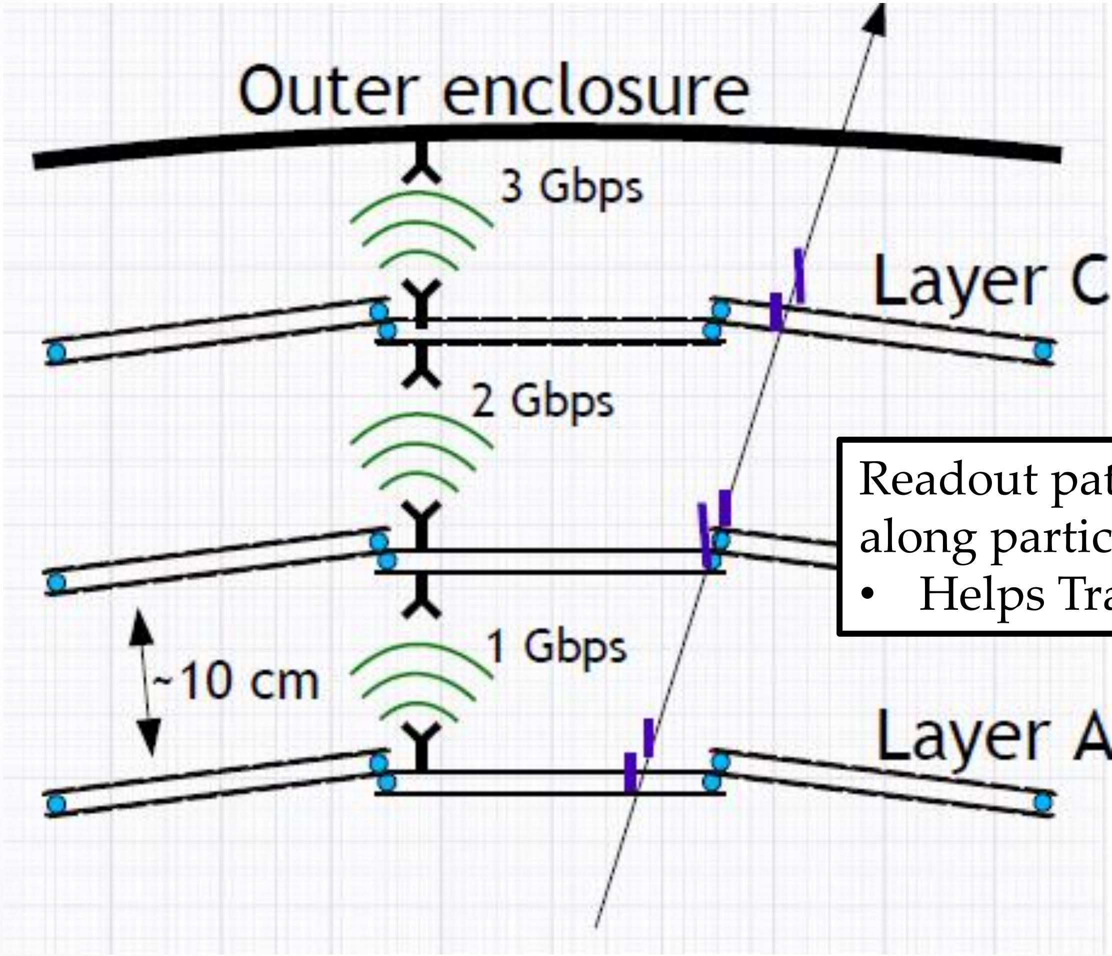
ATLAS UTOPIA Design for High Lumi LHC

Wireless Data Transmission for HEP

Wireless Readout?



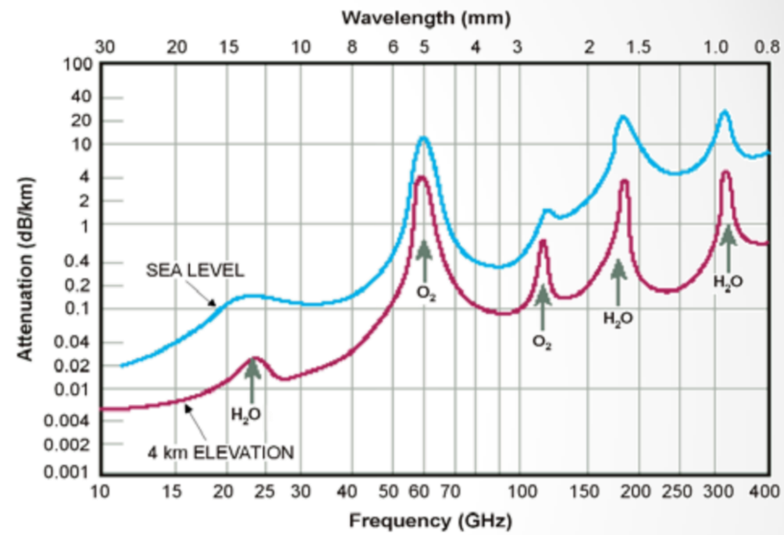
Data Path for Wireless

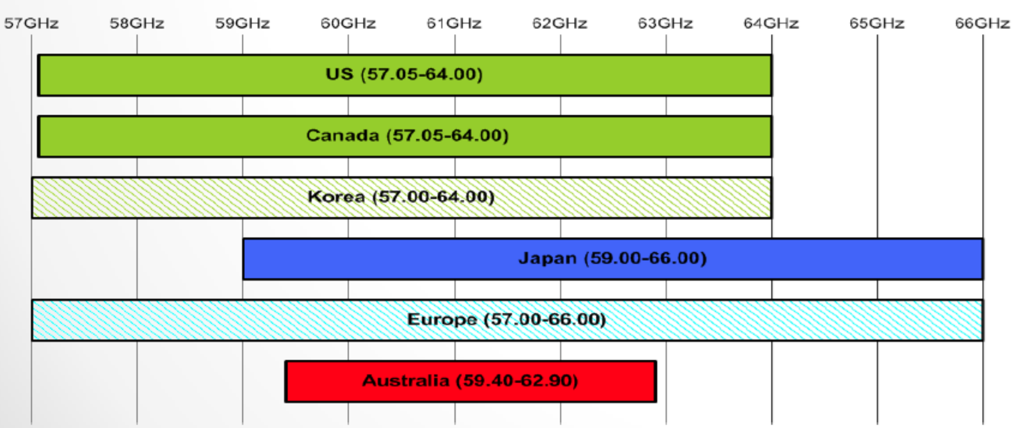


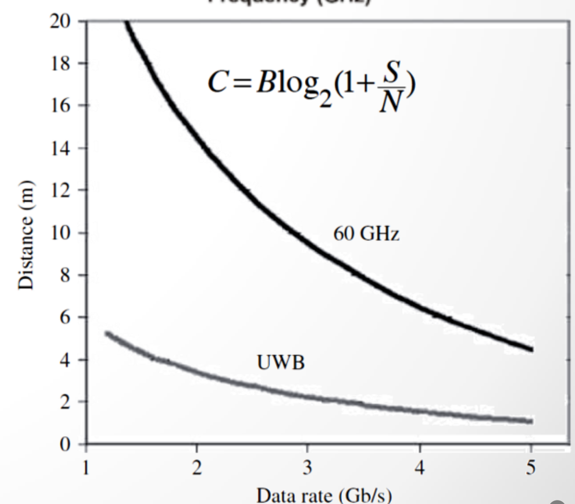
Readout path (ideally) along particle path:
- Helps Track Trigger!

The 60 GHz Band

- 60 GHz O_2 absorption
- Large damping over 10m
- Unlicensed band 57-66 GHz
- 9 GHz usable
- Multi Gbit/s transfer capacity

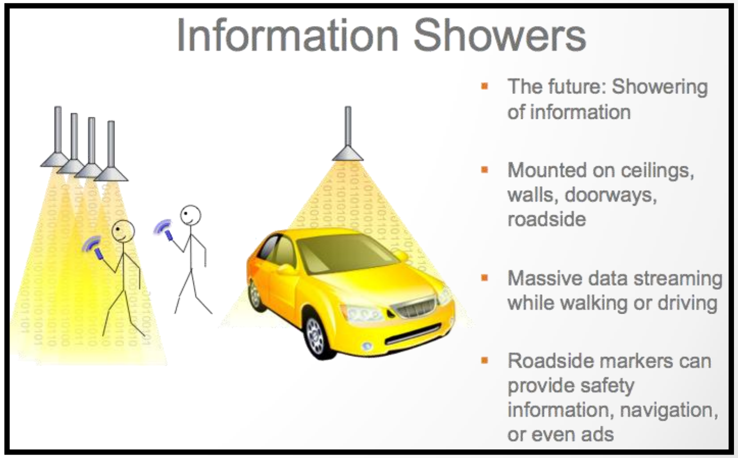






Why is the 60 GHz Band so attractive?

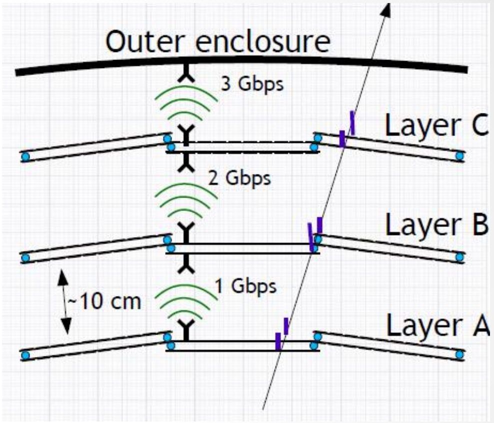
- The mm-wave frequency range is very attractive:
  - o Data rates and bandwidth are never enough
  - o Uncompressed video:
    - High definition multimedia interface (HDMI)(2Gb/s)
  - o High speed file transfer among electronic devices
  - o Fast movie or video game down load from kiosk

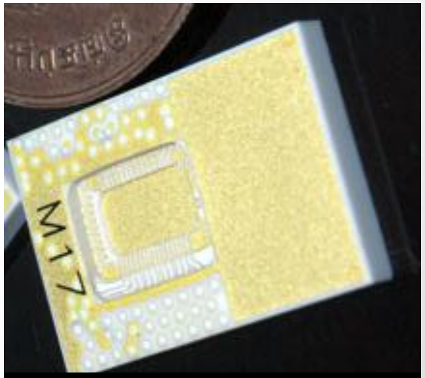


➢ And now the High Energy Physics

Requirements for Wireless in HEP

- High bandwidth
  - 60 GHz band could offer 5 Gb/s per link
- Low power
  - O(1000) RF interconnects
  - Cooling and power cabling limited
- Low material budget
  - Extra material causes multiple scattering
- High system integration
  - Direct coupling of readout chips to RF system
- Radiation hardness
  - O(MRad) levels in LHC detectors





60 GHz Antenna

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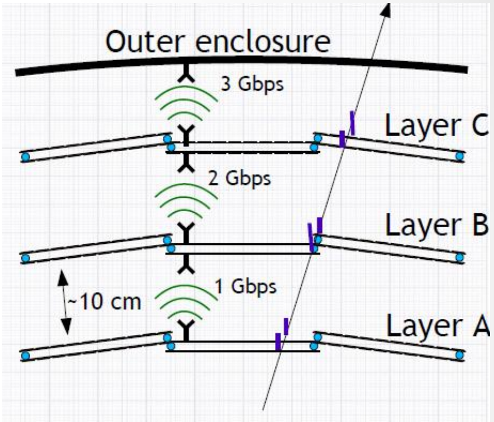
Multiple Wireless Readout

- O(1000) links needed
- … but only over short (10 cm) distance
- High directivity helps
  - Limits cross talk
  - Saves power
  - Typically sensor layers are well aligned
- Distance from sensor to RF link is kept small
  - Less material for data lines
  - Better for high speed electrical signals
- ➢ Application specific integrated circuit (ASIC) necessary!

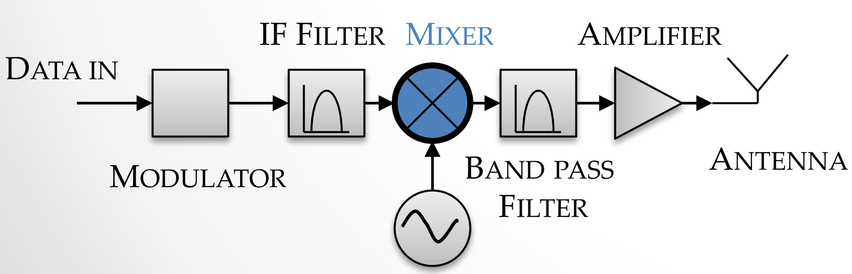


60 GHz ASIC

60 GHz Transceiver System

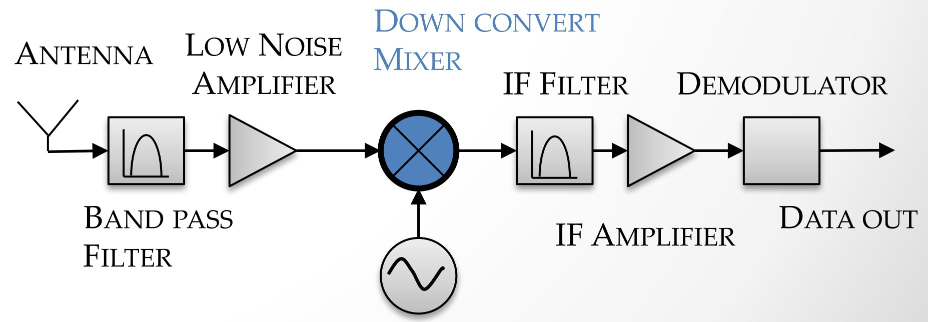
Transmitter

- High power efficiency
- High gain and stability



Receiver

- Low noise amplifier
- Balance gain, linearity and noise
- Low power dissipation



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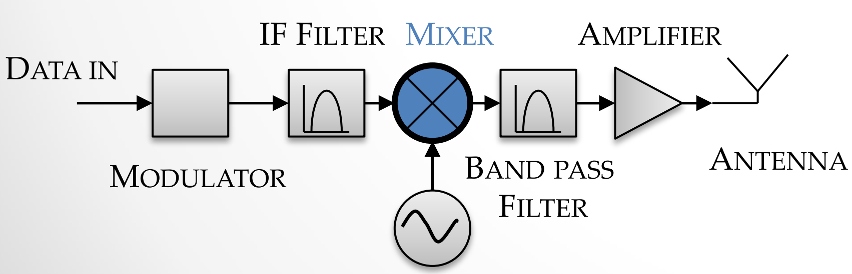
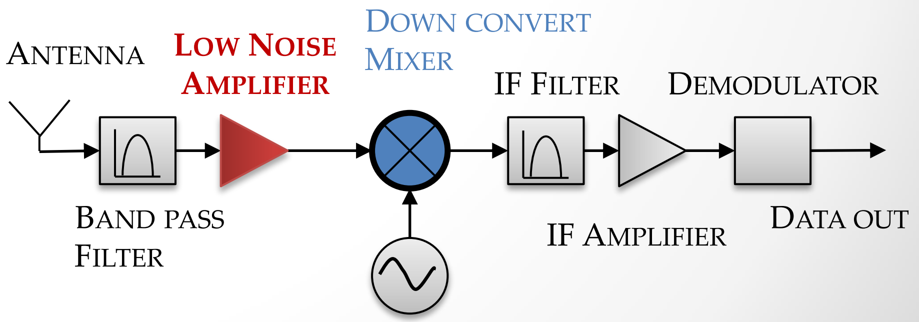
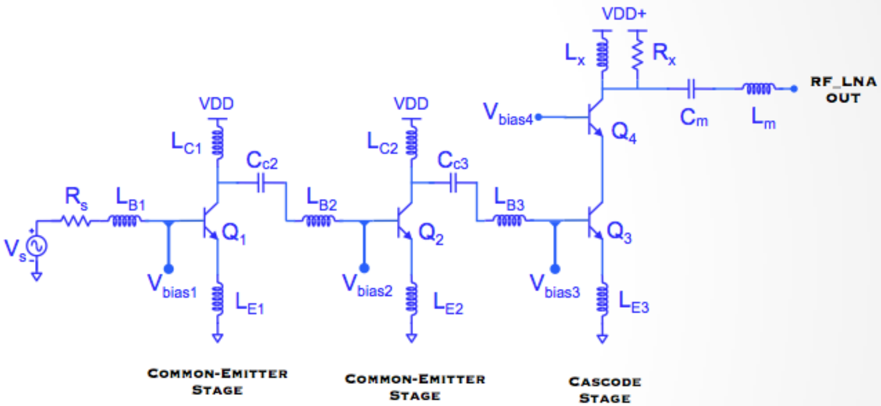




Low Noise Amplifier Issues

- Power dissipation (10 mW)
- Noise Figure (6dB)
- Linearity
- Stability
- Impedance matching
- Power gain (16dB)
- Bandwidth (>10GHz)
- Insensitive to process variation



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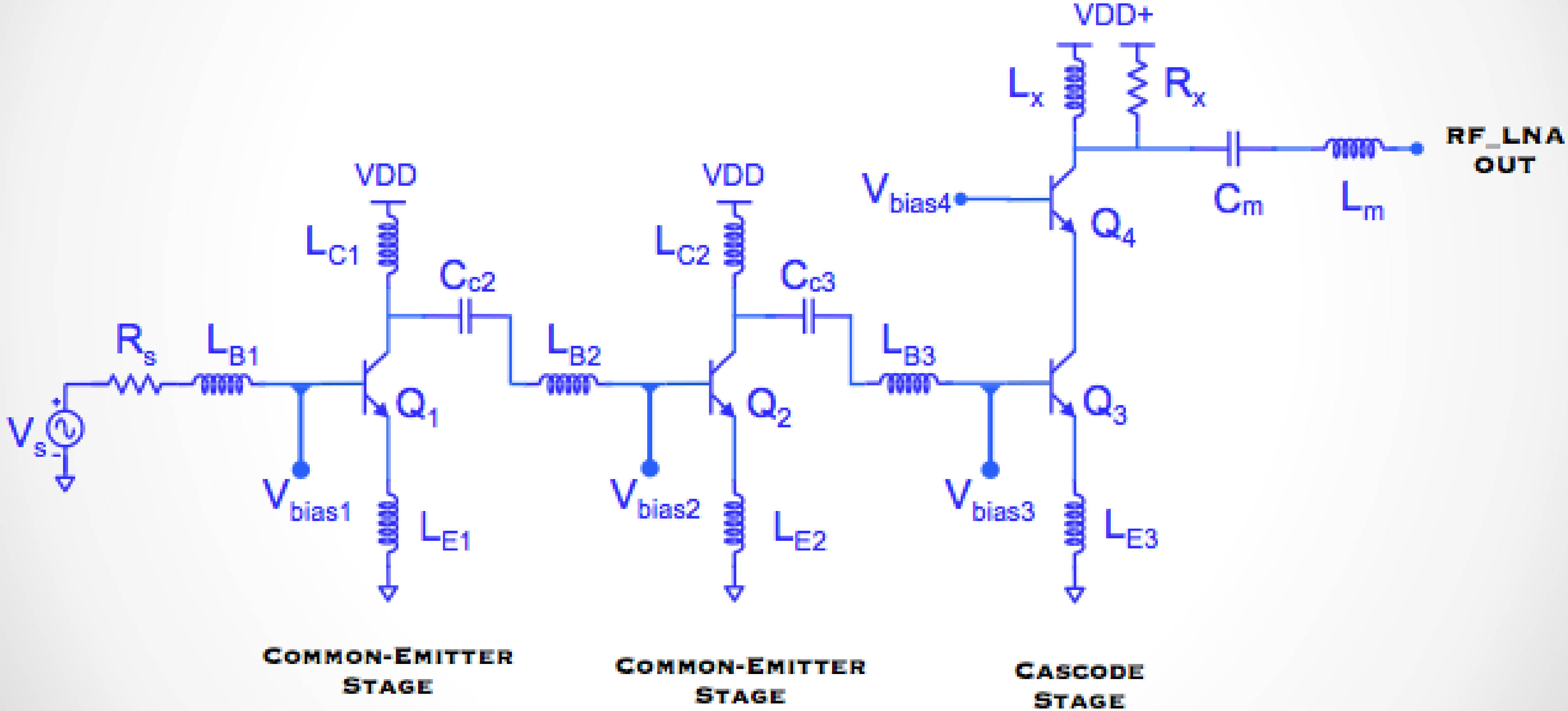
Low Noise Amplifier Issues



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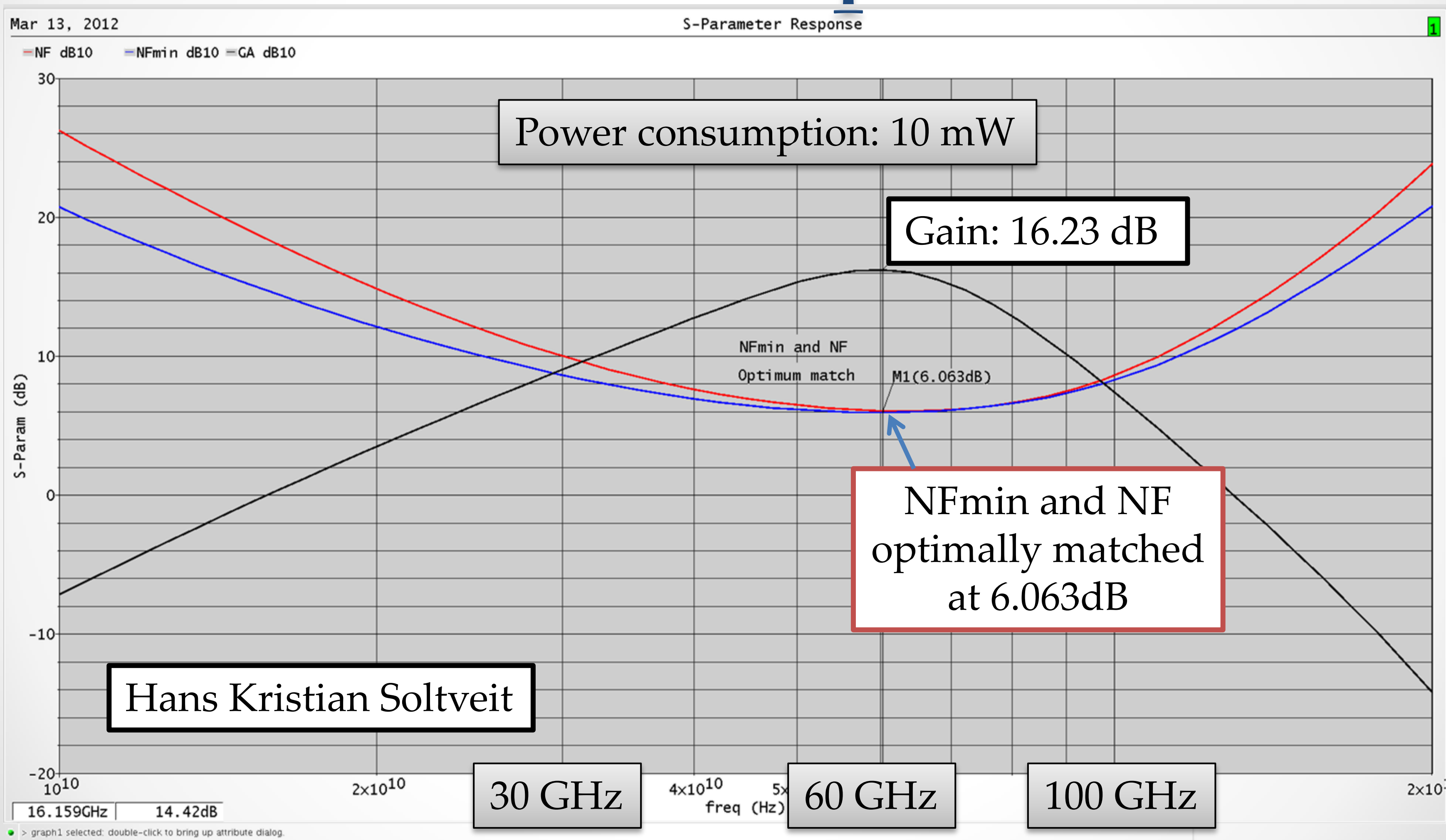
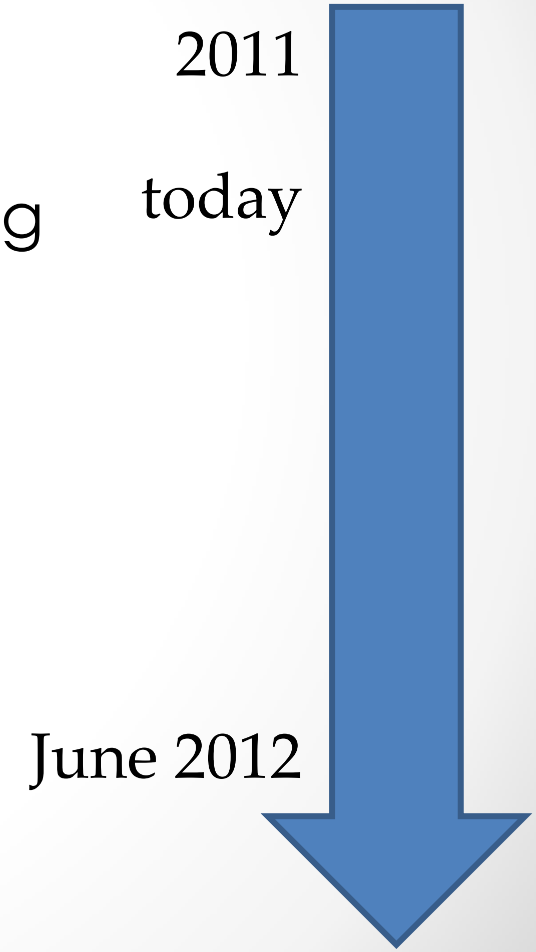
Characteristics of Low Noise Amplifier



ASIC Timeline

- Diploma thesis for VCO design: complete
- Full analogue chip design: progressing well
    - Low noise amplifier
    - Power amplifier
    - Mixer cell / Gilbert cell
    - Band pass filter + antenna
- Missing:
    - Matching between blocks
    - Corner simulation



Why ON-Chip Antennas?

- Wavelengths at 60 GHz: 5mm
- Possible to integrate receive and transmit antenna(s) on-chip
- High directivity is desired:
  - Better S/N-ratio
  - Reduce power consumption
  - Reduce inter-use interference
- SiGe process (HBT)
  - High dielectric constant in Silicon (11.7)
  - Multiple metal layers on ICs available
  - Can be used to fabricate mm-wave antennas

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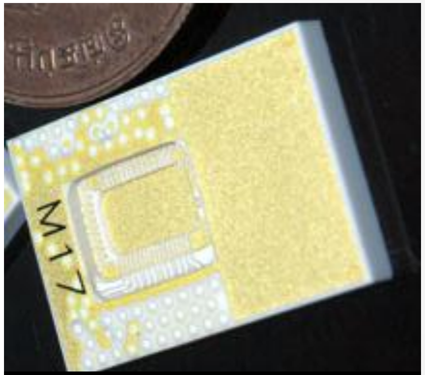

60 GHz Antenna

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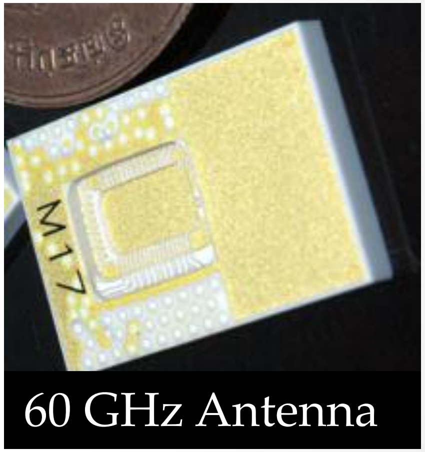
Why ON-Chip Antennas?

- Eliminate cable/connectors loss
- No need for high-frequency electrostatic discharge protection
- Save PCB real estate
- Reduce fabrication costs
- Alternatives:
  - On board antenna
  - Antenna (CMOS) on extra chip (MCP)
  - Antenna (non SiGe) in 3-D stack



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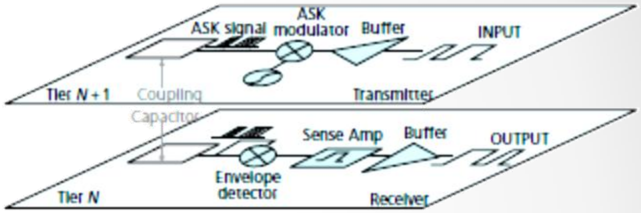
3D Chip Advantages

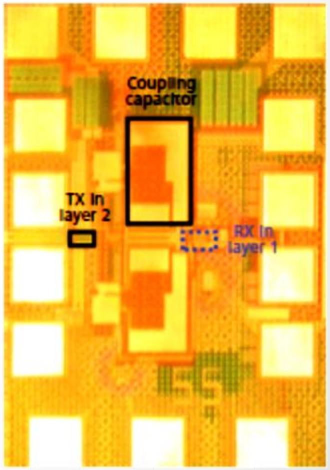
… for wireless readout chip

3D Chips opens up new Possibilities



(a)

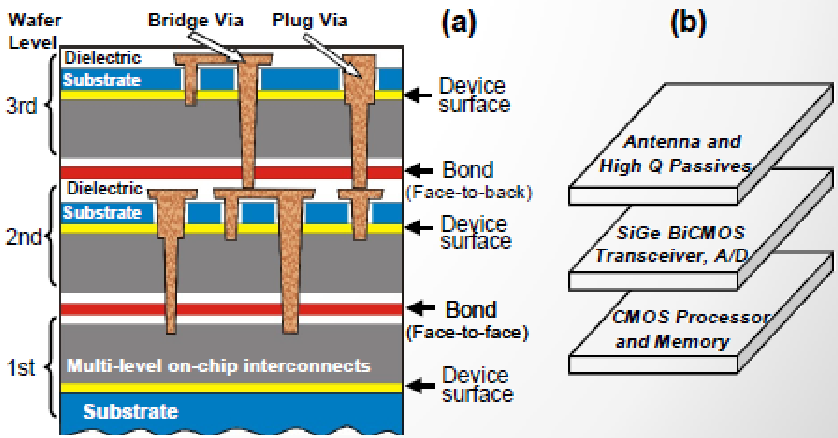
- RF signaling does not require direct connection
- Capacitive or inductive coupling for inter-layer transmission
- 3D chips become industry standard
- Other 3D chip projects advancing: ATLAS-FTK AMchip5



(b)

Why 3D Stacking ?

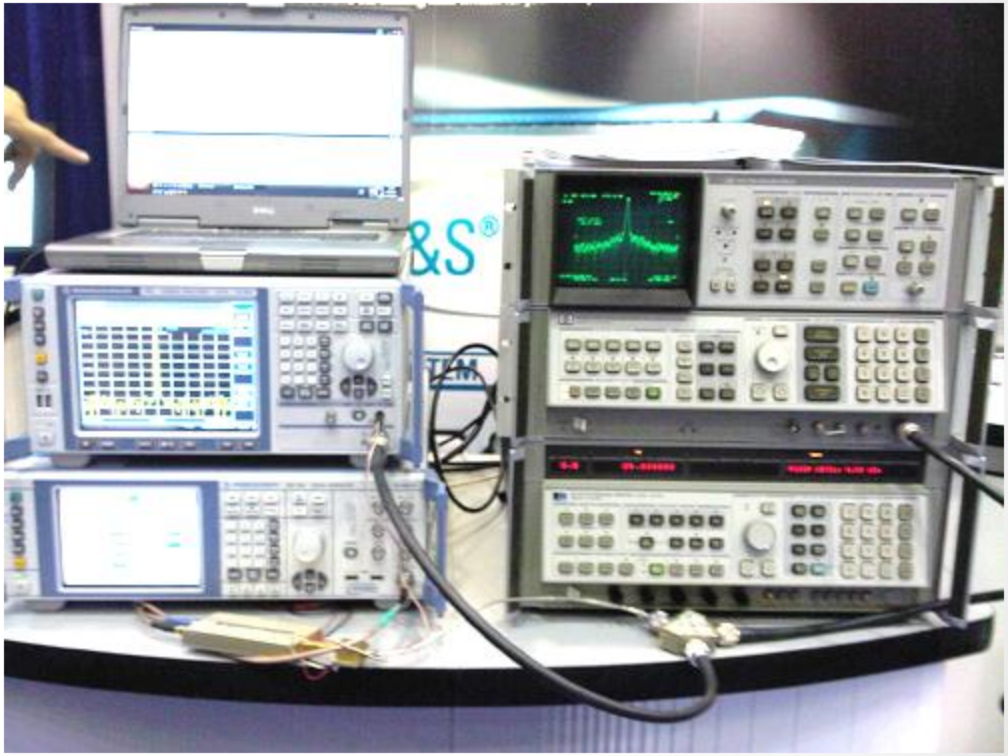
- 2-D chip layouts → 3-D chip stacking
- Increased performance –
  - Out scaling Moore's law
- Decreasing system risk
  - 130 nm analog + 65 nm digital
  - … instead of 65 nm mixed signal SOC.
  - Good for fast serializer (65nm)
  - Good for **antenna**



First Experience
…

Current Lab Setups

- Starting point
  - High end measurement equipment
- Goals:
  - Verification system: Demonstrator
  - Integration …
  - … with commercial ASICs
    - ➢ Replace by self made ASIC (blocks) later
    - ➢ Fully integrated ASIC



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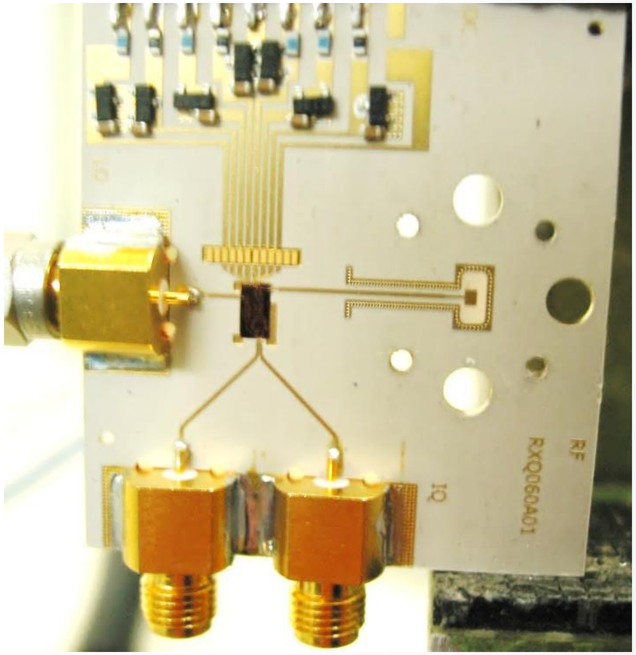
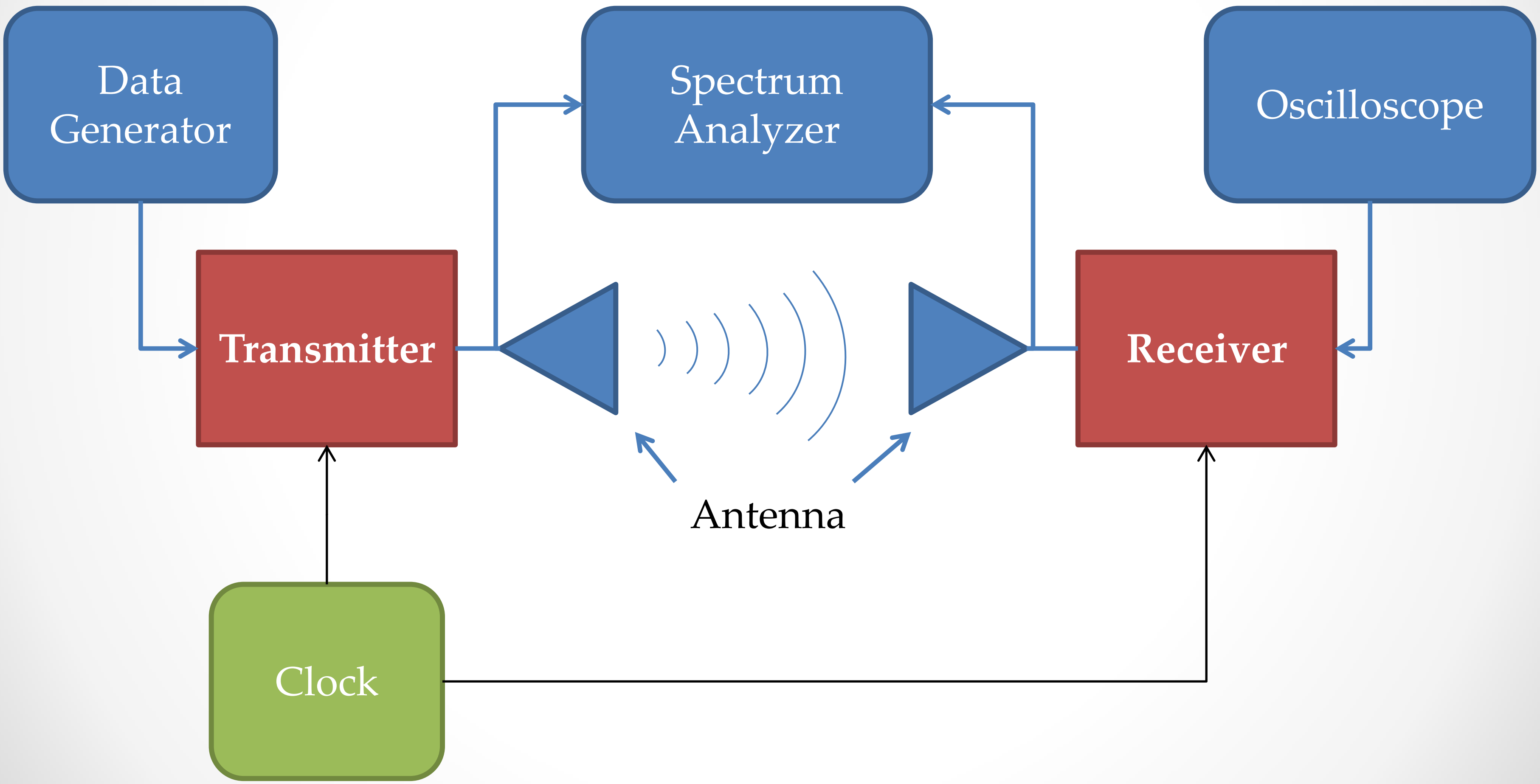
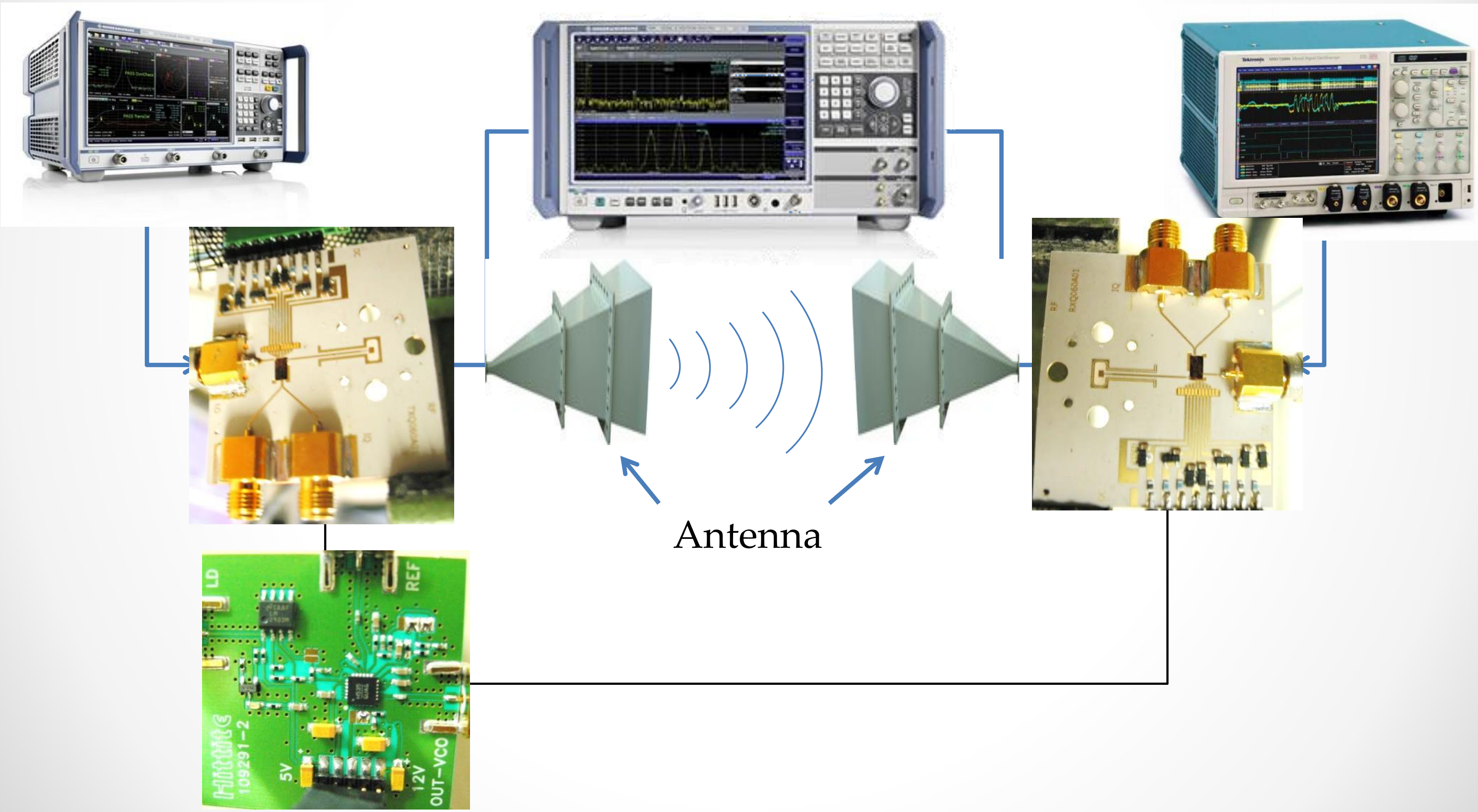


Receiver

Demonstrator 1/4

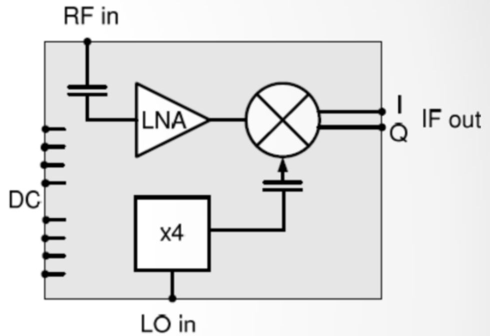


Demonstrator 2/4



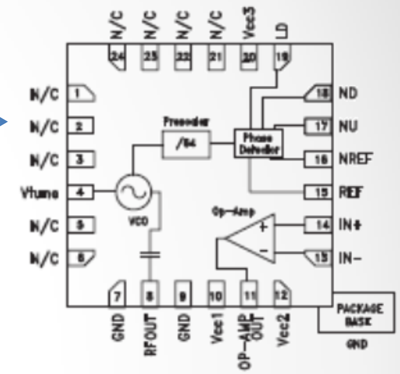
Demonstrator 3/4

- Demonstrator 60 GHz transmission setup
- Off the shelf components
  - Transmitter: Gotmic TXQ060A01
  - Receiver: Gotmic RXQ060A01
  - Hittite phase-locked oscillator
- Power distribution boxes
  - Many different voltages needed
  - Bias currents need attention
- 68 GHz spectrum analyzer



Demonstrator 4/4

- Reference clock system test (HD)
  - ASIC for 15 GHz reference clock generation
  - Signal quality promising
- Transmission test (Heinrich Hertz Institute):
  - Transmitter
    - Low gain
    - Broken mixer
  - Receiver
    - Operation at 1.7 Gbit/s (60 GHz carrier) achieved
    - I_{BIAS} fine tuning
    - External 15 GHz generator for higher sensitivity
    - External reference transmitter system used
    - Binary phase shift keying applied

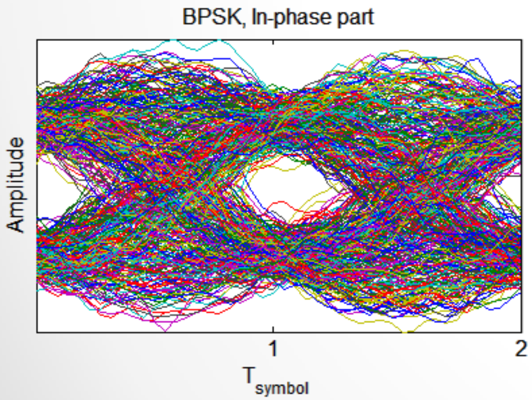


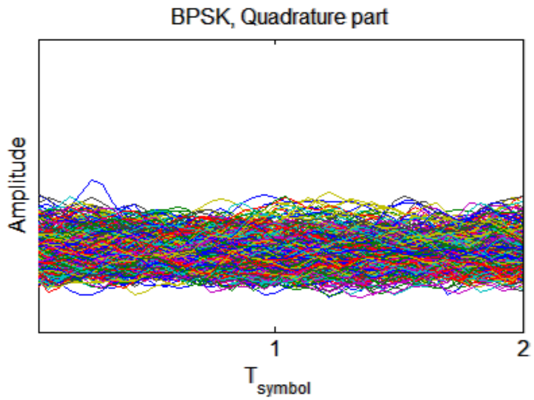
Fraunhofer
Heinrich Hertz Institute

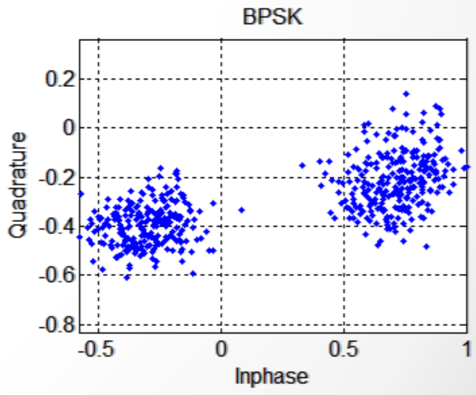
Data Transmission @ 60 GHz

- Data transmitted by modular reference system
- Data receiver in one chip (Gotmic RXQ060A01)
- 1.7 Gbit/s achieved
- Over 2 meters
- Signal quality can be improved …

Fraunhofer Heinrich Hertz Institute

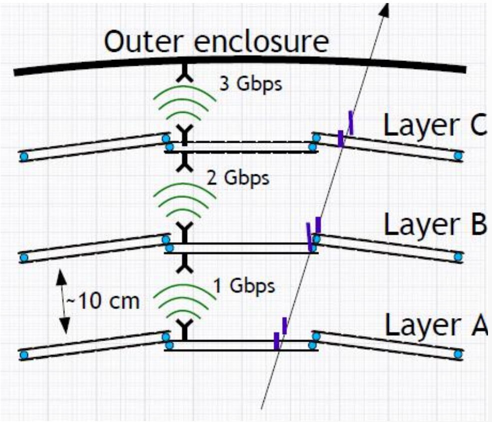






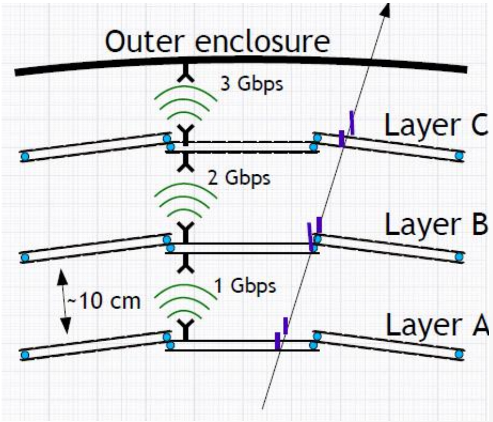
Summary

- The 60 GHz band interesting for Trigger-Tracker at LHC
- mm-wave systems on silicon substrate challenging
    - SiGe HBT technology chosen
    - ASIC design started
- 60 GHz demonstrator reference for future ASIC development
    - 1.7 Gbit/s achieved over 2m



Outlook

- Simulation of multi antenna system in detector environment with ray tracing
- Reference system with full 5 Gbit/s
- Design of full wire less transmission system on chip
- 3D-chip integration

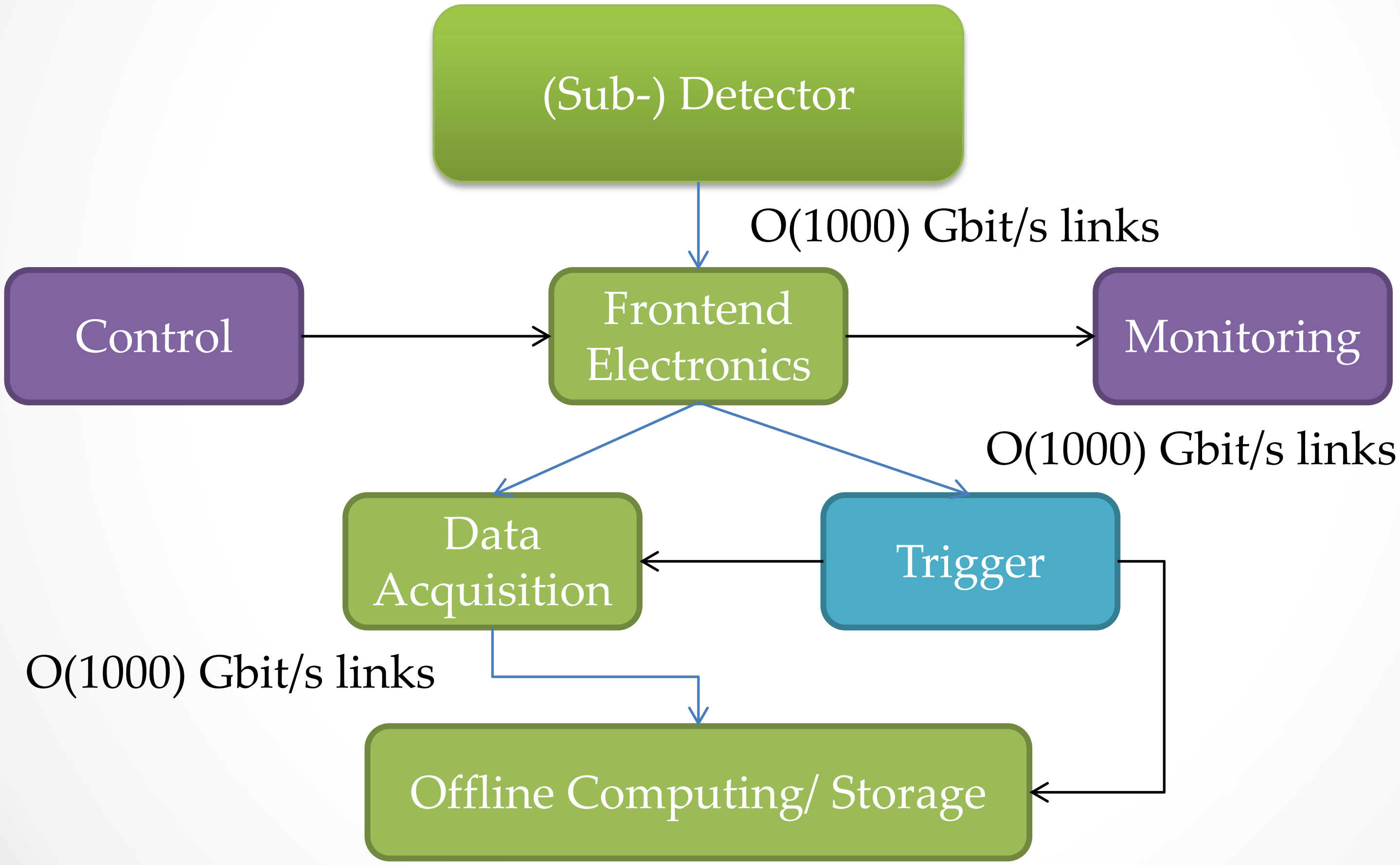


Backup Slides

Data Links in High Energy Physics

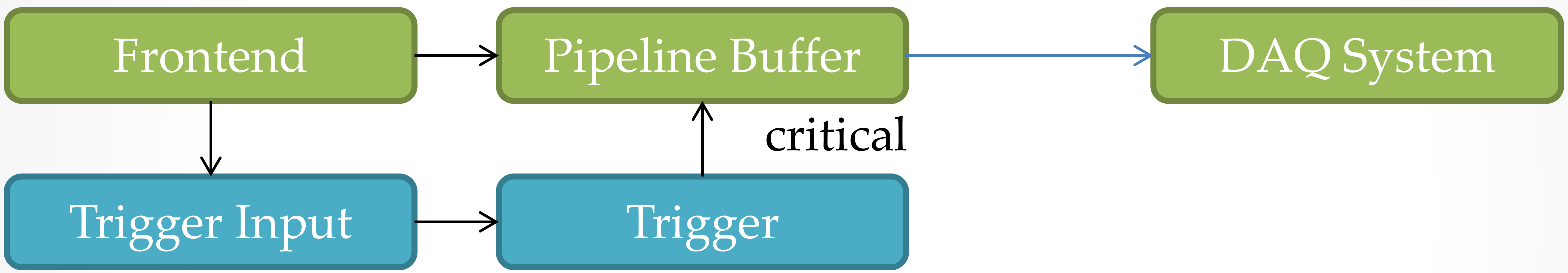
- Specialized solution at technology frontier in "difficult" environments
  - High bandwidth
  - Small form factors / low mass
  - Radiation tolerance
  - Specific solutions
  - Prototypes

Detector Readout Model

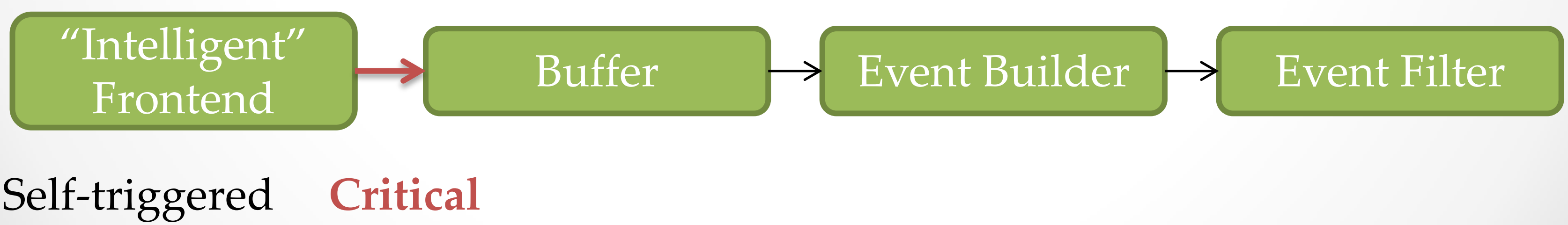


Readout/Trigger Concepts

- "Traditional Solution"
  - Multi trigger level system with pipelined front end buffers



- "Modern concept"
  - Self-triggered frontends with event buffers for event building

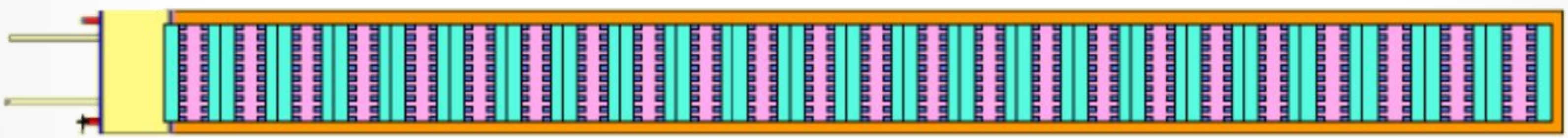


The “First Meter” Bottleneck

Example:
Upgrade ATLAS Barrel Strip Detector as first level trigger

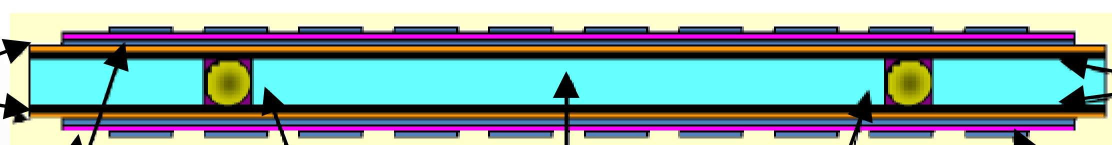
Stave Design

P-type sensors / n-side readout 160 MB/s per controller (12)



Bottleneck

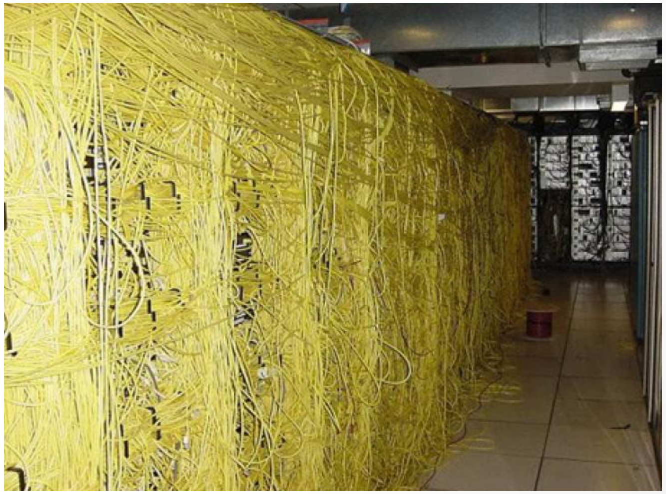
≈1.2 meter



Today's High Speed Interconnects

- Optical

- …or copper

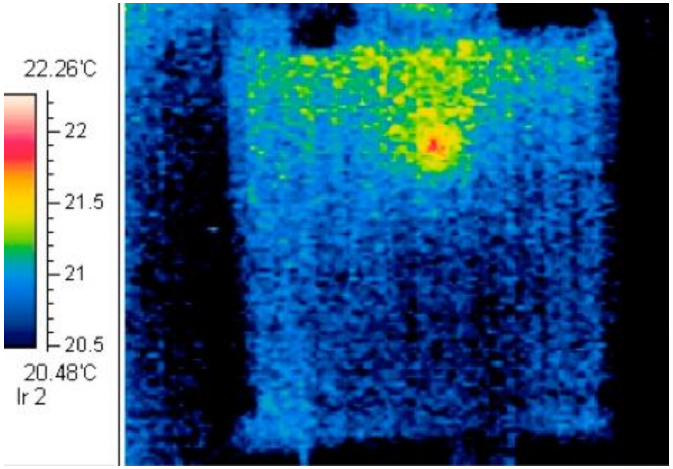


Today's High Speed Interconnects

- Km range optical
  - Between data centers and CERN
  - From experiments to CERN data center
- 100 m range optical (copper exceptions)
  - From front end electronics to counting house
  - Between counting house levels (rack rows)
- 1 m to 10 m range copper (optical exceptions)
  - Rack to rack
  - Front end boards to repeaters on detector
- cm range copper
  - Board to board
  - Detector to board

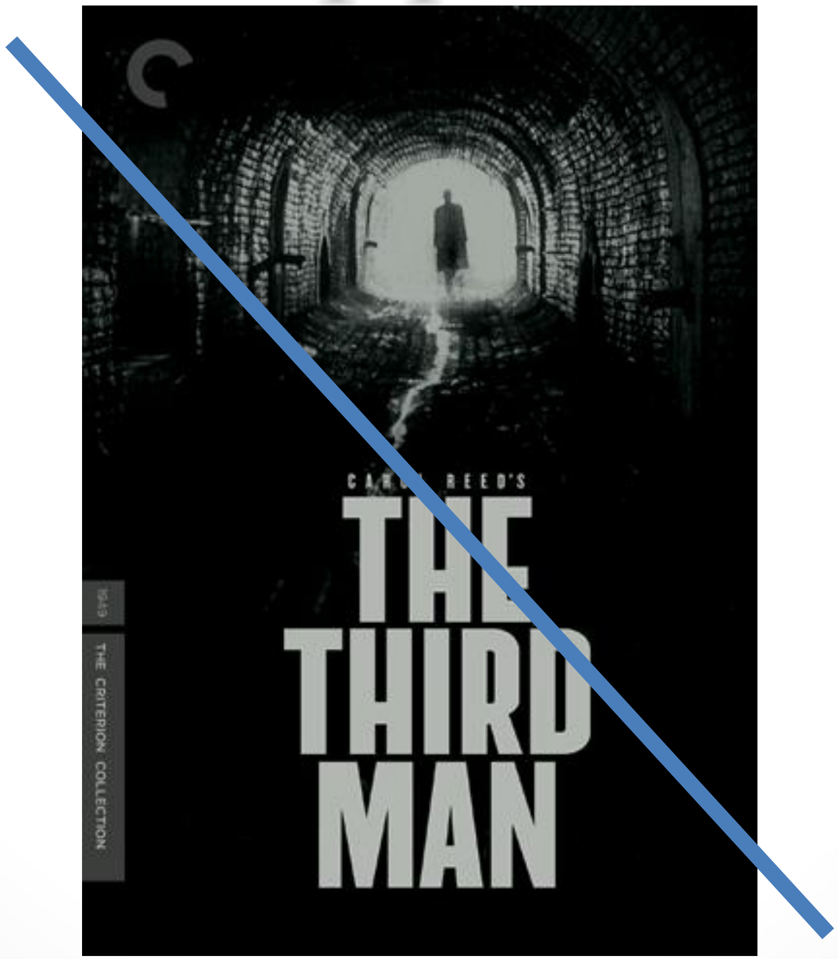
Critical Parameters

- The front end readout rate can be characterized by 3 numbers
  - Gbps / cm^2
  - Gbps / g
  - Gbps / W



- New technologies will push these numbers up!

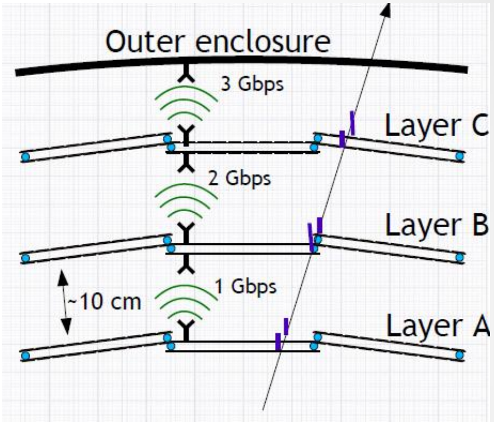
New Approaches



New Approaches

ASIC for 60 GHz Wireless

- Wireless data transfer …
- … between silicon sensor layers
- 60 GHz carrier frequency
- O(5)Gb/s per link
- O(1000) links
- Full system on chip approach
  - No external RF components required
  - Little material
  - Little power/cooling
- Radiation hard design



Why ON-Chip Antennas?

- Millimeter-Wave wavelengths at 60 GHz (5mm)
  - Possible to integrate receive and transmit antenna(s) on-chip
  - High directivity is desired to improve
    - S/N-ratio
    - reduce power consumption
    - reduce inter-use interference
  - SiGe process (HBT)
    - High dielectric constant in Silicon (11.7)
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    - Can be used to fabricate mm-wave antennas
  - Eliminate cable/connectors loss
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  - Save PCB real estate
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Low Noise Amplifier Issues

- Power dissipation
- Noise Figure
- Linearity
- Stability
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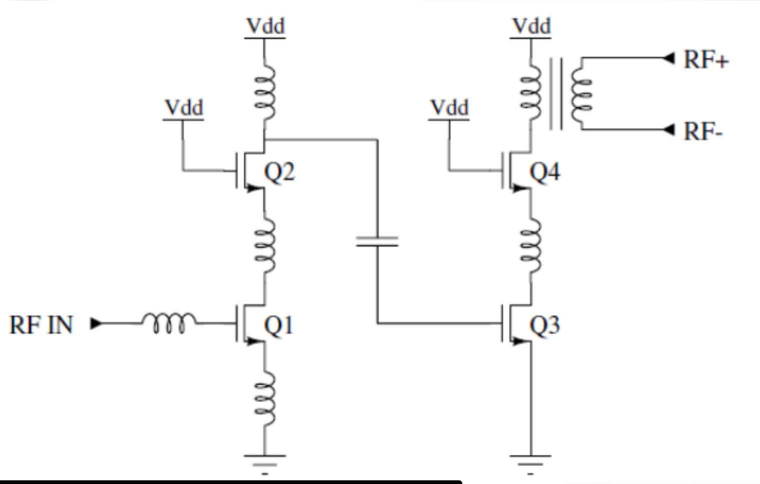
- Bandwidth
- Insensitive to process variation



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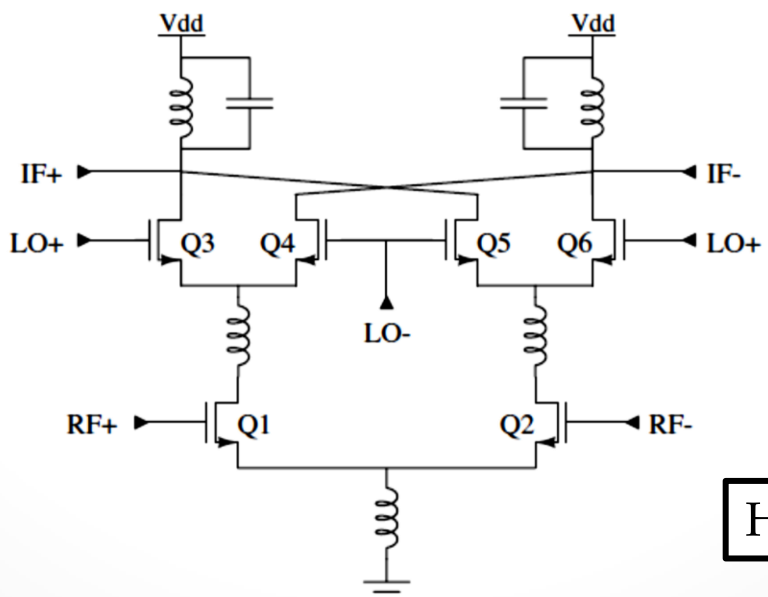
Three Fundamental differences compared to the lower frequency colleague:

1. Transistors operate much closer to their cut-off frequency
2. Parasitic elements represent a much larger portion of the total impedance
3. Signals with small wavelengths results in distributed effects within the circuit

Mixer Issues

- Double-balanced Gilbert cell for LO-RF leakage
- Design strategy: minimize noise, maximize linearity
- CM inductor for noise and headroom
- Middle inductors increase gain and reduce noise



Hans Kristian Soltveit

Power Amplifier Issues

- Multi-stage amplifiers
  - Initial stages are optimized for gain
  - Last stage for maximum output power
- Technology
  - Supply voltage
  - Substrate
  - Breakdown voltage
  - F_t
  - Thermal conductivity

Why 3D Stacking ?

- Reducing cost:
  - 3-D integration cheaper than shrinking 2-D design
  - Moving passives onto interposer
- Reduce the size of the overall chip
- Boost the speed between functional blocks
- Uses Through-Silicon Vias (TSV)
  - Vertical connection etched through the silicon wafer
  - Filled with metal
  - No wires between the chips
- Shortens the distance on a chip by 1000 times compared to a 2-D chip wire bonds

Further Applications

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Quantum Optics

- Quantum optics has flourished over the last decades
- RF requirements similar to ours
- Multi GHz technology can be used for Rydberg atom stimulation

Plasma Wake Field Acceleration

- Plasma wake field acceleration has been demonstrated
  - Unprecedented acceleration gradients feasible
  - LHC might become driving beam for PWA
- Micro-bunching important for PWA
  - Micro-bunches must be controlled
    - Stimulation
    - Characterization
  - Frequencies lie in the GHz range
  - Radiation hardness requirements and number of RF units similar to HEP detectors

Citation(s)

1) Valdes-Garcia, A.; Reynolds, S.; Natarajan, A.; Dong Kam; Duixian Liu; Jie-Wei Lai; Huang, Y.-L.O.; Ping-Yu Chen; Ming-Da Tsai; Zhan, J.-H.C.; Nicolson, S.; Floyd, B.; , "Single-element and phased-array transceiver chipsets for 60-ghz Gb/s communications," *Communications Magazine, IEEE* , vol.49, no.4, pp.120-131, April 2011 doi: 10.1109/MCOM.2011.5741156 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5741156&isnumber=5741133

2) Sun, M., & Zhang, Y. P. (2008). Design and integration of 60-GHz grid array antenna in chip package. In proceedings of the Asia Pacific Microwave Conference: Hong Kong, China, (pp.1-4).

Disclaimer

Most slides are based on material shown by André Schöning and Hans Kristian Soltveit during the

1st Detector Readout Link Topical Workshop of the Helmholtz Alliance