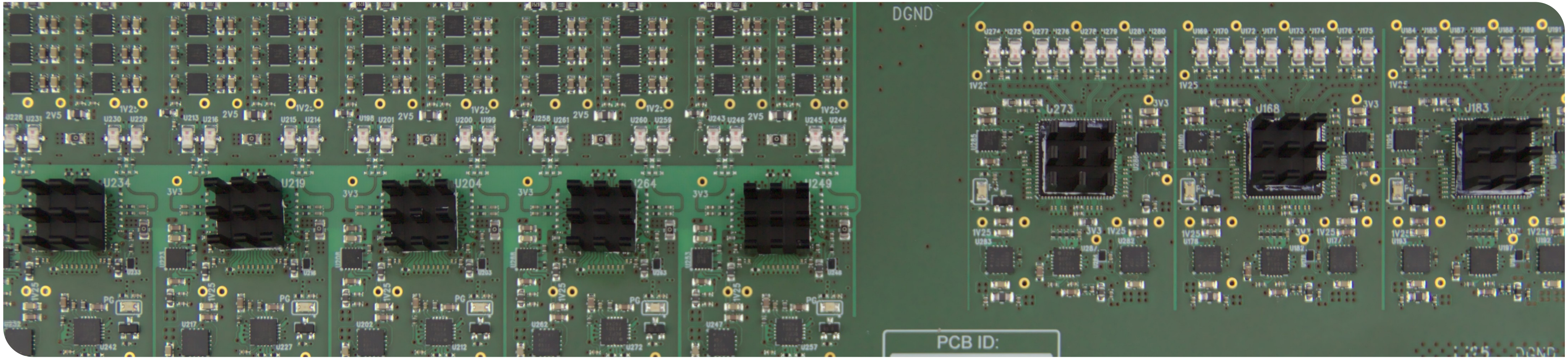
Karlsruhe Institute of Technology

Radio Frequency Electronics for Scalable Superconducting Quantum Circuit Interfacing

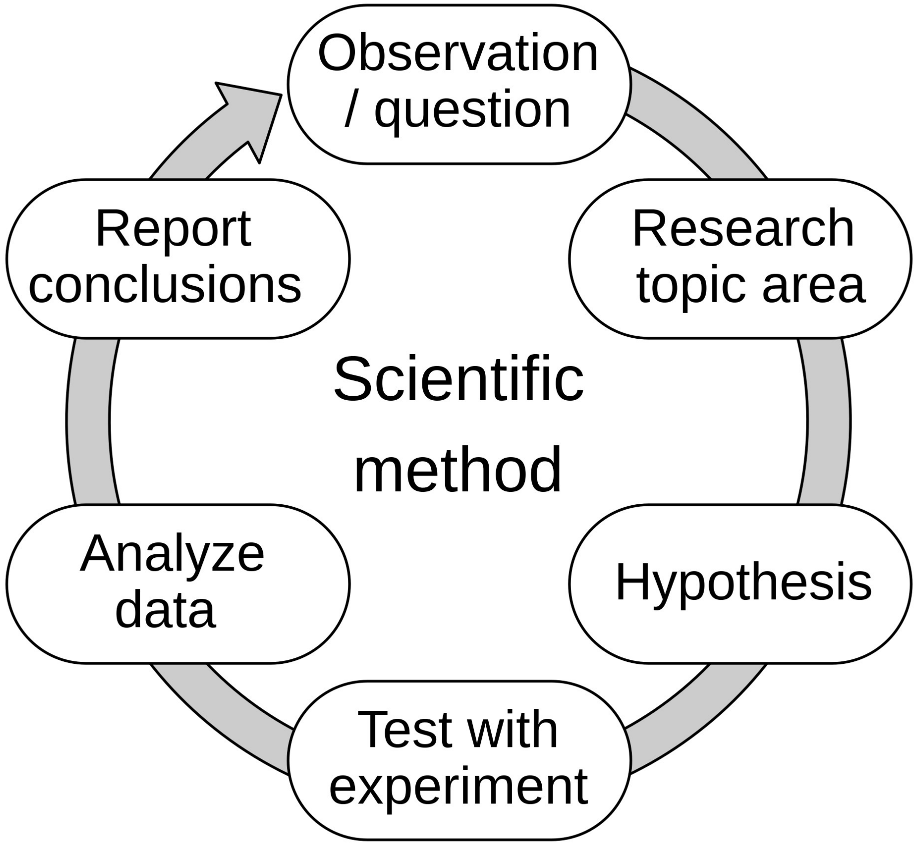
Robert Gartmann

Institute for Data Processing and Electronics



How to: Science

- Vaguely two fields:
  Theory & Experiment
- Back and forth => discovery
- Model building: Math, Statistics, ...
- Recently more simulations



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Experimentalists Need Sensors

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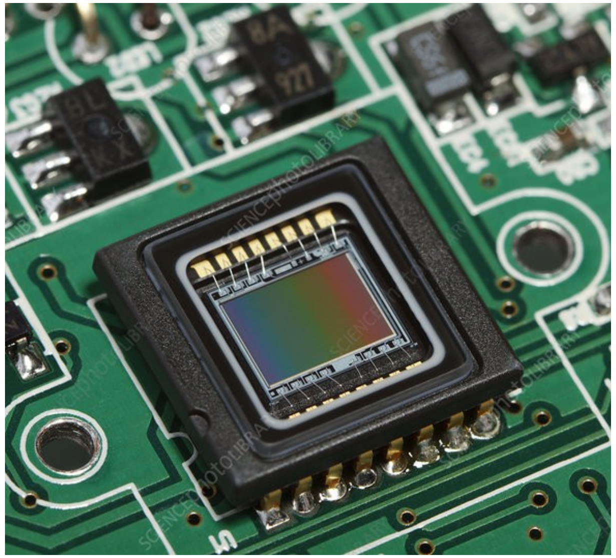
- Measurements continuously evolve
- Energy frontiers shifted
- Statistics increasingly important
- Rate, resolution, dead time, noise, …
- What would the ideal sensor be?



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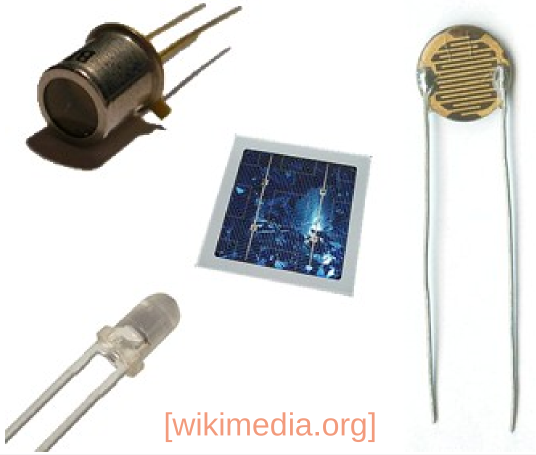

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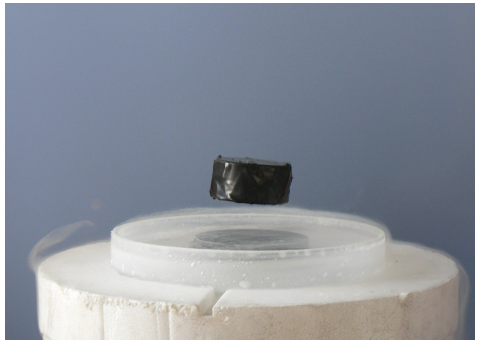
Croygenic Sensing

- Inherently low noise & loss
- Inherently tricky to interface
- Nudge system => build sensor

  TES, KID, SQUID, …
- Macroscopic quantum phenomena
- Josephson junction: nonlinear inductance
- Commonality: build resonator
- Multiplexing possible



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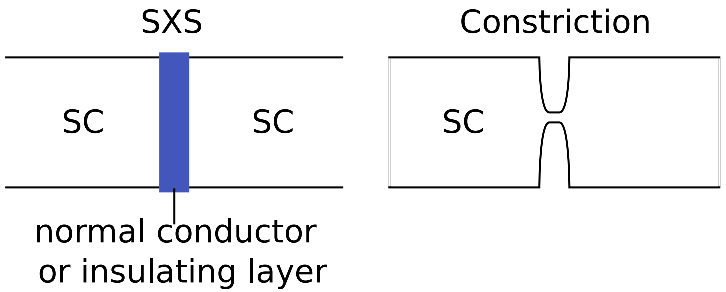

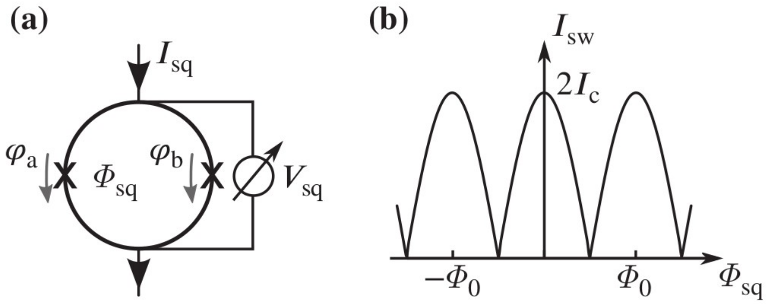

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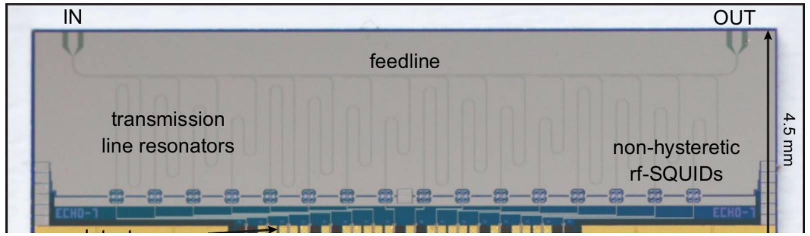
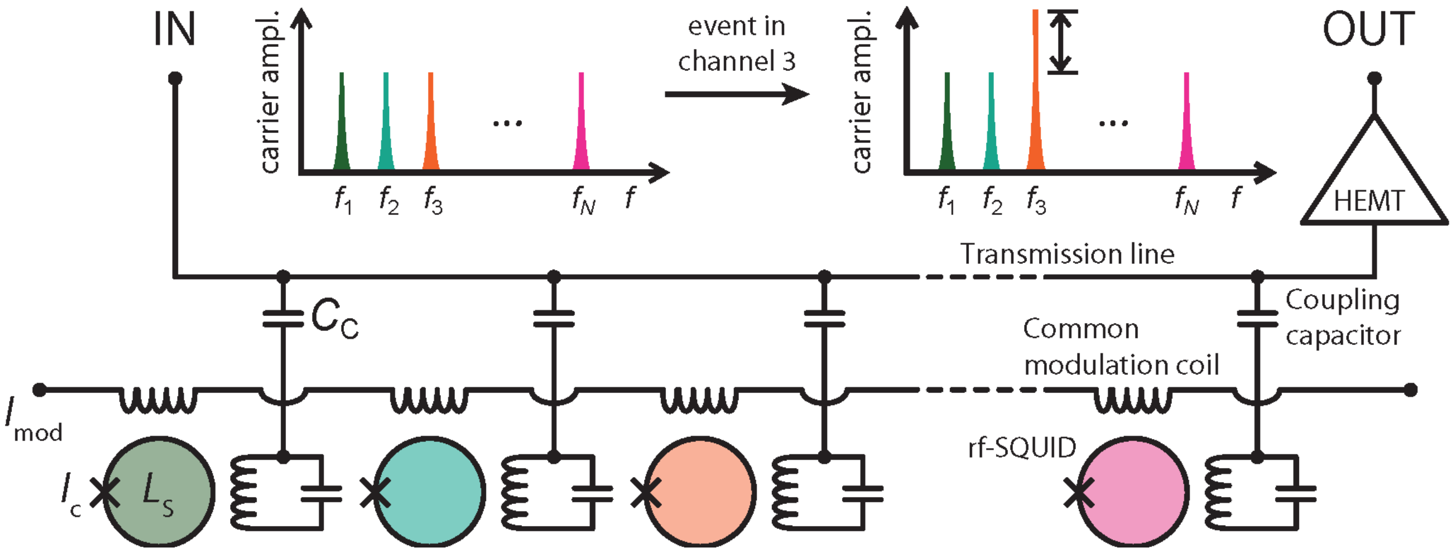
Solution: Flexible Signal Platform

- One-size fits-all possible?
- Different sensors, but common readout
- Demodulation?
- Number of sensors?
- How to tailor to experiment?





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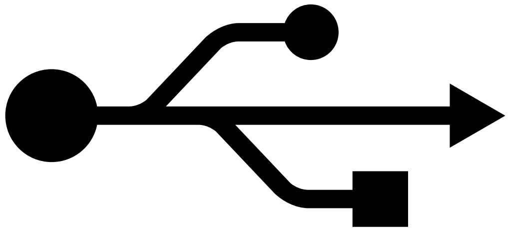

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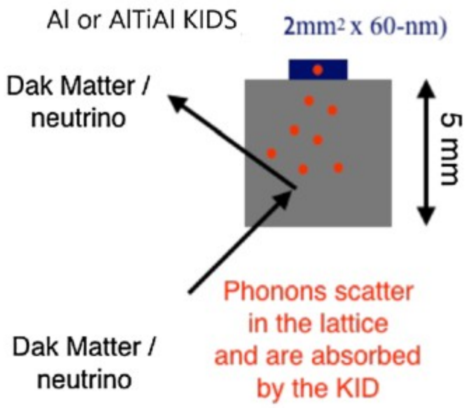
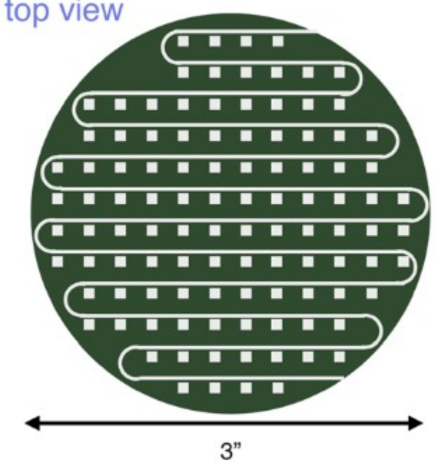
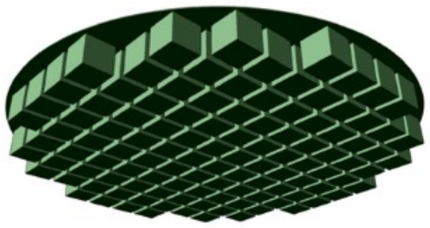
BULLKID

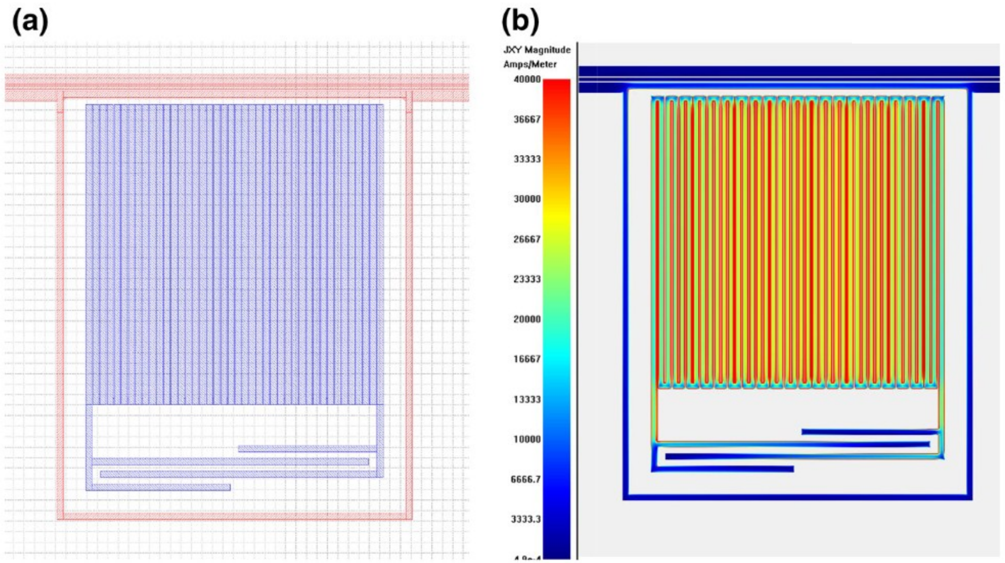
- Dark matter search
- Phonon based detection
- KID on silicon wafer
- Low activity environment

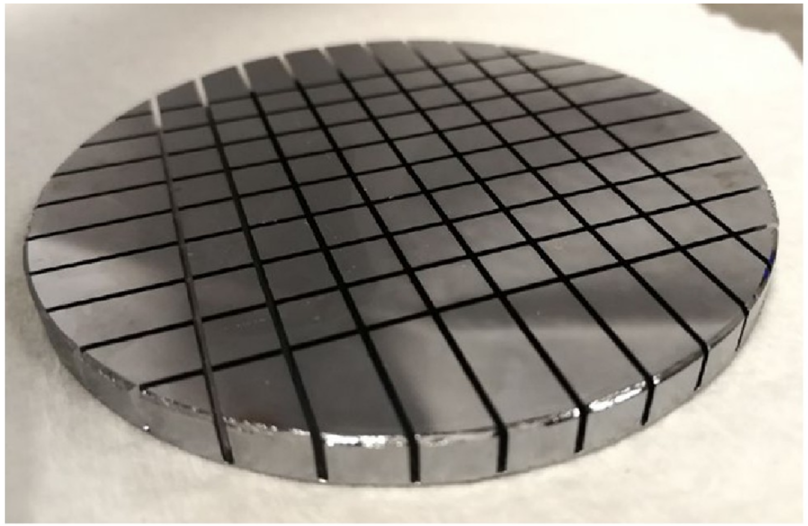






- Around 108 cubic voxels of 5x5x5 mm³ exploited.
- 0.29 g / voxel
- 31 g total target mass.





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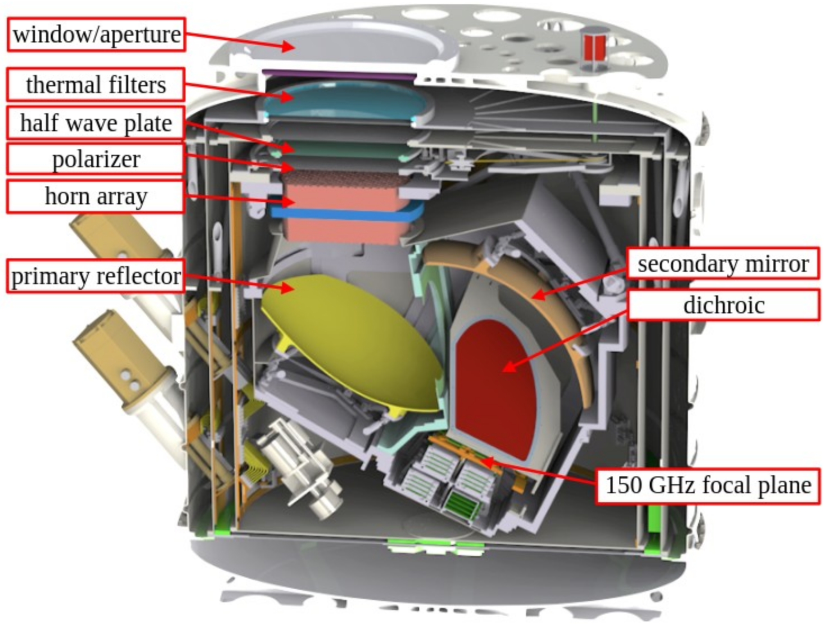
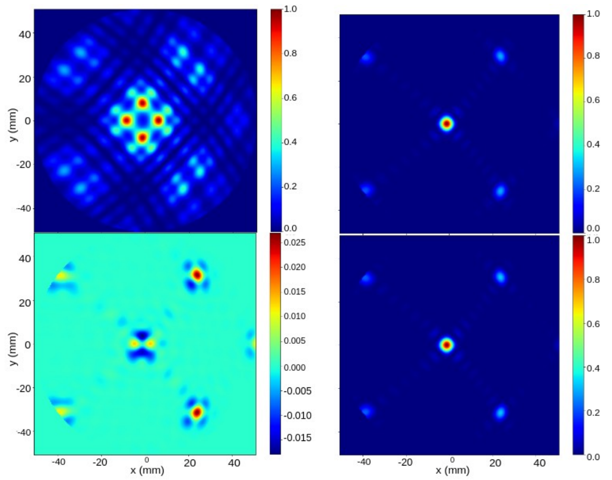
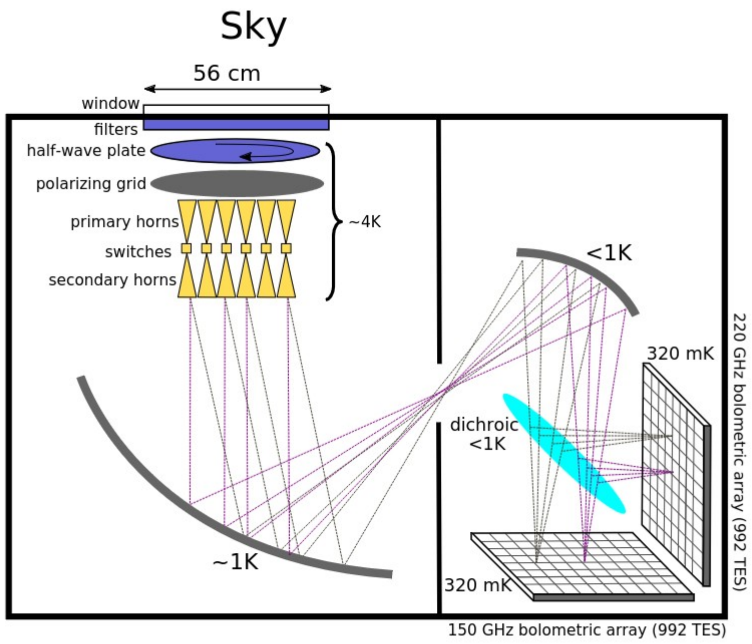
QUBIC

- Cosmic microwave background analysis
- B-mode polarisation MMB based telescope







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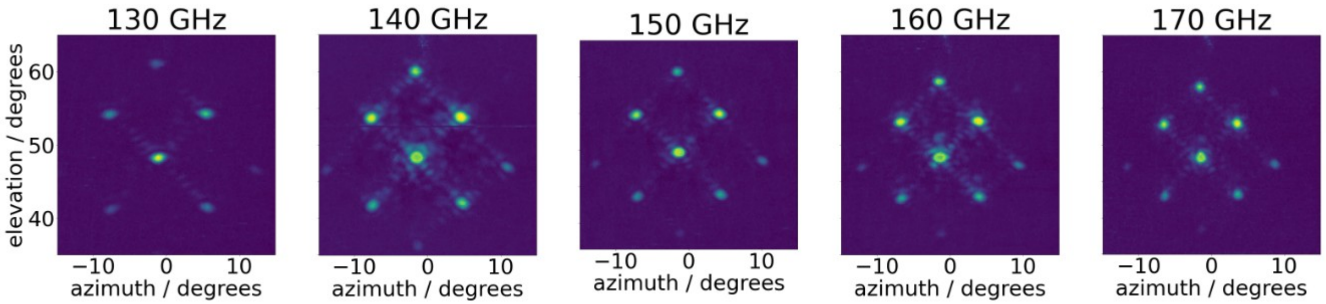
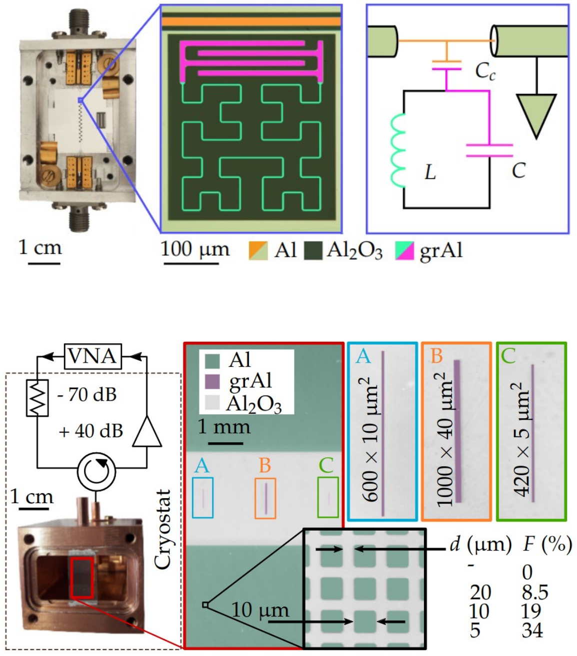
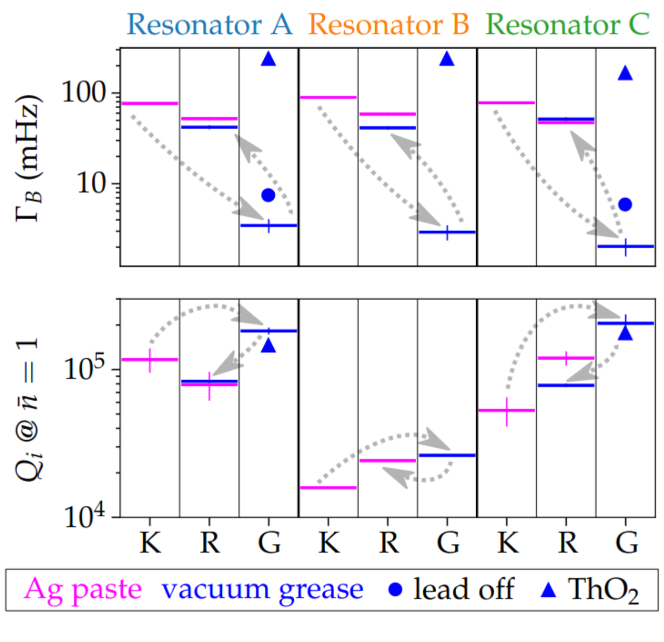
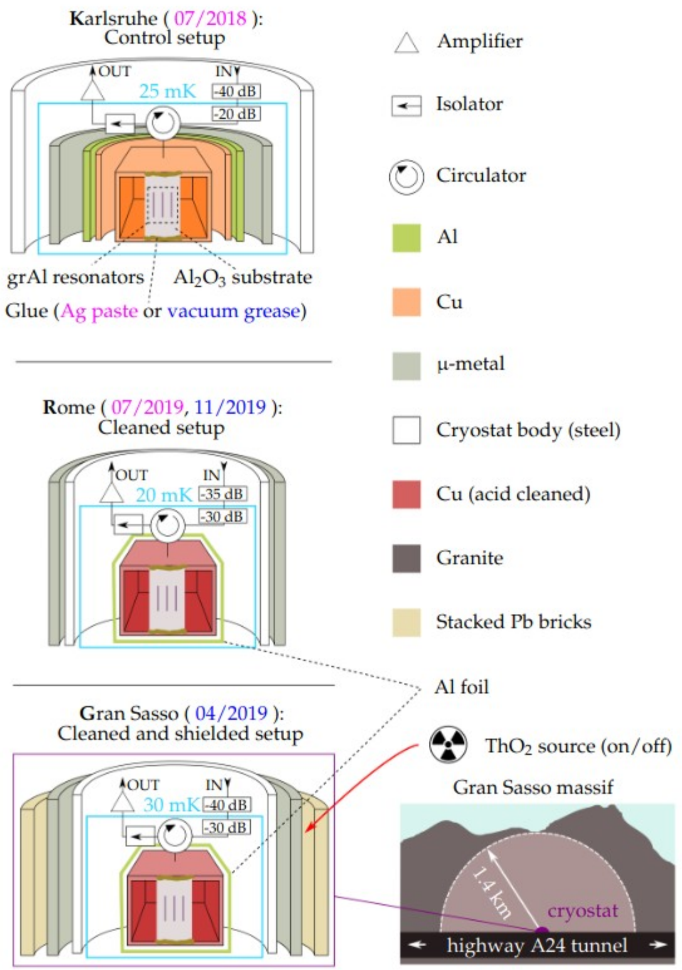


Ambient Radioactivity Monitoring

- Quasiparticle bursts from absorption
- High energy event upsets resonator
- Triangulate position







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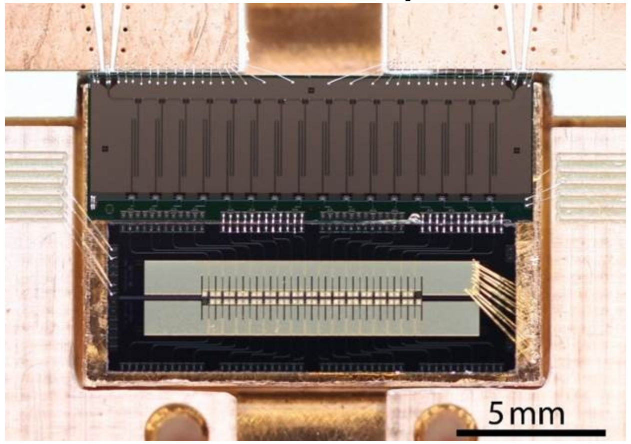
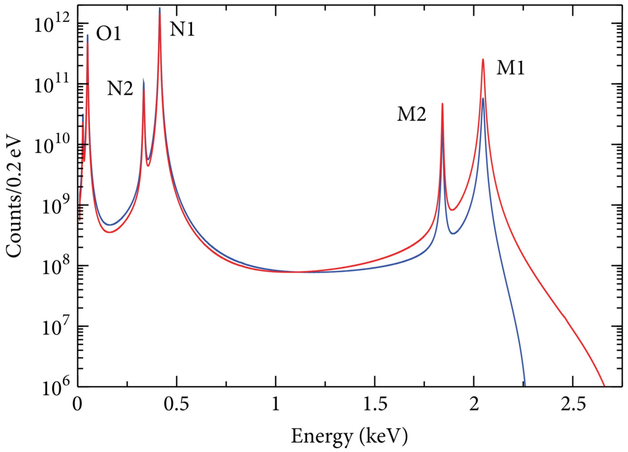
Electron Capture in ^{163}Holmium: ECHo

- Electron Capture in ^{163}Holmium
  (L. Gastaldo et al., EJP (2017))
- Sensors: magnetic microcalorimeters
- Neutrino mass cutoff through decay spectrum
- 12.000 pixel parallel readout
  microwave SQUID multiplexing
- Goals of ECHo-100k: Measurement sensitivity of < 5eV
  Technology demonstrator

ECHo chip:

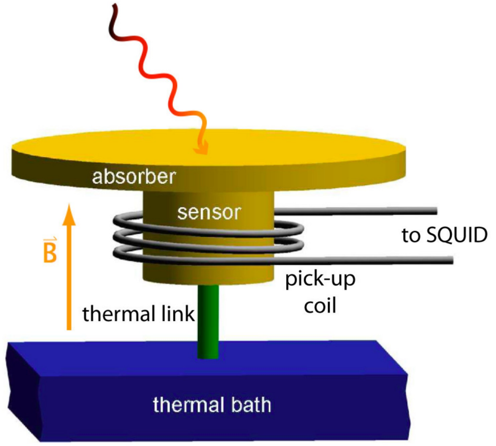


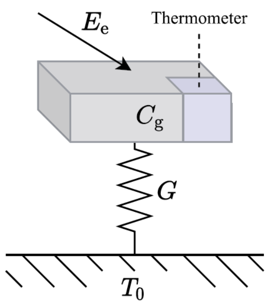
Ho^{163} spectrum:

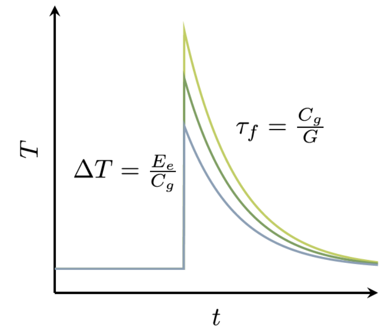


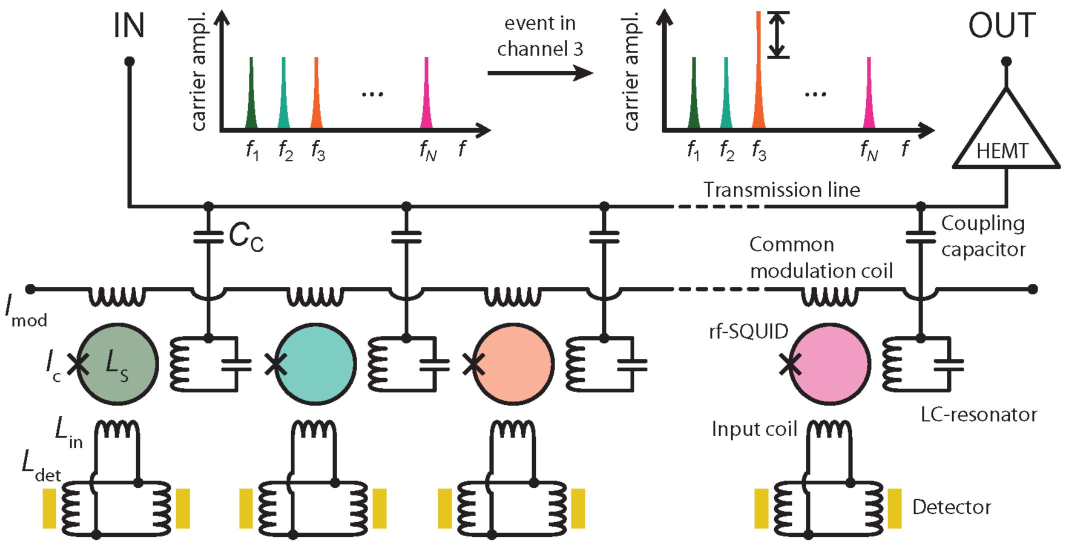
ECHo: Magnetic Microcalorimeters

- Detector pixel:
  Implanted absorber metal
  Paramagnetic doping in sensor
- Thermal capacity & weak link
  means step + decay
- Magnetometer = Thermometer
- Couple flux to coils & SQUIDs









Unified Readout

- Generic lab electronics can do the job
- Maximum flexibility through interconnects
- Inherent latency and limited throughput
- Decimation tricky

Bluefors | Tektronix | Anritsu, Marki, Mini Circuits | Spectrum | HP

Software Defined Radio

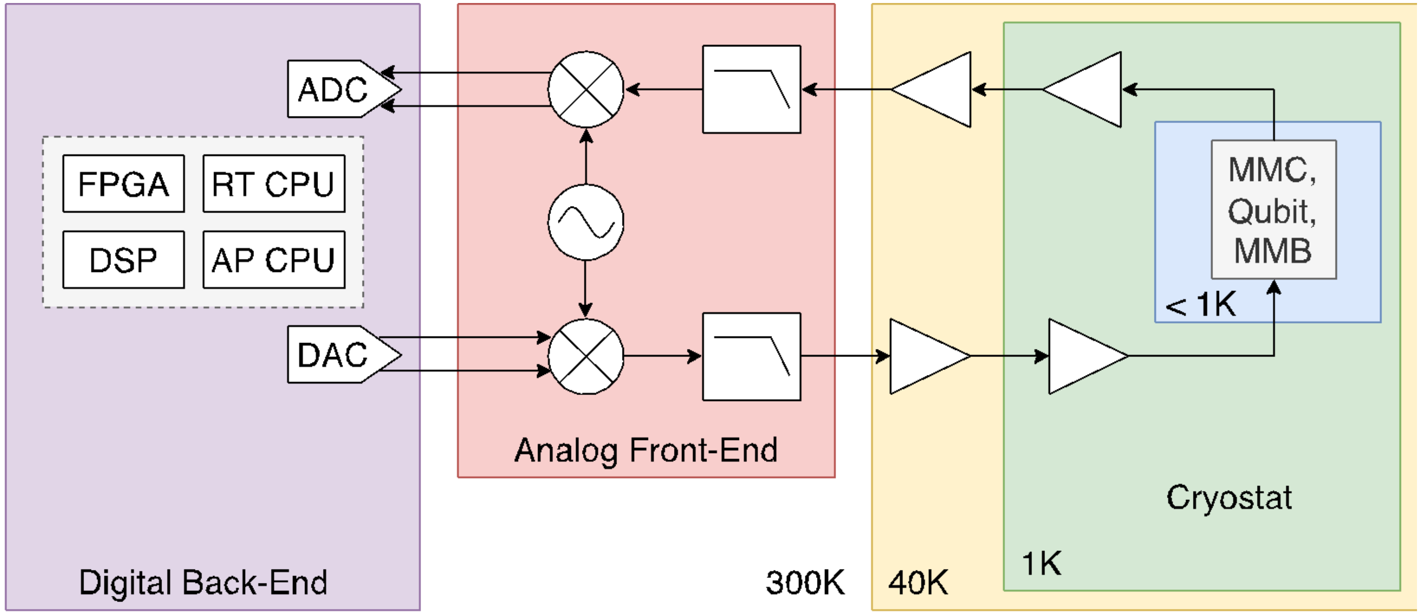
- Glorified sound card: play what you want
- Requires computing power

  Fast conversion to/from analogue
- Digital signal processing

  enables ideal transforms
- Parallel processing required

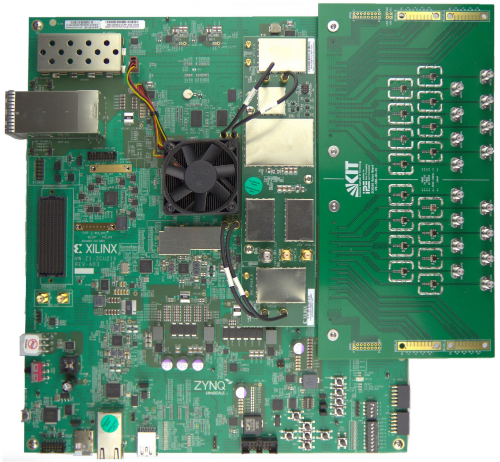
  potentially low latency

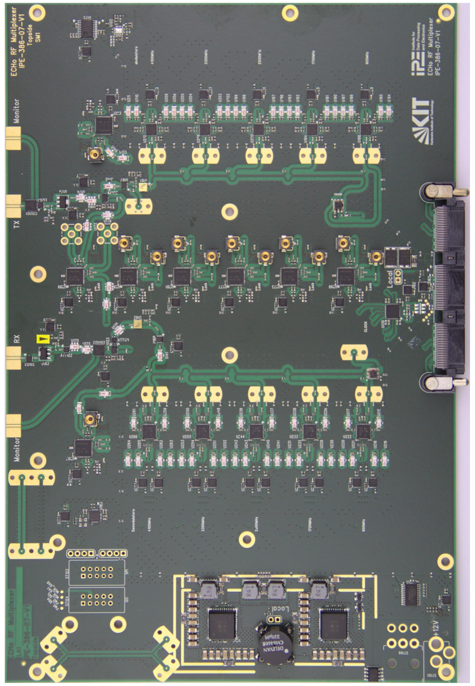
  => FPGA

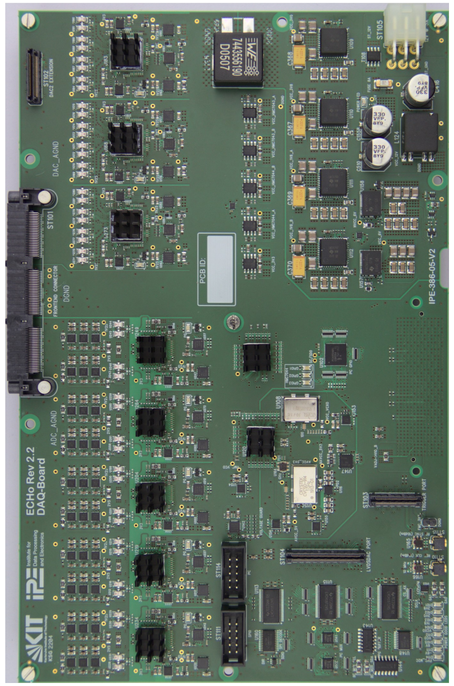


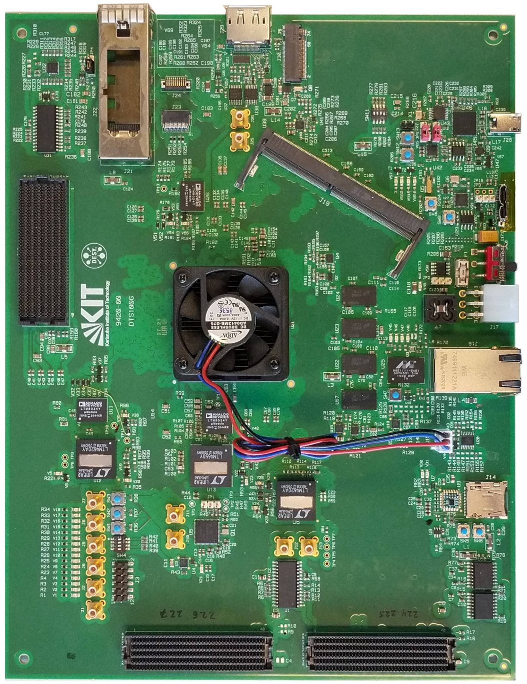
Physical Buildup

- Electrical engineering = printed circuit boards
- Custom and COTS
- Separate blocks (by function)

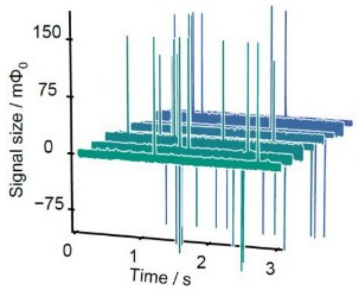




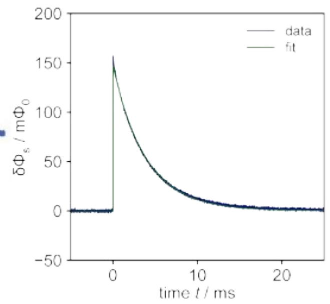




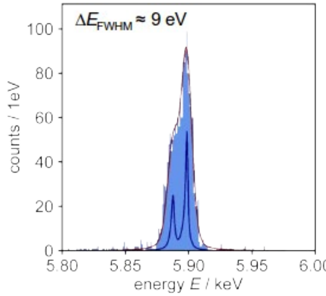
time traces of 16 detector pixels



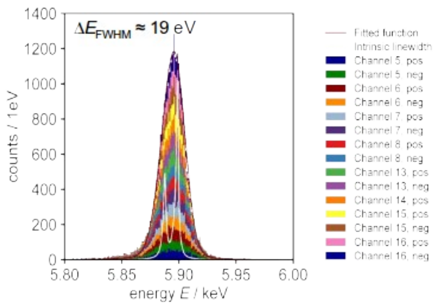
single raw data trace



'typical' spectrum

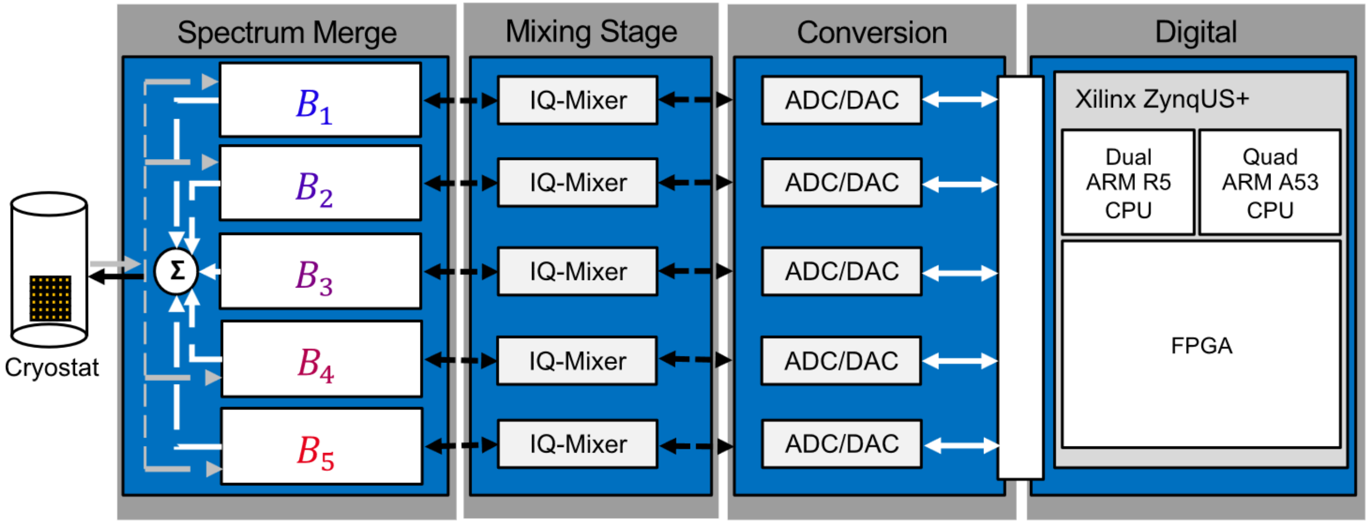


sum spectrum

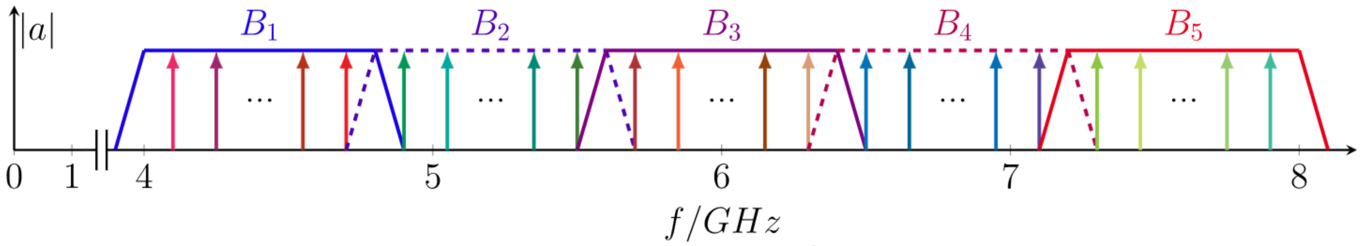


SDR Scaling

- Number of channels proportional to bandwidth
- Band =/= bandwidth
- How to increase?
  - Faster converters
  - Independent bands
  - Stitch frequencies together
  - Multiple concurrent systems

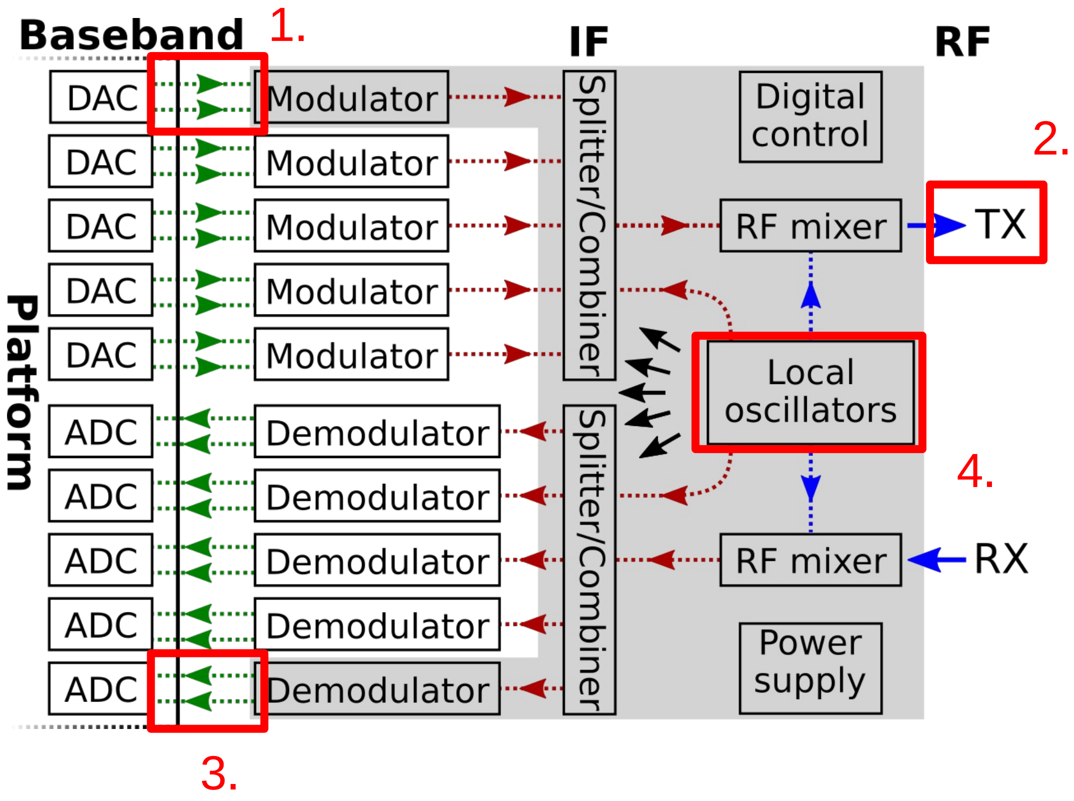


Software-defined Radio (SDR) system architecture



SDR Radio Frequency Conversion

- RF engineering:
  layout and wiring essential
  reduce size without crosstalk
- Frequency conversion
- Filtering and channelisation
- Level matching
- Key aspects: AM/PM noise, intermodulation, distortion, ...



Step 1: Ingest Signal

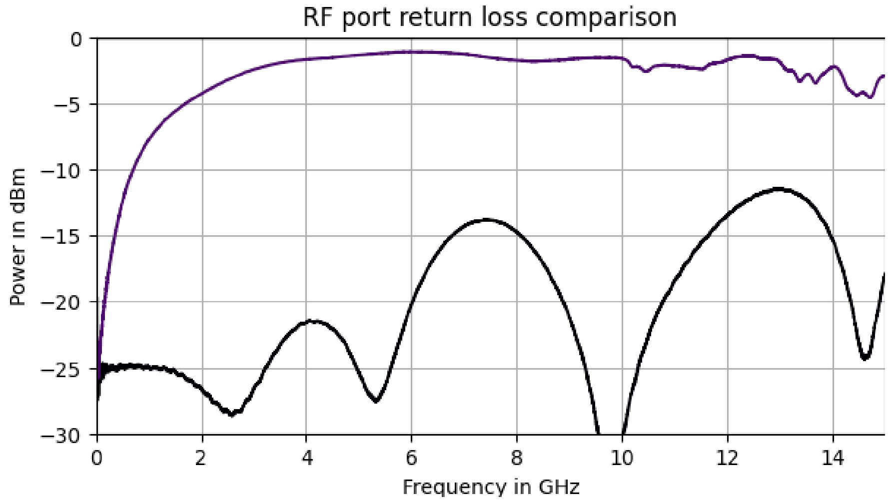
- GHz frequency ~ cm wavelength

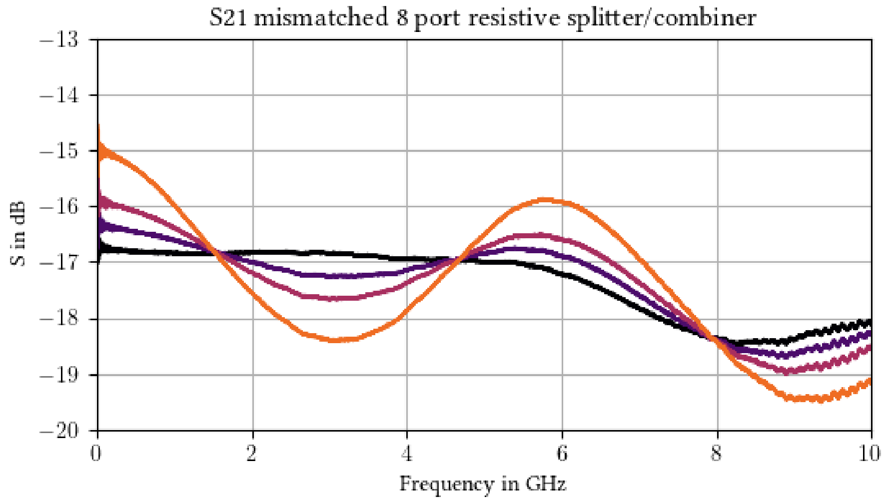
  lumped element approximation breaks
- Wave behaviour ensues

  nominal impedance imperative

  else reflections
- Controlled dimensions

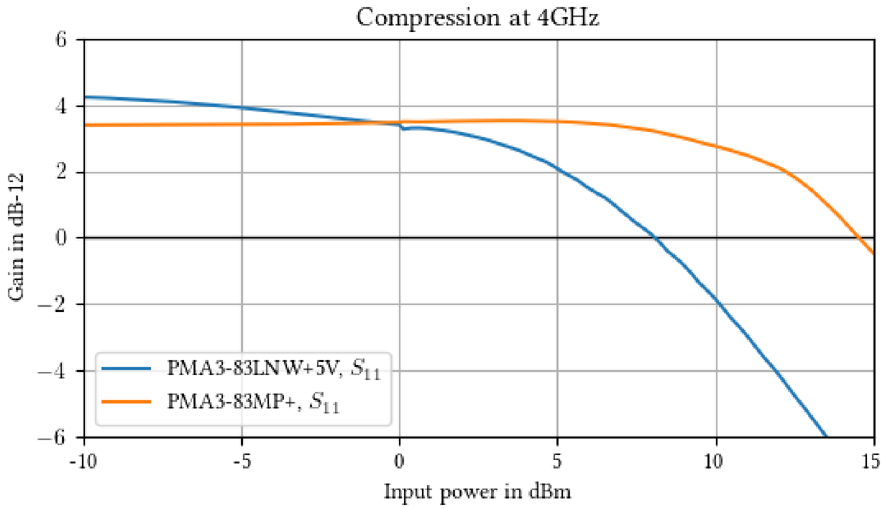
  trace width & angle dictated
- System dominated by parasitics!

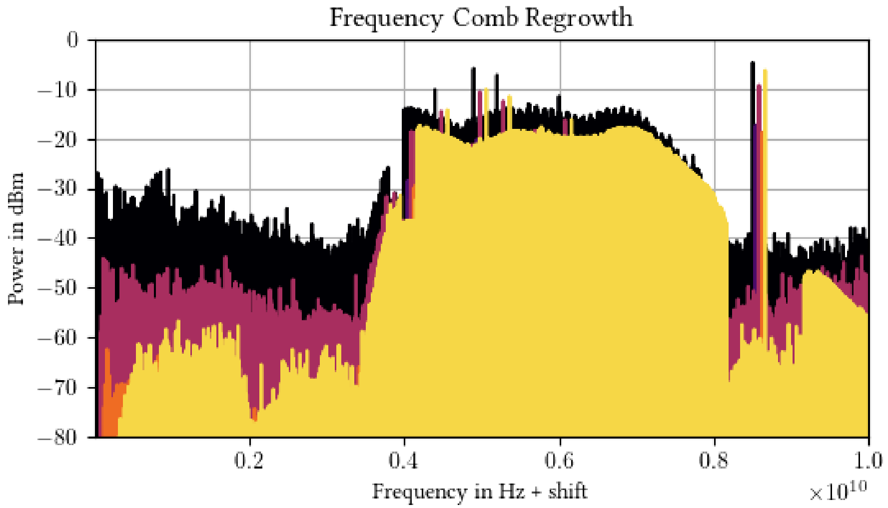




Step 2: Dispatch

- Gain = linear in-to-out relation
  breaks at some point
- Single digit spec misleading!
  “1dB compression point“
- Compression = distortion
  worst case: clipping
- Result: spectral regrowth



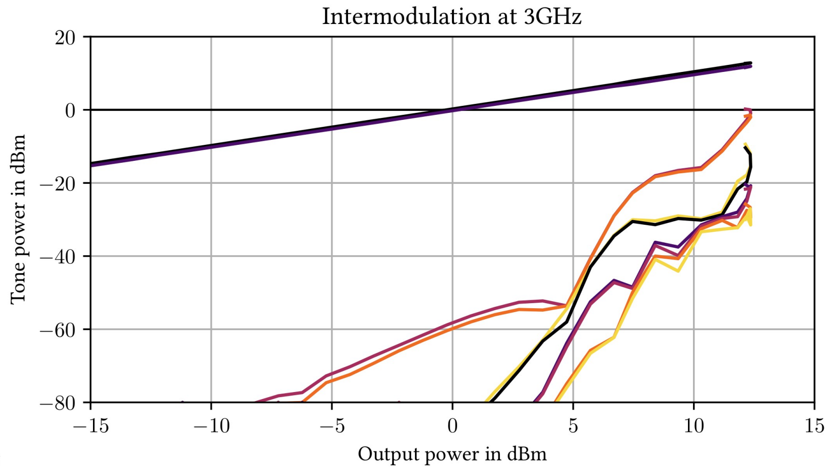


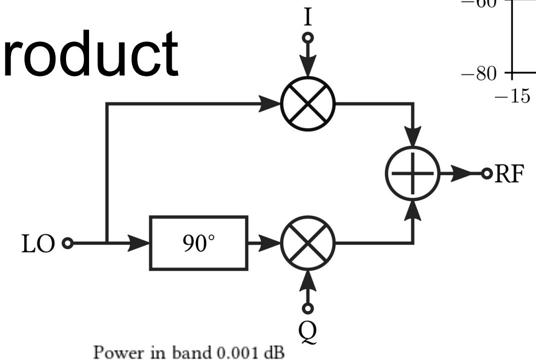
Step 3: Mixing

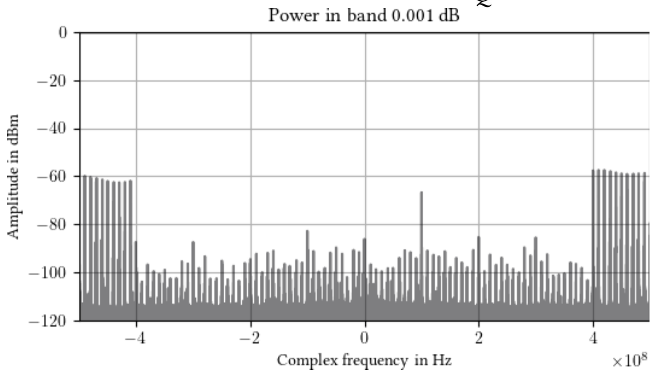
- Shift frequencies by deliberate nonlinearity
  - simple geometric relations

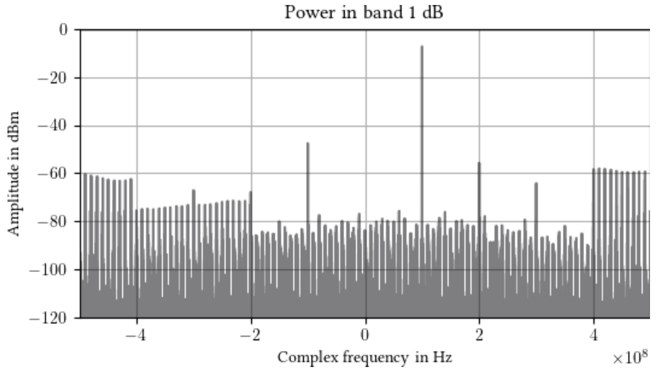
  $$\cos(\omega_1) * \cos(\omega_2) \sim \cos(\omega_1 + \omega_2) + \cos(\omega_1 - \omega_2)$$

- Complex signal eliminates second product
  - two voltages as real + image
- IQ-imbalance
- Precise power planning



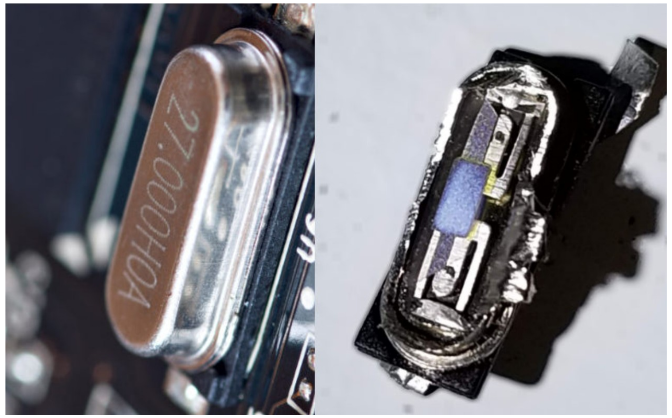






Step 4: Reference

- GHz reference frequencies necessary
  no fundamental precision oscillator
- Multiply by dividing: phase locked loop
- Stability essential: phase noise/jitter



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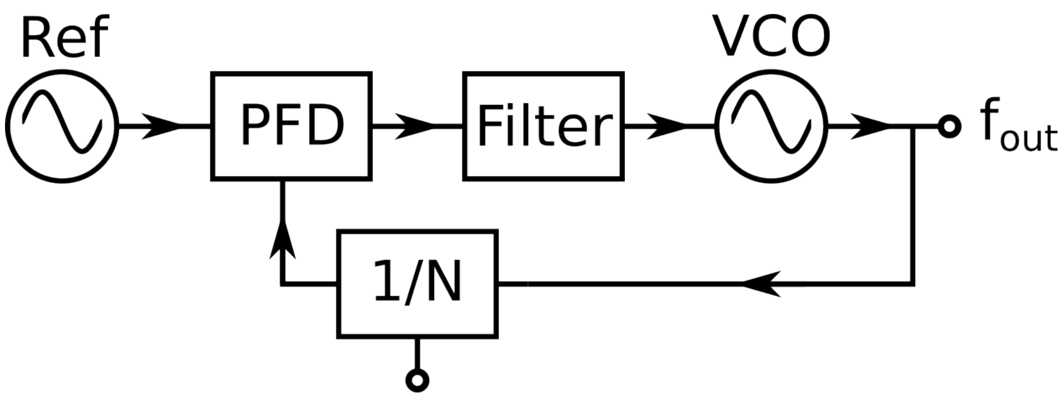
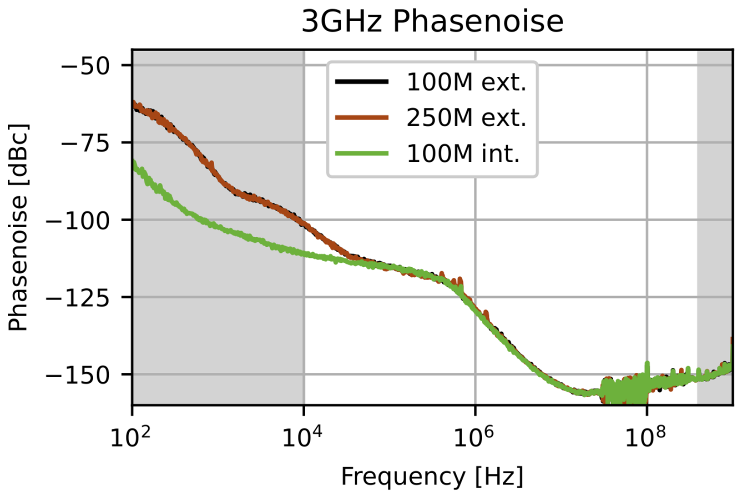




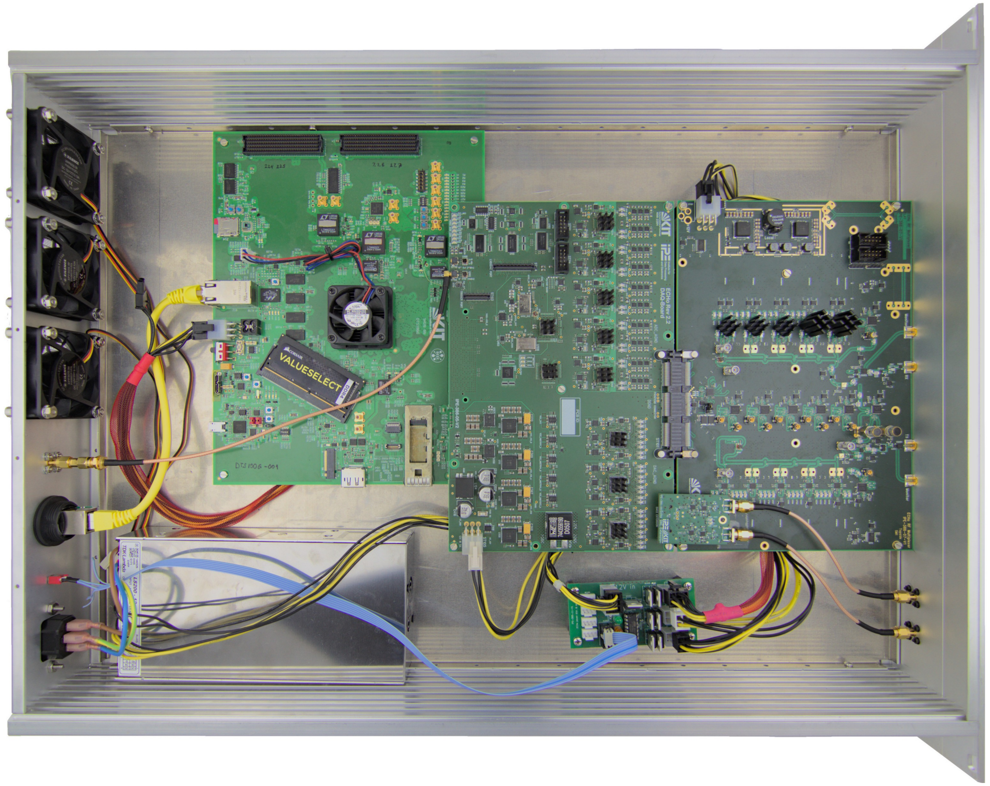
ECHo Deployment Incoming

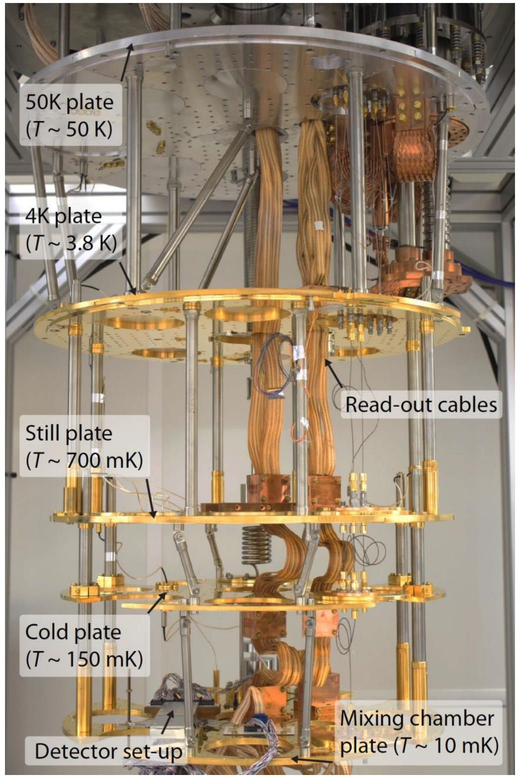
Current status:

- Ready for operation; fully contained in 19” box!
- Noise level below cryogenics
- Preliminary accuracy: 6.28 eV @ 3.31 keV

Outlook:

- 15x Assembly by 7/2024
- Full-scale FPGA-board
- In-house measurements





Future Developments

- Successful development & deployment
- Many users and parties of interest
- Path for longterm evolution
- Synergy of RF developments

Backup

ECHo Hardware Versions

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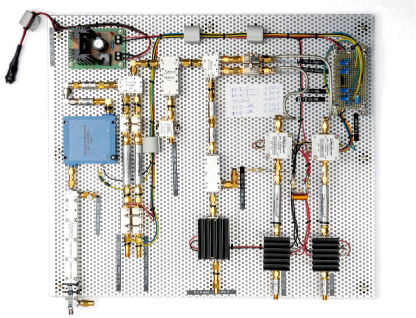
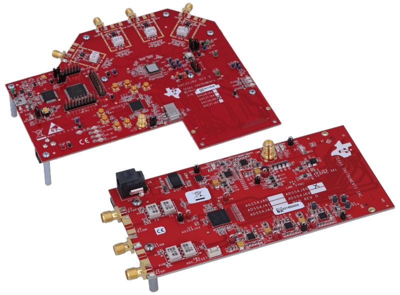
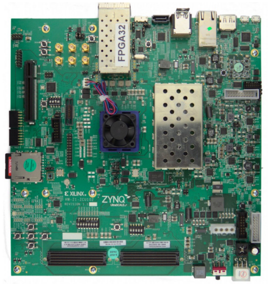
<u>Evaluation (V0)</u>:
2018 (2019)

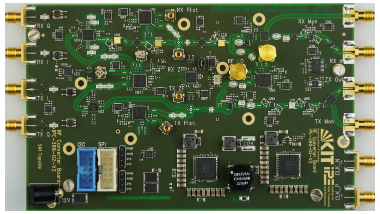


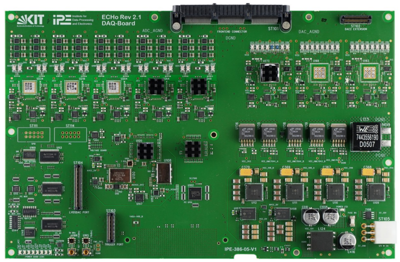


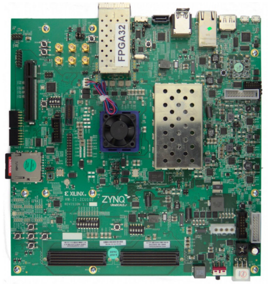


80 Resonator
800 MHz

<u>Prototype (V1)</u>:
2020 (2021)

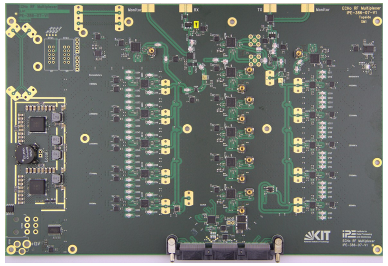


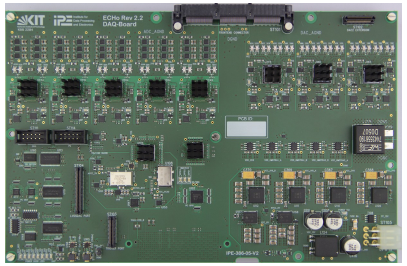


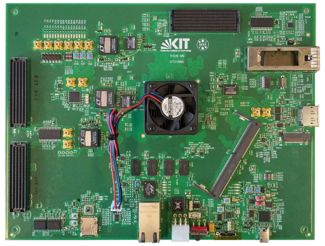


80 Resonator
800 MHz

<u>Full Scale (V2)</u>:
2021 (2024)

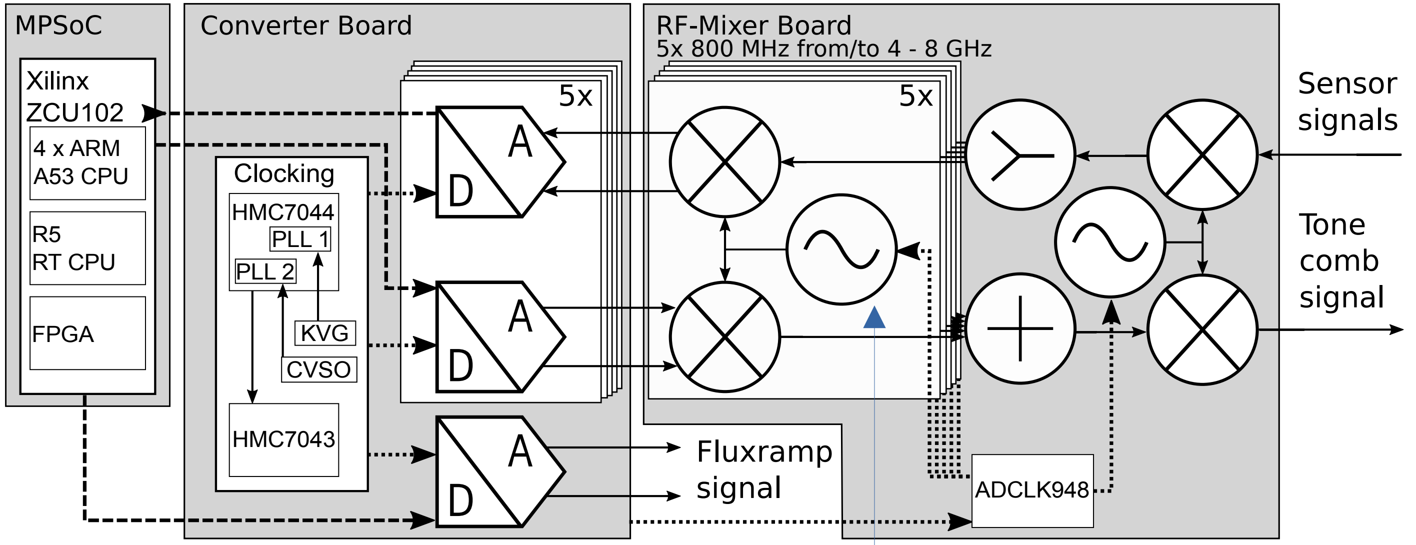


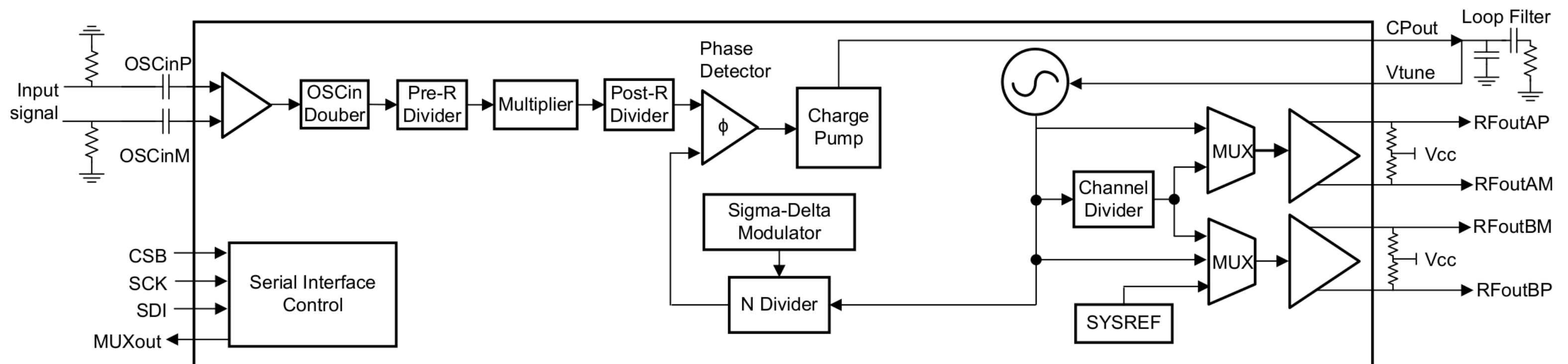




400 Resonator
4 GHz

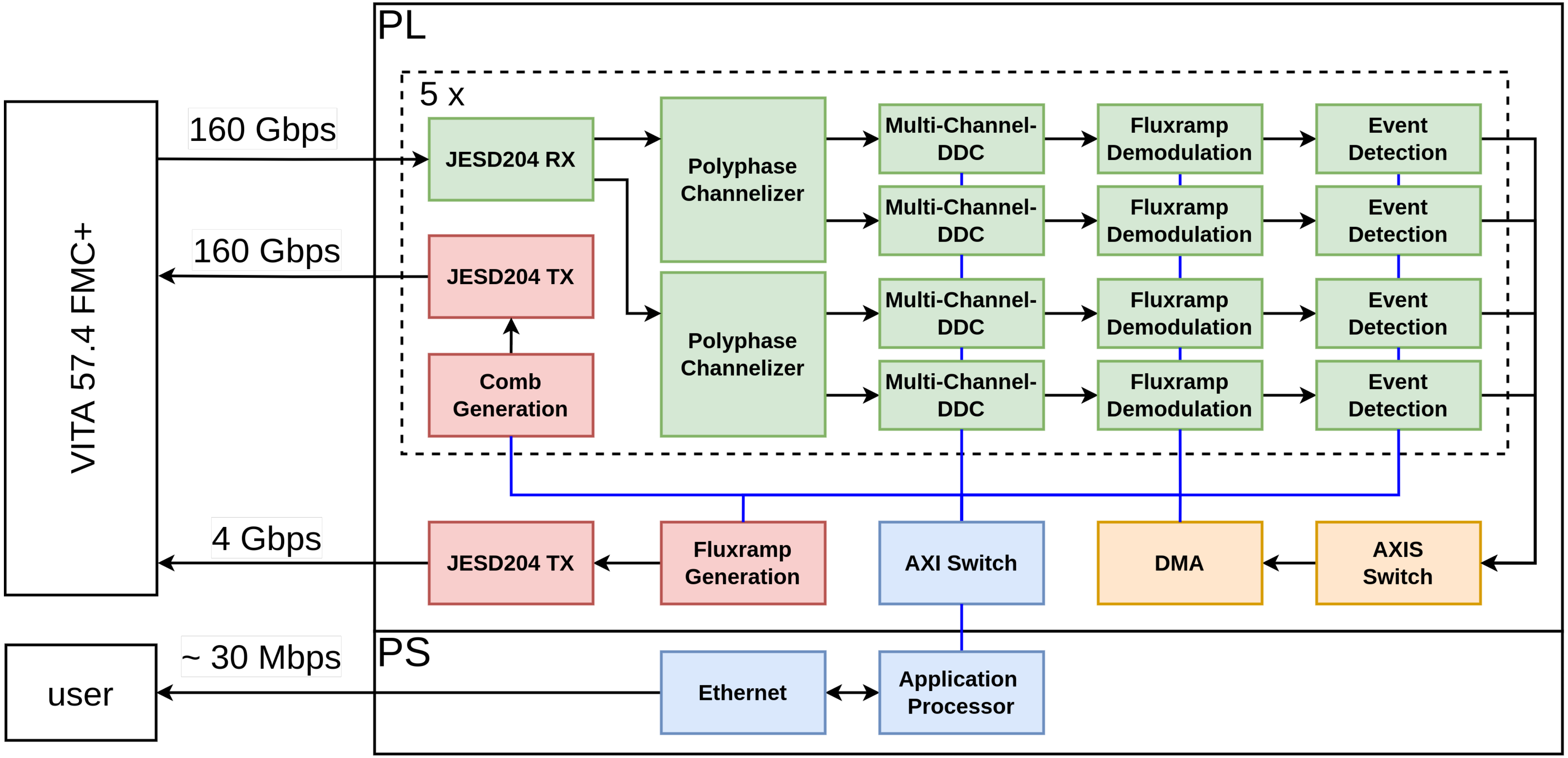
ECHo Clock Schematic





[ti.com]

ECHo Firmware

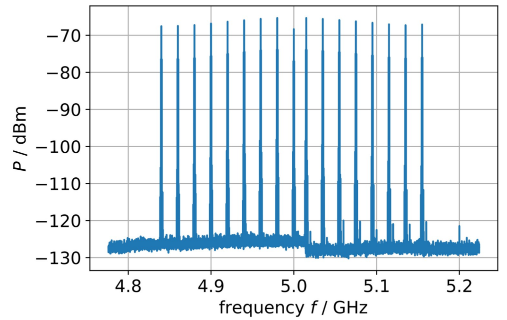


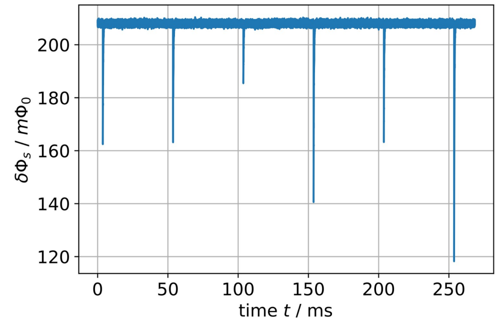
ECHo Data Decimation

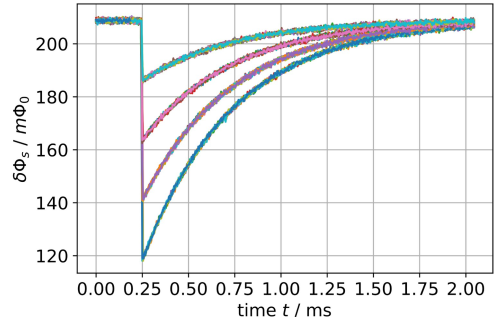
Karlsruhe Institute of Technology

Digitalization of frequency comb	ADC with internal DDC	
		10 parallel data streams à 500 MSPS (20 GB/s)
Tone separation into TDM-Scheme	Channelization stage	
		20 parallel TDM streams à 32 x 15.625 MSPS (40 GB/s)
Recovery of raw sensor signal	Fluxramp Demodulation	
		20 parallel TDM streams à 32 x 1.953 MSPS (10 GB/s)
Extraction of relevant samples	Event Detection	
		Single data stream with 8 MSPS (32 MB/s)

<u>Data rates:</u>

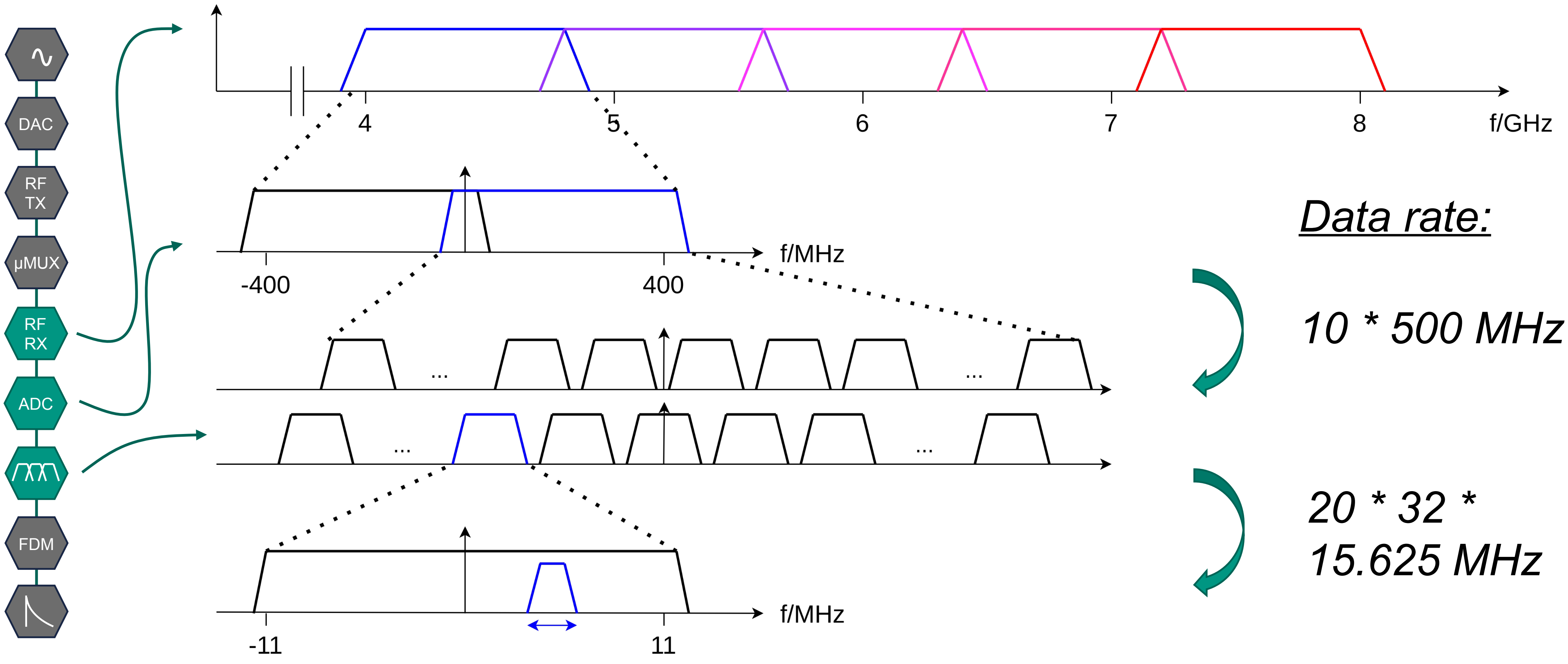






DOI: 10.1007/s10909-022-02858-x

ECHo Band Structure



Data rate:

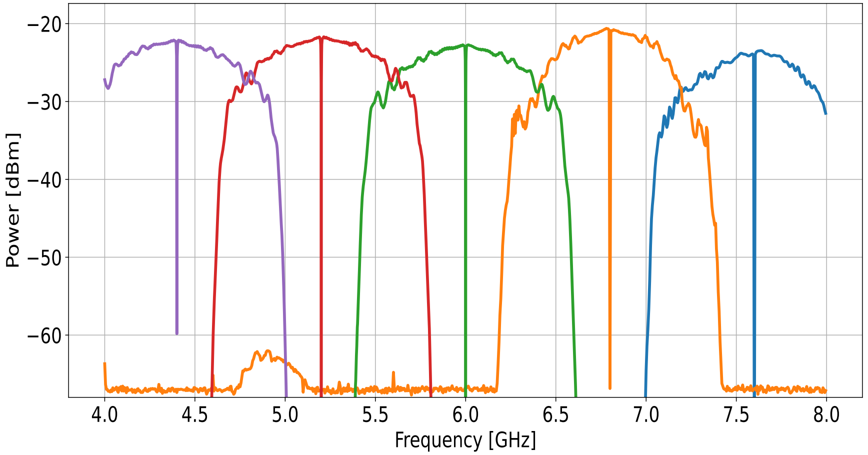
*10 * 500 MHz*

*20 * 32 * 15.625 MHz*

Crosstalk

Analog domain

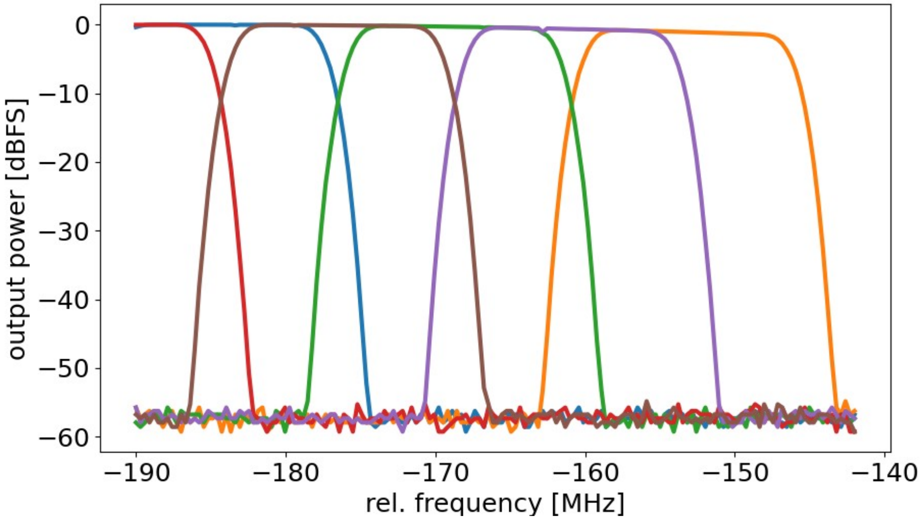
Crosstalk between subbands



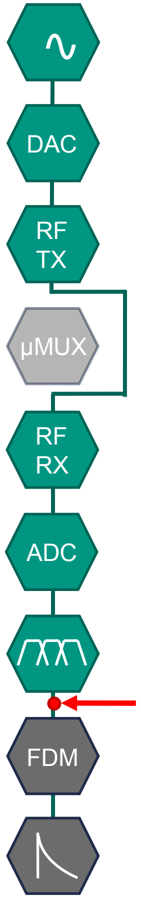
- Crosstalk (Band 1-3): **-50 dB**
- Band 4: Alias filter
- Band 5: Matching network

Digital domain

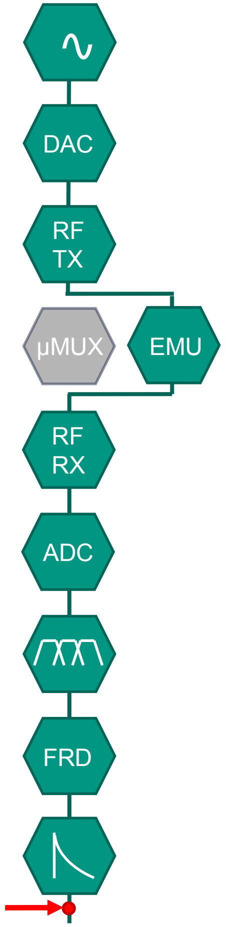
Crosstalk between channels

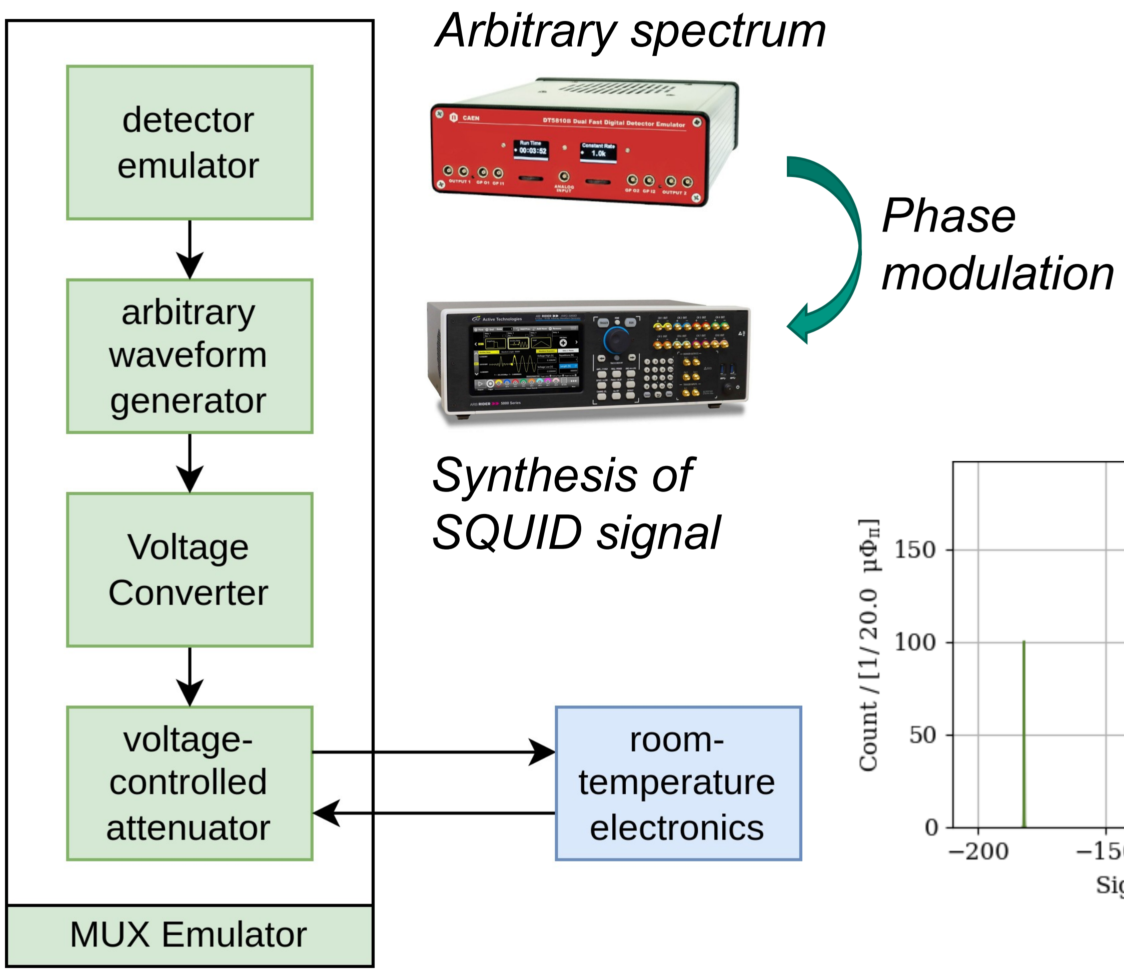


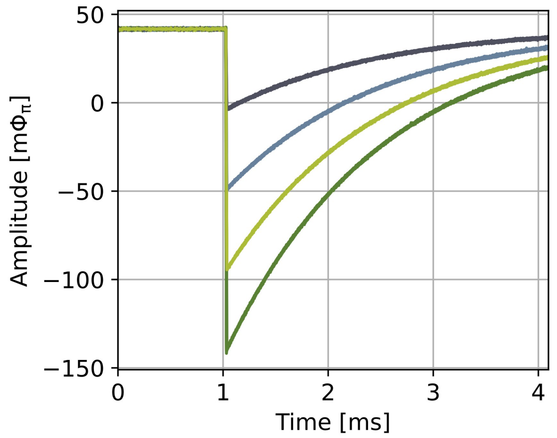
- Baseband: **-65 dB**
- RF-frontend: **-58 dB**

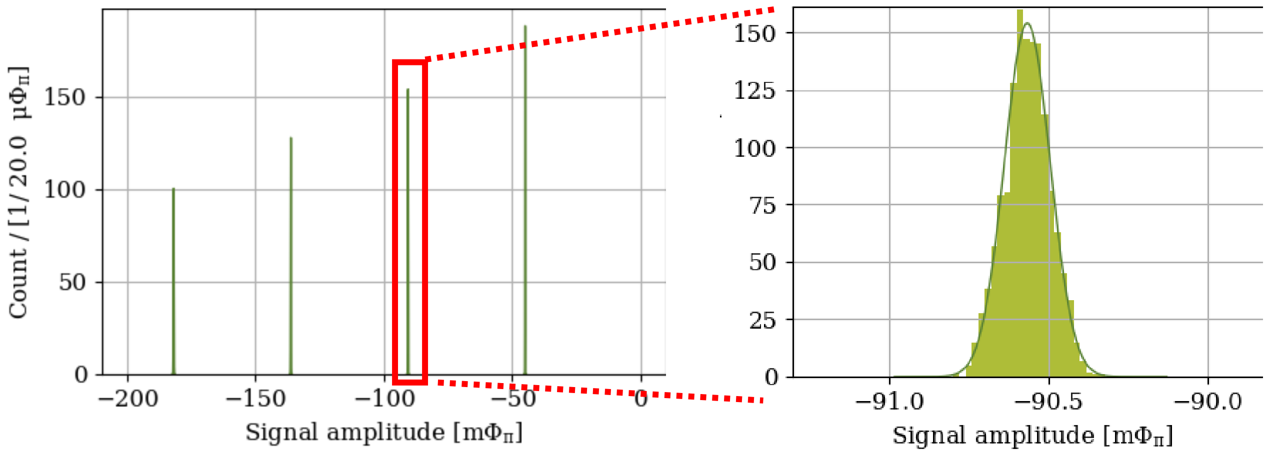


ECHo Room Temperature Verification



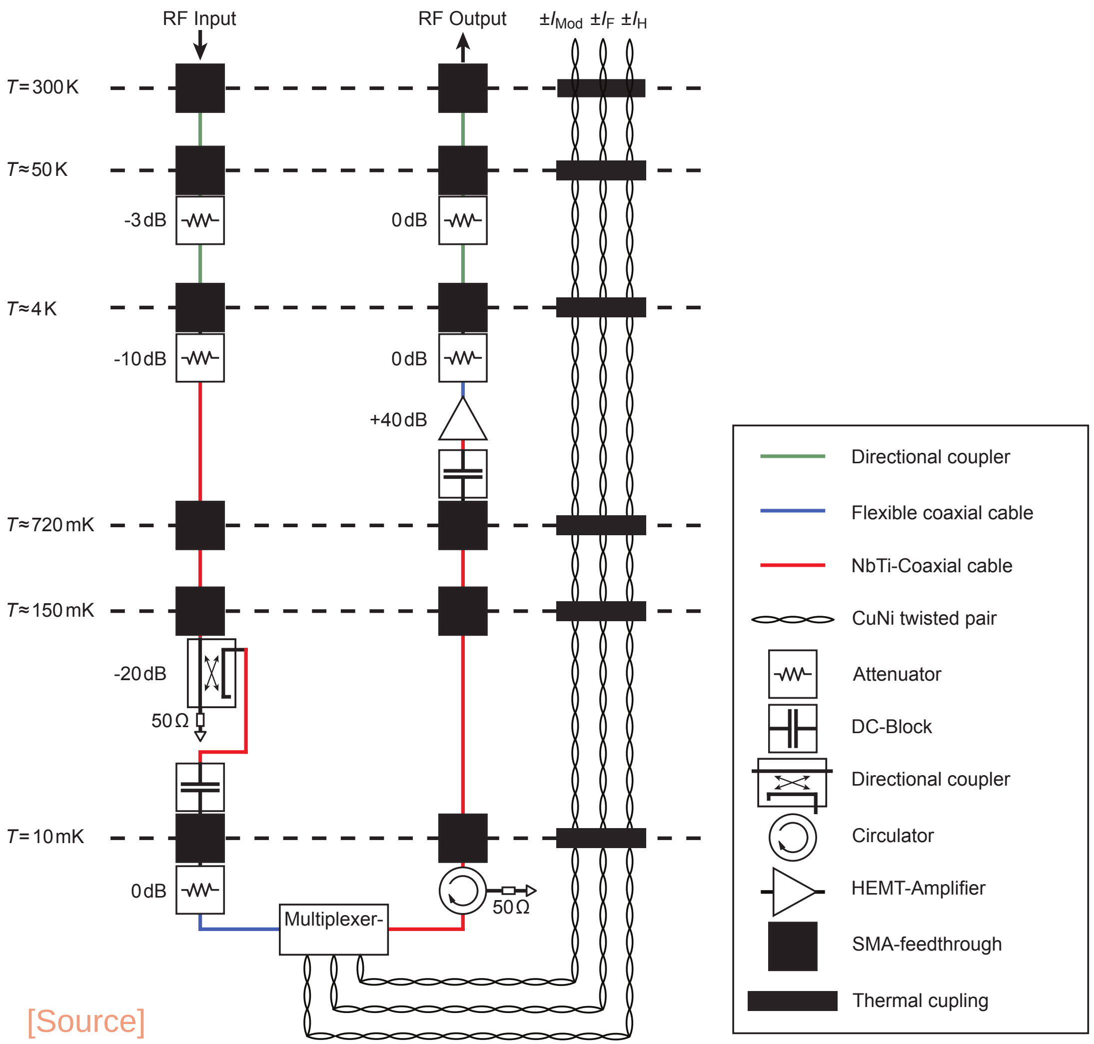




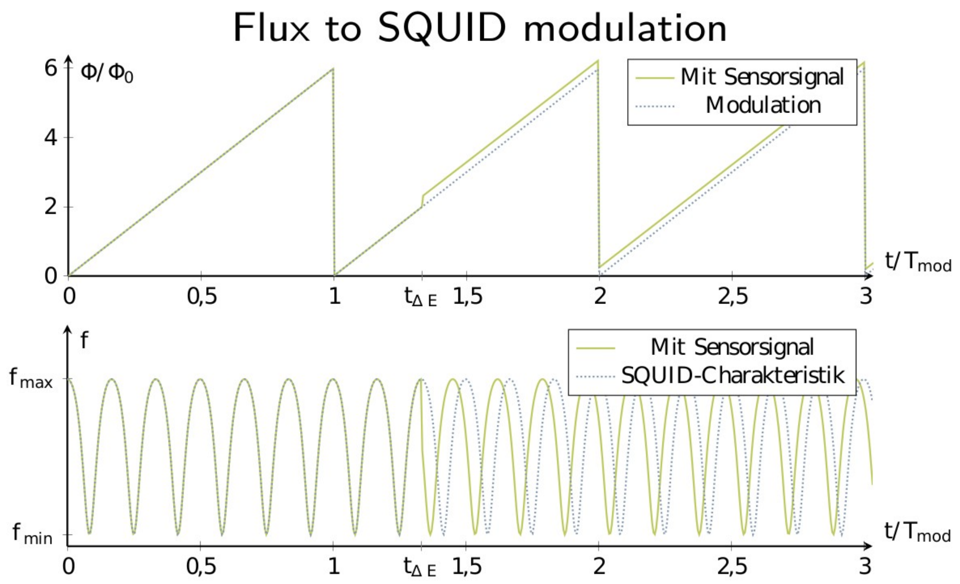


Preliminary FWHM: 6.28 eV @ 3.35 keV

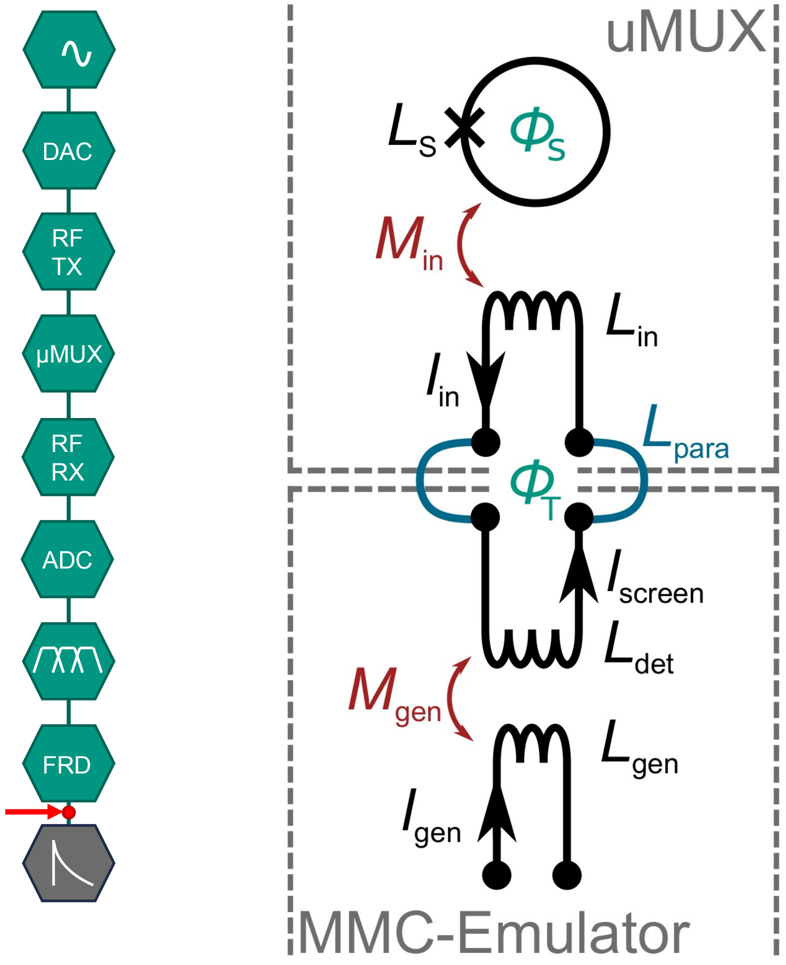
Sample Wiring Diagram

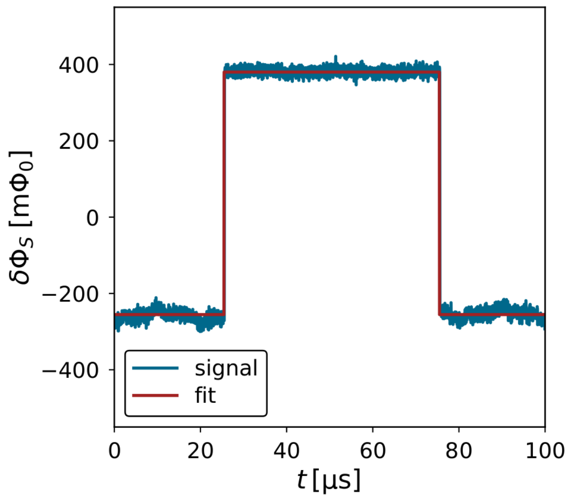


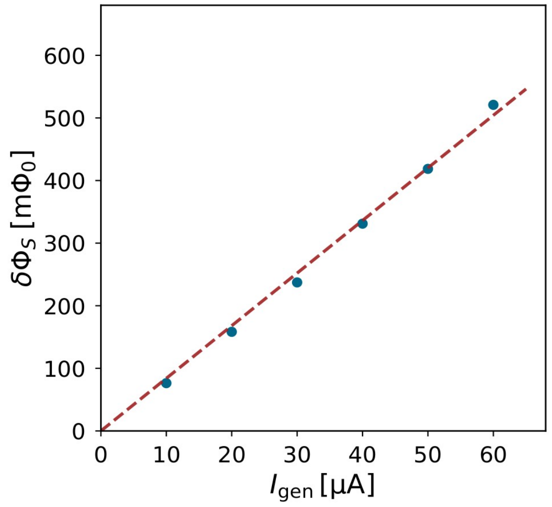
[Source]



ECHo Experimental Linearity (preliminary)





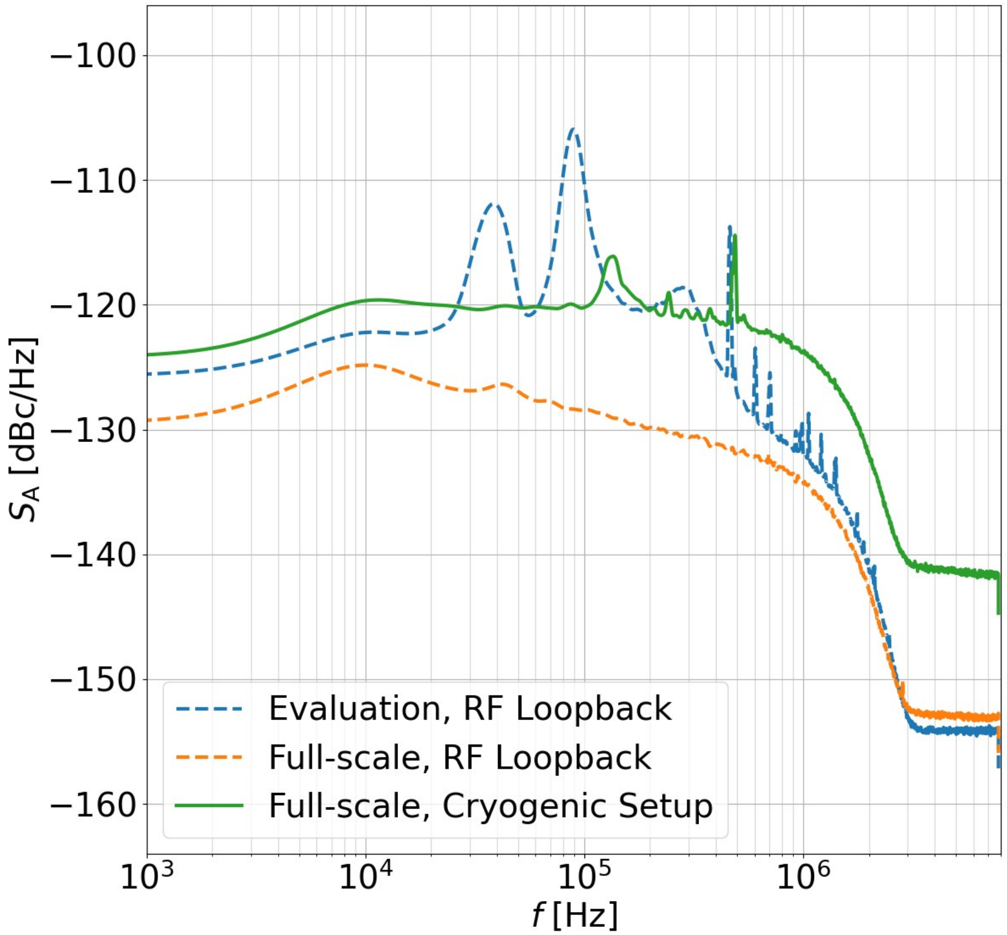


Averaging amplitude of fluxramp demodulated square wave signal

Linearity:

- **84.04 µA/Φ_0 ± 0.12**

ECHo Room Temperature Verification



Measurement procedure:

- Generation of a single tone
- Downconversion of carrier signal
- Signal PSD of noise

Results:

- room-temperature loopback shows lower noise than with cryogenic interface
- **SDR is not the limiting factor**

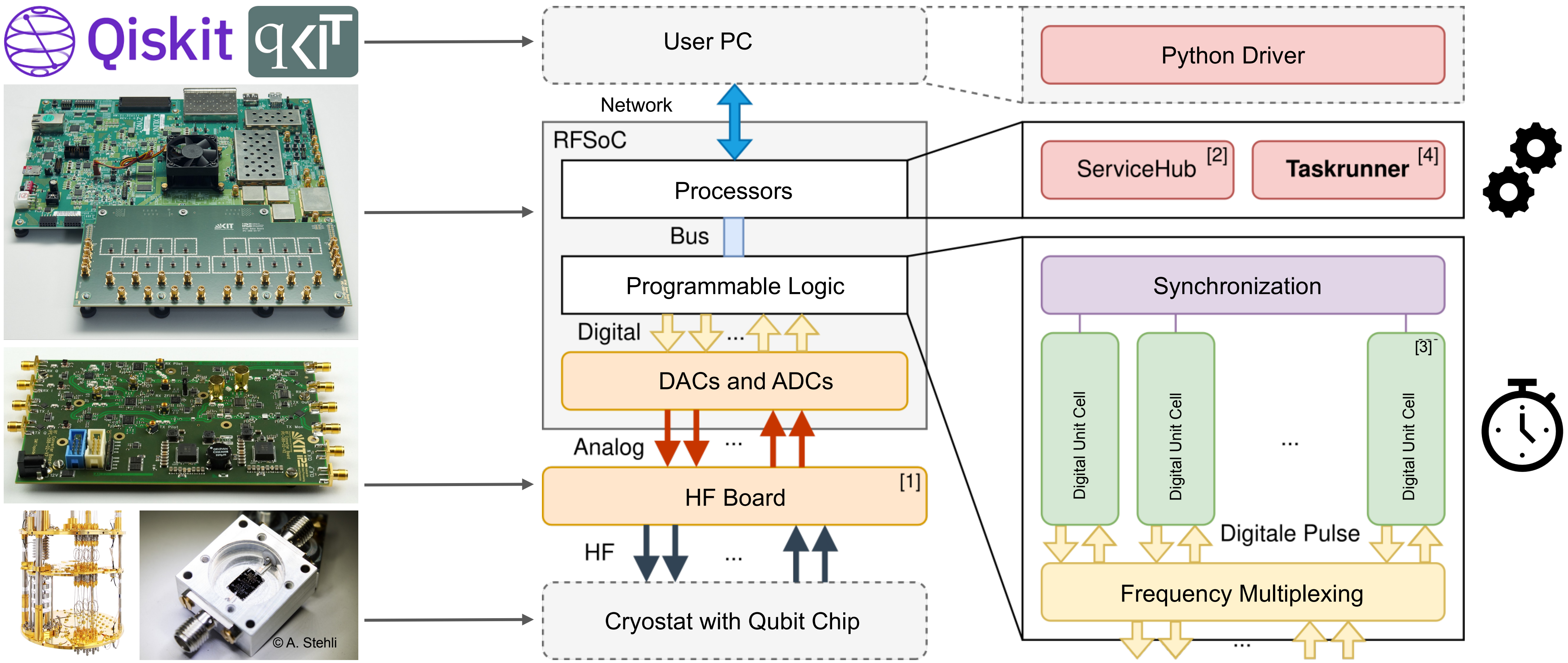
IPE EPS group (SDR branch)

- Group Lead: P.D. Dr.-Ing. Oliver Sander
- Post-Docs
  - Dr.-Ing. Luis Ardila-Perez
  - Dr.-Ing. Luciano Ferreyro (USAM-KIT)
- Doctoral Students
  - Timo Muscheid
  - Lukas Scheller
  - Marvin Fuchs
  - Robert Gartmann
  - Torben Mehner
  - Manuel Garcia (USAM-KIT)
  - Juan Salum (USAM-KIT)

- Previous Members
  - Dr.rer.nat. Richard Gebauer(*)
  - Dr.-Ing. Nick Karcher(*)
  - Dr.rer.nat. Francesco Valenti

(*) Received Helmholtz Awards 2023 for doctoral thesis.

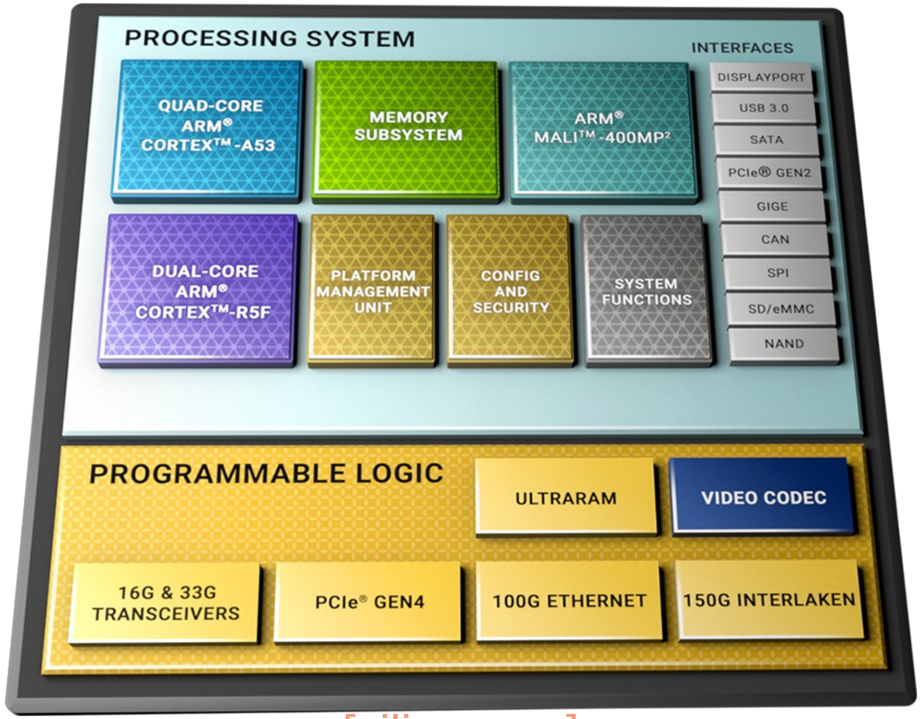
SDR for Qubit Applications



[1] Gartmann, Karcher, Gebauer et al., JLTP, 2021
[2] Karcher, Gebauer et al., IEEE TNS, 2021
[3] Gebauer et al., ICFPT, 2021
[4] Gebauer et al., IEEE SOCC, 2021

Heterogeneous Devices

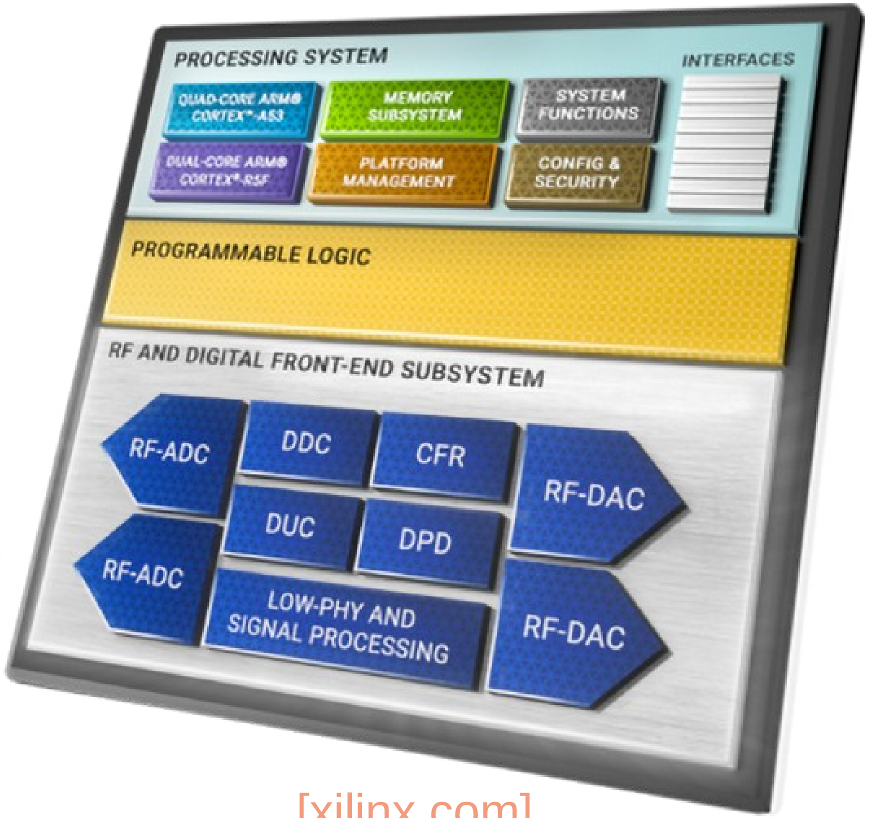
ZynqUS+ MPSoC



[xilinx.com]

hard processors and programmable logic

ZynqUS+ RFSoC

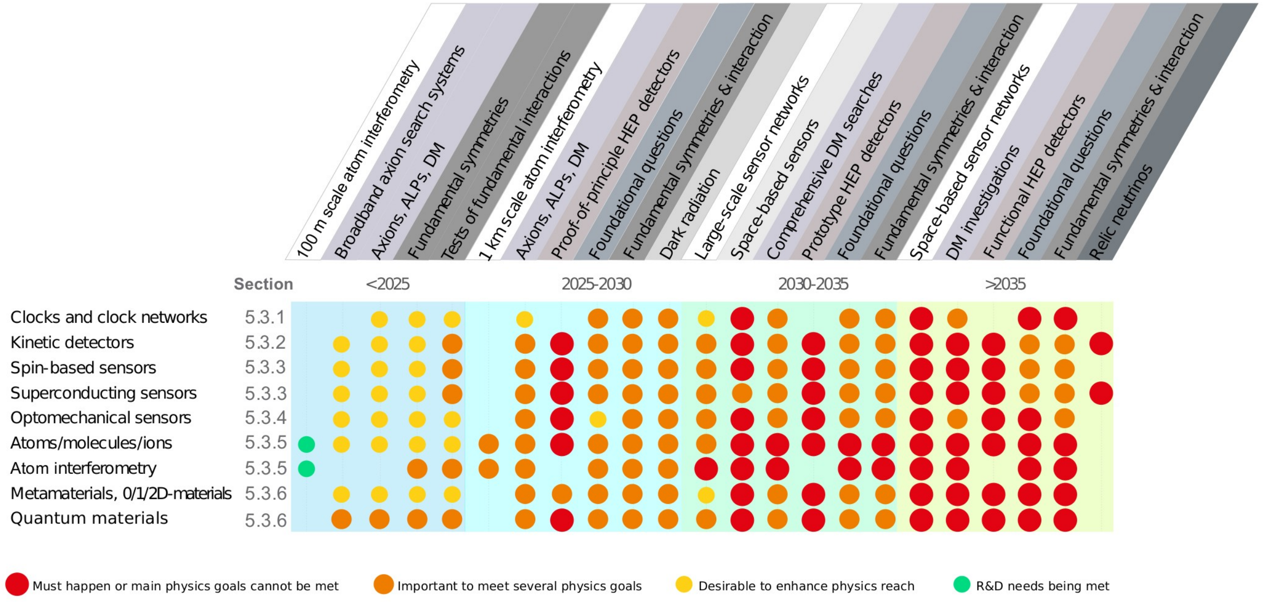


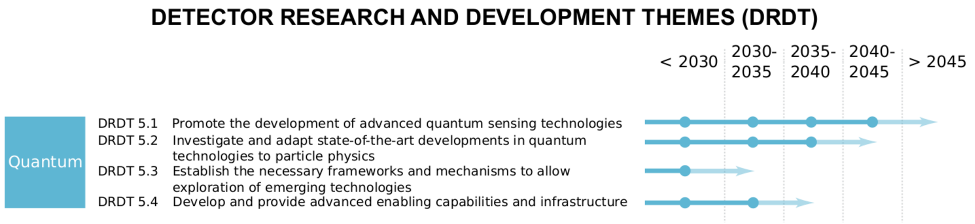
[xilinx.com]

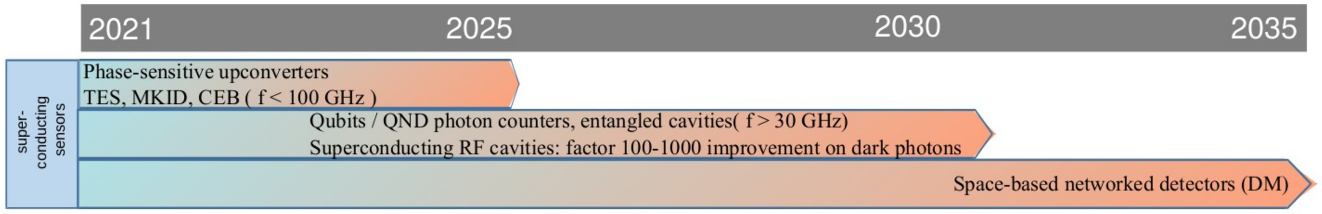
Integrated high-speed analog converters

ECFA Roadmap

- SDR easily repurposed
- More projects TBD
- DRDT 7.3 & DRDT 5.3.3
- Lots of work ahead!







[cern.ch]