Progress in the Effelsberg Cryo-PAF developments

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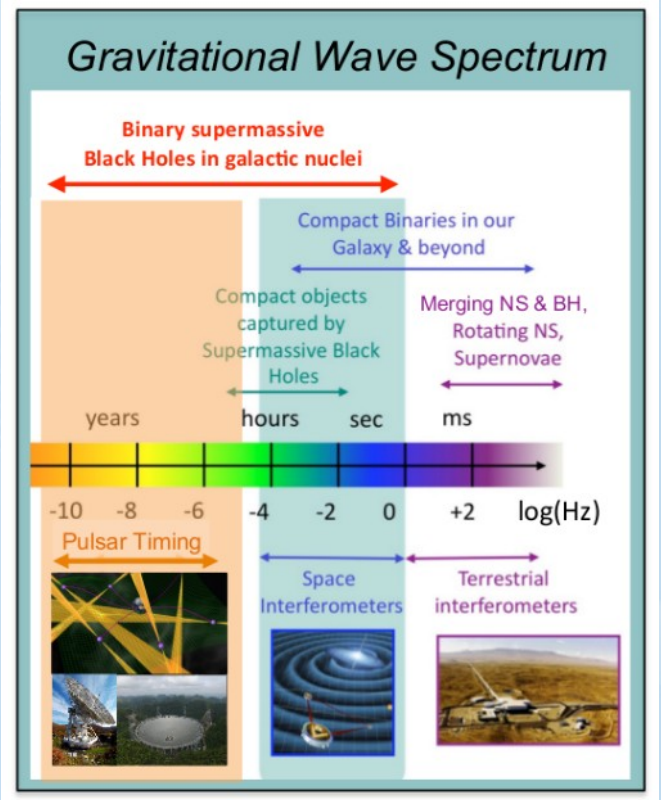
Outline

- Introduction / Background
- Overall layout
- Infrastructure setup
- Cryostat
  - antenna-array and cryogenic frontend
  - analog signal chain and digitizer
- Channelizer and backend-system
- Conclusions

Introduction / Background

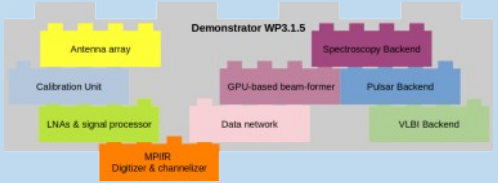
- Cryo PAF project at MPIfR is embedded into the
  "Low Frequency Gravitational Wave Astronomy and Gravitational Physics in Space"
  a collaboration of CAS and MPG
- MPIfR started technical activities in cryogenic PAF developments back in early 2018
  - starting with a 4 year period of unbiased design studies
    - ✘ in all technically important areas
      (e.g. antennas, LNAs, system integration, digitization, beamforming, backend architecture…)
  - design of the first gen. Cryogenic PAF for Effelsberg started late 2021
  - The frontend now also is embedded into the EU Radioblocks project as technology demonstrator for PAF backend developments



Gravitational waves are a prediction from Einstein's theory of general relativity:

- They are emitted when masses are asymmetrically accelerated, and propagate through the Universe, carrying information about the objects that they created them.
- Their existence has been confirmed first by observations of binary pulsars.

Sub-project B2 targets to develop PAF systems for Effelsberg and FAST



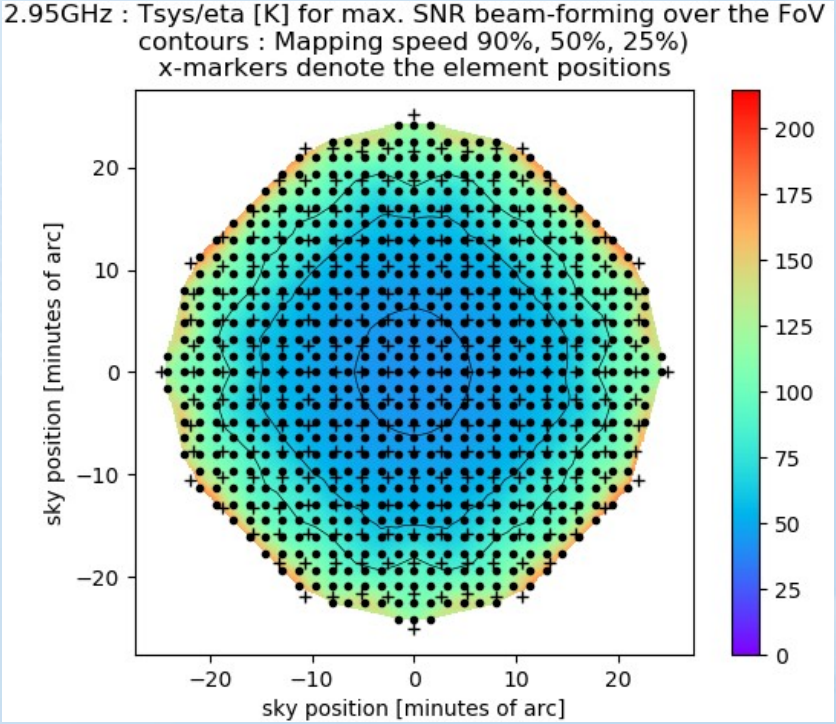
Phase of design studies

Extensive studies on

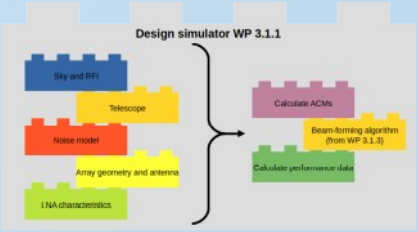
- PAF theory (e.g. different beamforming algorithms)
- Antenna types (e.g. dipoles, Vivaldi type antennas)
- PAF focal plane layout
  - geometries (e.g. squared, hexagonal, Vogels-pattern)
  - element spacing
  - reaction on dead elements
  - RFI mitigation capabilities

Talk of Y. Yiannakis (Session 4)

- LNA designs and options of integration
- Analog signal chain options and early prototypes
- Options for digitization and channelization
- Backend-options incl. Beamformer (e.g. FPGA-based beamformer vs. GPU based)



RADIO BLOCKS



CryoPAF frequency range

Band definition with astronomers on project start: above L-band, below C-band

Final down selection due to mainly technical reasons :

1. Possible physical size of the receiver
   - limits the accessible focal plane area to 60 cm diameter

   ➔ approx. 250 receiving elements (~125 elements per polarization) at 3 GHz

   ➔ but only ~37 pixels at 1.5GHz

   for proper beam-forming with the large blockage of the telescope 37 beams are tight

2. RFI situation
   - below 2.4 GHz the RFI situation is difficult

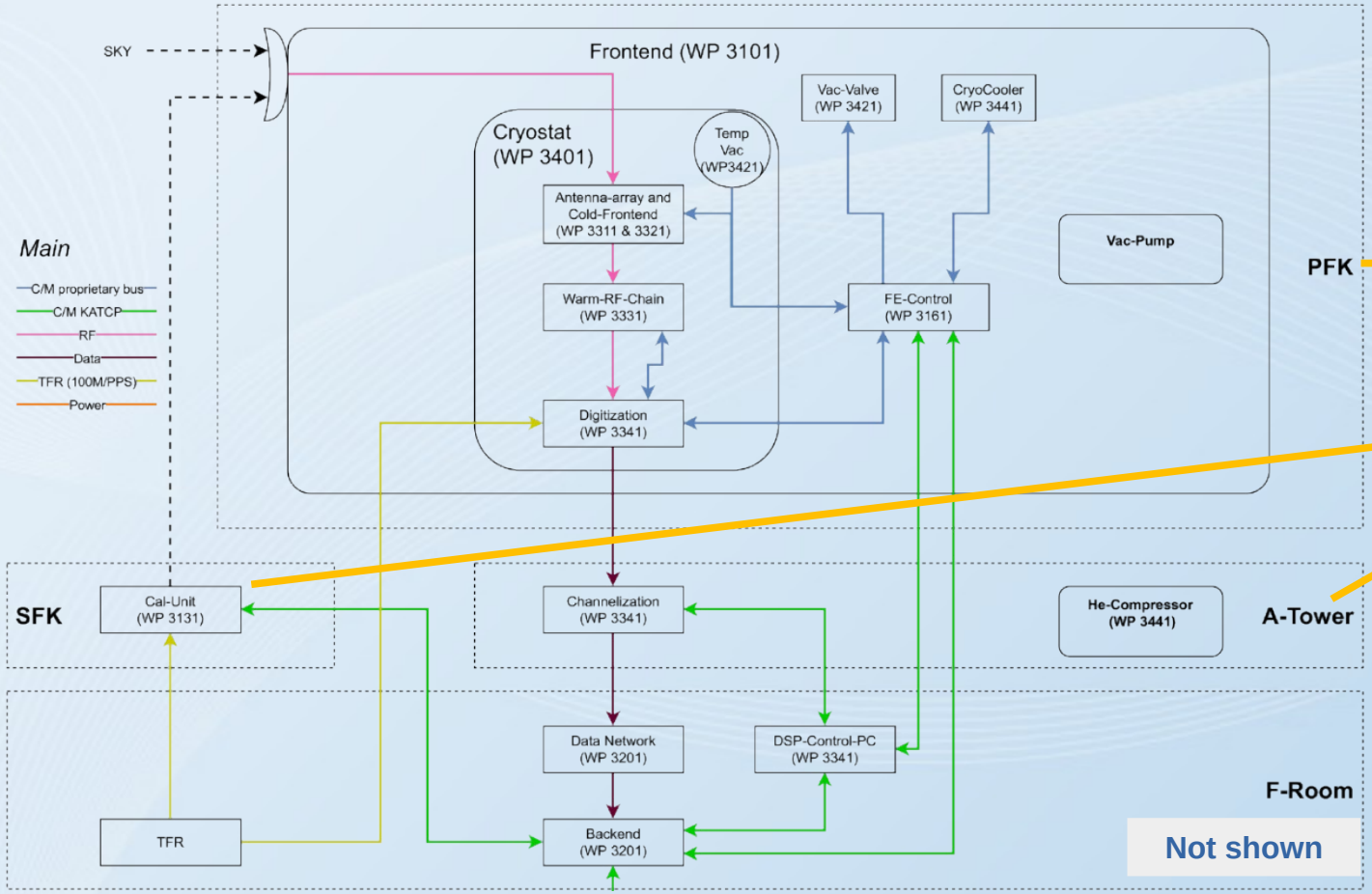
   ➔ a wider band PAF receiver could suffer from saturation

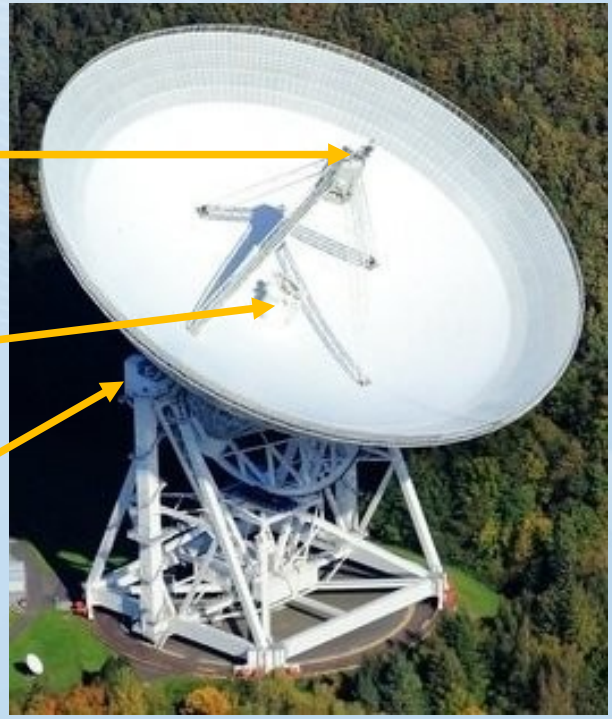
   ➔ requires many elements to do efficient RFI suppression (degrees of freedom)

3. Cost, risk, and required effort limit the upper band edge to in maximum 4 GHz
   - realistically even only to ~3.9 GHz

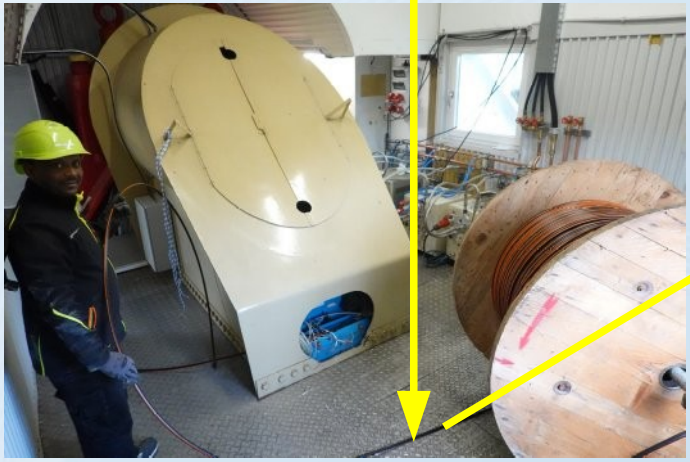
   ➔ **the given boundary conditions advice for roughly 2.6 to 3.9 GHz**

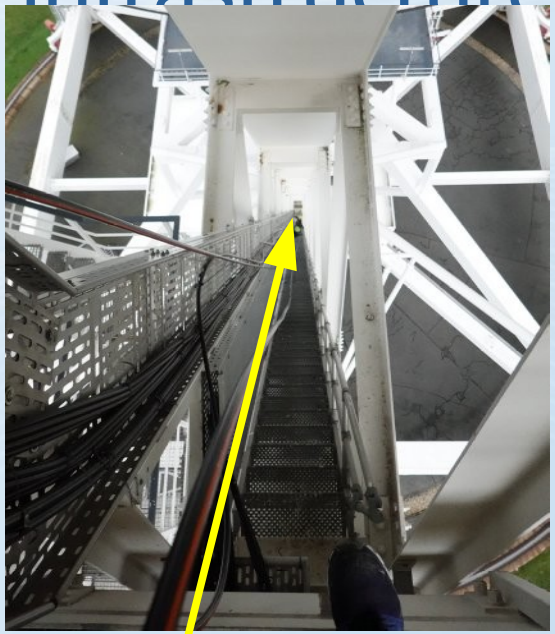
The receiver layout



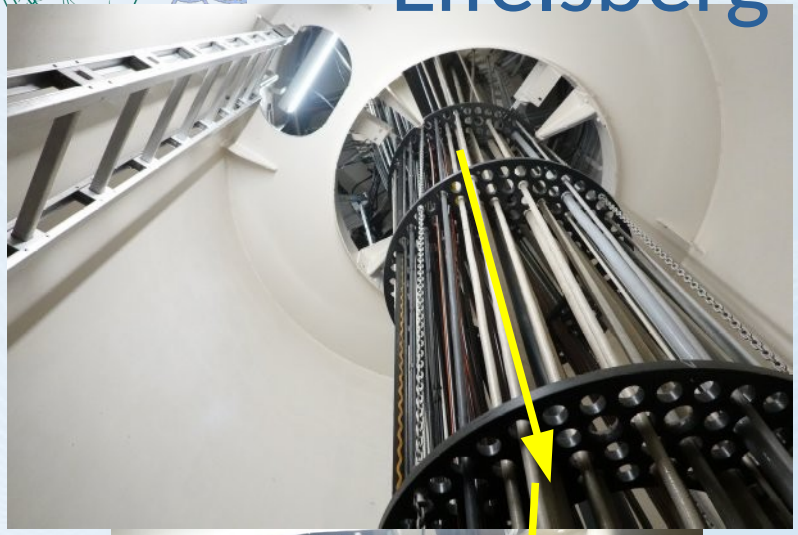


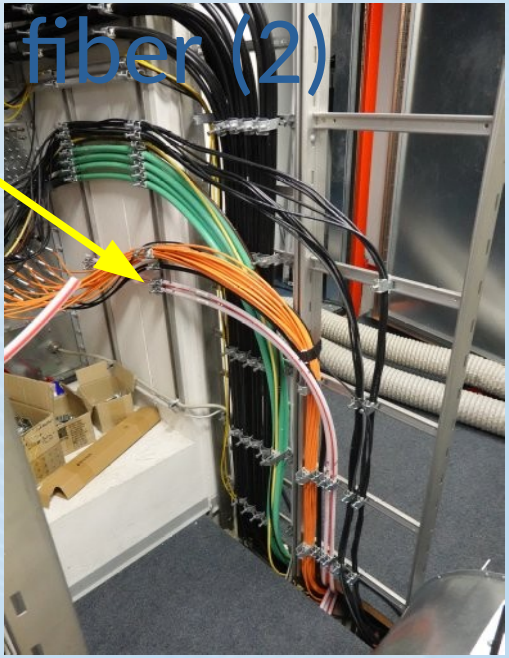
Effelsberg infrastructure: Data fiber (1)



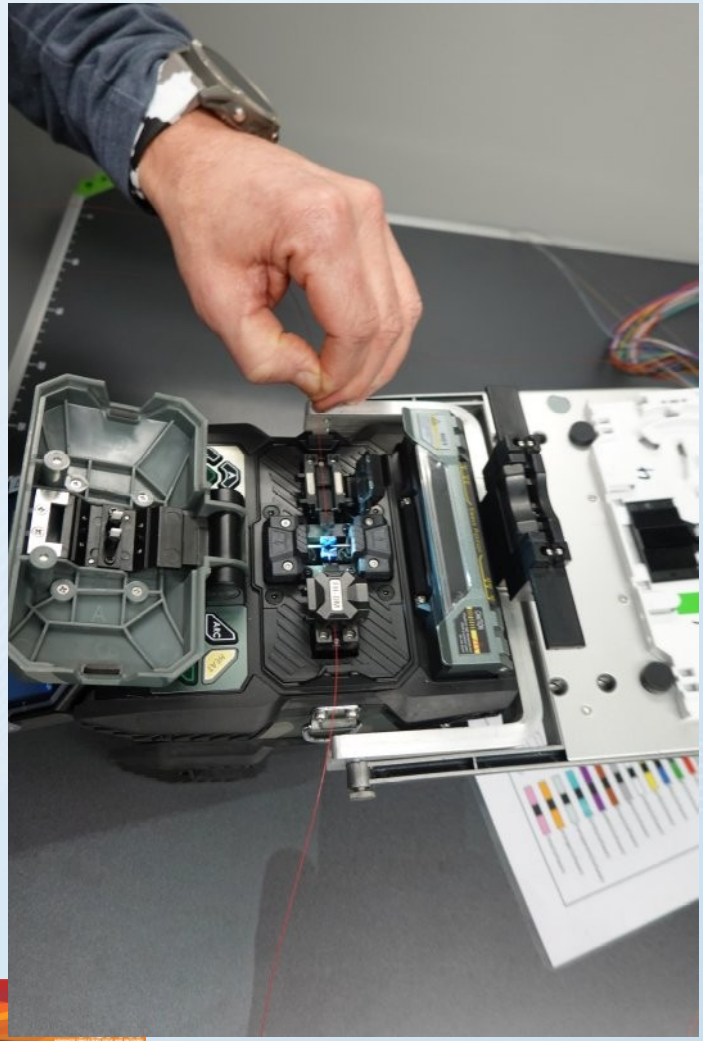


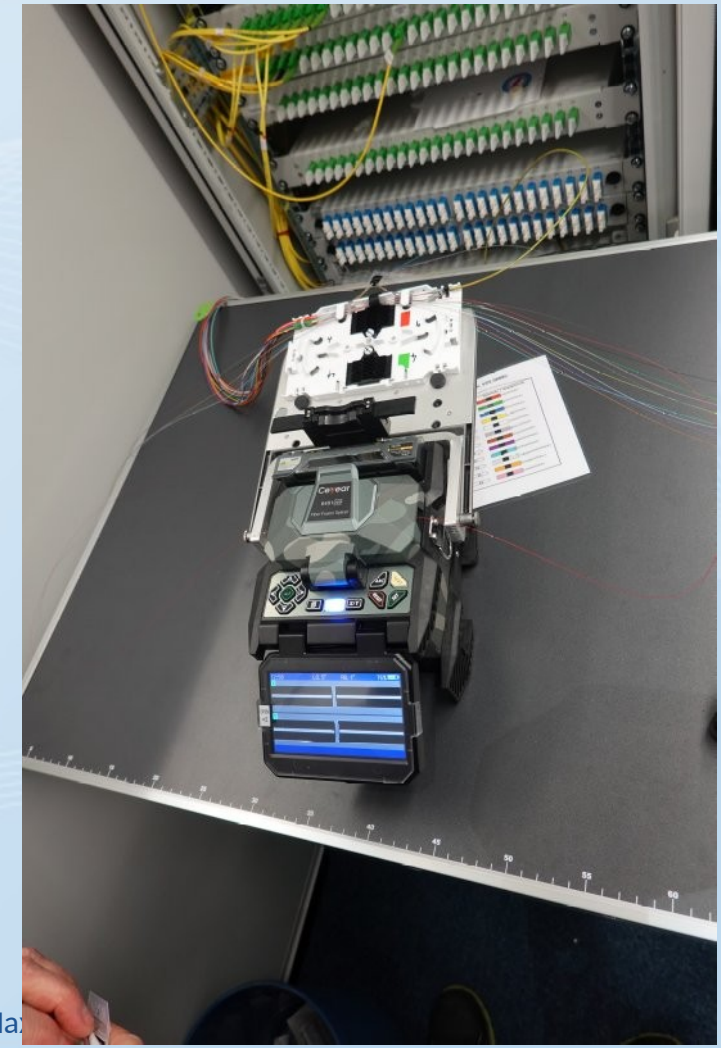
Effelsberg infrastructure: Data fiber (2)



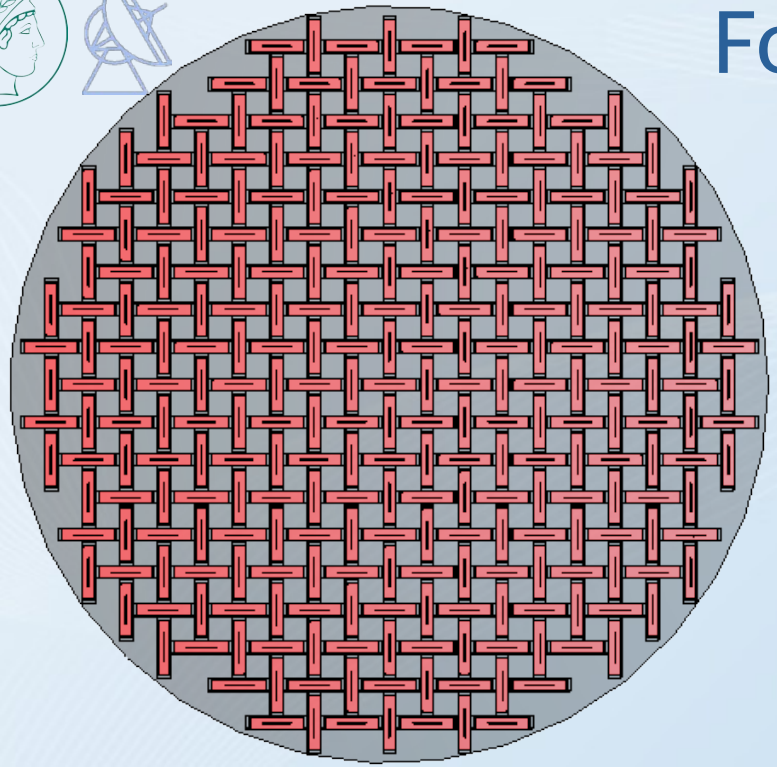


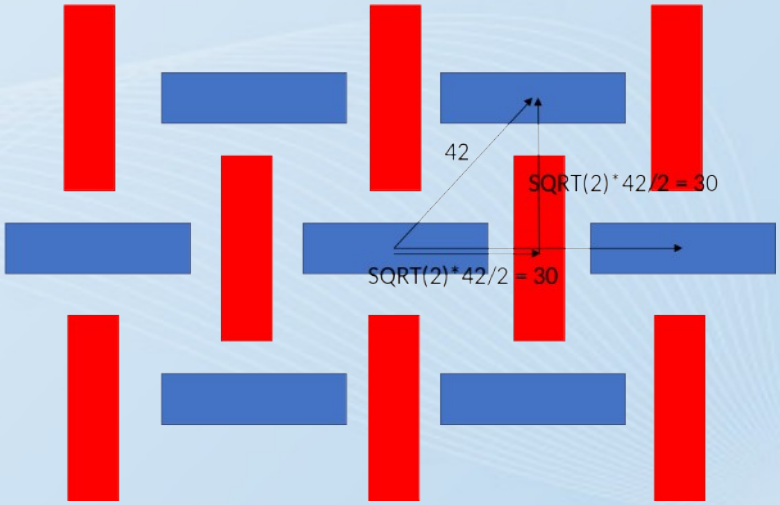
Effelsberg infrastructure: Data fiber (3)

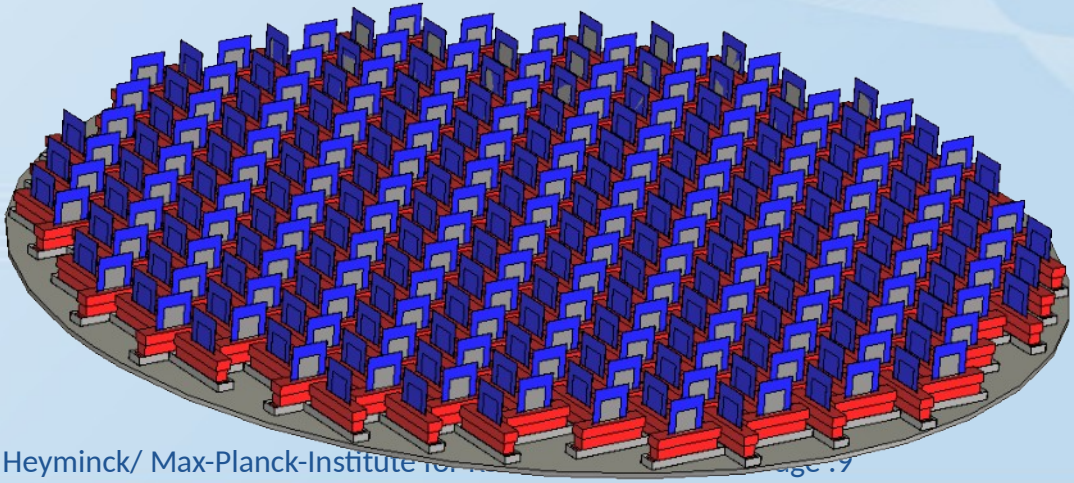




Focal plane layout





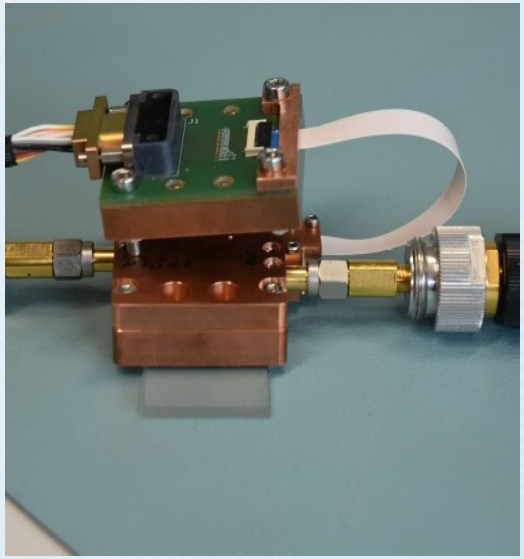


Nominal spacing: **42 mm**

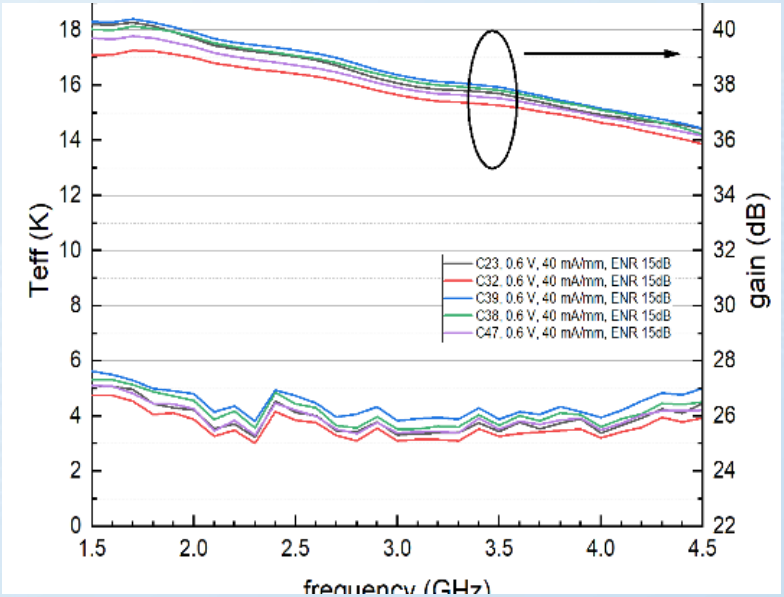
Number of elements: **253**

- Horizontal polarization : 124
- Vertical polarization : 129

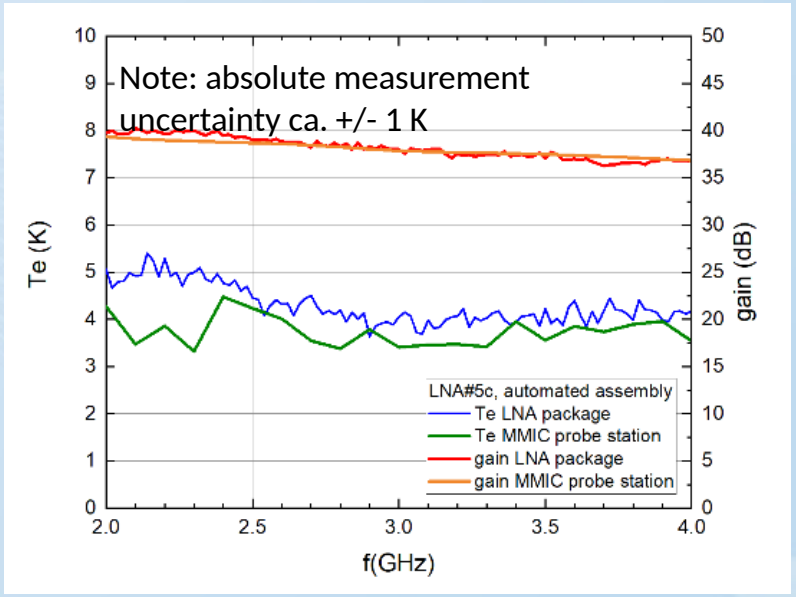
LNAs



Sub-circuit – warm testingtest fixtures



Noise-gain traces of several MMIC die measured in probe station.

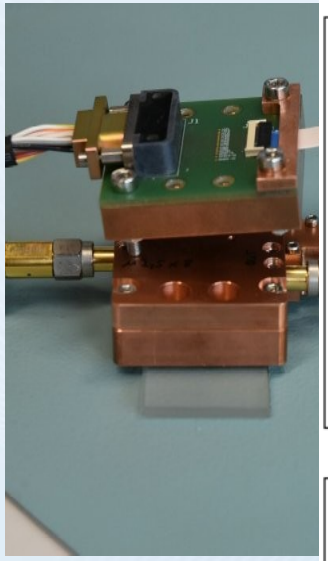


Comparison of noise-gain traces of packed LNA vs. MMIC die in probe station.

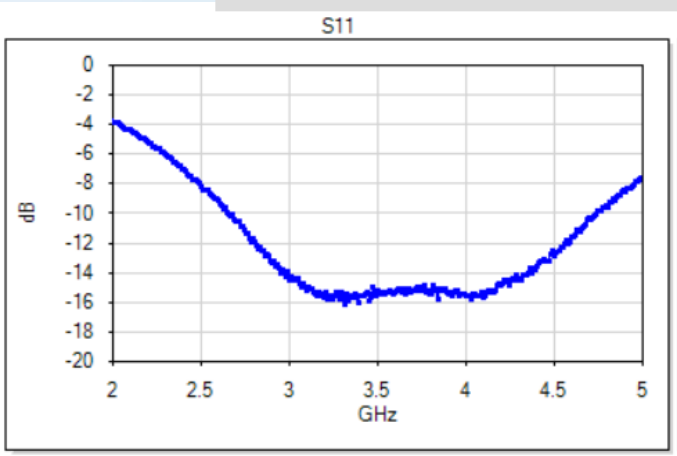
- 300 MMICs are ordered already
  - delivery expected in Spring 2024
  - actually we are establishing the production line for the cryogenic frontends

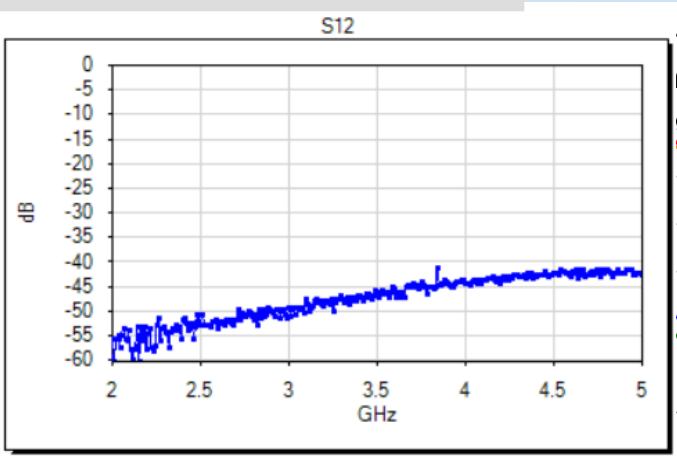
LNAs

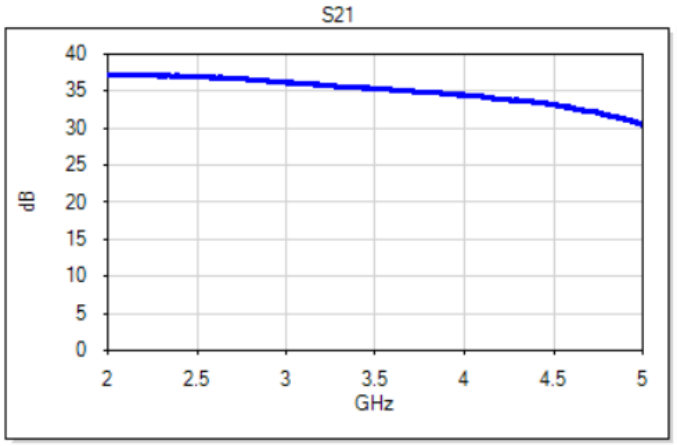
Room-temperature S-parametes

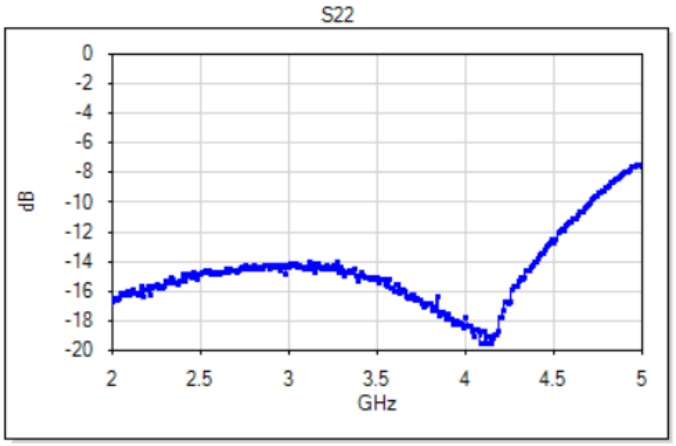


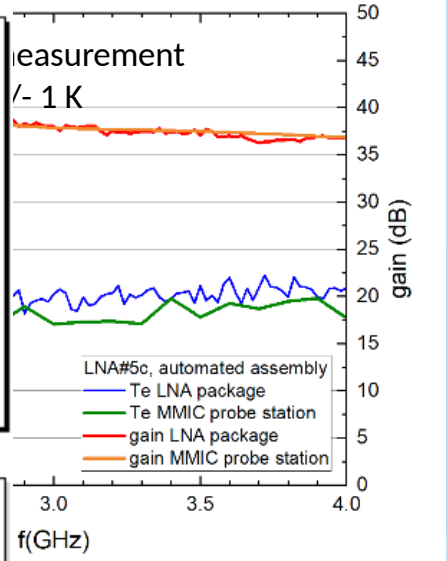
Sub-circuit – warm testi











traces of packed LNA
probe station.

- 300
  - c
  - a

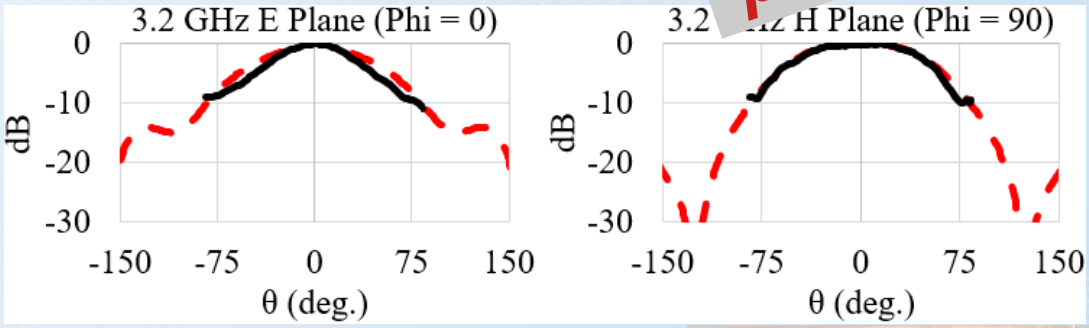
frontends

Integrated cryogenic frontend

- **Actual choice for the antenna is a modified DRA:**
  - already tested in house: survives cooling and shows the pred
  - can illuminate the Effelsberg main dish out of the pri
  - can be fully integrated into the cryogenic fr
  - low loss
  - easy to manufacture (e.g. 3

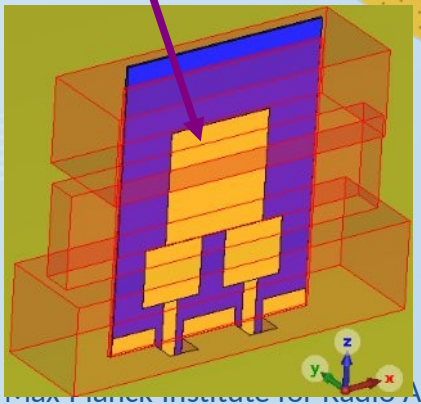
Automated production including pick and place of the LNA-MMIC

fully integrated frontend
- ✔ *Antenna feed-structure*
- ✔ *Balun*
- ✔ *RFI-bandpass filter*
- ✔ *LNA*
- ✔ *LNA DC bias circuitry*

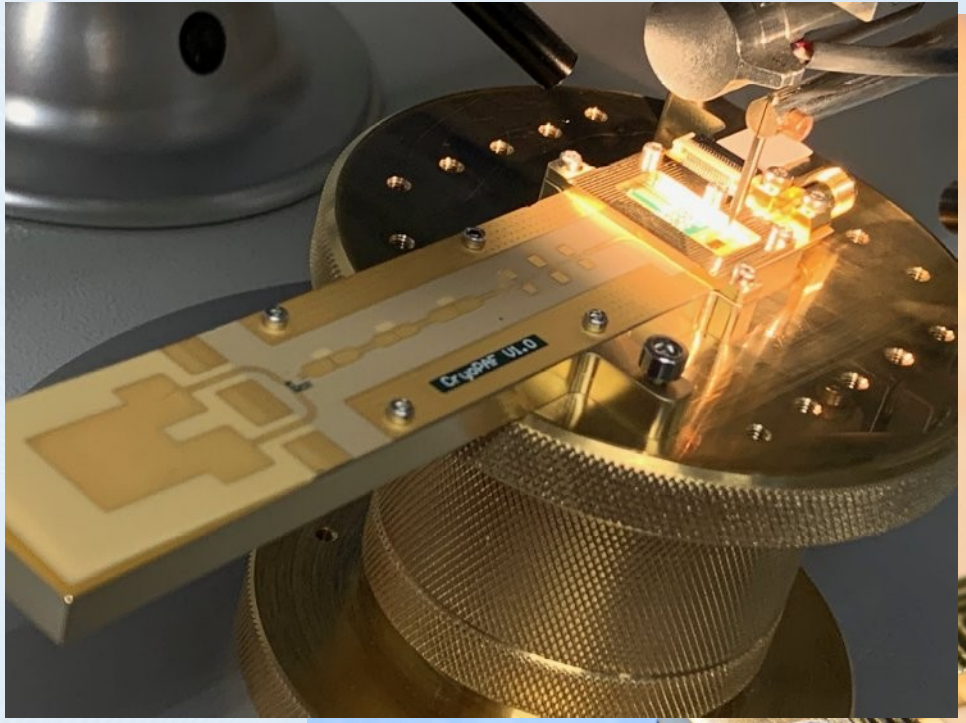


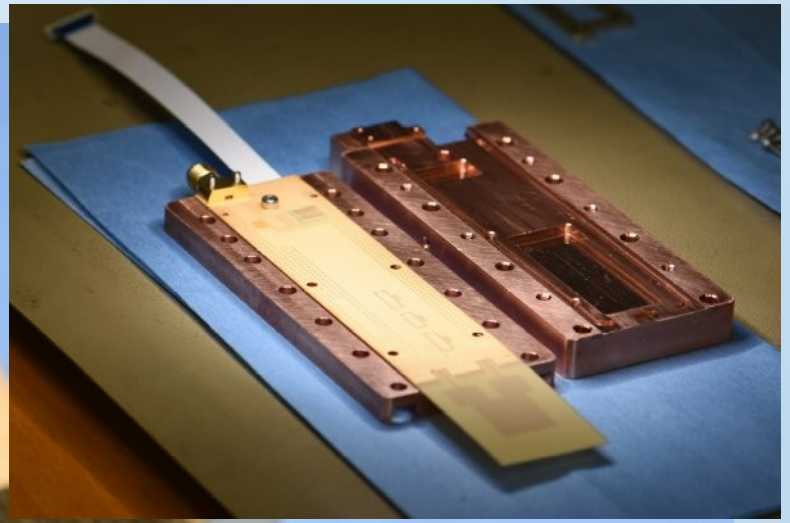
Above: far-field measurement
black: measurement data
red: simulation data

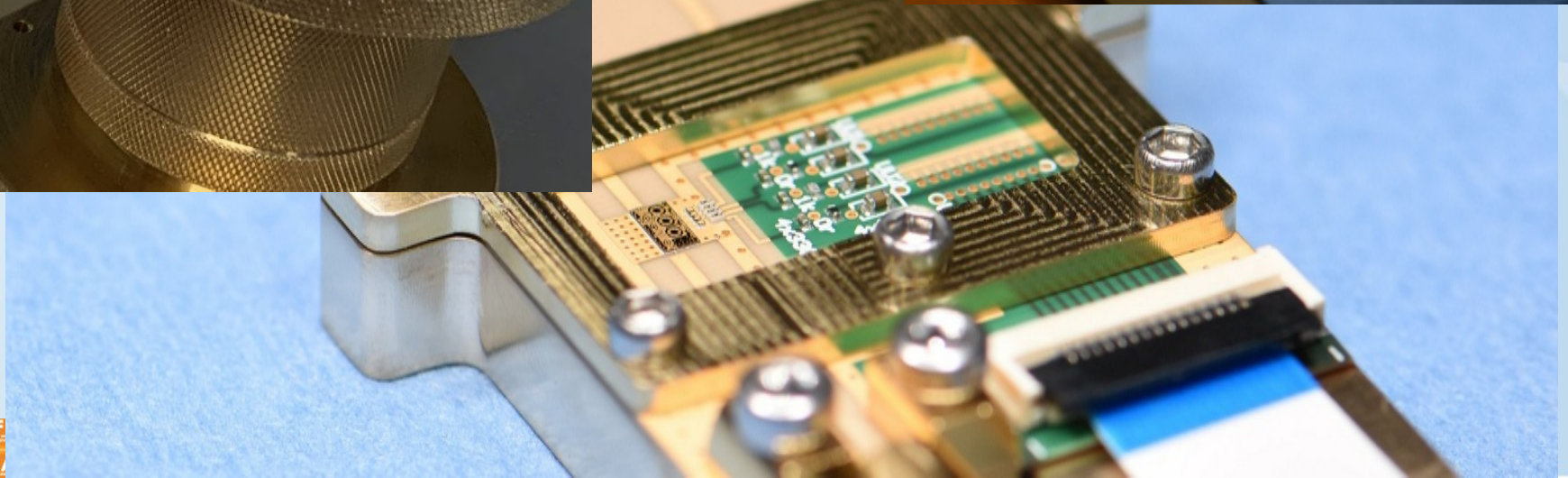
Right: early 3D-printed antenna prototype



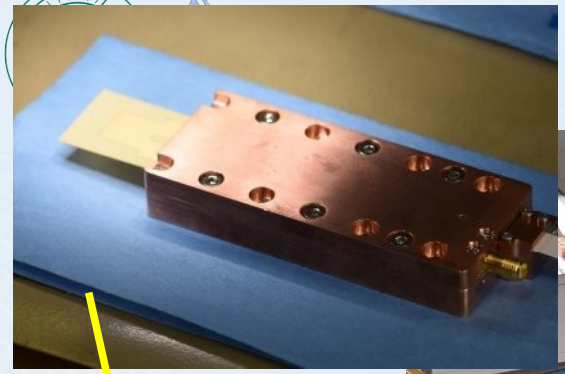
Cryogenic frontend – first assembly

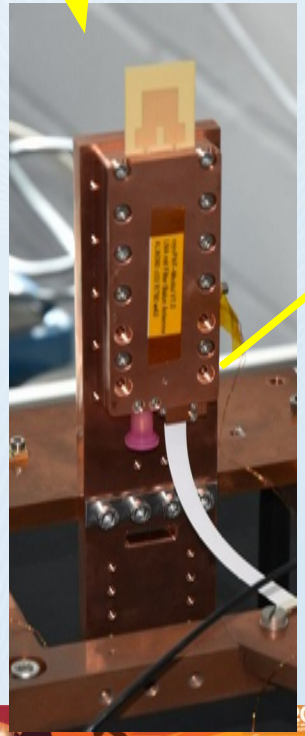


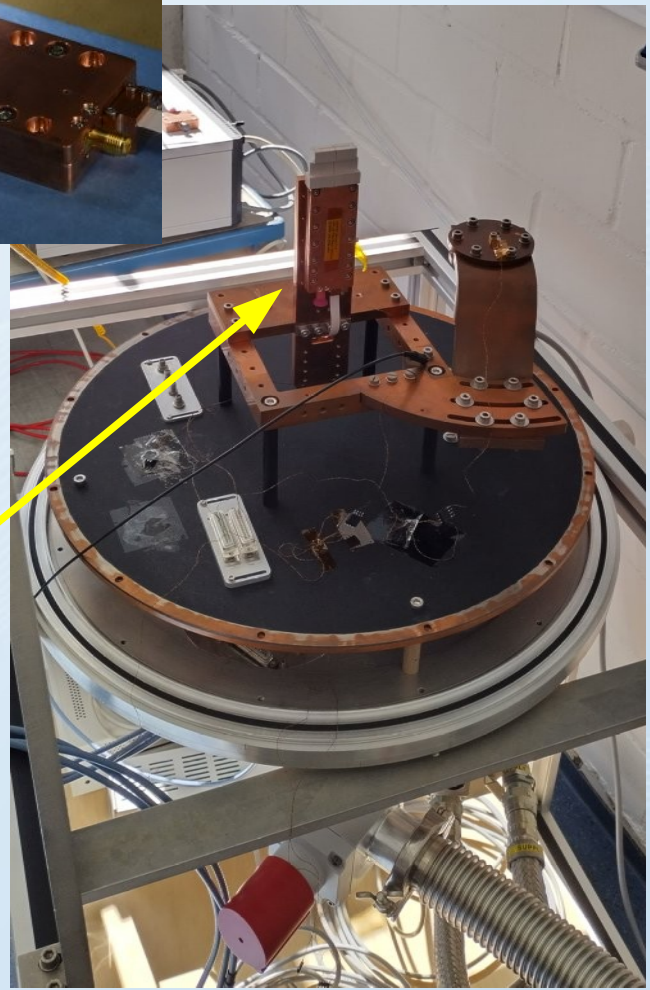


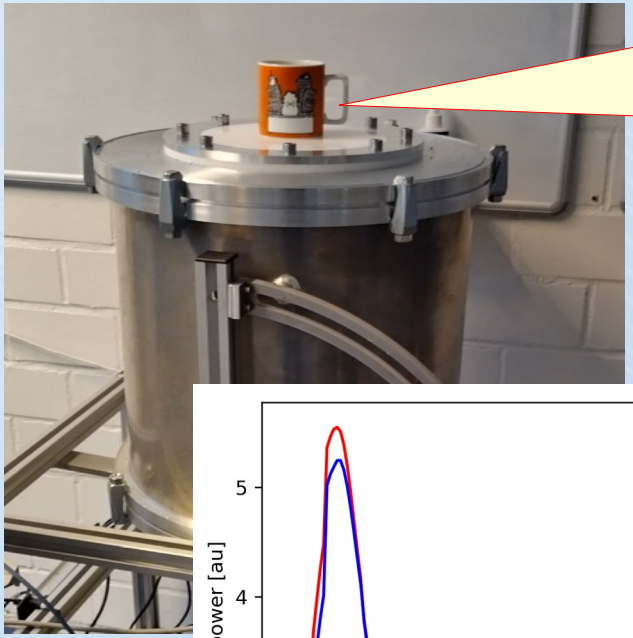


First cryogenic testing

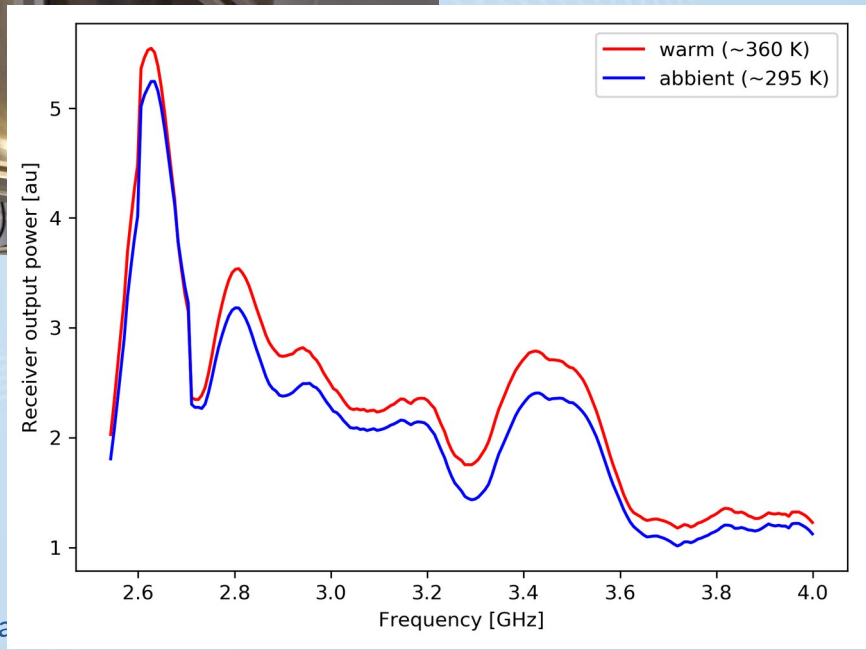




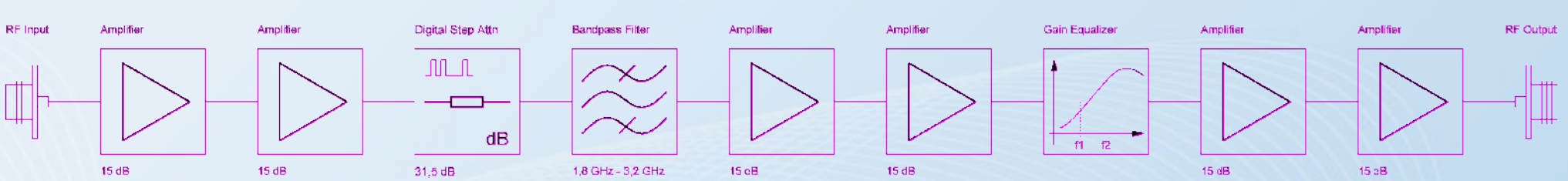




fully standardized
coffee cup
sensitivity test
... or ...
no nirtogen left



Analog signal processor

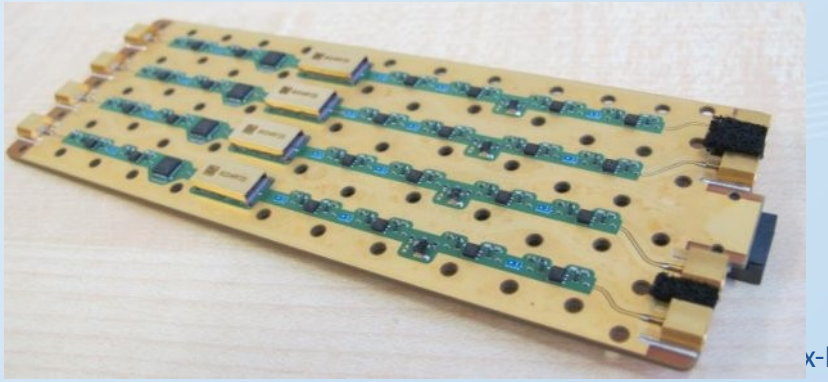


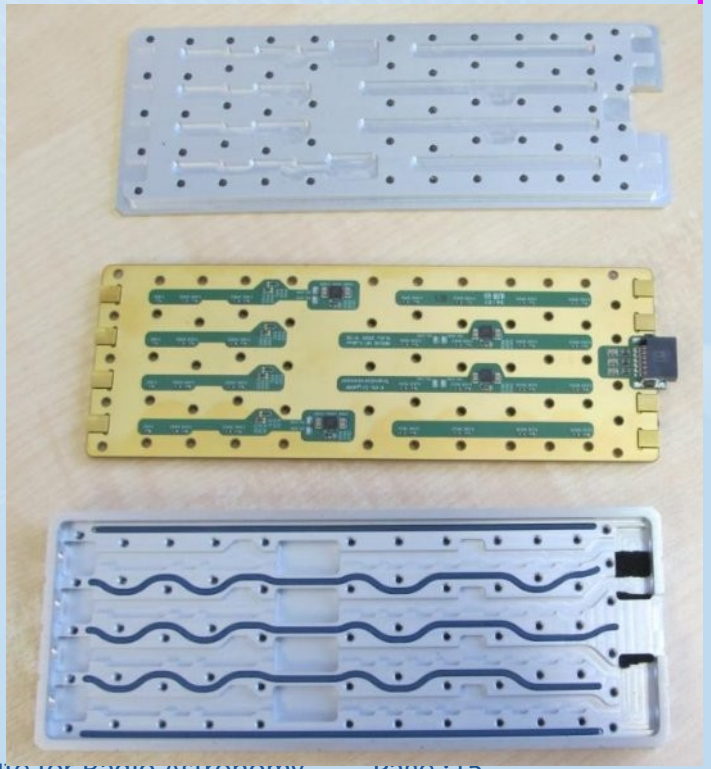
A highly integrated four channel signal processor

- main difficulty for the development was cross talk
  - gain is > 60 dB ⟶ cross talk should be < -60 dB !!
- is fully remote controlled by the digitizer

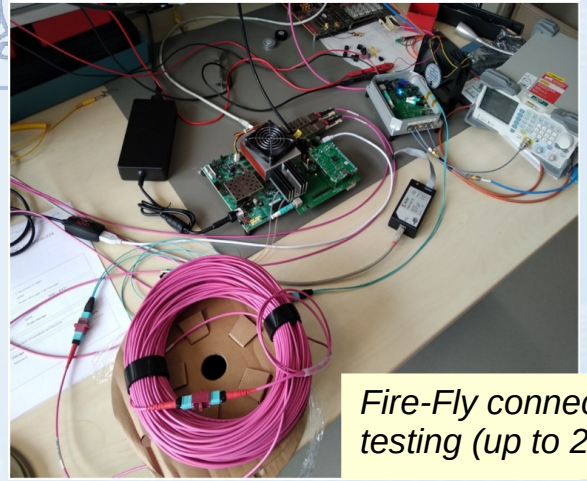
Final Production unit has 8 channels (under development)

- can be 1:1 connected to the digitizer

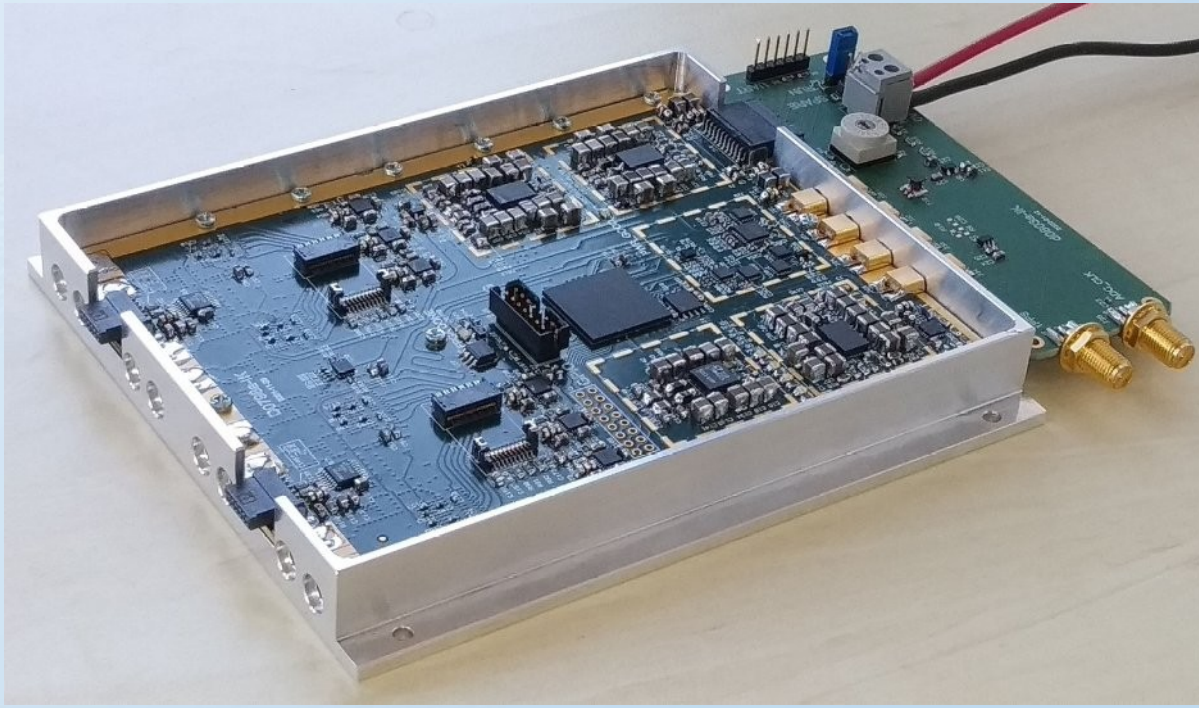




The digitizer

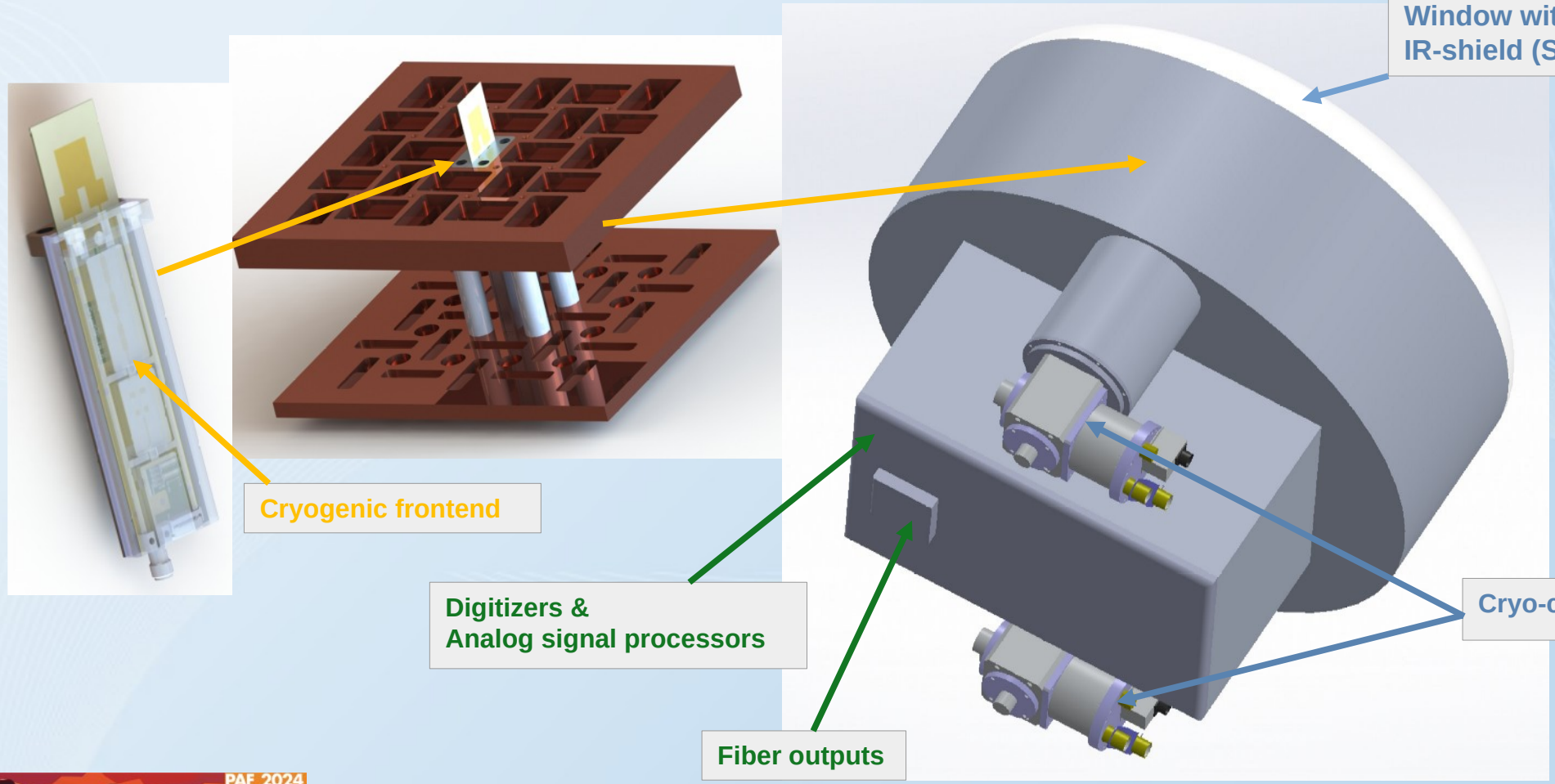


Fire-Fly connection testing (up to 200 m)



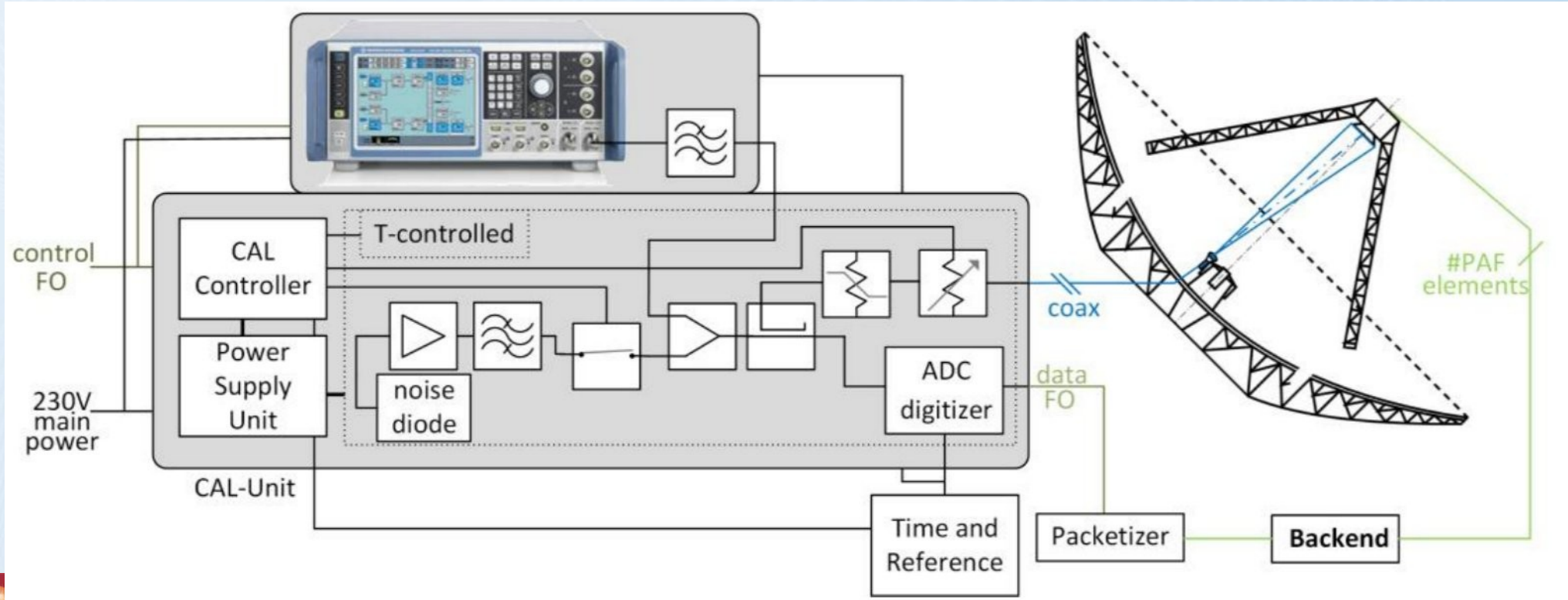
- foot-print and connectors are compatible to analog signal chain
  - can be directly 1:1 connected if required
  - ADC board can handle IO and power of the warm analog signal processor
- four ADCs with 2 inputs each (TI ADC12DJ4000, or ADC12DJ5200)
  - up to 2.0, or 2.6 GHz of bandwidth per channel possible
  - analog input bandwidth up to 5.2 GHz
- FireFly (JESD 204C protocol) connection towards channelizer
- first prototype is ready and currently being tested

The Cryostat (artist impression)



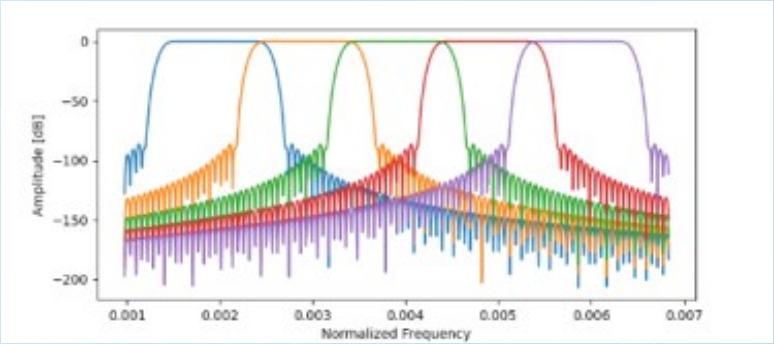
Calibration system

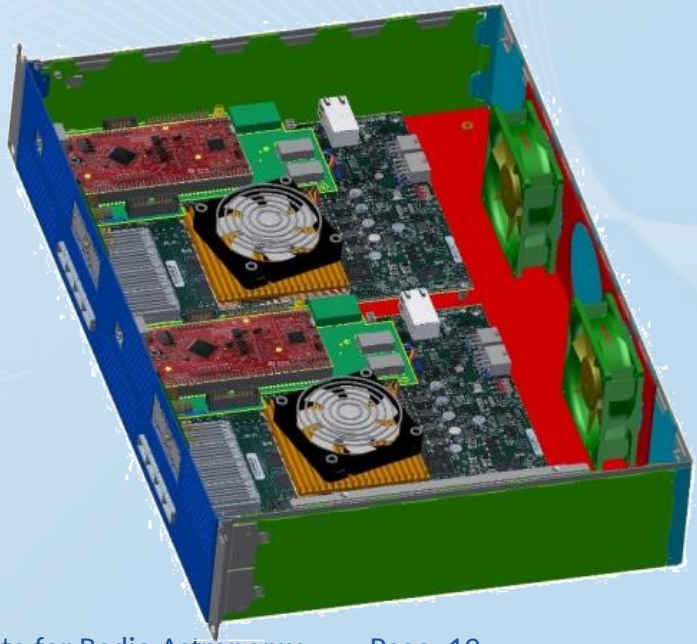
- to ensure relative phase & amplitude stability between the elements
- main layout of the system is ready
  - horn antenna is in production



The channelizer

- Dedicated Faraday cage in the A-Tower
- Channelizer
  - two FPGA boards, power supply
  - 16 ADC input channel in total (via FireFly)
  - over-sampled poly-phase filter-bank for each input
    - up to 2000 channels per input
  - Output: eight 100 GBit Ethernet connections
- Prototype is under test at the moment
- Production of 18 Units has started (all components are ordered)

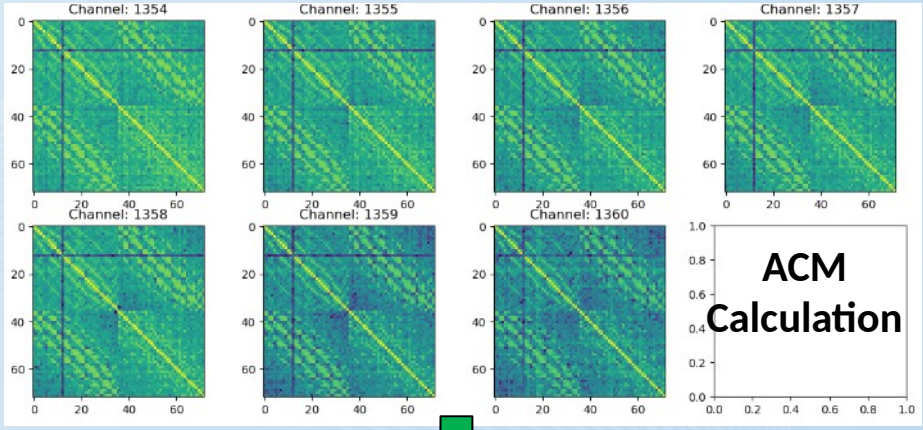


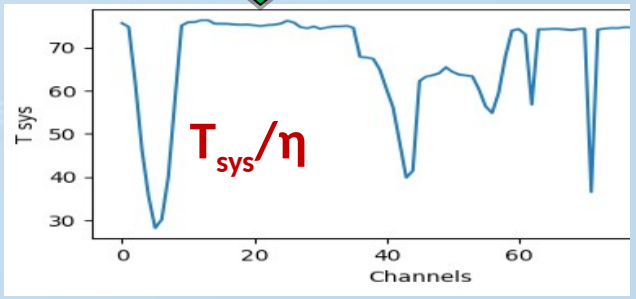


And its new home in the A-tower

Beam-former evaluation

	XILINX	NVIDIA GEFORCE RTX
Pro	●Low latency ●stand-alone device ●Energy saving	●Fast prototyping (PoC) / General Purpose ●Flexibility and less devel effort ●Tensor Core promising technology for CBF processing
Contra	●High development effort ●less flexibility ●Software maintenance	●Batch processing -> latency ●higher energy costs ●Availability
Power	16 kW 17520 kWh/a (12.5%)	36 kW 39420 kWh/a (12.5%)
Size	40 HU; 1.78 m	72 HU; 3.2 m
Est. costs	386,999 €	310,482 €



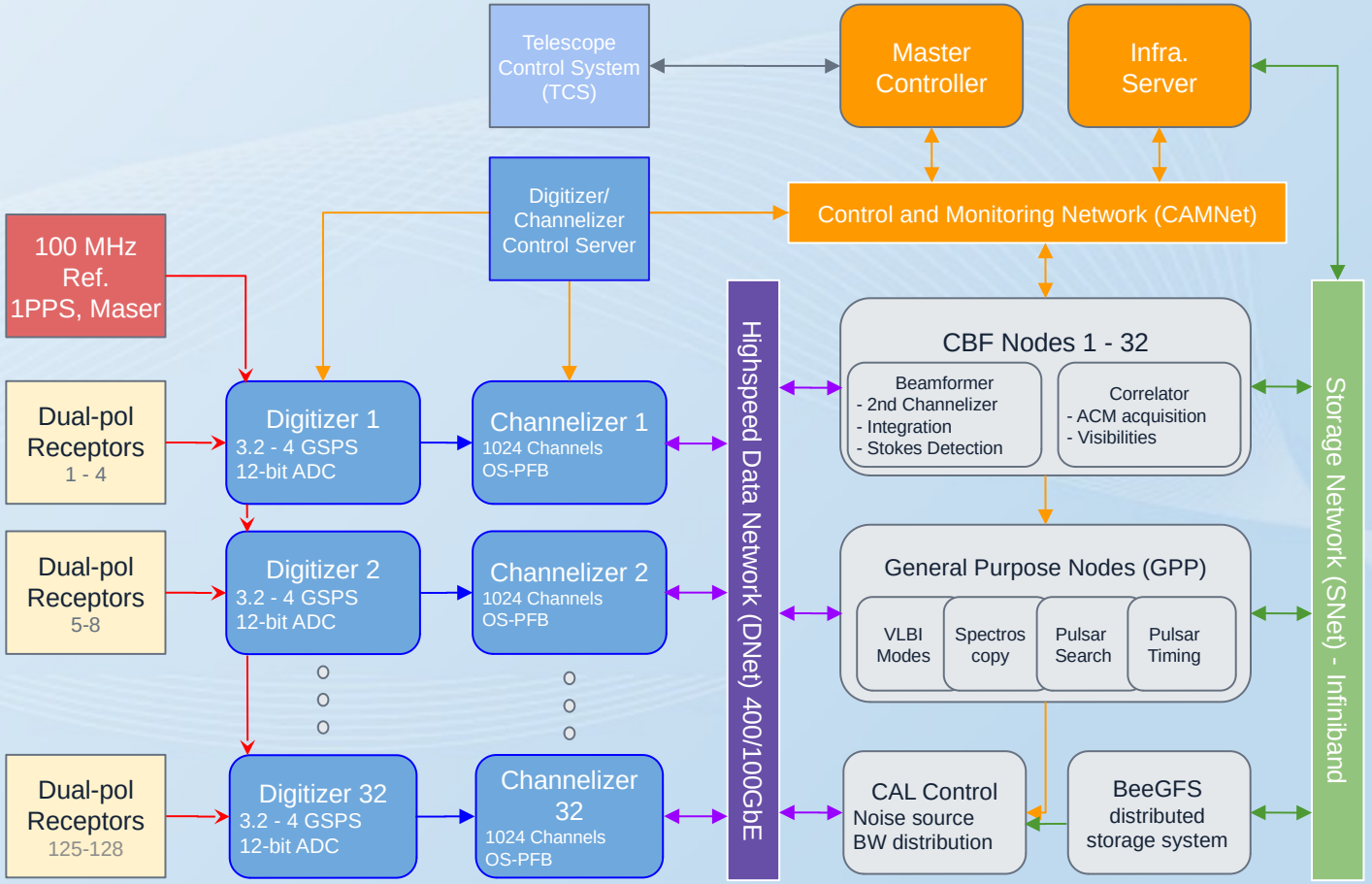


- existing Effelsberg PAF and its GPU cluster was used for a first test
- 36 voltage data streams of the Effelsberg PAF are accessible
  - via modified beam-weights
- first snap-shot data was recorded in December 2020
  - ACMs can be calculated, beam-weight determination algorithms are implemented / tested
- first on sky test-run in July 2021

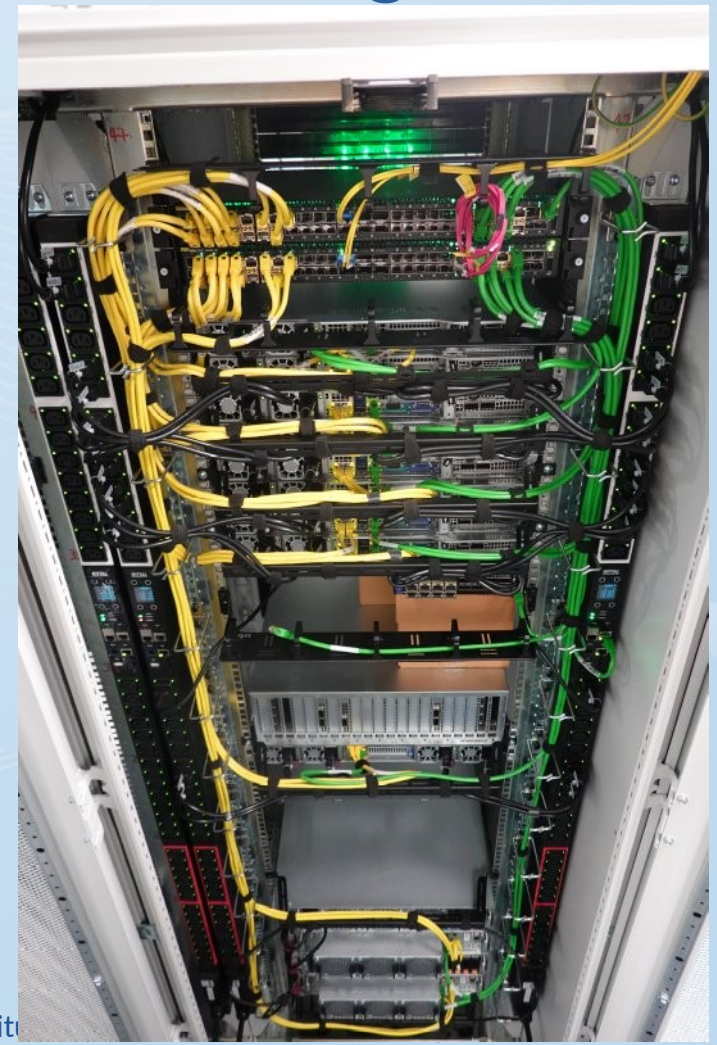
Backend

Key Specs

- Beamformer
  - 128 beams (integrated)
  - 2 x 8 dual-pol beams
- Data-products
  - VLBI (VDIF)
  - Full-Stokes spectra
  - Pulsar timing
  - Pulsar & transient search
- HPC-cluster
  - System can be used as HPC-cluster for data reduction while PAF is not in use



And finally … *EDDGAR* it is arriving …



Conclusions

- The first generation cryo-PAF for the Effelsberg 100 m is on its way
  - using a fully integrated cryogenic frontend
  - separating digitization and first FPGA processor by 100 m
- Most components are ordered
- Telescope infrastructure is ready
- Backend and digitization is in instllation process
  - software is under development and partly even ready for roll out
- Cryostat is coming closer to its final design
  - antenna array is nearly finalized
  - cryogenic frontend is in prototype state (tests are ongoing)