# A Novel Implementation of the Goertzel Filters Bank for Multitonal Signals Channelization in Experimental Physics

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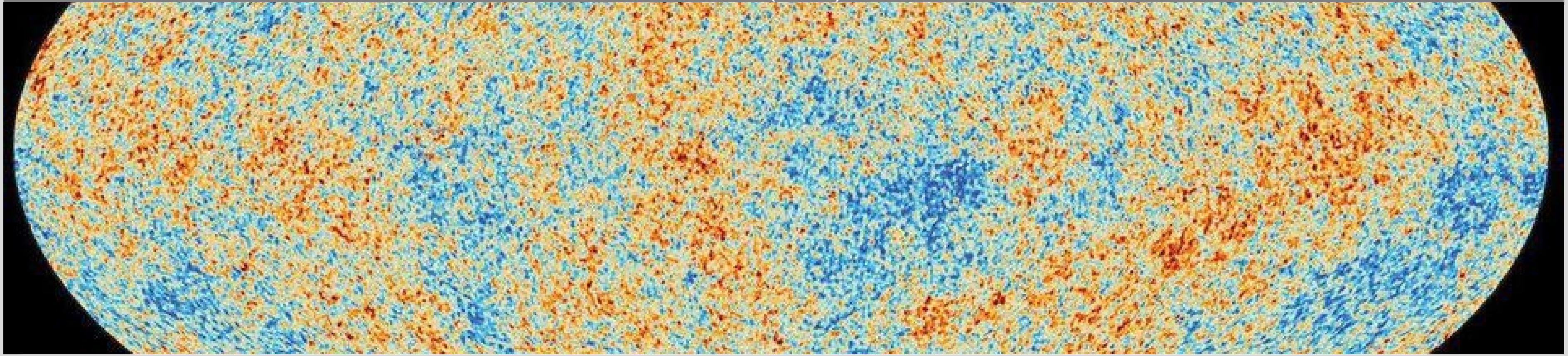


# Outlook

**Introduction:**

- LTDs: Low Temperature Detectors

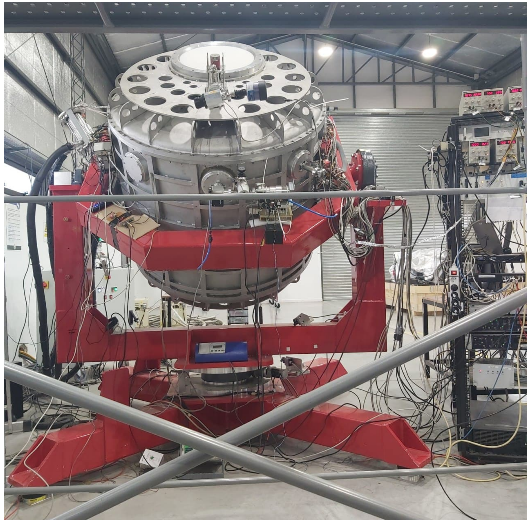
**Hardware R&D:**

- Proposed Read-Out Electronics
- Hardware Prototyping Platforms

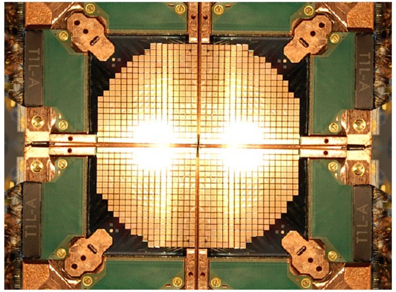
**Digital Backend**

**Preliminary Results**

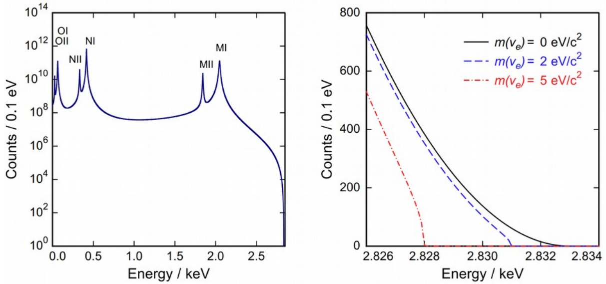
**Summary**



*The QUBIC Telescope at the "Integration Lab." in Salta Province, Argentina.*



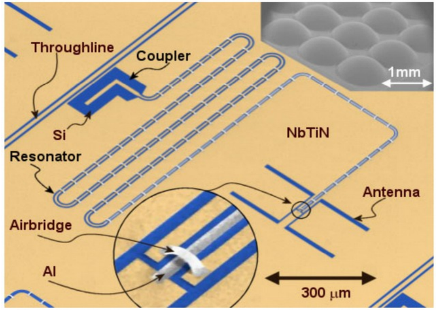
*QUBIC Telescope's (one) focal plane sensor array*



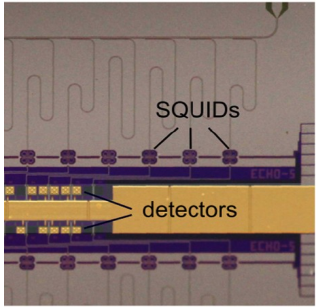
# LTDs: Low Temperature Detectors

- **MKID**: Microwave Kinetic Inductance Detector, can be used as calorimeters or bolometers,
- **MMC**: Metallic Magnetic Calorimeter,
- **TES**: Transition Edge Sensor, can be used as bolometers or calorimeters.

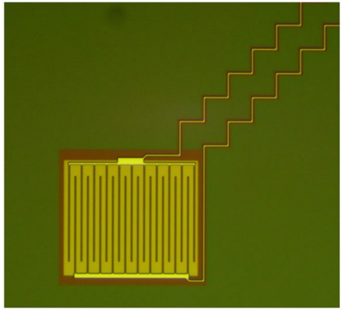
Can be read in two different ways: **T**ime-**D**omain **M**ultiplexing (**TDM**) scheme or in **F**requency-**D**omain **M**ultiplexing (**FDM**)



MKID[1]



MMC[2]


TES[3]

(1) Yates et al., arXiv: 1107.4330
(2) Kempf et al., AIP Advances, 2017
(3) Marnieros, S. et al., J Low Temp. Phys, 2020

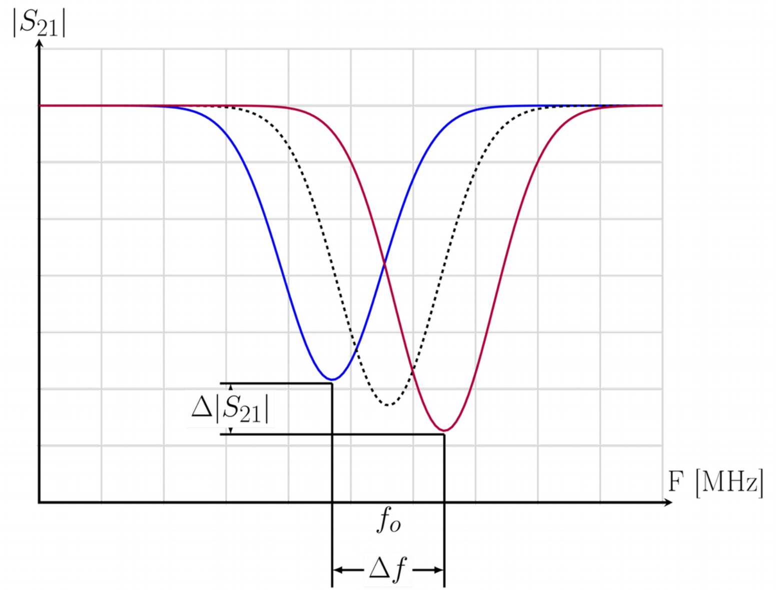
# LTDs: Low Temperature Detectors

How to read them?

# LTDs: Low Temperature Detectors

How to read them? → Microwave SQUID Multiplexers[1]

- Sensors coupled to a resonance circuit → FDM is possible,
- Resonance at some defined *f*.




(1) Kempf et al., AIP Advances, 2017

# LTDs: Low Temperature Detectors

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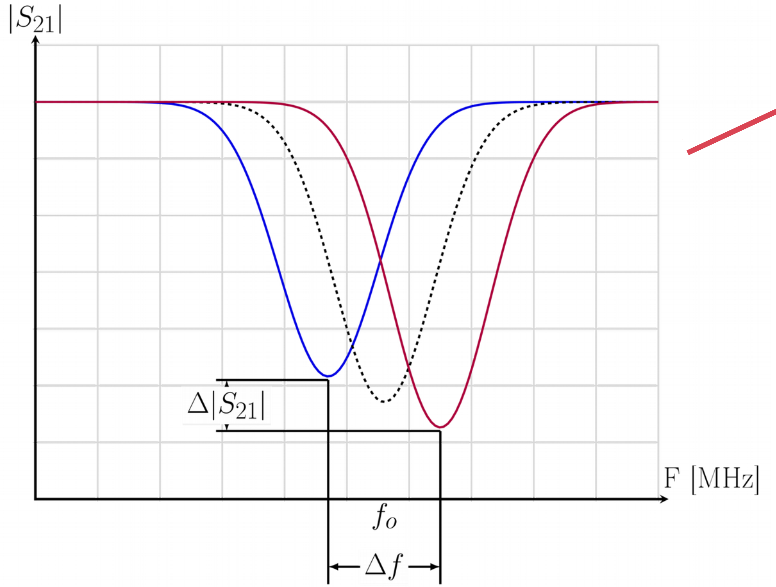
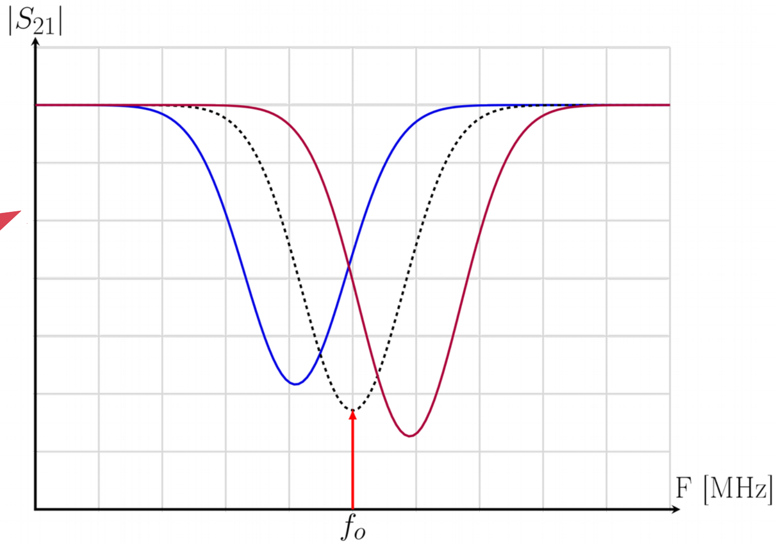


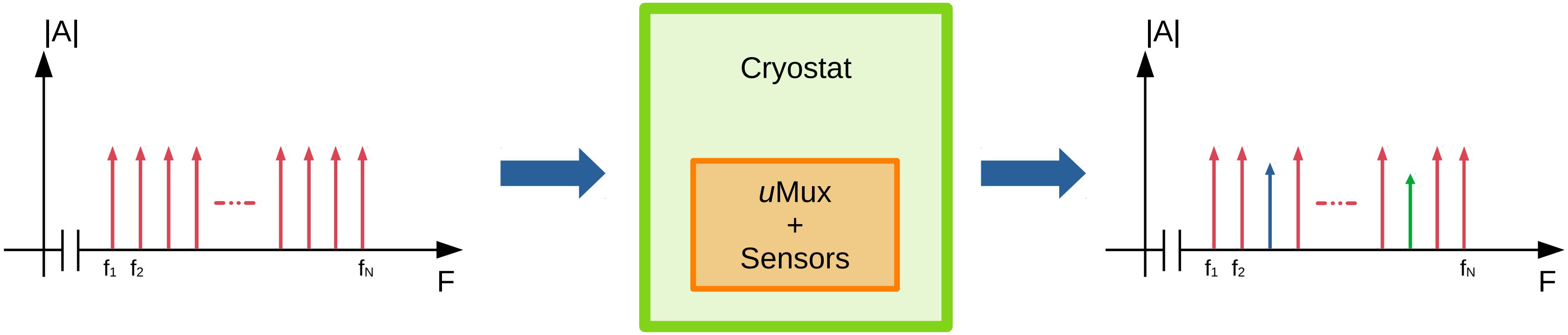

… we need to introduce a signal component in the resonator frequency and read it back!.

(1) Kempf et al., AIP Advances, 2017

# LTDs: Low Temperature Detectors

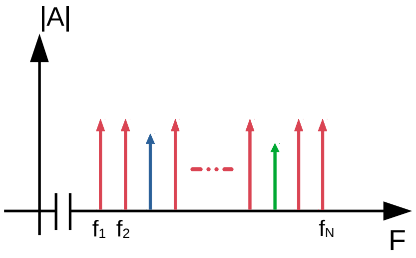
How to read them? → Microwave SQUID Multiplexers(1)

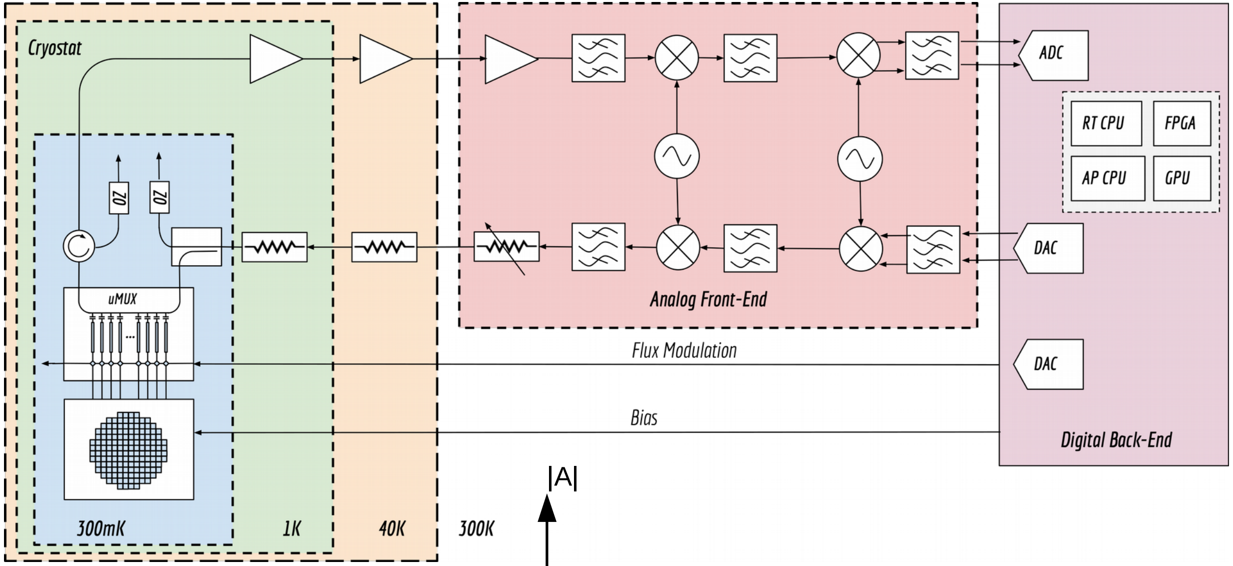
- We generate some multitonal signal (comb signal) with frequencies at each resonator to be read,
- And then we read them back and process the data.




(1) Kempf et al., AIP Advances, 2017

# Read-Out Electronics



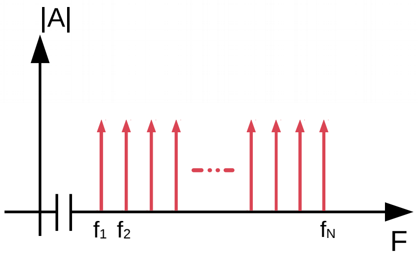




**QUBIC requirements:**

- Nº of Ch. (sensors): 1024 (per focal plane),
- Channel spacing: 4 MHz,
- Signal bandwidth: < 200 kHz.

**ECHo requirements:**

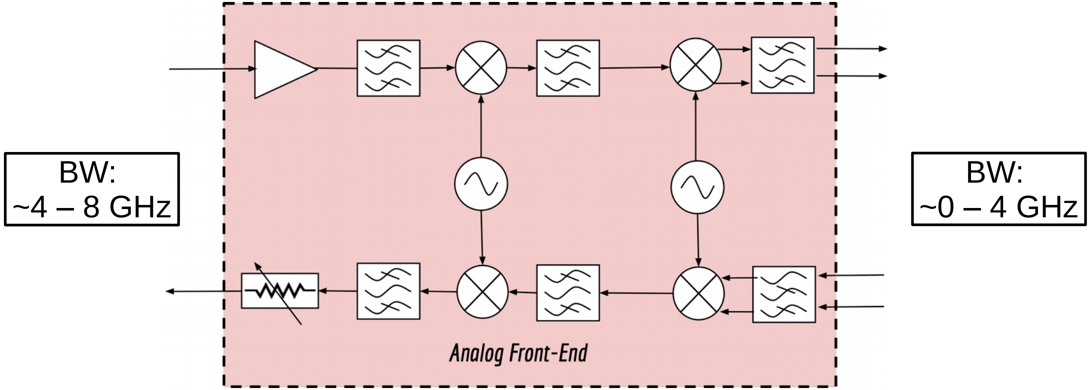
- Nº of Ch.: 6000,
- Channel spacing: 10 MHz,
- Signal bandwidth: ~1.6 MHz

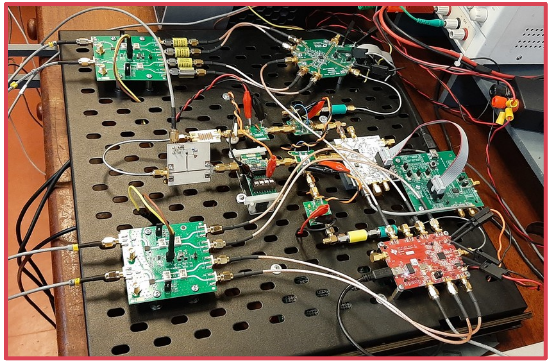



**Using commercial instruments**:

- R&S FSW, 5 GHz BW Spectrum Analyzer → Price: ~ 200.000 euros, (and then we need to solve the storage of 5 GHz acquisition, develop scripts, software, and even though it's not *real-time processing*).

# Radio Frequency Front-End (RF-FE)



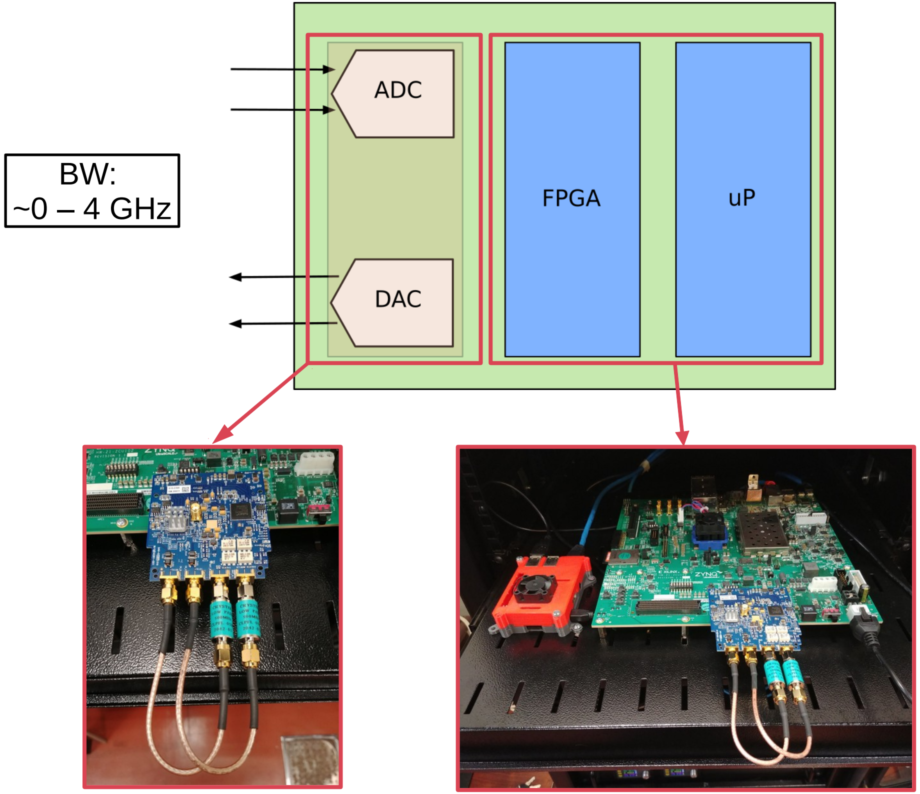



**Main goal**:

- perform the up-conversion (from ~0 – 4 GHz to ~4 GHz – 8 GHz) and down-conversion (the way back), maintaining a high signal-to-noise ratio (SNR) in both ways adapting the signals to and from the cryostat.

- Merge/split the spectrum from each mixing stage (which come from and goes towards to, the conversion chips: ADCs and DACs)

# Digital Electronics Back-End (DE-BE)




**Main goal**: generate base-band (BB) multitonal signals, deliver them to the RF-FE, read them back after the RF-FE down-converts the *result* and perform the pre-processing of the samples.

- <u>Converters board:</u> AD-DAQ2FMC (from Analog Devices):
  - ADC: AD9680 @ 1 GSPS (14 bits)
  - DAC: AD9144 @ 2.8 GSPS (16 bits)
- <u>Xilinx ZCU102:</u>
  - Zynq UltraScale+ MPSoC (9eg)

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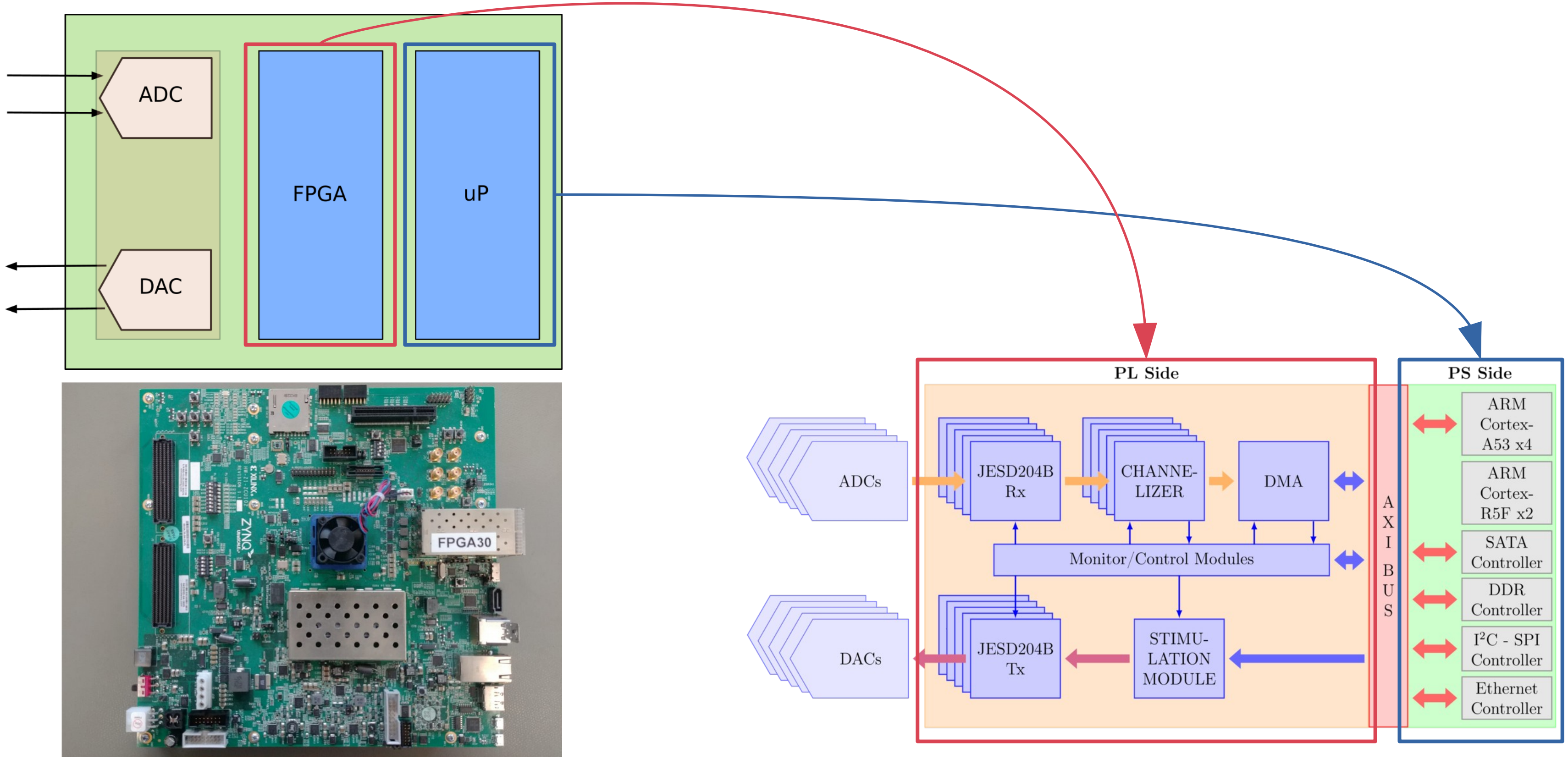

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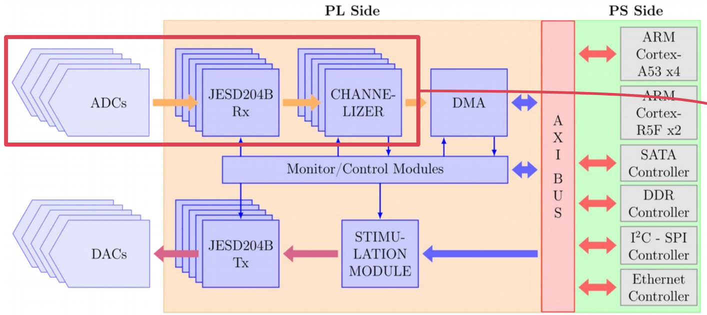
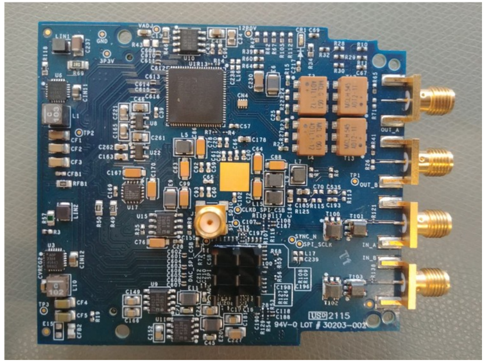
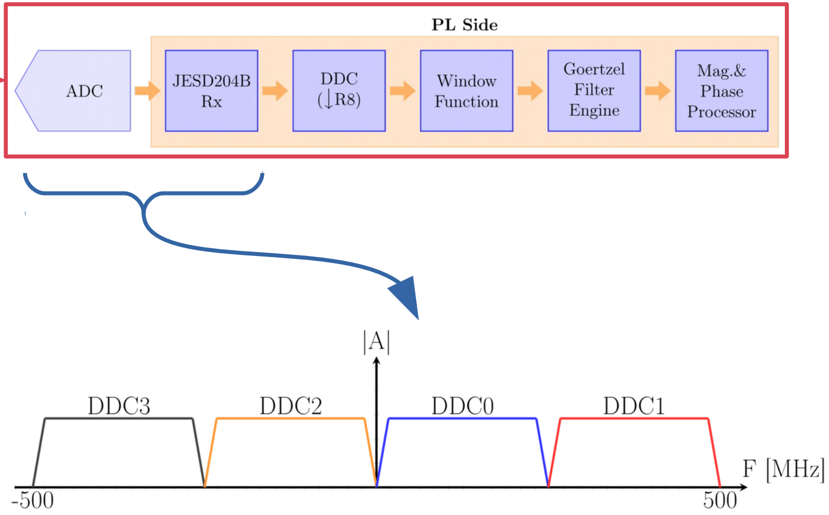


*AD-DAQ2FMC board*




- ADCs decimation capabilities: x4
  - From 1 GSPS → 4 channels @ 250 MSPS
- Final design:
  - 4 channels x 5 ADCs = 20 channels @ 250 MSPS

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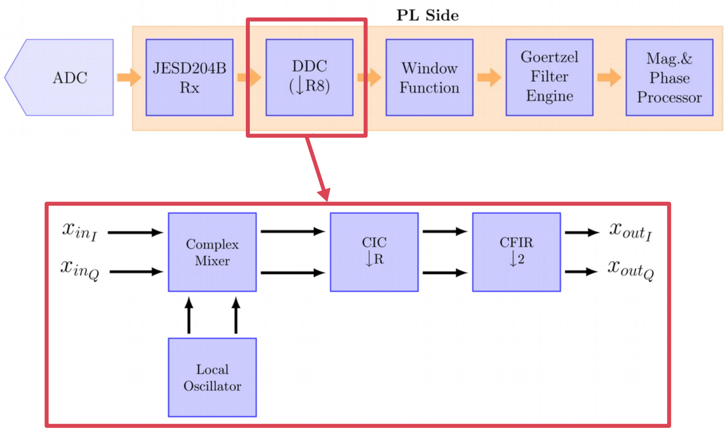

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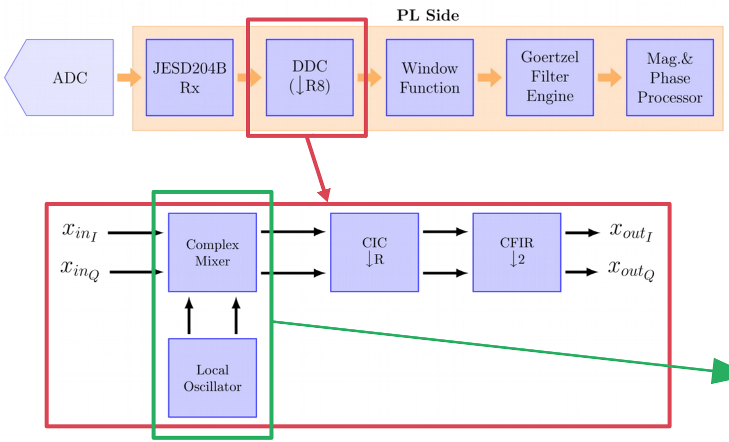


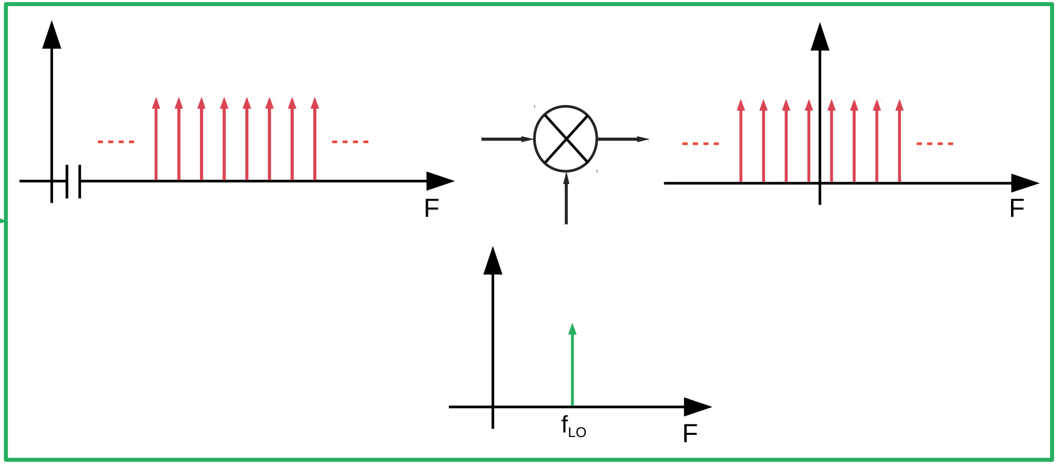




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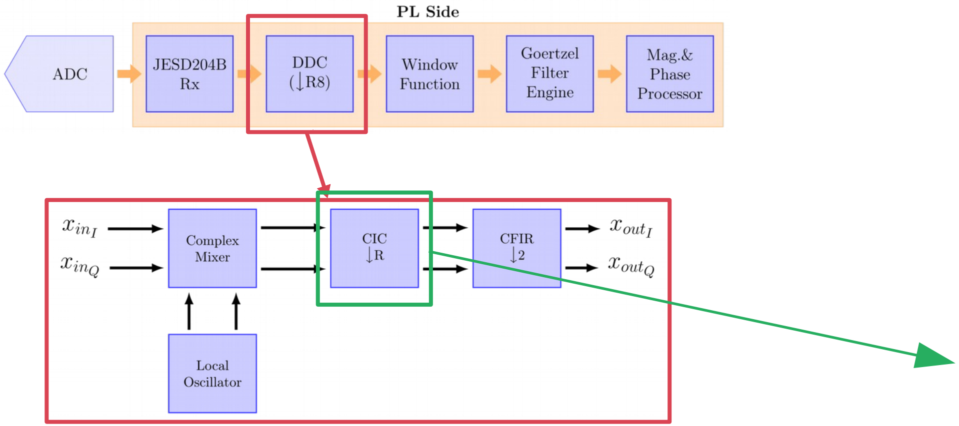


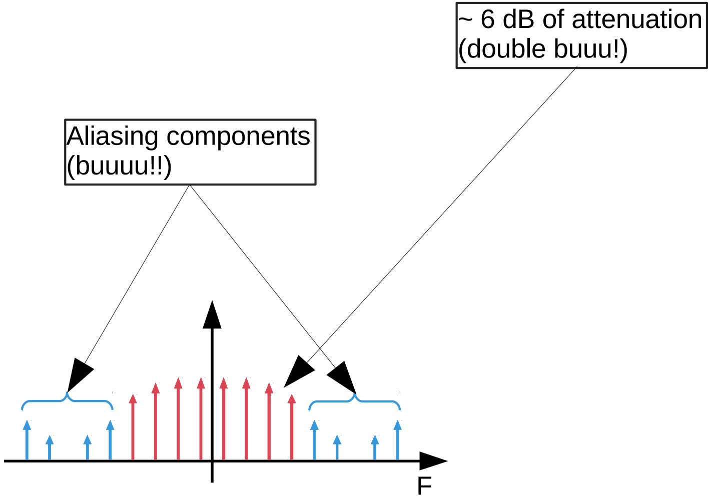

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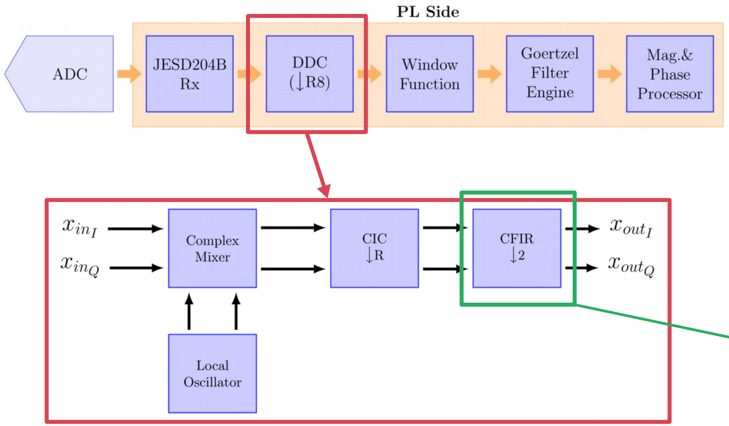


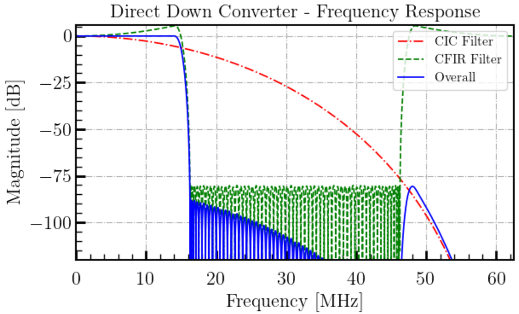


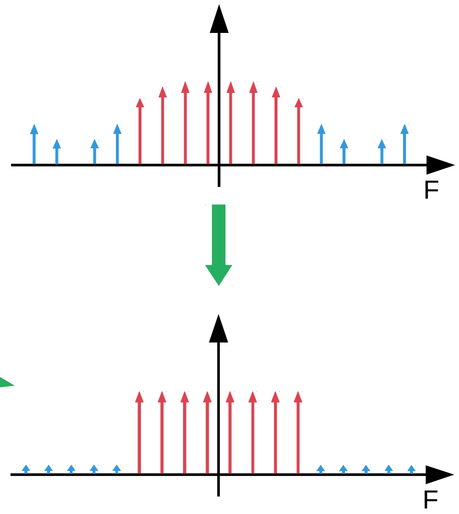


- Input sampling freq.: 250 MSPS,
- After CIC Decimation: 62.5 MSPS (with aliasing and undesired 6dB att.),
- After FIR Compensation Decimation filter:
  - 31.25 MSPS,
  - Compensated 6 dB,
  - Aliased components attenuated by 80 dB (as minimum).

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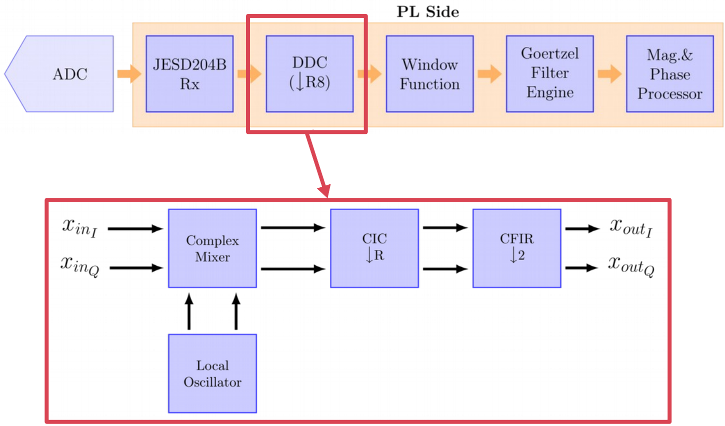


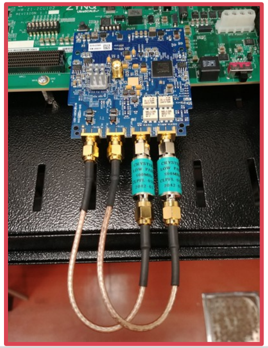

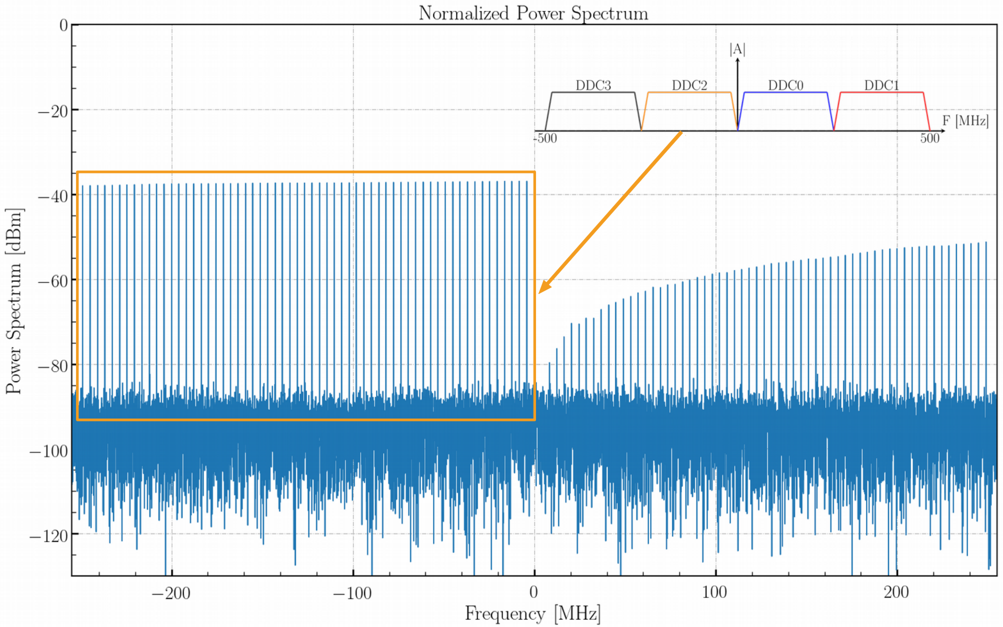


- Generated multitonal signal (I/Q modulated) with equally spaced (4 MHz) components from -250 MHz to 0 Hz

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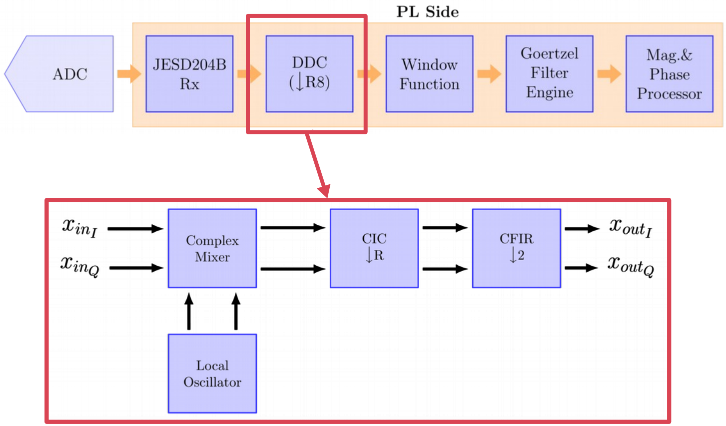


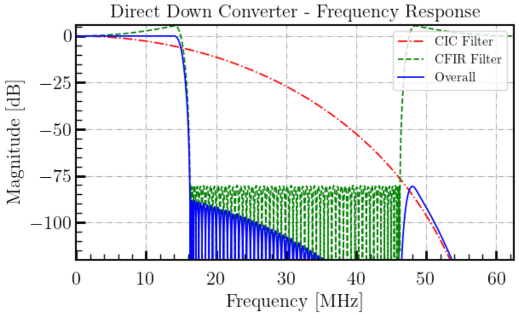


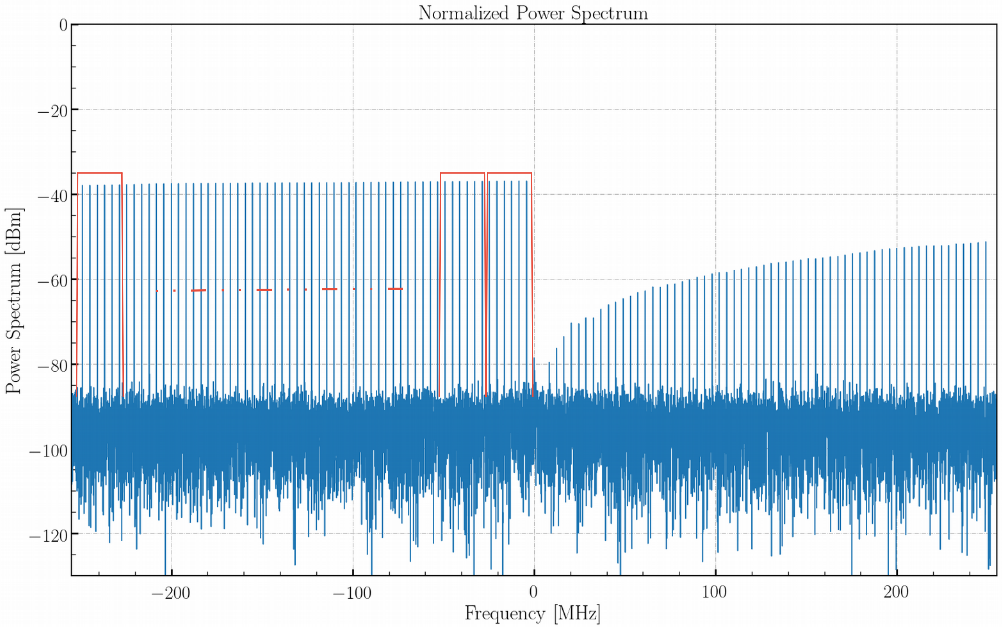


- Implemented 8 DDCs to cover the whole input

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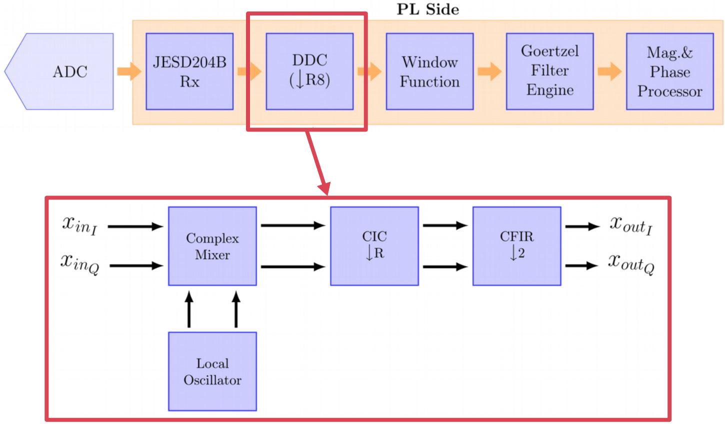


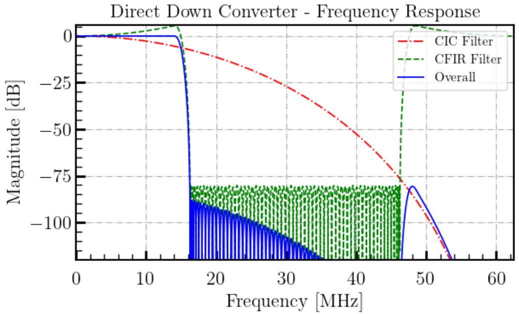


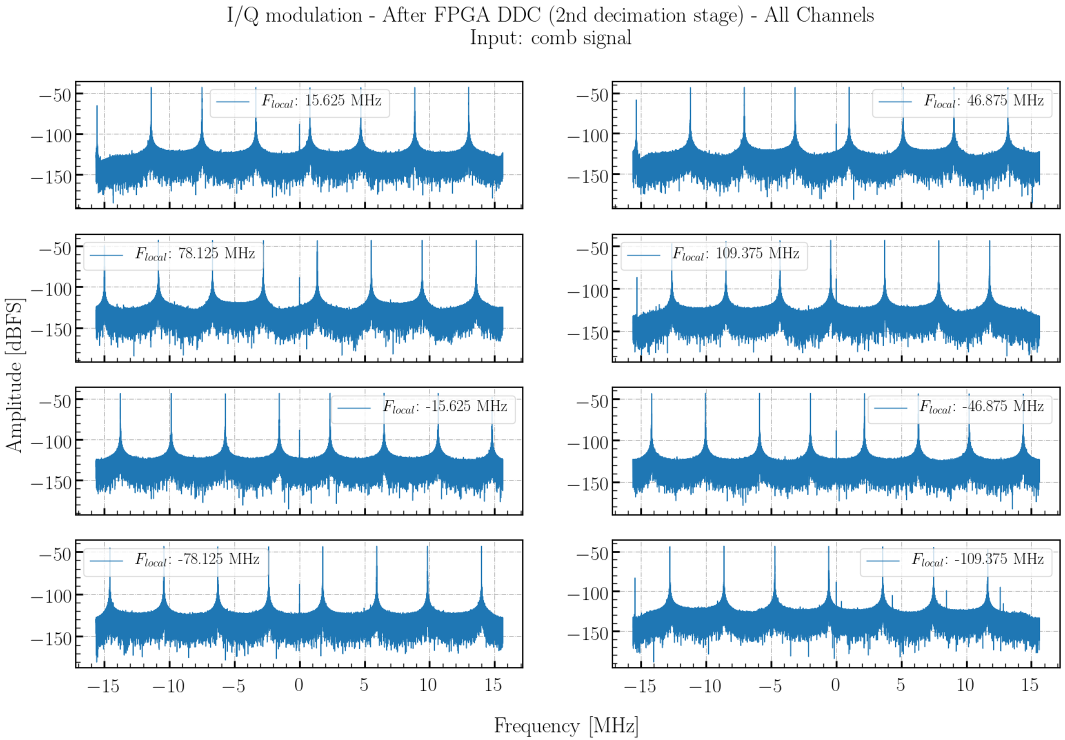

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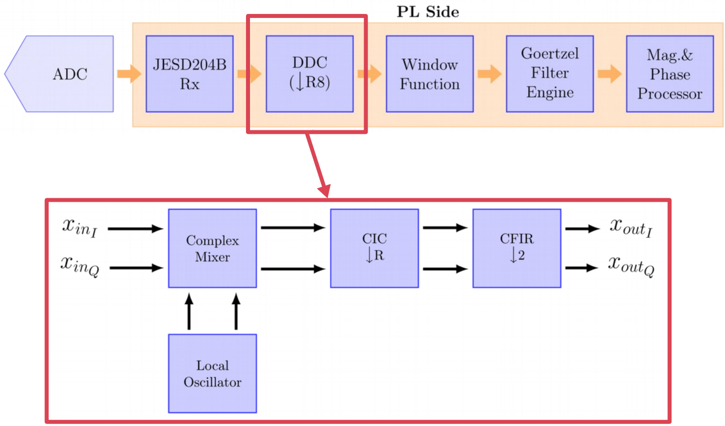


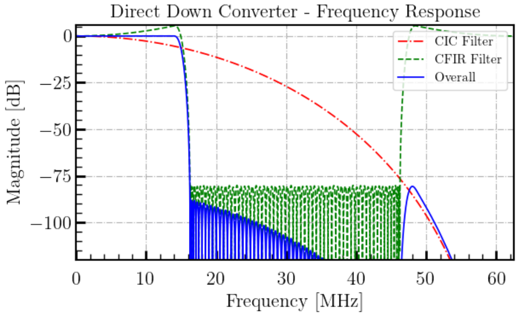


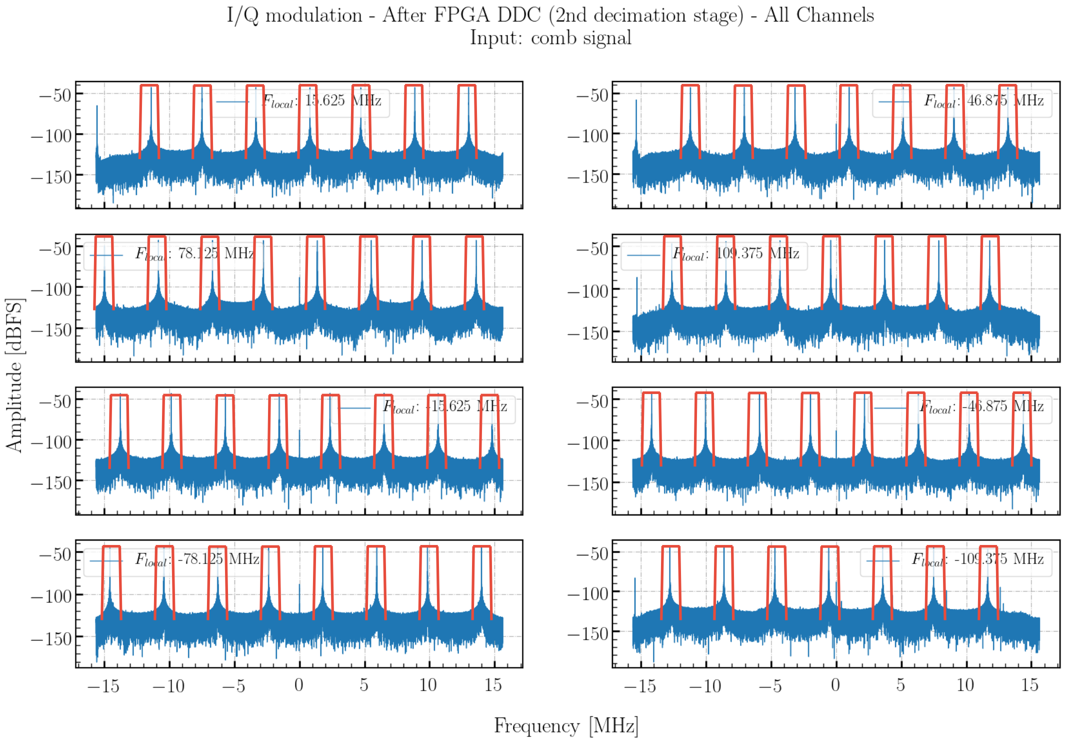

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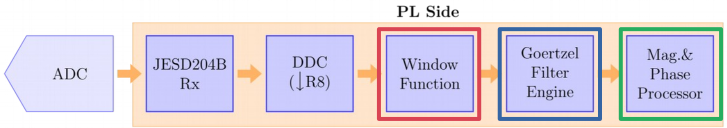


- The Goertzel Filter[(1)(2)] allows as to calculate one *desired* **bin** of the Discrete Fourier Transform (DFT)

(1) “An Algorithm for the Evaluation of Finite Trigonometric Series”, Goertzel G., 1958, AMM, 65(1): 34-35.

(2) Sysel, P., Rajmic, P. Goertzel algorithm generalized to non-integer multiples of fundamental frequency. EURASIP J. Adv. Signal Process. 2012, 56 (2012)

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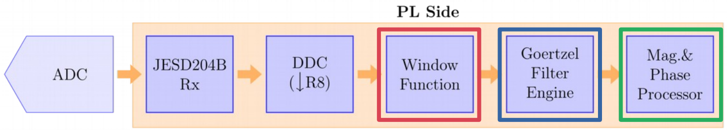


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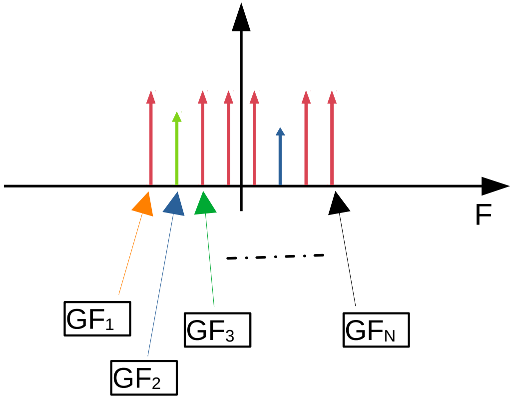


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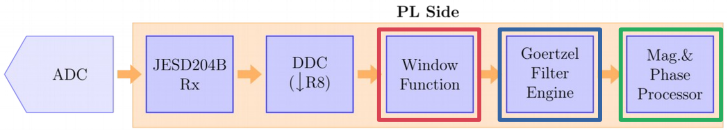


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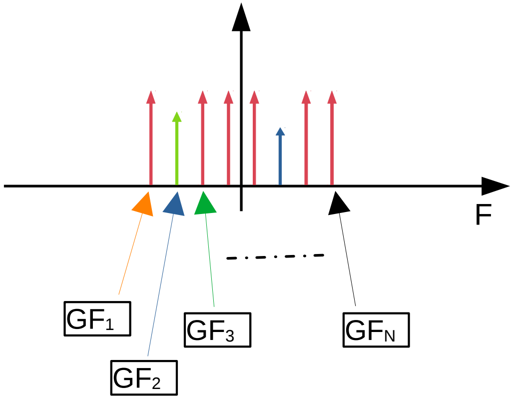


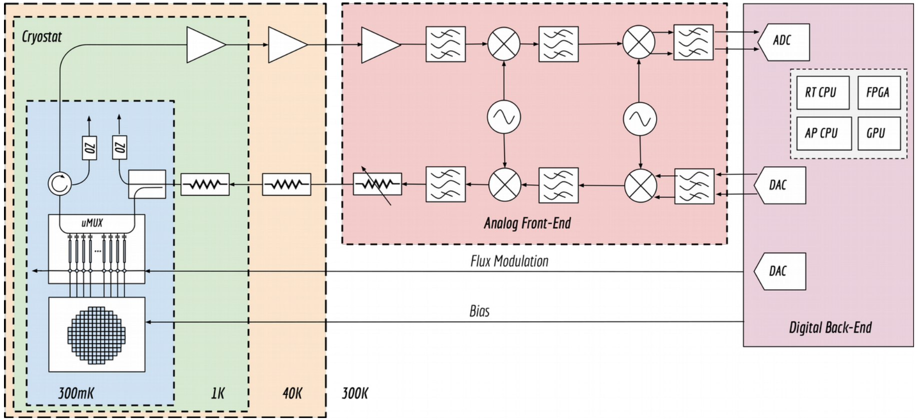


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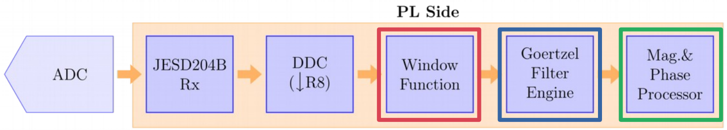


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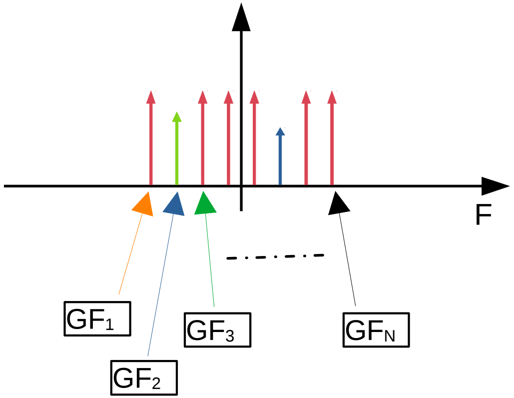


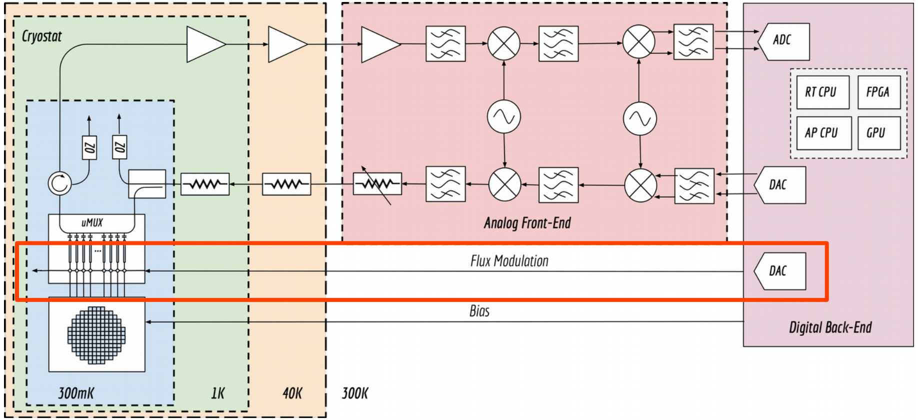


- Flux-Ramp Modulation method

(Mates, J.A.B. et al, J Low Temp. Phys 167, 2012)

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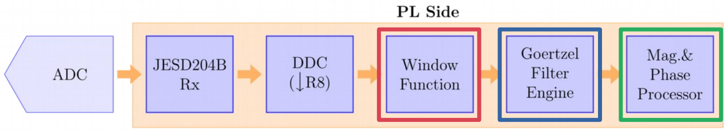


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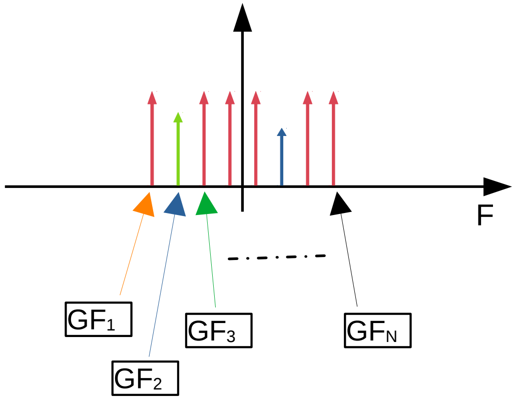


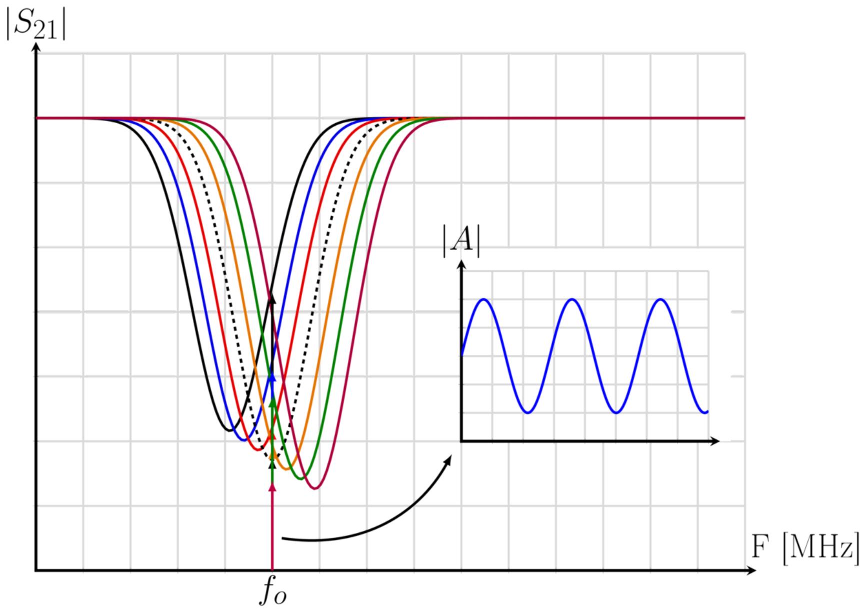


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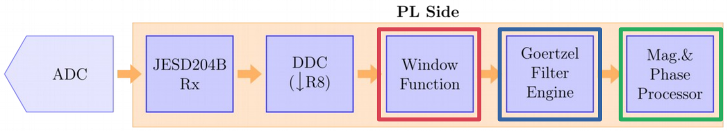
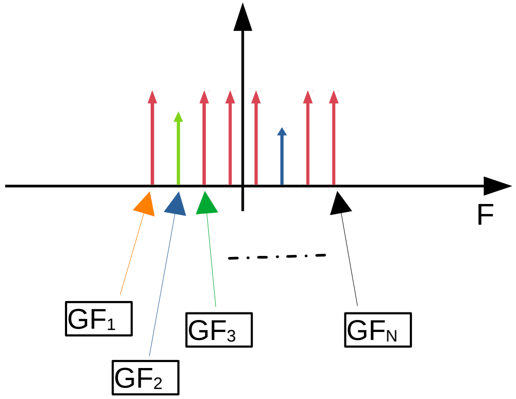
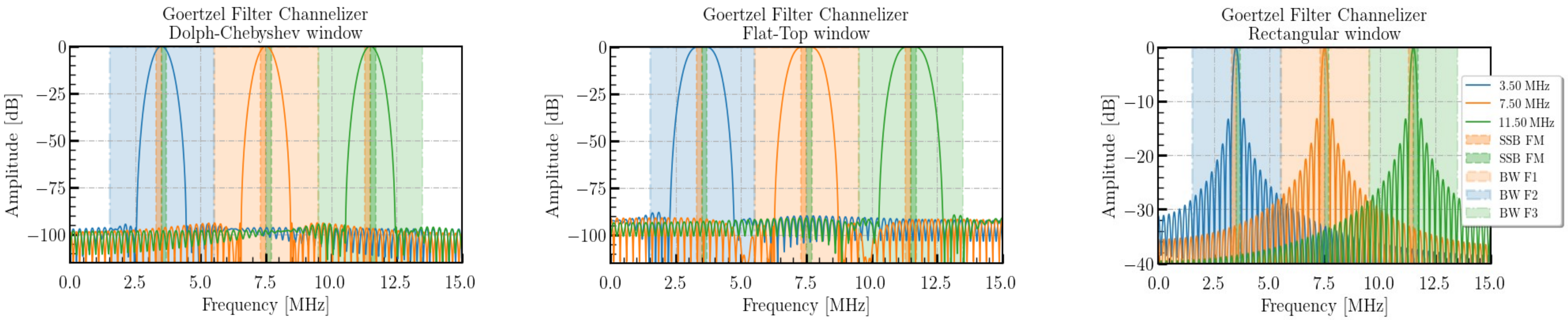



- The Goertzel Filter(1)(2) allows as to calculate one *desired* **bin** of the Discrete Fourier Transform (DFT),
- It's conformed of the last 3 marked modules,
- Window functions allows as to improve or modify the way we retrieve (or *see*) the spectrum, in particular for **channelization procedures**: isolation between channels and flatness within bandwidth of interest.



# Preliminary Results

Resource consumption of main modules

| Direct Down Converter | | | |
|---|---|---|---|
| Component | DSP | LUTs | BRAM / LUT |
| Complex multiplier | 3 | 92 | - / - |
| CIC Decimation filter | - | 999 | - / - |
| FIR Compensation Filter | 16 | 160 | - / 398 |
| Local Oscillator | - | 118 | 2 / 2 |
| **Total** | **19** | **1373** | **2 / 400** |

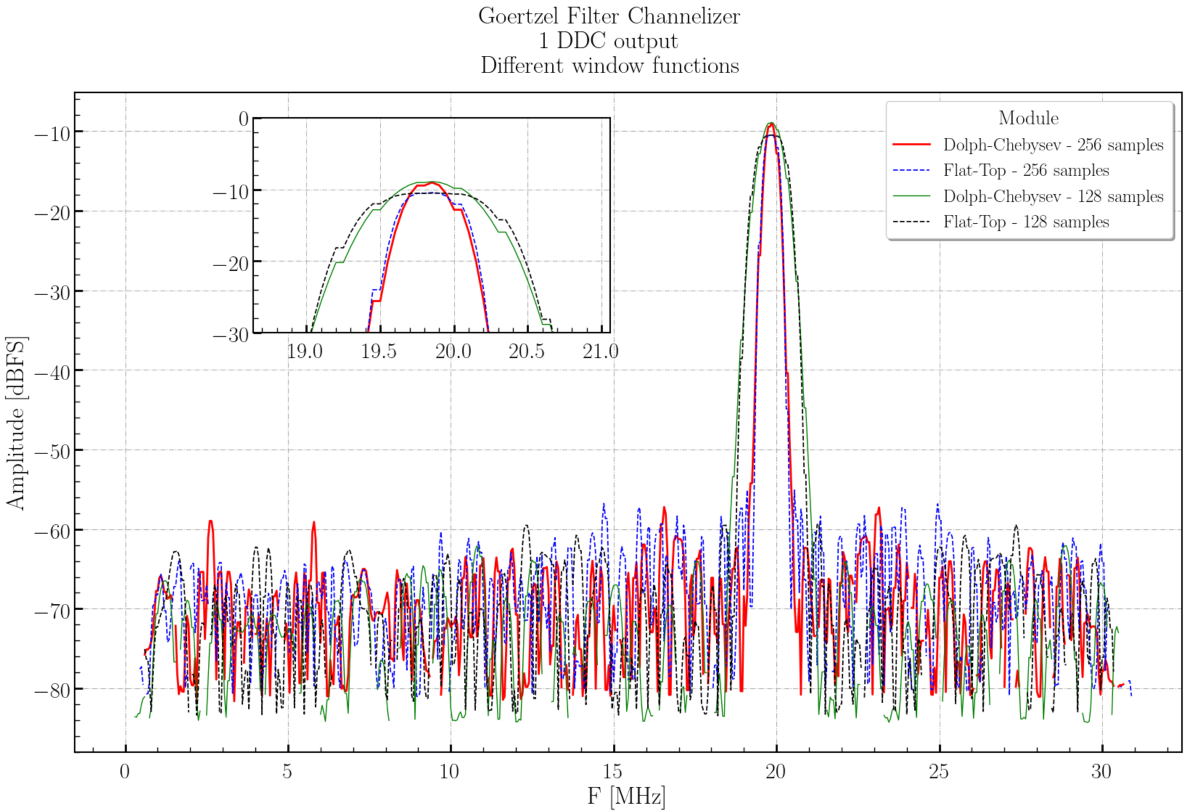
| Goertzel Filter Bank | | | |
|---|---|---|---|
| Component | DSP | LUTs | BRAM |
| Iterative section | 2 | 229 | - / 94 |
| Non-iterative section | 12 | 322 | - / 96 |
| **Total** | **14** | **551** | **- / 190** |

| Window Function | | | |
|---|---|---|---|
| Component | DSP | LUTs | BRAM / LUT |
| **Multiplication array** | **2** | **60** | **4 / 1** |

Current benchmark:

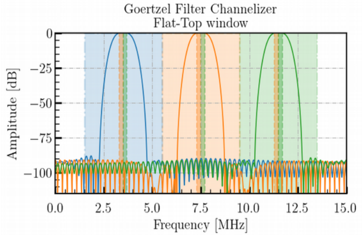
- logic@250 MHz → ~1 DSP Slice / channel (tone)
- logic@500 MHz → ~0.5 DSP Slice / channel (tone) (will be investigated)

# Preliminary Results

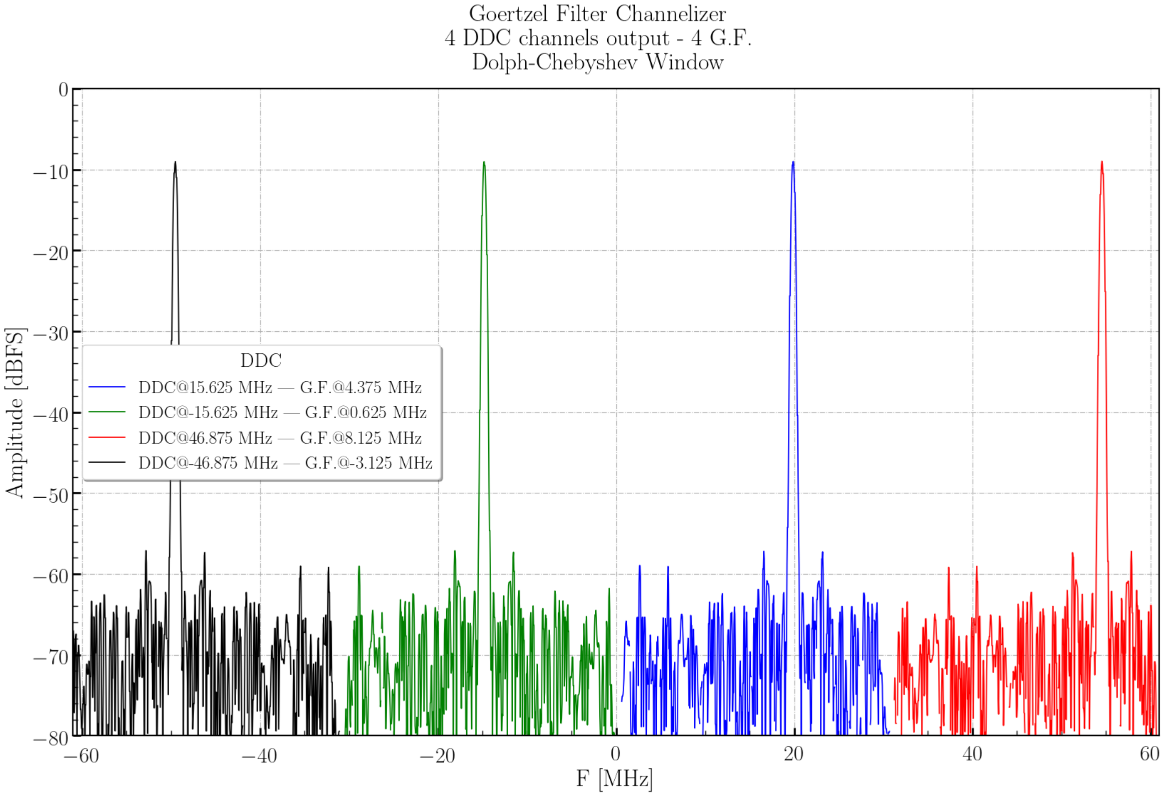



Perfomance with different window functions:

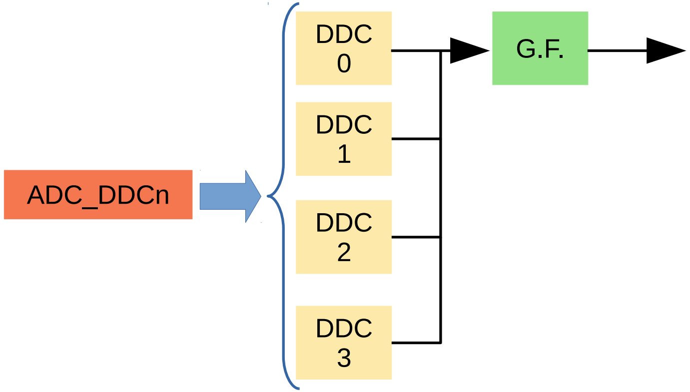
- Implemented firmware: 4 DDCs with 1 G.F. module → 4 tones to be processed in parallel,
- Frequency sweep: -61 MHz to 61 MHz (step = 0.05 MHz),
- 2 window functions:
  - Dolph-Chebyshev,
  - Flat-Top.
- 2 different window sizes:
  - 256 samples,
  - 128 samples.



# Preliminary Results

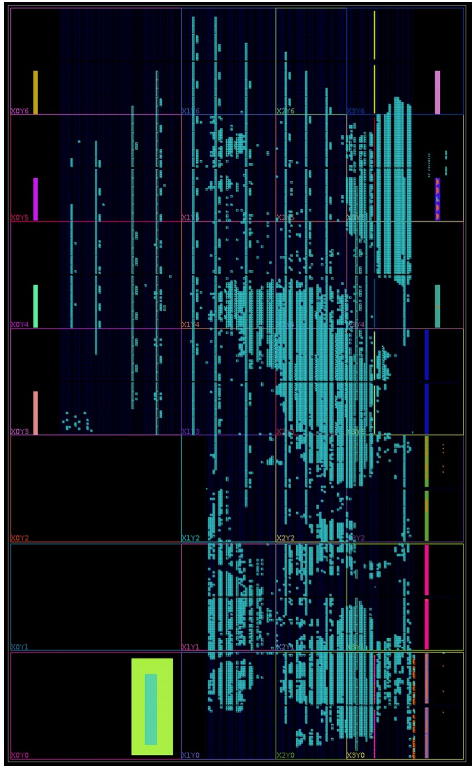



- Output of 1 G.F. module after the frequency sweep,
- Each colour represents a DDC (firmware).



# Summary

- Current prototypes showed very good preliminary results
  - Update the DE-BE design to work at 500 MHz in critical parts (FIR and GF) → will considerably reduce DSP Slices.
- Control software based on ServiceHub(1) is under development,
- Proof of principle **successfully built** and now is under **testing**,
- The combination of two levels of DDC stages allows the approach to give a **first level** of flexibility in order to attack the regions where the *information really is*,
- Adding the Goertzel Filter (bank) adds a **second level** of flexibility in order to only retrieve the desired components from the input signal, reducing the requirements in the storage afterwards,
- The combination of the two previous points implement a **highly flexible and scalable** approach, that also allows to double (or more) the density in one or any desired band without the necessity of **re-synthesis and re-implement** the design (a task that for large design usually takes several hours).



(1) "Versatile Configuration and Control Framework for Real time Data Acquisition Systems", N. Karcher et al, IEEE Transactions on Nuclear Science, 2021

Vielen Dank :)