Recent developments in frequency domain multiplexing

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Outline

- Frequency domain multiplexed readout building blocks
- Building a prototype: European/Japanese EURECA collaboration
- Status building blocks
- Increasing the number of channels
- Summary

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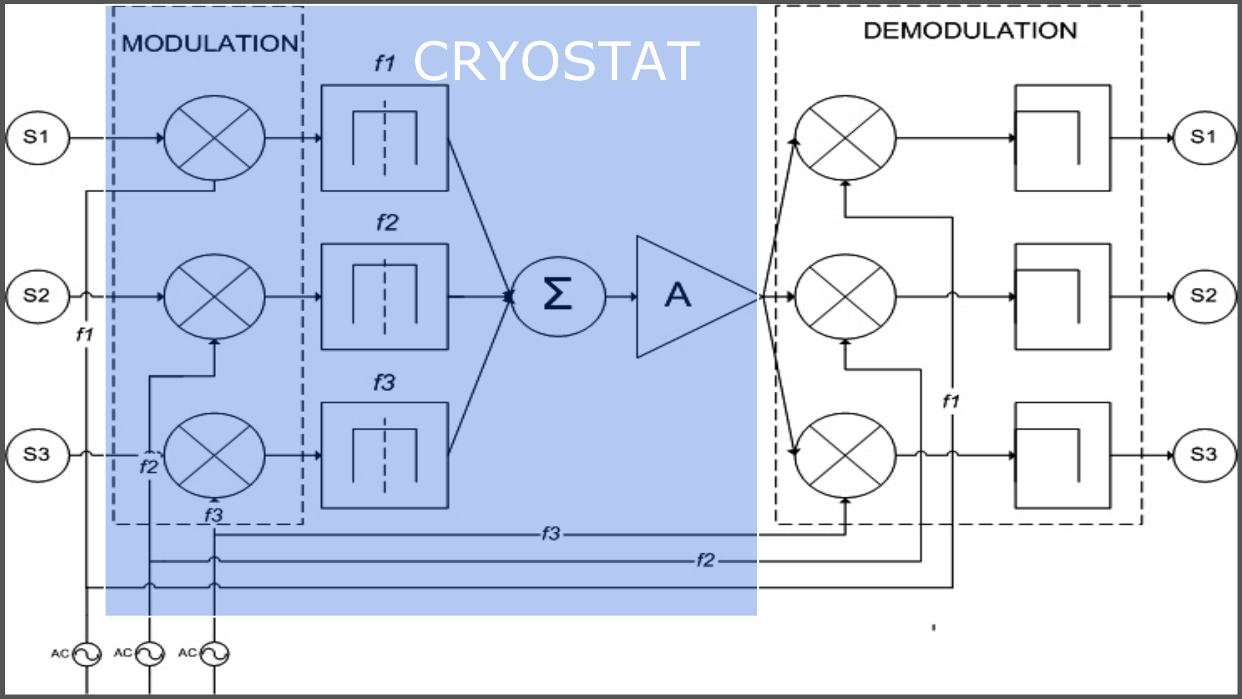
FREQUENCY-DOMAIN-MULTIPLEXING

Key characteristics:

- TESs act as AM-modulators of bias power
- Bias power sources separated in frequency space (i.e TESs AC-biased at frequencies *f1, f2, f3*, ….)
- LC band pass filter per pixel to prevent addition of wide-band noise
- Summed signal read-out by one SQUID-amplifier per column

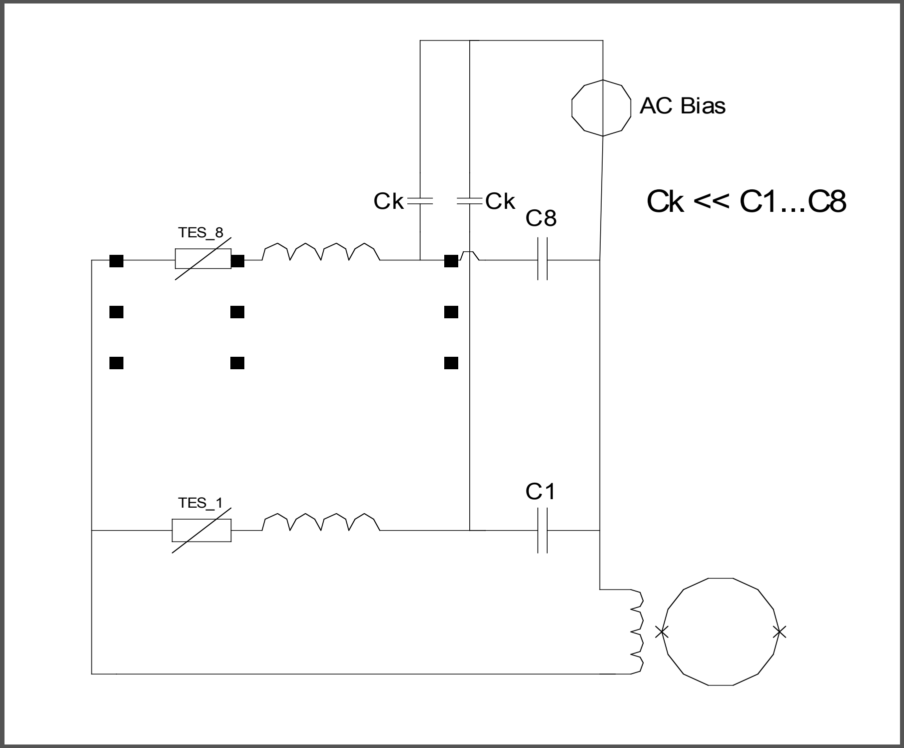


FDM compatible TES bias circuit

Dissipation-less voltage source

Capacitive voltage divider, instead of classical resistive voltage division

- Functional equivalent with resistive divider
- No extra dissipating element at base temperature
- Lower Q-requirements for capacitor



Building a prototype: the EURopEan Calorimeter Array (EURECA) Project

AIMS and Motivation:

- Design, build, and test of a prototype X-ray Imaging Spectrometer to demonstrate technical feasibility/readiness for a cryogenic space instrument by end 2007
- Use EURECA as a vehicle to breed a European/Japanese collaboration that is able and interested to deliver a cryogenic instrument for imaging X-ray spectroscopy
- Open up the potential to participate in future missions, like ESA's XEUS (>2020), NASA's Con-X (>2020), future Japanese missions like NEXT (2015) and DIOS (2012), Italian's Estremo (2015), Dutch NEW (2015)
- Acquire development funding at (multi) national level

EURECA Project Contibutions/Partners

ADR Cooler	
• Commercial ADR (Janis)	PSI (Zürich)
• Flight type ADR	MSSL (London)
Detectors	→SRON
• Si-micromaching	MESA (UTwente)
• Development + tests	TMU (Japan), INFN(Genua), INAF(Rome), KIP (Heidelberg)
• Mo-based bilayers	IMM(Madrid), ICMA(Barcelona, Zaragossa)
LC-filters	→SRON
• Alternative routes	INA + ICMA (Zaragossa)
SQUIDs	
• Three routes	PTB (Berlin), VTT (Helsinki), SII (Tokyo)
Electronics	→SRON
• LNA	VTT (Helsinki)
• AC-BIAS + C&C	PSI (Zürich)
• Cold FLL	Alcatel Alenia Space (Milano)
• Data Acquisition (BESSY)	X-ray Astronomy (Leicester)
Data analysis software	
• System	IFCA(Santander), MSSL(London), Astr. Obs (Geneva)
• Algorithms	X-ray Astronomy (Leicester)

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Prototype development items

- EMI Shielding
- Microcalorimeters (tomorrow)
- LC bandpass filters
- SQUIDs
- Cryogenic detector unit
- SQUID front-end electronics
- AC bias source electronics
- Demultiplexing electronics
- Data analysis/processing

Approach:

- Conservative baseline system
- lumped elements, which can be exchanged once better parts are available

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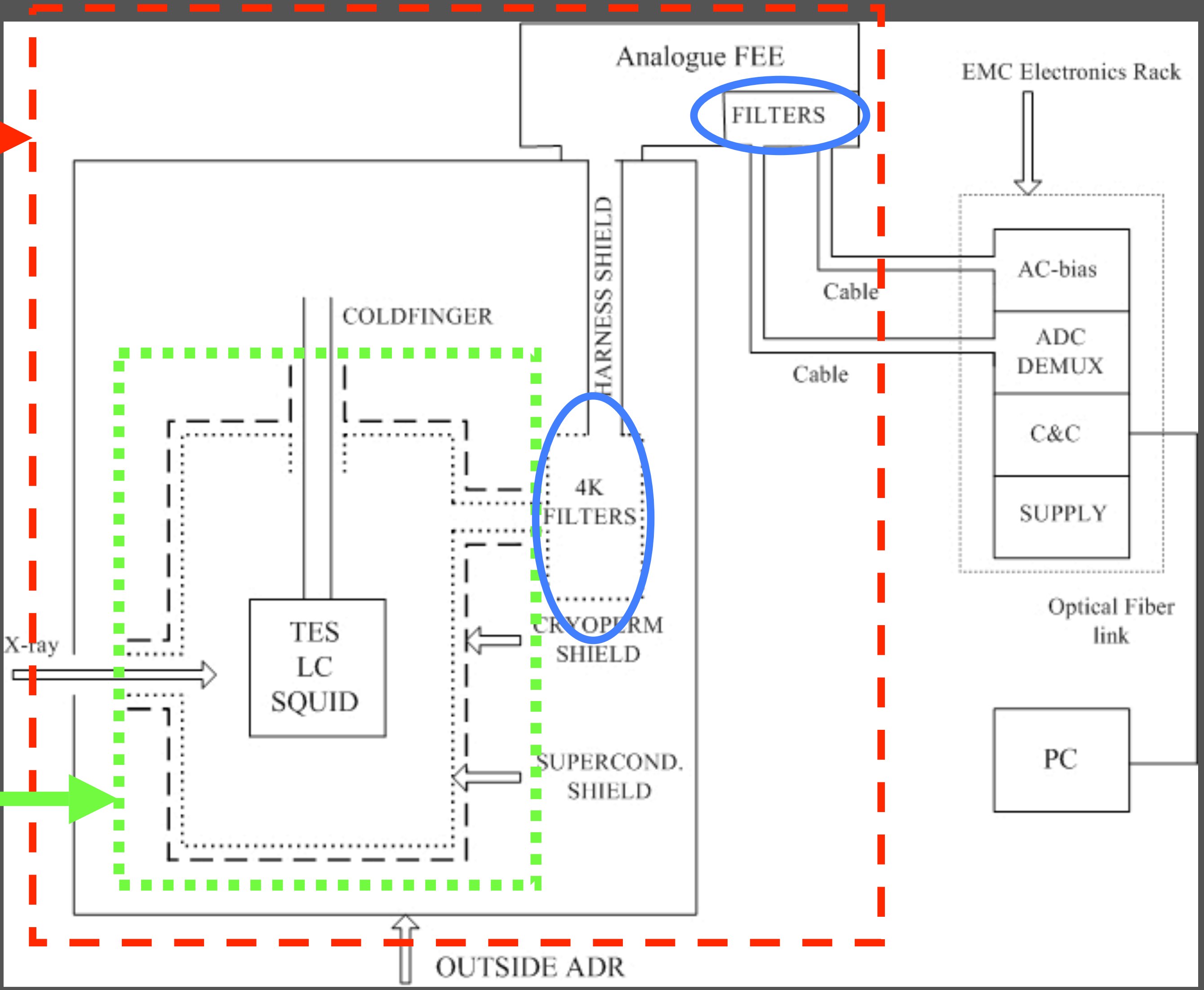
EMI prevention

- EMI origin and sensitivity:
  - pickup by wiring
  - 1 fW of power (broad band!) eq. ΔE of 1 eV
- Prevention approach:
  - Pickup attenuated by shielding and filtering in multiple stages
  - Minimize complexity within shielded environment
- Implementation:
  - Filters at entrance FEE-box and at 4 K interconnections
  - Differential electronics and twisted wire-pairs to reject common mode disturbances
  - Separation between SQUID FLL electronics and other parts
  - PC's + external equipment coupled by optical links

Prototype topological overview

Outer faraday cage

Inner faraday cage
+
Magnetic shield



Cross section cold head shielding

Radiation entrance window

Cryoperm outer shield 1 mm @ 4K

Superconducting inner shield
(Pb or SnPb plated OFHC copper) @ 500mK

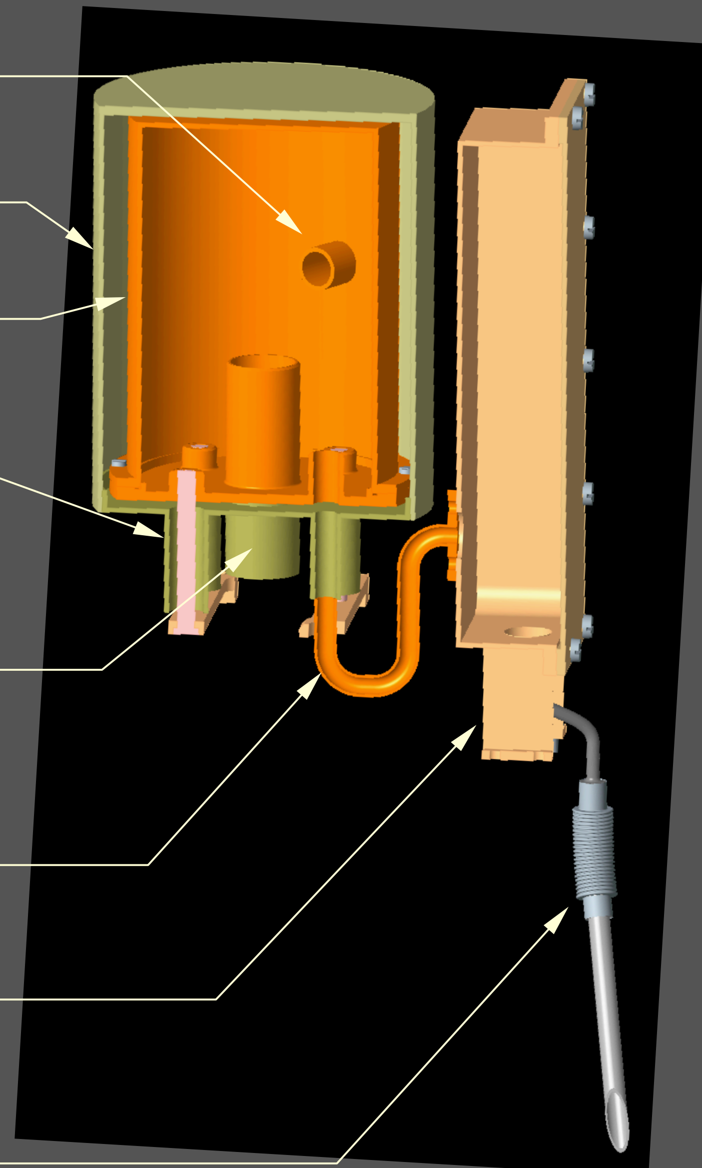
OFHC Copper support/thermal link
for inner shield @ 500mK

Cold finger entrance
Finger may be electrically coupled
with superconductor to inner shield
to reduce noise

Superconducting harness shield
(Pb plated OFHC copper) @ 4K

Superconductor shielded loom
interconnection & filter box @ 4K
(Pb plated OFHC copper)

Harness shield, ss304



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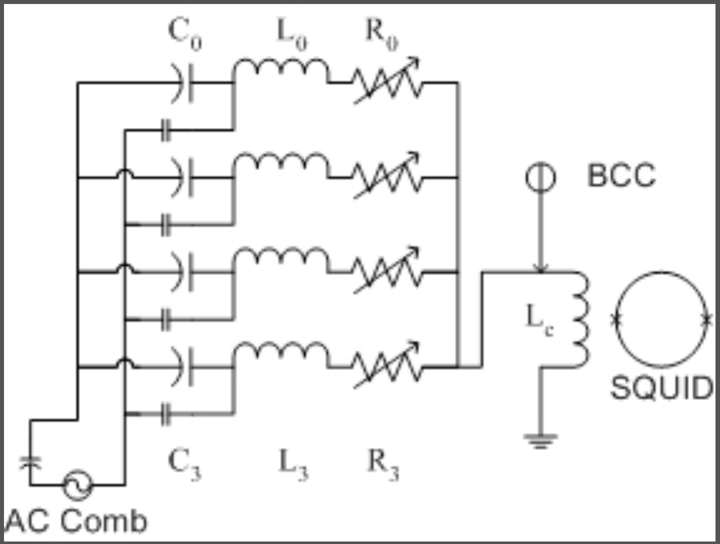
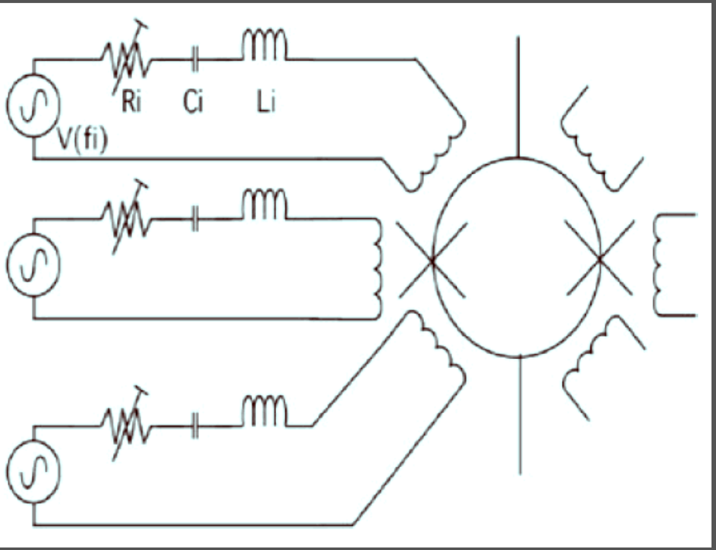
Summing Topology

Cold Head Layout

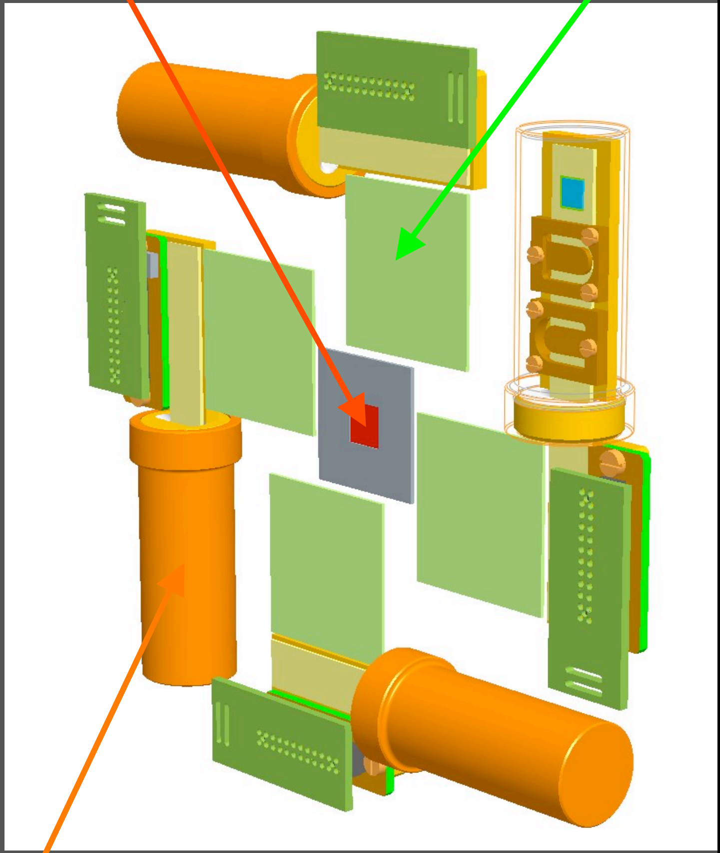


Current Summing
BCC at input
8 channels/squid

TES-ARRAY
LC-filters



Japanese Ch.
Flux Summing
8-input SQUID
BCC via FB



SQUIDs

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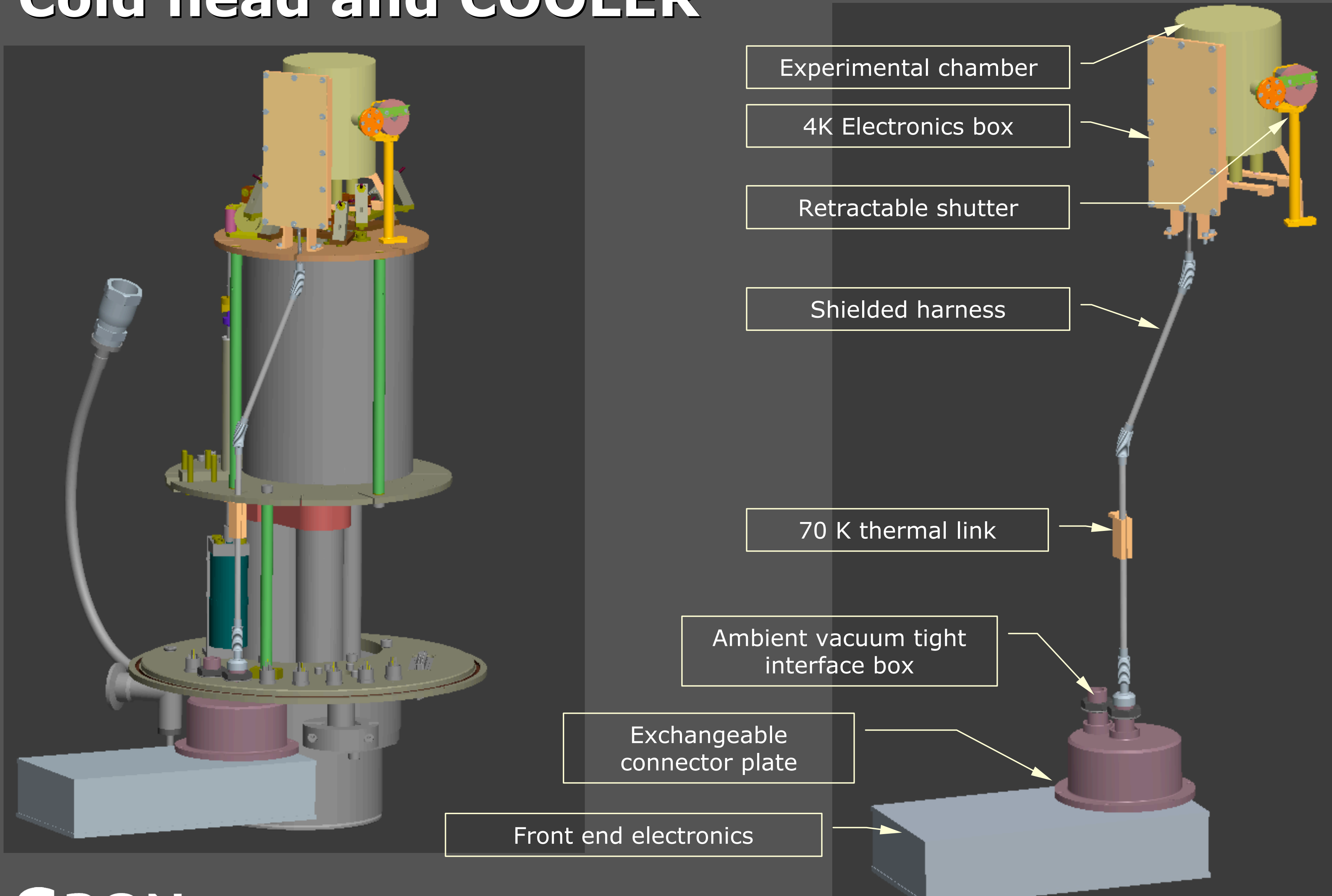
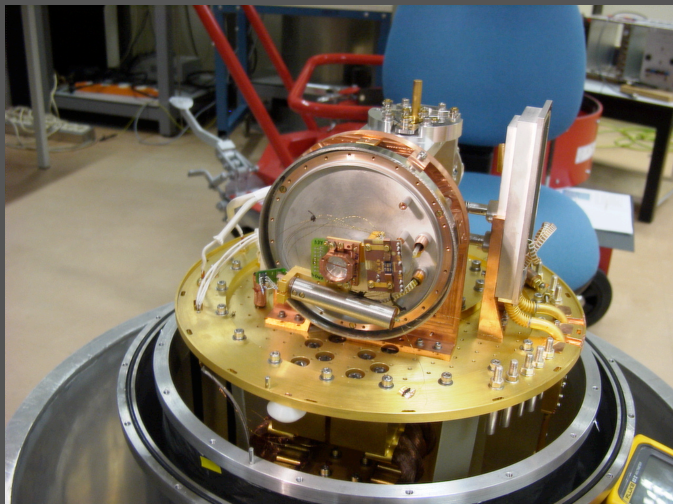
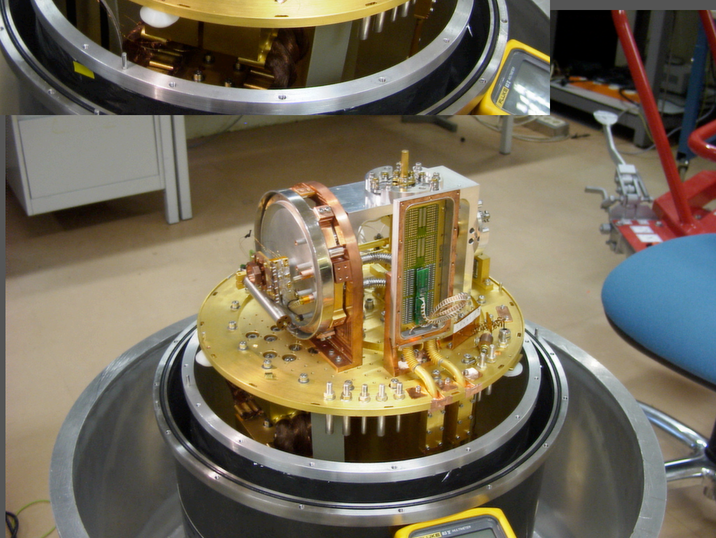
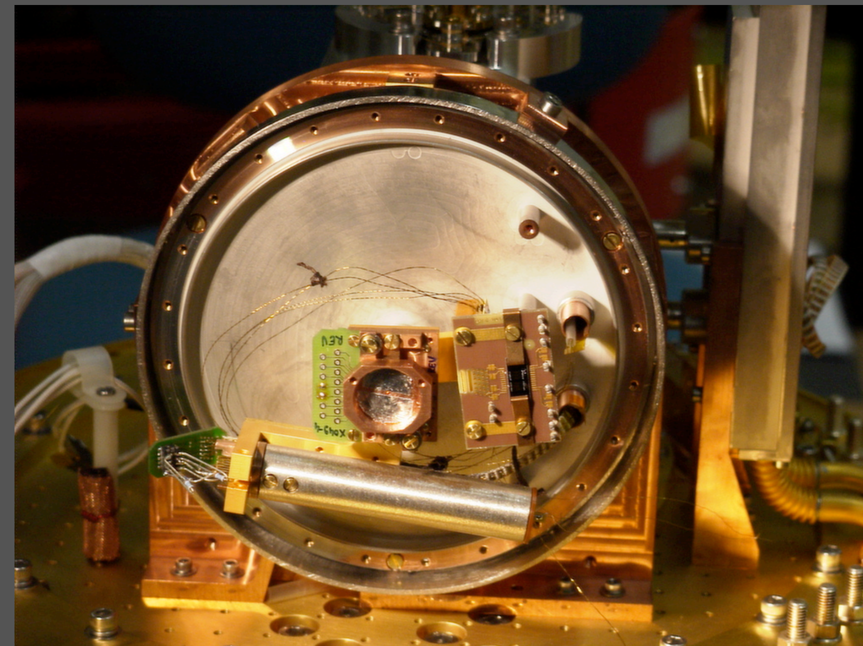
Cold head and COOLER



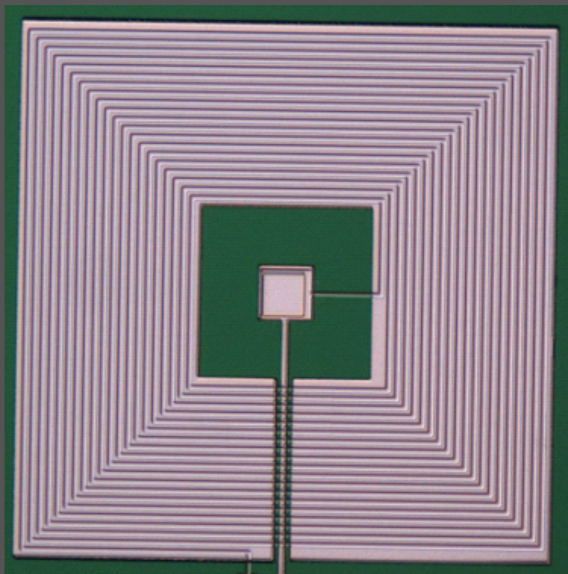
Cold head integration in progress







LC-filters



Filter Coil

0.75 x 0.75 mm²

Eureca design values

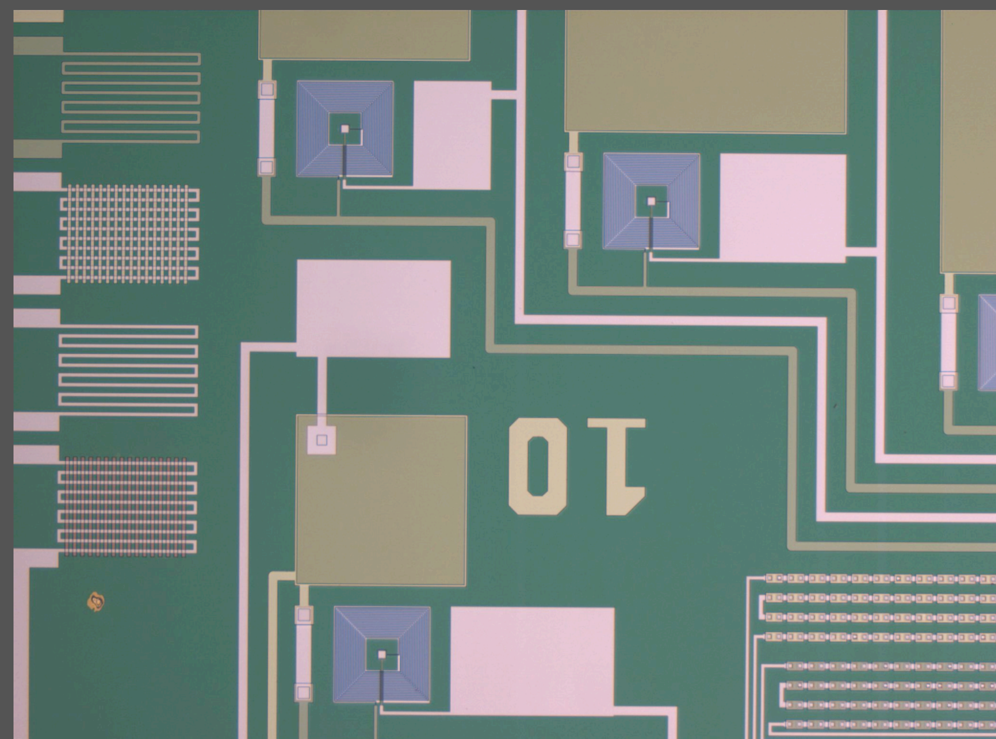
- $f = 0.8 - 2$ MHz; $\Delta f = 100 - 200$ kHz
- $L = 400$ nH for $R = 40$ mΩ
- So $C = 16 – 98$ nF
- $Q > 800\, f$ (MHz) for $R_{ESR} < 3.5$ mΩ

Dielectric material

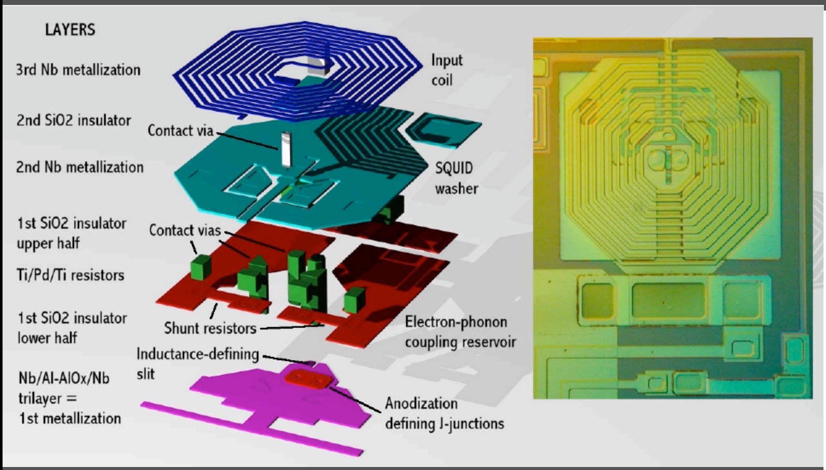
- Nb and Ta-oxides show too much absorption
- 25 nm Al_2O_3 with ε_R=9.8 has been chosen

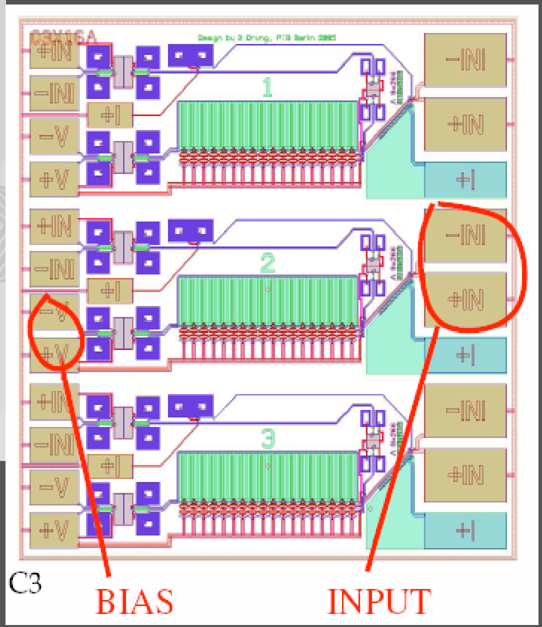
LC-wafer for EURECA:

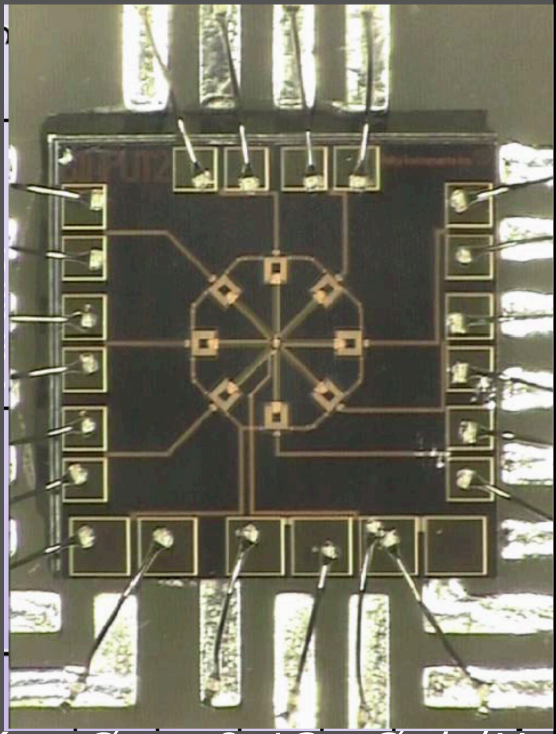
- $C = 4.3$ nF/mm²
- Q (expected) = 10.000



SQUID current amplifiers







VTT input SQUID

$Ø_N = 0.12\ \mu Ø_0/\sqrt{Hz}$ @ 4K

$L_{in} \approx 1nH$

$I_n = 3.5\ pA/\sqrt{Hz}$

$T_N = 8 - 12$ K (2nd SQUID-array required)

PTB 16-SQUID array

$Ø_N = 0.12\ \mu Ø_0/\sqrt{Hz}$ @ 0.3K

$L_{in} \approx 3$ nH

$I_N = 2.8\ pA/\sqrt{Hz}$

$T_N = 20$ K (direct coupling to LNA just possible)

$Ø_N = 0.13\ \mu Ø_0/\sqrt{Hz}$ @ 4.2K

(2nd SII SQUID-array planned)

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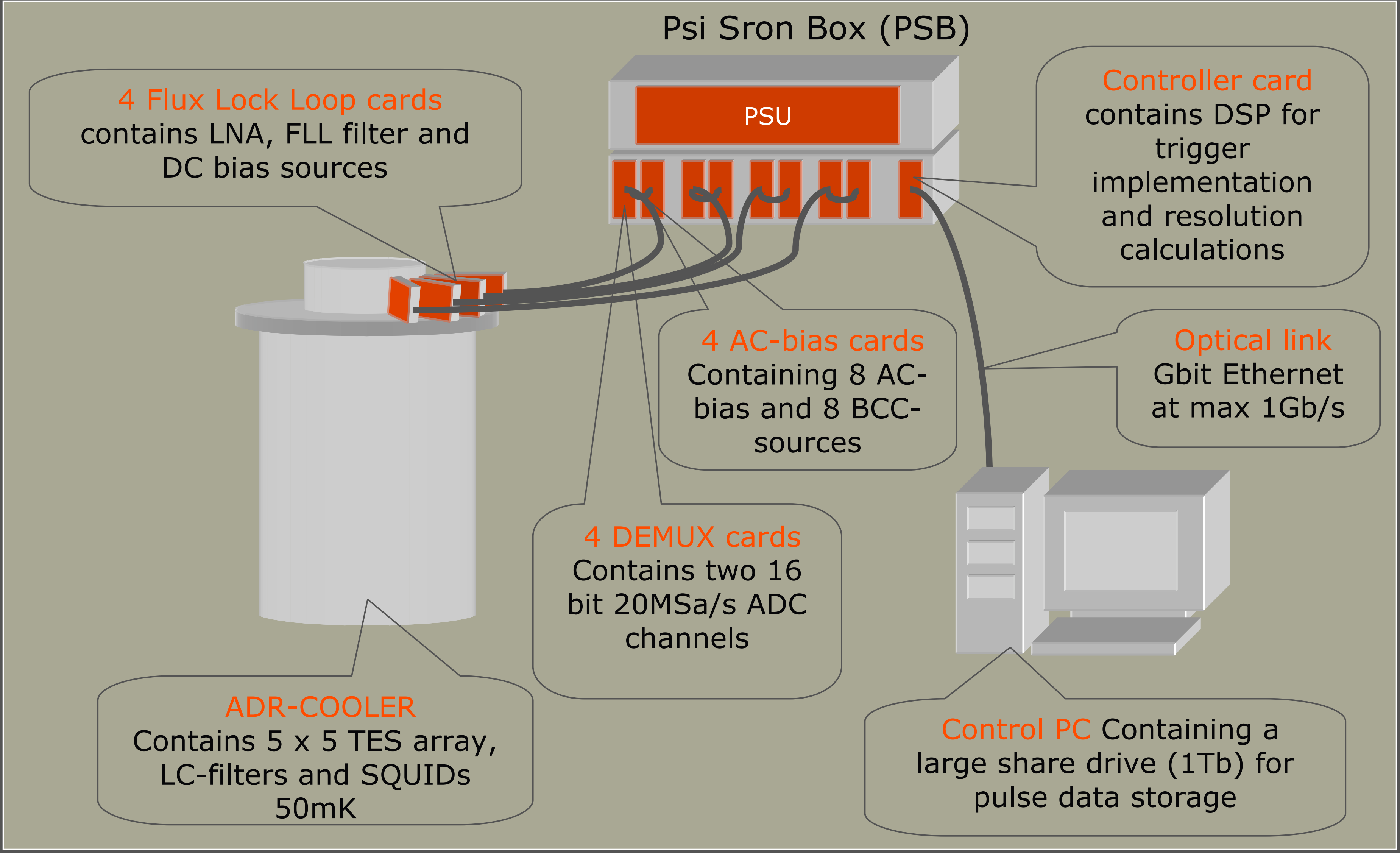
Artist impression of EURECA electronics



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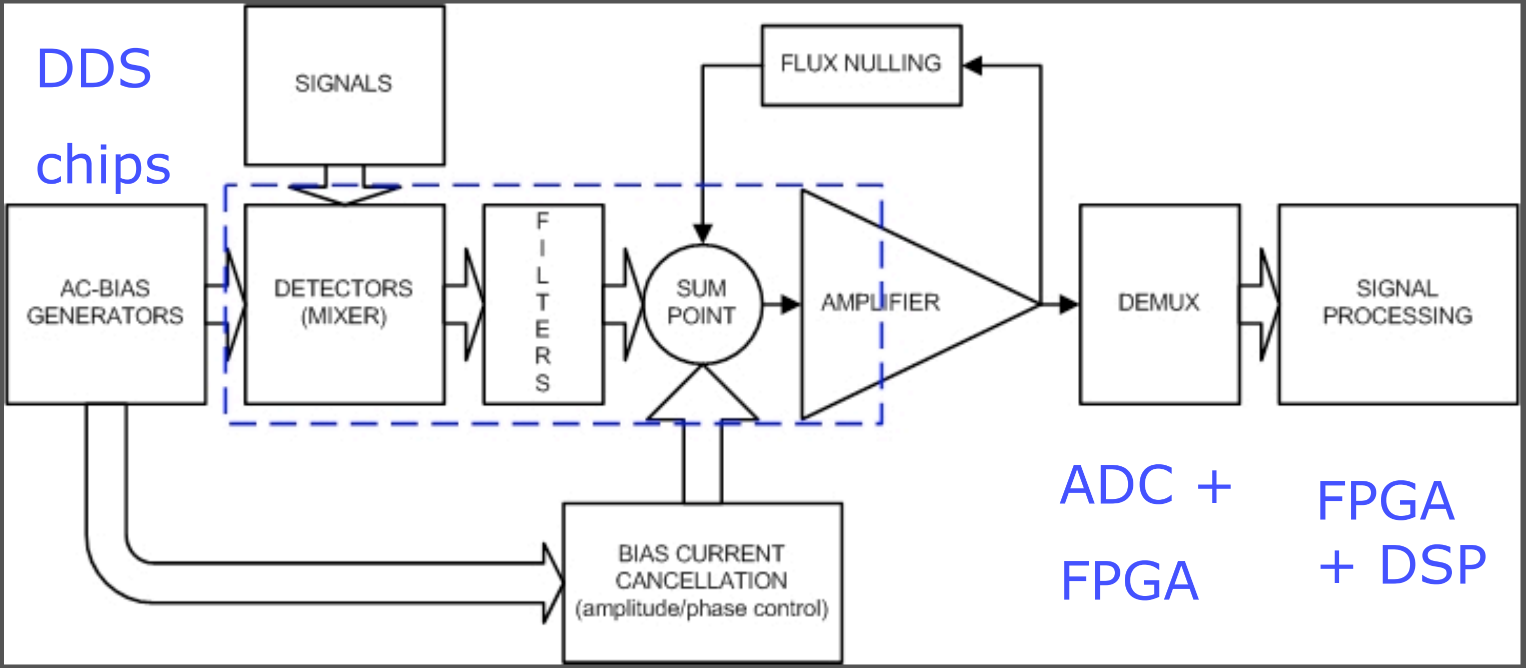
Functional diagram electronics

Applied technologies:

- AC-bias generation + Bias current cancellation (BCC): DDS chips
- DEMUX by ADC + digital processing: FPGA (later ASIC)
- Signal processing (photon energy extraction): FPGA + DSP

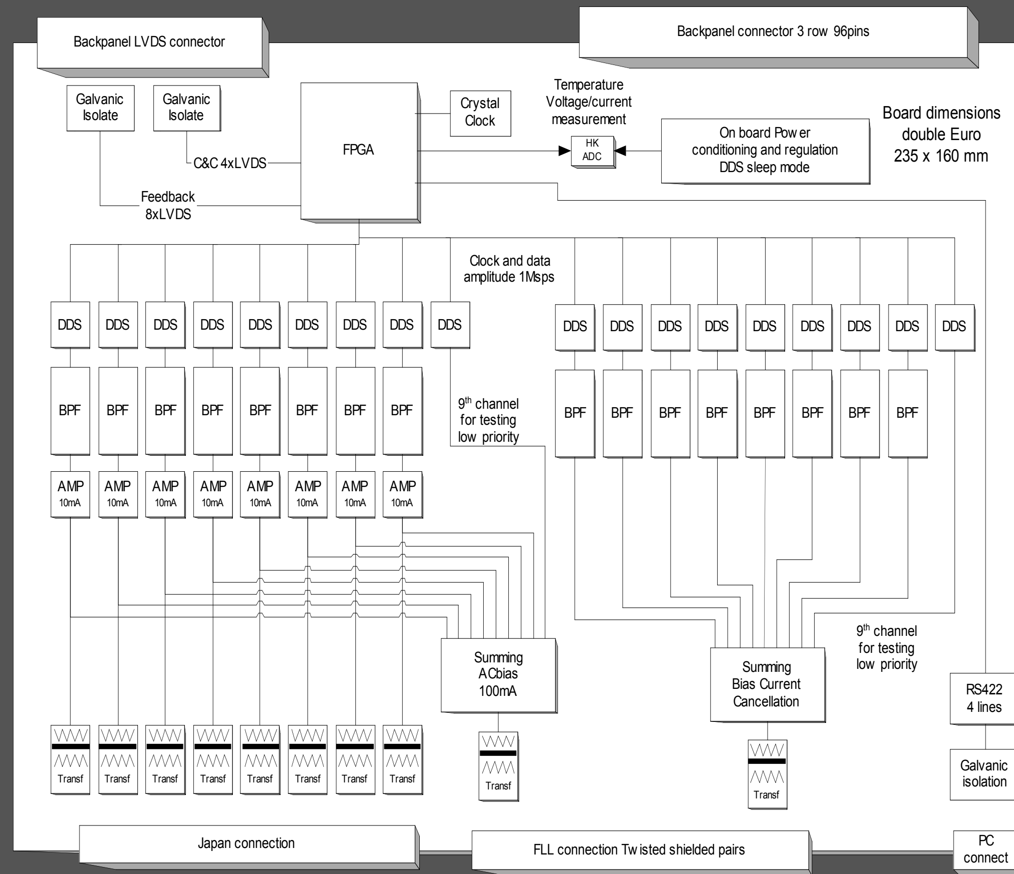


Functional diagram AC-bias sources

- 1 bias source/pixel (so *f* adjustable -relax of LC-filter *f*)
- +/-100 Hz < fc < +/-2 kHz

  <-120 dBc amplitude noise
  <-100 dBc phase noise

  < -80 dB spurs
- Digital (DDS-chips) meet the specifications
- FPGA + DAC's could as well
- ASICs under development for XEUS (power optimization)



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Functional 8-channel AC-bias card

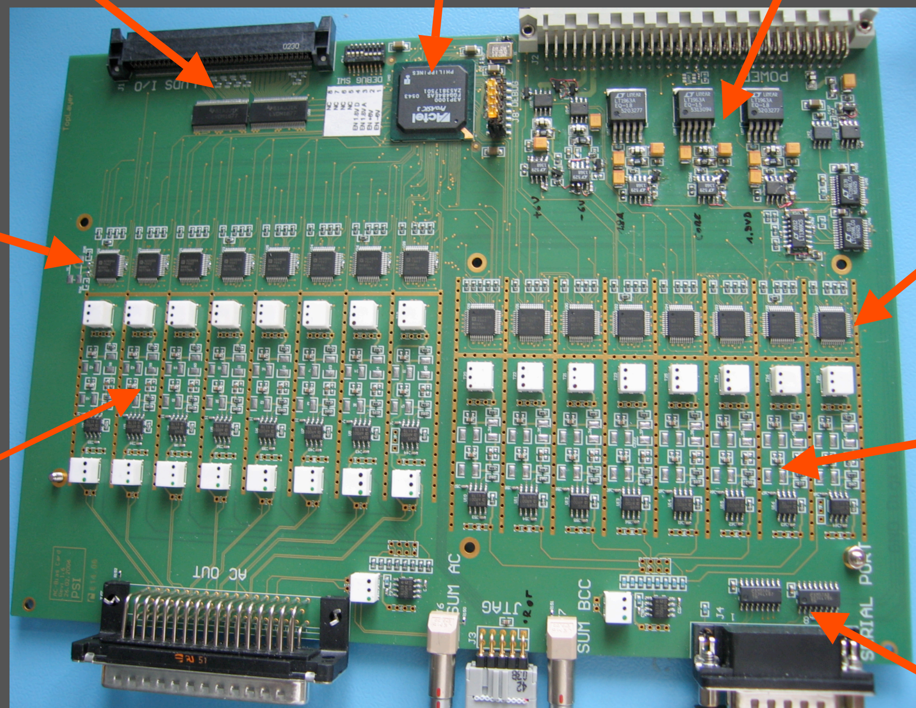
Backplane interface

ACTEL FPGA

HK

AC-bias
DDS
chips

BCC
DDS chips



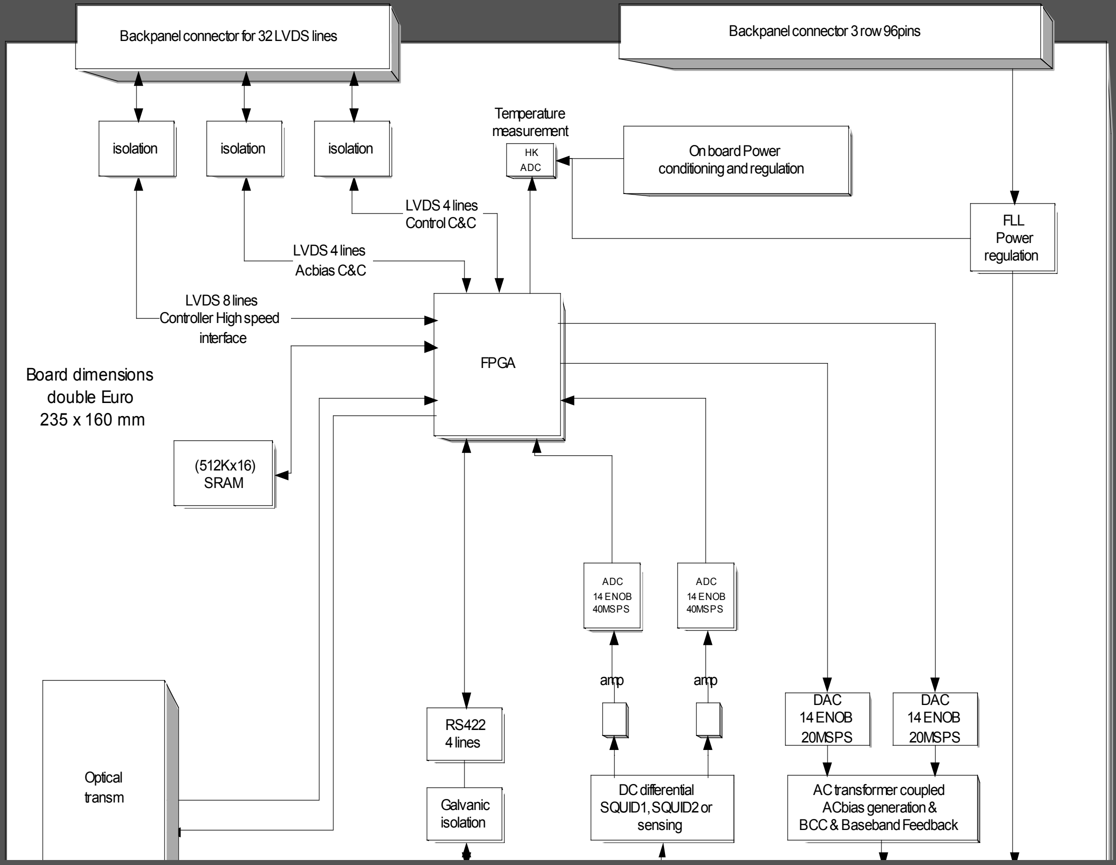
Band pass
Filters, buffers

Band pass
filters, buffers

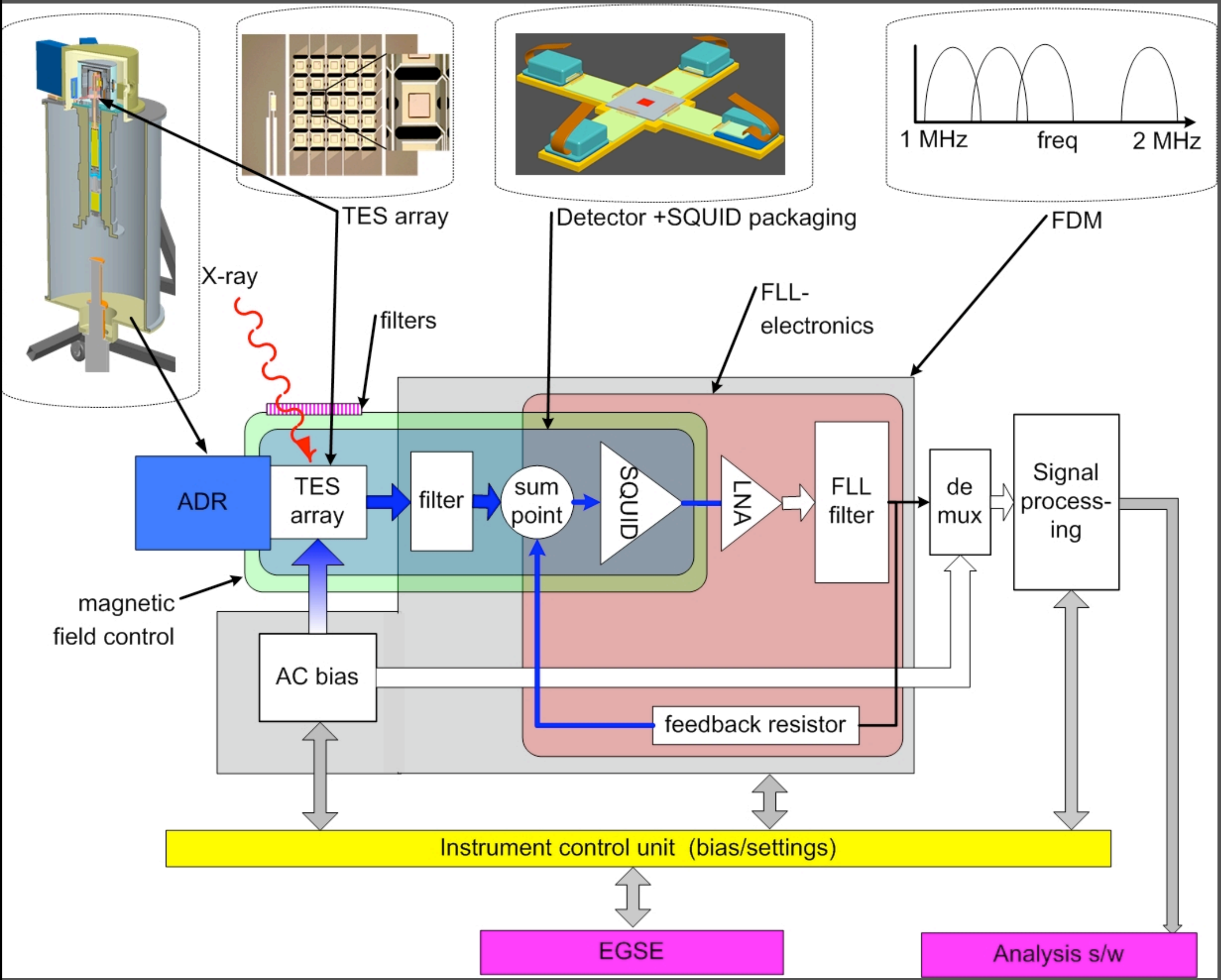
RS485

Functional diagram DEMUX-cards and C&C

- 2 16-bit ADC's (25 MSA/s)
- Digital DEMUX in an FPGA
- Fast DAC's allow generation of signals for base-band feedback
- C&C card has large DSP to run energy extraction algorithm on data



EUREKA Planning Overview



Qualification of a DC-biased pixel in dry ADR at BESSY
September 2006

Start Integration 5 x 5 array + FDM-readout
Autumn 2006

Initial testing (one channel)
Begin 2007

Synchrotron testing (all channels)
End 2007

Increasing the number of channels

Channels per SQUID

- Number of channels limited by bandwidth
- Bandwidth limited by FLL system
- Two methods to increase bandwidth
  1. Baseband feedback
  2. Coarse/fine amplifier topology

Channels per cm^2 electronics

=> Electronics miniaturization by ASICs

Remember:

EURECA will have 8 channels/ SQUID, 24 channels in total

Dynamic range and Flux locked loop (FLL)

Requirements:

1. Signal dynamic range: +/-5 $10^6\sqrt{\text{Hz}}$
2. Signal bandwidth: 150 - 200 kHz/pixel (crosstalk limited)

SQUID Dyn. Range:

- Typical SQUID: +/-0.25 $\Phi_0/\Phi_N = 2 10^6\sqrt{\text{Hz}}$
- SQUID in FLL:

[redacted]

Assuming G_{FLL} = 4 (Unity-GBW, propagation delay limited ≈ 10 MHz)

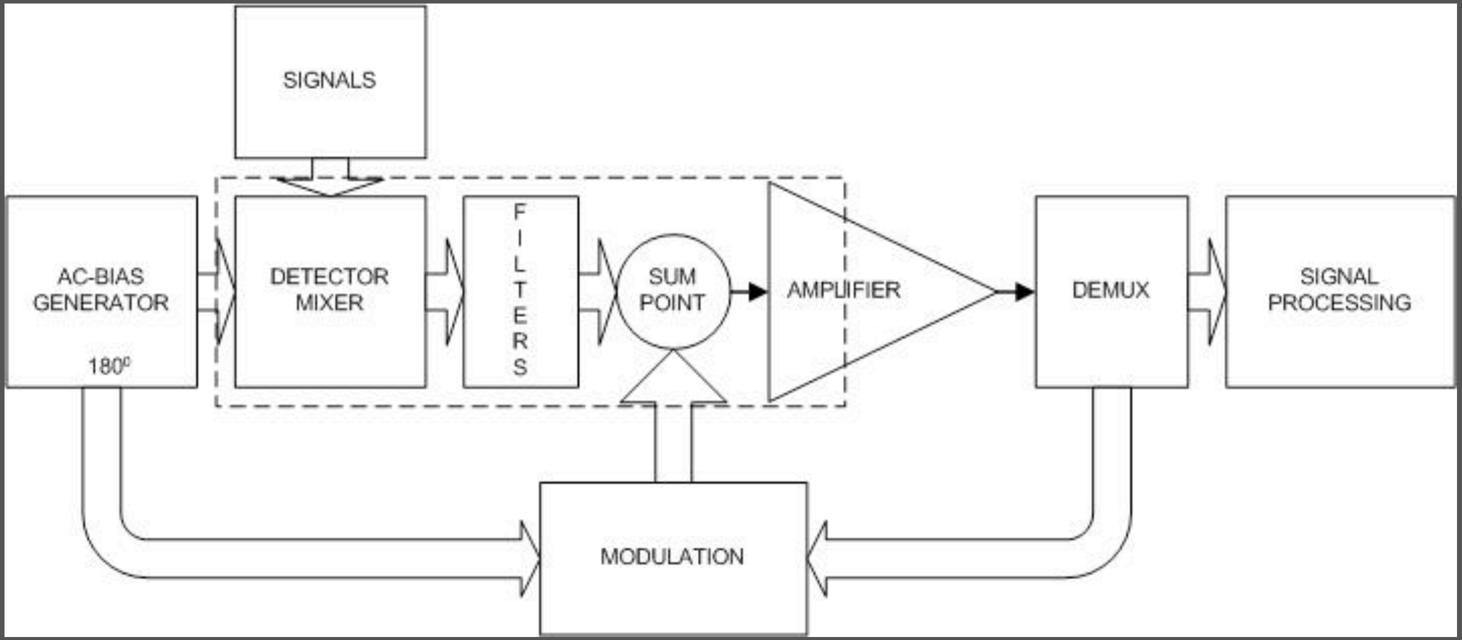
=> 2.5 MHz available, I.e. 9 - 12 channels/SQUID.

This will be build for EURECA.

- So for larger arrays, other systems than standard FLL required.

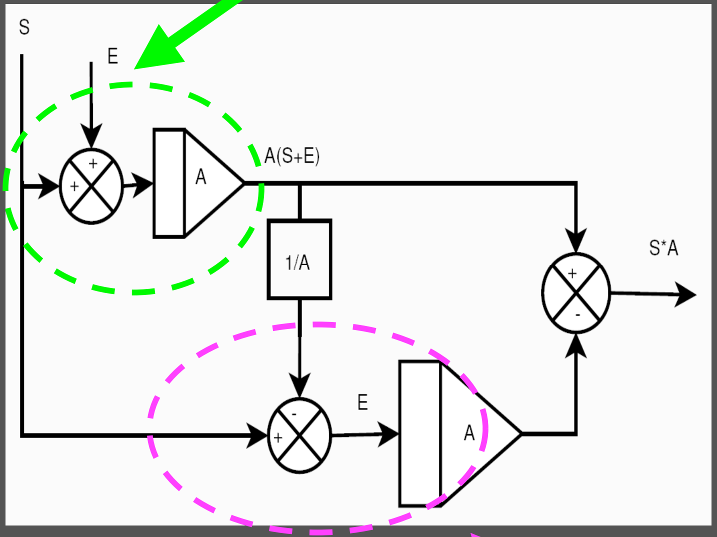
Bandwidth improvement by BASEBAND FEEDBACK

- Carrier contains no information => feedback only on envelope
- A bandwidth up to about 10 MHz possible (SQUID back-action noise and LC-filter Q-factor limited)
- Stability issues limit packing density of channels
- FLL-gain of 5x with 32 pixels between 1 – 10 MHz appears feasible



Bandwidth improvement by Coarse/Fine Amplifier Topology

Coarse SQUID



Fine SQUID

Operating principle:

- 2 SQUIDs: coarse and fine
- F-SQUID measures error made by coarse SQUID
- Subtraction of coarse and fine signal yields original signal

➢ Coarse/fine topology enables 10 MHz bandwidth (backaction noise limited) => 40 – 80 channels/squid (100 μs microcalorimeters)

Requirements:

- ➢ Coarse SQUID amplification sufficient to match RT-amplifier
- ➢ A*S and A*E > RT amplifier noise => 2 stage SQUID
- ➢ Largest signal < 0.5 ϕ_0
- ➢ Flux noise F-SQUID negligible => minimum M-value

Summary and Conclusions

- EURECA well under way with Preliminary Design Review in Jan. 2006. Start integration 1st channel in ADR by end-2006
- Integration of single TES-pixel with DC-electronics in dry ADR started with aim to perform BESSY-calibrations in 3rd week of September 2006
- FDM readout can be implemented without the bias resistors, and their dissipation
- FDM with standard FLL-electronics will only multiplex about 10 pixels per SQUID-channel with XEUS requirements (E_{max}=10 keV, ΔE = 2 eV, and τ = 100 μs)
- Coarse/Fine amplifier topology, Base-band feedback, or a combinations should offer appreciably better performance. It is planned to start working on this by 2007 in parallel to EURECA
- SQUIDs close to the requirements available. But further optimization still required
- ASIC developments for Space (power reduction) is starting

COLLABORATORS ON EURECA

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ISAS/JAXA + Metropolitan (SQUIDs + FLL for one read-out channel)
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Yoshitaka Ishisaki

Alcatel Alenia Spazio (Cold FLL)
Paolo Bastia

INA/ICMA (LC-filters)
Javier Sese

IMM (Mo-bilayers)
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