Title :

WP6: Read-out trade-off

Prepared by: Jan van der Kuur, Mikko Kiviranta — Date: 20 September 2016

Checked by: Jan-Willem den Herder — Date: 20 September 2016

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Contents

Applicable Documents

[AD#]	Doc. Reference	Issue	Title
AD1	AHEAD consortium agreement	15-06-2015, final version	Integrated Activities for the High-Energy Astrophysics Domain, consortium Agreement
AD2	AHEAD-PO-MIN-001/2015	15 September 2015	AHEAD Kick-Off meeting, Minutes of the Consortium Board meeting

Reference Documents

RD#	Doc. Reference	Issue	title
RD1	SPIE	July 2016	The Athena X-ray Integral Field Unit, Barret et al.
RD2	SRON-ESA-CTPO-TN-2016-01	March 2016	SQUID design update (pages 28-42)

Abbreviations and acronyms

Item	Meaning
AHEAD	Integrated Activities for the High-Energy Astrophysics Domain
CSIC	Consejo Superior de Investigaciones Cientificas
SRON	SRON Netherlands Institute for Space Research
SQUID	Superconducting Quantum Interference Device
TBC	To Be Confirmed
TBD	To Be Determined / Defined
VTT	VTT Technical Research center of Finland
X-IFU	X-ray Integral Field Unit

1 Introduction

In this report we present the trade-off analysis performed for the AC biased readout. In our baseline design we use one summing SQUID (front end SQUID) at 50 mK and one array SQUID (booster SQUID) at 2K and this will give us the required performance. However there are good reasons to explore other options as they may provide a better optimization of the instrument design. These include:

1. increase the temperature of the front-end SQUID as its internal temperature is already 300 mK. This will reduce the thermal load at the 50 mK level which is the most demanding for a cryogenic instrument
2. construct the summing point as a Wilkonson-like power combiner to increase the inductance budget in the summing point.
3. Apply local linearization at SQUID level to better tune the 2-SQUID combination, and to enhance the linearity of the system.
4. Apply flux ramp modulation to frequency modulate the amplitude modulated signals, to increase the multiplex factor, and to reduce EMI susceptibility.

First we summarize the read-out of a TES detector using AC bias followed by a description of the baseline readout using two SQUIDs. In section 4 we describe the enhancements/optimizations feasible in the design which go clearly beyond the baseline and which can be studied within the AHEAD context. This trade-off report is concluded by identifying the best way forward.

As reference we give below the WP description from the AHEAD consortium proposal (AD1: Call H2020-INFRAIA-2014-2015, proposal SEP-210187231) and the decision of the consortium board (AD2: AHEAD-PO-MIN-001/2015) as this provides the context.

The AHEAD proposal lists under WP 6.3 the following for the AC biased readout:

WP 6.3: ***AC biased readout***
(VTT, SRON)

Different schemes can be used to multiplex a number of pixels in a single read-out channel (with its own data handling hardware). In Europe the main emphasis is on Frequency Domain Multiplexing where the pixels are AC biased (with frequencies between 1 and 6 MHz, separated by 125 KHz) and the signals for the separate pixels are identified based on the frequency information. In the baseline design, we expect to be able to multiplex 40 pixels in one channel. In this design a first stage summing SQUID is operated at 50 mK and an array of SQUIDs is operated at a higher temperature (2K) as a second stage, providing the necessary signal to drive the lines to room temperature (where the digitization is done). The disadvantage of this approach is that the two SQUID amplifier stages are physically separated, resulting in additional interconnections which limit the bandwidth of the signals transmitted between the SQUIDs to about 6 MHz> Also the thermal load on the 50 mK is about a factor 2 larger than when the summing SQUIDs and array SQUIDs were to be operated both at 2K. This is caused by the need to bias the summing SQUIDs (and hence double the harness). Clearly, if both SQUID stages can be operated at 2 K a larger set of pixels can be operated for a given cooling power.

As part of this work package we will provide a detailed assessment of combining the two SQUIDs at the 2K level (VTT) and the feasibility to have a corresponding cryo-harness with the appropriate characteristics (cross talk, inductance, bandwidth) to allow for this (SRON).

To further increase the multiplexing factor, it is essential to improve the dynamic range of the SQUID combination. SQUIDs with a larger dynamic range allow faster pixels that can handle higher count rates, and more electronic filtering in the readout lines, and it opens the possibility for a higher readout bandwidth and thus a higher multiplexing factor. The two possible routes to be explored here for dynamic range improvement are linearization of the SQUID response and the enhancement of power dissipation and critical current density in the second SQUID stage.

The Mo/Au route also requires modifications of the SQUID input circuit due to the lower specific resistance of Mo/Au, which could be combined in this part of the WP.

At the first board meeting it has concluded to shift some of the emphasis from the detector to the read-out as this is a very critical subsystem. In addition it was concluded at the start of the project that some of the options are less critical than others, taking into account the planned observations with the Athena mission. More specific it was concluded that the spectral resolution and high countrate capability had clear priority over a larger field of view and therefore detailed studies of the so-called hydra pixels had no priority anymore (see below for the board decision).

The board was informed about developments in optimizing the detectors for Athena which were carried out between the AHEAD proposal and the kick-off. This work has been performed in the Athena X-IFU program development which started its activities around the submission of the AHEAD proposal. The goals of the detector work package (WP6) remain unchanged but some of the trades have been performed in the context of the XLIFU and this will be taken into account. Therefore the following two changes are proposed:

(a) the emphasis for the development of the detectors is the read-out and not the hydra pixels (based on recent analysis spectral resolution and count-rates have priority over a larger field of view with poorer resolution and additional under-sampling) (WP6.2)

(b) The optimization of the readout is not limited to the temperature levels of the electronics and SQUID dynamic range but will include a broader range of options (WP 6.3)

The deliverables and milestones remain unchanged.

The relevant deliverable addressed in this report is given below [AD1]:

Number	Name	Short name	Type	Dissemination level	Delivery date
6.2	Design trade off report: AC biased readout	VTT	R	CO	12

2 Read-out of a TES sensor

2.1 Rationale for SQUID readout

Readout of TES-based micro-calorimeters can be seen as monitoring the resistance of a temperature dependent resistor, which value is a function of the applied photon energy. The monitoring is generally done by applying a constant voltage, and reading the temperature-dependent current, as voltage biasing creates negative electro-thermal feedback. The negative feedback enhances the linearity and stability of the micro-calorimeter.

To comply with the required voltage bias condition, a current or trans-impedance amplifier is needed with an effective input resistance which is significantly smaller (~0.3 R_0) than the set point resistance (R_0=1.5mΩ) of the micro-calorimeter. In addition to that, electro-thermal stability requires that the electrical inertia of the bias circuit should be approximately a factor of 3 - 6 smaller than the thermal inertia. This limits the maximum input inductive reactance of the current amplifier at the thermal cutoff frequency of the micro-calorimeter to ~1/6 - 1/3 R_0.

Because of the stringent science requirements, it has been chosen that the readout circuit is allowed to consume <2.7% of the energy resolution budget. This implies that the required effective noise temperature of the current or trans-impedance amplifier should be no more than 2.7% of the effective noise temperature of the micro-calorimeter, taking into account that the detector noise and the amplifier noise are uncorrelated. The latter noise temperature is approximately equal to the operating temperature, i.e. ~100mK. Hence, the effective noise temperature of the amplifier has to be smaller than ~2.7mK. This requirement, combined with the low input impedance requirement, rules out the use of semiconductor amplifiers and leaves SQUID amplifier readout, either in a current or trans-impedance configuration, as the only viable option.

2.2 Multiplexing

Multiplexed readout implies that multiple pixels are readout by a single SQUID amplifier, and multiple TES bias voltages are fed through one wire pair. Multiplexed readout as opposed to direct readout of TES-based cryogenic micro-calorimeters is mainly driven by the goal to minimise the required cooling capacity and complexity at the cold stages. The main sources of heat load in the readout system are the SQUID amplifiers, the heat leak through the bias and readout wiring, and the size (and mass) of the interconnections. Without any multiplexing, each pixel would require a single wire pair for its voltage bias, and three wire pairs for operating the SQUID amplifier, i.e. ~16k pairs for the X-IFU instrument.

Simple addition of the TES signal currents in a single SQUID is not acceptable, because as the signals overlap in time, frequency and phase space, they become indistinguishable after simple addition.

The stringent Athena science requirements do not allow for significant energy resolution degradation as a result of multiplexing, as this can be avoided. In text books it can readily be found that any lossless multiplexing scheme, i.e. a scheme in which the constituent signals need to remain fully recoverable, requires two fundamental steps before the signals can be added while remaining (mathematically) independent. The first step is to confine the signal bandwidth, and the second step is to transform the signals (coding) in such a way that they become mathematically independent. The latter mathematical transformation implies the multiplication of the time-dependent signal functions of the pixels with an independent carrier function per pixel, in such a way that they become orthogonal and therefore mathematical independent and fully distinguishable after addition (``multiplexing'') and amplification with a single SQUID amplifier.

As a result of the mathematical transformation, *M* multiplexed signals require a bandwidth which is at least *M* times the bandwidth of a single signal, depending on the chosen set of carrier functions. As will become clear below, SQUID amplifiers can provide sufficient power gain over bandwidths of several MHz. On the other hand, X-IFU micro-calorimeter pixels require a bandwidth of less than 5 - 10 kHz per pixel (SSB). Therefore, from bandwidth point of view, SQUID amplifiers are in principle capable of accommodating the signals of at least several tens of micro-calorimeter pixels.

There are many orthogonal (carrier) basis sets for multiplexing conceivable, but in practice only a few are commonly applied. For micro-calorimeter readout time domain (TDM), frequency domain (FDM), and code domain multiplexing (CDM) are actively being developed. In TDM and CDM switching SQUIDs are used code the signals with boxcar and Walsh functions, respectively, while in FDM the each TES codes its signal by amplitude modulating a sinusoidal bias current of a distinct frequency per pixel.

When optimally dimensioned, and with full signal loading, the multiplexed signals require the same resources, independent of the applied basis set. The pro's and con's of each set merely depend on practical implementation issues.
However, in the X-IFU case, where most of the photons have a relative low energy because of the energy dependence of the effective area of the telescope (area α E^2), the dynamic range consumption in the SQUID amplifier in case of FDM is the smallest, as addition of detector responses to signals larger than the signal of a saturating photon is very small. As a result, tens of pixels can be readout with a single SQUID amplifier, without needing more dynamic range than what is needed for the readout of a single pixel. Each coding scheme has its own set of implementation characteristics, but further discussion is outside the scope of this paper. FDM has been chosen as the baseline multiplexing scheme for X-IFU, with TDM readout as a backup solution.

2.3 Implementation aspects of frequency domain multiplexing

As already mentioned above, multiplexing involves mounting a bandwidth-limited signal on a carrier function by means of multiplication (modulation), followed by summing of the modulated signals for transportation through a shared channel. In the X-IFU frequency domain multiplexing (FDM) implementation, the orthogonal set of carrier functions consist of sinusoidal TES bias voltages of different frequencies. The signal-dependent TES resistance amplitude-modulates the amplitude of the bias current.

The required bandwidth limitation, and separation in frequency space is provided by *LC* bandpass filters, consisting of an inductor (*L*) and a capacitor (*C*). A schematic diagram is shown in Fig.1. The bandwidth-limited signals are summed in a summing point, and measured by a SQUID with a total input impedance Z_c. Note that the rest of the SQUID amplifier chain is not shown in this diagram.

The bandpass filters are connected in series with the TESs. As a result, their parasitic series resistances add to the internal resistance of the TES bias circuits. This internal resistance is limited by the voltage bias condition requirement to <0.3 R_0, as mentioned earlier. This implies that the intrinsic *Q*-factor of the *LC* bandpass filters including the internal resistance of the voltage source has to be > 4 times higher than the *Q*-factor or the circuit with the TES in transition, to satisfy the voltage bias condition.

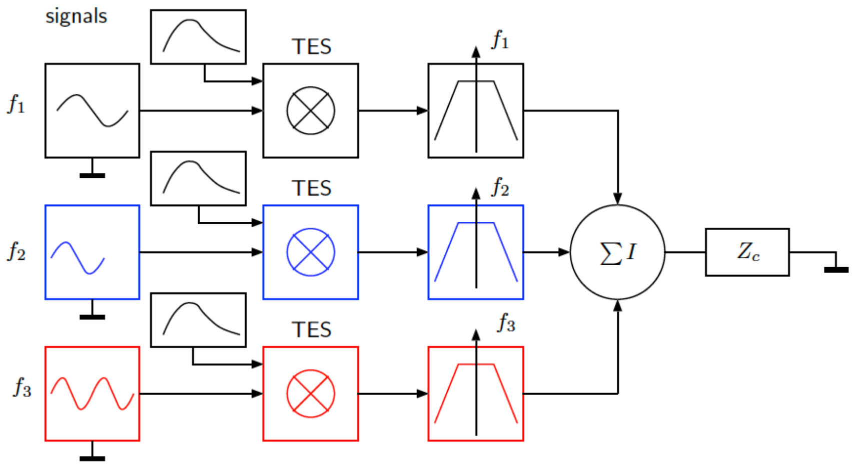

Figure 1: Schematic FDM implementation scheme for a single column. Each TES in a column is biased with a sinusoidal voltage bias of a different frequency. The TESs amplitude modulate the resulting bias currents. The signals are separated in frequency space by means of tuned *LC* bandpass filters, consisting of a coil (*L*) and capacitor (*C*). The filtered signals are summed in a current summing point, with finite impedance Z_c, which schematically represents the input impedance of the SQUID current amplifier. The SQUID amplifier chain has not been drawn in this schematic.

2.4 Electrical cross talk and EMI

Electrical cross talk occurs when a pixel modulates more than one carrier, when modulated signals cross couple in the wiring harness between the detector and the room temperature electronics, or as a result of nonlinearity which creates mixing between signals.

The first mechanism results from the fact that the attenuation provided by the bandpass filters is finite, so that cross talk occurs with an amplitude depending on the ratio of the bandwidth per pixel, and the frequency spacing between pixels. There are three cross talk mechanisms related to the *LC* filters.

First, the finite summing point impedance (in practice this is an inductance) is a shared element between bias circuits, so that it becomes a medium to transfer energy between pixels. This effect scales as $Q_{pixel}\ L_c/L$, where Q_{pixel} is the ratio of the bandwidth and the carrier frequency of a pixel, and L_c/L is the ratio of the common inductance and the filter coil inductance. The size of this effect sets an upper limit to the geometrical common inductance, and sets an upper limit to the tolerable energy resolution of the SQUID.

Second, magnetic cross-coupling between the inductances of the filters create a transformer coupling between bias circuits. This effect scales as $k\ Q_{sep}/2$, where k is the coupling factor between the filter inductors, and Q_{sep} the ratio of the frequency separation between two carriers, and the lower carrier frequency. The size of this effect depends on the proximity between filter coils, and can be further reduced by using gradiometric configurations.

Third, the multiplexed bias voltage comb creates finite leakage of neighbouring bias currents proportional to Q_{sep}/Q_{pixel}. Note that the size of this effect can be traded against wire usage, by decreasing Q_{sep} by splitting the bias comb over multiple wire pairs.

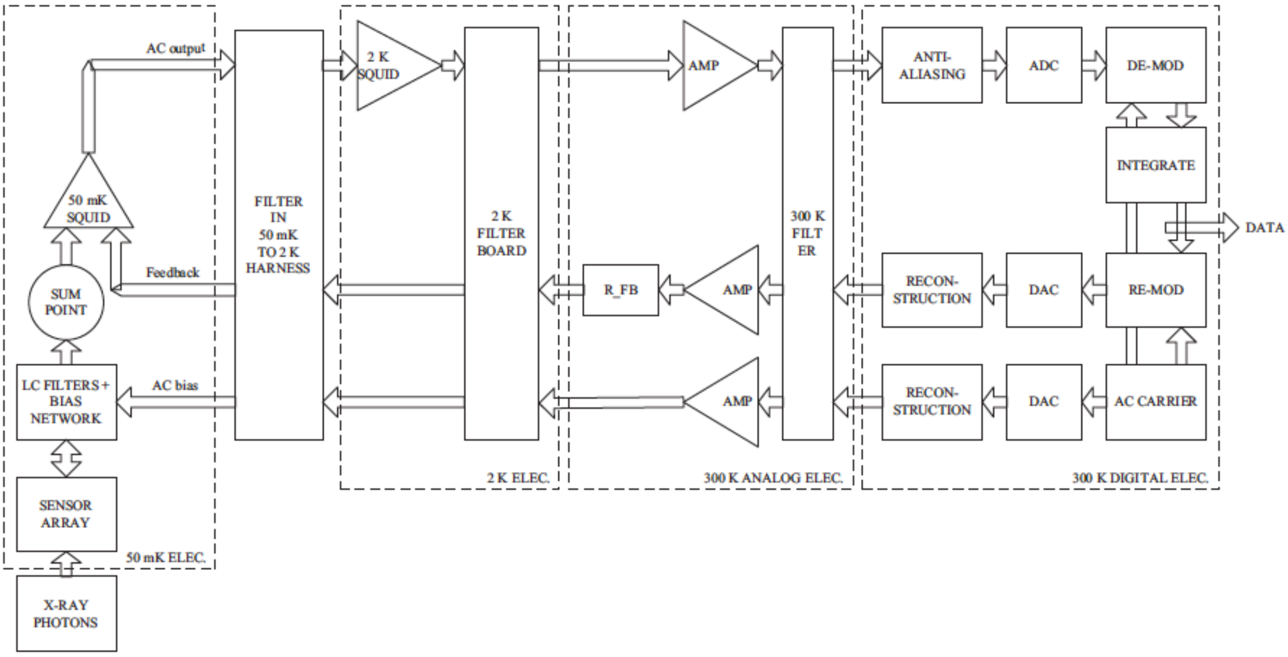

Figure 2. Overview of the FDM implementation concept for X-IFU. The cold electronics at 50mK consists of the sensor array, LC filters and front end SQUIDs. The electronics at the 2K level consists of the booster SQUIDs and EMI filters. The analog front end electronics at 300K provides signal and buffer amplifiers, as well as bias sources for the SQUIDs, heaters, and temperature sensors. The digital electronics provides the demodulation functionality, the sinusoidal (AC) carrier generation, and feedback generators to enhance the (linear) dynamic range of the SQUID amplifiers.

Cross talk in the wiring harness can be lowered by a combination of a careful symmetric design of the wire pairs, by careful routing of the common mode path, and by avoiding proximity between sensitive lines.

The dominant source of nonlinearity in the signal path is the SQUID transfer function. The amount of intermodulation products is a function of coincidence of modulated signals, and their amplitude. The size of the nonlinear effect of the SQUID transfer function can be designed by choosing the maximum flux excursion, at the cost of SQUID dynamic range, and by negative feedback. The requirements for non-linearity are still subject of investigation. End-to-end simulations are ongoing to provide this information.

Electromagnetic interference (EMI) creates signals which add to the detector signals, and which impair the energy resolving power when their levels exceed the NEP levels of the detector (~ 10^{-18} W/√Hz). Careful shielding, i.e. creating a solid Faraday cage around the detector and the low-level signals, is the best way to keep the EMI levels below the threshold levels. The effects of in-band EMI can further be attenuated by using balanced signals. For out-of-band EMI, further attenuation can be obtained by filtering.

3 Baseline readout using 2 SQUIDs

3.1 Read-out architecture

Fig. 2 shows an overview of the FDM implementation concept for X-IFU. The cold electronics at 50mK consists of the sensor array, LC filters and front end SQUIDs. The electronics at the 2K level consists of the booster SQUIDs and EMI filters. The analog front end electronics at 300K provides signal and buffer amplifiers, as well as bias sources for the SQUIDs, heaters, and temperature sensors. The digital electronics provides the demodulation functionality, the sinusoidal (AC) carrier generation, and feedback generators to enhance the (linear) dynamic range of the SQUID amplifiers.

A summary of the X-IFU requirements which drive the design of the readout chain are summarised in table 1 .A number of requirements are still under study, as the flow down of the science requirements to instrument requirements is still ongoing.

Property	Requirement
Energy range	0.2 - 12 keV
Energy resolution budget SQUID + LNA	2.7 % of ΔE = 2.5 eV FWHM @ 7 keV
Count rate extended sources .	2 cts/s/pixel
Count rate point sources	50 cts/s/pixel within the PSF
Linearity SQUID tandem	THD < 1% for E < 2 keV (TBC)
Number of pixels	3832
Pixel bias power	< 6 pW
Pixel thermal bandwidth	0.4 kHz
Cross talk	TBD%
EMI induced noise level after shielding and filtering	30% of LNA noise level

Table 1: summary of X-IFU requirements as relevant for the readout

3.2 SQUID chain design

The most important function of the SQUID amplifier is to raise the TES signals above the noise level of the first stage low noise amplifier (LNA) at room temperature, so that the contribution of the room temperature electronics to the energy resolution budget remains small, i.e. <2.7% following the preliminary energy resolution budget for X-IFU. To achieve this, a minimum amount of power gain in the SQUID is required. The amount of required power gain will be estimated below.

The minimum required amount of power gain G_P can be calculated from the noise temperatures a $G_P > (T_{N,LNA} + T_{N,sq})/T_{N,tes}/p_{budget}/F$, where $T_{N,tes} \approx T_c = 100mK$ the noise temperature of the TES, $T_{N,sq}$ the noise temperature at the output of the SQUID, $p_{budget} = 0.016$ the budget assigned to the SQUID/LNA combination of 2.7%, and F the mismatch factor between the output dynamic resistance of the SQUID and the noise matching resistance of the LNA. The noise temperature $T_{N,LNA}$ of a state-of-the-art LNA which is suitable to approximately noise-match to the low (~120Ω) output impedance of a SQUID equals $T_{N,LNA} > 70K$ in SiGe based technology. The intrinsic noise temperature at the output of an optimised SQUID operated at a temperature T_{sq} , equals $T_{N,sq} \approx 2.4\ T_{sq}$, which implies that the LNA the dominant noise.

source. So for X-IFU, where SQUID operation is intended at T_{sq} ~2 K, we estimate that $P_G >$ 54dB for a SQUID with a noise mismatch factor of F ~ 0.2. A SQUID with a relative high critical current density of J_c = 500A/cm^2, the theoretical maximum power gain per stage equals ~32 dB @ 5 MHz. So, a single stage SQUID is insufficient to provide the required power gain.

There are different ways in which the power gain can be increased. For example, it has been shown that positive feedback can be used to enhance the power gain moderately, at the cost of bandwidth and enhanced vulnerability to SQUID transfer variations. However, when other requirements such as linearity, stability, power dissipation, and multiplex factor (= bandwidth) are also taken into account, a two-stage SQUID cascade, though more complex, turns out to be more robust and attractive as the baseline for X-IFU. This is caused by the fact that all the required properties of the SQUID, such as the coupled energy resolution to minimise its noise contribution, the output resistance to drive a cable with sufficient bandwidth to enhance the multiplex factor, the power gain to boost the signals above the noise floor of the LNA, and the dynamic range density *DRD* to match the signal-to-noise ratio of the micro-calorimeter pixels to the SQUID range, scale linearly with the power dissipation of the SQUID with the exception of the dynamic range density which scales quadratically.

In the two stage configuration the front end SQUID is located close to the detector at the base temperature of the system. The second stage ("booster") SQUID resides at the 2K level, where the available cooling power is ample with respect to the base temperature stage, and the proximity to the first stage is much closer than to the LNA. In such a two-stage configuration, not only is sufficient power gain available, but the power dissipation of the front end SQUID can also be much smaller than in a single stage approach. This originates from two main differences between the two stages. First, the front end SQUID only needs to drive the (short) interstage cable and the input coil of the booster SQUID, while the booster SQUID drives the longer cable (factor of ~10) to the LNA. Second, the dynamic range density of the front end SQUID is not limited by the LNA noise temperature but by its own intrinsic flux noise instead, which saves a factor of $\sqrt{(T_A/2.4T_{sq})} \approx 10$ for an optimised SQUID design.

The baseline SQUID tandem consist of a multiloop front end, and a large array SQUID as booster stage. A summary of the properties is presented in table 2 . The output of the booster SQUID is balanced to enhance immunity against common mode disturbances which are picked by the cable between the SQUID and the room temperature electronics. Its signal output power is maximised in order to optimise the net dynamic range density. The front end SQUID is dimensioned such that it can drive the full range of the booster SQUID within the required interstage bandwidth, again to optimise the dynamic range density of the system, and consequently the multiplex factor. Simultaneously, this optimization sets a lower limit to the power dissipation in the front end SQUID to approximately 2 nW within the chosen parameter space.

3.3 Minimisation of SQUID power dissipation

As explained earlier, minimal power dissipation of the readout, specifically at the lowest temperature stage, is essential to fit within the stringent power and mass budgets of the X-IFU instrument. This implies that the total dissipation of the front-end SQUIDs should be minimised, and should occur at the highest possible temperature.

The total power dissipation at the lowest temperature stage by the front-end SQUIDs can simply be written as

$$\sum P_{sq} = N_{pix} P_{sq}/M$$

where P_{sq} is the power dissipation of a single front-end SQUID, N_{pix} = 3832 the number of pixels, and M the multiplex factor. It is trivial to observe that M needs to be maximised, and P_{sq} needs to be minimised to achieve the smallest heat load.

The multiplex factor M depends on the available bandwidth for multiplexing B_{mux}, and the inter pixel frequency spacing Δf as $M = B_{mux}/\Delta f$. In the two stage SQUID system, the value of B_{mux} is limited by the interstage bandwidth, which in turn is set by the dynamic output resistance of the first stage SQUID R_d, and the inductive load consisting of the interstage cable together with the input inductance of the second stage SQUID. The value of Rd is proportional to P_{sq}, as $R_d \propto P_{sq}/I_c^2$, with $I_c=J_cA_J$ the critical current of the SQUID with critical current density J_c, and junction area A_J. Note that because of fabrication limitations, A_J can not be decreased arbitrarily.

Next to the available R_d, or B_{mux}, the required dynamic rang density (DRD_{sq}) also drives the bias power of the SQUID, i.e. $DRD_{sq} \propto \sqrt{P_{sq}/k_bT_{sq}}$, with T_{sq} its operating temperature. So, the SQUID bias power provides both dynamic range and multiplexing bandwidth simultaneously.

Because the intrinsic DRD of an optimised state-of-the-art SQUID is smaller than the required DRD in the readout chain, an independent baseband feedback loop per pixel has been the baseline for the X-IFU. Note that this electronics simultaneously provides the demodulation and carrier nulling functionality. The integrator in the forward path of a baseband feedback loop provides a loop gain L with an amplitude which is a function of frequency distance to the carrier frequency of a pixel, fn, following $L(f - f_n) \approx GBP/|(f - f_n)|$. In a baseband feedback system, there is an upper limit to the GBP in relation to the distance between the carrier frequencies $\Delta f = f_n - f_{n-1}$, i.e. $GBP \approx \Delta f/6$ as a result of causality. For an available multiplexing bandwidth B_{mux} we find $GBP \leq B_{mux}/6M$.

The net DRD_{ro} of a SQUID chain with baseband feedback equals approximately $DRD_{ro} = DRD_{sq}(1 + 2\pi\tau_r GBP)$, with τ_r the rise time of the X-ray responses. Combining the results to express the total power dissipation by the SQUIDs in terms of Psq, the power dissipation in a single SQUID, yields in the limit of $2\pi\tau_r GBP >> 1$

$$P_{tot} = \sum P_{sq} \propto N_{pix} \frac{I_c^2}{2\pi\tau_r\sqrt{P_{sq}}}\sqrt{\frac{P_0}{k_bT_c}} \quad (1)$$

To interpret this result properly, we also need take into account that the required value of I_c^2 is determined by the required dynamic range in the second stage SQUID. In an optimised system the dynamic range of the second stage scales with and is slightly larger than the dynamic range of the first stage. When there would be no interstage cable inductance, it can be shown that $I_c^2 \propto DRD_{2nd} \propto DRD_{1st} \propto P_{sq}$. So, this would imply that the total power dissipation is independent of P_{sq}. When we include the interstage cable inductance, not all the created flux is detected by the second stage SQUID, so that we find that $I_c^2 \propto P_{sq}^m$, with $0 < m < 0.5$. This leads to the conclusion that, from power optimisation point of view, it is more effective to obtain DRD from the SQUID intrinsically, than from baseband feedback.

3.4 Impact of pixel speed

The pixel speed has a significant impact on the total power dissipation of the SQUIDs, as can seen in eq. 1. Here we see that $P_{tot} \propto \sqrt{P_0}/\tau_r$. Combining this result with $\tau_r \propto 1/G \propto 1/P_0$, we arrive to $P_{tot} \propto . \tau^{-3/2}$ Here we assume that the heat capacity is not used to lower the pixel speed, as in an optimal design its value has been minimized already to optimize the energy resolution of the detector. The impact of the pixel speed is more than proportional, because it influences both the *DRD* and the bandwidth consumption.

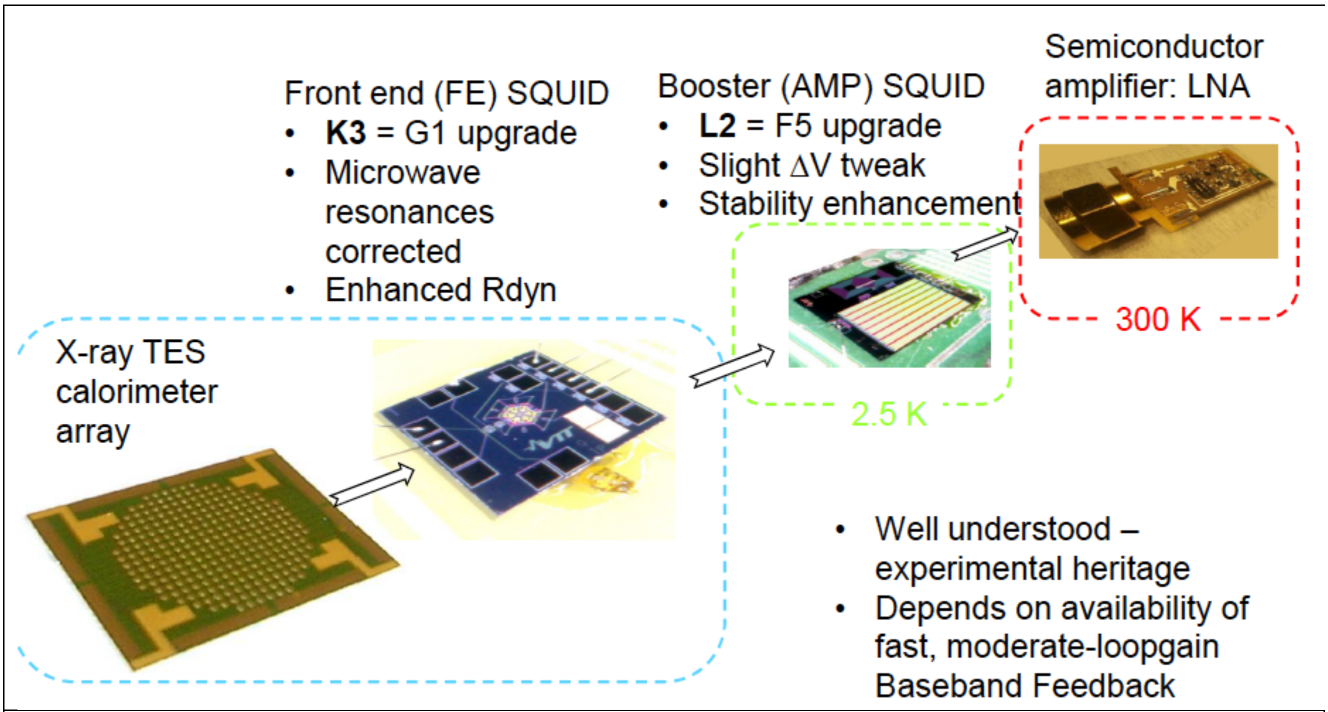

Figure 3: Graphical overview of the baselined SQUID the readout chain.

3.5 SQUID specification

In this section we present the baseline specification for the front end and for the booster SQUID as well as the requirements for the booster SQUID/cable/LNA combination. These SQUIDs are under development for the Athena X-IFU project. A summary of the requirements is given in the table below.

Property	Front end SQUID	Booster SQUID
operating temperature	50mK	2K
input inductance	< 3nH	< 160nH
power dissipation	< 2nW	> 0.5μ W to get dynamic range
input current noise	< 2.5 pA/p Hz, 2.0pA goal	N/A
operating mode	single ended	Differential, balance>40dB (TBD)
bandwidth 2-stage system	> 8MHz	
interstage cable inductance	< 100nH	
Full dynamic range density	$\Phi_{monotonic}$ / Φ_n > 3e6 sqrt(Hz) p-p	Including LNA and booster
Linear dynamic range density	Φ_{lin} / Φ_n > 3e5 sqrt(Hz) p-p	Including LNA and booster

Table 2. Summary of the SQUID properties for the X-IFU readout.

For these requirements, we assumed the following LNA/cable combination:

Assumed LNA/cable:
Voltage noise: < 1nV/sqrt(Hz)
Current noise: < 2pA/sqrt(Hz)
Input impedance: 50ohm
Cable resistance: <10 ohm
Effective cable noise temperature: 150K

4 Enhanced readout

The baselined readout used can be improved by:

- further reducing the resource consumption of the spacecraft by decreasing the heat load induced by the readout chain, by moving dissipating elements to higher temperatures, and/or by further increasing the multiplex factor.
- improving further the performance of the readout chain by improving the linearity of the readout chain.

Implementation options of these two points are discussed in the next sections.

4.1 Reduction of resource consumption

4.1.1 Operating temperature 1st stage SQUID

The first stage SQUID properties do not improve significantly below 300mK, as a result of electron-phonon coupling limitations in the shunt resistors. This implies that locating the first stage SQUIDs at the 300 mK level of the X-IFU would be sufficient to achieve full performance. A boundary condition for such a configuration is that the summing point inductance should be kept small, to avoid cross talk. Not only the first stage SQUIDs do not benefit from cooling below 300mK, also the net impact of the Johnson noise of the ESR in the capacitors of the LC filters is so low that its net effect on the detector performance will be □ 2 %. Furthermore, the baselined design of the focal plane assembly (FPA) is such that it will be relatively easy to thermally isolate the focal plane with the micro-calorimeter array from the LC filters and SQUIDs, because the flexible interconnects form a natural thermal barrier. This leads to the option to have the first stage SQUIDs at 300mK, so that a factor of □ 10 larger power dissipation can be allowed, which would provide a lot of head room in the readout chain, and possibly a higher multiplex factor.
Operation at 300mK makes it possible to increase the power dissipation in the front end SQUID from 2nW at base temperature, to 20nW at 300mK. The larger dissipation in the first stage SQUID provides a factor of √10 extra dynamic range, so that the dynamic range enhancement by external baseband feedback at room temperature and therefore the bandwidth consumption per pixel can be lowered by the same factor.

The extra power dissipation also provides a higher output dynamic resistance by a factor of 10. By using voltage sampling feedback, the extra bandwidth provided by the extra dynamic resistance can be traded against extra flux range, i.e. dynamic range, by a factor of ~10. As the baselined baseband feedback provides a factor of 15 dynamic range enhancement, this implies that operation at 300mK almost removes the necessity of BBFB from dynamic range point of view. This in turn can definitely lower the power requirements for the RT electronics, as the processing speed can be lowered.

A small array SQUID, e.g. a 20-series array of the SQUID cells of the 2nd stage SQUID provides the properties as discussed above. A cartoon of the foreseen readout chain is shown in Fig. ..

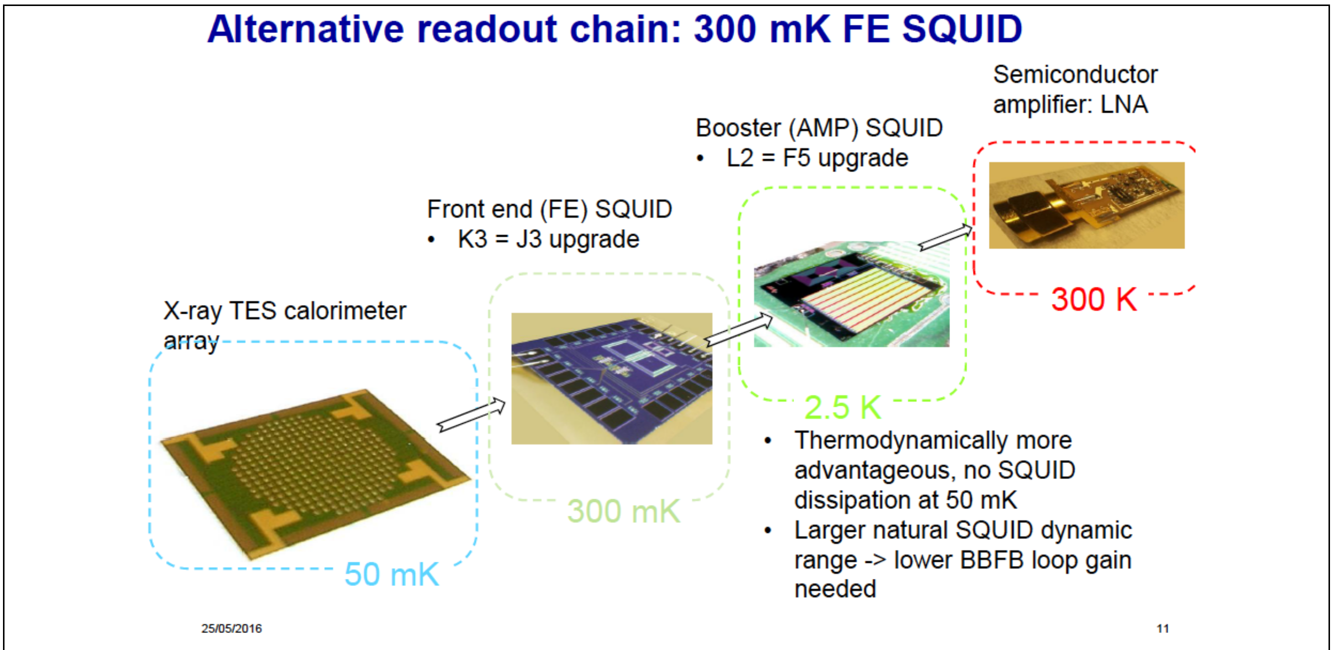

Figure 4: Graphical impression of the alternative SQUID readout chain, which envisions operation of the first stage SQUID at 300mK.

4.1.2 Increasing the multiplex factor

The baselined multiplex factor of 40 is driven by the available multiplex bandwidth (1-5MHz), and by the inter-pixel frequency separation. The latter value of 100kHz, is driven by the need to increase the dynamic range of the SQUIDs to the X-IFU requirement. When the 1st stage SQUIDs are operated at 300mK, their intrinsic dynamic range can be a factor of $\sqrt{20nW/2nW} \sim 3.2$, larger, assuming the available cooling power is 20nW (TBD). This implies that the inter-pixel separation can decrease with the same factor, so that the multiplex factor could increase to 120 based on this consideration only.

There are, however, other considerations to be taken into account. First, lowering the inter-pixel spacing puts more stringent requirements on the implementation of the summing point and on the implementation of the LC filters, to keep the cross talk within the requirements. Lowering the coupling factors in the LC filters, and lowering the common inductance in the summing point is not trivial. To reach this goal more robustly, a compensation technique is considered the most promising. This will be discussed in more detail in the next section.

Second, it needs to be verified to what extend the addition of extra pixels in a multiplexed channel leads to extra dynamic range requirements for the SQUID, as a result of pile-up. Note that also for the 40-pixel multiplexing factor pile-up assumptions need to be verified. In case of pile-up leading to a signal amplitude larger than what can be expected from a single pixel, compensation will be needed by baseband feedback, so that the net effect on the multiplex factor becomes smaller.

4.1.3 Flux ramp modulation

Flux ramp modulation (FRM) is a technique, which has been successfully used for the readout of TES-based detectors for gamma ray detection with L-SQUIDs at microwave frequencies. Flux ramp modulation involves applying a saw-tooth waveform to the SQUID feedback coil, so that a (approximately) sinusoidal waveform is created, because of the approximate sinusoidal transfer of the SQUID. The TES signal, which is added to this flux ramp, modulates the frequency/phase of this carrier. To limit the bandwidth of this frequency modulation, it is required that the signal flux change is small with respect to the flux ramp induced flux change, i.e. < 10%. Under this condition the bandwidth of signal with bandwidth B_{signal} modulated by FRM is approximately 2.1*B_{signal},.

We foresee two possible implementation forms of FRM for the X-IFU, which need to be evaluated.

4.1.3.1 FRM at the first stage SQUID

In this scenario FRM replaces the linearization and dynamic range enhancement functionality for the 1st stage SQUID. The flux ramp creates a carrier frequency of > 30 B_{signal}, which is >150MHz for B_{signal}=5MHz, the maximum modulation frequency as discussed before. In this way we obtain a modulated signal in a band of 150MHz ±5MHz. To implement this option we must fulfil a number of conditions:

- The intrinsic dynamic range of the 2nd stage SQUID must be sufficient to handle the full dynamic range of a multiplexed signal.
- The interstage bandwidth in this scheme must increase by a factor of 2 for the *M=40* baseline, or the multiplex factor must be lowered.
- The impact of SQUID noise increases with a factor $\sqrt{2}$.
- Termination resistors for the flux ramp lines @ 2K likely required (TBD).
- A capacitor should be added in the interstage circuit to move the resonant frequency to 150MHz in this example.
- The impact of back action (BA) from the 2nd stage SQUID increases in this configuration. At the FRM frequency the interstage inductance is tuned out by a capacitor. Because the coupling factor in the 2nd stage SQUID is ~0.7, the coupled inductance to the SQUID equals 180n*0.7^2=90nH. This implies a BA noise corner of 100n+180n/90n = 3 times the SSB interstage bandwidth, or 18MHz. The flux noise limited dynamic range of the 2nd stage SQUID is approximately a factor of 10 larger than in the 1st stage SQUID. This implies a BA limited multiplex bandwidth of ~180MHz. This limits the use of a wide range of frequencies, to separate multiplexed channels in frequency space. Increasing the power in the 1st stage SQUID would help in this respect. In a three-stage SQUID system the corner frequency can still be pushed up, so that more multiplexing space is created.

The properties we assume to get are:

- The linearization and dynamic range enhancement functionality will be provided by the flux ramp modulation. This implies that (fast) BBFB loops are not needed, though demodulation is still needed. Also, bias current cancellation is needed to null the carriers at the 1st stage SQUID. This potentially saves in the dissipation of the room temperature electronics (TBD).

- Assuming the pile-up factor allows it, we can combine the multiplexed signals of 2 or more 1st stage SQUIDs in a single 2nd stage SQUID, when flux ramps of different frequencies are used, so that we get savings on the amount of wire pairs to room temperature, and on the amount of LNAs.
- The technique uses frequency modulation (FM) as opposed to amplitude modulation (AM) in the current baseline. FM is much less sensitive to pickup from the environment in general.
- In the frequency range where the signals are coded (>150MHz), there are less EMI sources present. Note that DC-DC convertors and their harmonics are the main source of EMI in the MHz region in the baseline system.

4.1.3.2 FRM at the 2nd stage SQUID

In this approach we apply a flux ramp to the 2nd stage SQUID, so that the full multiplexed signal band of 40 pixels gets up-converted by FM modulation around a carrier of >150MHz. BBFB is still needed to linearize the 1st stage SQUID As different carriers can be used for different mux channels, the wires to room temperature can be combined. When we allow for a frequency range between 150 and 500MHz, where the gain of the 2nd stage SQUID is expected to be uniform, we can stack approximately 20 multiplexed channels in a wire pair.
The conditions which must be fulfilled are:

- Standard BBFB to operate the 1st stage
- Before the BBFB stages in the RT electronics there needs to be FM demodulation functionality which separates the different AM modulated BBFB channels.
- The LNA and the digitizer need to have a bandwidth of 100 – 600 MHz.
- Because the FM modulation occurs in the 2nd stage SQUID, there is no extra back action noise effect to be expected, and the interstage bandwidth can remain the same as in the baseline design.
- Termination resistors @ 2K to terminate the flux ramp lines (TBD).

The properties we assume to get are:

- Reduced wire count between 2K and 300K. We need approximately 5 channels with a high bandwidth.
- The impact of SQUID noise increases with a factor $\sqrt{2}$. As the dynamic range of the 2nd stage SQUID has margin, the impact of this factor is expected to be small.
- No risk of regenerative feedback, as the forward path and the feedback path of each BBFB loop operates at different frequencies.
- Reduced sensitivity to common mode pickup, gain variation, and cable loss variation in the 2K-300K section, as the signals are FM modulated.
- The impact of SQUID nonlinearity vanishes, as its nonlinearity is now used as a feature.
- Extra room temperature electronics to demodulate the FM modulated signals and distribute them between the BBFB channels.
- The BBFB signals are still sensitive to amplitude variations induced by common mode currents.

4.2 Improving the performance of the readout chain

4.2.1 Compensation techniques

Parasitic magnetic coupling in the LC filters leads to cross talk. The LC filter will be engineered such that the magnetic coupling factors are such that the cross talk levels will be below the required values. Also, the inductance in the summing point will be minimized. This, in combination with sufficient frequency spacing between pixels, leads to acceptable cross talk levels. Next to minimisation of coupling factors and inductance, more advanced techniques are available which provide the same effect, without having to compromise with the inter-pixel frequency spacing.
Instead of direct current summing, a Wilkinson-like current combiner can be used to isolate the individual pixel branches from each other. A sketch of this configuration is shown in Fig.5 Each branch is coupled to its

neighbours with a negative mutual inductance, so the voltage drop across the SQUID in the summing branch gets cancelled in each branch. Such a circuit can be implemented on the *LC* filter chip. It has to be investigated to what level the cancellation can be implemented in practice. Conservative estimations show that cancellation with a factor of 20 should be feasible.
This technique can be used to engineer the parasitic effects different parts in the circuit:

1. Parasitic coupling between filter coils in the LC filter can be compensated.
2. Summing point inductance can be compensated.
3. More inductance than the absolute minimum inductance value can be accepted, so that more engineering freedom in the SQUID summing point is created.

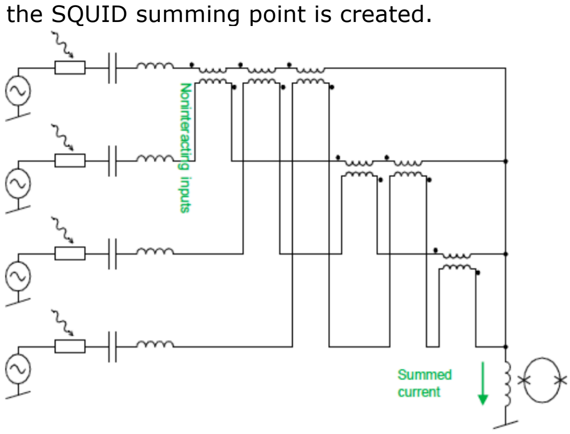

Figure 5: Wilkonson-like current combiner to isolate the individual branches, so that the voltage drop in the front end SQUID does not cause cross talk, so that the common inductance can be increased, without increasing cross talk.

4.2.2 Linearization

To minimize the use of resources, the baseline design assumes that non-linearity in the readout chain can be accepted for the higher photon energies, because the detectors themselves are also nonlinear. But, as the effects of nonlinearity on the accuracy of the retrieval of the photon energies need to be taken into account in the data processing, higher intrinsic linearity of the readout chain saves in the data processing.

Linearization can also be used to change the power gain and flux range of the SQUID, and to enhance the interstage bandwidth without adding extra power dissipation at the coldest stage.

Linearization can be achieved by negative feedback to the SQUID, so that in the limit of high loop gain the SQUID acts as a null detector. In the baseline design there is feedback provided by baseband feedback. Since this feedback acts only on the SQUID chain as a whole, it cannot be used to increase the interstage bandwidth without adding significant extra electronics.
Local linearization in the SQUIDs, i.e. feeding back the output of the SQUID locally without intervention from the room temperature electronics, does make it possible to change the interstage properties, e.g. by screening the input inductance of the 2^{nd} stage booster SQUID, so that the interstage bandwidth gets achieved with a lower power dissipation in the first stage SQUID.
Note that with feedback the fundamental limitations remain conserved, but better dimensioning can be achieved by making an exchange between properties which are plentiful and properties which are available insufficiently.

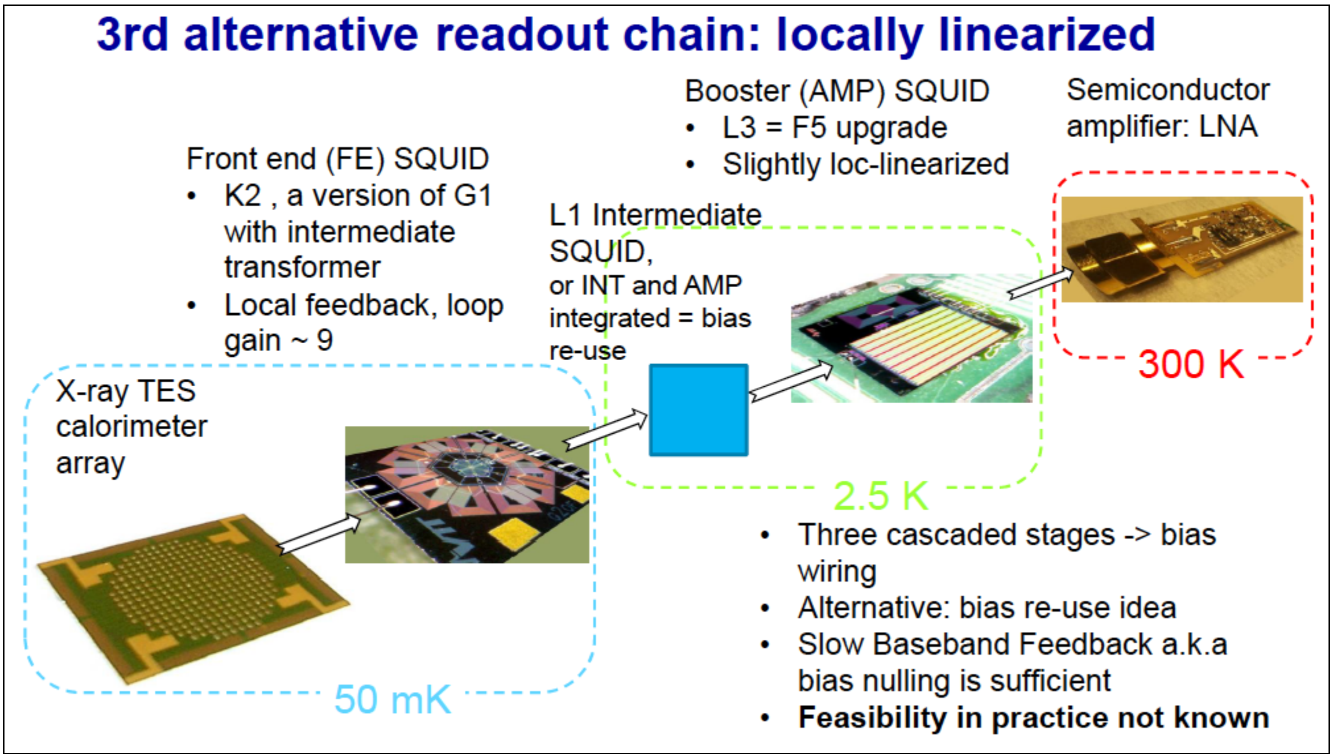

Figure 6: graphical representation of the components involved in a linearized readout chain.

5 Trade-off

The table below shows a summary of key pro/cons of the different alternative readout options as discussed in the previous sections.

Alternative option:	Pro:	Con:
1^{st} stage SQUIDs at 300mK	• Lowers power dissipation 1^{st} stage cooler with 200nW, plus the reduction of heat load from the lighter suspension (TBD). • No SQUID performance degradation • Lower suspended mass at mK. • Higher mux factor potential (upto factor 3) • Mechanically attractive configuration (small mass suspended on large mass)	• Possibly impairs temperature stability 50mK stage, because of heat load through the interconnects. (TBD) • Slight detector performance degradation (~2%) because of LC filters @300mK. • X-ray performance experimentally not yet demonstrated.
Screen input inductance 2^{nd} stage by local linearization	• Lowers requirements on 1^{st} stage SQUID (lower dynamic output	• Higher risk unintended feedback paths in 2^{nd} stage SQUIDs, with

	resistance required) (= dissipated power). • Increases the tolerance for interstage inductance.	instability as a result. • Experimentally not yet demonstrated.
Wilkonson-like current combiner on LC filter chip.	• Reduces cross talk • Makes more compact design LC filter possible • Releases common inductance requirements by factor of 20 (TBD).	• More complicated LC filter design. • Slightly more risk of lowering the LC filter fabrication yield.
Integrated two-stage as 2nd stage SQUID, so that effectively a 3-stage system is obtained.	• Lowers the interstage inductance, so lowers the 1st stage power dissipation up to a factor of ~3. • Increases the BA noise corner frequency by a factor of 10, depending on the dimensioning choices, which makes a flux ramp modulation scheme with a mux factor of ~40x10 =400 likely feasible.	• Unproven technology, risk of enhanced parasitics. • Complicated design.
Flux ramp modulation @ 1st stage SQUID replacing BBFB.	• Replaces the BBFB system with an open loop system, which intrinsically reduces the risk of parasitic feedback. • When dimensioned carefully, reduces the number of low ohmic connections between SQUIDs and LNA with a factor of 10. • Disturbances are generally in the amplitude domain, so FM coding on the long cables helps to provide EMI immunity. • Less LNAs and ADCs needed, upto factor 10. • Demonstrated technology @ NIST.	• Changes the baselined RT electronics significantly, so requires development effort. • Possibly more power consumption in the room temperature electronics, because of higher frequencies. • SQUID design differs slightly from baselined option, so more development effort.
Flux ramp modulation @ 2nd stage SQUID, combined with BBFB.	• Removes risks of parasitic feedback as the forward and feedback paths operate at different frequencies. • FM encoded signals, so less sensitive to EMI. • Less LNAs and ADCs required (though at higher bandwidth)	• Requires extra room temperature electronics to demodulate FM coded signals. • Development risks and effort.

6 Conclusions

All alternative options have in common that they are unproven, but lead potentially to significantly improved performance of the readout system. So from performance perspective, all options should be investigated further. However, given finite resources, and a drive to further increase the robustness of the baselined system, it is necessary to set priorities in the steps to be taken.

1) From development effort point of view, it is relatively straightforward to test the performance of the 300mK option, as no extra components are needed for this demonstration. Because of the significant impact on the cooler design and resources, this option will be evaluated experimentally.

2) Furthermore, local SQUID linearization will be developed further as it is the most promising way to improve the ratio between available dynamic range and SQUID power dissipation.

3) The next potential improvement can be realized by Wilkonson-like current combiner on LC filter chip which will be evaluated experimentally.

4) The three stage SQUID option, because of its intrinsic higher complexity level, will only be developed further if it turns out to be inevitable from requirement point of view.

5) The advantages of the flux ramp modulation are very significant in terms of wire count, cross talk, and in reduction of EMI susceptibility. However, it also requires significant additions to the baselined and demonstrated electronics. As a result, only the feasibility, and consequences for the room temperature electronics in a paper study will be evaluated.

The detector properties are the main driver for the SQUID specifications. For example, the pixel speed drives the total SQUID power dissipation to the power 1.5. However, since the detector properties themselves are still under optimization, we will assume the current LPA pixel as design reference for the SQUID optimization. As soon as the pixel optimization has settled, the optimized LC filter design could be tailored to the optimized pixel design.