Superconducting Cold-Electron Bolometers with JFET readout for OLIMPO balloon telescope

Leonid Kuzmin[1), and Phillip Mauskopf[2)
[1) Chalmers University of Technology, S-41296 Gothenburg, Sweden,
[2) Cardiff University, United Kingdom

***Abstract*— The OLIMPO experiment is a large balloon-borne telescope, aimed at measuring the Sunyaev-Zeldovich effect in many clusters of Galaxies. OLIMPO will carry out its surveys in four frequency bands centered at 140, 220, 410 and 540 GHz. The detector system is made of four bolometer arrays. In order to achieve low dispersion in the characteristics of the detectors, a fully photo-lithographic process producing sensors on silicon nitride islands or plane Si substrate should be developed. Filters and antennas can be integrated on the detectors wafer by means of micro-strip technology.**

Attractive variant is to use Capacitively Coupled Cold-Electron Bolometers (CEB) with JFET readout. The JFET readout has been developed already for the BOOMERanG and Planck-HFI. The problem is to match relatively low-ohmic dynamic resistance of CEB (1kOhm) and high noise equivalent resistance of JFET (1 MOhm).

The goal is to achieve level of noise-equivalen power (NEP) of CEB less than photon noise. Analysis of a single CEB with JFET readout has not given positive results in both current-biased and voltage-biased modes. Current fluctuations of JFET and feedback resistor are rather low. The main reason of fail is strong influence of voltage noise. The voltage is divided by small dynamic resistance of the junctions in cooling region (voltage-biased mode) and gives strong current noise. Any attempts to increase dynamic resistance moving to smaller voltages led to strong decrease of cooling and degradation of responsivity.

To achieve noise matching with JFET, a Cold-Electron Bolometer with a weak Superconducting Absorber (SCEB) has been proposed. In this case we can operate in voltage-biased mode with voltage in the range between (Delta 1-Delta 2) and (Delta1 + Delta 2). In this region the IV of SIS´ junctions is rather flat with considerably increased dynamic resistance up to the level of Rj=1000*Rn (typical level of leakage). Electron cooling will be still very effective for incoming power. Simulations show that we can achieve photon noise level for structure with Ti absorber and Al/Ti tunnel junctions (Al antenna electrode) for all frequency ranges with estimated power load.

***Index Terms*— Cold-Electron Bolometer, SIS´tunnel junction, superconducting absorber, Noise Equivalent Power**

I. INTRODUCTION

The OLIMPO experiment is a large balloon-borne telescope, aimed at measuring the Sunyaev-Zeldovich effect in many clusters of Galaxies, during long-duration balloon flights.The high Galactic latitude sky at far infrared and millimetric frequencies has three main sources of diffuse emission: the Cosmic Microwave Background (CMB) with its primary anisotropy and with the Sunyaev-Zeldovich effect from Clusters of Galaxies, and the Far Infrared Background (FIRB) from early galaxies. The "cosmological window" extends roughly from 90 to 600 GHz: at lower frequencies interstellar emission of spinning dust grains, free-free and synchrotron emission from the interstellar medium dominate over the cosmological background; at higher frequencies the clumpy foreground from "cirrus clouds" of interstellar dust dominates the sky brightness even at high Galactic latitudes. The only way to separate these different emissions and to extract cosmological information is using multi-band experiments. OLIMPO will carry out its surveys in four frequency bands centered at 140, 220, 410 and 540 GHz. CMB primary anisotropy can be detected in the lower frequency bands of OLIMPO. Taking advantage of its high angular resolution, and concentrating on a limited area of the sky, OLIMPO will be able to measure the angular power spectrum of the CMB up to multipoles around 3000, significantly higher than BOOMERanG, WMAP and Planck. The measurement of the damping tail of the power spectrum will provide estimates of the dark matter density and of the spectral index of the primordial perturbations. We will present the angular power spectrum which can be obtained with OLIMPO from 4 days of deep integration over 0.3% of the sky, and how the cosmic parameters can be inferred from such power spectrum.The OLIMPO bands are chosen to optimally sample the Sunyaev-Zeldovich effect in clusters of galaxies and distinguish it from CMB primary anisotropies and competing foregrounds. Moreover, the simultaneous observation of the positive effect at 410 and 540 GHz, in addition to the "zero effect" measurement at 220 GHz will allow us to measure the relativistic corrections and the temperature of the gas even in the absence of X-ray data. We have carried out extensive simulations of the OLIMPO

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L. Kuzmin is with the Chalmers University of Technology, S-41296 Gothenburg, Sweden, on leave from the SINF of Moscow University (phone: 46 31 772 3608; fax: 46 31 772 3471; e-mail: leonid.kuzmin@mc2.chalmers.se).

P. Mauskopf is with the Cardiff University, United Kingdom (e-mail: Philip.Mauskopf@astro.cf.ac.uk).

observations of clusters in the presence of Galactic Dust, CMB anisotropy, and instrumental noise. We plan to map about 40 known clusters for each long duration flight of the payload. Reasonable integration time for each target can thus easily be several hours, spread on a sky patch of about 1 square degree centered on the cluster. The OLIMPO payload is implementing a number of advanced technical solutions. The inner frame, with the attached telescope and the cryostat housing the detector system, can be tilted to set the observing elevation from 0^o to 60^o. The low elevations achievable allow accurate ground-based calibrations of the system and the observation of planets for calibration during polar flights. The telescope, developed in Rome, is an on-axis Cassegrain configuration with a 2.6m aluminum primary. The secondary mirror is suspended by means of thin stainless steel blades to minimize the background from local structures and to avoid beam vignetting. Sky scans are performed by slowly scanning the primary mirror in the cross-elevation direction. Up to 3o wide, 1o cross-elevation scans are possible with this system. The full payload can also perform azimuthal scans, to cover wider regions. The detector system is made of four bolometer arrays. These detectors are an evolution of the highly successful devices used in the BOOMERanG and Planck-HFIinstruments. In order to achieve low dispersion in the characteristics of the detectors, a fully photo-lithographic process producing TES (transition edge superconductor) sensors on silicon nitride islands on a Si wafer has been developed. In this way the entire bolometric array is fabricated with a single process. Filters and antennas can be integrated on the detectors wafer by means of micro-strip technology. The four arrays at 140, 220, 410 and 540 GHz will be composed of 19, 37, 37, 37 detectors respectively. Each array will fill the optically correct area of the focal plane (about 0.25 o in diameter projected in the sky). The bolometer arrays and the reimaging optics will be arranged into a modified version of the long duration cryostat developed for BOOMERanG. The main difference here is the use of fiberglass cylinders to replace the kevlar cords suspending the LN and LHe tanks. Fiberglass cylinders provide higher stiffness to the system.

II. POWER LOAD

We estimate the expected optical loading on the OLIMPO detectors assuming an emissivity of the OLIMPO telescope of 5%, an effective temperature of 250 K and an optical efficiency of the receiver of 30%. The power on each detector at 140, 220, 410 and 540 GHz is 4, 6, 14 and 28 pW respectively. Estimated detector parameters are given in Table 1.

Frequency (GHz)	150	220	410	540
Bandwidth (GHz)	35	45	50	50
Telescope loading (pW)	4	6	14	28
RJ sensitivity (μK/ÖHz)	90	100	80	65
CMB sensitivity (μK/ÖHz)	160	300	2100	10000

Table 1: Optical loading and sensitivities of OLIMPO detectors

III. SCEB – JFET

The main question is could we match the photon noise level with CEB-JFET?

Single CEB

Analysis of a single CEB bolometer [2] with JFET readout has not given any positive results in both current-biased and voltage-biased modes. The main reason for voltage-biased mode is strong influence of voltage noise. The voltage is divided by small dynamic resistance of the junctions in cooling region and gives strong noise current. Any attempts to increase dynamic resistance moving bias point to smaller voltages led to strong decrease of cooling and degradation of current responsivity.

A new idea: **to use a single SCEB (CEB with a weak superconducting absorber, SIS΄IS) in voltage-biased mode.**

The exciting chance to achieve photon noise level with single CEB has been proposed. For this purpose we should use a single CEB with superconducting absorber, SCEB [2]. In this case we can use v.-b. mode with V in the range between (Delta 1-Delta 2) and (Delta1 + Delta 2). In this region the IV of SIS΄junctions is flat or even with negative slope with considerably increased dynamic resistanse. Formally, it could be increased to infinity, in reality it will be limited by fluctuations or leakage resistance at the level of 1000*Rn-2000*Rn (typical level of leakage in our technology). Electron cooling will be still very effective for incoming power. The theoretical model of a cold-electron bolometer based on Superconductor-Insulator- weaker Superconductor-Insulator-Superconductor (SIS'IS) structure. has been developed with certain simplifying assumptions. First, complete relaxation of the quasiparticle distribution function in the absorber has been assumed and described by a single parameter – effective temperature. Second, Josephson current is ignored since the the structure is biased close to the gap voltage, in which case the Josephson current gives relatively weak contribution. Besides that Josephson effect can be suppressed by relatively weak magnetic field.

Within the framework of this model we can evaluate the responsivity and Noise Equivalent Power of the device and make the comparison with the corresponding values for CEB bolometer. This comparison shows that for JFET readout only a single SCEB can satisfy to noise requirements.

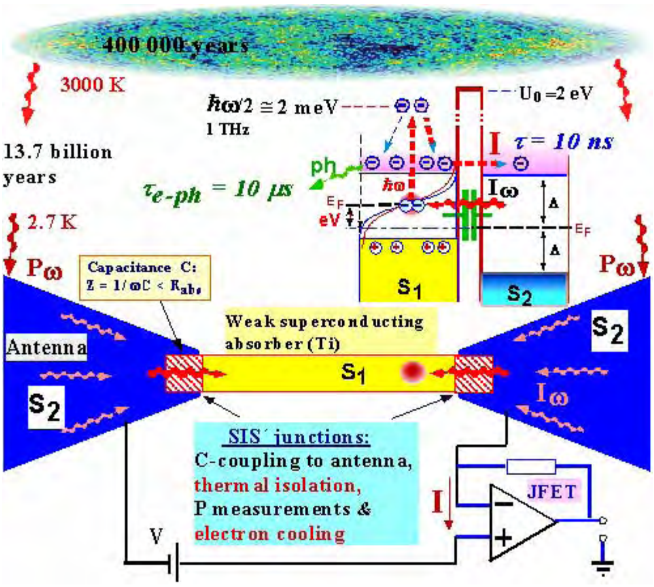

Fig 1. Schematic of a **Superconducting Cold-Electron Bolometer (SCEB) with capacitive coupling to the antenna**. The schematic covers different scales of time from **13.7 billion years** to **10 nanoseconds.**

Drawback of the SCEB is increase of shot noise due increased level of energy quantization, Delta 1, instead of kT_e for normal metal absorber [2]. Total noise will be determined by shot noise in this case but this increase does not still achieve the level of photon noise. Gain due to suppression of large voltage noise of JFET is larger than increase of shot noise.

Current fluctuations of JFET could be rather low and would be determined by feedback resistor.

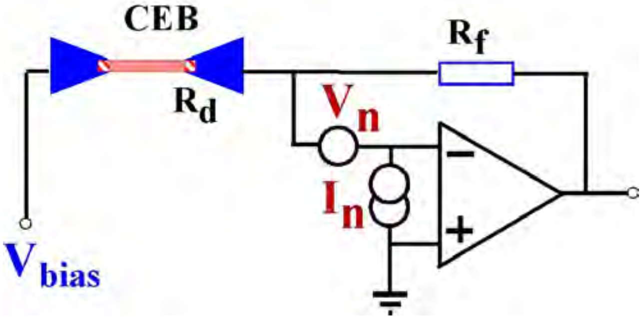

Fig 2. Schematic and noise sources of a JFET readout for superconducting cold-electron bolometer (SCEB).

For example, current noise of silicon JFET ”TIA” produced by Infrared Lab, is dominated by Johnson noise for feedback resistors up to $1x10^{11}$ Ohm. For 100 MOhm (acceptable for all range of our currents) at 4K the current noise will be at the level of 5 $fA/Hz^{1/2}$. The voltage fluctuations will be suppressed by high dynamic resistance of the junctions to this level or lower.
Simulations of the SCEB have been made with total noise current of 10 $fA/Hz^{1/2}$.

First estimations give optimistic figures of NEP better than photon noise for all channels for possible typical parameters of Al-Ti tunnel junctions.

1. Channel I: ”2.1 mm” (140 GHz)

Power load is relatively high: $P_0 = 2 – 3$ pW.
Let’s accept minimum value for NEP estimations: $P_0 = 2$ pW.

Photon noise: $NEP_{phot} = \sqrt{2P_0 * hf}$

For channel I, 140 GHz:

$$NEP_{phot} = 2*10^{-17} W/Hz^{1/2} .$$

Total NEP of CEB should be less than photon noise: $NEP_{tot} < NEP_{phot}$.

Single CEB doesn’t give proper results.
Only SCEB could give the proper NEP.

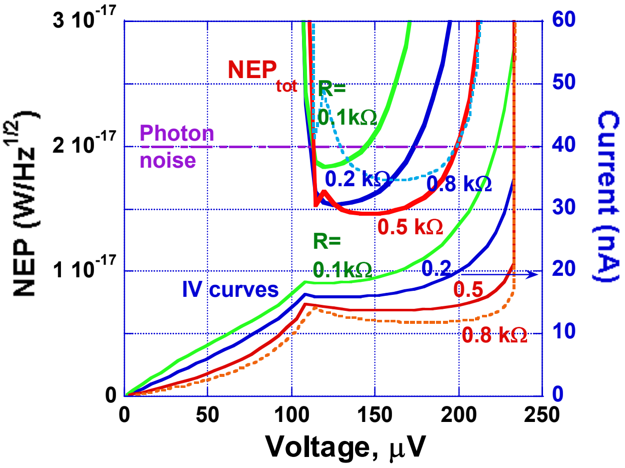

Fig. 3. Total NEP is less than NEPphot for SCEB, total i_{JFET}=10 $fA/Hz^{1/2}$, R=0.5 kOhm and 0.1 kOhm (one junction), Vol=0.05um^3, power load – 2 pW. IV curves are shown for estimation of high dynamic resistance of the junctions. Smearing of the gap (imaginery part of Delta = 0.01) is included in simulations. Leakage resistance is not included.

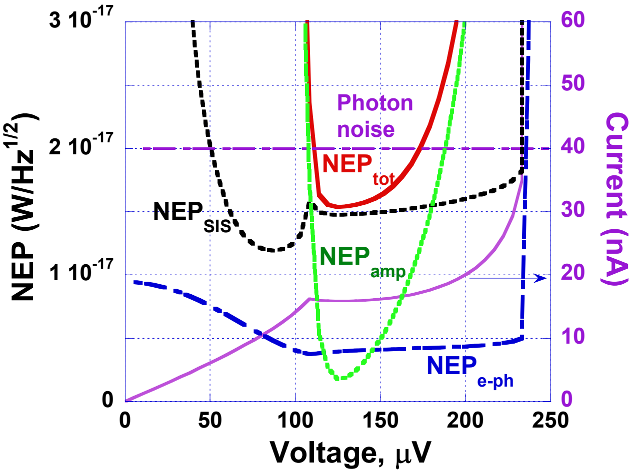

Fig. 4. NEP components for SCEB with JFET readout for i_{JFET}=10 fA/Hz$^{1/2}$, R=0.2 kOhm (one junction), Vol=0.1um^3, power load – 2 pW. IV curve is shown for estimation of high dynamic resistance of the junctions. Smearing of the gap (imaginery part of Delta = 0.01) is included in simulations. Leakage resistance is not included

The NEPtot of SCEB is mainly determined by shot noise (NEPsis) related with power load removed from Delta1 level by tunnel junctions (in contrast to the CEB with clear domination of JFET noise (NEPamp)).

<u>Channel IV: "0.5 mm" (600 GHz)</u>

Power load is rather high: P_0 = 10 – 20 pW.
Let's accept highest value for NEP estimations : P_0 = 20 pW.

Photon noise: $NEP_{phot} = \sqrt{2P_0 * hf}$

For channel IV – 600 GHz:

$NEP_{phot} = 1.2*10^{-16} W/Hz^{1/2}$.

Total NEP of CEB should be less than photon noise: NEPtot < NEPphot.
Single CEB doesn't give proper results.
Only SCEB gives proper NEP.

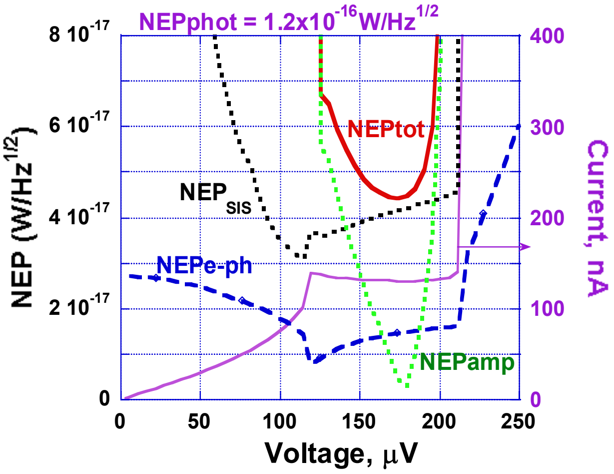

Fig. 5. Total NEP is less than NEPphot for SCEB, total i_{JFET}=10 fA/Hz$^{1/2}$, R=0.5 kOhm, 0.2 and 0.1 kOhm (one junction), Vol=0.05um^3, power load – 20 pW. IV curves are shown for estimation of high dynamic resistance of the junctions. Smearing of the gap (imaginery part of Delta = 0.01) is included in simulations. Leakage resistance is not included in this simulation.

Ideology of the SCEB - JFET matching:
For typical values of JFET noise: 5 nV/Hz$^{1/2}$ and 5 fA/Hz$^{1/2}$, we have an effective noise impedance around 1 MOhm. Typical resistance of CEB in operating point (near gap for strong electron cooling) is around 1 kOhm. We have clear mismatch at three orders of magnitude.
Replacing CEB by SCEB (with weak superconducting absorber) we choose a flat region of IV curve with very high dynamic resistance. Increase of resistance will be possibly limited by leakage resistance (or gap smearing) and is just around 3 orders of magnitude needed for noise-matching conditions.
Thus, the SCEB can bring remarkable progress in implementation of bolometers with JFET readout for all channels of OLIMPO.
The proper technology of Al/Aloxide/Ti junctions should be developed for this purpose. Possibly it should be a three-layer technology due to rather large areas of the junctions for lower frequencies (difficult for shadow evaporation technique). In principle, all steps in this technology, including etching the tunnel junctions area (say 2x2 um^2) could be done by photolithography..

IV. Series array of CEBs in current-biased mode

Analysis of lumped bolometer with one absorber and JFET readout has not given any positive results in both current-biased and voltage-biased modes. Typical results for current-biased mode can be seen in Fig. 3 for N=1 (single bolometer). The main reason is degradation of responsivity under high power load.
The only chance to achieve photon noise level is to use array of the bolometers. In this case each bolometer is not overload and show high responsivity. The resulting signal is collected from all bolometers. In the case of lumped antenna coupled

bolometer it could be realized as parallel connection of bolometers for HF and series connection of them for DC.
In the case of distributed antenna or array of slot antennas for one pixel, it could be realized rather natural as series connection of bolometers for dc signal.
First estimations give optimistic figures of NEP for array of bolometers even for existing level of technology. The gain of array is especially effective for 600 GHz channel with higher power load.

Channel IV: "0.5 mm" (600 GHz)

Power load is rather high: $P_0 = 10 – 20$ pW.
Let's accept highest value for NEP estimations : $P_0 = 20$ pW.

Photon noise: $NEP_{phot} = \sqrt{2P_0 * hf}$

$$NEP_{phot} = 1.2*10^{-16} W/Hz^{1/2} .$$

Total NEP of CEB should be less than photon noise: NEPtot < NEPphot.
Single CEB doesn't give proper results.
Only array gives proper NEP

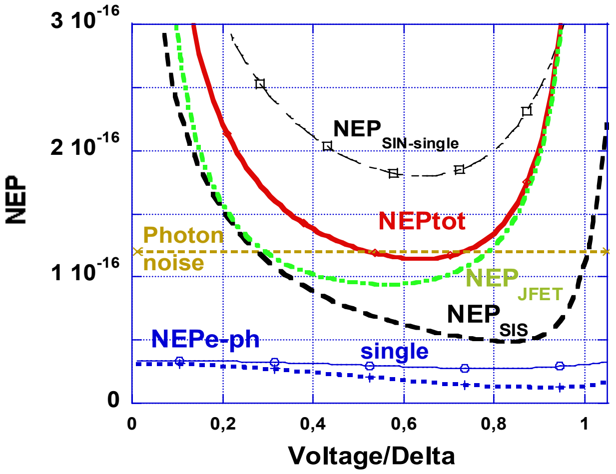

Fig. 1. Total NEP for array of 10 CEB, v_{JFET}=3 nV/Hz$^{1/2}$, R=0.5 kOhm (one junction), Vol=0.05um^3, power load – 20 pW. Junction noise and e-ph noise for single junction are shown for comparison. The power is split between bolometers and responsivity is considerably improved. For larger number of CEBs, the relation between NEPtot and NEPphot is even better (see fig. 3).

The NEPtot is still mainly determined by JFET noise (NEPamp)..

2. Channel I: "2.1 mm" (140 GHz)

Power load is relatively high: $P_0 = 2 – 3$ pW.
Let's accept minimum value for NEP estimations : $P_0 = 2$ pW.

Photon noise: $NEP_{phot} = \sqrt{2P_0 * hf}$

$$NEP_{phot} = 2*10^{-17} W/Hz^{1/2} .$$

Total NEP of CEB should be less than photon noise: $NEP_{tot} < NEP_{phot}$.
Single CEB doesn't give proper results.
Only array gives proper NEP

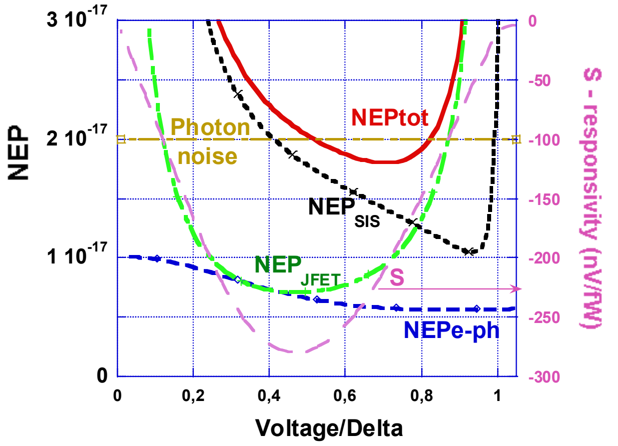

Fig. 2. Total NEP is less than NEPphot for array of 10 CEB, v_{JFET}=2 nV/Hz$^{1/2}$, R=0.5 kOhm (one junction), Vol=0.02um^3, power load – 2 pW. The power is split between bolometers and responsivity is considerably improved. The resistance is typical minimum resistance for our structures. Technological parameters are tougher than for previous case of array for 600 GHz.

Optimal number of CEBs in series array

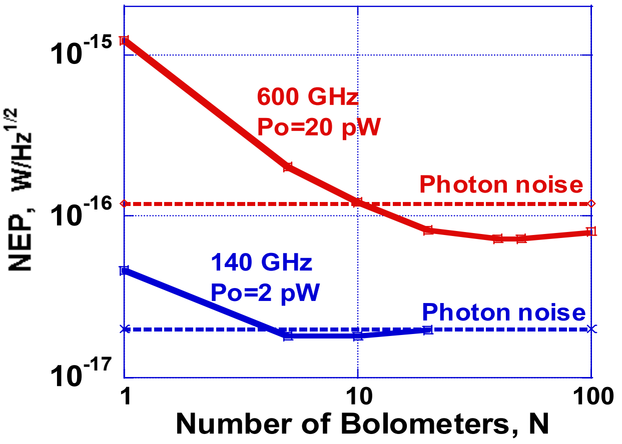

Fig. 3. Total NEP of CEB and NEPphot for series array of CEBs in dependence on number of CEBs a) ***600 GHz, power load P_0 = 20 pW***, v_{JFET}=3 nV/Hz$^{1/2}$, R=0.5 kOhm (one junction), Vol=0.05um^3. The power is split between bolometers and responsivity is considerably improved. The resistance is typical minimum resistance for our structures. Optimal number of bolometers is 40-50.
b) ***140 GHz, power load P_0 = 2 pW***, v_{JFET}=2 nV/Hz$^{1/2}$, R=0.5 kOhm (one junction), Vol=0.02um^3. The power is split between bolometers and responsivity is considerably improved. Optimal number of bolometers is 5-10.

The general rule of array design is the following:
Number of bolometers, N, should be increased to split Po between bolometers but up to the moment when $P_0/N = P_{ph}$, where $P_{ph} = T_{ph}^5 \Sigma V$, V- volume.

There is no sense to increase number of bolometers more than this figure because power load in each bolometer becomes less than power from phonons. The phonon power is determined by only one parameter, volume of absorber. The volume should be decreased as much as possible to decrease this figure (in contrast to SQUID readout where resistance of the junctions is the most important).

Thus, the progress in improvement of NEP for series array of bolometers is determined by technological limit of absorber volume. For higher power limit, the use of array is more effective than for lower power limit.
Channel IV, 600 GHz, looks more preferable for use of array of CEBs with JFET than channel I, 140 GHz.

V. Conclusions

For typical values of JFET noise: 5 nV/Hz$^{1/2}$ and 5 fA/Hz$^{1/2}$, we have an effective noise impedance around 1 MOhm. Typical resistance of CEB in operating point (near gap for strong electron cooling) is around 1 kOhm. We have clear mismatch at three orders of magnitude.
Replacing CEB on SCEB (with weak superconducting absorber) we choose flat region of IV curve with very high dynamic resistance. Increase of resistance will be possibly limited by leakage resistance and is just around 3 orders of magnitude that is enough for noise-matching conditions.

Thus, the SCEB can bring remarkable progress in implementation of bolometers with JFET readout for all channels of OLIMPO.
The proper technology of Al/Aloxide/Ti junctions should be developed for this purpose. Possibly it should be a three-layer technology due to rather large areas of the junctions for lower frequencies (difficult for shadow evaporation technique). In principle, all steps in this technology, including etching the tunnel junctions area (say 2x2 um^2) could be done by photolithography.

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