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CX-4

Cryogenic *Super Low Noise* Amplifier

- Datasheet -

V. 1.3 Oct. 2021

Features:

- **Frequency Range approx. 1kHz to 4MHz**
- **Very High Input Impedance**
- **Super Low Noise (0.31nV/√Hz @ 1MHz, ~4pF=C_{IN})**
- **Operation in strong magnetic fields (6T) and low temperatures down to 4.2 K and even lower**

Applications:

- **Quantum Transport Effects**
- **Tuning Forks**
- **Schottky Noise Measurements**
- **Single Ion FT-ICR**

Introduction

The CX-4 is a highly sensitive voltage preamplifier, intended for low-temperature, low-noise applications. The circuit can be used directly inside a cryogenic vacuum setup. Cryogenic GaAs (Gallium-Arsenide)-FET technology allows for deep-cryogenic operation, even in strong magnetic fields up to several Tesla, as they are present in NMR, FT-ICR or solid state research applications. The amplifier module covers a frequency range of approx. 1kHz....4MHz and has very high input impedance. The latter is suited specially for sensing induced image currents (slow ions, tuning forks) or for semiconductor noise measurements. The ultra-low input voltage noise around 310pV/√Hz around 1MHz is quite outstanding and represents the state-of-the art technology for high-impedance amplifiers.
The module is delivered as printboard-stack with aluminium lids and comes together with a mating room temperature biasing controller. Bias- and signal lines can be connected by normal soft-soldering procedures by the user. The device is available as 1- or 2-channel version.

Application Example

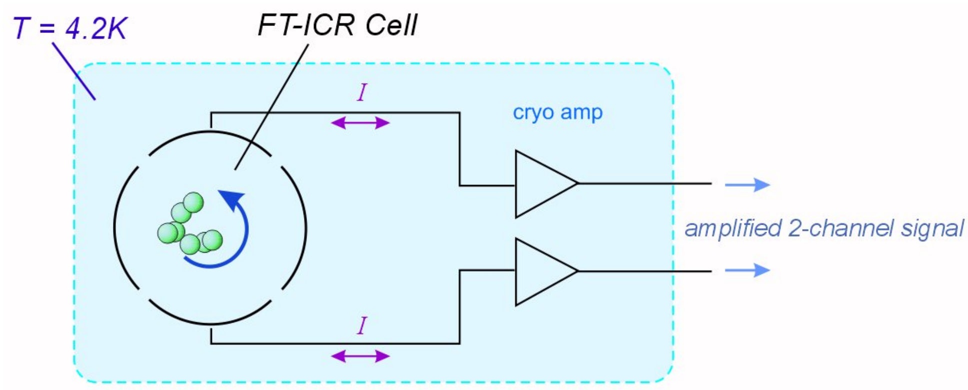


Fig. 1: Typical Application: High Impedance Signal Detection in FT-ICR Cells

Solder Connections

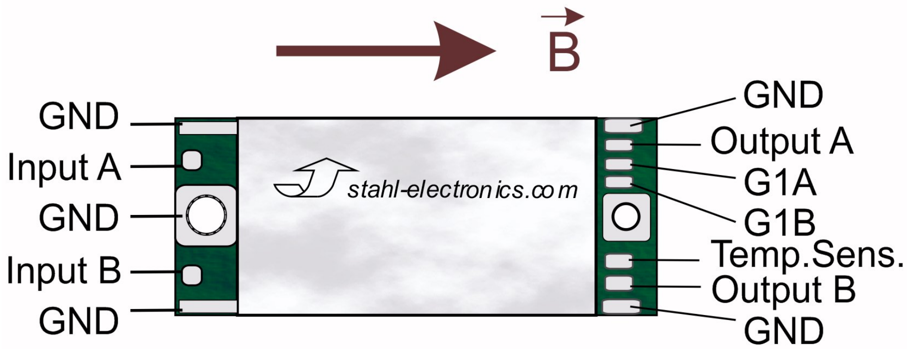
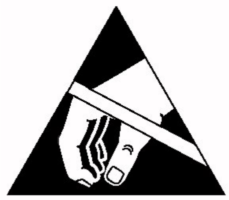


Fig. 2: Pinout / Solder Pad Connections, 2 channel version,
and external B-field orientation in terms of direction and polarity

Electrostatic Sensitivity



This device can be **damaged** by ESD (Electrostatic Discharge). It is **strongly recommended** to handle the device with appropriate precaution. Failure to observe proper handling and installation procedures can cause serious damage. This ESD damage can range from subtle performance degradation to complete device failure.

Practical Hints:
Whenever the device is picked up by hand, ensure that the ground pin or aluminium case is touched <u>first</u> before touching any other pin. Touching any other pin than ground first, ***may destroy this device****. Similar precaution has to be applied when changing the location of the device: Most important the destinations ground has to be on the same potential as the devices ground (ground balancing). Therefore connect both grounds first (using a resistor around 100kOhm, or simply by hand without gloves) before making any other connection or changing the amplifier position. Failure to perform ground balancing may easily lead to severe irreversible damage of the device. Always ensure to take thorough measures to avoid static charges building up in the vincinity of this device or laboratory equipment connected to it.*

Connection to Room Temperature Biasing Unit

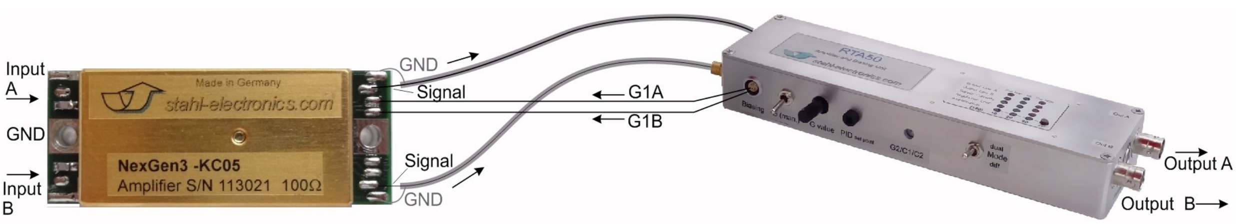


Fig. 3 Cabling to Room Temperature Biasing Unit A3-5 (2-channel version)

As indicated in the figure above, the device is connected to its mating room temperature controller through two biasing lines (G1A, G1B) and the output signal lines (coaxial lines preferred). G1A and G1B are negative supplies (typical values for G1A, G1B are -25mV at cryogenic temperatures) and will be regulated by the Biasing Unit.

Absolute Maximum Ratings

Note: Stress above these ratings may cause permanent damage or degradation of device performance. Exceeding these conditions for extended periods may also degrade device reliability.

Quantity	Limits		Remarks
	min.	max.	
neg. Supply Voltage G1A/B	+1.0V	-10V	
Input Voltage absolute value (AC+DC) AC		100 V_{pk} vs. GND, $3V_{pp}$, f = 0 ... 5MHz	derating inversely proportional with frequency above 5MHz
Input Current		$40mA_{eff}$	continuous current through protection circuitry
Output Voltage	-1.2V	+5.3V	Under normal conditions no voltage source must be applied to the outputs.
Storage Temperature	3.5K	125°C	
Storage Humidity		65% @ 40°C	
Cool-down Rate, Heating Rate		+/- 20K / minute	Care has to be taken in the cool down and warm up phases. A sudden drop into cryogenic liquids may destroy the device.

Table 1: Absolute Maximum Ratings

Cleaning and Baking

The CX-4 device may be carefully purged from organic attachements by rinsing with a mild solvent like ethanol or isopropanol. It may be also dipped for a while into these solvents. Stronger solvents like acetone are not recommended. Due to sensitive internal parts (bond wires of approx. only 40µm Gold thickness), in no case pressurised air or pressured solvents must be guided into the inner parts of the device. Baking is possible up to 125°C, and should not last longer than 48 hours prior to use at cryogenic temperatures.

Characteristic Data and Operating Parameters Cryogenic Amplifier CX-4 in conjunction with mating Room Temperature Biasing Unit A3-5

Parameter	typical Value	Remarks/Conditions
Freq. Range @ 4.2K for ±3dB deviation	1 kHz....4 MHz (intrinsic range)	±3dB range 4 kHz … 4MHz in conjucntion with A3-5 controller
Gain linear voltage gain @300K linear voltage gain @ 4.2K (for elevated temperatures >4.4K see data at end of this document)	x 60 V/V ± 30% x 150 V/V ± 30% x 300 V/V ± 30% x 600 V/V ± 30% x 250 V/V ± 4% x 600 V/V ± 4% x 1200 V/V ± 6% x 2400 V/V ± 8%	f = 1MHz over-all amplification including biasing controller, on 50 Ohm load 4 amplification steps are available
Gain Mismatch between both cannels	typ. 2%	T = 4.2K, f = 100kHz ... 1MHz
Input Impedance vs. GND at either input DC, T = 4.2K … 300K AC, 300K AC, 4.2K input capacitance vs. GND	> 40MΩ capacitively coupled >1MΩ capacitively coupled ≥ 15MΩ 4.2pF ±1.0pF	f < 1kHz f < 100kHz T = 4.2K … 300K
Dynamic Output Impedance cryogenic stage @ 4.2K max. AC Output Power	4 kΩ ± 25% 3 mW	f = 100kHz
Expected Impedance Biasing Unit max. AC Output Power	60 Ω ± 10% 5 mW	
Input Noise **T = 300K** voltage noise density **T = 4.2K** voltage noise density current noise density	12 nV/√Hz 6 nV/√Hz 3.3 nV/√Hz 3.0 nV/√Hz 0.6 nV/√Hz 0.35 nV/√Hz 0.31 nV/√Hz 0.5 nV/√Hz 7.5 fA/√Hz, T = 4.2K	f = 100kHz 500kHz 1MHz 4MHz f = 100kHz 500kHz 1MHz 4MHz f = 100 kHz
Operating voltages positive supply voltage on signal line G1A, G1B negative supply voltage	+0.25 V -0.1V to -3.0 V @ 300 K -25mV @ 4.2 K	Positive and negative supply should be provided by a room temperature biasing unit

Supply Currents @ 300K…4.2K positive supply on signal line negative supply current G1A/B	1.6 mA each channel < 30 µA	
Operating Temperatures	T = 4.2 K... 70K and 300 K	The device is primarily designed for low temperature applications
Applicable external magnetic field B	B = 0 to 6T	external field must be in parallel to the long-side of the device (+/-3.5°) at fields above B = 0.1T and oriented like shown in fig. 2 (not reversed)
Magnetic Properties	Device consists mostly of non-magnetic materials. Spurious amounts of ferromagnetic substances < 5 x 10^{-3}gr. are possible	For use with FT-ICR cells, it is recommended to locate the device min. 5cm away from the ion trap/FT-ICR cell structure in order to avoid magnetic disturbance
Size CX-4 1-ch. Size CX-4 2-ch. Room Temperature Biasing Unit	40.5mm x 16mm x 8.9mm 54.5mm x 21.2mm x 8.9mm approx. 210mm x 65mm x 34 mm	
Outgassing	(to be determined)	
Weight Cryogenic Unit Room Temperature Biasing Unit	approx. 25 gr. 400 gr.	
Power Supply for Room Temperature Biasing Unit	Output +/-5V on Lemo Connector 3-pole 0B-style	**Attention: the external B-field into which the mains adaptor is placed must not exceed B = 10mT to prevent damage or fire hazard.**

Table 2: Characteristic Data

Required External Circuitry

The cryogenic preamplifier requires negative biasing lines, which should be adjusted to hold the device at stable working conditions. The room temperature controller (e.g. Type A3-5), which is provided along with the cryogenic amplifier regulates these bias lines (G1A for channel A, G1B for channel B) to be around -25mV at 4.2K environmental temperature, by means of an automatic PID regulation loop. For testing purposes one can also disable the regaulation and set values manually (optional knob on front side of amplifier). Increasing (making more positive) these values leads to an increase of current consumption, which is normally around 1.6mA each channel and vice versa.

The biasing controller of the CX-4 serves also as a tool for error finding and debugging. The controller provides further AC amplification in discrete step, normally set to x 250 V/V, x 600 V/V, x 1200 V/V or x 2400 V/V of voltage amplification at 50 Ohm load (twice as much on high impedance load). In case of two channels, it supports also a differential operation, by building the signal difference between the two channels.

Figure: 4: the roomtemperature controller indicates the status of the cryo amplifier and allows for setting the overall-amplification factor. The stated values of amplification factors refer to cryogenic operation.

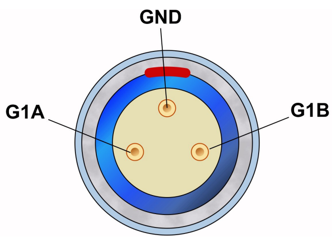


Figure 5: Pinout of connector socket (Lemo 0B type) at the side of the roomtemperature controller for providing bias lines to the cryogenic amplifier.

A connection cable is provided by the manufacturer, to connect this Biasing output socket to a vacuum flange towards the cryogenic amplifier. The open ends of this cable should be mounted in an electrically shielded way to corresponding feedtrough pins. The 3 open wires are G1A (brown), GND (white) and G1B (green).

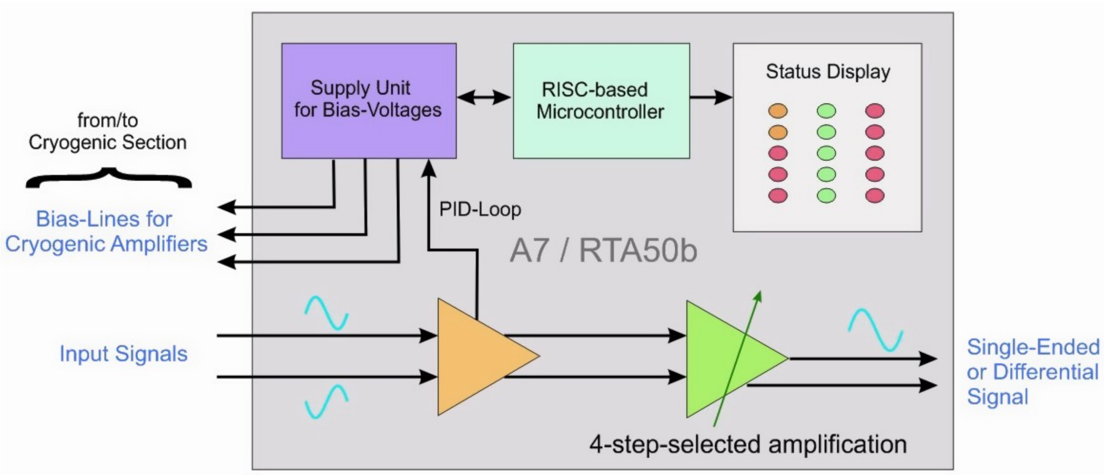


Figure 6: Block diagram of 2-channel roomtemperature controller

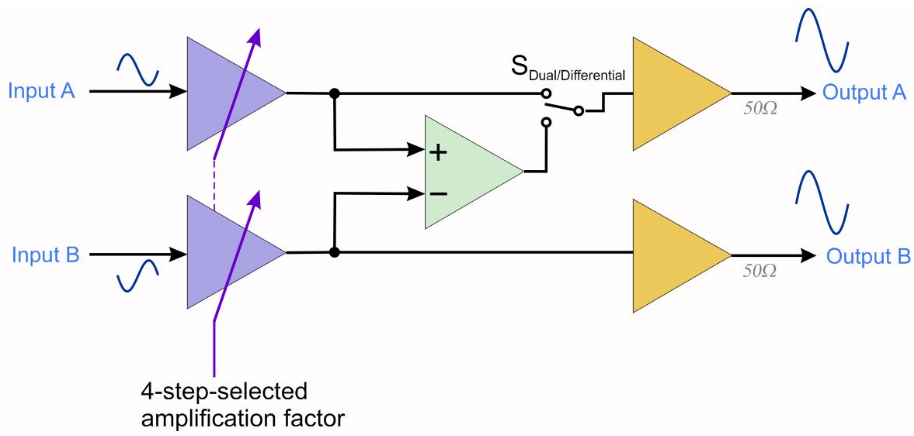


Figure 7: Schematic diagram of the analog signal amplifier circuitry inside the roomtemperature controller. The mode switch $S_{Dual/Differential}$ allows for choosing between dual-channel or differential operation

Monitoring section

This section consists mainly of a microcontroller and an attached LED (light emitting diode) status display. The microcontroller makes use of instrumentation amplifiers inside the supply unit and observes the biasing currents and voltages once a cryogenic amplifier is connected. This information is processed and the results are displayed on a LED-display, such that an overview of the cryogenic amplifier's status is obtained. Eventual problems in the cryogenic region are therefore easier to locate.

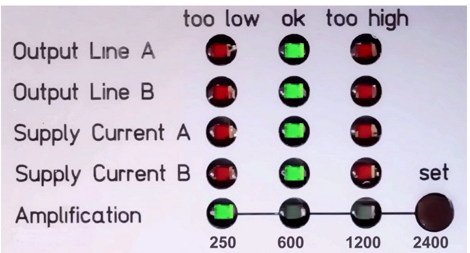


Figure 8:
LEDs indicate the status of biasing lines, assisting to find problems in the cryogenic region. The bottom row represents the amplification factor, and the amplification selection switch. Pressing the switch increases the amplification factor, a long press resets to the minimum value.

The threshold levels, upon which the LEDs change their status, are set by default (software programming) to the values stated in the Appendix. In normal operation all light up green.

Connections inside Vacuum

Biasing Lines

The 2 Biasing lines GA1 and G2B carry only minor currents and can therefor be implemented as thin wires, e.g. made of Constantan™ or Manganin™, to ensure low thermal conductivity to avoid thermal load on the cryogenic part of a setup.

AC connections to Room Temperature

The signal connection from cryogenic to room temperature (Output A, Output B) should be implemented as short coaxial lines, in order to minimize external interference and the possibility of unwanted feedback from the output to the high-impedance input. Cable impedance of the room temperature connection is not critical, unless the cable length greatly exceeds ~2m. A cryogenic low-capacitance cable is preferable.

Input Connections and Grounding, Risk of Self-Oscillations

Using high impedance amplifiers, such as the CX-4, requires proper *Grounding and Shielding* at the input side. A thorough grounding and shielding is essential to maintain good device performance and low noise characteristics, and to avoid the creation of parasitic oscillations. Typical RF (radio frequency) -design rules for proper grounding and shielding apply here, even though the upper limit of the frequency range just barely reaches the HF (high frequency) regime. To ensure a "clean" electrical environment provide good ground connections especially around the amplifier input. The gounding hole at the input (see subsequent photo) may serve as central connection point, to which the signal ground may be connected. All lines from the signal source to the amplifiers inputs should be kept as short as possible and of low inductance-style.

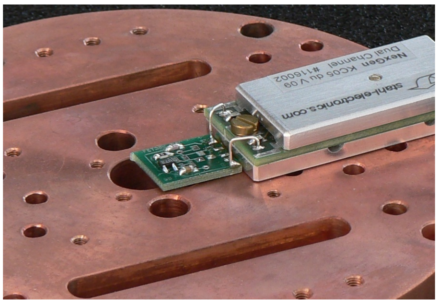


Figure 9:
Illustration of connecting a sample to the amplifiers inputs. Very short silver-plated wires represent the electrical signal connection while a brass scew establishes a tight mechanical GND contact to a well-conducting copper substrate. In the cold state the brass will keep tight, improving the GND and thermal connection.

Please note that insufficient grounding or shielding around the signal source, may lead to a considerably increased noise level and furthermore increases the risk of self-oscillations. These uncontrollable oscillations appear typically at MHz- frequencies and are normally an indication of insufficient shielding at the input. Also note that the supply lines of the preamplifier should be free of noise before reaching this device. In noisy environments this can be achieved by filtering the voltages through RC lowpasses, consisting of R (approx. 10kΩ to 50kΩ for G1A/B) and C of approx. 10nF (plastic dielectric, or NPO type) to GND.

External Magnetic Field

In case a static external magnetic field is applied (e.g. FT-ICR or NMR setups) the CX-4 amplifier must be oriented like shown in figure 2, i.e. with the long side parallel to the external field, max. 3.5 degrees deviation. Also, the polarity is decisive and thus the field orientation matters. This applies for magnetic fields higher than about 0.1T. Figure 2 depicts the proper orientation and refers to the usual convention of polarity definition, i.e. the field line arrow points from a magnetic north pole to a magnetic south pole. For instance, earth's geographic North Pole is a magnetic south pole; a conventional mechanical compass or Smart Phone App may be therefore used, to determine the magnetic field direction at a given experimental setup at safe distance from a strong magnet.

Input Circuitry

The subsequent figure illustrates the input protection circuitry for each input. DC blocking capacitors are provided in order to maintain a reasonable amount of admissible DC offset voltage being applied to the inputs without harm. These blocking capacitors $C_{blocking}$ are located outside the upper aluminium housing (see figure) and can be bridged / removed in favour of zero-ohm resistors for an optimised noise figure or in case a different coupling scheme is required. In case they are kept in place, the maximum allowed offset voltage at each input is +/-100V versus GND.

The limited pulse capability of maximum $1A_{pk}$ for less than 10ms duration has to be kept in mind, which is restricted by the maximum possible current through antiparallel protection diodes (see fig. 10a). This matters especially if attached circuitry is operated in a switched or pulsed mode, or exposed to high-power radio frequency bursts (like in FT-ICR or NMR experiments).

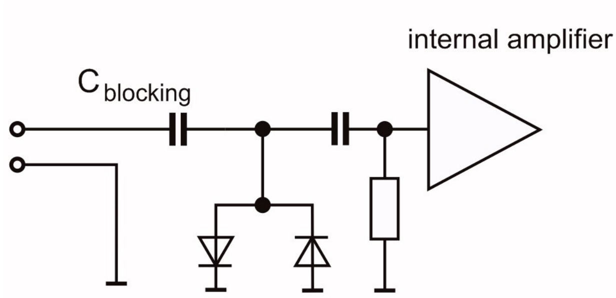


Figure: 10a

Input protection scheme (each channel)

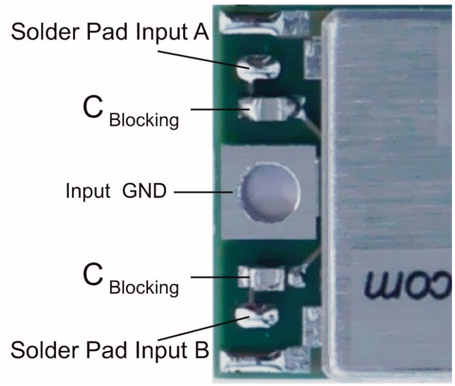


Figure: 10b

Location of removable blocking capacitors

In case the blocking capacitors are bridged, the input ESD-protection diodes limit the maximum voltage to about +/-750mV. Behind this protection circuitry the subsequent amplifier stages follow capacitively (AC) coupled.

Thermal Anchoring

Mounting the device into a cryogenic setup demands for a good thermal coupling, which is essential to achieve the specified performance of the CX-4 series amplifiers at low temperatures. The substrate, on which the circuitry is placed, should be connected by the user to an appropriate heat sink or cold finger. It is recommended to use a high conductance thermal agent like "Apiezon N" to provide a good

heat flow between the adjacent surfaces (apply only as very thin layer, to bridge possible vacuum gaps). We recommend using one of the 3mm-holes for mounting with brass or (preferably) aluminium screws on a cold surface, or cold finger. Using brass or aluminium material (rather than other metals) is essential, since it will contract stronger than for instance steel or copper, which have a smaller thermal contraction when getting cold. Note that using stainless steel screws can drastically impair the thermal connection, due to thermal contraction mismatch (screws getting loose) and also low thermal conduction at cryogenic temperatures.
When mounting the thermal connection, ensure to avoid mechanical tension of the remaining parts of the amplifier or other kind of mechanical stress. It is recommended, not to connect both amplifier ends with screws, unless the substrate to connect shows a similar thermal expansion like the amplifiers aluminium (AlMg alloy) housing. Copper or Aluminium substrates serve well in this respect.

Commissioning in a Vacuum or Cryogenic Setup

After cleaning and baking (in case required, see also page 4) the CX-4 device can be mounted and wired up in a cryogenic vacuum chamber. It is very important to connect ground lines first for **ESD reasons** (fatal damage by Electrostatic Discharge). The device may be checked for obvious mounting problems and eventually powered up with appropriate supply voltages (e.g. A3-5 Biasing Unit).
Before power is applied to the device, one should carefully check the cable connections in order to avoid damage or malfunction. With a standard multimeter (DMM) one can perform a quick check of resistances. The following table lists typical terminal values of the amplifier lines versus GND.

Line designator or Pad	Resistance vs. GND	Remark
G1A, G1B	1.04 MΩ	value slightly differs over 4K-300K range
Output A, Output B	approx. 80Ω ± 15Ω @ 300K approx. 55 Ω @ 4.2K	Since the device output features protection diodes, the value shown on a DMM display depends on the measurement current and voltage in resistance measuring mode.

Table 3: typical resistance values of lines versus GND, measured with standard multimeter.

Cool-Down Procedure and Readjustments

After a complete check of the cabling (using a DMM in Ω-Mode, table above) and in case the latter is correct, one may temporarily power-up the device. The biasing currents on G1A, G1B are in the µA range. The room temperature controller will adjust the voltage on G1A, G1B such that the supply currents on the signal lines are around 1.6mA. During cool down in a cryostat the device **must** be switched off. The reason are strong offset shifts, which may cause temporary malfunctions otherwise. Please turn the power only on, once the final temperature is reached or temperature is already below 45K. After cooling down one may recheck the resistance of lines to be sure the device is operational.

Note:

During cool-down/warm-up procedures always maintain a temperature rise or decrease of no more than +/-20 degrees Kelvin per minute. Note that exceeding this temperature slew/fall rate may damage the device due to formation of mechanical cracks. **Never apply thermal shocks to the device like dipping into a cryogenic liquid**.

Cool-Down and Warm-Up Cycles

Care has to be taken in the cool down and warm up phases. A fast drop into cryogenic liquids can **damage** the device because of excessive mechanical stress, caused by rapid thermal contractions or expansions. It is strongly recommended to keep the rate of temperature change below +/- 20K / minute. A complete cool down from room temperature into a cryogenic liquid like liquid Nitrogen or liquid Helium should take at least 20 minutes (liquid Helium) or 15 minutes (liquid Nitrogen).

Care has also to be taken, in case the device is brought from the cold state into normal air because of humidity condensing on the cold surfaces. In case the device is still powered up with supply voltages, a water film on the surfaces will lead to immediate destructive galvanic corrosion. It is strongly recommended to let the device dry thoroughly before next operation, eventually using a conventional hair dryer, after the device was brought out of vacuum. Beware of overheating the device in this procedure. The use of so-called “hot air guns” is not allowed, since the latters air temperature easily exceeds 150 deg Celsius, which may lead to rapid overheating and substantial, non-reversible damage of the device. Even using conventional hair dryers, they should be set to minimum heat output and the device temperature carefully monitored in order to never exceed 150 deg. Celsius.

Temperature Check Diode

One of the soldering pads (see figure 2) is internally connected by a silicon diode to GND, by which the temperature of the device can be monitored. The diode should by biased with an electrical current of 5 to 7µA, and will display a voltage of around 0.7V at roomtemperature, 1.05V at 77K and approx. 1.35V at 4.2 Kelvin environmental temperature. The diode is not (explicitely) calibrated, but its voltage serves well to get a coarse estimate of the local temperature and helps finding thermal issues (e.g. heating up of the amplifier because of bad cooling inside a cryostat)

Amplification and Noise Data

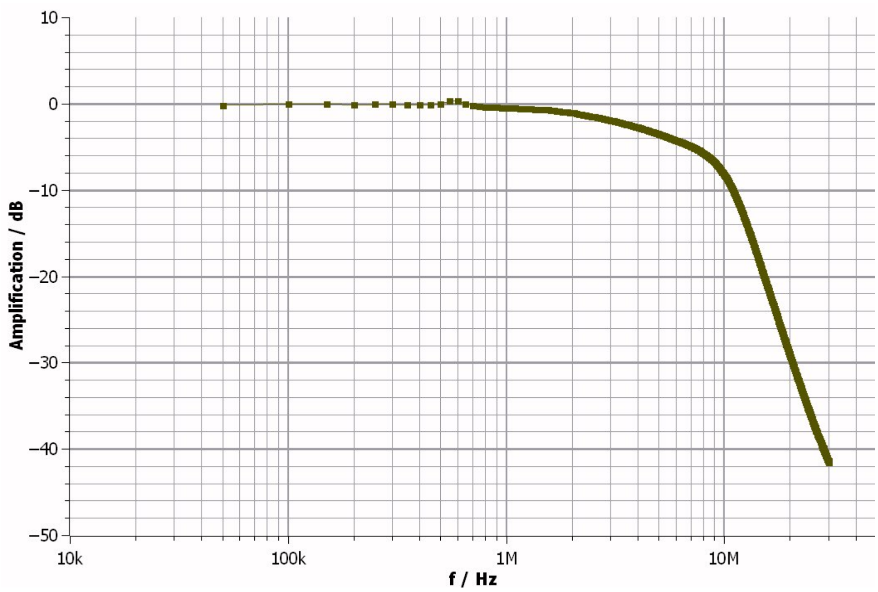


Fig. 11: Amplification at Cryogenic Temperature as Function of Frequency, expressed in dB relative to the amplification factor at f = 100kHz.
The data set comprises the cryogenic amplifier (at 5.6K) including the biasing section with 50 Ohm load.

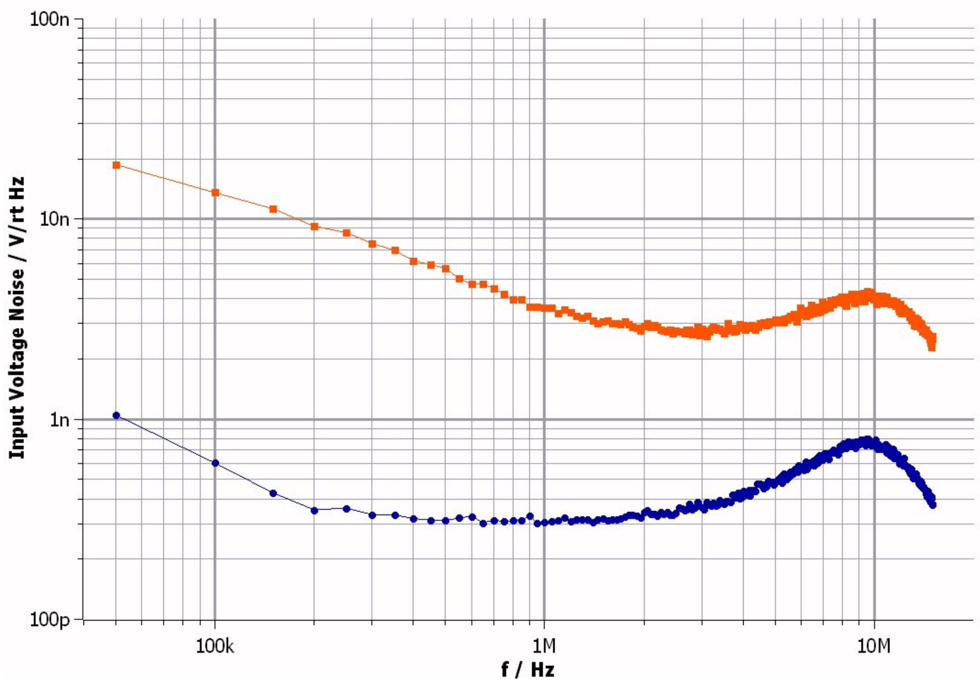


Fig. 12: Input Voltage Noise Density at 300K and at 4.2K in a cryogenic vacuum chamber

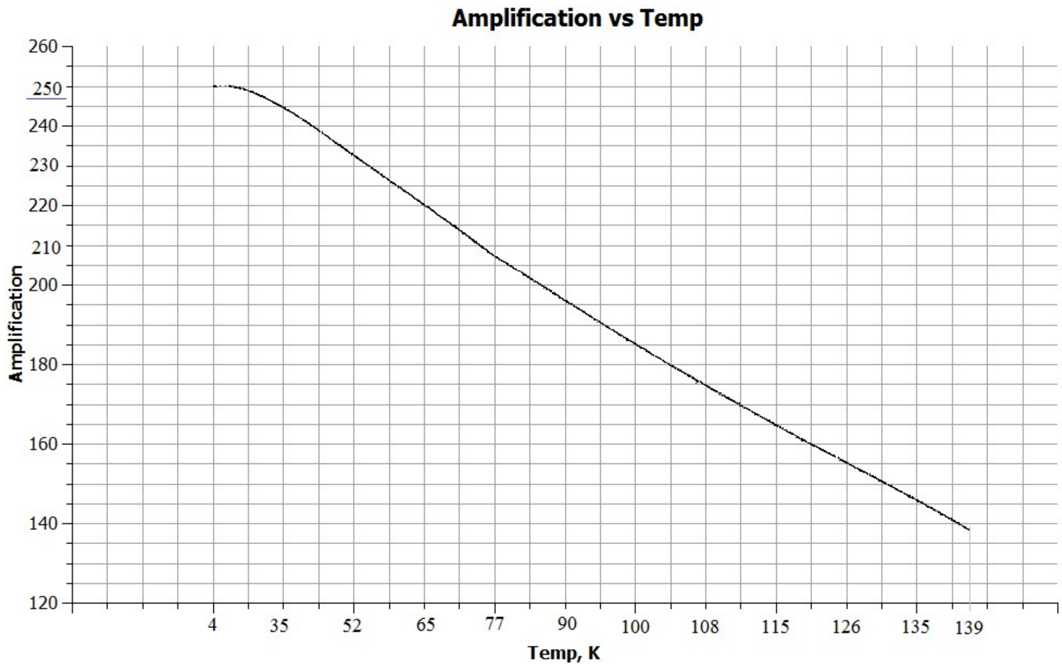


Fig. 13: Voltage Amplification factor as function of ambient temperature, from ~4.2K to elevated cryogenic temperatures.

Note, that the voltage amplification labels on the A3-5 biasing unit ONLY refer to 4.2K operation. The loss of amplification at elevated temperatures (say, above ~15K) is not automatically being corrected, since the nominal operating temperature is around 4.2K.

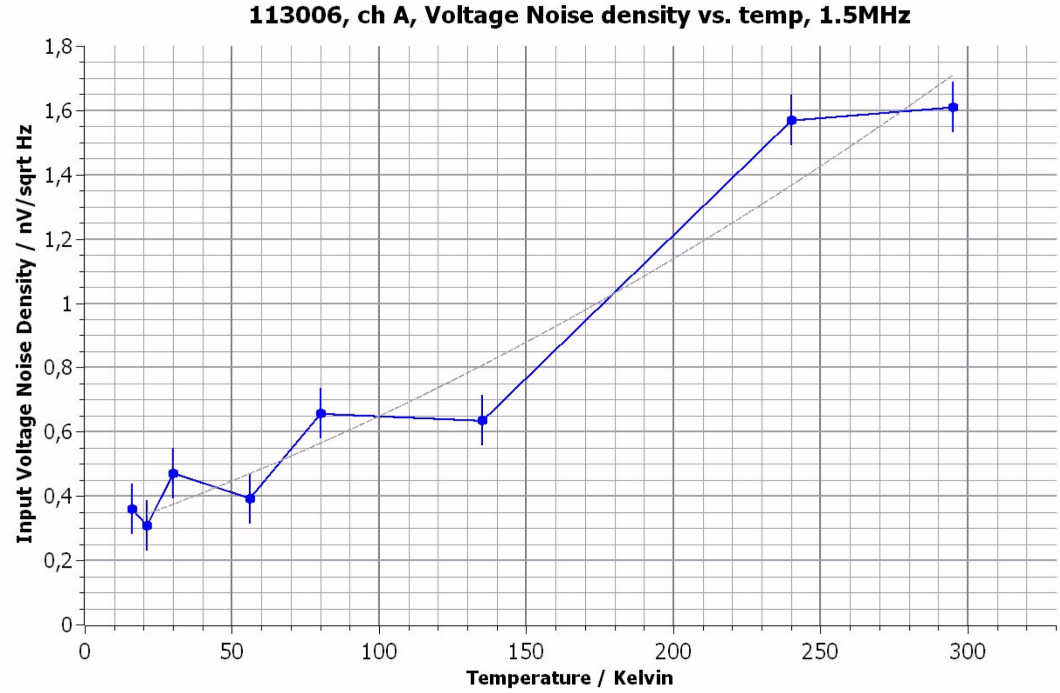


Fig. 14: Voltage Input Noise Density at f = 1.5MHz as function of ambient temperature

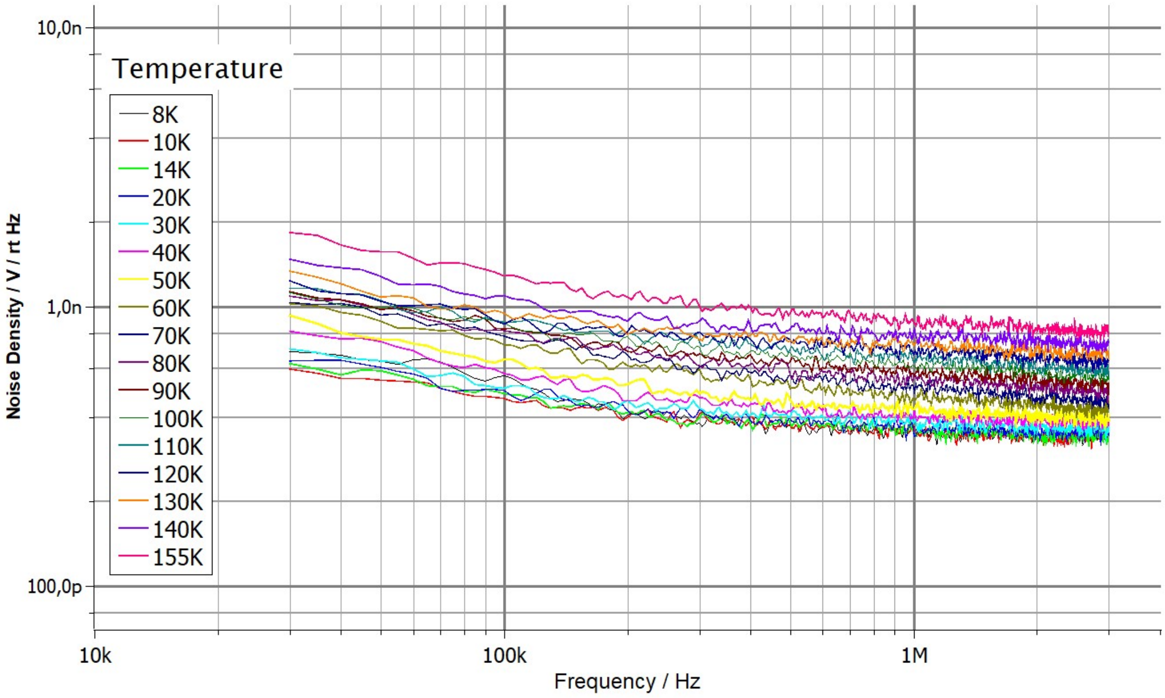


Fig. 15: Voltage Input Noise Density Graphs as function of ambient temperature from 8K to 162K

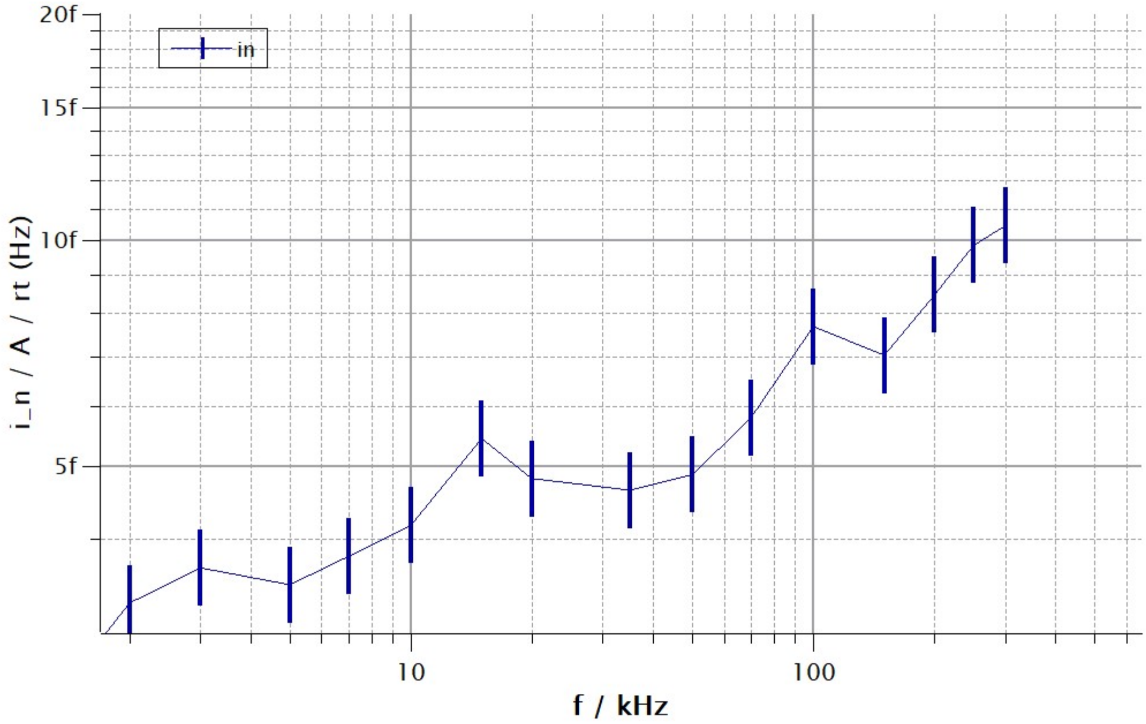


Fig. 16: Input Current Noise Density, determined at distinct frequencies; ambient temperature 8K

Geometrical Outline

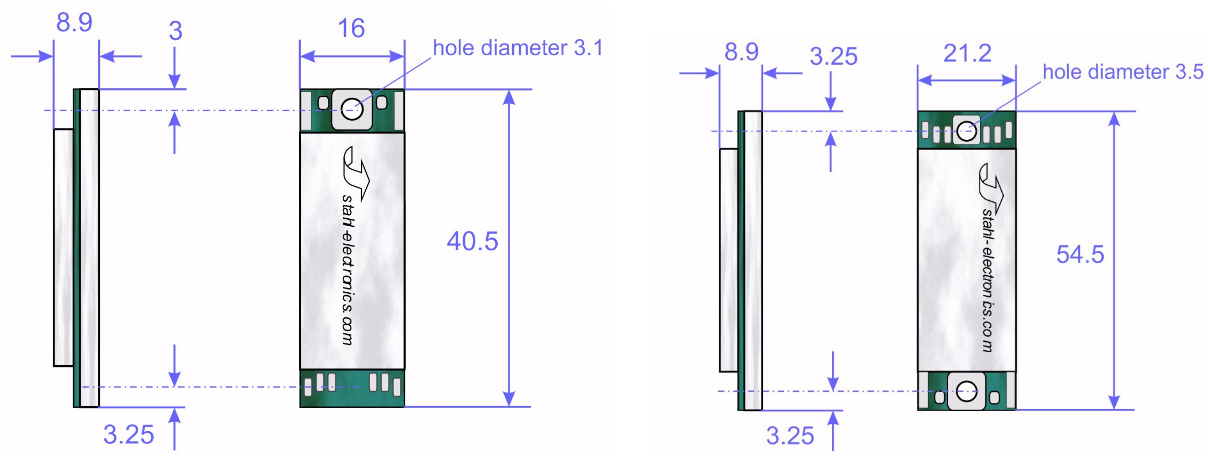


Figure 17a, b: Outline dimensions 1-channel version and 2-channel version (units: mm)

Appendix

LED Indicator threshold values of A3-5 biasing unit

	too low	**ok**	**too high**	remark
Output Line A and B (monitoring DC level)	< 0.2V	0.2V … 0.33V	>0.33V	
Supply Currents	< 1.0mA	1.0mA … 2.0mA	>2.0 mA	currents flow through A3-5 inputs and CX-4 outputs

Table 4: typical DC threshold levels, defining the range in which individual LEDs will lighten up.

Trouble Shooting

In case not all LEDs show green light, there could be the following reasons.

DC level on Output line A or B too low:

- there could be a short from a cryogenic signal output line to GND or
- wrong biasing on the G1A or G1B line or Biasing not connected.

DC level on Output line A or B too high:

- may be caused by an open line (cable towards cryogenic amplifier interrupted and open) or wrong biasing on the G line.
- A missing GND connection (300K-to-cryogenic) could also be the reason.

Supply current too low:

- biasing G too negative (maybe not in 'Auto-Mode')
- missing GND connection (300K to cryogenic)

Supply current too high:

- short cut from signal line to GND or short cut from an output to GND
  → disconnect cryogenic amplifier to prevent damage
- biasing G too positive (e.g. during manual operation, PID disabled)
- biasing line G not connected at all or shorted to GND

If one of these error conditions occurs, check carefully all connections, eventually also the nominal resistances of the supply lines to the cryogenic amplifier according to the value listed above. Note that in case the cryogenic amplifier is operated at room temperature, the regulation loop may not lock due to occurrence of leakage currents. This problem will disappear as soon as the amplifier is cooled down substantially below 0°C. Please note that the amplifier must be **switched off during the cool-down process**, until final temperature is reached. Otherwise the PID regulation loop may have problems to stabilize the working point. If one assumes, that the power was accidentally turned on during cooling, one can restore the correct operating condition by warming up completely to 300K and starting again in the off-state.