Applications for Radiation Hardened Analogue and Mixed-Signal ASICs

A radiation-hardened and low flicker noise ASIC preamplifier designed in CMOS technology for the ultra-sensitive ESA JUICE search coil magnetometer

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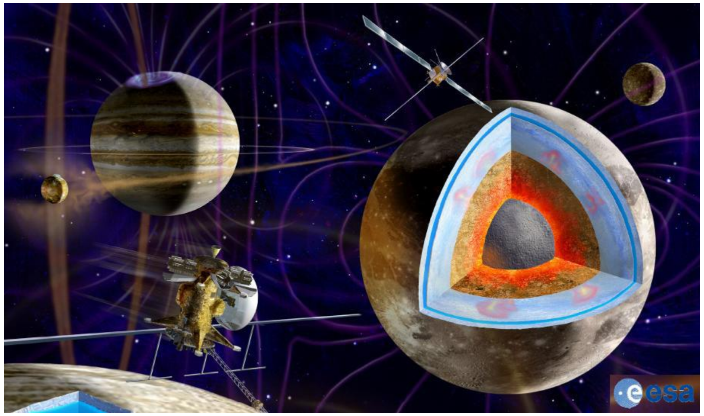
Mission: JUICE for JUpiter ICy moons Explorer (ESA mission)

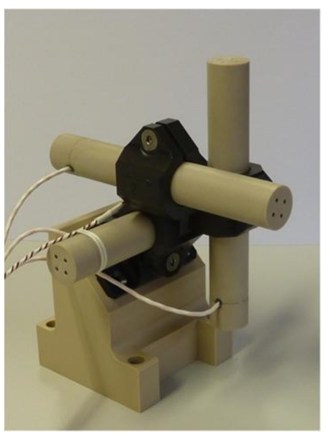


- For launch in 2022 – arrival in 2030

- To observe Jupiter's atmosphere and magnetosphere, and the interaction of all four Galilean satellites with the gas giant planet

- It will carry a total of 11 scientific experiments

Our contribution: Ultra-sensitive Search Coil Magnetometer and ASIC Electronics



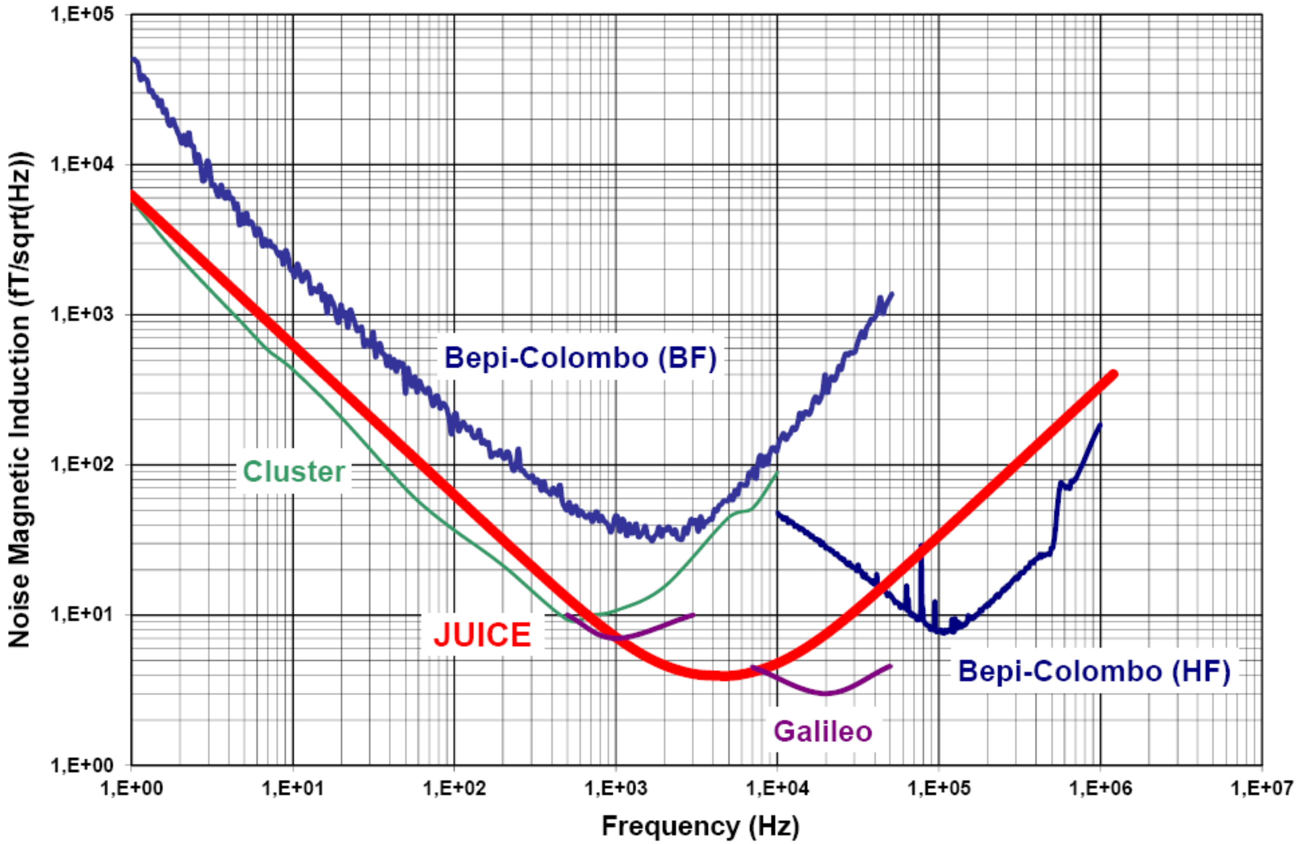
The NASA/MMS SCM (launching in 2015)

The SCM will operate in 0.1 Hz - 20 kHz

Temperature = 123 °K up to 373 °K

TID = 300 krads

Sensitivity is defined by the Noise Equivalent Magnetic Induction (NEMI) of the sensor



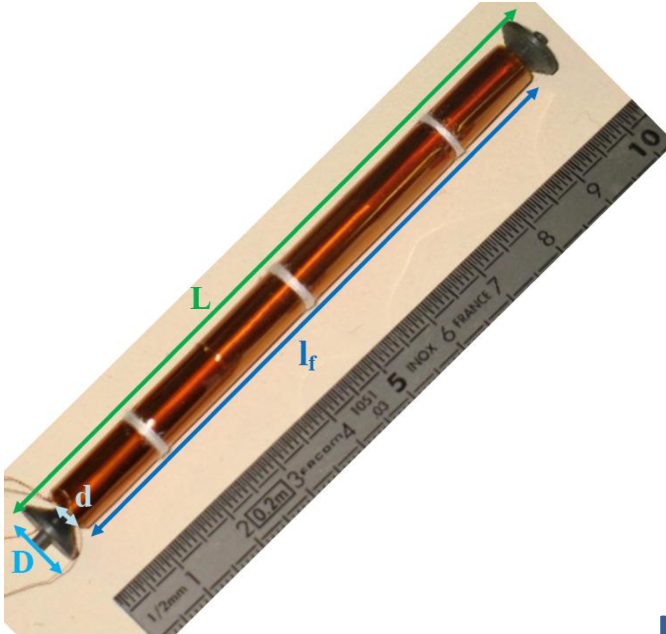
$$NEMI(f) = \sqrt{\frac{PSD_{out}(f)}{T(j\omega)^2}}$$

Expressed in [T/sqrt(Hz)] and defined as the output noise related to the transfer function of the induction magnetometer.

$600 \frac{fT}{\sqrt{Hz}}$ *requires* $4 \frac{nV}{\sqrt{Hz}}$ *of noise @ 10 Hz* ⟵-------- **1/f noise**

$6 \frac{fT}{\sqrt{Hz}}$ *requires* $2.7 \frac{nV}{\sqrt{Hz}}$ *of noise @ 1 kHz* ⟵-------- **Thermal noise**

Principle of the SCM



L = 10 cm	
D = 4 cm	
d = 1 cm	
N = 19600	

Principal: Lenz-Faraday's Law

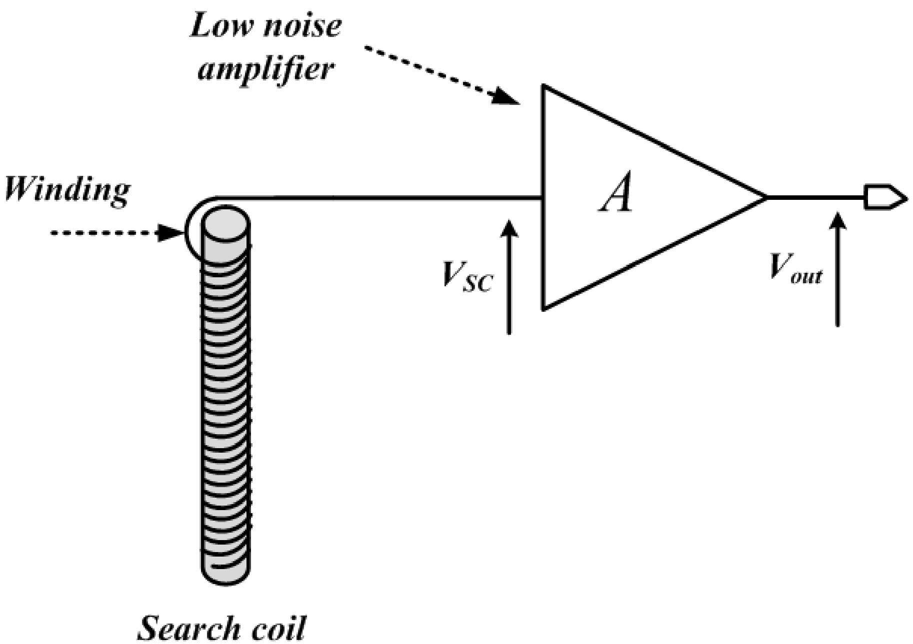
$$e = -N \frac{d\Phi}{dt} = -N\,S\,\frac{dB}{dt}$$

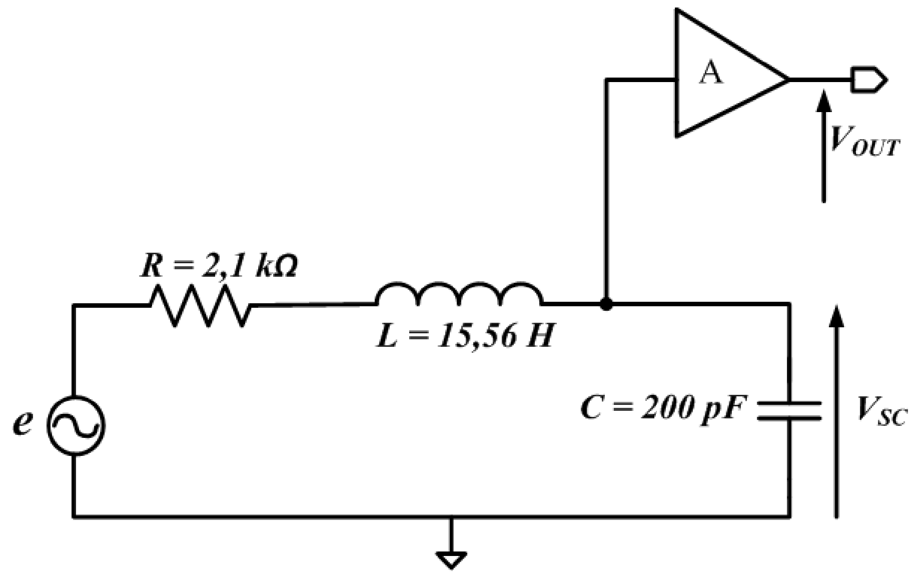
High magnetic gain: because of the use of a ferromagnetic core

$$G_{mag} = \frac{B}{B_{ext}}$$

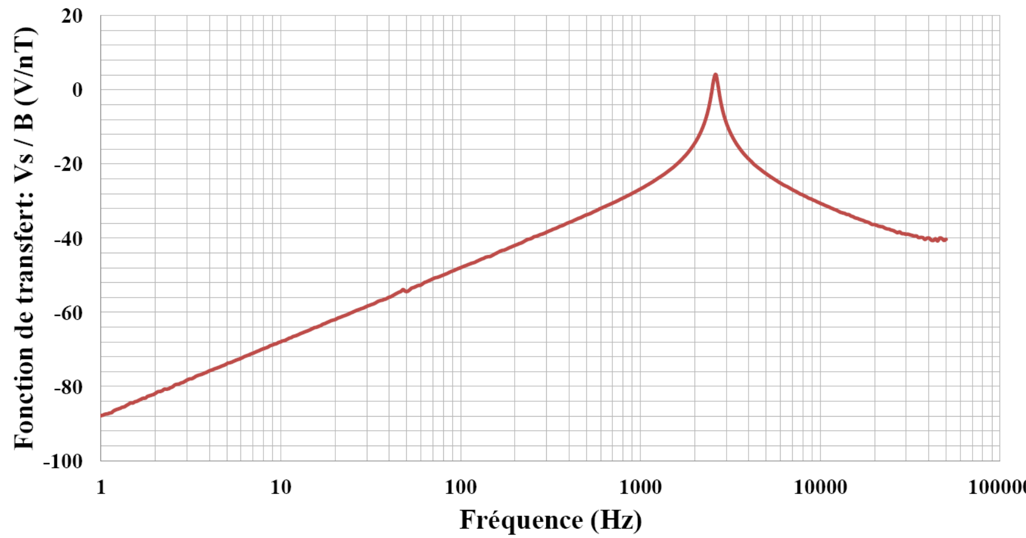
$$e = -N\,S\,G_{mag}\frac{dB_{ext}}{dt}$$

Principle of the feedback flux

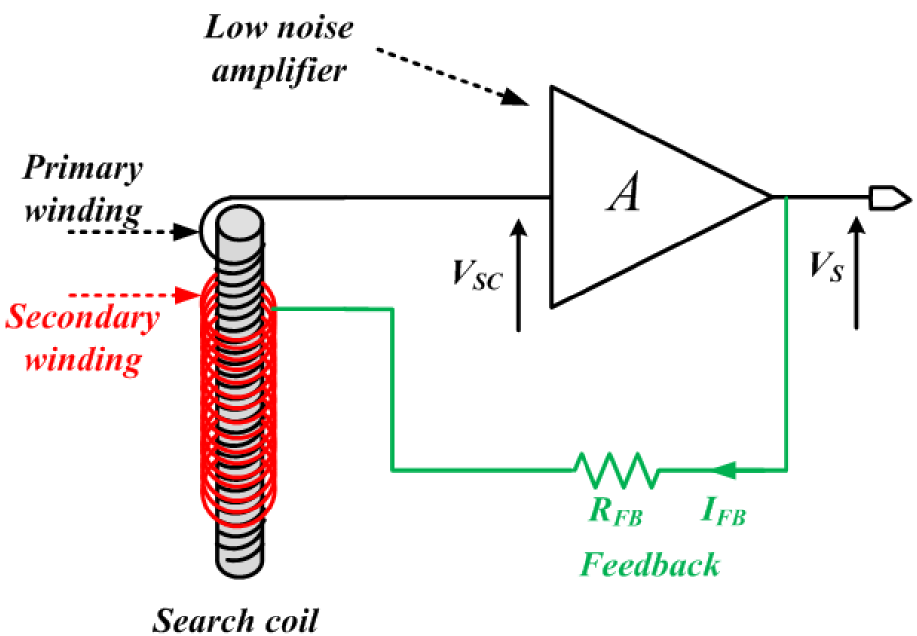


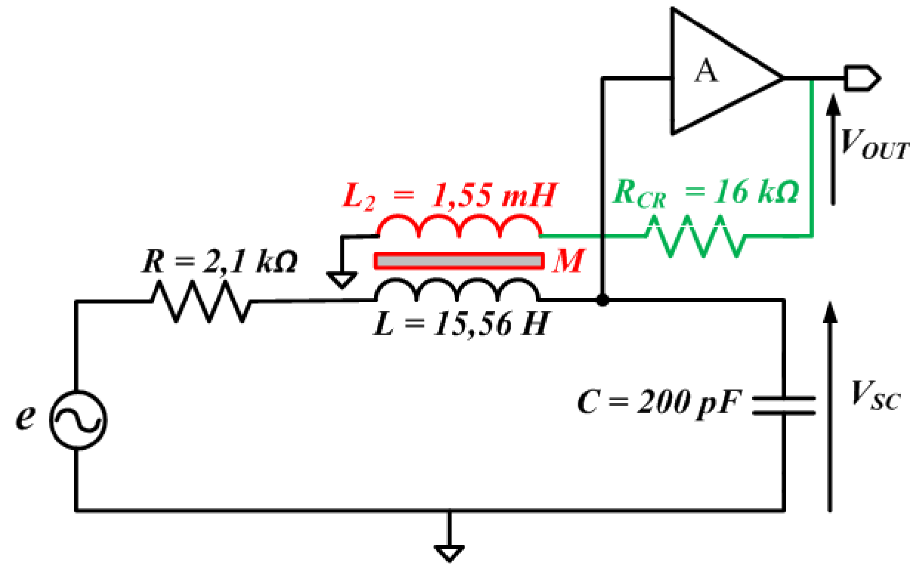


$$\frac{V_s}{B} = \frac{-j\omega N S_{noyau} G_{mag} A}{(1 - LC\omega^2) + j\omega RC}$$

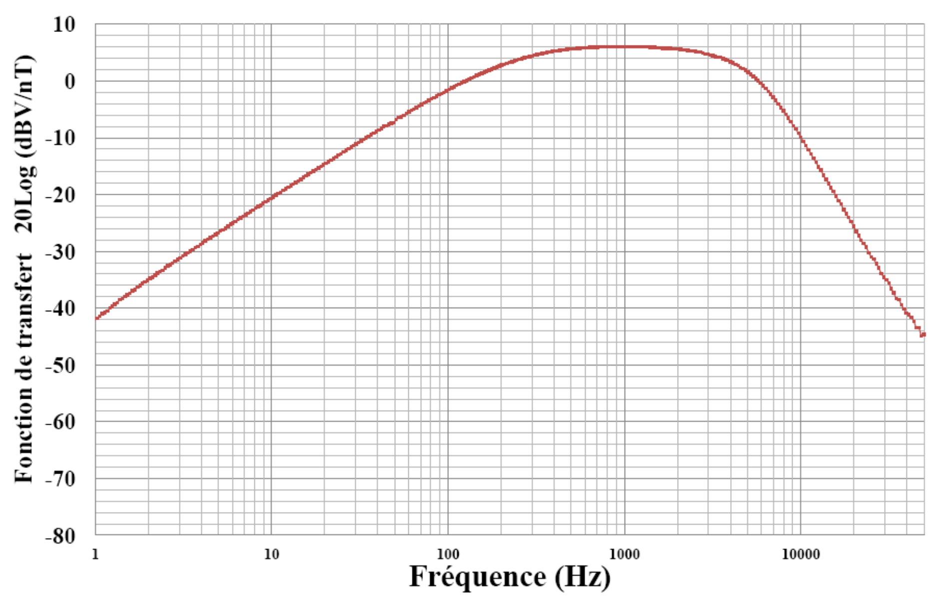


Principle of the feedback flux





$$\frac{V_s}{B} = \frac{-j\omega N S_{noyau} G_{mag} A}{(1 - LC\omega^2) + j\omega\left(RC + \frac{AM}{R_{CR}}\right)}$$



The preamplifier specifications

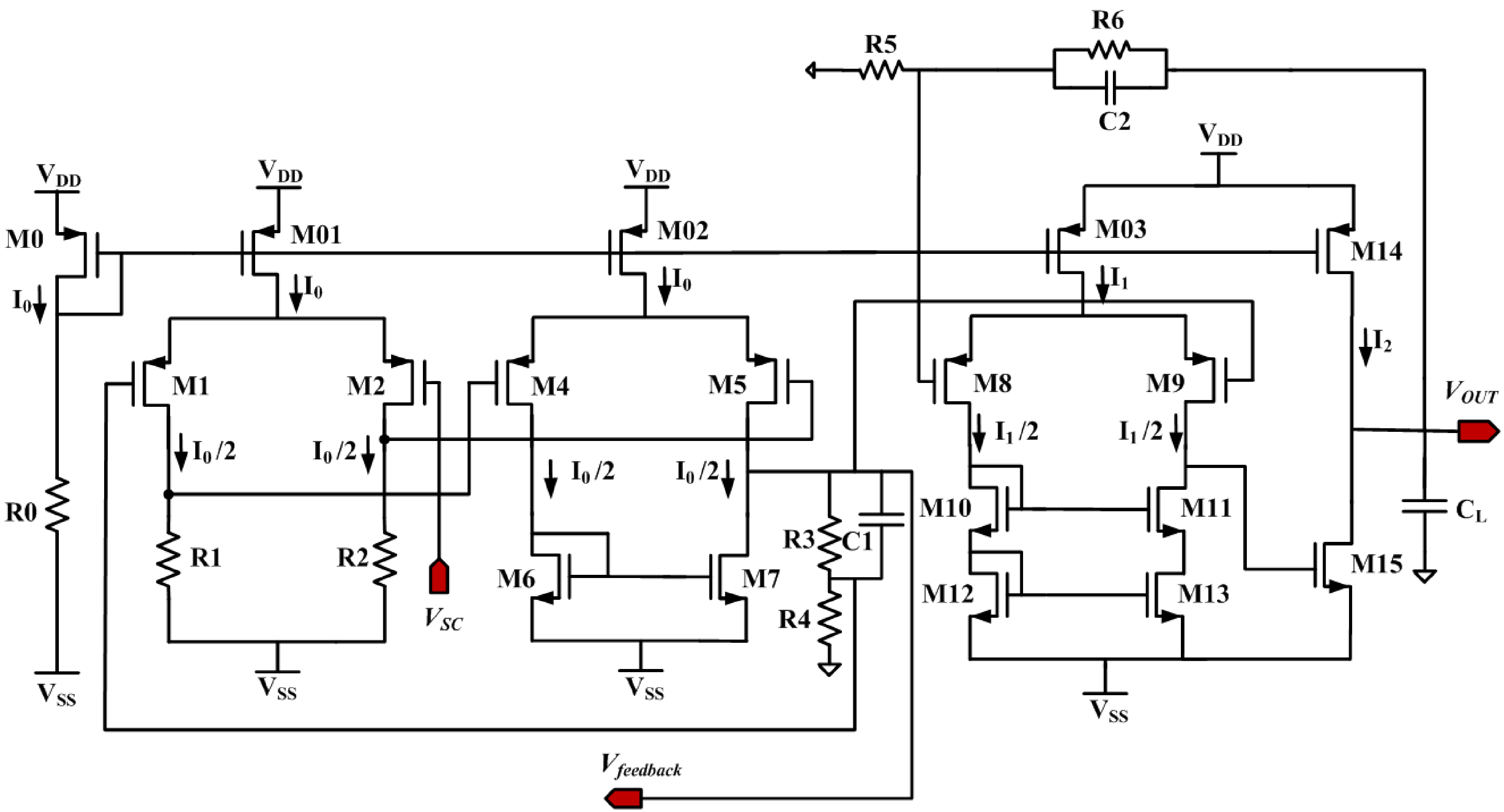
Equivalent Input Noise

$$\begin{cases} 4\ \dfrac{nV}{\sqrt{Hz}}\ @\ 10\ Hz \\ 2.7\ \dfrac{nV}{\sqrt{Hz}}\ @\ 1\ kHz \end{cases}$$

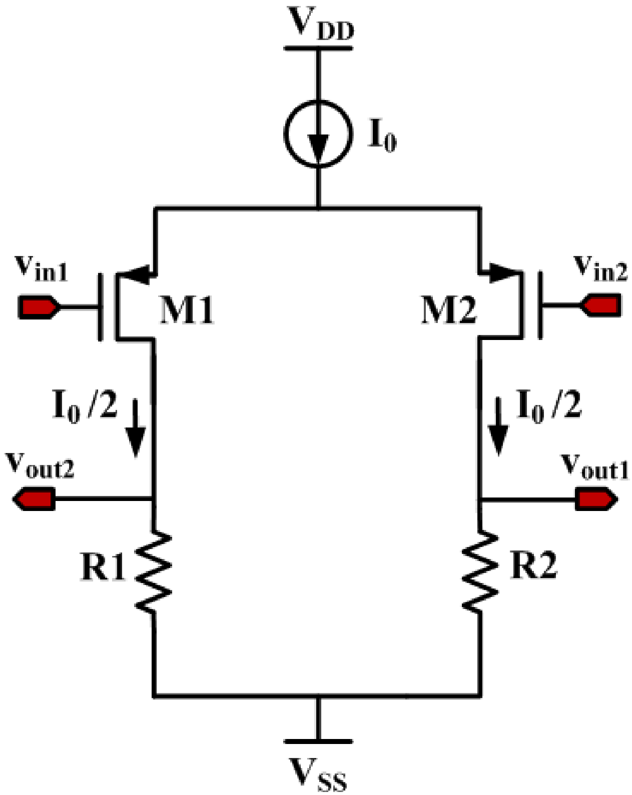
Minimum Gain: **80 dB**

Power consumption: < **30 mW**

The chosen preamplifier design



Flicker and thermal noises modeling for the Preamplifier's first stage



The total equivalent input noise equation:

$$e_{in0}^2 = 2\left(\frac{8kT}{3\sqrt{2 I_{d1} K'_P \frac{W_1}{L_1}}} + \frac{B_P}{W_1^2 f} I_{d1}^{AF-1} + \frac{4kT}{2 I_{d1} K'_P \frac{W_1}{L_1} R1}\right)$$

Design parameters:

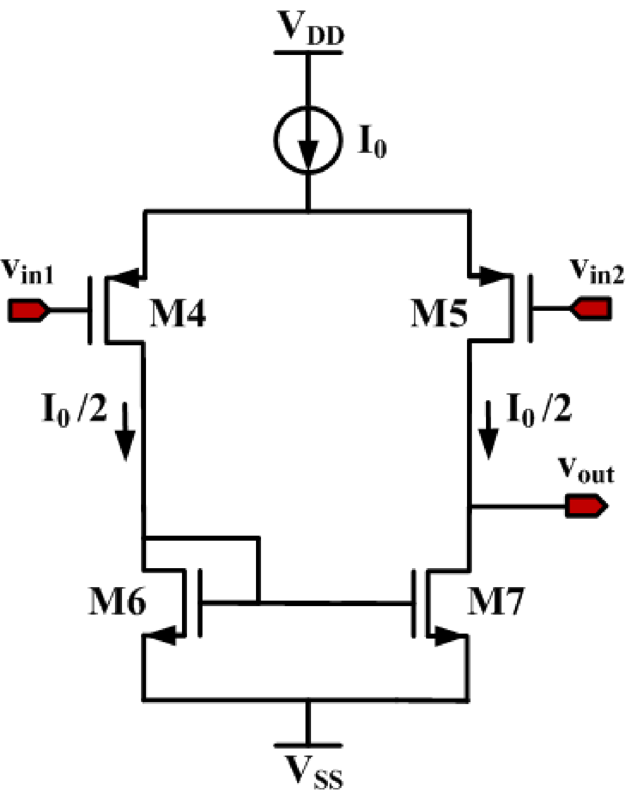
$$\frac{W_1}{L_1} = \frac{W_2}{L_2} = \frac{20\,000\ \mu m}{10\ \mu m}$$

$$I_{d1} = I_{d2} = 300\ \mu A$$

$$R_1 = R_2 = 10\ k\Omega$$

→ A = 34.64 dB and e_{in0} = 3.7 nV / √H @ 10 Hz

Flicker and thermal noises modeling for the Preamplifier's second stage



The total equivalent input noise equation:

$$e_{in1}^2 = \frac{2B_P {I_{d5}}^{AF}}{I_{d5} W_5^2 f}\left(1+\frac{K'_N B_N}{K'_P B_P}\frac{L_5 W_5}{L_7^2}\right)+\frac{16kT}{3\sqrt{2 I_{d5} K'_P \frac{W_5}{L_5}}}\left(1+\sqrt{\frac{K'_N W_7 L_5}{K'_P W_5 L_7}}\right)$$

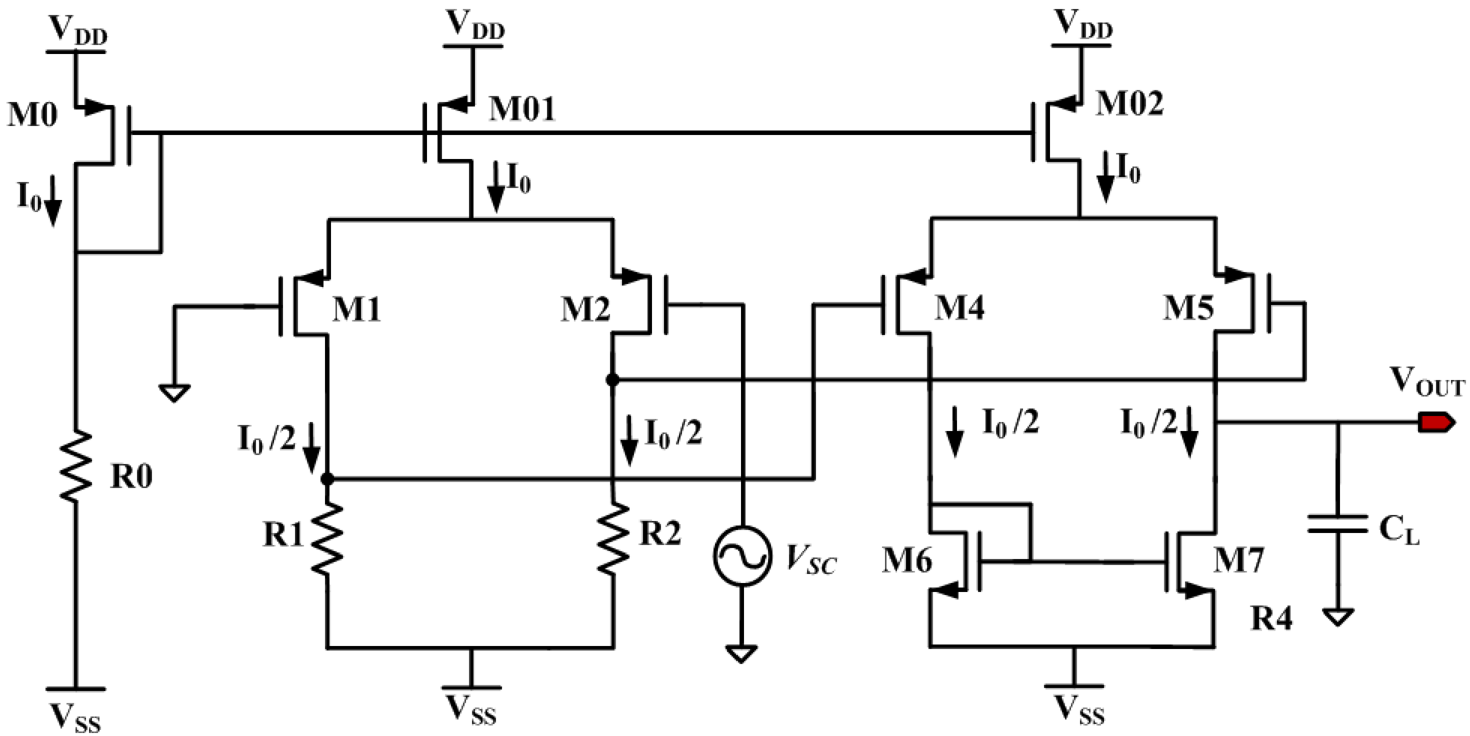
Design parameters:

$$\frac{W_4}{L_4} = \frac{W_5}{L_5} = \frac{4000\ \mu m}{10\ \mu m} \qquad \frac{W_6}{L_6} = \frac{W_7}{L_7} = \frac{20\ \mu m}{10\ \mu m}$$

$$I_{d4} = I_{d5} = 300\ \mu A$$

→ A = 63.77 dB and e_{in1} = 51.8 nV / √H @ 10 Hz

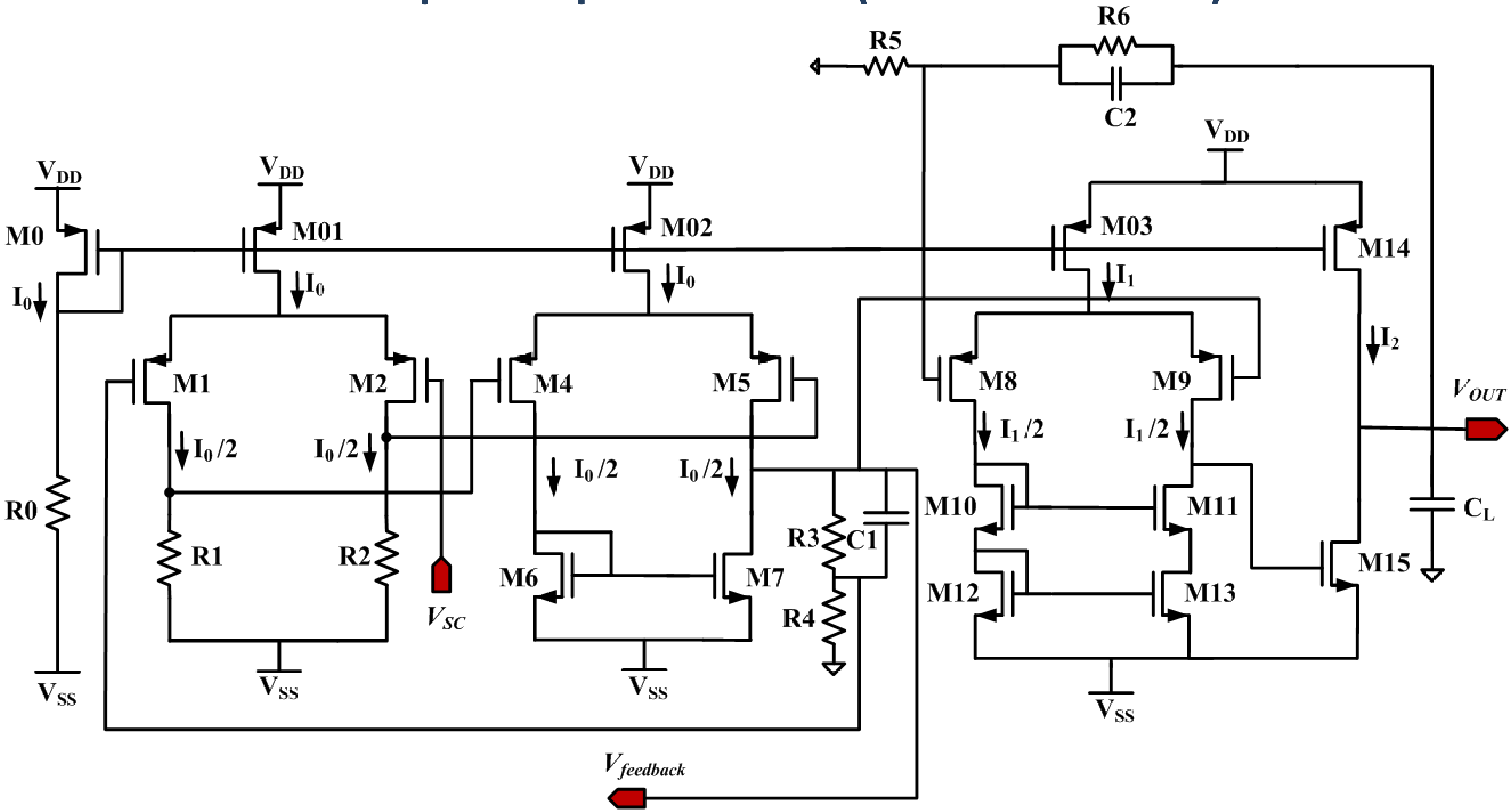
Both the first and the second stage combined in an open-loop configuration



→ A = 98.95 dB and e_{out} = 335 µV / √H @ 10 Hz

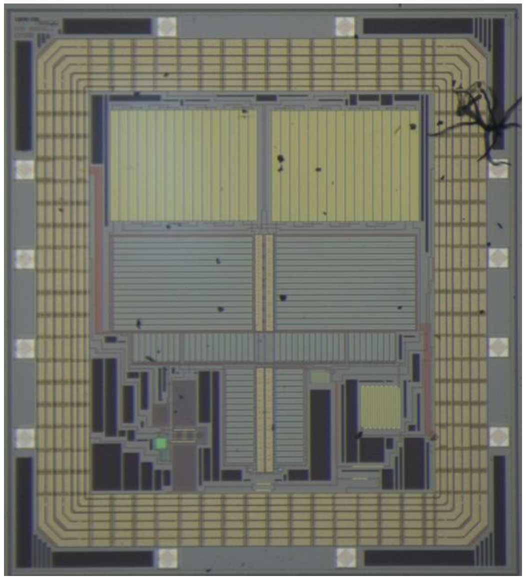
e_{in} = 3.85 nV / √H @ 10 Hz

Preamplifier specifications (from simulation)

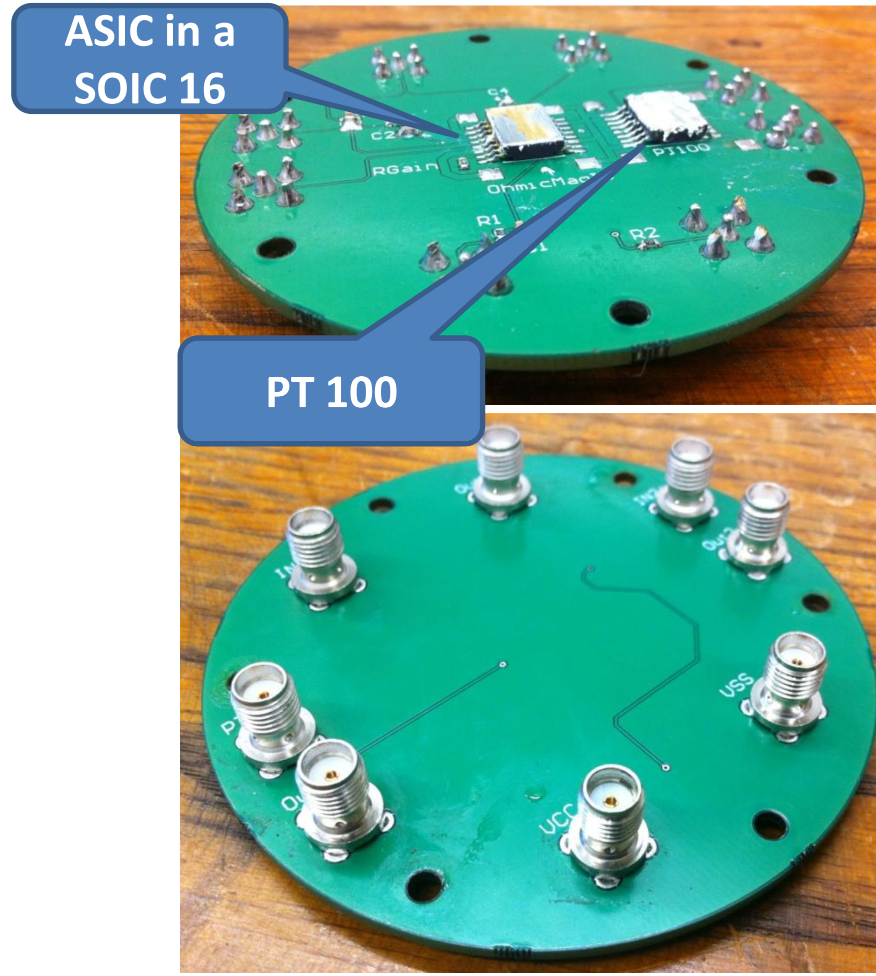


1/f Noise = 3.92 nV / √H @ 10 Hz Thermal Noise = 2.45 nV/ √H	Gain = 83 dB Power consomption = 16 mW (+/- 3V)

Fabricated ASIC and test board

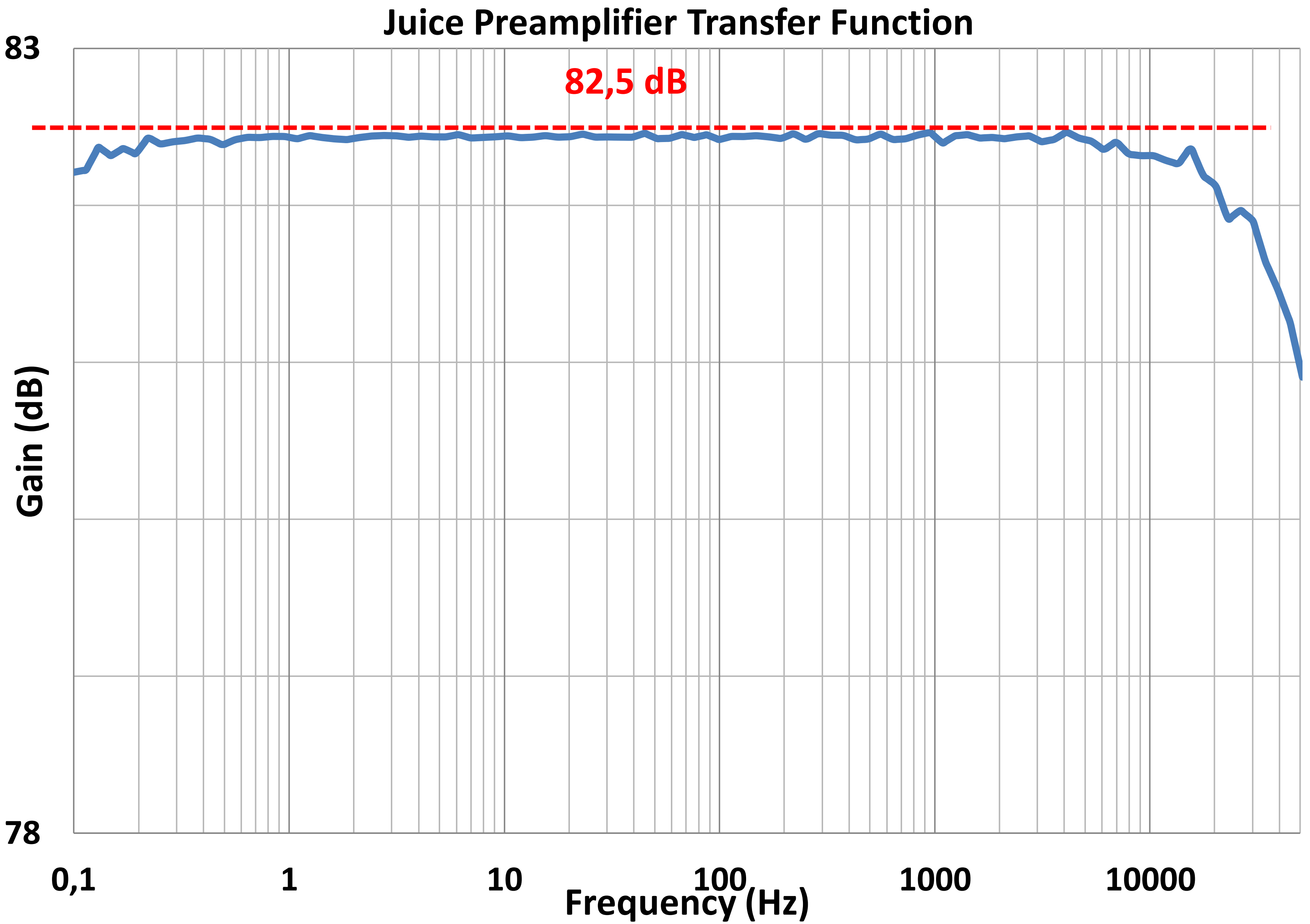


First JUICE ASIC prototype (5 mm²) designed in AMS 0.35 µm CMOS technology

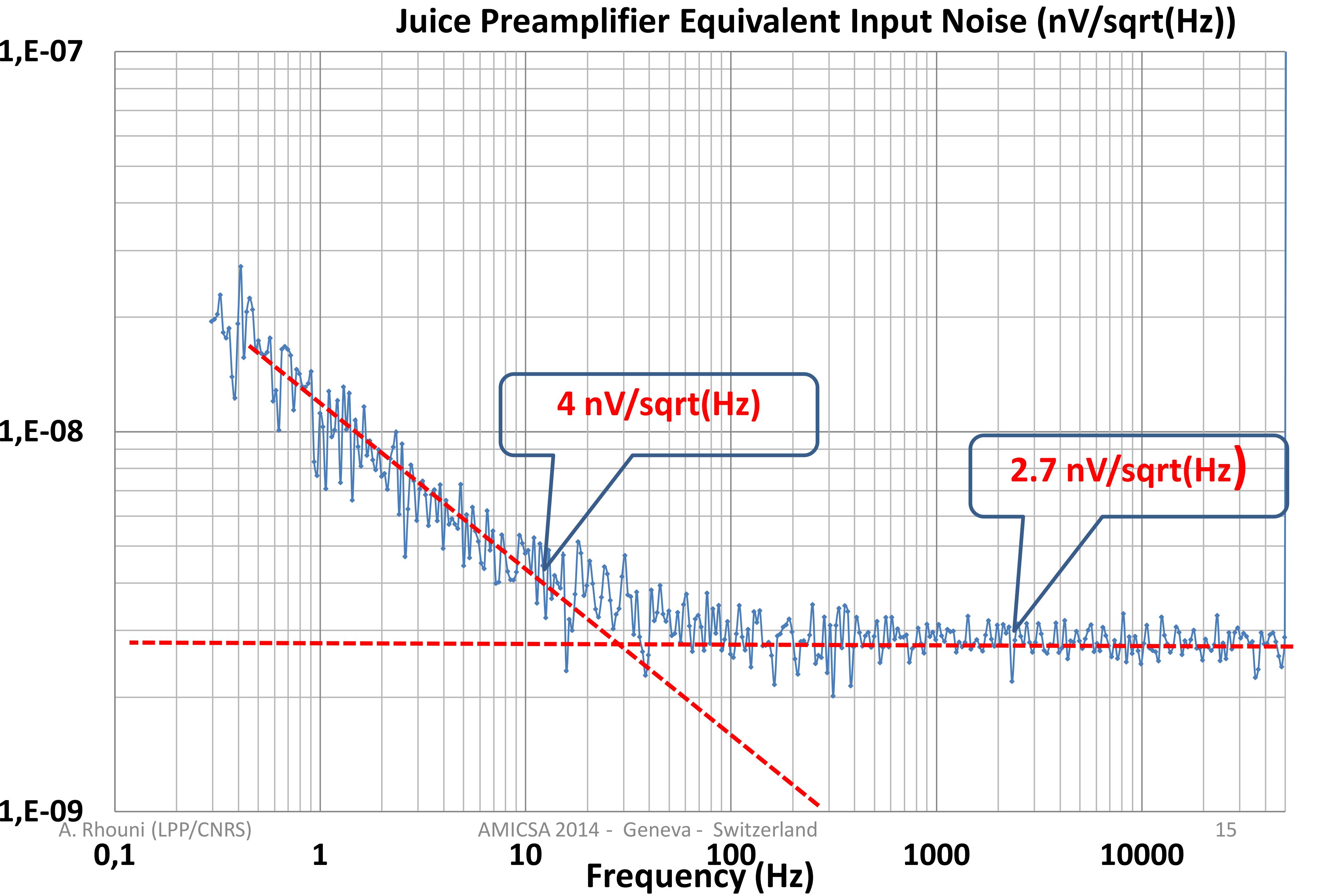


Characterization printed board (designed to be used in a Cryostat for Cryogenic measurements)

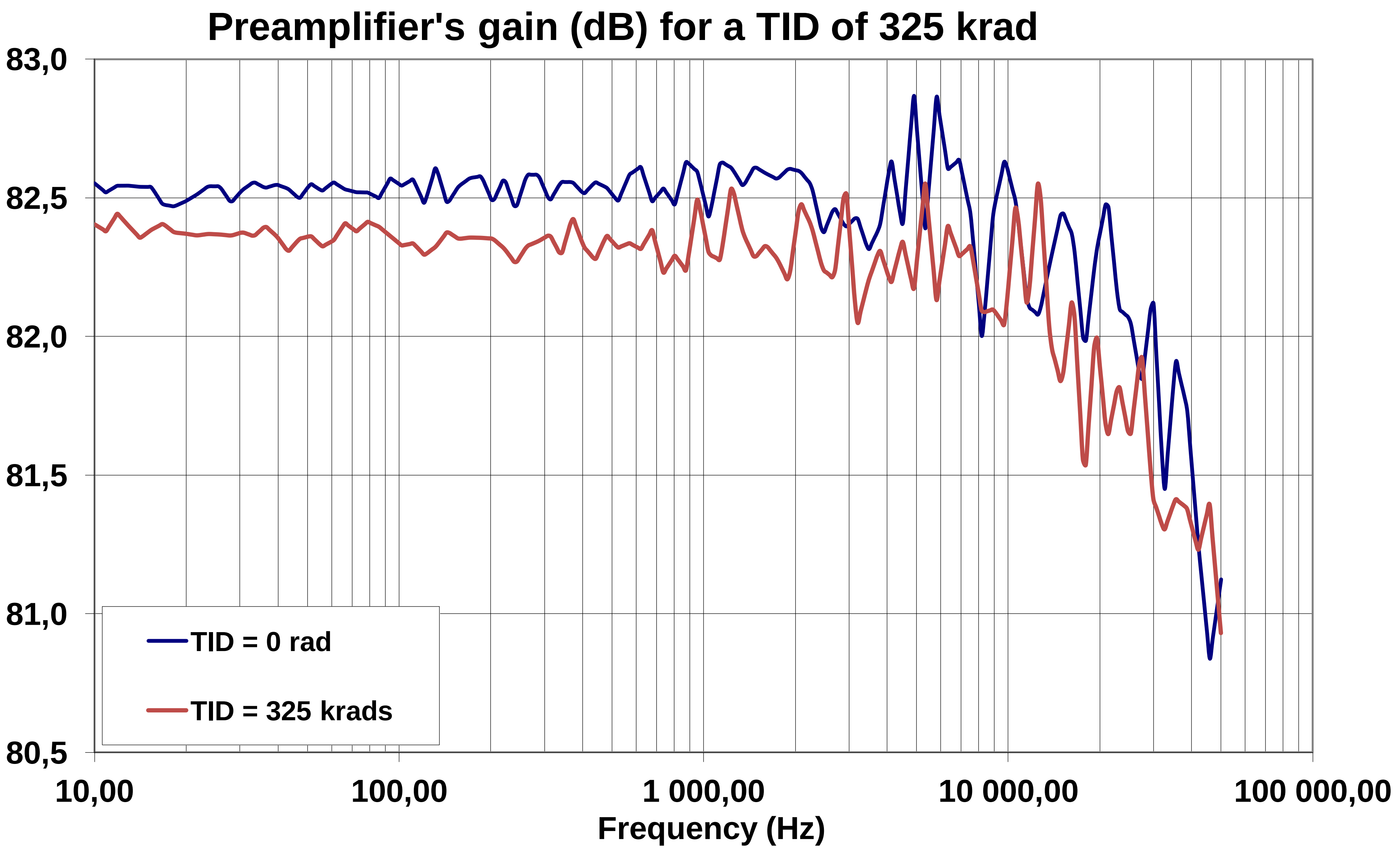
Room temperature measurements: Gain



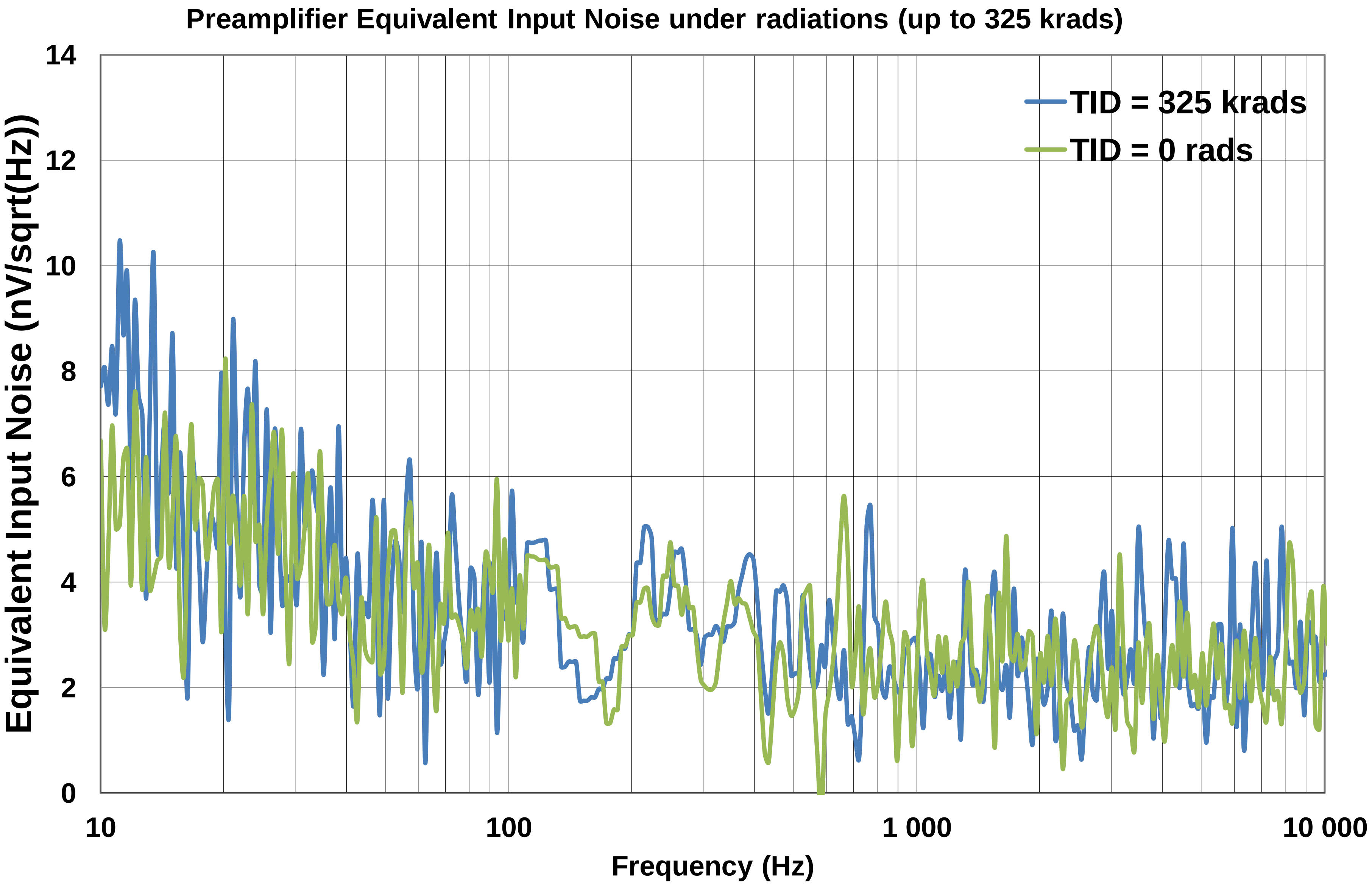
Room temperature measurements: Input Noise



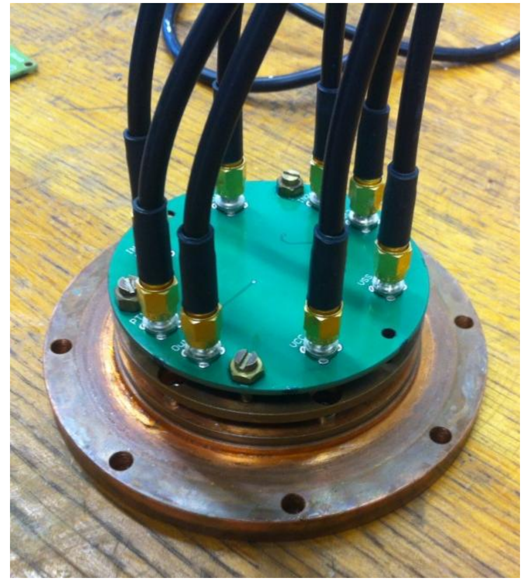
TID effect on the transfer function of the ASIC preamplifier

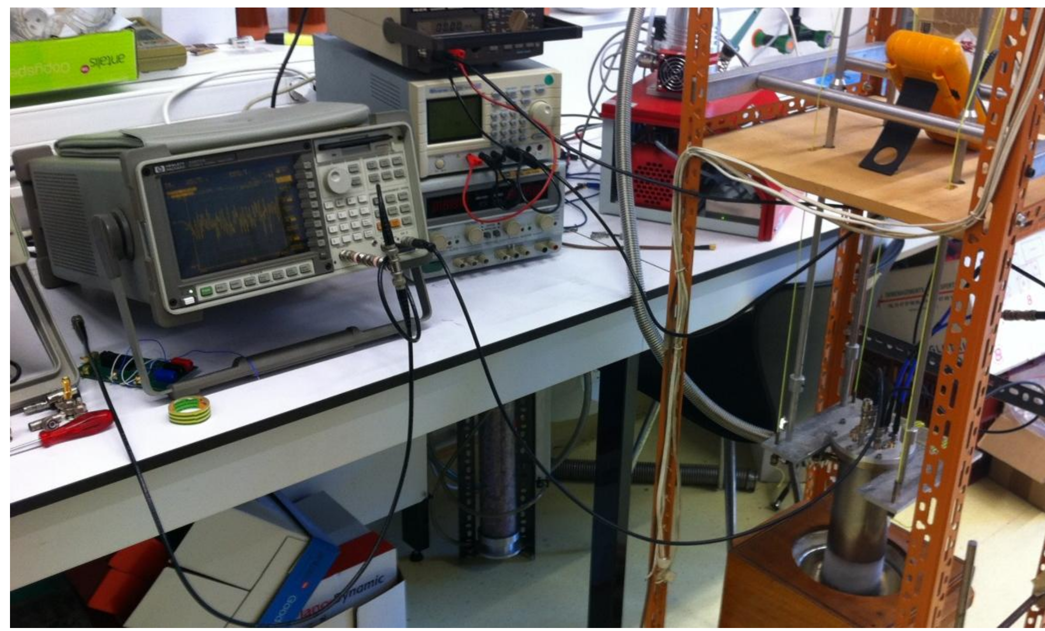


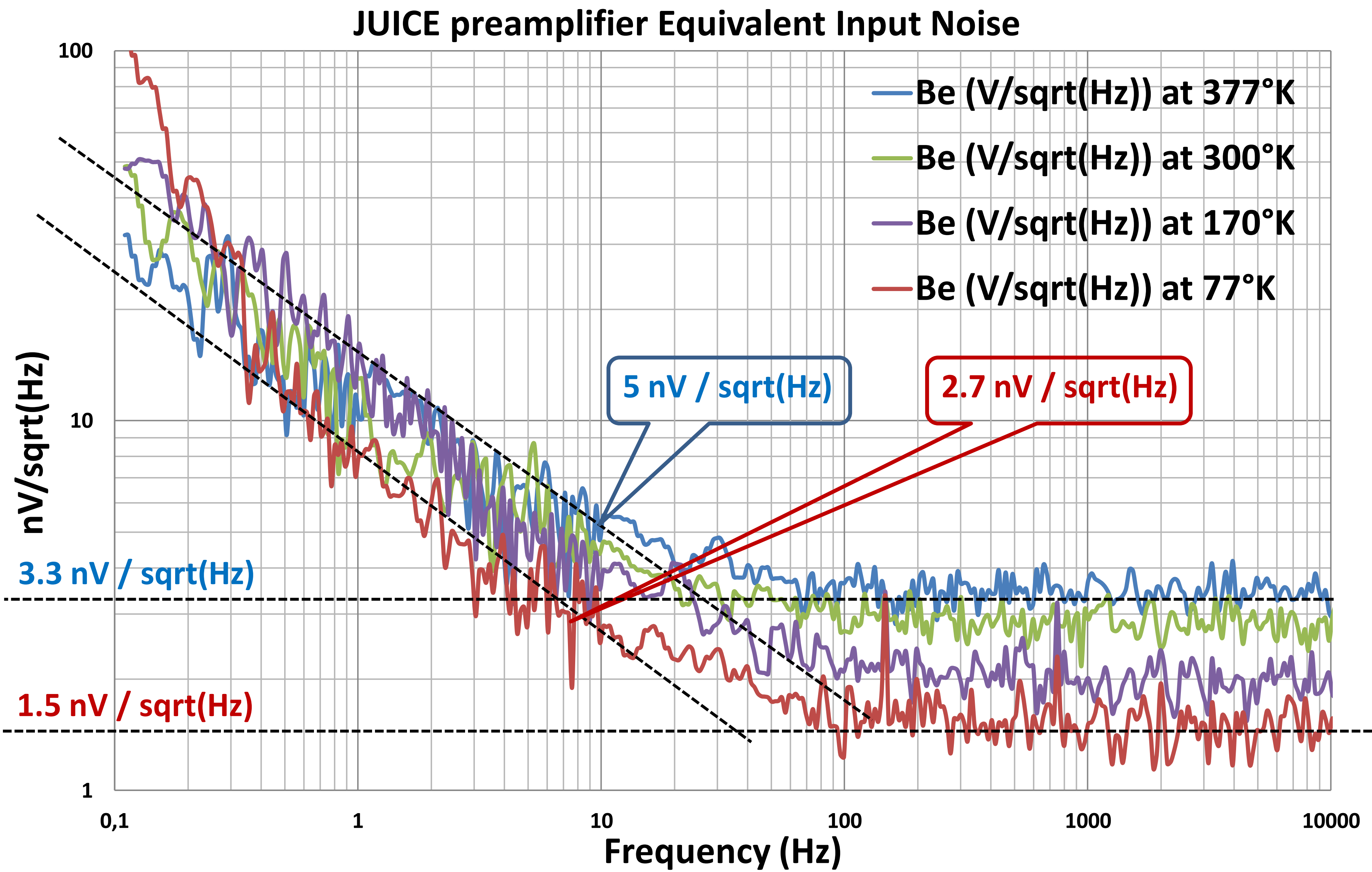
TID effect on the equivalent input noise of the ASIC preamplifier




FLUKE
-197.0






JUICE preamplifier Equivalent Input Noise
Be (V/sqrt(Hz)) at 377°K
Be (V/sqrt(Hz)) at 300°K
Be (V/sqrt(Hz)) at 170°K
Be (V/sqrt(Hz)) at 77°K
nV/sqrt(Hz)
100
10
1
5 nV / sqrt(Hz)
2.7 nV / sqrt(Hz)
3.3 nV / sqrt(Hz)
1.5 nV / sqrt(Hz)
0,1
1
10
100
1000
10000
Frequency (Hz)

Conclusion

- The Search-Coil Magnetometer (SCM) principle was explained
- The ASIC preamplifier system design was presented
- A complete modeling of the preamplifier noise contribution was given

- The preamplifier performances are proved by measurements:
  - Gain = of 83 dB
  - Power consumption of 16 mW
  - Input flicker noise = 4 nV/sqrt(Hz) at 10 Hz
  - Thermal noise = 2.7 nV/sqrt(Hz).

- Radiations tests were done up to a TID of 325 krads and no significant degradation in noise and gain was observed.

- The preamplifier is characterized in the T° range: 77 °K up to 373 °K

Perspectives

- A supply voltage regulation (under routing) using a bandgap voltage reference, which operates from 77 °K up to 373 °K will be integrated to the preamplifier in the second prototype of JUICE ASIC


D
S
G
2.5mm
INSIDE
ASIC
LPP
ÉCOLE
POLYTECHNIQUE
L2e