Temperature dependence measurements on K5 503 irradiated module

April 2, 2003

The module is in a Freiburg box, with thermal grease on both cooling points. The climate chamber temperature is set at -7^{o}C and nitrogen is constantly flushed inside the box. A noise vs time dependence measurements was performed during six days before starting varying the temperature. So, low voltage and bias were on for a long period.

The procedure used is the following: the environment temperature is kept constant at -7^{o}C. The chiller is first set to $T_{chiller} = -20^oC$. A measurement consists of

1. adjusting the chiller temperature,
2. waiting till the leakage current at 500V is stable,
3. performing the successive tests: strobe delay, trimming, response curve and noise occupancy.

Then the chiller temperature is increased by one degree and the same set of tests is redone.

The results obtained for the ENC noise extracted from the response curve (RC) and from the noise occupancy are shown in figure 1. The blue curves are the ENC at 2 fC, extracted from the RC. The red ones represent the noise from the noise occupancy scan. It is obtained assuming that all sources of noise are gaussian, fitting the occupancy as a function of the threshold, by:

$$NO(t, ENC) = \frac{1}{2}\,\mathrm{erfc}(\frac{t}{ENC\sqrt{2}}) \tag{1}$$

where NO, ENC and t are the noise occupancy, ENC and threshold values respectively. Plots indicated as "corrected" include the calibration factor (1.03 for K5 503). It can be seen that the variation of ENC with temperature is not linear. But the most striking conclusion is that the module cannot run at the expected temperature of 2^{o}C, since the leakage current reaches the 5mA limit of the HV power supply. The temperature range of the measurements is limited from below by the chiller, and from above by the fact that the module trips due

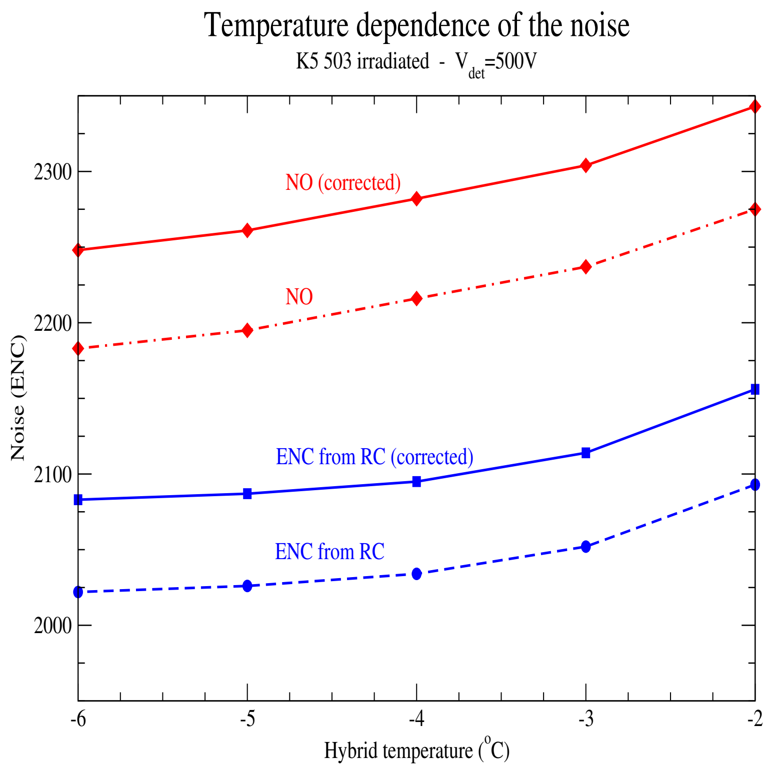

Figure 1: *Temperature dependence of the ENC noise for irradiated K5 503. The curves in solid are corrected by the calibration factor (1.03).*

to the 5 mA power supply limit, when the chiller temperature is set higher than about $-15C$ ($T_{hyb} \approx -2^o\mathbf{C}$).

Figure 2 shows a fit of the ENC vs temperature. The left hand side plot is the ENC from the noise occupancy and the right hand side one comes from the RC (same plots as solid curves in figure 1). Fitting by a straight line gives slopes varying between 17 or 24 e$^-$/^{o}C (RC and NO respectively) when the fit range is the whole interval [-6^{o}C;-2^{o}C], and 30 e$^-$/^{o}C when fitting only the last part of the plots.

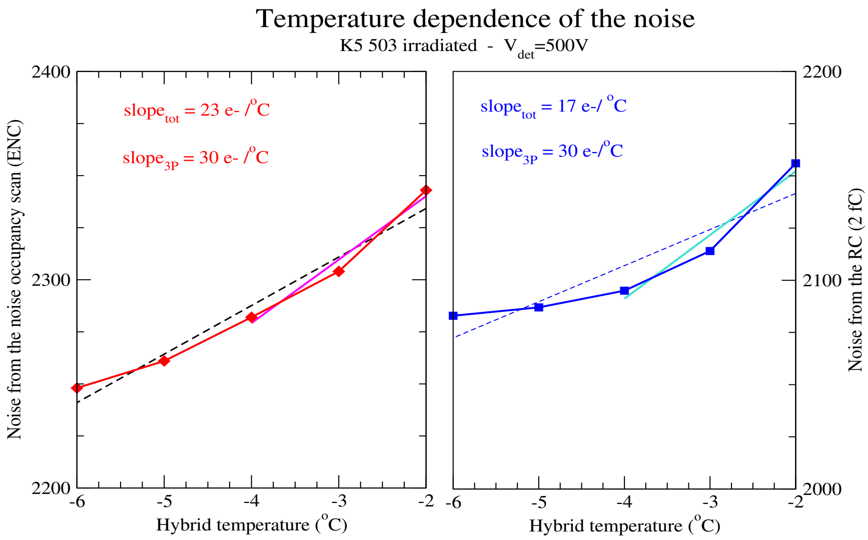

Figure 2: *Temperature dependence of the ENC for irradiated K5 503. On the lhs: ENC from the noise occupancy; on the rhs: ENC from the RC. Values are corrected for the calibration factor and fitted by a straight line. The first value of the slope corresponds to a fit over the whole range of temperature, and the second one over the last part of the plots.*

To try to figure out what kind of variation with temperature is expected, I used analytical expressions for the different noise contributions.

Five different contributions to the noise can be isolated [1]:

$$ENC_{Ic} = \frac{e^3}{12\sqrt{3}}\sqrt{\frac{2kT}{g_m}}\frac{C_e + C_d + C_F}{\sqrt{t_{peak}}}\frac{1}{q}$$

$$ENC_{Ib} = \frac{e^3}{36}\sqrt{\frac{5}{3}}\sqrt{t_{peak}}\sqrt{\frac{2qI_C}{\beta}}\frac{1}{q}$$

[1] Jan Kaplon, private communication

$$ENC_{det} = \frac{e^3}{36}\sqrt{\frac{5}{3}}\sqrt{t_{peak}}\sqrt{2qI_{leak} + 4kT\left(\frac{1}{R_F} + \frac{1}{R_{bias}}\right)}\frac{1}{q}$$

$$ENC_{rbb} = \frac{e^3}{12\sqrt{3}}\sqrt{4kTR_{bb}}\,\frac{C_d + C_F}{\sqrt{t_{peak}}}\frac{1}{q}$$

$$ENC_{corr} = \frac{e^3}{12\sqrt{3}}\sqrt{\frac{4kT}{g_m}}\sqrt{\frac{(C_d + C_e + C_F)C_C}{t_{peak}}}\frac{1}{q}$$

where $e = 2.718...$, q is the electron charge, k the Boltzman constant, β is the current gain (between 150-200 for a non irradiated module and 20-50 for an irradiated one), T is the temperature, either of the chips, or of the detectors for ENC_{det}. $C_F = 120fF$ is the feedback capacitor, $C_e = 0.6pF$ is the internal input capacitance of the chip, $C_d \approx 18pF$ is the detector capacitance, I_C is the collector current per channels (about 110 μA per channel for irradiated modules), $g_m = qI_C/kT$ is the transconductance of the transistor and $t_{peak} = 20ns$ is the peaking time. Typical values for the resistances are $R_{bb} = 180\Omega$ and $R_F = 80k\Omega$. The main uncertainties are the detector and chip temperatures. Since there is no way from the previous measurements to have an estimation, the temperature of the detectors are taken to vary between -15^{o}C and -7^{o}C and the chips are supposed to be 20 degrees warmer. The results are not very dependent on the detector temperature range, and are summarized in figure 3.

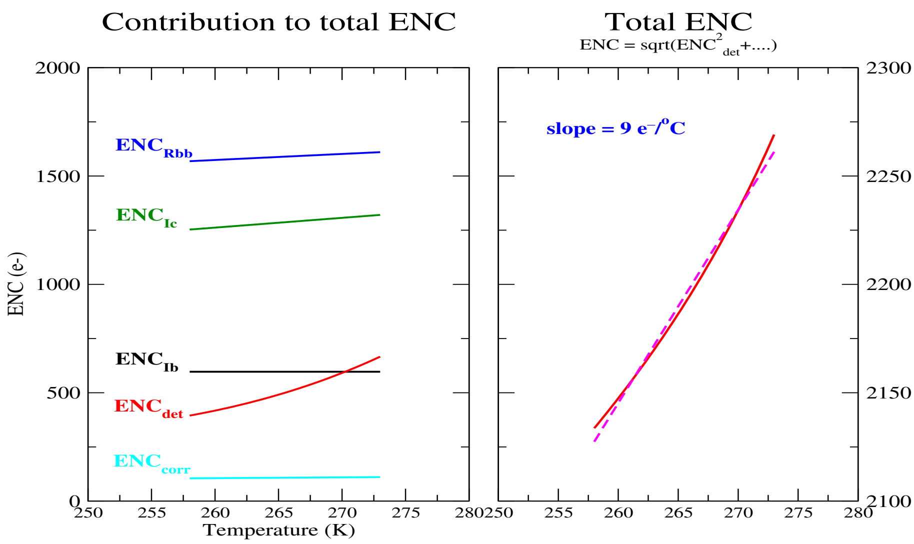

Figure 3: *Different contributions to the total ENC noise, plotted vs detector temperature.*

I've used the following parameters:

$$
\begin{aligned}
R_{bb} &= 180\Omega \quad R_F = 80k\Omega \\
C_F &= 120\, fF \quad C_e = 0.6\, pf \quad C_d = 22\, pf \\
\beta &= 40 \quad t_{peak} = 20\, ns \quad I_c = 110\mu A
\end{aligned}
$$

The leakage current reference is the measurement at $T_{hyb} = -6C$: $I_{leak} = 1.5\mu A$ per channel, and $I_{leak}(T)$ is given by

$$
I(I) = I(T_0) \left(\frac{T}{T_0}\right)^2 exp\left[-\frac{E_g}{k}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \tag{2}
$$

The measurements and this estimation are apparently not consistent, since the slope deduced from the measurements is around 30e$^-$/^{o}C, whereas the estimated one is around 9e$^-$/^{o}C. If instead of using the leakage current given by (2), I use the data, the slope is 11 e$^-$/^{o}C.

Another set of tests was made, measuring only the leakage current (IV scan) for different temperatures with the module powered. The IV curves are plotted in figure 4. IV curves have been taken first decreasing the cooling temperature

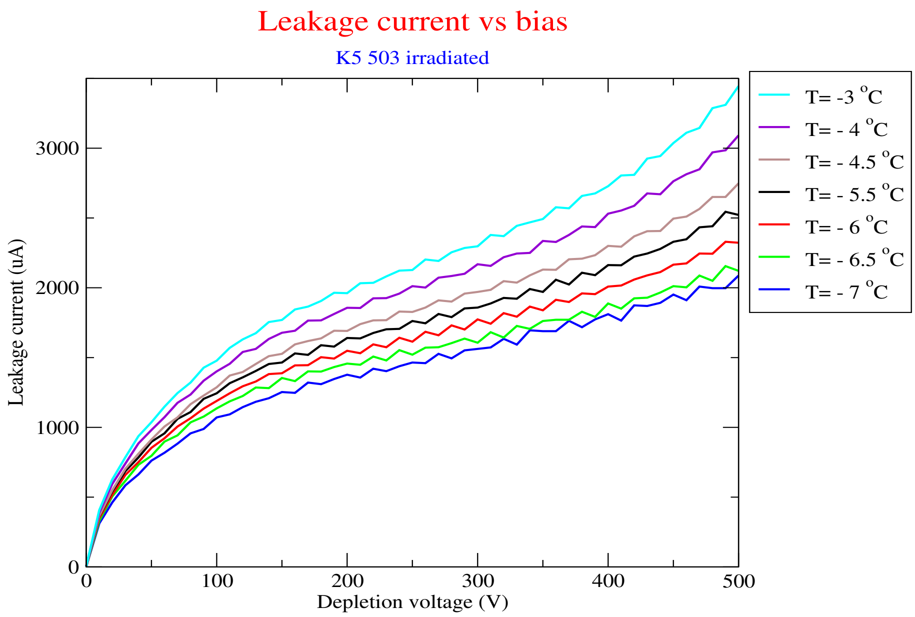

Figure 4: *IV curves at different temperatures, with hybrid powered on.*

from $T_{chiller} = -15^oC$ down to $T_{chiller} = -20^oC$ and then increasing back to $T_{chiller} = -14^oC$. Both sets of measurements are consistent. IV curves were started few minutes after setting the chiller temperature. For a given bias voltage (150V, 350V and 500V have been considered), the leakage current variation with the **temperature of the hybrid** is represented in figure 5. The solid curves are the measured leakage current. The main problem here is once more that the detectors temperature is not known. Assuming a (too...) simple dependence of the form $T_{det} = a_1 T_{hyb} + a_2$ and trying to fit the leakage current as a function of the hybrid temperature by:

$$\tilde{I}(T_{hyb}) = I(a_1 T_{hyb} + a_2) = I(a_1 T_{hyb}^{(0)} + a_2) \left(\frac{a_1 T_{hyb} + a_2}{a_1 T_{hyb}^{(0)} + a_2} \right)^2 \times exp[-\frac{E_g}{2k}(\frac{1}{a_1 T_{hyb} + a_2} - \frac{1}{a_1 T_{hyb}^{(0)} + a_2})]$$

doesn't lead to any reasonable values of the detector temperatures. It seems that there is no simple way, given the hybrid temperature and the leakage current, to "guess" the detector temperature, which depends on too many parameters (chiller temperature, coolant at both cooling points, etc...).

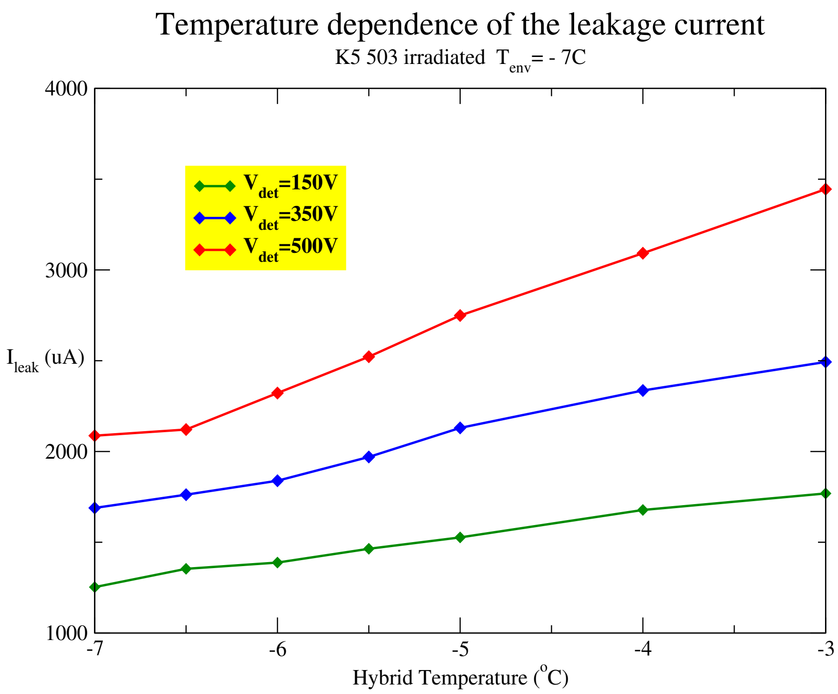

Figure 5: Leakage current variation with hybrid temperature.

"Conclusions":

- The aim of these tests, which was the evaluation of the noise dependence versus temperature, didn't really lead to any definite conclusion. The measured ENC dependence versus temperature can be roughly approximated by a straight line whose slope is between 17 e$-/^o$C and 30 e$-/^o$C, depending which ENC and fitting range are used. Close to the temperature of interest $T_{hyb} = +2^o$C, the correction is 30 e$-/^o$C. But this doen't match the values calculated using analytical expressions for the total ENC.

- It would probably make more sense to normalize to a given leakage current, rather than a given hybrid temperature, even if the leakage current seems to depend very much on the humidity.

- The detectors seem to heat up in a way which is rather unexpected for the (cooling) temperatures considered. It is in particular worrying that the module is unable to run at the foreseen $T_{hyb} = +2^o$C, tripping the HV supply for T_{hyb} around -2^oC. The self-heating of the detectors, visible in the measurements performed, should really be understood.

- Considering this latter point, measurements should be done in more realistic conditions, that is using a split block with evaporative cooling, and checking that in these conditions, the module can be run at $T_{hyb} = +2^o$C. This could be done in RAL, mounting the module in the thermal box in the freezer at the rig in at least two conditions: $T_{env} = 0^oC$, $T_{cool} = -30^o$C and $T_{env} = 0^oC$, $T_{cool} = -14^o$C. The temperature range available at the cooling rig is furthermore much wider than the one we had using the chiller. So the main conclusion is that checking there is no thermal problem with the module is more important than determining which is the correction to apply for the noise.