How to characterize SQUIDs PTB-style

Christian Pies

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This document is supposed to give information on how to extract all (at least for the PTB guys) interesting SQUID parameters. Each PTB SQUID is equipped with a MS Excel sheet where all measurements of this kind should be entered.

In this document, the names of the parameters to be inserted in the Excel sheet are printed in bold face. For the sake of completeness, I explain here everything for an integrated two-stage SQUID. In case you measure a single-stage SQUID, some parameters will not be available. Since some values in the Excel sheet will be calculated automatically from other numbers, first copy and paste an already filled column and enter your measured values. Please mind the units and orders of magnitude!

The following quantities will be used in the course of this document:

- Γ: Peak-to-peak value of a generator signal as set in the Generator palette of the electronics
- C: Voltage difference between the two cursors on the osciloscope
- S_{pp}, S_{min}, S_{max}: Peak-to-peak, minimum and maximum values of a voltage signal as measured on the osciloscope
- A: Amplification of the electronics in Amp mode, given in the Mode palette, usually set to 2000

1 SQUID preparation

Contact the usual bonding pads of the SQUID chip with aluminum bonding wires. If you want to measure the resistance of the input coil of the front-end SQUID, also contact the +IN and -IN pads. However, if you want to measure SQUID noise, it is better to connect nothing to the input coil.

2 Resistances at room temperature

Connect the SQUID to the cryostat/dipstick and measure the resistances with a multimeter.

- **V300K**: resistance between +V and -V or +V and GND
- **F300K**: resistance between +Φ and -Φ
- **IN300K**: resistance between +IN and -IN
- **I300K**: resistance between +I and IGND
- **FX300K**: resistance between ΦX and ΦXGND

3 Resistances at 4.2 K

Repeat the resistance measurements at helium temperature. For every pair of wires, measure 'in both directions' and take the average of the two values. By doing so, you eliminate errors in the measurement due to the Seebeck effect.

- **V4K**
- **F4K**
- **IN4K**
- **I4K**
- **FX4K**
- **RN**: normal resistance of one SQUID in the amplifier array. $(R_+ - R_-)/n$.
  R_+: resistance between $+V$ and GND
  R_-: resistance between $-V$ and GND
  n: number of SQUIDs in the array

4 Amplifier SQUID

- Go to the **temperature** where you want to characterize the SQUID and enter the value in the top section of the Excel sheet.
- Give a triangular generator signal on Φ_{x}.
- Change I_{b} to maximize S_{pp}.
- **Ibmax**: I_{b}
- **DVmax**: S_{pp}/A
- Set coupled cursors on two identical points of the response signal, as many Φ_0 between them as possible, but stay within one slope of the generator signal. Set the cursors to the generator channel.
- **1/Mfx**: $\frac{1}{M_{\mathrm{fx}}} = \Gamma C/n$ with n being the number of Φ_0
- Change V_{b} to center the response around zero.
- Enter values for **Ib** and **Vb** in Excel sheet under working point.
- I_{b} and V_{b} will from now on **not** be changed.
- **2DV**: S_{pp}/A, should be the same as DVmax
- **2Vmax**: S_{max}/A
- **2Vmin**: S_{min}/A
- Switch on Input Termination @ Amp in the Mode palette.
- **2DV50**: S_{pp}/A
- **2Vmax50**: S_{max}/A

- **2Vmin50**: S_{min}/A
- Switch off Input Termination @ Amp.
- Switch off generator.
- Lock the amplifier SQUID on the positive slope with a feedback resistance R_{fx}.
- Shift the SQUID signal towards zero by using Φ_{x}. Zoom in as much as possible.
- Give a square generator with the smallest peak-to-peak value possible on V_{b}. Set the osciloscope to average mode to get rid of noise. If you do not see a step-like behaviour in the response, increase the generator amplitude until it appears.
- Set vertical cursors to the plateaus of the SQUID response.
- **2VphiPos**: $V_{\Phi} = \Gamma R_{\mathrm{fx}} \frac{1}{M_{\mathrm{fx}}} / C$
- Switch off generator.
- Give a square generator with the smallest peak-to-peak possible on I_{b}.
- Set vertical cursors to the plateaus of the SQUID response.
- **2_1/MdynPos**: $\frac{1}{M_{\mathrm{dyn}}} = \Gamma R_{\mathrm{fx}} \frac{1}{M_{\mathrm{fx}}} / C$
- Switch to the negative slope, shift the SQUID signal towards zero using Φ_{x} and repeat the measurements of V_{Φ} and $\frac{1}{M_{\mathrm{dyn}}}$.
- **2VphiNeg**
- **2_1/MdynNeg**
- Turn off generator. Keep amplifier SQUID locked. Switch GBP to the highest possible value, where the SQUID is still stable. Enter value **Rfx** in the top section of the Excel sheet and at row labeled **2Rf** in the section **2nd-stage Noise**. In the same section note the values of **2GainBandwProd** and **2Slope**.
- Record noise spectra to cover the frequency range between 0.1 Hz and 1 MHz. Use low pass filters to avoid aliasing effects.
- **2SPhi...**: noise density values at the corresponding frequency

5 Front-end SQUID and two-stage setup

- I_{b} and V_{b} should still be set to the same values as before.
- Lock the amplifier SQUID with a resistance R_{fx}.
- Give a triangular generator to Φ_{b}.

- Increase I until the characteristics starts to show up. Use Φ_x to shift the response towards zero.
- **Istar**: value of I where the characteristics starts to show up.
- Increase I to maximize the response.
- **Imax**: I
- **DIXmax**: $S_\mathrm{pp}/(2R_\mathrm{fx})$. Peak-to-peak of the response of the front-end expressed as current in the input coil of the amplifier.
- Set coupled cursors on two identical points of the response signal, as many Φ_0 between them as possible, but stay within one slope of the generator signal. Set the cursors to the generator channel.
- **1/Mf**: $\frac{1}{M_\mathrm{f}} = \Gamma C/n$ with n being the number of Φ_0
- Enter values for **I** and **PhiX** in Excel sheet under working point.
- I_b, V_b, I and Φ_x will from now on **not** be changed.
- **DIX**: S_pp/A,, should be the same as DIXmax
- **IXmax**: S_max/A
- **IXmin**: S_min/A
- Unlock the amplifier.
- **DV**: S_pp/A
- **Vmax**: S_max/A
- **Vmin**: S_min/A
- Switch on Input Termination @ Amp in the Mode palette.
- **DV50**: S_pp/A
- **Vmax50**: S_max/A
- **Vmin50**: S_min/A
- Switch off Input Termination @ Amp.
- Switch off generator.
- Lock the front-end SQUID on the positive slope with a feedback resistance R_f.
- Shift the SQUID signal towards zero by using Φ_b. Zoom in as much as possible.
- Give a square generator with the smallest peak-to-peak value possible on V_b. Set the osciloscope to average mode to get rid of noise. If you do not see a step-like behaviour in the response, increase the generator amplitude until it appears.

- Set vertical cursors to the plateaus of the SQUID response.
- **VphiPos**: $V_\Phi = \Gamma R_\mathrm{f} \frac{1}{M_\mathrm{f}}/C$
- Switch off generator.
- Give a square generator with the smallest peak-to-peak possible on I_b.
- Set vertical cursors to the plateaus of the SQUID response.
- **1/MdynPos**: $\frac{1}{M_\mathrm{dyn}} = \Gamma R_\mathrm{f} \frac{1}{M_\mathrm{f}}/C$
- Switch off generator.
- Give a square generator with the smallest peak-to-peak possible on Φ_x.
- Set vertical cursors to the plateaus of the SQUID response.
- **GphiPos**: $G_\Phi = \Gamma R_\mathrm{f} \frac{1}{M_\mathrm{f}}/(C \frac{1}{M_\mathrm{fx}})$. Flux-to-flux amplification between front-end and amplifier.
- Switch off generator.
- Give a square generator with the smallest peak-to-peak possible on I.
- Set on vertical cursor at the plateau and the other on the peak after the step of the generator signal.
- **dI/dPhiPos**: $\frac{\mathrm{d}I}{\mathrm{d}\Phi} = \Gamma R_\mathrm{f} \frac{1}{M_\mathrm{f}}/C$.
- Switch to the negative slope, shift the SQUID signal towards zero using Φ_b and repeat the measurements of V_Φ and $\frac{1}{M_\mathrm{dyn}}$, G_Φ and $\frac{\mathrm{d}I}{\mathrm{d}\Phi}$.
- **VphiNeg**
- **1/MdynNeg**
- **GphiNeg**
- **dI/dPhiNeg**
- Turn off generator. Keep front-end SQUID locked. Switch GBP to the highest possible value, where the SQUID is still stable. Enter value **Rf** in the top section of the Excel sheet. Note the values of **GainBandwProd** and **slope** in the **Noise** section.
- Record noise spectra to cover the frequency range between 0.1 Hz and 1 MHz. Use low pass filters to avoid aliasing effects.
- **SPhi...**: noise density values at the corresponding frequency

6 New working point and/or temperature

Select a different working point, i.e. where the noise seems to be the best, or a different temperature and repeat the previous measurements for these values. Some of the values should remain the same (i.e. $\frac{1}{M_\mathrm{f}}$, $\frac{1}{M_\mathrm{fx}}$), but some should change significantly.