Effects of 1/f Noise on Decoherence in Superconducting Flux Qubits

Dale J Van Harlingen
University of Illinois at Urbana-Champaign

Trevis Crane, Sergey Frolov, and Madalina Colci
University of Illinois at Urbana-Champaign

Britton Plourde, Paul Reichardt, Tim Robertson, and John Clarke
University of California at Berkeley
**Superconducting flux qubit**

![Diagram of rf SQUID and quantum oscillations](image)

**Superconducting flux qubits --- the experimental picture**

<table>
<thead>
<tr>
<th>Design</th>
<th>Group</th>
<th>Quantum oscillations</th>
<th>Level splitting</th>
<th>Rabi oscillations</th>
<th>Ramsey fringes</th>
<th>Spin echoes</th>
<th>$\tau_\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>rf SQUID (excited)</td>
<td>Friedman et al. (Lukens) -- Stony Brook</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>3-junction qubit</td>
<td>van der Wal et al. (Mooij) -- Delft</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>200 ns</td>
</tr>
<tr>
<td>3-junction qubit</td>
<td>Chiorescu, Nakamura et al. (Mooij) -- Delft</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>500 ns</td>
</tr>
<tr>
<td>single JJ qubit</td>
<td>Martinis et al. NIST Boulder</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>50 ns</td>
</tr>
<tr>
<td>single JJ qubit</td>
<td>Yu et al. (Han) -- Kansas</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td>---</td>
</tr>
<tr>
<td>quantronium (hybrid charge/phase qubit)</td>
<td>Vion et al. (Esteve, Devoret) -- Saclay</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>500 ns</td>
</tr>
</tbody>
</table>
Decoherence in superconducting flux qubits

A key challenge of Qubit Engineering is to minimize internal and external noise sources that reduce decoherence times ...

consider \textbf{low frequency noise} in flux qubits $\rightarrow f \ll \omega_p, 1/\Gamma, \Omega, \ldots$.

**Macroscopic Quantum Tunneling (MQT)**

- \textbf{High frequency noise} suppresses the quantum tunneling rate $\Gamma$
- \textbf{Low frequency noise} has little effect on the tunneling rate (but can perturb the junction potential)

**Macroscopic Quantum Coherence (MQC)**

- \textbf{High frequency noise} suppresses the coherent oscillation frequency $\Omega$ and shortens decoherence times
- \textbf{Low frequency noise} causes dephasing by fluctuating the qubit potential via internal critical current fluctuations and external magnetic flux noise
Sources of low frequency noise in superconducting circuits

**Flux noise ... vortex motion**

- Vortex hopping in SC film induces flux changes in SQUID
- dominates for large loops and large junctions

**Critical current noise ... charge motion**

- Charge trapping in Josephson junction barrier blocks tunneling in localized region → change in critical current
- dominates for small loops and small junctions

Single vortex/charge trap creates switching noise → Lorentzian in power spectrum
Multiple vortices/charge traps add to give ~1/f noise spectrum (Dutta-Horn model)

Example: charge traps in tunnel junctions (Wakai, Van Harlingen)
Effect of low frequency noise on the measurement of coherent quantum oscillations

1/f flux noise in qubit and coil current noise modulates flux bias from $\frac{1}{2} \Phi_0$

1/f critical current noise modulates tunneling barrier height

Fluctuation of the tunneling frequency causes phase noise $\rightarrow$ results in an effective decoherence since $\Omega$ is different for each successive point of a distribution measurement

Dephasing factor: $\Lambda = \left( \frac{d\Omega}{dI_c} \right) / \left( \frac{\Omega}{I_c} \right)$
rf SQUID qubit
A.J. Leggett; J. R. Friedman, Nature

\[ \frac{1}{2} \Phi_0 \]

\[ \beta_L = \frac{2\pi LI_c}{\Phi_0} > 1 \]

Barrier height: \( \Delta U = \frac{3E_1}{4\pi^2} (\beta_L - 1)^2 \)

Plasma frequency: \( \omega_0 = 2\sqrt{\frac{\beta_L - 1}{LC}} \)

“Degree of classicality”: \( \lambda = \sqrt{\frac{8I_cC\Phi_0^3}{\pi^3 \hbar^2}} \)

Tunneling frequency: \( \Omega = \omega_0 \exp \left[-\frac{(\beta_L - 1)^{3/2} \lambda}{\sqrt{2}}\right] \)
rf SQUID qubit --- ground state --- Stony Brook parameters*


\[ I_c = 1.46 \mu A \]
\[ L = 240 \text{ pH} \]
\[ A = 2 \mu m^2 \]
\[ C = 103 \text{ fF} \]
\[ \omega_0/2\pi = 98.5 \text{ GHz} \]
\[ \Omega/2\pi = 2.52 \text{ GHz} \]

Ground state:
\[ \Lambda = 40.6 \]

*Excited state:
\[ \Lambda = 35 \]

\[ \Lambda = \frac{d(\Omega/2\pi)}{d\beta L} \]

\[ \delta \Lambda/\Lambda = 10^{-3} \]
\[ \delta \Lambda/\Lambda = 10^{-4} \]
\[ \delta \Lambda/\Lambda = 10^{-5} \]
Three-junction qubit
T. P. Orlando et al., PRL 60, 15398 (1999)

Josephson energy: \( E_J = I_0 \Phi_0 / 2\pi \)

Charging energy: \( E_C = e^2 / 2C \)

Plasma frequency: \( \omega_m = \frac{1}{\hbar} \left[ \frac{4(4a^2 - 1)}{a(1 + 2a)} \frac{E_J E_C}{E_J} \right]^{1/2} \)

Phase minimum: \( \phi_m^* = \cos^{-1}\left( \frac{1}{2a} \right) \)

Tunneling frequency: \( \Omega(E_J) = \omega_m \exp\left[ -\frac{4a(1 + 2a)E_J}{E_C} \right]^{1/2} \left( \sin \phi_m^* - \frac{\phi_m^*}{2a} \right) \)
Three-junction qubit --- Delft parameters


$I_c = 570$ nA  \( a = 0.82 \)  \( L = 11 \) pH  
\( A = 2 \) \( \mu \)m\(^2\)  \( C = 2.6 \) fF  
\( \omega_0/2\pi = 81.4 \) GHz  \( \Omega/2\pi = 1.14 \) GHz  

Modulation of only smallest junction:  \( \Lambda = 20.4 \)  
For all junctions:  \( \Lambda = 14.0 \)
Single Josephson junction qubit

Current-biased single junction

Oscillations between energy levels in washboard potential well

Barrier height:
\[ \Delta U = \frac{2\sqrt{2} I_c \Phi_0}{3\pi} \left(1 - \frac{I}{I_c}\right)^{3/2} \]

Plasma frequency:
\[ \omega_p = \left(\frac{2\sqrt{2} \pi I_c}{C \Phi_0}\right)^{1/2} \left(1 - \frac{I}{I_c}\right)^{1/4} \]

Tunneling frequency:
\[ \Omega = \frac{E_1 - E_0}{\hbar} \approx \omega_p \]
Single junction qubit --- NIST parameters

\[ I_c = 20 \, \mu A \]
\[ I_b = 19.33 \, \mu A \]
\[ I/I_c = 0.987 \]

\[ A = 100 \, \mu m^2 \Rightarrow C = 5 \, pF \]

\[ \Omega/2\pi = \omega_0/2\pi = 7.06 \, GHz \]

\[ \Lambda = 19.3 \]

\[ \Lambda = (d\Delta/dI)/(\Delta/I_0) \]
Effect of critical current fluctuations on tunneling frequency

\[ \Lambda = 40.6 \]
\[ \Lambda = 19.3 \]
\[ \Lambda = 14.0 \]
\[ \Lambda = 1.0 \]
Determining the decoherence time from 1/f noise

• Assume a measurement of the coherent oscillations in a qubit

![Graph showing oscillations over time](image)

\[ \tau_{ss} = \text{single shot flux sampling time (\sim 1ms)} \]
\[ N_{ss} = \text{number of flux samples at each time (> 1000)} \]
\[ N_p = \text{number of time points to map oscillations (> 100)} \]
\[ N = N_{ss} \times N_p = \text{total number of measurements (> 10^5)} \]
\[ N \tau_{ss} = \text{total measurement time (> 100s)} \]

• Put in 1/f critical current noise with spectrum appropriate to the measurement scheme:

\[ S_{Ic} = 1 \text{ pA}^2/\text{Hz} \]

• Determine decoherence time \( \tau_\phi \) limited by dephasing
I. Analytical calculation  

*Phase shift:* \[ \delta \phi(t) = \int_0^t dt' \delta \Omega(t') = \int_0^t \left( \frac{d\Omega}{dI_c} \right) \delta I_c(t') \]

*Phase noise:* \[ \langle \phi^2(t) \rangle \approx \left[ \ln \left( \frac{0.4}{f_{\text{min}} t} \right) \left( \frac{\partial \Omega}{\partial I_c} \right)^2 S_{I_c} (1\text{Hz}) \right] t^2 \approx \left( \frac{t}{\tau_\phi} \right)^2 \]

*Decay of oscillation amplitude:* \[ \Phi_{\text{env}} \sim \exp \left[ -\frac{1}{2} \left( \frac{t}{\tau_\phi} \right)^2 \right] \]

*Decoherence time:* \[ \tau_\phi \sim \left( \frac{1}{\ln(0.4N)} \right)^{1/2} \left( \frac{I_c}{\Omega \Lambda} \right)^{1/2} \left( \frac{1}{S_{I_c} (1\text{Hz})} \right)^{1/2} \text{ where } N = f_{\text{min}} \tau_{ss} \]

*For } N = 10^5 \Rightarrow \tau_\phi \approx 0.3 \left( \frac{1}{\Omega \Lambda} \right)^{1/2} \left( \frac{I_c^2}{S_{I_c} (1\text{Hz})} \right)^{1/2} \]

fractional change in } I_c
II. Numerical simulation

Assume a $1/f$ critical current noise spectrum:

$$S_{I_0}(f) \sim \frac{1}{f}$$

Generate critical current fluctuation distribution:

$$\delta I_0(t)$$

Example:

$$S_{I_0}(f) = \frac{1pA^2}{f}$$

Calculate flux oscillations averaged over the ensemble of measurements:

$$\Phi_{\text{ave}}(t) = \frac{1}{N} \sum_{n=1}^{N} \cos \left[ \left( \Omega_0 + \frac{d\Omega}{dI_0} \delta I_0(t + n \text{ tss}) \right) t \right]$$

$$I_c = 1 \mu A$$

$$\Omega/2\pi = 10 \text{ GHz}$$

$$\Lambda = 10$$

$$\tau_\phi = 450\text{ns}$$

$$\tau_\phi \sim \left( \frac{1}{\Omega\Lambda} \right) \left( \frac{I_0^2}{S_{I_0} (1\text{Hz})} \right)^{1/2}$$
Noise measurements in a finite voltage state

Shunted Al-AlO\(_x\)-Al Josephson tunnel junctions and dc SQUIDs fabricated by electron-beam lithography and shadow-mask evaporation

Typical parameters:
- \( A = 200\text{nm} \times 400\text{nm} \)
- \( C = 4 \text{fF} \)
- \( I_c = 1\text{–}10 \mu\text{A} \)
- \( R = 5\text{–}20 \Omega \)
- \( R_D(\text{max}) = 40\text{–}200 \Omega \)

Current bias in finite voltage state → determine changes in \( I_c \) from voltage noise

\[ \Delta V = R_D \Delta I_c \]
Noise measurements in single junctions

Preamp noise

$I = 0 \quad V = 0$
$I = 2.3 \mu A \quad V = 1 \mu V$
$I = 3.0 \mu A \quad V = 180 \mu V$
$I = 5.5 \mu A \quad V = 330 \mu V$

$V_{\text{noise}}$ (V/Hz$^{1/2}$)

$I_c = 2 \mu A \quad R = 65 \Omega$

$\langle V \rangle = 1.05 \mu A$

Distribution
Noise measurements (dc SQUID)

- Preamp current noise
- Preamp voltage noise

Voltage noise (V/Hz$^{1/2}$) vs. Frequency (Hz)

- $V = 0\mu V$
- $V = 1\mu V$
- $V = 5\mu V$
- $V = 10\mu V$
- $V = 20\mu V$
- $V = 40\mu V$
- Preamp

- Preamp current noise
- Preamp voltage noise

- dV/dΦ(max) = 600 $\mu V/\Phi_0$
- $S_{\Phi}^{1/2}$ (100 Hz) = $3 \times 10^{-5}$ $\Phi_0$/Hz$^{1/2}$

- BW~1kHz

- rms Voltage

- Bias voltage ($\mu V$)

- I vs. V
- V vs. Φ

- Image: Preamp structure with dimensions 10μm

- Image: Oscilloscope traces

Extracting critical current fluctuations from noise spectra

\[ S_V = 2 \times 10^{-16} \text{ V}^2/\text{Hz} \quad S_V^{1/2} = 1.4 \times 10^{-8} \text{ V/Hz}^{1/2} \]

\[ R_D = 200 \Omega \quad \Rightarrow \quad S_{Ic}^{1/2} = S_V^{1/2}/R_D = 7 \times 10^{-11} \text{ A/Hz}^{1/2} \]

\[ \text{BW} = 100 \text{ Hz} \quad \Rightarrow \quad \Delta I_c = 0.7 \text{ nA} \quad I_c = 8 \mu\text{A} \quad \Rightarrow \quad (\delta I_c/I_c) = 8.8 \times 10^{-5} \]

Assuming that \((\delta A/A) = (\delta I_c/I_c) \Rightarrow \delta A = 7 \text{ nm}^2 \Rightarrow \ r = 1.5 \text{ nm}\]
Extracting critical current fluctuations from switching noise

Time traces exhibit switching “random telegraph” noise

100 ms

dc SQUID parameters: \( L = 40 \, \text{pH} \quad I_c = 8 \, \text{µA} \quad A = 8 \times 10^4 \, \text{nm}^2 \)

Bias parameters: \( R_D = 40 \, \Omega \quad \frac{dV}{d\Phi} = 600 \, \mu \text{V}/\Phi_0 \)

\( \Delta V = 0.8 \, \mu \text{V} \quad \Rightarrow \quad \Delta I_c = 15 \, \text{nA} \)

Assuming that \( \frac{\delta A}{A} = \frac{\delta I_c}{I_c} \quad \Rightarrow \quad \delta A = 152 \, \text{nm}^2 \quad \Rightarrow \quad \delta s = 12.3 \, \text{nm} \)
A trapped electron changes local barrier height over a radius of $\sim 1 \text{ nm}$

Change in critical current: $\delta I_0 = (\delta A/A) I_0$

For one trap: $S^{(1)}(f) \propto (\delta I_0)^2$

For $N$ independent traps: $S_I(f) \sim N(\delta I_0)^2 \sim (nA)\left[\left(\frac{\delta A}{A}\right) I_0\right]^2$

Thus: $S_I(f) \sim \frac{I_0^2}{A}$

assuming a uniform areal trap density $n$

For given junction technology, we expect $A^{1/2} S^{1/2}_I(f)/I_0$ = constant
Compilation of Josephson junction critical current 1/f noise results

\[ T = 4.2K \quad f = 1 \, Hz \]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Area (µm²)</th>
<th>( I_0 ) (µA)</th>
<th>( S_{I_0}^{1/2} ) (1 Hz) (pA/Hz(^{1/2} ))</th>
<th>( A^{1/2}S_{I_0}^{1/2} ) (1 Hz)/( I_0 ) [µm(pA/Hz(^{1/2} ))/µA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-AlOx-Nb (^a)</td>
<td>9</td>
<td>9.6</td>
<td>36</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2.6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>115</td>
<td>48</td>
<td>35</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>12</td>
<td>41</td>
<td>20</td>
</tr>
<tr>
<td>Nb-Ox-PbIn (^b)</td>
<td>4</td>
<td>21</td>
<td>74</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.6</td>
<td>46</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.5</td>
<td>25</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5.7</td>
<td>34</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11.4</td>
<td>91</td>
<td>16</td>
</tr>
<tr>
<td>Nb-NbOx-PbInAu (^c)</td>
<td>1.8</td>
<td>30</td>
<td>184</td>
<td>8</td>
</tr>
<tr>
<td>PbIn-Ox-Pb (^d)</td>
<td>6</td>
<td>510</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

\(^a\) Savo, Wellstood, Clarke \(^26\) \hspace{1cm} \(^b\) Wellstood\(^27\) \hspace{1cm} \(^c\) Foglietti \textit{et al.}\(^28\) \hspace{1cm} \(^d\) Koch, Van Harlingen, Clarke\(^29\)

“Universal” value of 1/f noise:

\[ S_{I_0} (1 \text{Hz}, 4.2K) \approx 144 \left( \frac{I_0}{\mu \text{A}} \right)^2 \frac{\text{pA}^2}{(A/\mu \text{m}^2)/\text{Hz}} \]
Temperature dependence of 1/f critical current noise

Only known study: Fred Wellstood, Ph.D. thesis

• SQUIDs biased at low voltage (eV<<Δ)
  and at flux Φ = 0 (dV/dΦ=0)

• Measured current fluctuations with a
  SQUID magnetometer

• Found T^2 dependence down to ~ 0.3K
  (possible flattening at lower T?)

? No known mechanism for T^2 variation for charge traps in the tunneling regime
  (can be explained by thermal activation in an anisotropic potential)

? Source of charge for trapping is unknown --- should be frozen out in SC state

Temperature-dependent 1/f noise (optimistic):

\[
S_{I_0}(f, T) \approx \left[ \frac{144}{(A/\mu m^2)} \left( \frac{T}{4.2K} \right)^2 \frac{pA^2}{\mu A} \right] \frac{1}{f}
\]
Plan for 1/f noise measurements

Bias junction with current $I$:

- with feedback, $I_J = I = \text{constant} \rightarrow$
  - measure IV curve
- without feedback, $V \approx RI \approx \text{constant} \rightarrow$
  - measure current fluctuations $\delta I \sim \delta I_c$

sensitivity set by SQUID noise: $S_{Ic}^{1/2} \sim 10fA/Hz^{1/2}$
Measurements on Nb-Al-AlOx-Nb Josephson tunnel junctions (10µm × 10µm)
(fabricated by John Martinis --- NIST Boulder)

Parameters: \[ I_c = 2.5 \mu A \]
\[ A = 100 \mu m^2 \]
\[ T = 90 mK \]

\[ S_{\text{VSQUID}}(1\text{Hz}) = 4.5 \times 10^{-5} \text{V/Hz}^{1/2} \]

From universal 1/f model:
\[ S_{I_0}(1\text{Hz}) = 60 \text{ fA/Hz}^{1/2} \]
\[ S_{I_0}(1\text{Hz}) = 180 \text{ fA/Hz}^{1/2} \]
[larger by x 3]
General expression: decoherence from 1/f critical current noise

1/f critical current noise:

\[ S_{I_c}(f, T) \approx \left[ 144 \frac{(I_c / \mu A)^2}{(A / \mu m^2)^2} \left( \frac{T}{4.2 K} \right)^2 \right] \frac{pA^2}{f} \]

decoherence time:

\[ \tau_\phi \approx 0.3 \left( \frac{1}{\Omega \Lambda} \right) \left( \frac{I_c^2}{S_{I_c}(1 \text{Hz})} \right)^{1/2} \]

\[ \tau_\phi (\mu s) \approx 17 \frac{\sqrt{A(\mu m^2)}}{\Lambda f_{osc}(\text{GHz}) T(K)} \]

\[ N_{osc} = \frac{\Omega \tau_\phi}{2\pi} \approx 17,000 \frac{\sqrt{A(\mu m^2)}}{\Lambda T(K)} \]

Number of oscillations before decoherence
Qubit parameters and predicted performance (T=100mK)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>rf SQUID</th>
<th>3-junction SQUID</th>
<th>single JJ</th>
<th>Quantronium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_0$ (µA)</td>
<td>1.46</td>
<td>0.57</td>
<td>20.0</td>
<td>0.036</td>
</tr>
<tr>
<td>$L$ (pH)</td>
<td>240</td>
<td>11</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$\beta_L$</td>
<td>1.06</td>
<td>0.019</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$A$ (µm²)</td>
<td>2</td>
<td>0.05</td>
<td>100</td>
<td>0.11</td>
</tr>
<tr>
<td>$C$ (fF)</td>
<td>103</td>
<td>2.6</td>
<td>5000</td>
<td>5.4</td>
</tr>
<tr>
<td>$\Omega / 2\pi$ (GHz)</td>
<td>2.52</td>
<td>1.14</td>
<td>7.06</td>
<td>36.2</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>40.6</td>
<td>14.0</td>
<td>19.3</td>
<td>1.0</td>
</tr>
<tr>
<td>$\tau_0$ (µs) calc</td>
<td>2.4</td>
<td>2.5</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>$\tau_0$ (µs) meas</td>
<td>---</td>
<td>0.200</td>
<td>0.050</td>
<td>0.500</td>
</tr>
<tr>
<td>$\Omega \tau_0 / 2\pi$ calc</td>
<td>6300</td>
<td>2800</td>
<td>82,000</td>
<td>56,000</td>
</tr>
<tr>
<td>$\Omega \tau_0 / 2\pi$ meas</td>
<td>---</td>
<td>240</td>
<td>340</td>
<td>29,000</td>
</tr>
</tbody>
</table>

**Conclusion:** Predicted decoherence times from 1/f noise are longer than what has been obtained by measurements (<< 1µs) → may not be the limiting mechanism but may become a problem in the future.
Conclusions/Plans

1/f noise is a serious problem for superconducting flux qubits, and perhaps all solid state qubits --- may limit coherence times

- Characterization of 1/f critical current noise in qubit junctions
  - vs. size and technology (Nb trilayer, Al shadow, ...)
  - temperature dependence (T < 100mK)
  - voltage dependence (V < 2Δ/e)

- Materials approaches to reduce noise: (with Jim Eckstein, UIUC)
  - superconducting electrode material (Nb vs. Al vs. Pb vs...)
  - tunneling barrier morphology (amorphous vs. epitaxial vs. defect doped),

- Flux noise calculations: effects of 1/f flux noise on decoherence ⇒ introduces chial asymmetry/breaks degeneracy (with Tony Leggett, UIUC)

- Novel junction designs: SFS π-junctions --- decoherence concerns due to low resistance and 1/f magnetic domain noise (with Valery Ryazanov, ISSP)

- Measurement schemes: “spin-echo” pulse sequences to reduce effects of low frequency noise (cancels 1/f noise below pulse interval frequency)
\[ I = I_c \sin \phi \]

**Basic Qubit = rf SQUID**

- **Superconducting loop**
- **Magnetic flux \( \Phi \)**
- **Circulating current \( J \)**

Qubit states correspond to clockwise and counterclockwise currents

\[ \Phi = \frac{1}{2} \Phi_0 \]

**Our approach:** utilize \( \pi \)-Josephson junctions in superconducting flux qubit

**\( \pi \)-junction**

Negative \( I_c \) \( \rightarrow \) minimum energy at \( \pi \)

Spontaneous circulating current in rf SQUID
SFS Josephson junctions

**Principle:** FM Exchange field produces oscillations of the superconducting order parameter. For certain thickness of the FM-layer, the order parameter is of the opposite sign on two sides of the junctions, i.e. it is shifted by $\pi$.

The critical current of SFS Josephson $\pi$-junctions changes sign as a function of temperature [Ryazanov et al.]

![Diagram of SFS Josephson junctions](image-url)
Ongoing research projects/plans

1. Verify $\pi$-junction behavior via phase-sensitive tests

**Trombone experiment:** measure spontaneous flux for phase shift of $\pi$

**Current phase-relation experiment:** map out $I(\phi)$ by SQUID interferometry

2. Observe coherent quantum oscillation in a flux qubit incorporating $\pi$-junctions.
Trombone Current Injection Experiments: determination of $\beta_L$

$$\beta_L = \frac{2\pi I_c L}{\Phi_0}$$

SQUID (V) vs. $I_{trombone}$ (µA) for different values of $\beta_L$:
- $\beta_L < 1$
- $\beta_L = 1$
- $\beta_L > 1$
- $\beta_L >> 1$