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Resonant escape in Josephson tunnel junctions under millimeter-wave irradiation

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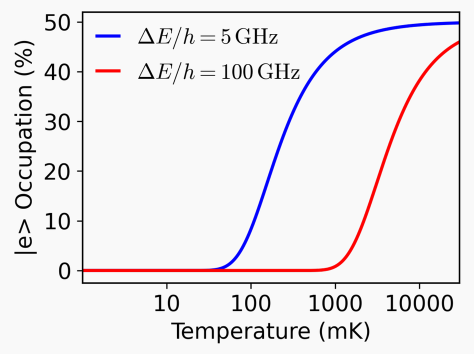
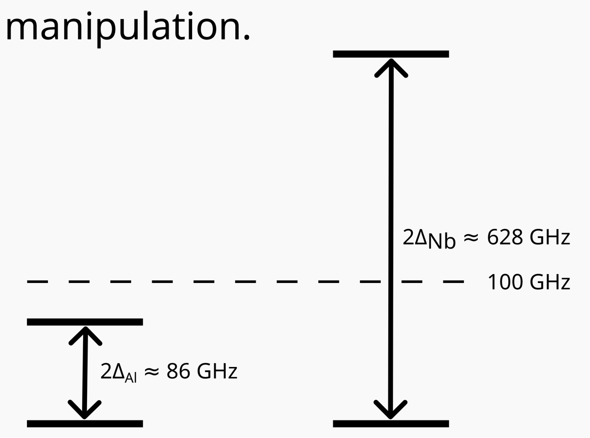
Abstract

Josephson junctions are an essential building block for superconducting electronics and are used, e.g., to form various types of superconducting qubits. Current implementations of qubits operate at frequencies on the order of several GHz, requiring cooling to temperatures well below 300 mK. Our goal is to eliminate these requirements by selecting frequencies of about 100 GHz. This not only allows for higher temperatures, but also increases the qubits' resilience to temperature fluctuations. It also reduces the size of the quantum circuit, with the possibility of higher integration density.

mm-Wave Quantum Circuits



- Promise operation at temperatures up to 1K.
- Are less susceptible to thermal fluctuations.
- Enable faster qubit manipulation.
- Require the use of superconducting materials with a sufficiently large energy gap, like e.g. niobium.
- Require a Josephson junction technology with a high plasma frequency above 100 GHz.

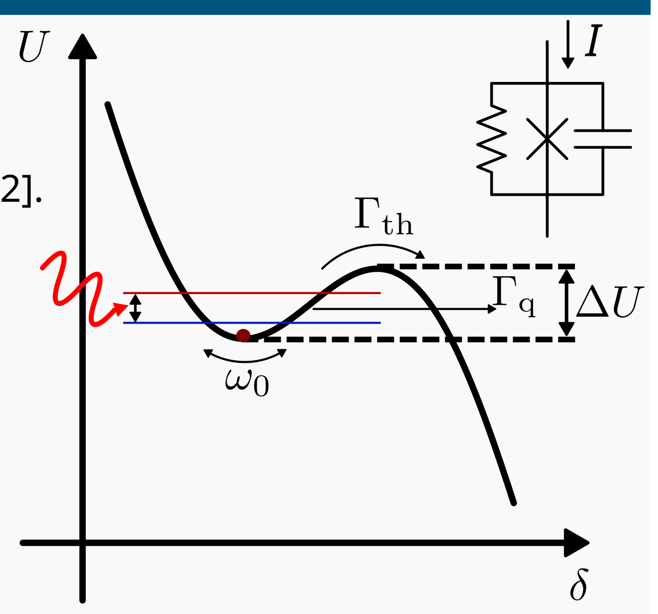


Escape in the RCSJ-Model

- S-state to R-state switching resembles escape from a metastable well.
- Escape by thermal activation or quantum tunneling[1,2].
- Microwave radiation resonantly enhances the escape rate[2].

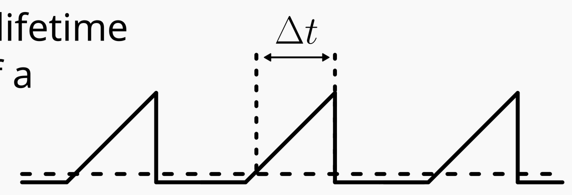
$$C\left(\frac{\Phi_0}{2\pi}\right)^2\ddot{\delta}+\frac{1}{R}\left(\frac{\Phi_0}{2\pi}\right)^2\dot{\delta}+\frac{I_0\Phi_0}{2\pi}\left(\sin\delta-I/I_0\right)+I_F(t)=0$$

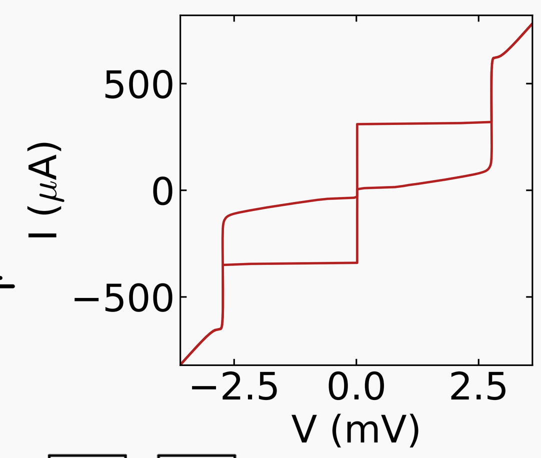
$$\Gamma=\frac{\omega_0}{2\pi}\exp\left(-\frac{\Delta U}{k_BT_{\mathrm{esc}}}\right)$$

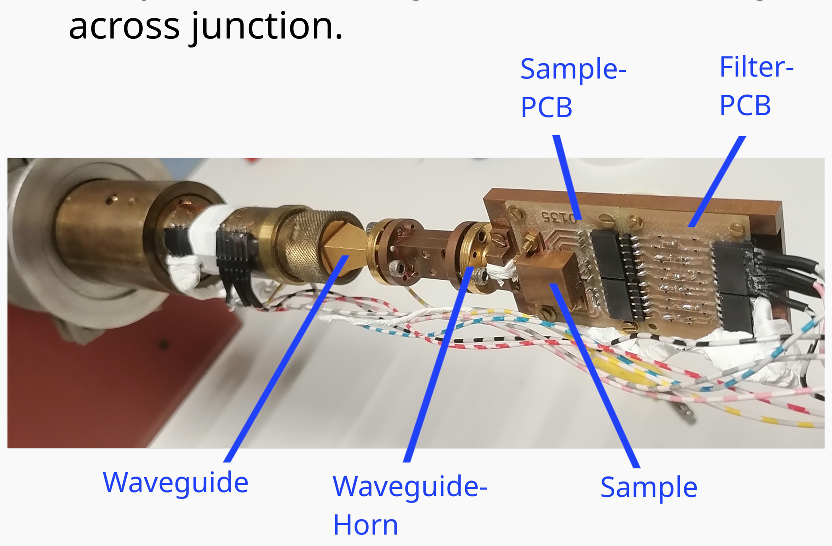


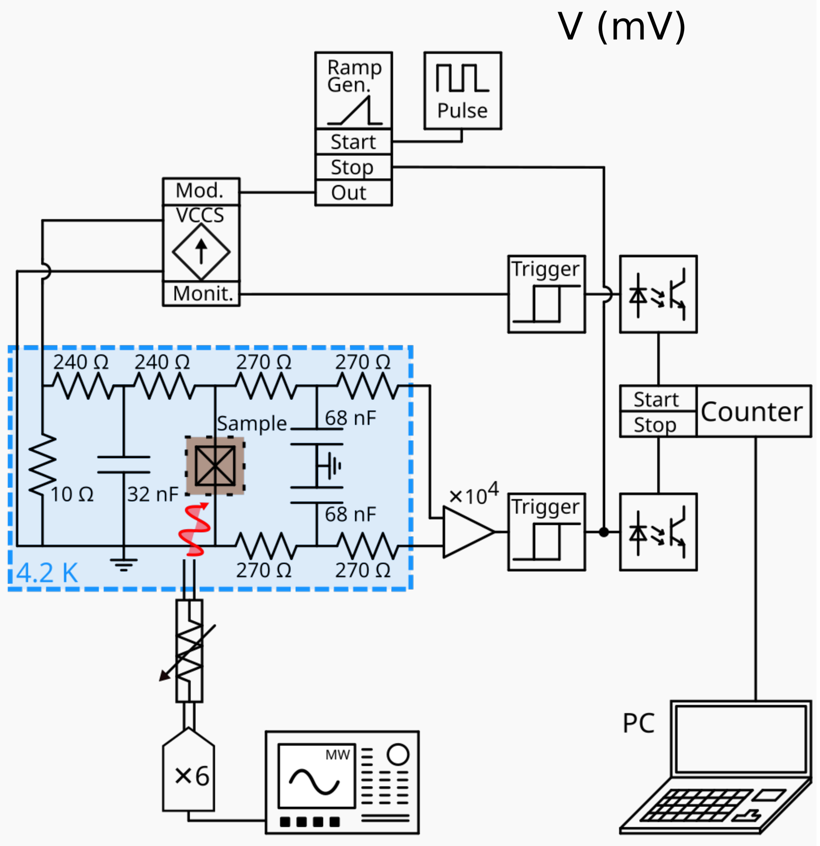
Experimental Setup

- Switching current measurements are used to determine the lifetime of the zero-voltage-state of a Josephson junction[1].
- Repeatedly increase the bias current through the junction with constant ramp rate.
- Measure time intervall between start of ramp and exceeding of threshold voltage across junction.









Escape in the Thermal Regime

- Measured escape probability allows to calculate escape rate.
- Theory of thermal escape enables the determination of the junction critical current.

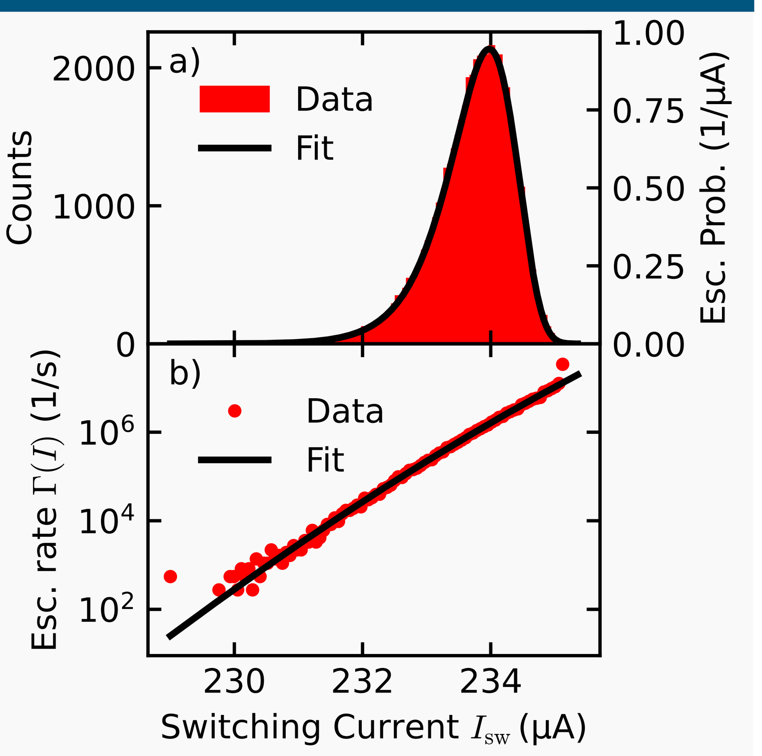
$$\Gamma=\frac{\omega_0}{2\pi}\exp\left[\left(\frac{4\sqrt{2}E_J}{3k_BT_{\mathrm{esc}}}\right)\cdot\left(1-\frac{I}{I_0}\right)^{3/2}\right]$$

$$T_{\mathrm{esc}}=\frac{T}{1-\ln a_t/(\Delta U/k_BT)}$$

$$I_0=(242\pm1)\,\mu\mathrm{A}$$

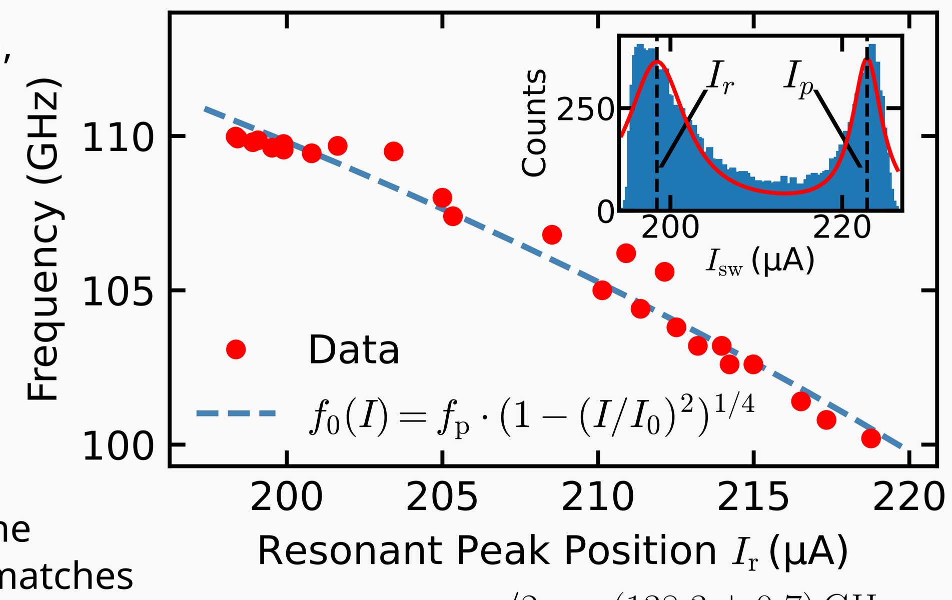
$$T_{\mathrm{esc}}=(6.3\pm0.4)\,\mathrm{K}$$

$$\omega_{\mathrm{pl}}=(0.1\pm0.2)\,\mathrm{THz}$$



Escape under mm-Wave Irradiation

- In presence of mm-wave radiation, the switching current distribution displays a double peak structure.
- The resonant peak position depends on the frequency of the applied radiation.
- The incident radiation enhances the escape rate, when the frequency matches the energy level spacing in the potential well.



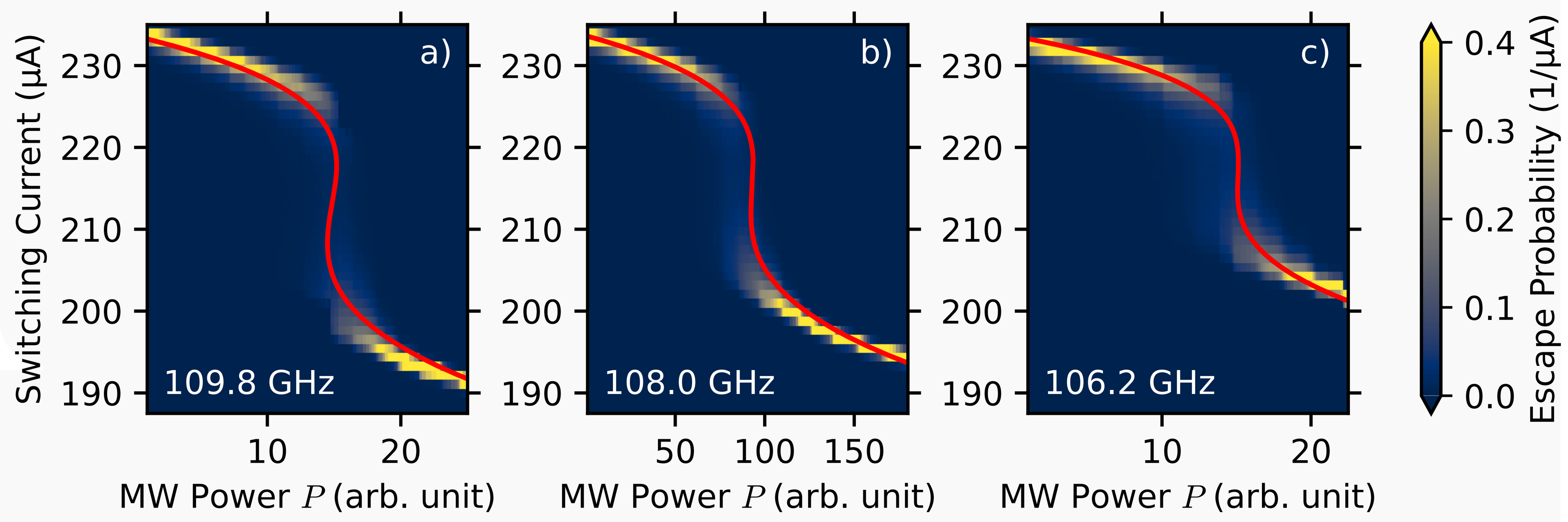
$$\omega_{\mathrm{pl}}/2\pi=(138.3\pm0.7)\,\mathrm{GHz}$$

$$I_0=(258\pm0.3)\,\mu\mathrm{A}$$

Power Dependence

- Measurement of the power dependence exhibits two coexisting branches.
- Comparison to quantum model of effective barrier suppression[3]. The suppression is particularly strong, if the resonance condition is fullfilled.
- There is a critical power level, above which the barrier suppression is so strong that only the resonant peak is observed.
- Simultaneous fit at different frequencies in harmonic approximation is used to extract the plasma frequency[4].

$$\omega_{\mathrm{pl}}/2\pi=145.5\,\mathrm{GHz}$$



Conclusion

We have measured the switching current distribution in the presence of millimeter(mm)-wave radiation at frequencies above 100 GHz and observed clear double-peak structures.
The data indicates a resonant escape of the phase as well as an irradiation-induced suppression of the potential barrier.
These measurements probe the microwave-driven dynamics of Josephson junctions in the previously unstudied millimeter-wave regime. The behavior is well described by existing theoretical models[3], which are utilized to determine the plasma frequency of the investigated samples, which is on the order of 140 GHz [4].

References

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