Quantum enhanced magnetometry on a transmon qutrit based on phase estimation algorithm

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Introduction

Superconducting artificial atoms offer a versatile platform for various applications, including quantum computing and precision magnetometry. In high-precision measurements, both the ultimate sensor sensitivity and the measurement time required to achieve this sensitivity are crucial.

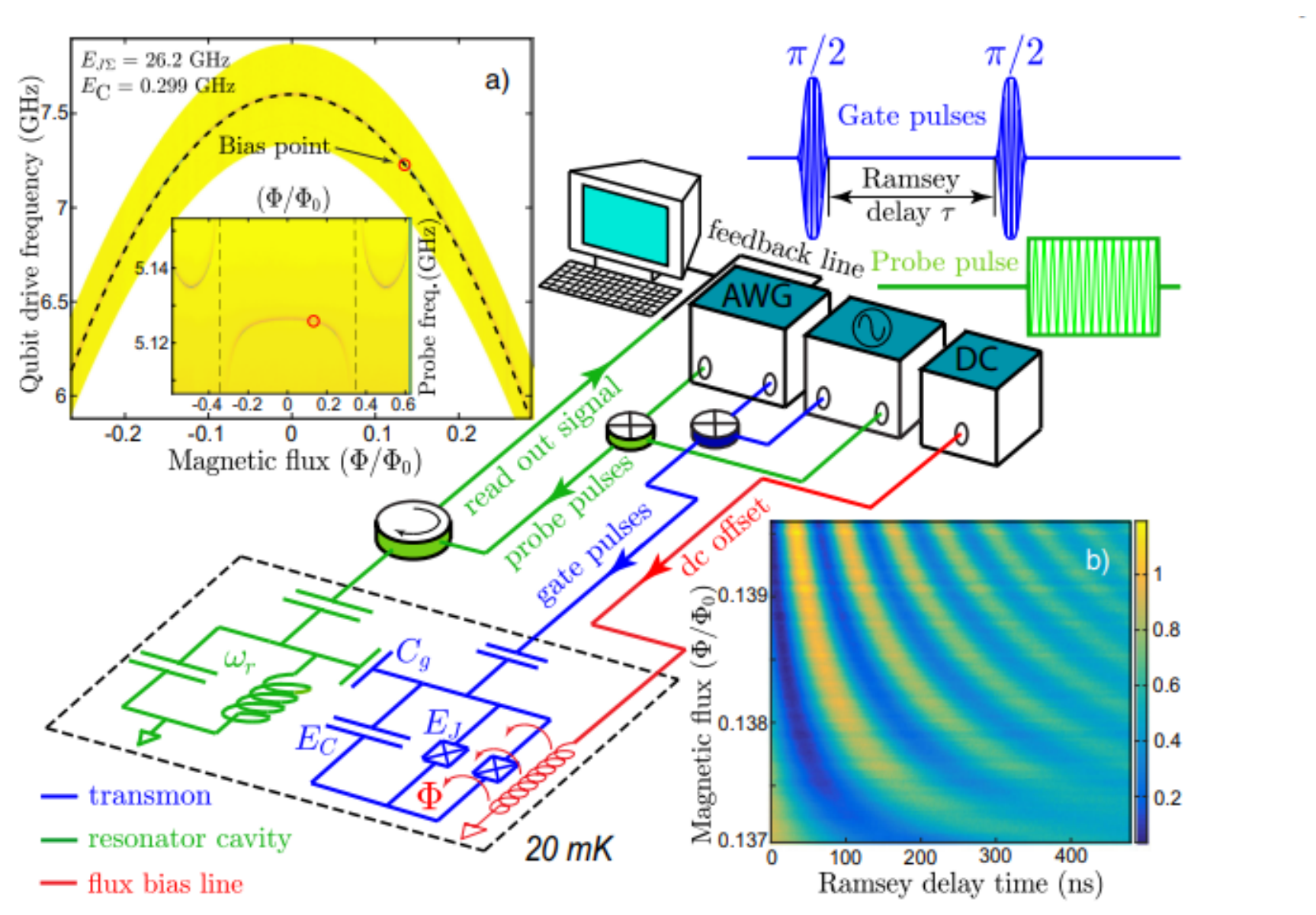
Leveraging quantum technologies to create precision sensors enables significant enhancements in sensitivity, ultimately approaching the Heisenberg limit. One strategy to further reduce the necessary measurement time is to utilize a larger number of levels in the artificial atom [1].

This work demonstrates that employing a qutrit protocol can decrease the measurement time required to achieve a given precision compared to a qubit-based approach using phase estimation algorithms

Transmon in an external magnetic field

Transmon Hamiltonian in magnetic field:

$$\hat{H} = 4E_C(\hat{n} - n_g) - E_J(\Phi)\cos\phi \quad [2]$$



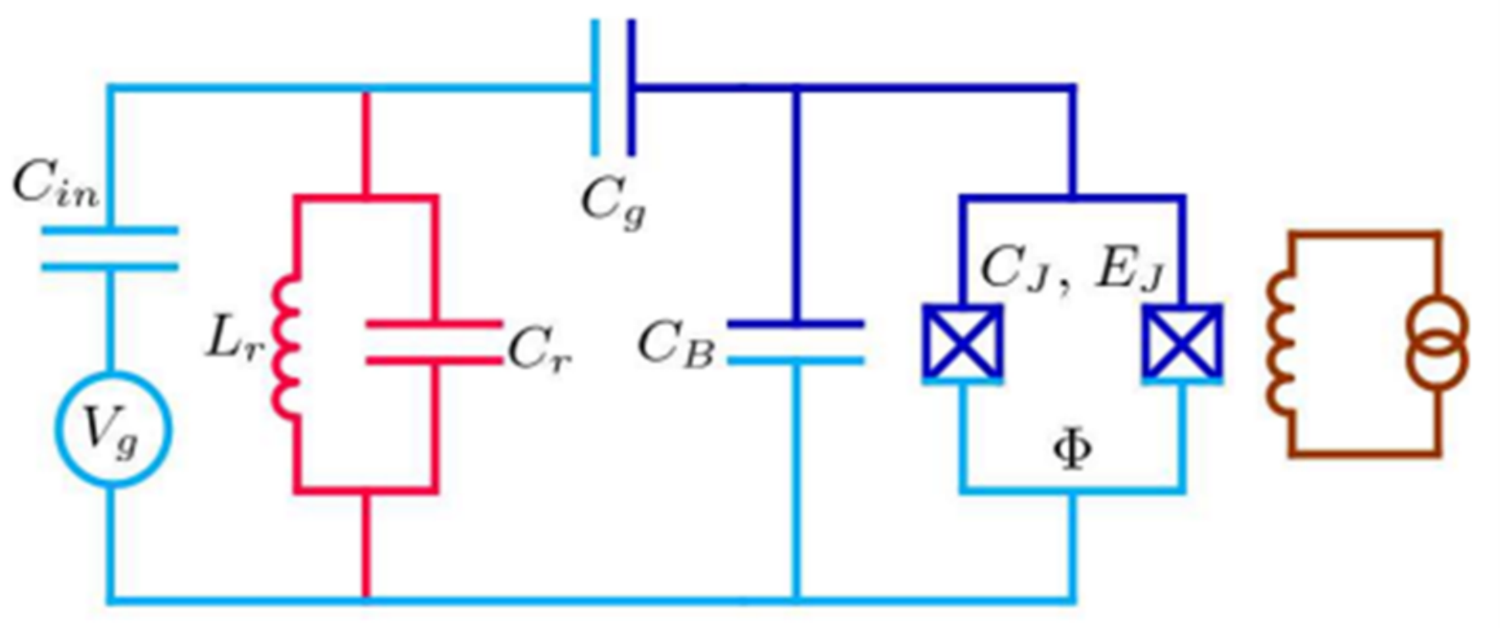
Transmon magnetic sensor experimental setup.

$$\frac{E_J}{E_C} >> 1$$

$$E_J = \sqrt{(\cos\pi\frac{\Phi}{\Phi_0})^2 + a^2(\sin\pi\frac{\Phi}{\Phi_0})^2}$$

$$E_m = -E_J(\Phi) + \sqrt{8E_J(\Phi)E_C} * (m + \frac{1}{2}) - \\ -\frac{E_C}{12}(6m^2 + 6m + 3)$$

$$\omega = \sqrt{8E_C E_J(\Phi)}$$



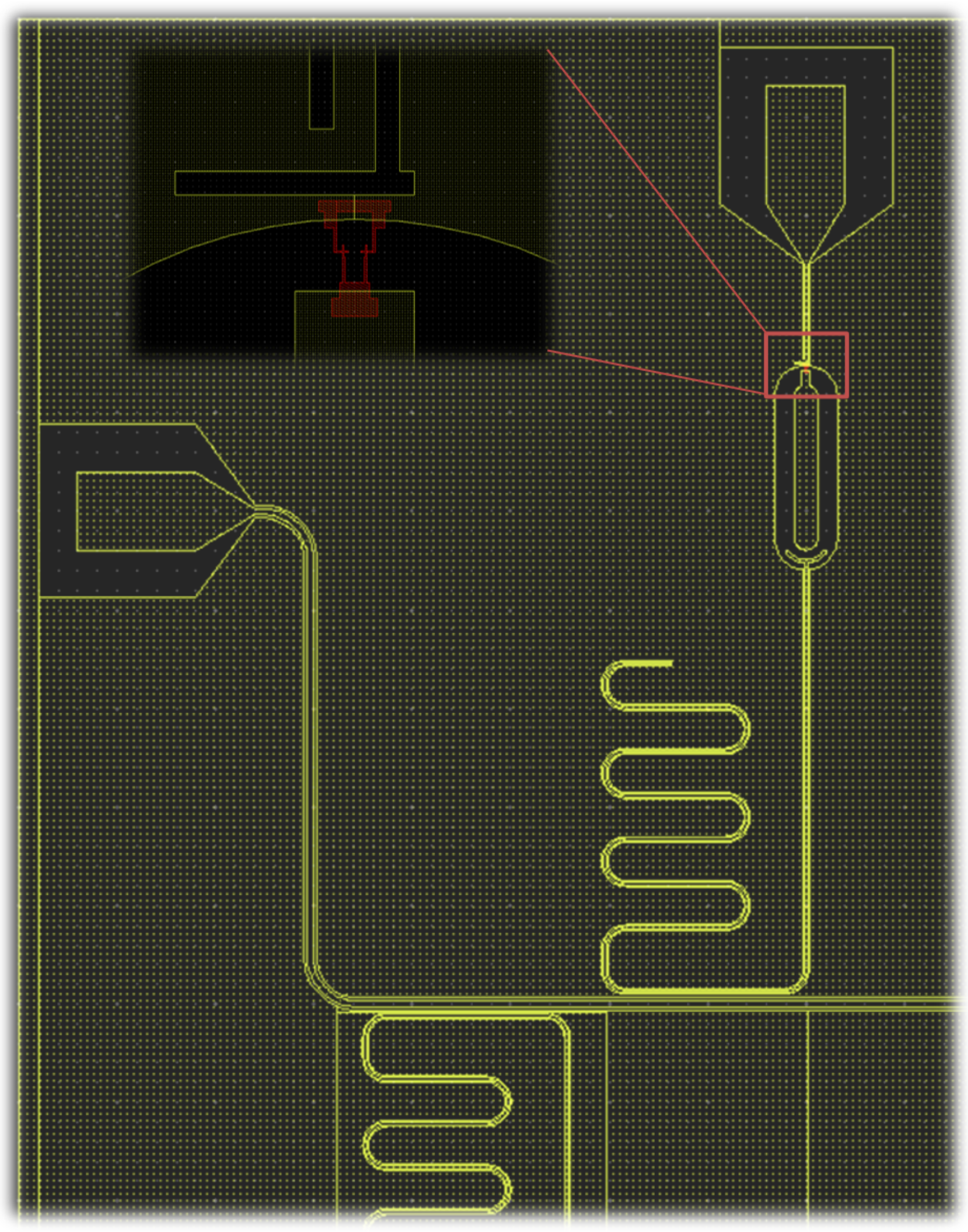
Transmon equivalent scheme

$$\omega \approx \frac{\mu(\Phi_{bias})}{\hbar} * B_{ext}, B_ext * S << \Phi_0$$

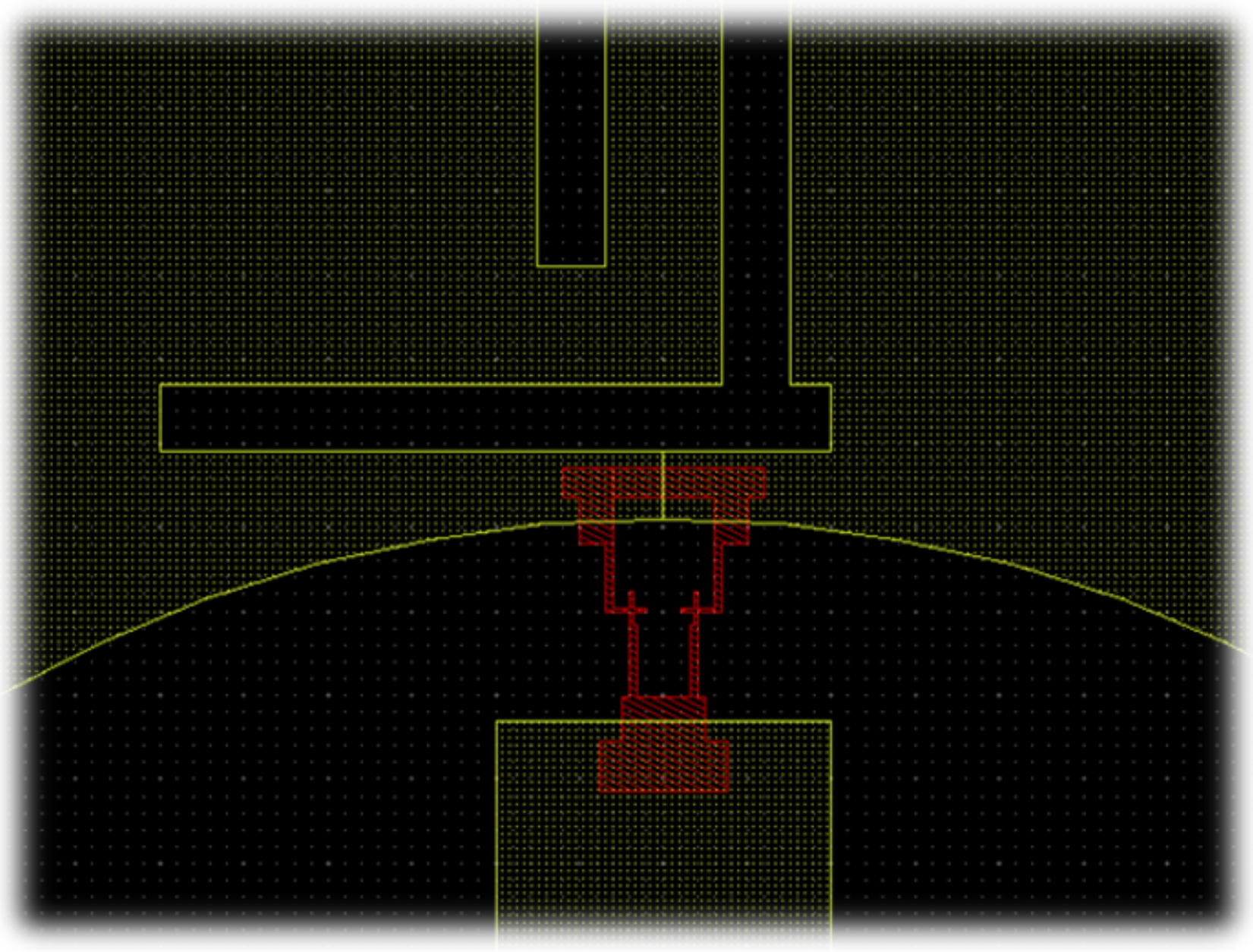
$$\mu(\Phi) = \hbar S\frac{d\omega(\Phi)}{d\Phi}$$

$$(\delta H)_{qd} = \frac{2\pi\hbar}{\mu(d-1)T_{qd}^{meas}}$$

Topology and design



Sensor topology



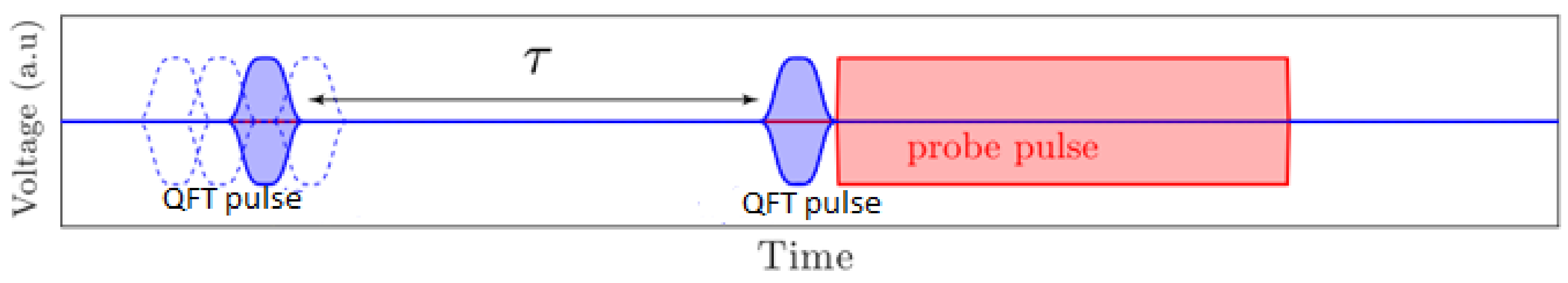
Transmon's SQUID

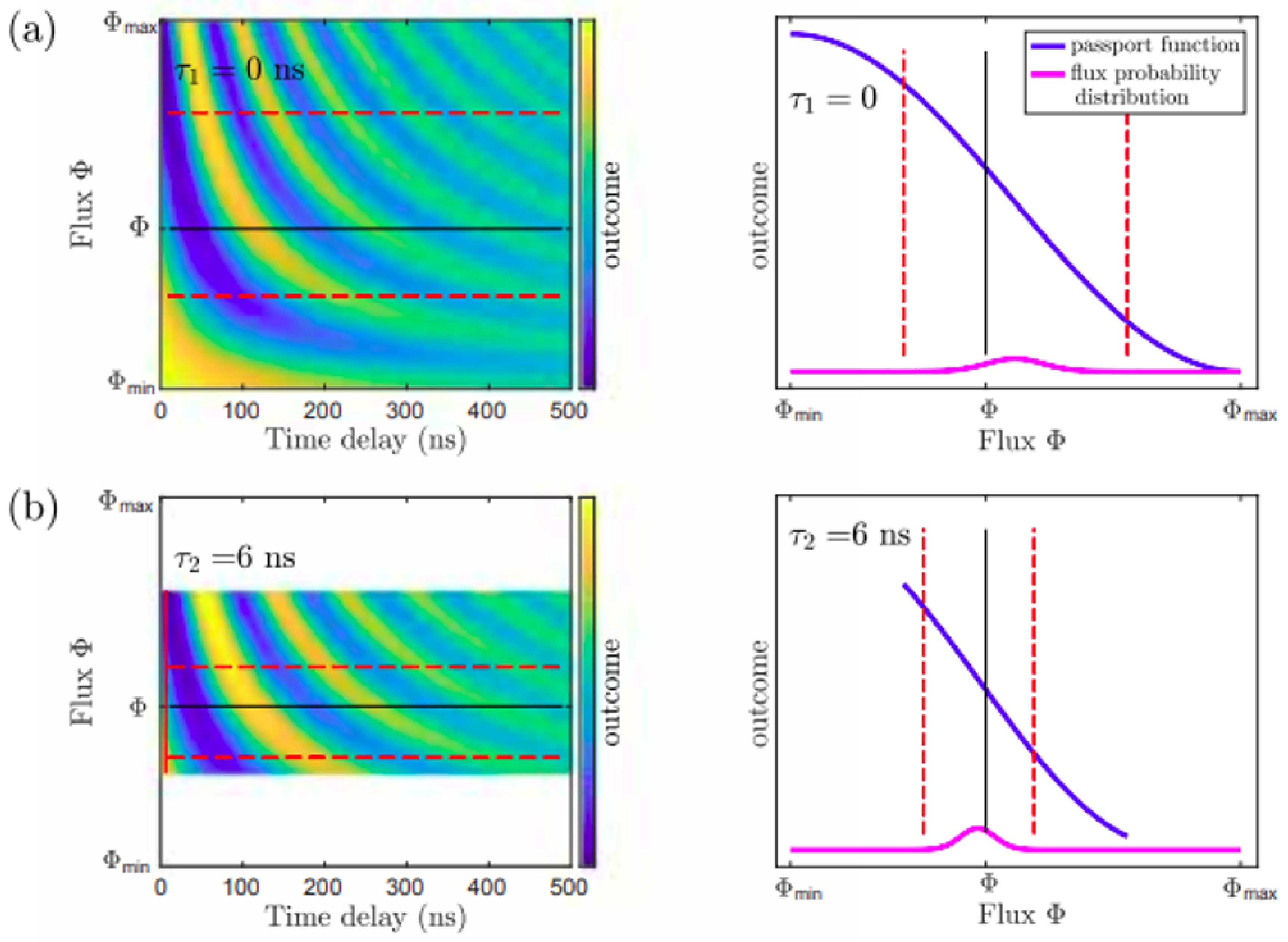
References

[1] Danilin, Sergey & Lebedev, Andrey & Vepsäläinen, Antti & Lesovik, Gordey & Blatter, G. & Paraoanu, G.. (2018). npj Quantum Information. 4. 10.1038/s41534-018-0078-y

[2] Koch J. A. et al. Charge-insensitive qubit design derived from the Cooper pair box // Physical Review A. 2007. Vol. 76. No. 4. 042319

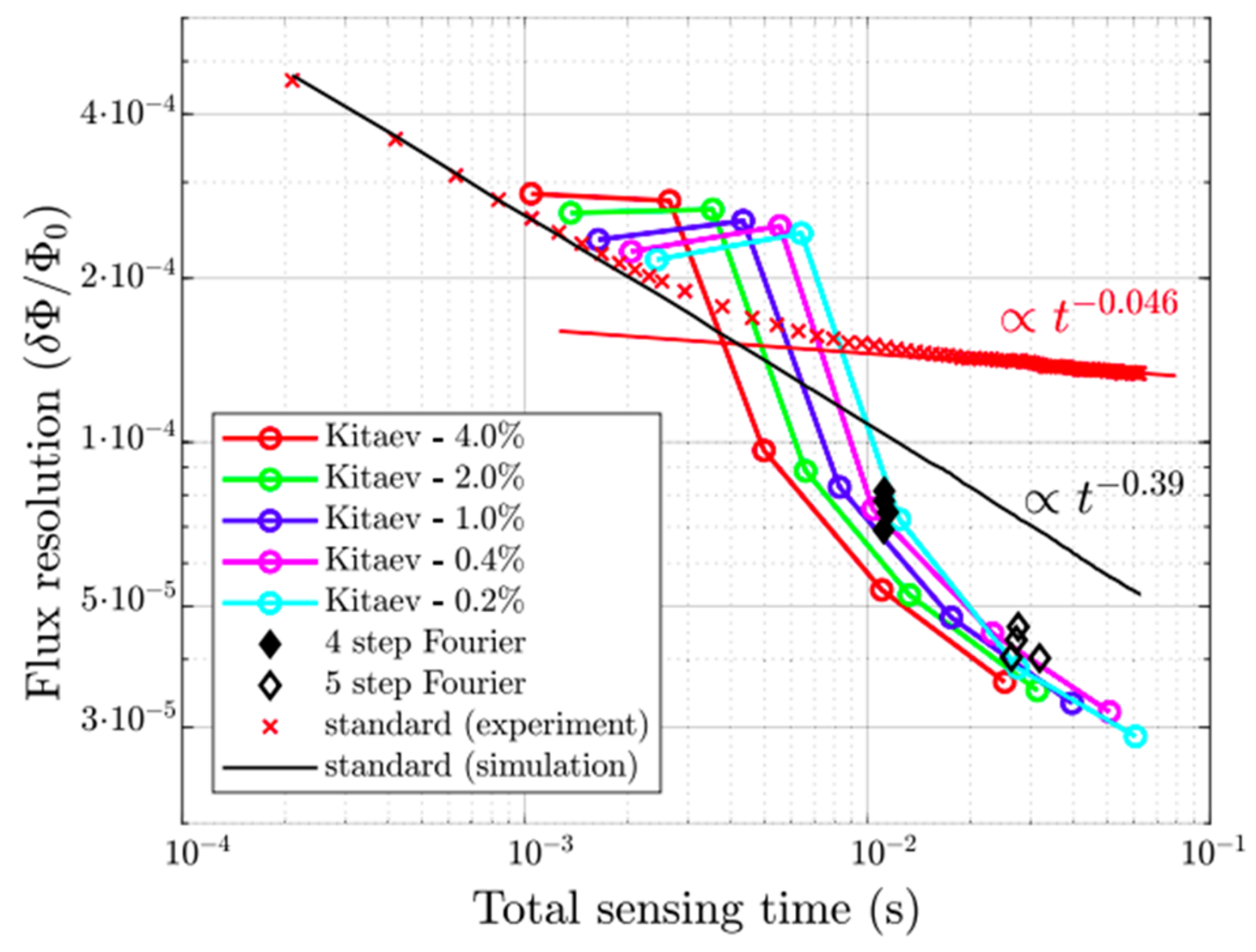
Metrological protocol



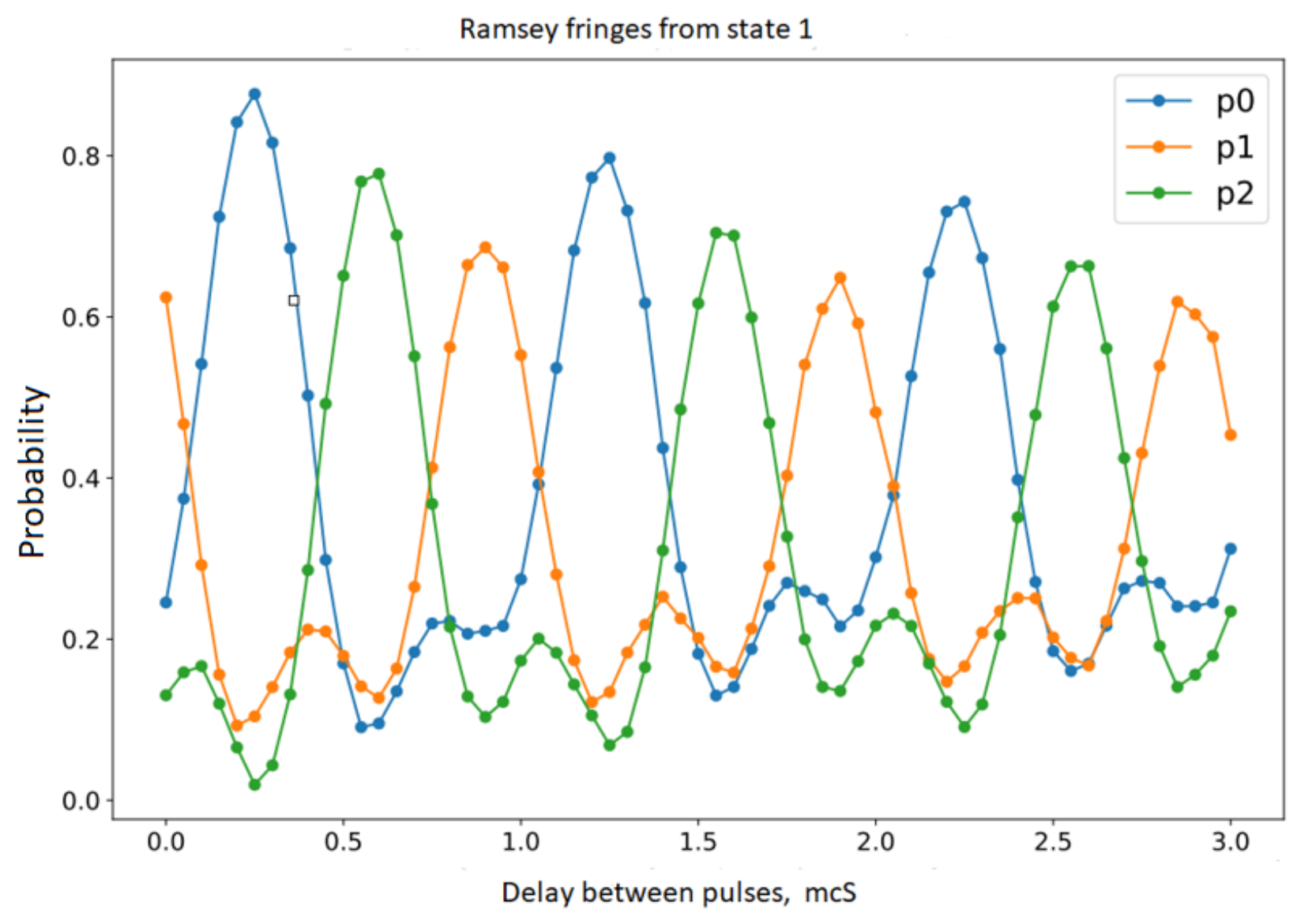


Kitaev algorithm

Main results



Precision of defined magnetic field as a function of measurement time



Qutrit Ramsey fringes. States probability as a function of delay between QFT pulses. Detuning - 1 MHz

Sensor type	Magnetic field sensetivity
Transmon qubit magnetometer	20.7 pT $Hz^{-1/2}$
Atom magnetometer	0.1–1.0 pT $Hz^{-1/2}$
NV-centers magnetometer	6.1 nT $Hz^{-1/2}$

Conclusions

(i) In this study, we explored magnetometers based on superconducting qubits and qutrits. In the qubit mode, transmons demonstrated high measurement precision of magnetic flux even at coherence times of around 300-400 nanoseconds. By improving the design and utilizing new technologies, we can achieve coherence times of several hundred microseconds, even in the presence of SQUIDs and magnetic fields, whose fluctuations significantly reduce the qubit lifetime. This increase in lifetime significantly enhances the sensor's sensitivity and precision.

(ii) Additionally, we obtained a Ramsey fringe pattern for qutrit using 80 ns Fourier pulses, which is much shorter than the measurement duration. The use of qutrit practically does not alter the dynamic range of the sensor - the Ramsey fringe pattern in both cases begins to blur at detuning frequencies of several megahertz. However, it noticeably enhances the sensor's sensitivity, making the use of qutrits promising for precision magnetic field sensing.

(iii) In the near future, we plan to measure the new design in both qubit and qutrit modes. The developed scheme includes 9 qubits with different resonator quality factors, allowing us to find a balance between reducing the qubit readout time and changing its lifetime. Further plans include applying the Purcell filter to improve both characteristics.

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