

Simultaneous sweet-spot locking of gradiometric fluxonium qubits

Denis Bénâtre^{1,*} Mathieu Féchant¹ Nicolas Zapata¹ Nicolas Gosling¹ Patrick Paluch¹
 Thomas Reisinger¹ and Ioan M. Pop^{1,2,3,†}

¹*IQMT, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

²*PHI, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany*

³*Physics Institute 1, Stuttgart University, 70569 Stuttgart, Germany*

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Efforts to scale up superconducting processors that employ flux qubits face numerous challenges, among which is the crosstalk created by neighboring flux lines, which are necessary to bias the qubits at the zero-field and $\Phi_0/2$ sweet spots. A solution to this problem is to use symmetric gradiometric loops, which incorporate a flux-locking mechanism that, once a fluxon is trapped during cooldown, holds the device at the sweet spot and limits the need for active biasing. We demonstrate this technique by simultaneously locking multiple gradiometric fluxonium qubits in which an aluminum loop retains the trapped fluxon indefinitely. By compensating the inductive asymmetry between the two loops of the design, we are able to lock the effective flux bias within $\Phi_{\text{eff}} = -3 \times 10^{-4} \Phi_0$ from the target, corresponding to only 15% degradation in $T_{2,E}$ when operated in zero external field. The design strategy demonstrated here reduces integration complexity for flux qubits by minimizing crosstalk and potentially eliminating the need for local flux bias.

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The last decade has seen rapid developments in flux-qubit engineering and design, parallel to those in transmons. In this type of superconducting qubit, the states are encoded in symmetric and antisymmetric superpositions of counterpropagating current states in an inductive superconducting loop, which includes at least one Josephson junction to give it nonlinearity. Flux qubits generally have higher anharmonicity compared to transmons, which allows faster gates, and are insensitive to charge offset thanks to their inductive shunt [1]. Using superinductors [2–4], the so-called fluxonium qubit can be designed to reach state-of-the-art coherence times above 1 ms [5] similarly to the most recent improvements in transmons [6].

While quantum nondemolition readout [7] and high-fidelity single-qubit and two-qubit gates have been demonstrated with fluxoniums [8–12], implementations of multifluxonium processor designs remain a rarity. Scaling up fluxonium processors has its specific challenges [13], among which is the crosstalk created by neighboring flux lines. Characterizing and inverting the flux-crosstalk

matrix becomes increasingly computationally demanding with the number of qubits, couplers, and resonators on chip, and is rendered difficult by the nonlinearity of the joint frequency response of these elements [14,15]. Additionally, it requires frequent recalibration due to flux-offset drifts and jumps over a cooldown. One solution could be “prebiased” flux qubits, such as the ones realized with so-called π junctions made from ferromagnetic materials [16,17]; however, they complicate fabrication and may introduce new decoherence channels.

In this work, we propose to exploit the flux-locking mechanism arising from flux quantization in gradiometric flux qubits [18,19]. Cooling a superconducting ring in a magnetic field B_{cd} , then removing it at base temperature, leaves a persistent current corresponding to a magnetic flux value given by the nearest integer multiple of Φ_0 [20,21]. The gradiometric fluxonium [see Fig. 1(a)] is built by splitting the ring into two inductive loops connected by a Josephson junction. Following Ref. [19], this type of fluxonium is modeled by the Hamiltonian

$$\hat{\mathcal{H}} = 4E_C \hat{n}^2 + \frac{E_L}{2} \left(\hat{\phi} + \varphi_{\text{eff}} + 2\pi m \frac{1+\alpha}{2} \right)^2 - E_J \cos \hat{\phi}, \quad (1)$$

where m is the number of trapped fluxons corresponding to B_{cd} and the area of the ring, $\alpha = (L'' - L')/(L'' + L')$ is the inductive asymmetry between the loops, and the effective

*Contact author: denis.benatre@kit.edu

†Contact author: ioan.pop@kit.edu

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flux bias induced by a uniform applied field B_{ext} is given by

$$\Phi_{\text{eff}} = \varphi_{\text{eff}} \frac{\Phi_0}{2\pi} = \frac{\Phi'_{\text{ext}} - \Phi''_{\text{ext}}}{2} + \alpha \frac{\Phi'_{\text{ext}} + \Phi''_{\text{ext}}}{2}, \quad (2)$$

where Φ'_{ext} and Φ''_{ext} are the external fluxes created by B_{ext} in each loop. Note that the effective flux Φ_{eff} only designates the flux created by the applied magnetic field B_{ext} , which we distinguish from the flux arising from the trapped fluxons and given by $m(1 + \alpha)/2$, and that magnetic field gradients increase the effective flux bias via the first term in Eq. (2).

For even numbers of fluxons m trapped in the ring, including $m = 0$, the fluxonium is locked at the zero-flux sweet spot (hereafter designated 0-locked). For odd m , the qubit is locked at the half-flux-quantum sweet spot, π -phase biasing the junction (designated π -locked). Following Eq. (2), in the ideal case of a completely symmetric sample, the qubit is susceptible only to field gradients, suppressing crosstalk from homogeneous fields and removing the need for static field bias, which additionally reduces the heat load in the cryostat. As the magnetic field is proportional to $1/d^2$, with d the distance to the next-neighbor's flux line, the gradient is proportional to $1/d^3$, which reduces flux crosstalk by orders of magnitude (see Appendix G). In a real device, some asymmetry is unavoidable. By tuning the area and inductive asymmetries of the loops, both the effective area $A_{\text{eff}} = \Phi_{\text{eff}}/B_{\text{ext}}$ and the remaining flux offset at zero field $\text{sgn}(A_{\text{eff}})m\alpha/2$ can in principle be made arbitrarily small, independently.

The samples [cf. Fig. 1(a)] are fabricated in a single electron-beam lithography step, using three-angle shadow evaporation, similarly to Ref. [23] (cf. Appendix A). Six chips, each hosting one or two qubits, are mounted in the same three-dimensional copper waveguide, equipped with a global magnetic field coil, similar to Refs. [24,25]. We estimate the relative contribution to Φ_{eff} from magnetic field gradients to be 10^{-4} via the first term in Eq. (2), which in the following can be neglected. We perform standard dispersive microwave reflection measurements at 30 mK, as shown in Fig. 1(b). In order to achieve single-shot readout, we employ a Josephson parametric amplifier (JPA) [22] operated in reflection.

In Fig. 1 we show a demonstration of the flux-locking mechanism at the zero-flux and at the half-flux-quantum sweet spots for qubits a–h, as visible in the measured 0–1 transition frequency for $m = 0$ [Fig. 1(c)] and $m = 1$ [Fig. 1(d)] fluxons trapped in the ring. We can achieve $m = 1$ by cooling down in a magnetic field $B_{\text{cd}} \approx 0.66 \mu\text{T}$ corresponding to $1\Phi_0$ in the ring area of $A_{\text{ring}} = 107 \times 29.4 \mu\text{m}^2$. The 0-locked and π -locked data are fitted together to a fluxonium spectrum [cf. Eq. (1)] from which we extract the Josephson energy E_J , the capacitive energy E_C , the inductive energy E_L (see Table I and Appendix C), and the effective area A_{eff} . Spectra versus magnetic field

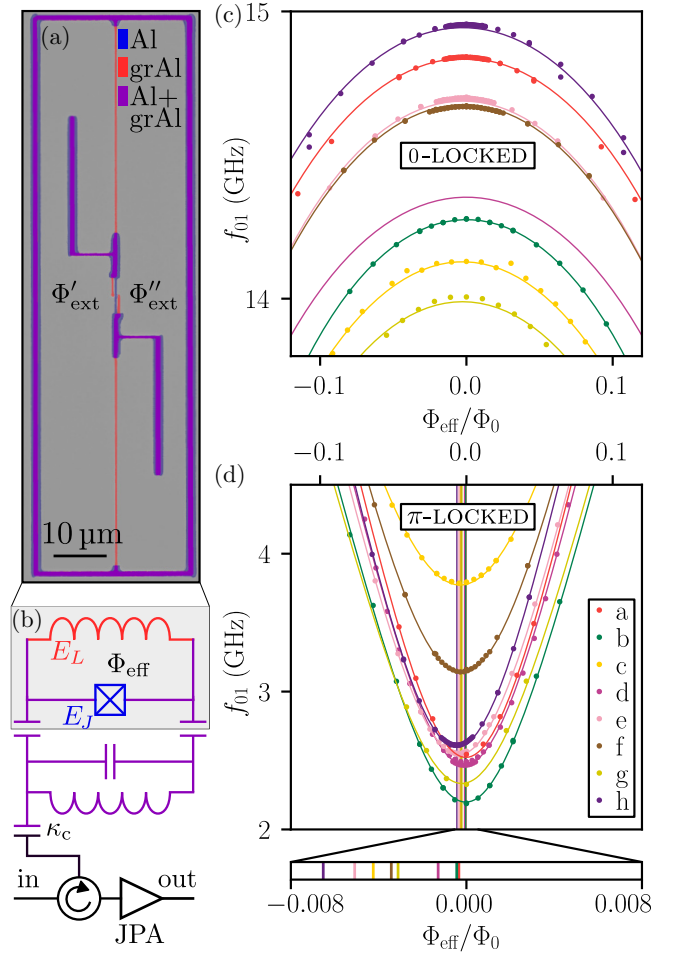


FIG. 1. Demonstration of flux locking. (a) False-colored microscope picture of the gradiometric fluxonium featuring a standard Al/AlO_x/Al junction (blue), Al capacitive pads to couple to the resonator (purple), and granular aluminum (grAl) inductors with normal-state resistivity $\rho_n \approx 2 \times 10^3 \mu\Omega \text{ cm}$ and thickness 40 nm (red). Purple parts are stacks of grAl above two layers of Al shunt. The fluxes threading the two loops Φ'_{ext} and Φ''_{ext} give rise to an effective flux bias Φ_{eff} [see Eq. (2)]. (b) Reflection measurement setup. All samples, each consisting of a qubit capacitively coupled to an LC resonator, are placed in a single three-dimensional waveguide and measured in reflection by a Josephson parametric amplifier (JPA) [22]. (c),(d) Spectra of eight gradiometric fluxonium samples measured in the vicinity of $\Phi_{\text{eff}} = 0$, after cooling down either (c) in zero field or (d) in a field $\Phi_0/2 < \Phi'_{\text{ext}} + \Phi''_{\text{ext}} < 3\Phi_0/2$, corresponding to Φ_0 trapped in the aluminum ring of the device. Markers depict the frequency of the 0–1 transition extracted from two-tone spectroscopy, and lines represent a fit to the fluxonium Hamiltonian in Eq. (1). Vertical lines indicate the position of the minimal frequency and are shown in detail in the bottom enlarged inset.

are shown in Appendix C, illustrating the variation of A_{eff} . All samples have similar fluxonium parameters, with mean values $\bar{E}_J/h = 8.8 \text{ GHz}$, $\bar{C} = 4.7 \text{ fF}$ (with about 2.5 fF coming from the intrinsic capacitance of the junction), and

TABLE I. Qubit parameters for samples a–h.

Sample	E_J/h (GHz)	E_C/h (GHz)	E_L/h (GHz)
a	9.21 ± 0.16	3.97 ± 0.07	1.95 ± 0.05
b	9.19 ± 0.16	4.05 ± 0.04	1.59 ± 0.04
c	7.50 ± 0.13	4.48 ± 0.07	1.96 ± 0.03
d	8.87 ± 0.23	3.88 ± 0.03	1.87 ± 0.03
e	9.06 ± 0.15	4.09 ± 0.06	1.84 ± 0.05
f	8.45 ± 0.15	4.16 ± 0.05	2.05 ± 0.05
g	8.90 ± 0.14	4.09 ± 0.08	1.58 ± 0.04
h	9.22 ± 0.15	3.97 ± 0.07	2.01 ± 0.06

$\bar{L} = 88$ nH, corresponding to a sheet inductance $\bar{L}_{\square, \text{grAl}} = 0.22$ nH/ $\square$.

A previous implementation [19] with a granular aluminum ring has shown flux escape at base temperature, mediated by ionizing radiation interactions with the substrate in the vicinity of the device. In above-ground conditions, these flux escapes occurred on a time scale of one hour, and they were completely removed when operating in an underground laboratory shielded from ionizing radiation. We solve this issue by using a wide, pure aluminum ring. Because of its orders-of-magnitude higher superfluid stiffness ($\rho_{s, \text{Al}}/\rho_{s, \text{grAl}} \sim 100$), persistent currents in aluminum are less susceptible to phase slips. As a result, we never observe flux escapes after locking (cf. Appendix F for a time trace over 50 h).

Nevertheless, we typically observe simultaneous π -locking for only 80% of the qubits, which means that in each cooldown one or two devices lock to even values of m instead of odd. This behavior is unexpected and could be due to ionizing-radiation-activated flux escapes happening during the cooldown, when the superfluid stiffness $\rho_{s, \text{Al}}$ is suppressed close to the superconducting critical temperature, rendering the ring vulnerable to phase slips. We note that this yield is similar to that found in Ref. [26], despite using a wider TiN outer ring. Potential mitigation strategies align with those used to address quasiparticle poisoning in superconducting circuits, such as employing quasiparticle traps adjacent to the sample [27] or shielding from cosmic radiation underground [19]. An additional strategy could involve accelerating the cooldown or enhancing sample thermalization to minimize the time spent near the transition.

The inset of Fig. 1(d) displays the measured flux offsets from perfect sweet-spot locking across the samples, resulting from a deliberate sweep of the loop width asymmetry $(w' - w'')/2$ [inset of Fig. 2(a)] over the range -200 to 200 nm. We observe a linear dependence of α [Fig. 2(a)] and A_{eff} [Fig. 2(b)] on the asymmetry, as expected. From the slopes, we extract a surface change of $93 \mu\text{m}^2/\mu\text{m}$ and a change in α corresponding to -0.12 nH/ μm , assuming the aluminum ring sheet inductance $L_{\square} = 10$ pH/ $\square$ (cf. Appendix D).

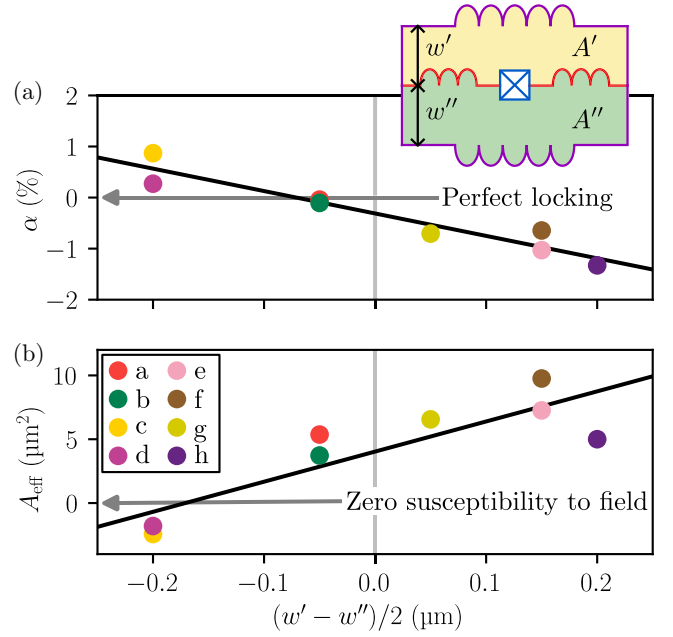


FIG. 2. Tuning of the asymmetry. Inset: Circuit diagram of the gradiometric fluxonium, showing the Josephson junction (blue), the granular aluminum inductances (red) in the middle, and the low-value inductances (purple) of the aluminum ring. The difference in loop widths $w' - w''$ is tuned while keeping the total size constant. (a) Inductive asymmetry $\alpha = (L'' - L')/(L'' + L')$ versus loop width asymmetry. The α value is obtained from the offset of the spectrum when the fluxonium is π -locked [cf. Fig. 1(d)], such that $\Phi_{\text{offset}}/\Phi_0 = \alpha/2$. Perfect sweet-spot locking is realized when $\alpha = 0$. (b) Effective area A_{eff} versus loop width asymmetry. The A_{eff} value is extracted from fitting the spectra together with fluxonium parameters E_J , E_C , and E_L . Zero susceptibility to homogeneous magnetic field is achieved when $A_{\text{eff}} = 0$.

While the surface change aligns with the device's $107\text{-}\mu\text{m}$ length, the observed α change is roughly three times larger than expected for a constant sheet inductance around the loop. This discrepancy suggests a larger-than-expected inductive contribution of the horizontal wires in Fig. 1(a). The zero crossings of α and A_{eff} occur at different values of $(w' - w'')/2$, shifted away from zero. This observation implies that adjusting $w' - w''$ alone cannot offer a device that simultaneously locks perfectly to the sweet spots and remains insensitive to magnetic fields. The shift in A_{eff} corresponds to a 100-nm geometric offset, which is explained by the persistent current path through the two aluminum layers with different kinetic inductances (cf. Appendix H). The shift in α is explained by a small difference in the inductance of the left and right loops of 20 pH, whose origin could be a combination of the geometric inductance and the supercurrent path factors mentioned above.

To investigate the locking accuracy in more detail, we measure $T_{2,E}$ around zero field for samples a and b,

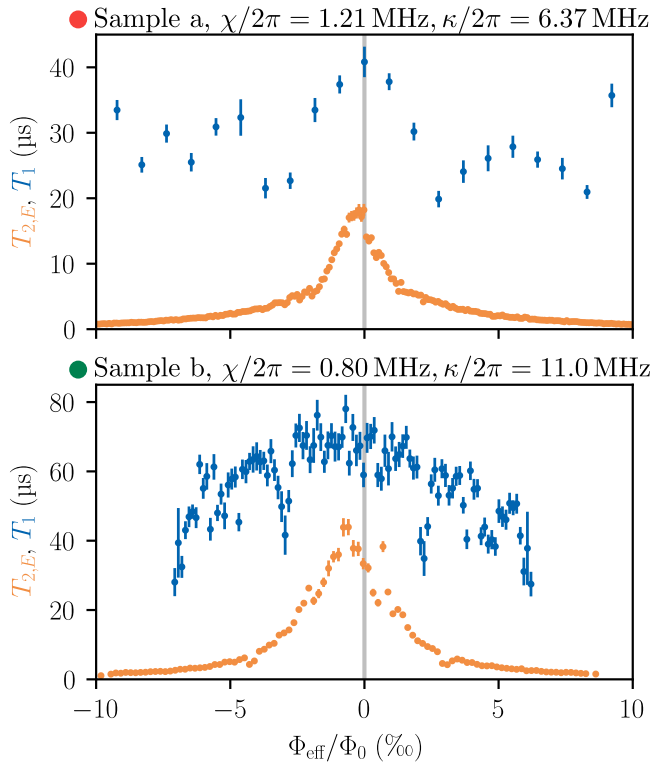


FIG. 3. Qubit time-domain characterization. Coherence times T_1 (in blue) and $T_{2,E}$ (in orange) for samples a (•, top) and b (•, bottom) with $m = 1$ fluxon trapped versus effective flux Φ_{eff} around zero field, illustrating the precision of the locking mechanism. Markers show the measured values with uncertainty. The gray vertical line indicates zero field. In each legend, χ is the dispersive shift at the sweet spot and κ is the resonator's linewidth.

which are the closest to zero in Fig. 2(a). In Fig. 3, we report $T_{2,E}$ values of respectively 20 and 44 μs at $\Phi_{\text{eff}} = -3 \times 10^{-4} \Phi_0$ and $\Phi_{\text{eff}} = -5 \times 10^{-4} \Phi_0$, similar to values reported for granular aluminum fluxoniums in Ref. [23]. At zero field, they correspond to degradations of 15% and 32%, respectively. For both samples, $T_{2,E}$ at the sweet spot follows an exponential decay, not limited by T_1 , which could be explained, for example, by critical current noise or photon shot noise with $n_{\text{res}} \approx 0.01$ residual photons in the resonator. Additionally, Appendix E reveals significant correlated fluctuations in T_1 and $T_{2,E}$ over several hours, as commonly observed in the literature [3], though their origin remains unknown. The coherence times measured on both devices are larger than previously measured gradiometric fluxoniums with granular aluminum in the outer ring [19], which suggests no detrimental effect of the aluminum ring on the coherence.

In conclusion, we demonstrate simultaneous and stable sweet-spot flux locking of gradiometric fluxoniums, enabled by flux quantization in an aluminum ring. These devices exhibit no flux escapes, unlike previously reported

gradiometric fluxoniums with granular aluminum rings. We are able to reduce the field susceptibility and asymmetry of our samples down to an effective area of a few micrometers squared and an inductive asymmetry less than 1%. The latter implies that, in zero field, fluxonium qubits can be locked within $\Phi_{\text{eff}} = -3 \times 10^{-4} \Phi_0$ from the half-flux-quantum sweet spot, with $T_{2,E}$ reduced by only 15% from its maximum. As an outlook, we anticipate this scheme to be beneficial for large-scale integration, and the stability of the flux locking to allow the implementation of more complex systems of trapped fluxons in superconducting circuits [28].

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DATA AVAILABILITY

The data that support the findings of this research article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: SAMPLE FABRICATION

All samples shown in this research article were fabricated on a single double-side-polished *c*-plane 330- μm -thick sapphire wafer. A double stack of methyl methacrylate and methacrylic acid MMA(8.5)MAA EL13 and poly(methyl methacrylate) 950 PMMA A4 resists was spin-coated on the wafer and patterned using a 50-keV electron-beam lithography tool. After developing in an

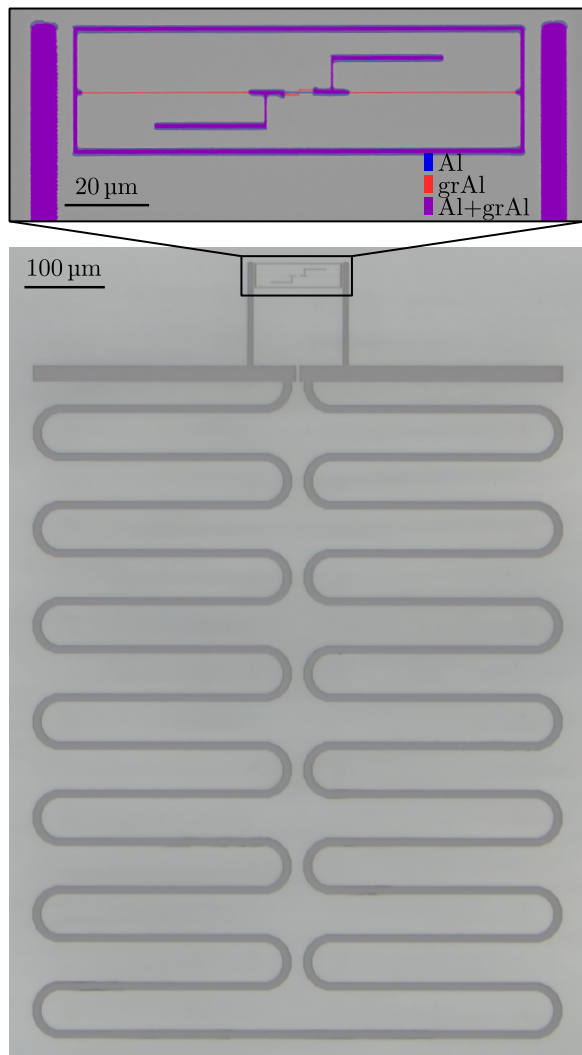


FIG. 4. Optical microscope pictures of the qubit (top) and the aluminum LC resonator (bottom) for one of the samples. Each sample's resonator is designed with a different number of meanders in order to spread the frequencies between 6 and 8 GHz. Each chip contains two such samples and does not have any ground plane.

isopropyl alcohol IPA:H₂O 3:1 solution for 2 min 30 s, aluminum was deposited in a three-angle shadow evaporation process in a Plassys electron-beam evaporation system.

The thin-film deposition recipe includes plasma cleaning and Ti gettering to clean the sample and the chamber, -31° -tilted aluminum evaporation at 1 nm/s for 20 s, 6-min oxidation at 11.54 mbar, 31° -tilted aluminum evaporation at 1 nm/s for 30 s, argon milling to ensure contact, and granular aluminum deposition consisting of a 0° aluminum evaporation at 1 nm/s for 36 s under a constant oxygen flow at 5.0 sccm. After lift-off in hot acetone (50°C , 13 h) and hot *N*-ethylpyrrolidone NEP (90°C , 27 min), the wafer was cleaned in acetone and IPA. Finally, the wafer was diced into $15\text{ mm} \times 3\text{ mm}$ chips after coating it with a protective S1818 G2 photoresist, which is removed in hot

dimethyl sulfoxide DMSO (80 °C, 10 min). Each chip contains one or two working samples, such as the sample shown in Fig. 4.

APPENDIX B: CRYOSTAT SETUP

All experiments were performed in a Qinu Sionludi XL cryostat, at a base temperature of 20 to 30 mK, over different cooldowns, with the setup shown in Fig. 5. Frequency-domain experiments were performed using a vector network analyzer (VNA) to read out the resonator and a microwave source to drive the qubits. The total attenuation was 60 dB, spread between the 4-K, the 200-mK,

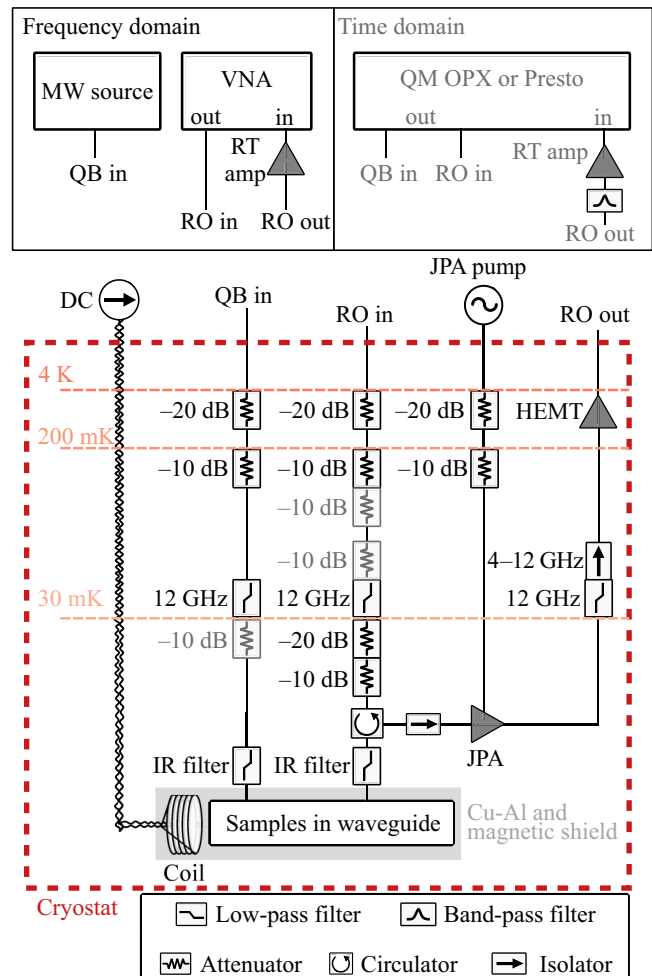


FIG. 5. Cryostat and measurement setup. For frequency-domain experiments, we use a vector network analyzer (VNA) and a microwave source as indicated in the top-left corner. The cryostat is set up with all black components; in particular, the total attenuation is 60 dB on the readout input line and 30 dB on the qubit drive line. For time-domain experiments, we use a Quantum Machines’ Operator-X or an Intermodulation Products’ Presto. The cryostat is set up with the additional attenuators in gray, increasing the total attenuation to 80 dB on the readout input line and 40 dB on the qubit drive line.

and the 30-mK stages for the readout line, and 30 dB on the qubit drive line. For these measurements, the JPA was kept turned off and no bandpass filter was used at the output.

For time-domain experiments, the total attenuation on the readout line was increased to 80 dB as represented in gray in Fig. 5, in order to reduce the photon shot noise. The attenuation on the qubit drive line was also increased by adding a 10-dB attenuator on the 30-mK stage. The JPA was turned on and the room-temperature bandpass filter, used to filter out the strong JPA pump signal, was tuned to the measured resonator frequency. The time-domain experiments were performed using an OPX from Quantum Machines (data in Fig. 3) and a Presto from Intermodulation Products (additional measurements).

APPENDIX C: SPECTRA

We measured the spectra of the devices shown in the main text by standard continuous-wave two-tone spectroscopy in reflection on the readout resonator of each sample individually. The transition frequencies were then extracted by fitting a Lorentzian function at each field. To illustrate the different A_{eff} measured in our samples, we

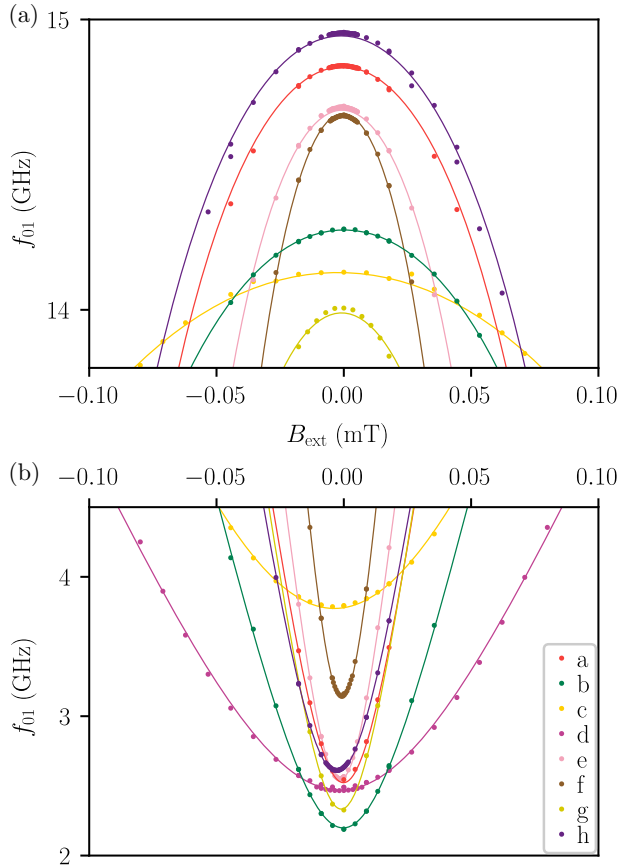


FIG. 6. Spectra of all eight samples in the vicinity of zero field, in (a) the 0-locked and (b) the π -locked cases, as a function of the applied field B_{ext} , as opposed to the effective flux in Fig. 1.

show in Fig. 6 the spectra of the same eight samples as in the main text, in the 0-locked [Fig. 6(a)] and π -locked [Fig. 6(b)] cases, as a function of the applied magnetic field B_{ext} .

All eight samples were fitted to the fluxonium Hamiltonian using the `scqubits` PYTHON package [29]. On top of the fluxonium parameters E_J , E_C , and E_L , we also fitted the effective area A_{eff} that gives the scaling in Φ_{eff} . The data used in the fits include the 0–1 transition in the 0-locked and π -locked cases, as well as higher transitions such as 0–2, multiphoton transitions, and transitions mediated by resonator photons. The fits are shown in Fig. 7 as a function of $\Phi_{\text{tot}} = \Phi_{\text{eff}} + m(1 + \alpha)/2$ to illustrate the fluxonium spectrum.

APPENDIX D: ASYMMETRY

The asymmetry in gradiometric fluxoniums has both a geometric and an inductive contribution. The geometric contribution is linked with the exact path taken by the current in the loops and introduces a variation in $\Delta A = A' - A''$. The inductive contribution comes directly from the inductance of each loop and affects the value of α . Because $A_{\text{eff}} = \Delta A/2 + (\alpha/2)(A' + A'')$, the effective area depends on both contributions. For a better understanding, we plot the inductance difference [Fig. 8(a)] and the area difference [Fig. 8(b)] between each loop as a function of the asymmetry $(w' - w'')/2$ introduced in the main text. Linear fits are as follows:

$$\Delta L = (-120 \text{ pH}/\mu\text{m}) \frac{w' - w''}{2} - 8.5 \text{ pH}, \quad (\text{D1})$$

$$\frac{\Delta A}{2} = (92.7 \mu\text{m}^2/\mu\text{m}) \frac{w' - w''}{2} + 8.9 \mu\text{m}^2. \quad (\text{D2})$$

For reference, the linear fits in Fig. 2 of the main text are:

$$\alpha = (-4.4\%/ \mu\text{m}) \frac{w' - w''}{2} - 0.31\%, \quad (\text{D3})$$

$$A_{\text{eff}} = (23.6 \mu\text{m}^2/\mu\text{m}) \frac{w' - w''}{2} + 4.0 \mu\text{m}^2. \quad (\text{D4})$$

APPENDIX E: COHERENCE

After calibrating the position of the ground and excited states in the I - Q plane (in-phase versus quadrature components) with our single-shot readout, we calibrated a π pulse and a $\pi/2$ pulse from Rabi oscillations when driving the qubit. Energy relaxation time T_1 was obtained by applying a π pulse and measuring the relaxation of the qubit, which is then fitted to an exponential decay e^{-t/T_1} . Coherence time $T_{2,E}$ was obtained from a Hahn-echo sequence consisting of two $\pi/2$ pulses with a π pulse in between. At the sweet spot, $T_{2,E}$ is fitted with only an exponential decay $e^{-\Gamma_{2,E}^0 t}$. Away from the sweet spot, an additional Gaussian

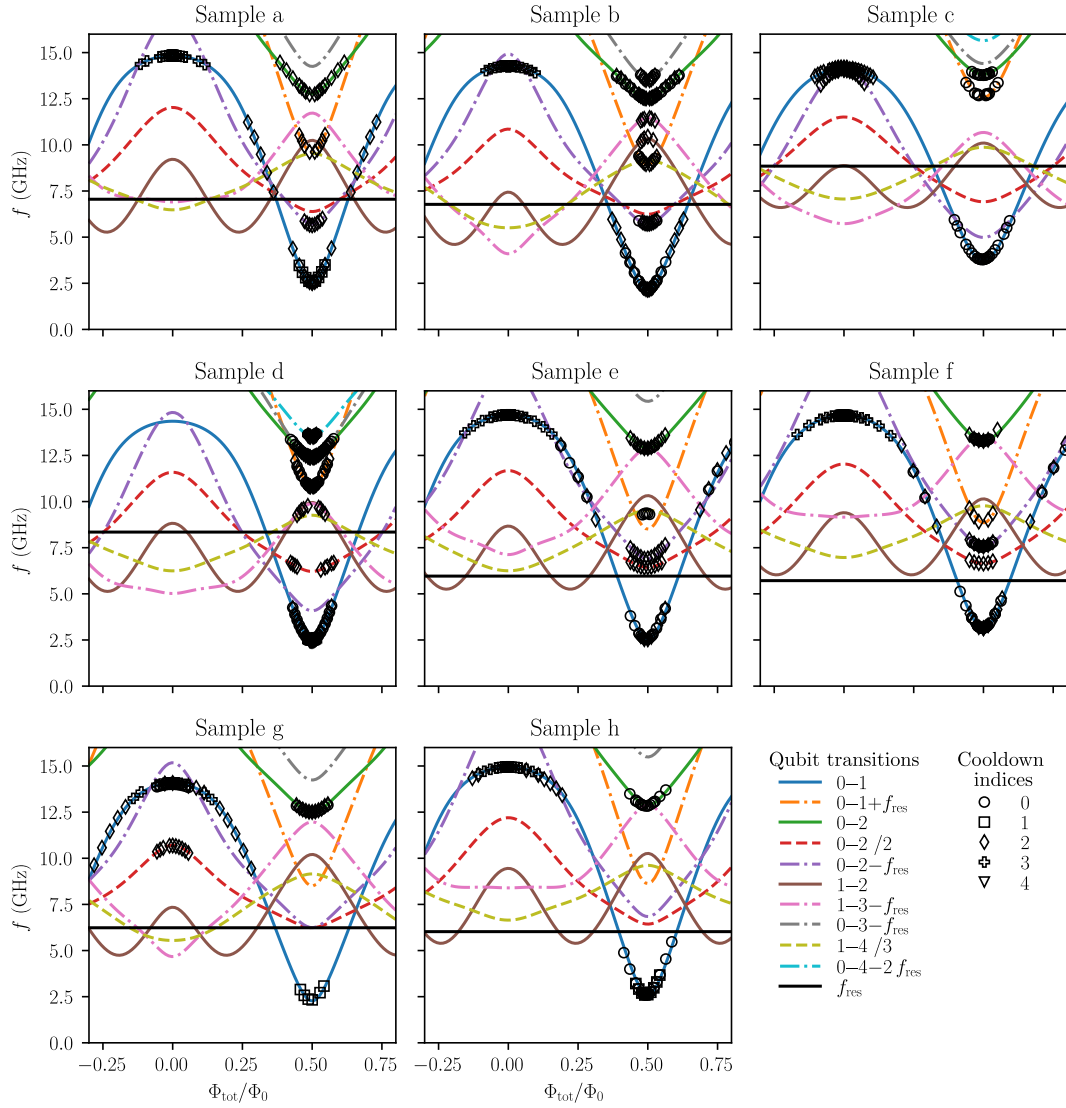


FIG. 7. Spectra with fits of all eight samples shown in the main text. Markers depict the transition frequencies extracted from two-tone spectroscopy, with marker type indicating different cooldowns. Colored solid lines represent the main transition frequencies, dashed lines represent multiphoton transitions, and dash-dotted lines represent transitions mediated by resonator photons. Black solid lines represent the readout resonator frequency f_{res} of each sample.

decay $e^{-(\Gamma_{2,E}^{\Phi} t)^2}$ is fitted on top of the exponential decay, and $T_{2,E}$ is then calculated as

$$T_{2,E} = \frac{\sqrt{(\Gamma_{2,E}^0)^2 + 4(\Gamma_{2,E}^{\Phi})^2} - \Gamma_{2,E}^0}{2(\Gamma_{2,E}^{\Phi})^2}. \quad (\text{E1})$$

The values of T_1 and $T_{2,E}$ were measured around zero field (Fig. 3 of the main text), as well as at the sweet spot over 50 h [Fig. 9(a)] and 23 h [Fig. 9(b)]. These measurements over time were performed interleaved, i.e., each few-minute-long measurement alternated between a T_1 sequence and a Hahn-echo sequence. Both samples show large fluctuations of their coherence times, which appear to be correlated between T_1 and $T_{2,E}$.

APPENDIX F: FLUX ESCAPE

In order to confirm the absence of the flux-escape phenomenon previously reported in Ref. [19], we repeated two-tone spectroscopy over two days. The trace, shown in Fig. 10, does not show any flux escape over 50 h. The measurement was performed on a sample fabricated in a different batch with similar evaporation parameters to the samples in the main text.

APPENDIX G: FLUX CROSSTALK

Let us take two fluxoniums separated by a distance d (typically $d \approx 500 \mu\text{m}$ in a quantum processor) and each of them at a distance d_{FL} from their flux line, as represented in

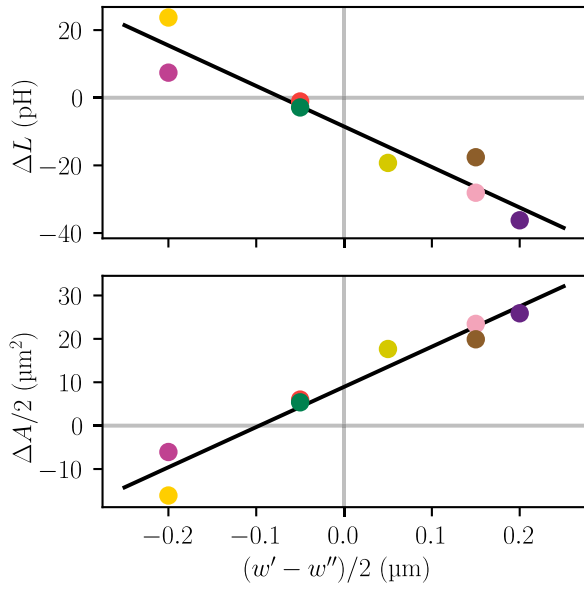


FIG. 8. Inductance and area difference between the loops as a function of the asymmetry $(w' - w'')/2$. The inductance is calculated by assuming a sheet inductance of $10 \text{ pH}/\square$ for the aluminum ring. The $\Delta A/2$ value is calculated from the measured A_{eff} and α and fits with the expected variation.

Fig. 11. For the regular one-loop fluxonium and the gradiometric fluxonium cases, we can calculate the flux Φ_A seen by the qubit closer to the flux line and the flux Φ_B seen by the qubit further from the flux line, for a given current I .

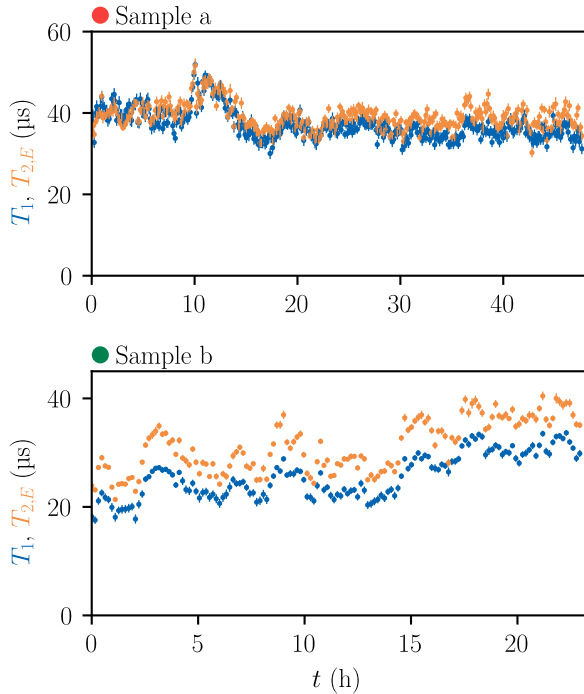


FIG. 9. Interleaved T_1 and $T_{2,E}$ coherence times at the sweet spot for samples a and b π -locked, over time.

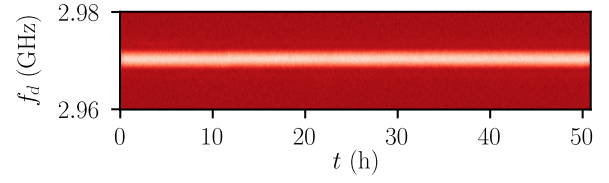


FIG. 10. Response of the resonator for an additional sample, when the qubit is driven at frequency f_d , in standard two-tone spectroscopy. The qubit was biased to the sweet spot and measured over 50 h.

For one-loop fluxoniums, following the Biot-Savart law we get

$$\Phi_A \propto B(d_{\text{FL}}) \propto \frac{1}{d_{\text{FL}}^2},$$

$$\Phi_B \propto B(d + d_{\text{FL}}) \propto \frac{1}{(d + d_{\text{FL}})^2}.$$

Therefore, the flux crosstalk, characterized by the ratio $\beta = \Phi_B/\Phi_A$, is $\beta \approx (d_{\text{FL}}/d)^2$, about 4×10^{-4} for $d = 500 \mu\text{m}$ and $d_{\text{FL}} = 10 \mu\text{m}$. In contrast, for gradiometric fluxoniums what matters is the magnetic field gradient, and following the same argument we get

$$\Phi_A \propto \frac{dB}{dr}(d_{\text{FL}}) \propto \frac{1}{d_{\text{FL}}^3},$$

$$\Phi_B \propto \frac{dB}{dr}(d + d_{\text{FL}}) \propto \frac{1}{(d + d_{\text{FL}})^3}.$$

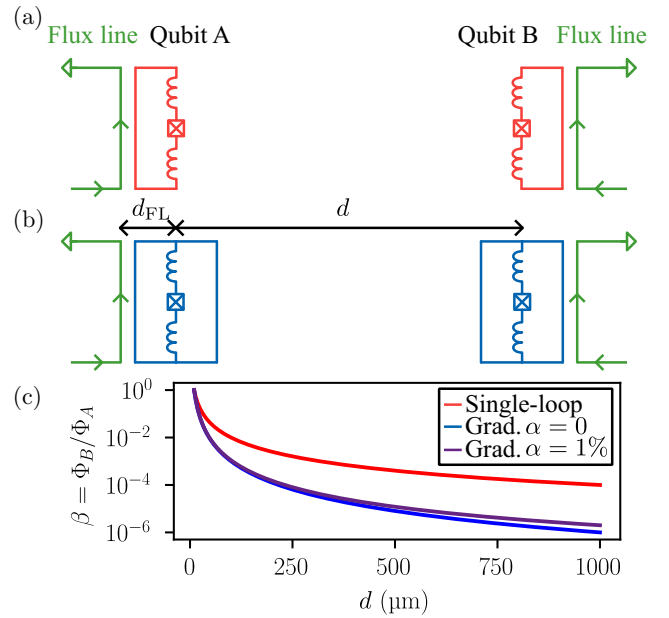


FIG. 11. Generic diagram for a two-qubit chip. (a) Two single-loop fluxonium qubits. (b) Two gradiometric fluxonium qubits. (c) Variation of the ratio $\beta = \Phi_B/\Phi_A$ for single-loop (red) and gradiometric with $\alpha = 0$ (blue) and $\alpha = 1\%$ (purple) fluxoniums.

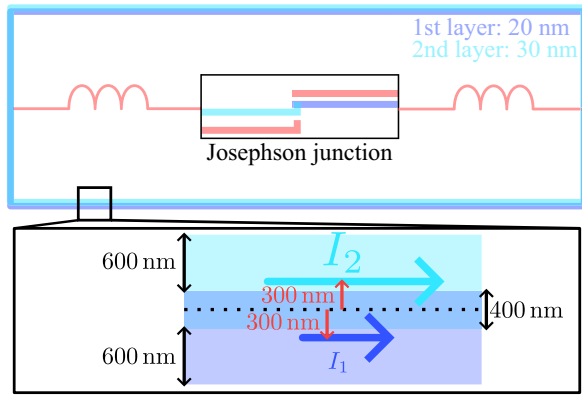


FIG. 12. Sketch of the device with the aluminum layers in different colors to illustrate their different thicknesses. The arrows in the enlargement illustrate the positions of the persistent current centerlines in each layer. The length of each arrow gives the magnitude of the current.

The flux crosstalk ratio is then $\beta \approx (d_{\text{FL}}/d)^3$, about 8×10^{-6} for $d = 500 \mu\text{m}$ and $d_{\text{FL}} = 10 \mu\text{m}$. In summary, we gain about two orders of magnitude on the crosstalk because of the gradiometric nature of the devices. Additionally, we gain three orders of magnitude on the current needed to bias each qubit to its sweet spot.

APPENDIX H: AREA ASYMMETRY

In order to fabricate the superconductor-insulator-superconductor Josephson junction in the middle of the qubit, we evaporate two layers of aluminum, with tilt angles -31° and 31° . This shadow evaporation creates a stack of 20-nm-thick and 30-nm-thick aluminum layers, respectively, creating two paths for the supercurrent with different kinetic inductances, as illustrated in Fig. 12. We estimate, from the empirical scaling of Ref. [30], the sheet inductance of each layer to be 2.1 and 0.9 pH/ $\square$, respectively. The current is thus twice as large in the 30-nm-thick layer as in the 20-nm-thick layer: $I_2/I_1 = 2$. The aluminum layers are 600 nm apart, with 400 nm overlap, i.e., the middle of the thicker layer is $\delta = 300$ nm away from the middle of the bilayer stack. Correspondingly, the effective offset for the persistent current path is $\delta(1 - I_1/I_2)/(1 + I_1/I_2) = 100$ nm, close to the value we find experimentally.

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