

Superconducting flux qubit with ferromagnetic Josephson π -junction operating at zero magnetic field

Corresponding Author: Dr Sunmi Kim

Version 0:

Decision Letter:

Dear Dr. Kim,

Thank you for submitting your manuscript, "Superconducting flux qubit with ferromagnetic Josephson π junction operating at zero magnetic field", to Communications Materials. It has now been seen by 2 referees, whose comments are appended below. You will see that while they find your work of interest, some important points are raised. We are interested in the possibility of publishing your study in Communications Materials, but would like to consider your response to these concerns in the form of a revised manuscript before we make a decision on publication.

We therefore invite you to revise and resubmit your manuscript, taking into account the points raised.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

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-A response letter with a point-by-point reply to each of the referee comments and a description of changes made. Please include the complete referee report in the response letter. Please note that the response letter must be separate to the cover letter to the editors.

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Please do not hesitate to contact me if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Nicola Poccia, PhD
Editorial Board Member
Communications Materials
orcid.org/0000-0001-7982-0113

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

In the manuscript "Superconducting flux qubit with ferromagnetic Josephson junction operating at zero magnetic field" the Authors report on the observation of microseconds coherence times in a flux qubit comprising a pi-junction. The paper is interesting and well-written. Furthermore, the clear observation of quantum coherent dynamics in such a system is impressive and it is of interest not only for the superconducting qubits community but more in general for condensed matter physicists. I am therefore in favor of its publication in Communications Materials.

However, before publication, the Authors should consider the following questions.

1) It is unclear why the two flux qubits have approximately the same frequency, in spite of having different circuit schemes and in spite of the fact that the pi-junction differs significantly from conventional junctions. To clarify this point, the Authors should briefly discuss the Hamiltonians of the two qubits presenting a theoretical estimate of the fundamental frequencies, recalling the results of L. V. Abdurakhimov et al. Appl. Phys. Lett. 115, 383 262601 (2019) and providing the formula used for the fit.

2) The Authors trace the difference in coherence times back to the metallic nature of the junction referring to T. Kato et al. Phys. Rev. B 76, 172502 (2007). While, it is clear that the metallic nature of the pi junction is detrimental for coherence, the role of the different noise sources is not properly discussed. In particular, by looking at the data I see that in the standard flux qubit they find $T_2 > T_1$ indicating the presence of substantial dephasing, while in the pi-flux qubit $T_2 \sim T_1$ possibly indicating smaller dephasing rate as compared to relaxation. Can the Authors provide a possible explanation of this result? In the text (e.g. line 223) they speak about "gapless quasi-particle" induced dissipation but this is yet another possible decoherence channel. Dielectric losses are present in both devices but they could couple differently. A synthetic recap of active decoherence channels in the two devices would be useful.

3) Related to the previous question. Apart from yielding a pi-state, the ferromagnetic nature of the junction is assumed to

have no effects and very little is said by the Authors on the junction's magnetization and on the possibility that the magnetization dynamics or fluctuations influences the qubit state. Looking at the data in Figure 3, however my impression is that in the pi-junction there are significant quasi-static fluctuations yielding experimental points scattered in the plane. Such kind of noise may come from magnetization fluctuations or slow movement of magnetic domains. Can the Authors comment on this point?

4) As I already said the paper is well-written and interesting, however it lacks some comment on potential fabrication issues, in particular to explain why it was not used an insulating junction and to provide an outlook on potential future developments.

Reviewer #2 (Remarks to the Author):

The manuscript by S. Kim et al. reports on the realization and experimental characterization of flux qubits comprising ferromagnetic Josephson junctions as pi-phase shifters, allowing for qubit operations at zero-flux bias. The results reported in the manuscript are compared to more standard flux qubits, which do not employ the ferromagnetic pi-shifter junction in the loop. This kind of comparison allows to discuss about coherence properties of the ferromagnetic flux qubit, where the main dissipation channel has been identified in the quasiparticles, exited in the ferromagnetic barrier of the pi-junction.

In my opinion, the topic of the manuscript is timely and quite interesting, the analysis is well supported and the paper is well written. Therefore, I recommend publication of the manuscript in Communications Materials, nevertheless I think a considerable revision is necessary.

Specifically, the idea of the use of a ferromagnetic junction as a pi-shifter in a phase or flux qubit is not new, and first experimental results are reported in Ref. 19 of the manuscript, for instance. I think the Authors should address more clearly the novelty of their work, in terms of choice of materials, qubit layout and so on.

For instance, even if zero-flux bias qubit operations have been demonstrated, the Authors should comment on how tuning of the qubit frequency can be achieved, which is particularly relevant for two-qubits gates. Is it possible to perform two-qubits gates without applying external magnetic field? More in general, the use of ferromagnetic junctions in a qubit can be useful for alternative control (and therefore alternative layouts) of the qubit operations (see for instance E. Goldobin et al., Appl. Phys. Lett. 102, 242602 (2013), H. G. Ahmad et al., Phys. Rev. B 105, 214522 (2022), D. Razmadze et al., Phys. Rev. B 107, L081301 (2023)), not only to enhance device coherence (indeed in the present work, the coherence times of the ferromagnetic flux qubit are one order of magnitude lower with respect to the standard flux qubit).

Concerning the coherence times, in both cases (flux qubit with and without the ferromagnetic junction in the loop), T_1 and T_2 are almost the same, while T_2 in the optimal case is expected to be twice T_1 . Can the Authors comment on this?

From the comparison between the measured coherence times on the two types of flux qubits, it turns out that quasiparticles arising from the metallic ferromagnetic barrier constitute the main dissipation channel and the main reason for the reduced coherence times, which is also quite expected. The Authors also stress that the use of a ferromagnetic insulator can be helpful in reducing the effect of quasiparticles. In this sense, I think the Authors should provide more insights on which kind of ferromagnetic junctions can be employed, given the fact that different types of ferromagnetic junctions with an insulating layer have been reported in literature (T. Larkin et al., Appl. Phys. Lett. 100, 222601 (2012), H. G. Ahmad et al., Phys. Rev. Appl. 13, 014017 (2020), L. Ai et al., Nat. Commun. 12, 6580 (2021), A. Vettoliere, et al., Appl. Phys. Lett. 120, 262601 (2022)).

Other minor comments:

- Did the Authors measure the R_n resistance from the 4.2K measurements? Why they didn't use this value for the estimation of the coherence time?
- The Authors mention that the third junction in the loop has a smaller area, what is the reason for this choice?

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Author Rebuttal letter: The author's response to these comments can be found at the end of this file.

Version 1:

Decision Letter:

<*** REMEMBER TO ATTACH AIP TABLE ***>

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Dear Dr Kim,

Your manuscript titled "Superconducting flux qubit with ferromagnetic Josephson π -junction operating at zero magnetic field" has now been seen again by our referees, whose comments appear below. In light of their advice I am delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Materials.

We therefore invite you to edit your manuscript to comply with our journal policies and formatting style in order to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if the process may take longer.

Best regards,

Nicola Poccia, PhD
Editorial Board Member
Communications Materials
orcid.org/0000-0001-7982-0113

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have satisfactorily addressed all questions and comments posed by the referees. I recommend the manuscript for publication in Communications Materials.

Reviewer #2 (Remarks to the Author):

In my opinion, the Authors have clearly addressed the concerns of both the Referees, therefore I recommend the publication of the manuscript in Communications Materials.

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Response to Reviewer #1

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We thank you very much for your interest in our manuscript and your valuable comments. Our point-by-point reply to your comments and revised points are described below. We sincerely hope that our responses satisfy you and that you now find our manuscript suitable for publication in Communications Materials.

1. First comment from Reviewer #1: “It is unclear why the two flux qubits have approximately the same frequency, in spite of having different circuit schemes and in spite of the fact that the pi-junction differs significantly from conventional junctions. To clarify this point, the Authors should briefly discuss the Hamiltonians of the two qubits presenting a theoretical estimate of the fundamental frequencies, recalling the results of L. V. Abdurakhimov et al. Appl. Phys. Lett. 115, 383 262601 (2019) and providing the formula used for the fit.”

Author response: Thank you very much for pointing this out.

- (1) To clarify the theoretical estimate of the fundamental frequencies, we have replaced the sentence “The qubit spectrum $\omega_{01}/2\pi$ is reproduced by the theoretical fitting curve¹³ (dash-dotted line in Fig. 2b) with the following qubit parameters: the area ratio of the small JJ relative...” with the following sentences, including the formula used for the fit, on pages 6–7 (marked in red in the manuscript).

“The dash-dotted line in Fig. 2b is the theoretical fitting curve. Following ref. 13, the transition frequency of a C-shunt flux qubit is given by

$$\hbar\omega_{10} = \Delta + \frac{2\varepsilon^2}{\Delta} \quad (1)$$

where the energy gap Δ and the flux-dependent energy shift ε are defined by

$$\Delta = \sqrt{4E_c E_J (1 - 2\alpha)} + \frac{8\alpha - 1}{4(1 - 2\alpha)} E_c \quad (2)$$

$$\varepsilon = 2\sqrt{2}\pi\alpha E_J \left(\frac{E_c}{E_J(1 - 2\alpha)} \right)^{1/4} \left(\frac{\Phi}{\Phi_0} - 0.5 \right) \quad (3)$$

Here, $E_c = e^2/2C_\Sigma$ is the effective charging energy determined by the total qubit capacitance C_Σ . Other parameters include the area ratio of the small JJ

relative...”

(2) Also, we added the following sentences on page 8 to discuss why the two flux qubits have approximately the same frequency.

“To explain why the conventional flux qubit and the π -junction qubit have similar frequencies despite their different circuit schemes, we examine the Lagrangian of the circuit in the Supplementary Information. Here, in the process of deriving the Hamiltonian of the π -junction qubit from the Lagrangian, for the π -junction with almost no phase change (i.e. the phase is fixed to π), the kinetic energy of π -junction can be ignored. Thus, the Hamiltonian and the qubit frequency of the π -junction qubit is almost same as those of the conventional flux qubits except for the phase shift of π in the potential energy. We believe that the small frequency difference between the two qubits can be attributed to the unavoidable small variation of α in the two qubits.”

(3) To discuss the Hamiltonian of the π -junction qubit, we prepared the Supplementary Information as follows:

“Let us take the qubit loop shown in the inset of Fig. 1(d). Since the Lagrangian of each junction is defined as the difference between the kinetic energy ($T = \frac{C_i \phi_0^2}{2} \dot{\delta}_i^2$) and potential energy terms ($U = E_{J,i}(1 - \cos \delta_i)$), the

Lagrangian of the whole circuit can be written as

$$\mathcal{L} = T - U$$

$$= \sum_{i=1}^3 \left(\frac{C_i \phi_0^2}{2} \dot{\delta}_i^2 - E_{J,i}(1 - \cos \delta_i) \right) + \frac{C_\pi \phi_0^2}{2} \dot{\delta}_\pi^2 - E_{J,\pi}(1 - \cos(\delta_\pi + \pi)) \quad (\text{S1})$$

where C_i is the capacitance, $\phi_0 = \Phi_0/2\pi$, Φ_0 is the superconducting flux quantum, $E_{J,i}$ is the Josephson energy given by $E_{J,i} = I_{c,i}\Phi_0/(2\pi)$, $I_{c,i}$ is the critical current, and δ_i is the dimensionless phase variable. Here, the index i labels the three conventional Josephson junctions ($i=1,2,3$), as well as π for the π -junction. Importantly, the terms that correspond to the π -junction look almost identical to those of the other junctions, except for the π -phase shift in the potential energy term. Flux quantization leads to the constraint:

$$\sum_{i=1}^3 \delta_i + \delta_\pi = \frac{2\pi\Phi_{\text{ext}}}{\Phi_0} + 2\pi n \quad (\text{S2})$$

where n is an integer. In principle, to analyze the quantum dynamics of the

different variables, we need to substitute the constraint into the Lagrangian, calculate the Hamiltonian via a Legendre transformation, introduce the quantum commutation relations and then analyze the properties and dynamics of different variables. However, we can already say something about the behavior of the variables based on the Lagrangian in Eq. (S1).

The classical ground state of the system is obtained by minimizing the potential energy. Since the π -junction's critical current is four orders of magnitude larger than those of the other junctions, its potential energy term will dominate in comparison to the other junctions. The classical ground state must therefore have $\delta_\pi \approx \pi$. Furthermore, since the capacitance C_π is comparable to those of the conventional Josephson junctions¹, the strong confinement of the variable δ_π implies that, to a very good approximation, quantum fluctuations in δ_π are negligible compared to the other phase variables δ_i . As a result, we can set $\delta_\pi = \pi$ and $\dot{\delta}_\pi = 0$ to obtain the approximate Lagrangian

$$\mathcal{L} = \sum_{i=1}^3 \left(\frac{C_i \phi_0^2}{2} \dot{\delta}_i^2 - E_{J,i} (1 - \cos \delta_i) \right) \quad (\text{S3})$$

with the flux quantization condition

$$\sum_{i=1}^3 \delta_i = \frac{2\pi\Phi_{\text{ext}}}{\Phi_0} + 2\pi n - \pi \quad (\text{S5})$$

In other words, the Hamiltonian of the π -junction flux qubit reduces to that of an equivalent circuit without the π -junction, but with half a flux quantum added to the applied flux bias.”

2. Second comment from Reviewer #1: “The Authors trace the difference in coherence times back to the metallic nature of the junction referring to T. Kato et al. Phys. Rev. B 76, 172502 (2007). While, it is clear that the metallic nature of the π junction is detrimental for coherence, the role of the different noise sources is not properly discussed. In particular, by looking at the data I see that in the standard flux qubit they find $T_2 > T_1$ indicating the presence of substantial dephasing, while in the π -flux qubit $T_2 \sim T_1$ possibly indicating smaller dephasing rate as compared to relaxation. Can the Authors provide a possible explanation of this result? In the text (e.g. line 223) they speak about “gapless quasi-particle” induced dissipation but this is yet another possible decoherence channel. Dielectric losses are present in both devices but they

could couple differently. A synthetic recap of active decoherence channels in the two devices would be useful.”.

Author response: Thank you for your valuable feedback. We agree with the referee and follow his/her suggestion. Possible noise sources are discussed below and added to the manuscript on page 9.

“Since T_2 is related to both the pure dephasing time T_ϕ and T_1 as described by $\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$, if the pure dephasing rate is negligible, T_2 becomes larger than T_1 , approaching the $2T_1$ limit. Our current results for the coherence times of the conventional flux qubit ($T_1 = 15.8 \mu\text{s}$ and $T_2 = 11.3 \mu\text{s}$) show $T_1 > T_2$, indicating the presence of substantial dephasing. The estimated T_ϕ for the conventional flux qubit is about $17.6 \mu\text{s}$. Usually, this tendency of $T_1 > T_2$ is common for conventional flux qubits (see Ref. 31). This shortened T_2 is often attributed to factors such as low-frequency charge TLS and spins.

In contrast, in the π -junction flux qubit, $T_2 \approx T_1$. Also, both the T_1 and T_2 times of the π -junction qubit are one order of magnitude smaller than the respective times for the conventional flux qubit. From their coherence times ($T_1 = 1.45 \mu\text{s}$ and $T_2 = 1.47 \mu\text{s}$), the T_ϕ is estimated to be about $2.98 \mu\text{s}$, which is shorter than that of the conventional flux qubit. The additional dephasing source, such as inelastic quasiparticle tunneling through the metallic π -junction, causes T_ϕ of the π -junction qubit to be shorter than that of the conventional flux qubit.”

3. Third comment from Reviewer #1: “Related to the previous question. Apart from yielding a pi-state, the ferromagnetic nature of the junction is assumed to have no effects and very little is said by the Authors on the junction’s magnetization and on the possibility that the magnetization dynamics or fluctuations influences the qubit state. Looking at the data in Figure 3, however my impression is that in the pi-junction there are significant quasi-static fluctuations yielding experimental points scattered in the plane. Such kind of noise may come from magnetization fluctuations or slow movement of magnetic domains. Can the Authors comment on this point?”

Author response: Thank you for the careful observation. To address the data showing significant quasi-static variations in coherence time for π -junction qubits, we agree with the referee’s opinion and have added the following sentence on page 10:

“Furthermore, as shown in Figure 3(c) and (d), the experimental data points exhibit large deviations from the fitting curve, indicating significant quasi-static fluctuations. Interestingly, the noise appears to be stronger at longer delays, which is unusual. This suggests that there might be an additional noise source affecting the data variability in π -junction qubit. One possible cause of this fluctuation could be magnetization fluctuations or slow movement of magnetic domains in the π -junction. However, further investigation is required to confirm this hypothesis.”

4. Fourth comment from Reviewer #1 : “As I already said the paper is well-written and interesting, however it lacks some comment on potential fabrication issues, in particular to explain why it was not used an insulating junction and to provide an outlook on potential future developments.”

Author response: Thank you for your constructive comments. In response to the referee's suggestion, we have added the following statement on page 13:

“In this work, we prioritized implementing a flux qubit with a well-established S/F/S structure that reliably achieves a stable π -state²⁴ and focused on demonstrating flux bias-free operation. This study is highly significant, as it is the first to experimentally demonstrate a flux qubit with SFS π -junction operating without flux bias.

Based on the π -junction qubit fabrication techniques we established in this experiment, we are considering incorporating recent advances such as S/I/F/S³³⁻³⁶ and S/ferromagnetic insulator (FI) (e.g., GdN)/S junctions^{37, 38} in future research. This approach holds promise for further improving the performance and understanding of qubit systems.”

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Response to Reviewer #2

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We would like to thank you for the careful reading of the manuscript and your valuable comments. Our point-by-point reply to your comments and revised points are described below. We sincerely hope that our responses satisfy you and that you now find our manuscript suitable for publication in Communications Materials.

5. First comment from Reviewer #2: “Specifically, the idea of the use of a ferromagnetic junction as a π -shifter in a phase or flux qubit is not new, and first experimental results are reported in Ref. 19 of the manuscript, for instance. I think the Authors should address more clearly the novelty of their work, in terms of choice of materials, qubit layout and so on.”

Author response: Thank you for your valuable comments. To describe the novelty of our work, we have added the following statement on page 13.

“Unlike the phase qubit studied in Ref. 19, reporting clear coherence properties such as T_1 and T_2 for a flux qubit that incorporates a π -junction is a novel result. Additionally, while Shcherbakova and colleagues have attempted to implement π -junctions in flux qubits (in Ref. 20), they have not confirmed flux bias-free operation or measured T_1 . Therefore, experimentally demonstrating flux bias-free operation of a flux qubit and the clear role of the π -junction in determining the coherence properties for the first time is a significant step. By fabricating the π -junction using the same NbN-based electrodes in the qubit structure, we are able to construct monolithic quantum circuits, which may have advantages for large-scale integrated circuits”

6. Second comment from Reviewer #2: “For instance, even if zero-flux bias qubit operations have been demonstrated, the Authors should comment on how tuning of the qubit frequency can be achieved, which is particularly relevant for two-qubits gates. Is it possible to perform two-qubits gates without applying external magnetic field? More in general, the use of ferromagnetic junctions in a qubit can be useful for alternative control (and therefore alternative layouts) of the qubit operations (see for instance E. Goldobin et al., Appl. Phys.

Lett. 102, 242602 (2013), H. G. Ahmad et al., Phys. Rev. B 105, 214522 (2022), D. Razmadze et al., Phys. Rev. B 107, L081301 (2023)), not only to enhance device coherence (indeed in the present work, the coherence times of the ferromagnetic flux qubit are one order of magnitude lower with respect to the standard flux qubit)."

Author response: Thank you for these insightful comments. Regarding frequency tuning, it depends on the intended coupling method and configuration. If the configuration is the same as the fixed transmon coupling, a two-qubit gate can be implemented without an external magnetic field. Also thank you for the comments on the use of ferromagnetic junction in qubits and other alternative control of qubit operations. We have added the references with the following description on page 14.

"It is also worth noting that the use of ferromagnetic junctions in qubits can be useful for alternative control (and therefore alternative layouts) of qubit operations⁴⁰⁻⁴²."

7. Third comment from Reviewer #2: "Concerning the coherence times, in both cases (flux qubit with and without the ferromagnetic junction in the loop), T_1 and T_2 are almost the same, while T_2 in the optimal case is expected to be twice T_1 . Can the Authors comment on this?"

Author response: Thank you for the valuable feedback. We have added a discussion about the coherence times and possible noise sources on pages 9-10. We also include the new text below.

"Since T_2 is related to both the pure dephasing time T_ϕ and T_1 as described by $\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$, if the pure dephasing rate is negligible, T_2 becomes larger than T_1 , approaching the $2T_1$ limit. Our current results for the coherence times of the conventional flux qubit ($T_1 = 15.8 \mu\text{s}$ and $T_2 = 11.3 \mu\text{s}$) show $T_1 > T_2$, indicating the presence of substantial dephasing. The estimated T_ϕ for the conventional flux qubit is about $17.6 \mu\text{s}$. Usually, this tendency of $T_1 > T_2$ is common for conventional flux qubits (see Ref. 31). This shortened T_2 is often attributed to factors such as low-frequency charge TLS and spins.

In contrast, in the π -junction flux qubit, $T_2 \approx T_1$. Also, both the T_1 and T_2 times of the π -junction qubit are one order of magnitude smaller than the respective times for the conventional flux qubit. From their coherence times

($T_1 = 1.45 \mu\text{s}$ and $T_2 = 1.47 \mu\text{s}$), the T_φ is estimated to be about $2.98 \mu\text{s}$, which is shorter than that of the conventional flux qubit. The additional dephasing source, such as inelastic quasiparticle tunneling through the metallic π -junction, causes T_φ of the π -junction qubit to be shorter than that of the conventional flux qubit.”

8. Fourth comment from Reviewer #2: “From the comparison between the measured coherence times on the two types of flux qubits, it turns out that quasiparticles arising from the metallic ferromagnetic barrier constitute the main dissipation channel and the main reason for the reduced coherence times, which is also quite expected. The Authors also stress that the use of a ferromagnetic insulator can be helpful in reducing the effect of quasiparticles. In this sense, I think the Authors should provide more insights on which kind of ferromagnetic junctions can be employed, given the fact that different types of ferromagnetic junctions with an insulating layer have been reported in literature (T. Larkin et al., Appl. Phys. Lett. 100, 222601 (2012), H. G. Ahmad et al., Phys. Rev. Appl. 13, 014017 (2020), L. Ai et al., Nat. Commun. 12, 6580 (2021), A. Vettoliere, et al., Appl. Phys. Lett. 120, 262601 (2022)).”

Author response: Thank you for these constructive comments. This response partially overlaps with the response to reviewer #1's fourth comment. We added the suggested references and comments as appropriate on page 13, as shown below.

“Based on the π -junction qubit fabrication techniques we established in this experiment, we are considering incorporating recent advances such as S/I/F/S³³⁻³⁶ and S/ferromagnetic insulator (FI) (e.g., GdN)/S junctions^{37, 38} in future research. This approach holds promise for further improving the performance and understanding of qubit systems.”

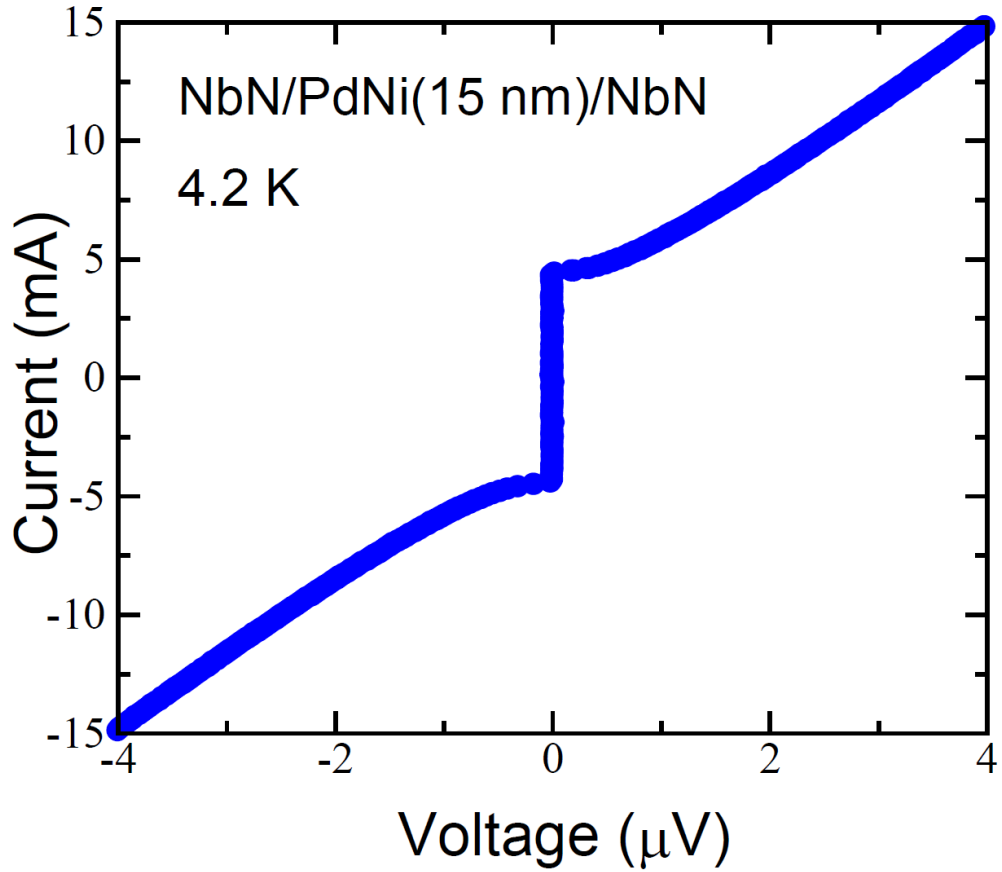
9. Fifth comment from Reviewer #2: “Other minor comments:
(1) Did the Authors measure the R_n resistance from the 4.2K measurements? Why they didn't use this value for the estimation of the coherence time?

Author response: Each response is as follows.

- As suggested, we used the R_n from the 4.2 K measurements for the estimation of the coherence time. The detailed information is described

in the Supplementary Information as follows:

“For the NbN/PdNi/NbN junction with the area of $10 \times 10 \mu\text{m}^2$, we measured I-V characteristics at 4.2 K as shown in the following figure. Their critical current (I_c) and the normal resistance (R_n) are about 4.4 mA and $270.3 \mu\Omega$. The current density (J_c) of the π -junction is estimated to be about 4.4 kA/cm^2 . Considering a circular shape with a diameter of $10 \mu\text{m}$ used for a π -junction in qubit, the extracted I_c and R_n are 3.5 mA and $344.3 \mu\Omega$.”



Supplementary Figure 1. Current-voltage (I-V) characteristics of a $10 \times 10 \mu\text{m}^2$ π -junction with a 15 nm-thick PdNi interlayer measured at 4.2 K.

- By applying these values, we have modified the corresponding values, including the relaxation time, on pages 11–12 as follows (marked in red in the manuscript).

“Our NbN/PdNi/NbN π -junction is an overdamped junction with $R_{N,\pi} \approx 344.3 \mu\Omega$ and a critical current $I_{c,\pi} \approx 3.5 \text{ mA}$, which are estimated from I-V characteristics measured at 4.2 K (refer to the Supplementary Information). The obtained current density of the π -junction was 4.4 kA/cm^2 . In our case,

the condition of the qubit level splitting $\Delta \gg 2eI_{C,\pi}R_{N,\pi}$ is satisfied, allowing us to use a simple approximate expression for the relaxation time $\tau_{relax} \approx$

$\frac{\Delta}{2I_C^2 R_{N,\pi}}$,^{19, 32} where $\Delta \approx h \cdot (4 \text{ GHz})$ (with e being the elementary charge).

Here the energy $2eI_{C,\pi}R_{N,\pi} \approx h \cdot (583 \text{ MHz})$ is associated with the characteristic Josephson frequency of our NbN/PdNi/NbN π -junction. Based on these calculations, we theoretically estimate the relaxation time to be approximately $\tau_{relax} \approx 87.3 \text{ ns}$. Here $I_C \approx 210 \text{ nA}$ is the critical current of the small NbN/AlN/NbN qubit JJ (taking into account the current density obtained from the fitting parameter of qubit spectrum (59 A/cm^2) and the reduced JJ diameter due to the etching process to be $0.67 \text{ }\mu\text{m}$). It is worth noting that this estimated value is quite lower than the experimentally measured value.”

(2) The Authors mention that the third junction in the loop has a smaller area, what is the reason for this choice?”

Author response: Thank you for your comment. To answer this question and provide more information to readers, we added the following sentences on pages 16-17 with an additional reference 45 on page 20.

“Figure 1c illustrates the three-junction type of the flux qubit⁴⁵, which consists of a superconducting loop with three Josephson junctions. Here, the third junction in the flux qubit loop has a smaller area to control the anharmonicity. The ratio between the size of the smaller junction and the bigger ones, i.e. the parameter α , is typically chosen such that the effective potential energy term for the flux variable is a double-well potential, as opposed to the single-well potential that is typical for phase qubits.”

Added reference:

45. Mooij, J. E. et al., Josephson Persistent-Current Qubit, *Science* **285**, 1036, (1999).