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On-chip digital readout of a superconducting qubit using a Josephson Digital Phase Detector

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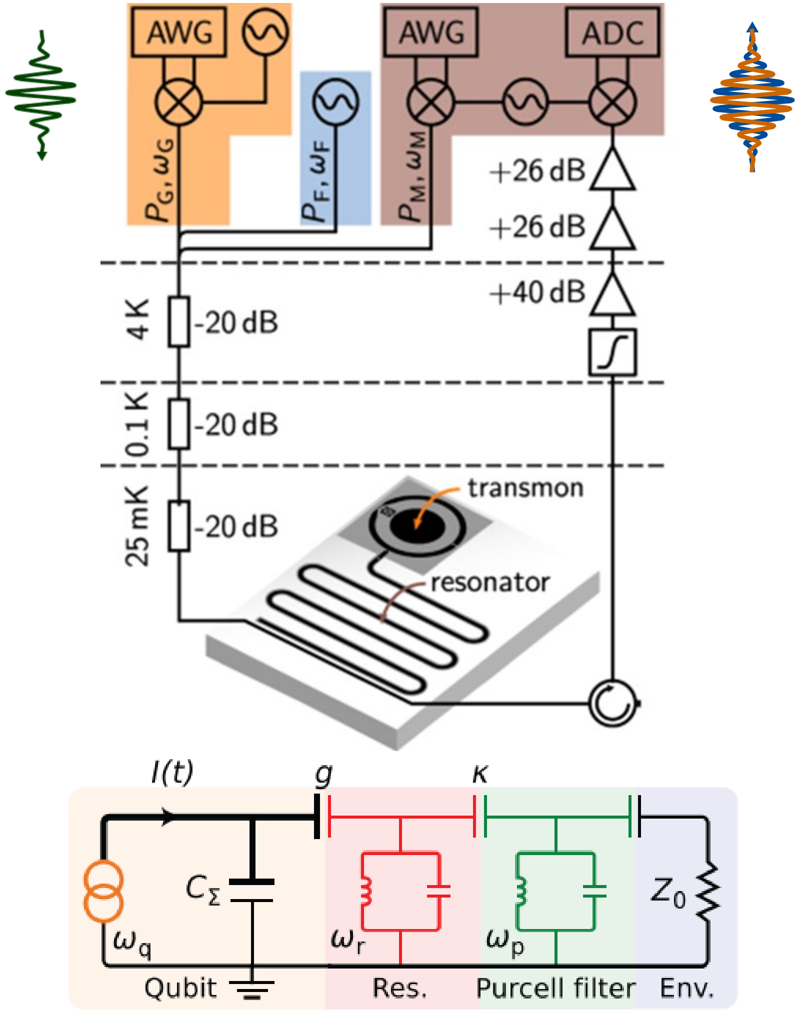
Demand for fast and high-fidelity readout

1. A **scalable** physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence time
4. A “universal” set of quantum gates
5. A qubit-specific **measurement** capability

- Error thresholds for fault tolerant QC: $\varepsilon_{measurement} \leq 0.5\%$
- Fast to not degradate the qubit state

Martinis, J. npj Quantum Inform. 1, 15005 (2015).
DiVincenzo, David P, Fortschr. Phys., vol. 48, no. 9-11, 1

Dispersive readout and figures of merit



- Conventional method for superconducting qubits requires pulsed microwave tones generated at room temperatures
- Probing a cavity coupled to a qubit, it's possible to gain information about its state.
- The result is elaborated at RT

P. Krantz, at al., Appl. Phys. Rev. 6, 2 (2019)

State of the art of dispersive readout

- 140 ns – 99%

ARTICLE OPEN

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Transmon qubit readout fidelity at the threshold for quantum error correction without a quantum-limited amplifier

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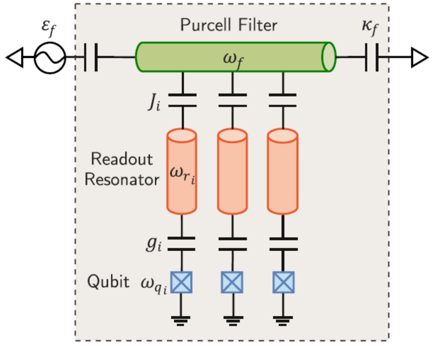

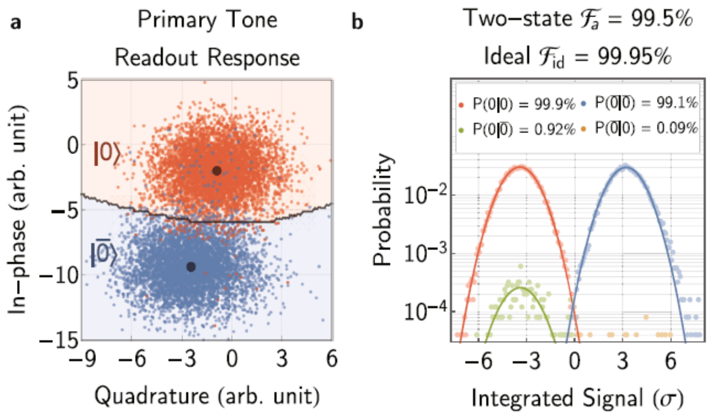

- 50 ns – 98%

Rapid High-Fidelity Single-Shot Dispersive Readout of Superconducting Qubits

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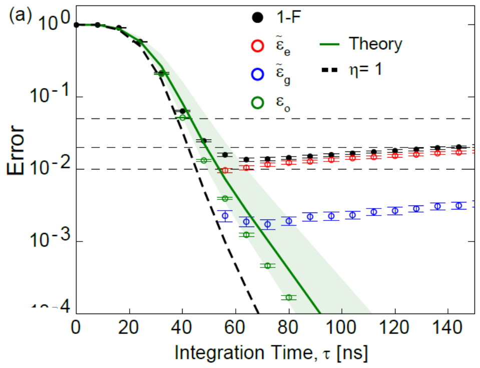

Rapid high-fidelity multiplexed readout of superconducting qubits

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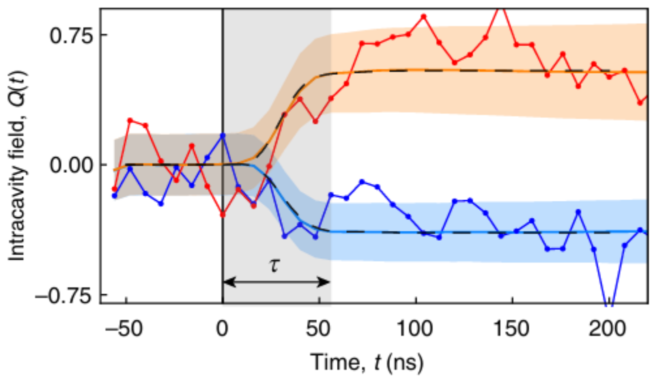
[1]*Department of Physics, ETH Zurich, CH-8093 Zurich, Switzerland*
(Dated: July 11, 2018)



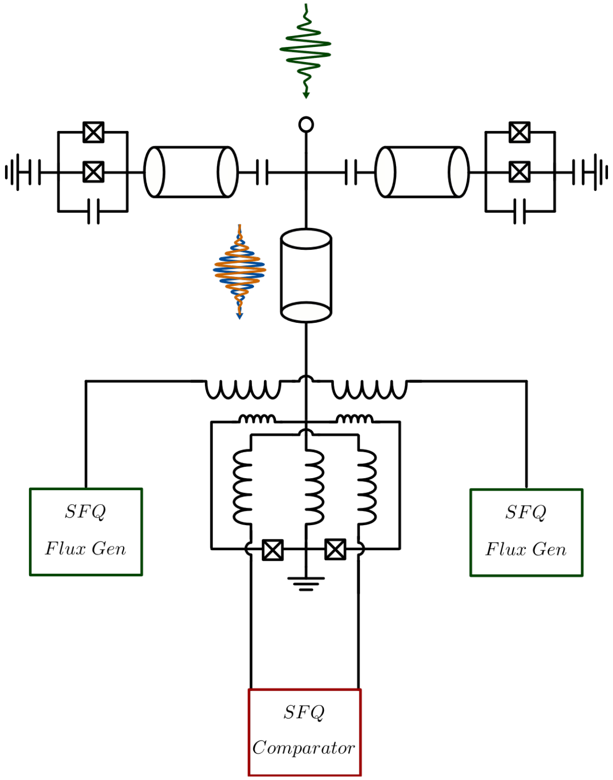
Conventional readout pros and cons

- Fast with 80-150 ns integration time
- Delivers high-fidelity >99.5%
- Demonstrated on multi-qubit chips (lower fidelity)

- Complex experimental setup: cryo and RT
- Hard to calibrate and not stable
- Not scalable to large scale
- Signal latency
- Expensive
- Not suited for high-band rate data link

SEEQC on-chip SFQ-based digital readout

1 patent, a second in preparation



Quantum-to-Digital Converter:

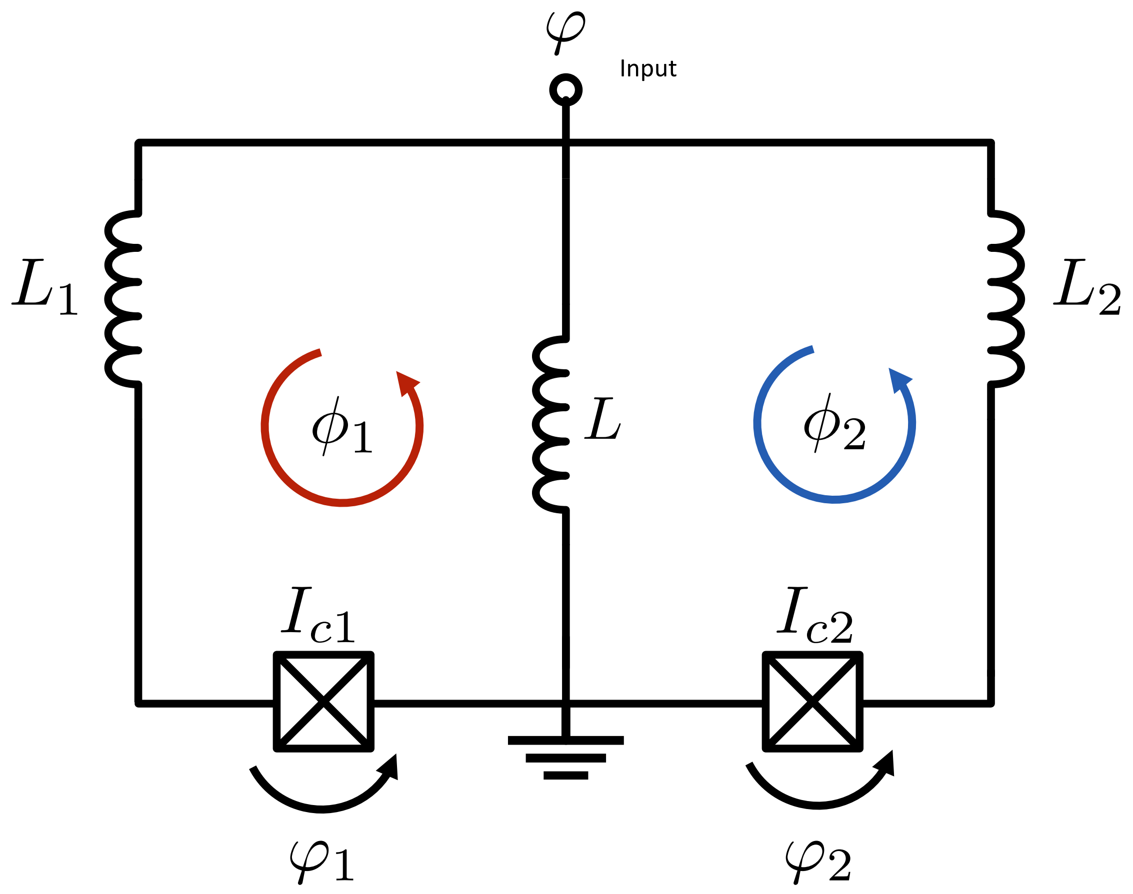
- Performs phase detection in time domain using co-located superconducting integrated circuit
- Converts output to digital SFQ data
- Readout multiplexing
- Self-contained, co-located readout circuit:
  - All readout circuits of part of DQM chip MCM-integrated with qubit chip at 20mK
  - All control signals are generated locally in DQM chip: SFQ master clock and trigger, no external signals

The big advantage in scalability comes with SFQ

	Conventional readout w JPA/TWPA	JDPD w/o SFQ circuitry	JDPD w SFQ circuitry
Cryo coax lines	3	3	0-1[c]
AWG channels	1-2[a]	3	0
CW RF source	1-2[b]	1	0-1[c]
Digitizer channels	2	2	0
DC/digital lines	0	1	2-5[d]

a. Depending if IQ-mixing or direct digital synthesis of GHz tones is used.
b. The second is needed if IQ-mixing is used for up/down-conversion of GHz tone.
c. Depending if clock is provided from room temperature or generated on-chip.
d. Depending on SFQ-circuits design.

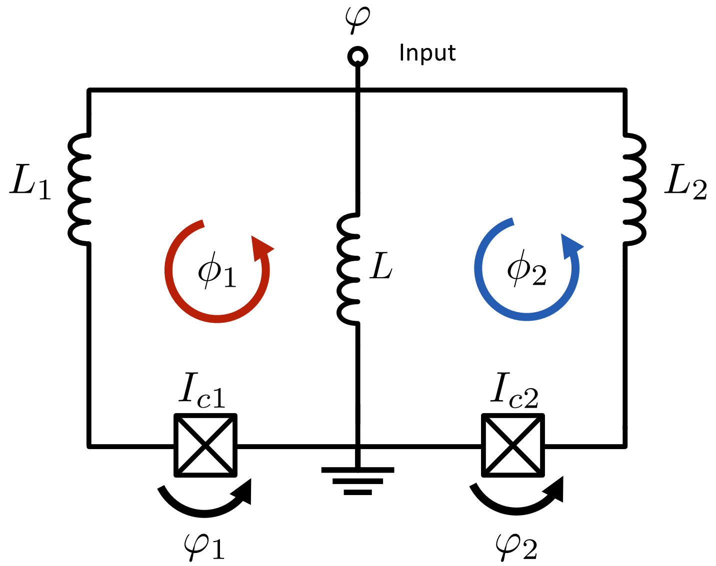
The Josephson Digital Phase Detector (JDPD) approach

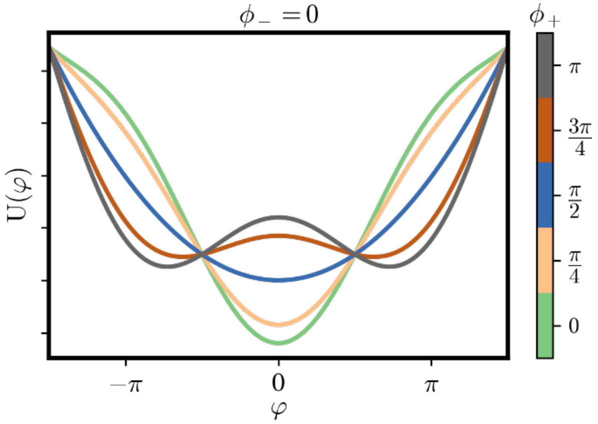


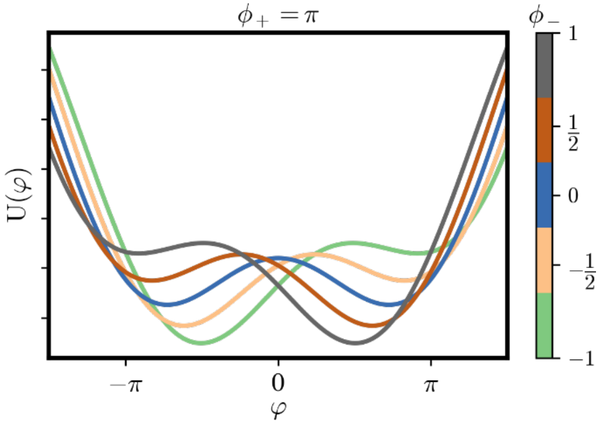
- Digital phase detection of a microwave signal at the millikelvin stage of a cryogenic fridge, reducing hardware complexity
- Works at different frequencies with respect to qubit and resonator
- Fast readout with low latency compatible with the SFQ logic
- Control over the device asymmetries thanks to two fluxes control ϕ_1 and ϕ_2

Di Palma, L., et al. ,Phys. Rev. Appl., vol. 19, no. 6, 7 June 2023
Patent pending

Device model







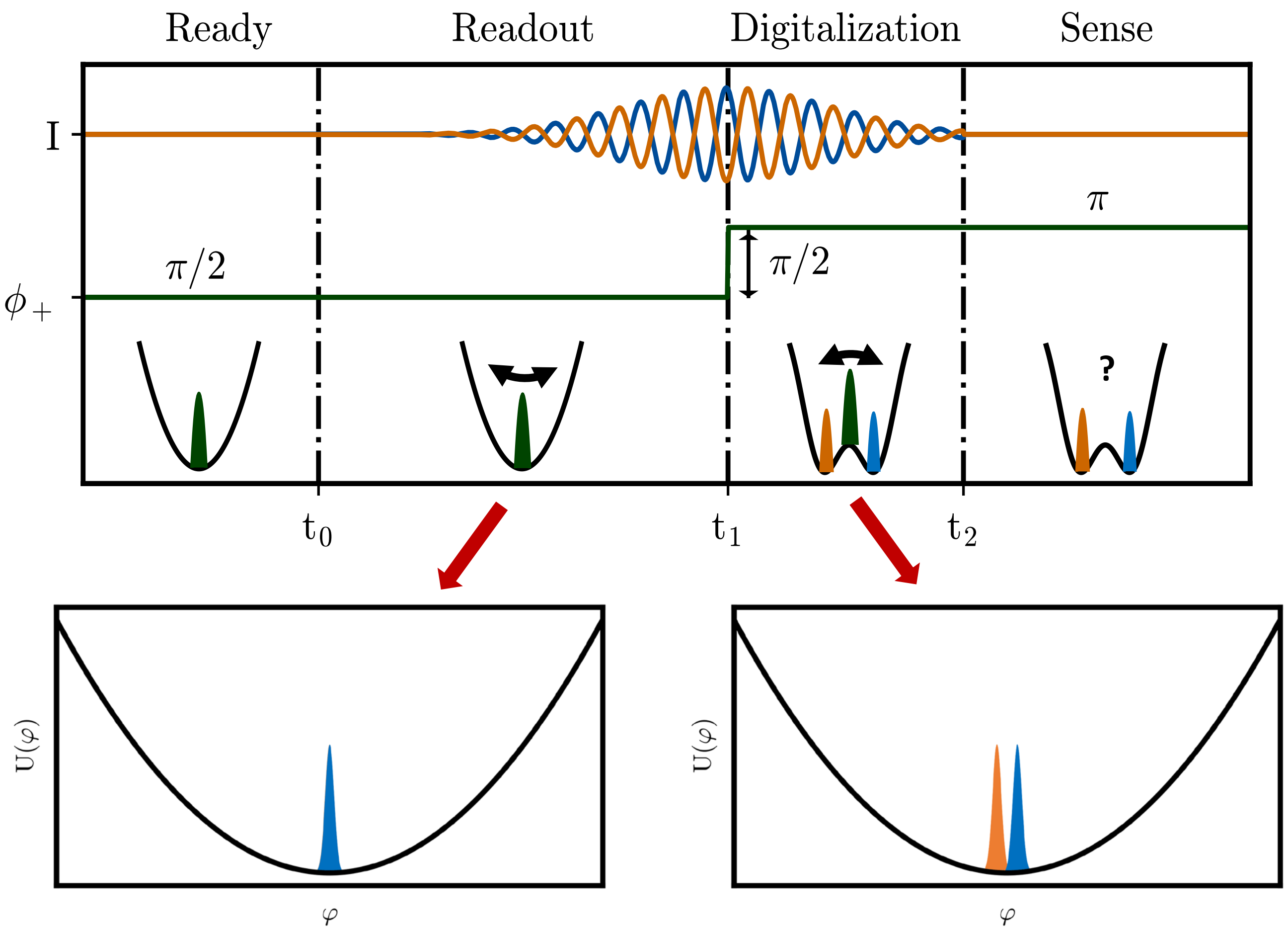
- JDPD is composed by two RF-SQUIDs that share an inductive load
- The potential energy can be written as:

$$U(\varphi) = \frac{1}{2L}\left(\frac{\Phi_0}{2\pi}\right)^2 \varphi^2 - \frac{\Phi_0}{2\pi} 2I_c \cos(\phi_- + \varphi)\cos(\phi_+)$$

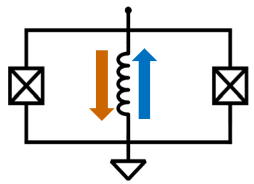
- The potential can assume single and multiple minima configuration depending on ϕ_+ and ϕ_-

Di Palma, L., et al. ,Phys. Rev. Appl., vol. 19, no. 6, 7 June 2023
Patent pending

Phase detection protocol



- Phase detection involves 4 distinct steps
- Device is initialized ("Ready step") in the harmonic configuration
- The action of the external input tone makes the wavefunction swinging around the potential minimum
- The device is diabatically flipped in the double well configuration
- The information on the phase is encoded in the wells occupation probability, corresponding to opposite currents flowing through the inductor L



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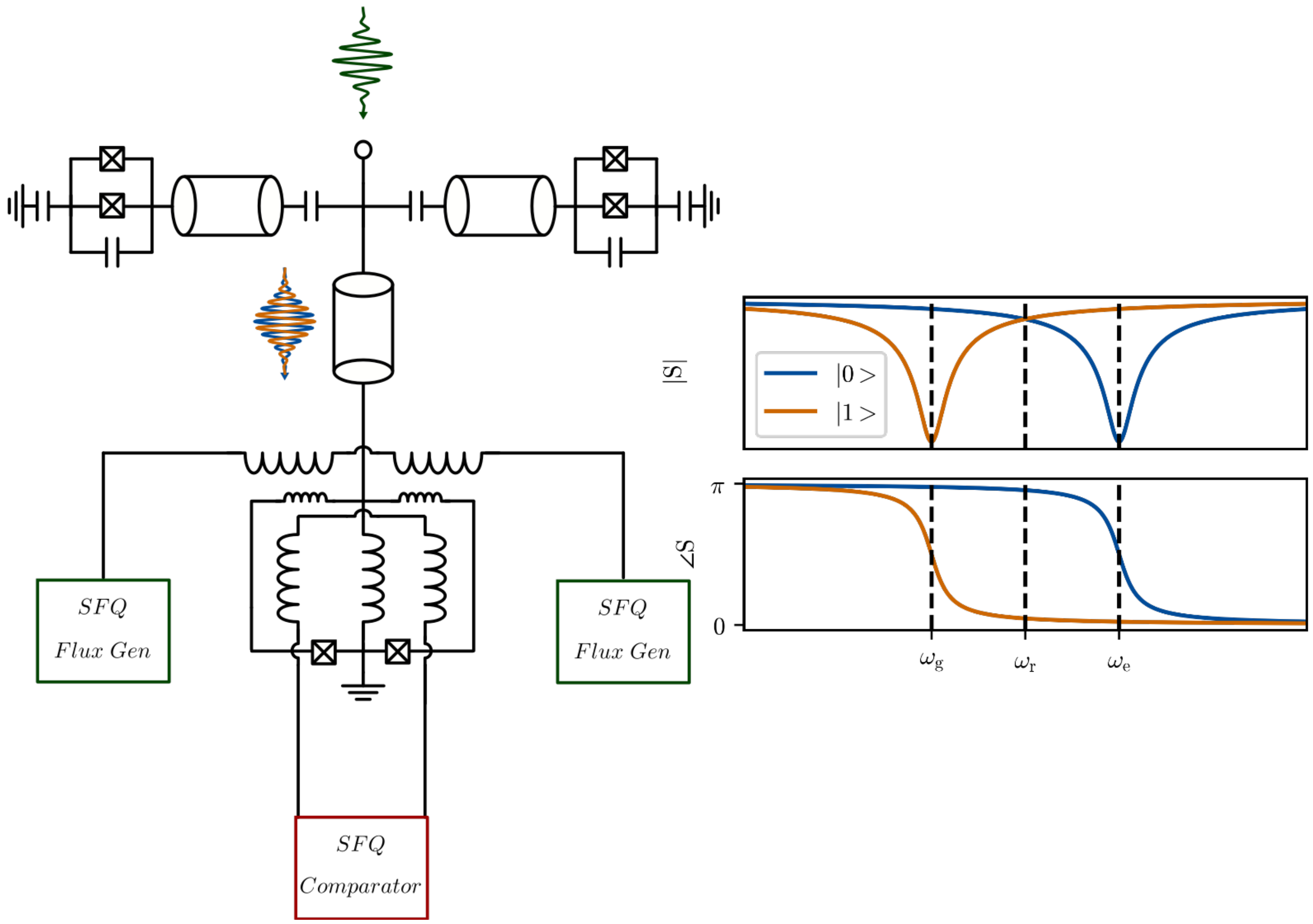
Patent pending

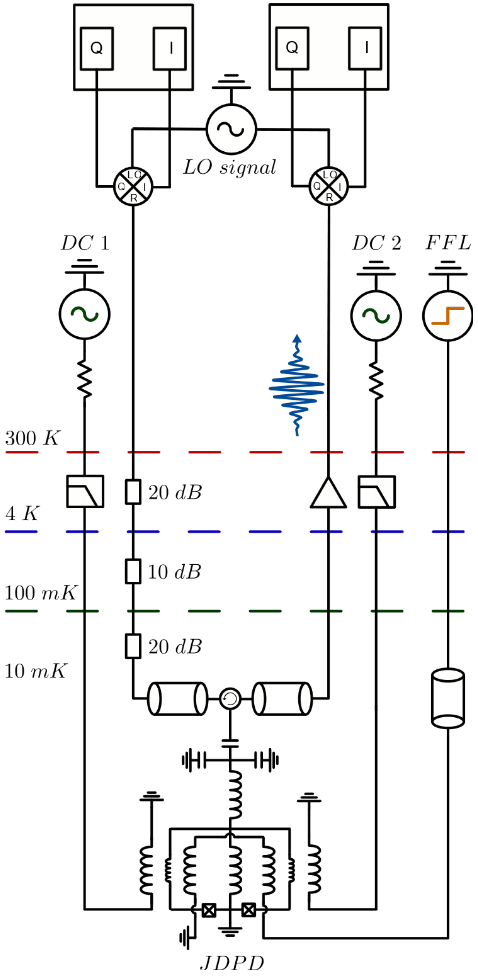
Phase detection protocol applied to qubit readout

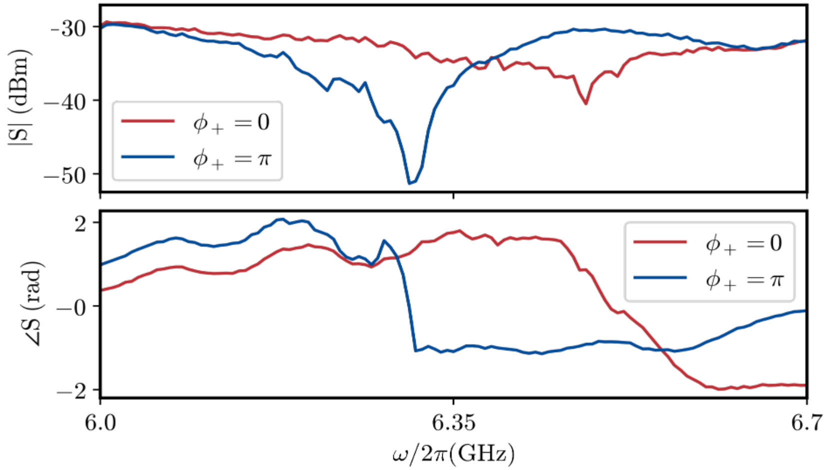


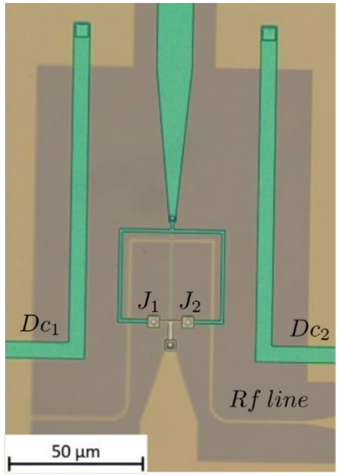
- Qubit state is encoded in phase of output readout signal, which drives the device ' s wavefunction
- The information on the qubit state, stored in the current flowing through the JDPD inductor L is converted in propagating fluxons by an SFQ comparator
- The operation to change the potential's shape can be perfomed by using an SFQ Flux generator
- The JDPD approach is suitable also for other type of quantum architecture such as spin qubits,

Di Palma, L., et al. ,Phys. Rev. Appl., vol. 19, no. 6, 7 June 2023
Patent pending

JDPD working principles verified with external RF source







- JDPD state is measured in reflection, connecting in series an LC resonator

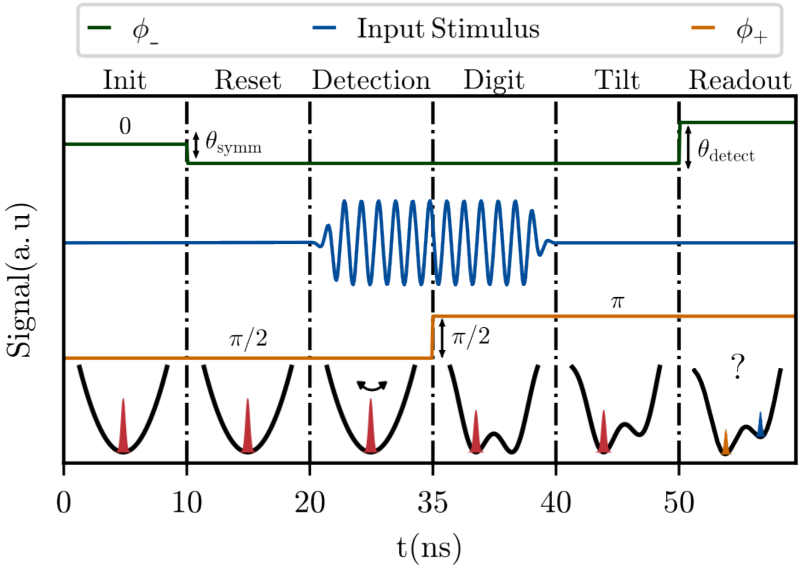
- JDPD works as a tunable inductor that changes the measured resonance frequency depending on the values of ϕ_+ and ϕ_- :

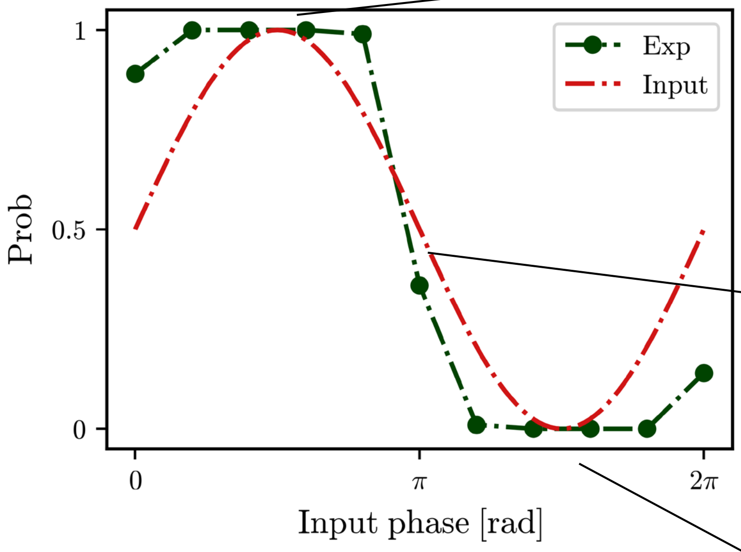
$$L_{JDPD} = \left(\frac{\Phi_0}{2\pi}\right)^2 \left[\frac{d^2U}{d\varphi^2}\right]^{-1}$$

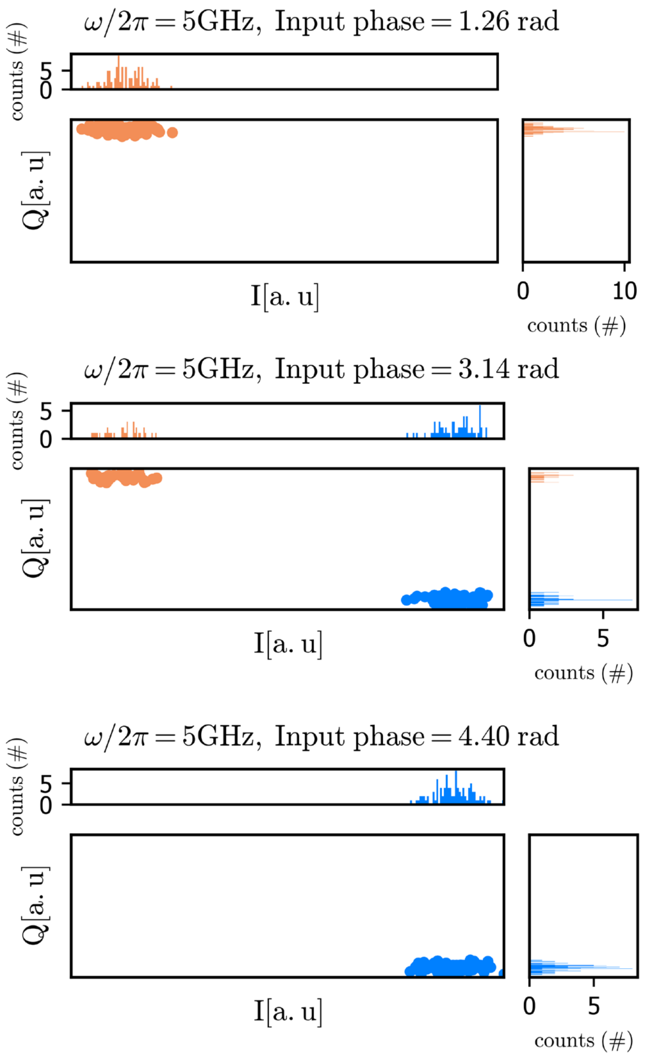
$$U(\varphi\ ) = \frac{1}{2L}\left(\frac{\Phi_0}{2\pi}\right)^2 \varphi^2 - \frac{\Phi_0}{2\pi}\, 2I_c \cos(\phi_- + \varphi)\cos(\phi_+)$$

Di Palma, L., et al. ,Phys. Rev. Appl., vol. 19, no. 6, 7 June 2023
Patent pending

Phase detection of a GHz tone in 50 ns sequence duration







Detection fidelity >99%

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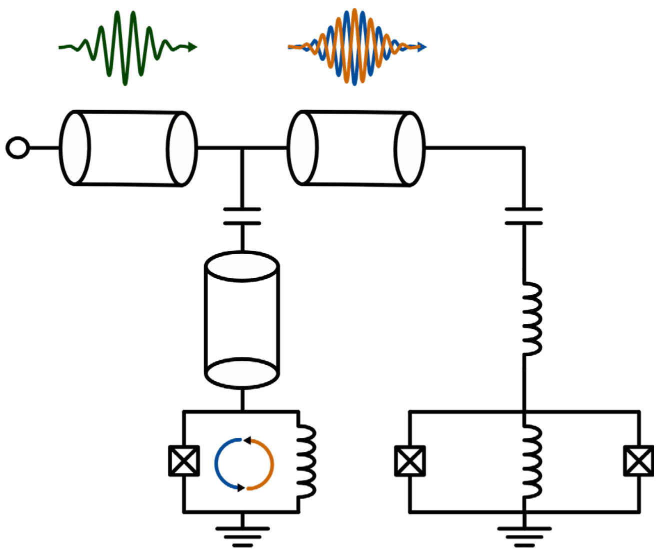
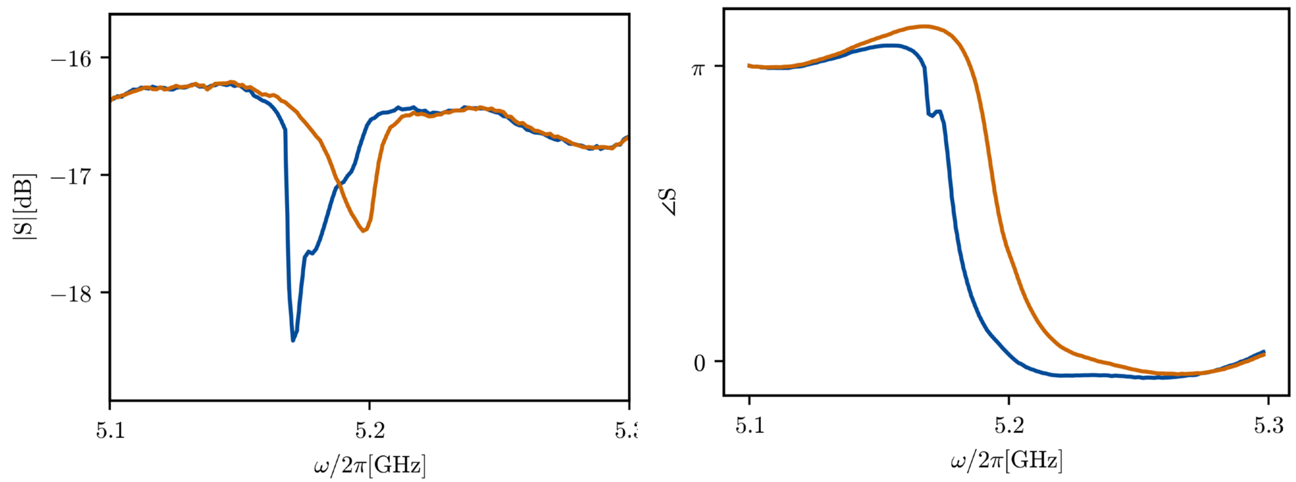
Patent pending

Idea validated with tunable Resonator



- The JDPD is connected to a tunable resonator
- The resonance frequency is adjusted by changing the flux state of a coupled RF Squid, which emulates the behaviour of the qubit
- The JDPD measures the phase response of the output tone



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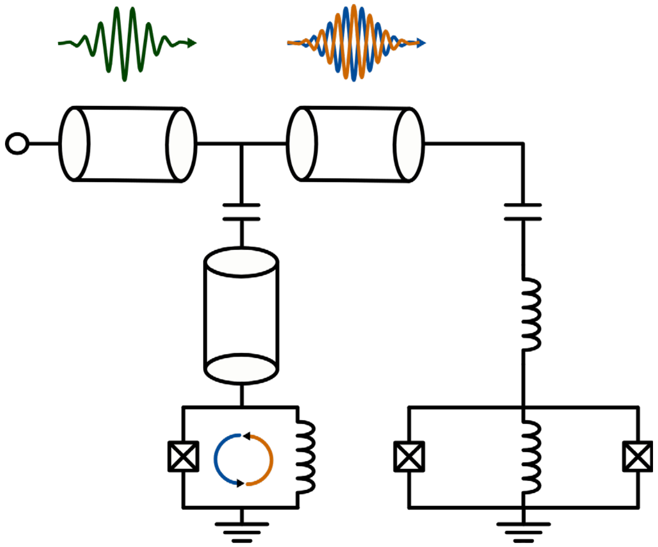
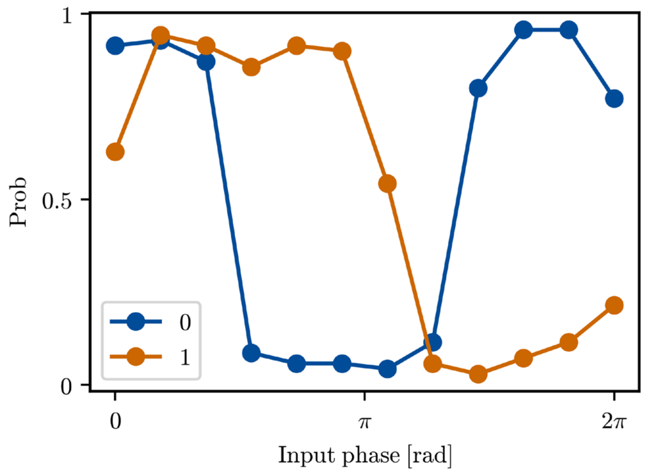
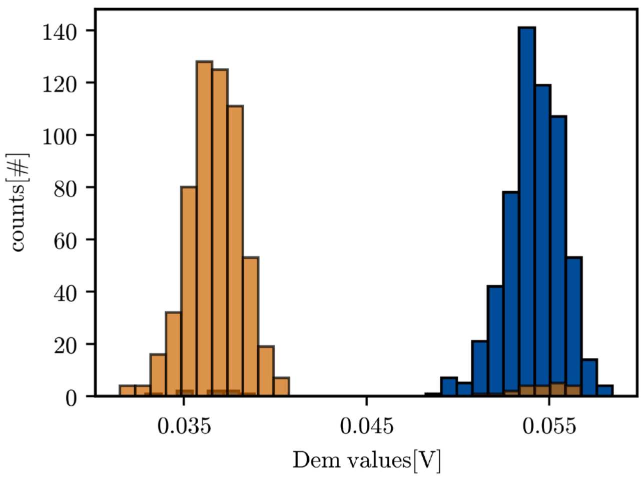
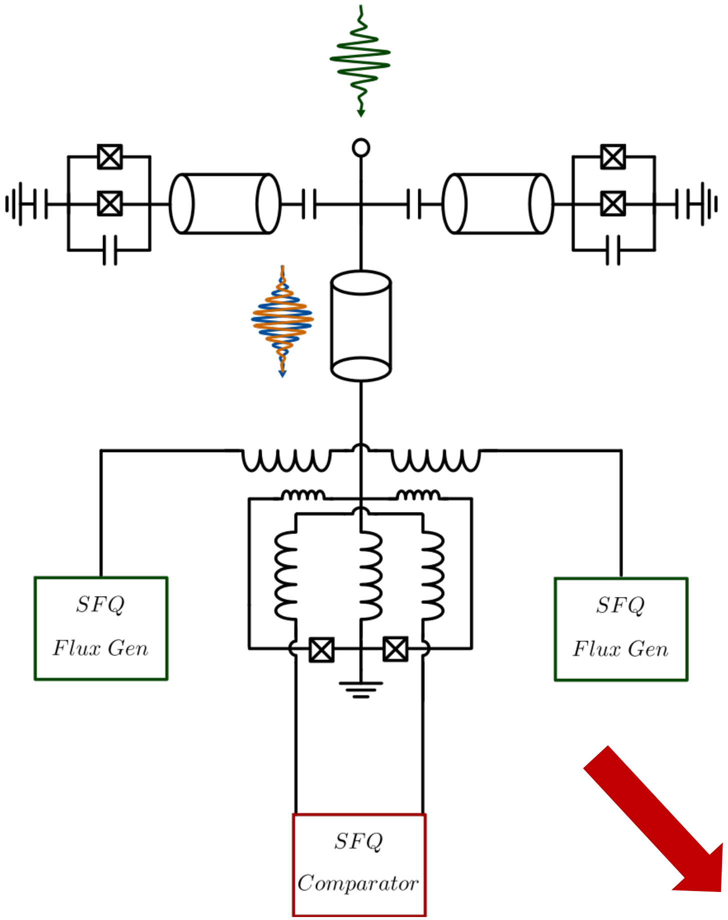


- JDPD can detect the tunable resonator state with a fidelity approaching 99%
- Detection is performed in a time scale of tens of nanoseconds, comparable with the fastest readout protocols in literature
- Results validate the idea





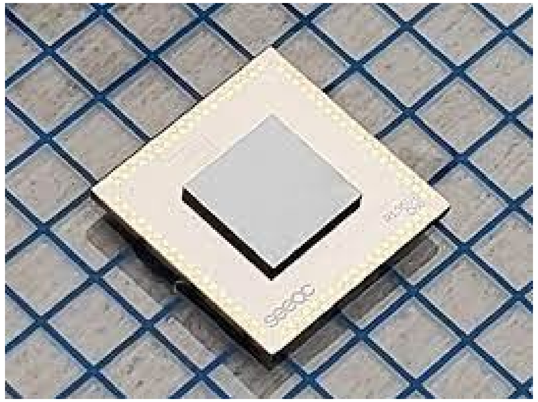
Conclusions



- Fast digital phase detection of a microwave signal at the millikelvin stage of a cryogenic fridge, reducing hardware complexity
- JDPD can resolve the state of a tunable resonator with 99% of fidelity, validating the idea

Outlook

- Currently we are testing a Multi Chip Module (MCM) chip in which the JDPD is coupled to working qubits
- Working on the integration with the SFQ architecture



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Thank you