

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE (DD-MM-YYYY) 03-07-2002	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 3 August 2001 - 03-Aug-02
--	---------------------------------------	--

4. TITLE AND SUBTITLE State Preparation and Readout of Fluxon Qubit by RSFQ Circuitry	5a. CONTRACT NUMBER F61775-01-WE053
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S) Professor Alexey Ustinov	5d. PROJECT NUMBER
	5d. TASK NUMBER
	5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Erlangen-Nuremberg Erwin-Rommel-Str. 1 Erlangen 91058 Germany	8. PERFORMING ORGANIZATION REPORT NUMBER N/A
---	--

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) EOARD PSC 802 BOX 14 FPO 09499-0014	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) SPC 01-4053

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report results from a contract tasking University of Erlangen-Nuremberg as follows: The contractor will investigate the use of Rapid Single Flux Quantum (RSFQ) logic circuitry to read qubits in 3-micron wide Josephson transmission line (JTL). He will construct semiconductor chips as necessary to test his theories on RSFQ circuitry and document his findings in a final report.

15. SUBJECT TERMS
EOARD, Quantum Computing, Superconductivity, Quantum Dots

20020927 174

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UL	18. NUMBER OF PAGES 21	19a. NAME OF RESPONSIBLE PERSON David M. Burns, Lt Col, USAF
a. REPORT UNCLAS	b. ABSTRACT UNCLAS	c. THIS PAGE UNCLAS			19b. TELEPHONE NUMBER (Include area code) +44 (0)20 7514 4955

UNIVERSITY OF ERLANGEN-NUREMBERG
GERMANY

STATE PREPARATION AND READOUT OF A FLUXON QUBIT BY RSFQ CIRCUITRY

FINAL REPORT ON
EOARD CONTRACT F61775-01-WE053

JULY 2002

DISTRIBUTION STATEMENT A
Approved for Public Release
Distribution Unlimited

AQ F02-12-3395

EXECUTIVE SUMMARY

This contract has been aimed at proving concept of the RSFQ test circuits, which will be used in the future for experiments with Long Josephson Junction (LJJ) qubit in the dilution refrigerator at mK temperatures at University of Erlangen. In collaboration with Conductus Inc., we made a prototype of the digital read-from-LJJ and write-to-LJJ circuits, which will be working at extremely low temperatures. This automatically required these types of circuits to be optimized for the extremely low power consumption. The superconducting Single Flux Quantum (SFQ) approach is a very favorable digital technology in that:

- It has very low power consumption of about four orders of magnitude less than advanced semiconductor circuits.
- It is extremely fast, and the 20 GHz level achieved with the current fabrication technologies is not a physical limitation. Further development relatively easy will enable downscale power consumption (and still keep reasonable operation speed) to the level of a few microwatts per chip required by quantum computer devices.
- The connection link between LJJ and RSFQ circuits invented and tested at Conductus is a natural way to make interface to quantum computer.
- The proposed qubit based on LJJ is a very sensitive element, which can be magnetically coupled to other than superconducting type quantum cells.

For this contract, we had an objective to develop an approach for practical implementation of the qubit based on LJJ. We have developed and successfully measured a test chip operating at 4.2K. The results are:

- Two circuit architectures were explored. Both of them were using superconducting transformer to introduce fluxon into LJJ. Readout cells were different. The first test circuit was using T-Flip-Flop, and the other one – RS-Flip-Flop. Both circuits were intensively simulated and optimized for wide operating margins.
- One chip has been designed, fabricated at Hypres, and successfully tested at Conductus. Both test circuits were operated as expected. We are able to send fluxon into the LJJ, trap it in a barrier, release fluxon, and send it to the readout circuit.
- The final architecture of the test circuit at mK temperature is established. Measurement shows that close attention should be paid to the interface between LJJ and RSFQ circuits. The wrongly selected current across the LJJ edge may cause fluxon reflection from that edge, and even produce multiple reflections. The weak point was writing fluxon to the LJJ. The superconducting transformer sends fluxon to LJJ and keeps anti-fluxon. Then it releases anti-fluxon, which, as it was observed, may reflect from the edge. For the future development we suggest to use extra RSFQ dc-to-sfq converter instead of transformer, and RS-Flip-Flop as readout circuit to reduce heating during quantum experiment.
- Three approaches are suggested to decrease chip power consumption, which mainly defined by the dc bias current supplied by resistors. The first one is the ten times reducing of the critical currents of the junctions. This is the best way to miniaturize the circuit, but it required the complete RSFQ circuit redesigning. This is because ten time larger inductors made as micro-strip lines will significantly increase parasitic capacitances. Other type of inductors will require developing new set of tools for precise inductance extractors from layout. The second approach, which looks more attractive, is to decrease the bias voltage on current supply lead. This adds very long inductor leads and extra filters to the chip. The third approach is to use complementary RSFQ approach, which eliminates all bias resistors at cost of doubling the number of Josephson junctions.

INTRODUCTION

This report covers the first period of the work performed towards realization of a fluxon qubit furnished with state preparation and readout stages based on RSFQ (Rapid Single Flux Quantum) circuitry. We intend to prepare and probe quantum bits (qubits) based on macroscopic quantum states of magnetic flux quanta in the Josephson transmission lines. Theory predicts that a vortex (fluxon) trapped in a double-well potential of a low-dissipation Josephson transmission line behaves as a quantum-coherent two-state system. The potential can be modified during operation of the qubit by using external magnetic field generated by on-chip control lines. In this project, we would like to prepare and test the measurement scheme of the time-domain quantum coherence experiment with a single fluxon. The RSFQ logic circuit will be used to set fluxon in the initial state of a qubit. Then the potential variation over the given time period will induce the quantum superposition of states, and resulting state will be detected by the RSFQ fluxon counter. Reproducing this procedure over the time allows us to perform stroboscopic measurements of Rabi oscillations of the fluxon.

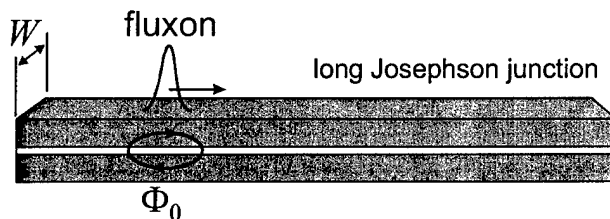


Figure 1. Schematic view of a long Josephson junction with a fluxon inside it.

A Josephson fluxon is a magnetic flux quantum Φ_0 located between superconducting electrodes of a long Josephson junction. It can be considered as a quantum quasi-particle described by the Kato-Imada theory¹, in which quantum effects are expected to occur at temperatures, as a rough estimate, below 100 mK. The mass of a Josephson fluxon m_f as a quantum particle is proportional to the width W of the junction and for a small width of $W \sim 1 \mu\text{m}$, constitutes to about $10^{-3} m_e$, where m_e is the electron mass. As for any other phase qubit, the dynamics of the fluxon qubit is governed by the superconducting phase difference across the junction rather than by the charge on the superconducting electrodes.

The main idea of the experiment that we would like to do is using Nakamura-like technique² with Josephson fluxons, namely measuring the fluxon „current“ versus the superposition time of two quantum states. We would like to perform macroscopic quantum coherence (MQC) experiment with a Josephson fluxon as a quantum particle located in the Josephson transmission line (JTL). Figure 2 presents the experimental scheme. Dashed line outlines the quantum part of the circuit. The measurement procedure which we would like to demonstrate includes preparation of the initial state of the fluxon qubit, formation of a quantum superposition of the two classically separated states over the given time interval, and read out the final qubit state. These measurements in this project are going to be done at the conventional temperature of 4.2 K, using classical fluxons states preparation and readout. If these tests are successful, we would like to use the same technique at the mK-temperature range and, finally, perform quantum measurements in the continuation of this project.

¹ T.Kato and M. Imada, J. Phys. Soc. Japan **65**, 2963 (1996).

² Y. Nakamura, Y. A. Pashkin, and J. S. Tsai, Nature **398**, 786 (1999).

To prepare the initial state of our qubit we will use a standard RSFQ fluxon injector. The locally applied current I_2 forms a repulsive potential that traps the arriving fluxon in the region $|0\rangle$. Then another local current I_1 ($I_1 > I_2$) is switched on and due to the chosen local current injection configuration, the double potential well for the fluxon is formed.

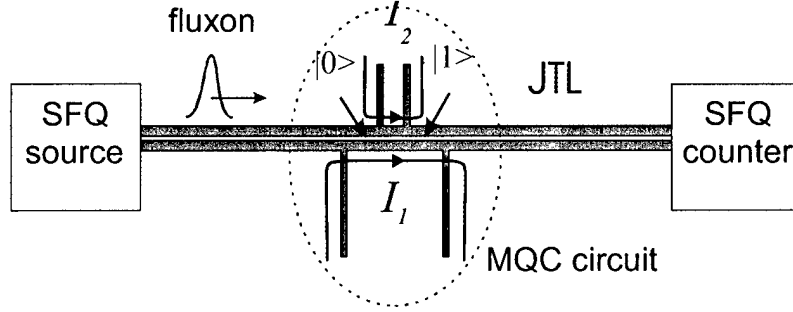


Figure 2. The schematics of the proposed experiment.

CALCULATION OF THE POTENTIAL

Figure 3 shows the intended fluxon potential energy profile at zero bias current. The potential barriers $U_1 \sim I_1$ and $U_2 \sim I_2$ in the initial state are wanted to be high enough to locate fluxon in the left well (region $|0\rangle$). This is a process of initial set of the qubit.

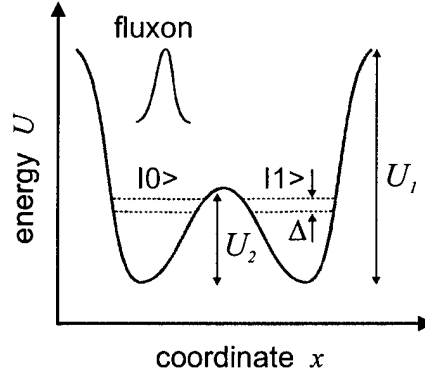


Figure 3.

In order to make realistic predictions towards possible potential shape, we performed analytical calculation of the fluxon interaction potential with a current injector. Using the coordinate x -dependent fluxon potential known through the perturbed sine-Gordon equation

$$U(x, y, \varepsilon) = -\varepsilon \arctan(e^{x-y}), \quad (1)$$

we calculate the effective energetic potential of four δ -function current injectors as

$$W(x, \varepsilon_1, \varepsilon_2, d_1, d_2) = U(x, -\frac{d_1}{2}, \varepsilon_1) + U(x, \frac{d_1}{2}, -\varepsilon_1) + U(x, -\frac{d_2}{2}, \varepsilon_2) + U(x, \frac{d_2}{2}, -\varepsilon_2), \quad (2)$$

where d_1 and d_2 are the spacings between the pairs of current injectors, $\varepsilon_1=I_1/(j_c\lambda_J)$ and $\varepsilon_2=I_2/(j_c\lambda_J)$ are the normalized currents flowing through them.

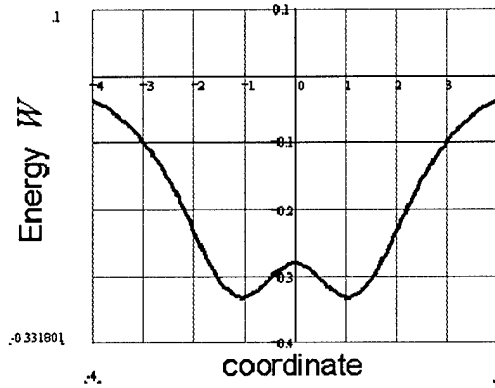


Figure 4. Double-well potential calculated according to Eq.(2).

Figure 4 illustrates the energy for a particular case of the distance between current injectors $d_1=3$ and $d_2=1$ with normalized currents $\varepsilon_1=0.8$ and $\varepsilon_2=-1.3$. The required double-well potential is formed in the junction under the above parameters.

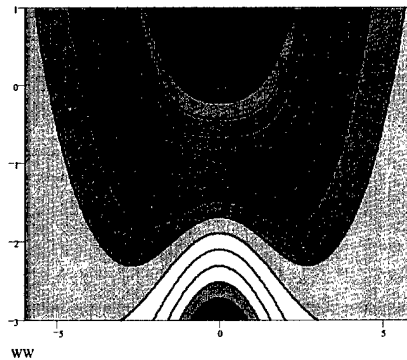


Figure 5. Tuning of the potential (2) by the current ε_2 .

The tuning of the potential $W(\varepsilon_2)$ is illustrated in Fig.5. One can see that varying the current ε_2 in the range from -3 to 0 allows modifying the potential profile from a single-well to a double-well form.

MEASUREMENT PROCEDURE

We plan to measure the quantum coherent behavior in the time domain, i.e. the Rabi oscillations of the fluxon between the two degenerate states. The measurements procedure includes (i) preparation of the initial state of the qubit, (ii) making a superposition of two states over a time Δt , and (iii) readout of the resulting state of a qubit.

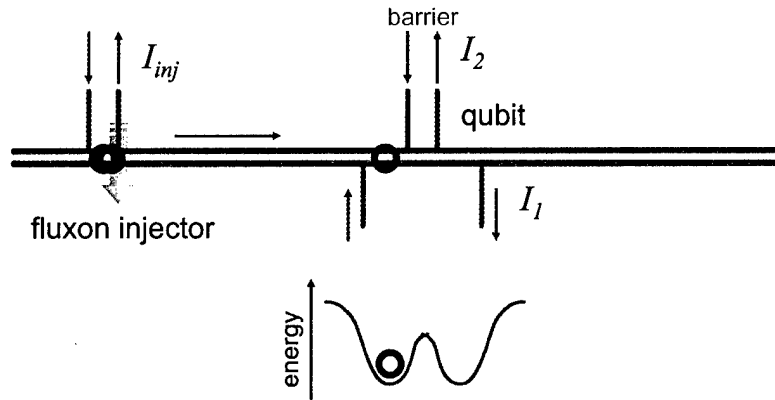


Figure 6. Scheme of the initial fluxon state preparation.

The state preparation procedure is illustrated in Fig.6. In order to prepare a fluxon in a desired state, we use a fluxon injector to produce a fluxon-antifluxon pair in the left part of the circuit. A small bias current applied in this region breaks this pair apart and moves the fluxon towards the center of the circuit where a quantum superposition experiment will be made. Trapping the fluxon there is achieved by applying the current I_2 which forms a potential barrier. The initial state is set by locking the fluxon by current I_1 in the left well of the potential. Meanwhile, the antifluxon is removed from the circuit at its left boundary using an RSFQ absorber stage.

After the initial state of the fluxon qubit is set, the local current I_2 is reduced to a smaller level and remains unchanged for a short time interval Δt . The appropriate current level is defined by the lowest energy level for the fluxon in the well to be split in two levels separated by the energy difference Δ proportional to the Rabi oscillation frequency f_{Rabi} . The fluxon will tunnel between the wells A (left) and B (right) through the barrier U_2 . After the time Δt is passed, the current I_2 is raised again and the fluxon has a certain probability to be found either in the well A or well B. If the quantum decoherence time t_{dec} is larger than Δt , the probability of finding the fluxon in one of the wells is expected to oscillate as a function of Δt , with the period $1/f_{\text{Rabi}}$. This enables us to test the coherence of the macroscopic quantum state of the qubit.

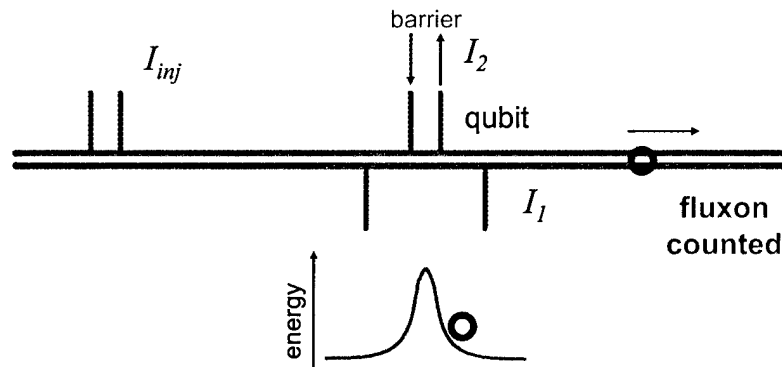


Figure 7. Scheme of the readout procedure.

The final state of the fluxon will be read by reducing potential U_1 to zero level and by switching on a small uniform bias current in the JTL, which try to move the fluxon in direction to the SFQ counter (see Fig.7). The fluxon will move there and hence counted only if it is located at the well B. If the fluxon is located in the well A, it will remain there due to the large potential barrier U_2 formed by current I_2 . The whole circuit is reset to original state by applying a negative bias current that removes the fluxon from well A through the RSFQ absorber the left boundary of the circuit.

Figure 8 presents the time diagram of the measurement cycle. At the time t_1 the fluxon gets locked in the potential well. The potential tilt is removed at $t=t_2$ by turning bias current to zero. The quantum superposition is switched on at $t=t_3$ and switched off at $t=t_4$. The bias current turned on at $t=t_5$, and if the fluxon is located at the well B, it will moves in direction to the counter. The current I_1 switches off at $t=t_6$ and removes the fluxon through the input buffer stage, thus resetting the system to the initial state.

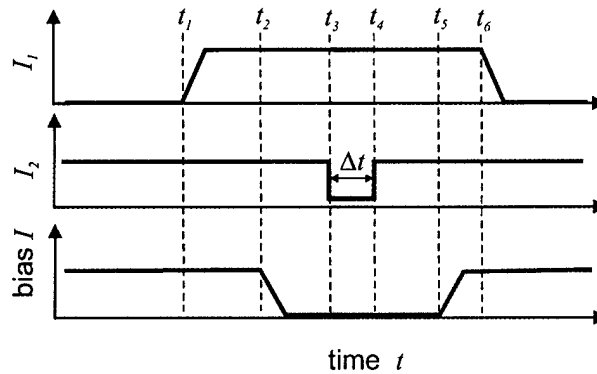


Figure 8. Time diagram of the measurement cycle.

Being repeated many times, these measurements reflect the probability of finding the fluxon in either state A or B as a function of Δt , thus sampling the Rabi oscillations. The oscillations decay probability as a function of Δt characterizes the decoherence time t_{dec} , which is important to prove the possible use of the superconducting electronics for quantum computing.

The above measurement scheme (based on magnetic flux states) is conceptually close to the one proposed by Nakamura et al. Their experiment demonstrated of the coherence of two charge states. We intend to measure similar effect, but instead of charge we will measure the “current” of magnetic by using an RSFQ counter.

LAYOUT AND CIRCUIT SIMULATION

The circuit layout that we developed for testing of the above described measurement scheme is shown in Fig. 9. The layout includes all required components for the experimental procedure described above. The purpose now is to test this measurement protocol at a temperature of 4.2 K and, after making it work, transfer this scheme to future measurement at mK temperatures. The total length of the device is about 690 μm and the width is 190 μm . The design is made according to the Hypres design rules. Anti-fluxon absorber is a resistor, which prevents fluxon reflection at the LJJ end. In the first design iteration fluxon injector is implemented by using superconducting transformer. Applied to transformer current sends fluxon to the right and keeps anti-fluxon in the

injector area. While that current decreases the anti-fluxon is sent to absorber, and system returns to the original state.

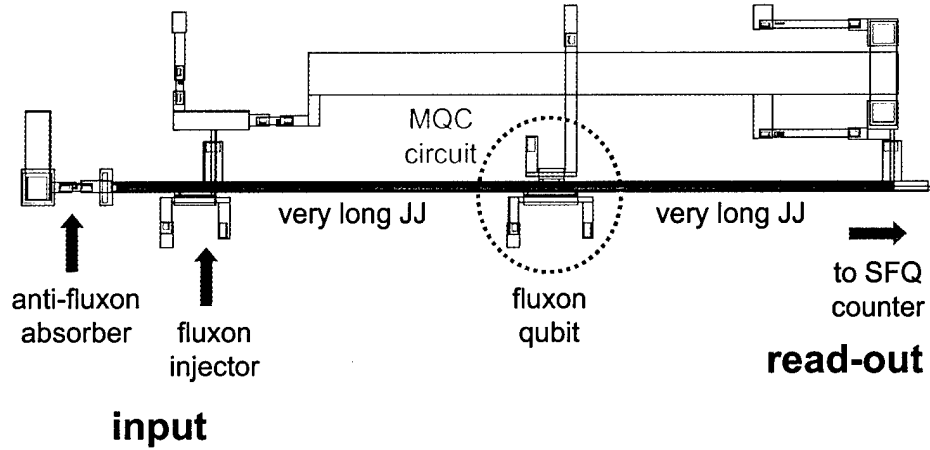


Figure 9. Layout of the designed test circuit.

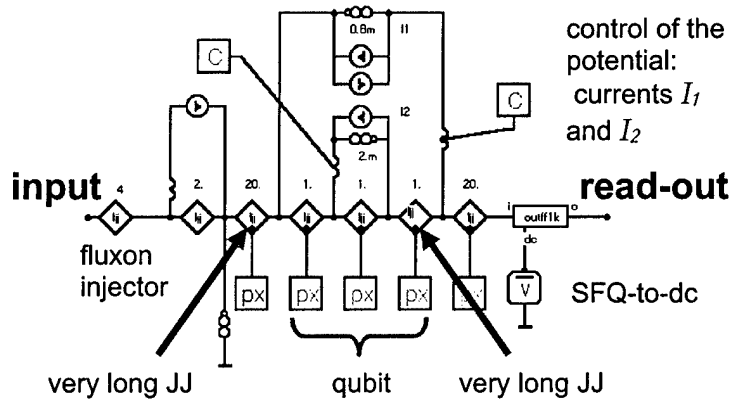


Figure 10. Symbolic scheme of the circuit used with WINS simulator.

Component	Value	Unit
R1 Resistor 1	90.0	90.0
I2 dc Current 17.464	14.8	17.2
I1 dc Current 6.008	24.6	46.7
P1 Programmable Pulse Generator	12.253	21.4
P2 Programmable Step Generator	1.6	90.0 90.0
P3 Programmable Pulse Generator	6.4	62.2 90.0
P4 Programmable Pulse Generator	16.48	32.3 38.3
I4 dc Current 1.76	90.0	90.0
P5 Programmable Step Generator	-13.6	90.0 74.9
I3 dc Current 8	46.1	43.9
rsf7 SubCircuit 1.92	29.2	31.6
Loss External Parameter 0.01	74.9	90.0
Len External Parameter 4	90.0	90.0

Figure 11. The optimization results table produced by WINS simulator.

In order to verify the functionality of the circuit, we performed its simulation and optimization using the Superconducting Schematic Editor and Simulator WINS (<http://www.kapl.tv>). The symbolic scheme used in this simulation is presented in Fig.10. The circuit was found successfully functioning with layout margins of about $\pm 29\%$ and bias current margins of $\pm 15\%$.

This layout for testing the circuit at 4.2 K includes 7 biased SFQ resistors and has no reset of SFQ flip-flops. This means that there will be two resistive Josephson junctions per SFQ register during the circuit operation. The total dissipated power is thus about 0.8 mW. For the future measurements in the quantum regime, we plan to put all resistors at 1 K pot of a dilution refrigerator. The design will be also modified to include SFQ flip-flops with reset, such that there will be no Josephson junctions in the non-zero voltage state. Thus, we will have no dissipation via resistors on the future quantum chip during its operation.

CIRCUIT TEST AT TEMPERATURE 4.2 K

The chip microphotograph is shown in Fig. 12. The following Fig. 13 shows the enlarged image of the area where the double potential is mastered. Note that extra loop (in a picture it looks as a hole) was used in transformer to create potential. This is because one needs to prevent any change of the electrodes geometry near the place where the quantum experiment is performed.

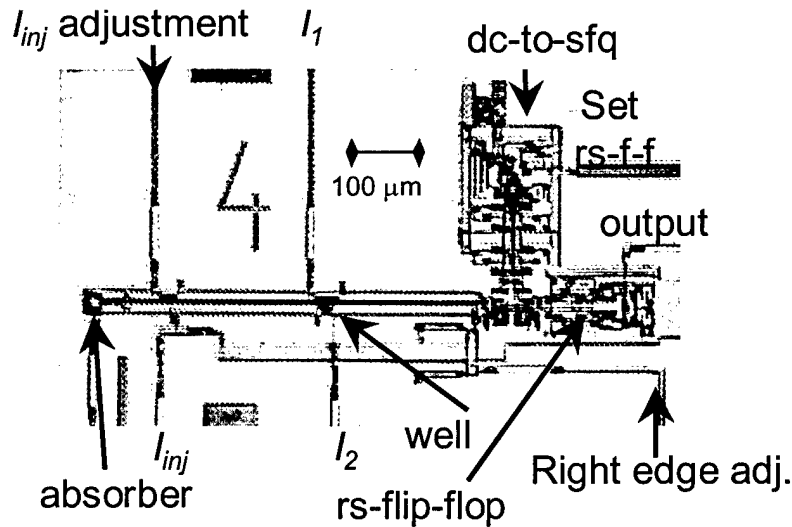


Figure 12. Photo of the tested circuit. Extra dc-to-sfq converter was used to set rs-flip-flop.

Figure 14 shows functionality of the interface between LJJ and RSFQ circuit. First I_{set} current switches rs-flip-flop to the voltage state. Then I_{inj} sends fluxon through LJJ, and switches flip-flop back to zero voltage state. The margin of injector current is not high, so for future development we propose to use dc-to-sfq converter instead of transformer. In contrast, the interface to flip-flop has large enough margins that prove its feasibility.

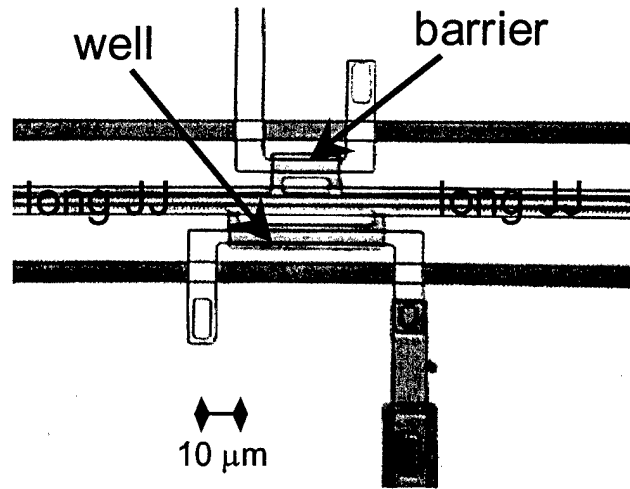


Figure 13. Double-well potential area of the LJJ.

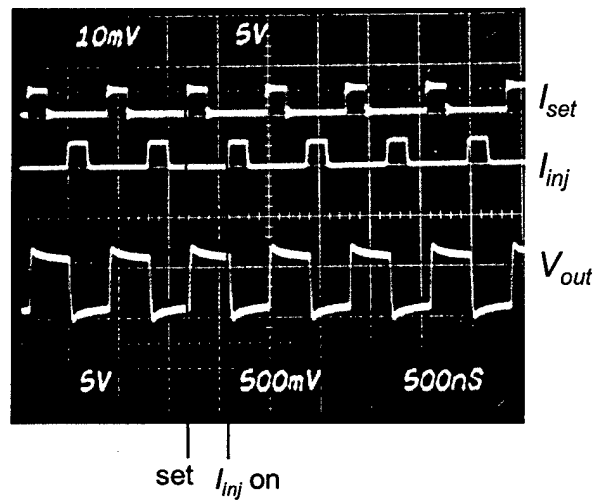


Figure 14. Free run of fluxon from injector to rs-flip-flop in absence of any barrier. The switching on injector current sends fluxon to LJJ. The output amplitude of rs-flip-flop is 0.3 mV. Common bias current is 5.4 mA (margin 4.88÷5.92 mA). Injector current has margins of $\pm 3\%$, injector adjustment current can vary from -0.115 mA to 0.55 mA, and LJJ right edge adjustment current from -0.58 mA to 0.77 mA.

Next tested task was to catch a fluxon using control currents I_1 and I_2 . We were able to demonstrate that using either I_1 or I_2 . Figure 15 shows the result of such an experiment using I_1 . First, rs-flip-flop is set to voltage state. Then positive current I_1 is applied to create the potential barrier for fluxon, and after while injector sent fluxon to LJJ (" I_{inj} on" in Fig. 15). The following event is different from one in Fig. 14. Flip-flop switched to zero voltage step only when barrier released it (" I_1 off" point in Fig. 15). Similar behavior was observed for current I_2 (see Fig. 16). The only difference is that I_2 should be negative to form a barrier. By setting I_1 to negative value we were able also catch fluxon by the single well, these data are presented in Fig. 17.

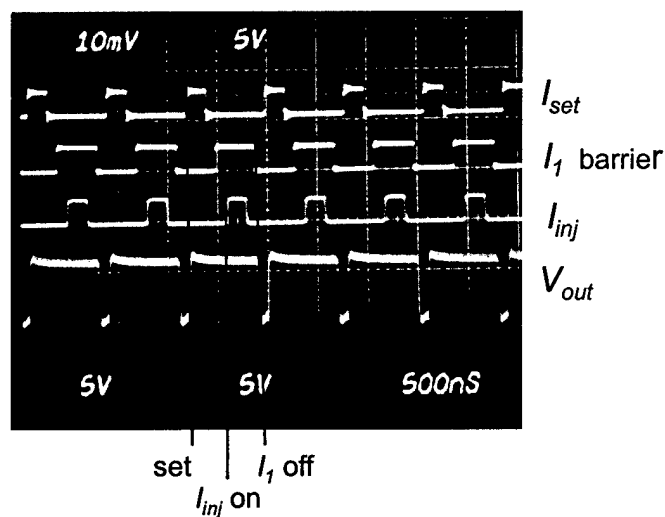


Figure 15. Fluxon is trapped by barrier formed by current I_1 . The output amplitude of rs-flip-flop is 0.3 mV. Common bias current is 5.4 mA (margin 4.81÷5.77 mA), Injector current has margins of $\pm 3\%$, injector adjustment current is -0.265 mA, and can vary from -0.045 mA to -0.495 mA. LJJ right edge adjustment current is not used. The amplitude of I_1 is 8.6 mA, and has margins from 4.4 to 9.8 mA.

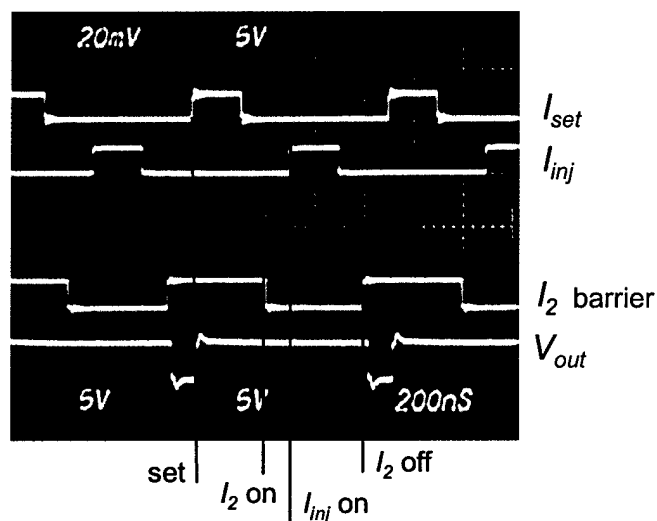


Figure 16. Fluxon is trapped by barrier formed by current I_2 . The output amplitude of rs-flip-flop is 0.3 mV. Common bias current is 5.5 mA (margin 4.81÷5.77 mA), Injector current has margins of $\pm 3\%$, LJJ right edge adjustment current is -0.675 mA, and injector adjustment current is not used. The amplitude of I_2 has margins from -10.15 to more than -2 mA.

The additional tests have shown that it is also possible to catch fluxon in double well potential, and even observe thermo-activated jumps of the fluxon between wells. The operating margins were found to be low, as can be expected.

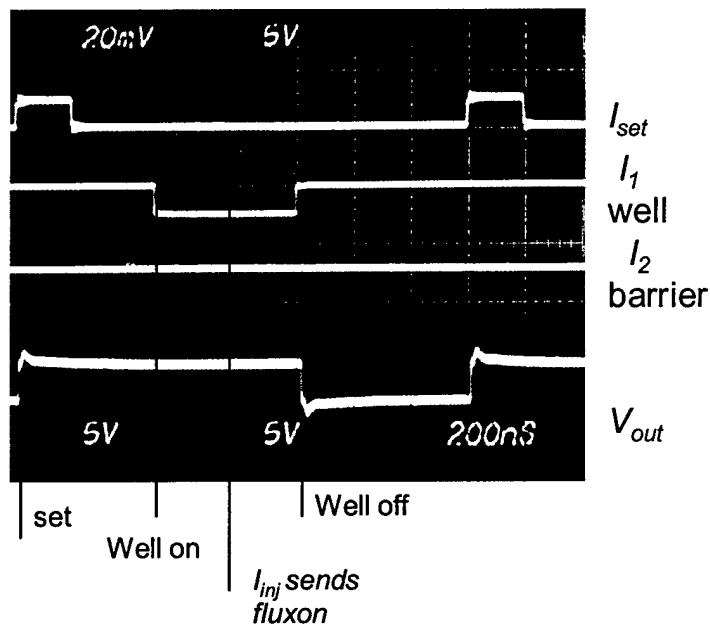


Figure 17. Fluxon is trapped by well created by negative current I_l . The output amplitude of rs-flip-flop is 0.3 mV. Common bias current is 5.51 mA. Injector adjustment current is -0.075 mA. LJJ right edge adjustment current is 0.615 mA. The amplitude of I_l is -2.05 mA. Injector current is not shown.

Further analyses have shown that due to the finite width of the injection leads each well is shrink in width to 8 microns. Remind that the Josephson penetration depth λ_j is about 12 microns. In the future, we will simply increase the distance between the I_l leads that should solve the problem. Another improvement will be using extra dc-to-sfq converter instead of the transformer, which definitely increase operation margins.

CONCLUSION

To summarize, the work performed within this project included the following milestones and results:

- calculation of the fluxon potential ;
- full circuit (RSFQ + fluxon qubit) simulation ;
- circuit optimization ;
- making a layout for 4.2 K ;
- testing the circuits fabricated at Hypres ;
- exercising the proposed measurement protocol at 4.2 K ;
- the circuit worked from the first try, no extra design-and-test iteration was required .

DECLARATIONS

(1) The Contractor, Prof. Dr. Alexey Ustinov, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No. F61775-01-WE053 is complete, accurate, and complies with all requirements of the contract.

DATE: _____ July 2, 2002 _____

Name and Title of Authorized Official:

Alexey Ustinov, PhD

(2) I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract.

DATE: _____ July 2, 2002 _____

Name and Title of Authorized Official:

Alexey Ustinov, PhD

Professor of Experimental Physics

University of Erlangen-Nuremberg, Germany

UNIVERSITY OF ERLANGEN-NUREMBERG
GERMANY

STATE PREPARATION
AND READOUT OF A
FLUXON QUBIT BY
RSFQ CIRCUITRY

INTERIM REPORT ON

EOARD CONTRACT F61775-01-WE053

FEBRUARY 2002

INTRODUCTION

This report covers the first period of the work performed towards realization of a fluxon qubit furnished with state preparation and readout stages based on RSFQ (Rapid Single Flux Quantum) circuitry. We intend to prepare and probe quantum bits (qubits) based on macroscopic quantum states of magnetic flux quanta in the Josephson transmission lines. Theory predicts that a vortex (fluxon) trapped in a double-well potential of a low-dissipation Josephson transmission line behaves as a quantum-coherent two-state system. The potential can be modified during operation of the qubit by using external magnetic field generated by on-chip control lines. In this project, we would like to prepare and test the measurement scheme of the time-domain quantum coherence experiment with a single fluxon. The RSFQ logic circuit will be used to set fluxon in the initial state of a qubit. Then the potential variation over the given time period will induce the quantum superposition of states, and resulting state will be detected by the RSFQ fluxon counter. Reproducing this procedure over the time allows us to perform stroboscopic measurements of Rabi oscillations of the fluxon.

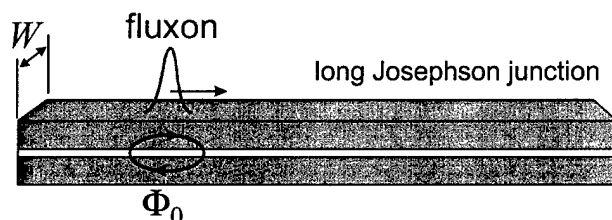


Figure 1. Schematic view of a long Josephson junction with a fluxon inside it.

A Josephson fluxon is a magnetic flux quantum Φ_0 located between superconducting electrodes of a long Josephson junction. It can be considered as a quantum quasi-particle described by the Kato-Imada theory¹, in which quantum effects are expected to occur at temperatures, as a rough estimate, below 100 mK. The mass of a Josephson fluxon m_f as a quantum particle is proportional to the width W of the junction and for a small width of $W \sim 1 \mu\text{m}$, constitutes to about $10^3 m_e$, where m_e is the electron mass. As for any other phase qubit, the dynamics of the fluxon qubit is governed by the superconducting phase difference across the junction rather than by the charge on the superconducting electrodes.

The main idea of the experiment that we would like to do is using Nakamura-like technique² with Josephson fluxons, namely measuring the fluxon „current“ versus the superposition time of two quantum states. We would like to perform macroscopic quantum coherence (MQC) experiment with a Josephson fluxon as a quantum particle located in the Josephson transmission line (JTL). Figure 2 presents the experimental scheme. Dashed line outlines the quantum part of the circuit. The measurement procedure which we would like to demonstrate includes preparation of the initial state of the fluxon qubit, formation of a quantum superposition of the two classically separated states over the given time interval, and read out the final qubit state. These measurements in this project are going to be done at the conventional temperature of 4.2 K, using classical fluxons states preparation and readout. If these tests are successful, we would like to use the same technique at the mK-temperature range and, finally, perform quantum measurements in the continuation of this project.

To prepare the initial state of our qubit we will use a standard RSFQ fluxon injector. The locally applied current I_2 forms a repulsive potential that traps the arriving fluxon in the region $|0\rangle$. Then

¹ T.Kato and M. Imada, J. Phys. Soc. Japan **65**, 2963 (1996).

² Y. Nakamura, Y. A. Pashkin, and J. S. Tsai, Nature **398**, 786 (1999).

another local current I_1 ($I_1 > I_2$) is switched on and due to the chosen local current injection configuration, the double potential well for the fluxon is formed.

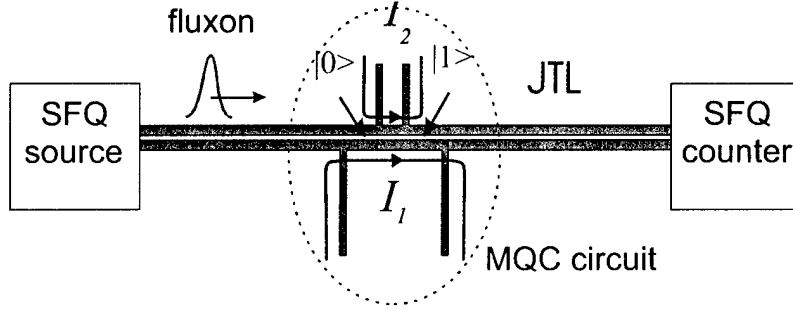


Figure 2. The schematics of the proposed experiment.

CALCULATION OF THE POTENTIAL

Figure 3 shows the intended fluxon potential energy profile at zero bias current. The potential barriers $U_1 \sim I_1$ and $U_2 \sim I_2$ in the initial state are wanted to be high enough to locate fluxon in the left well (region $|0\rangle$). This is a process of initial set of the qubit.

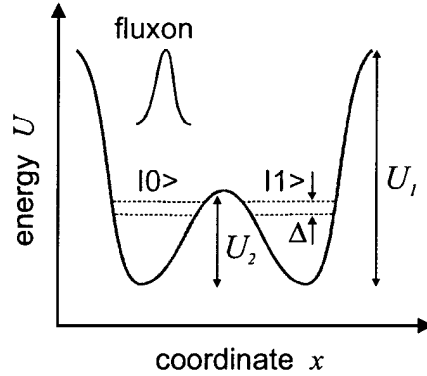


Figure 3.

In order to make realistic predictions towards possible potential shape, we performed analytical calculation of the fluxon interaction potential with a current injector. Using the coordinate x -dependent fluxon potential known through the perturbed sine-Gordon equation

$$U(x, y, \varepsilon) = -\varepsilon \arctan(e^{x-y}), \quad (1)$$

we calculate the effective energetic potential of four δ -function current injectors as

$$W(x, \varepsilon_1, \varepsilon_2, d_1, d_2) = U(x, -\frac{d_1}{2}, \varepsilon_1) + U(x, \frac{d_1}{2}, -\varepsilon_1) + U(x, -\frac{d_2}{2}, \varepsilon_2) + U(x, \frac{d_2}{2}, -\varepsilon_2), \quad (2)$$

where d_1 and d_2 are the spacings between the pairs of current injectors, $\varepsilon_1 = I_1 / (j_c \lambda_J)$ and $\varepsilon_2 = I_2 / (j_c \lambda_J)$ are the normalized currents flowing through them.

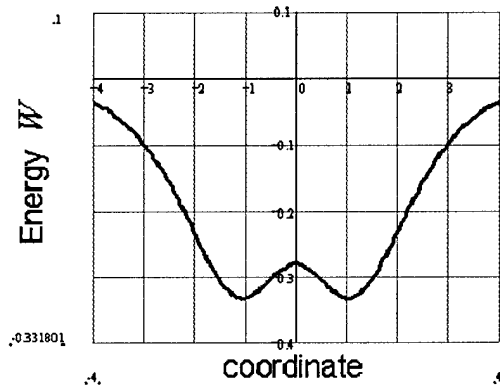


Figure 4. Double-well potential calculated according to Eq.(2).

Figure 4 illustrates the energy for a particular case of the distance between current injectors $d_1=3$ and $d_2=1$ with normalized currents $\varepsilon_1=0.8$ and $\varepsilon_2=-1.3$. The required double-well potential is formed in the junction under the above parameters.

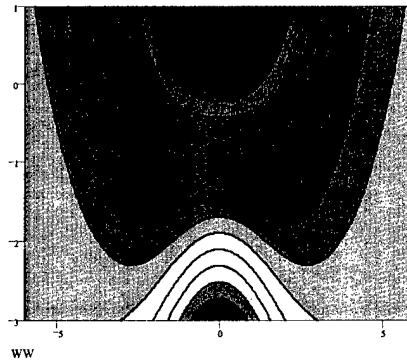


Figure 5. Tuning of the potential (2) by the current ε_2 .

The tuning of the potential $W(\varepsilon_2)$ is illustrated in Fig.5. One can see that varying the current ε_2 in the range from -3 to 0 allows modifying the potential profile from a single-well to a double-well form.

PLANNED MEASUREMENT PROCEDURE

We plan to measure the quantum coherent behavior in the time domain, i.e. the Rabi oscillations of the fluxon between the two degenerate states. The measurements procedure includes (i) preparation of the initial state of the qubit, (ii) making a superposition of two states over a time Δt , and (iii) readout of the resulting state of a qubit.

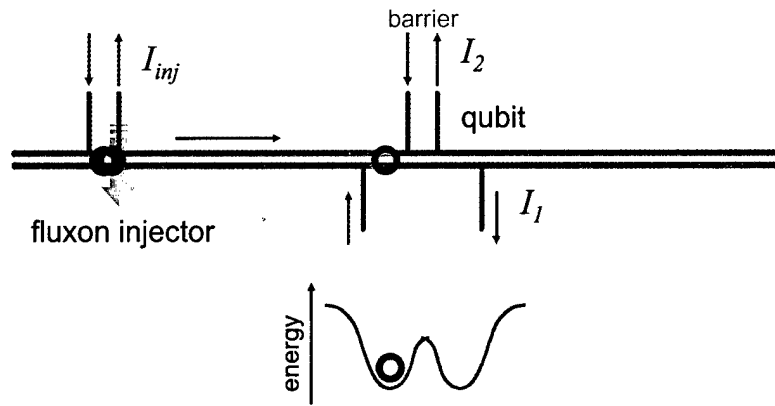


Figure 6. Scheme of the initial fluxon state preparation.

The state preparation procedure is illustrated in Fig.6. In order to prepare a fluxon in a desired state, we use a fluxon injector to produce a fluxon-antifluxon pair in the left part of the circuit. A small bias current applied in this region breaks this pair apart and moves the fluxon towards the center of the circuit where a quantum superposition experiment will be made. Trapping the fluxon there is achieved by applying the current I_2 which forms a potential barrier. The initial state is set by locking the fluxon by current I_1 in the left well of the potential. Meanwhile, the antifluxon is removed from the circuit at its left boundary using an RSFQ absorber stage.

After the initial state of the fluxon qubit is set, the local current I_2 is reduced to a smaller level and remains unchanged for a short time interval Δt . The appropriate current level is defined by the lowest energy level for the fluxon in the well to be split in two levels separated by the energy difference Δ proportional to the Rabi oscillation frequency f_{Rabi} . The fluxon will tunnel between the wells A (left) and B (right) through the barrier U_2 . After the time Δt is passed, the current I_2 is raised again and the fluxon has a certain probability to be found either in the well A or well B. If the quantum decoherence time t_{dec} is larger than Δt , the probability of finding the fluxon in one of the wells is expected to oscillate as a function of Δt , with the period $1/f_{\text{Rabi}}$. This enables us to test the coherence of the macroscopic quantum state of the qubit.

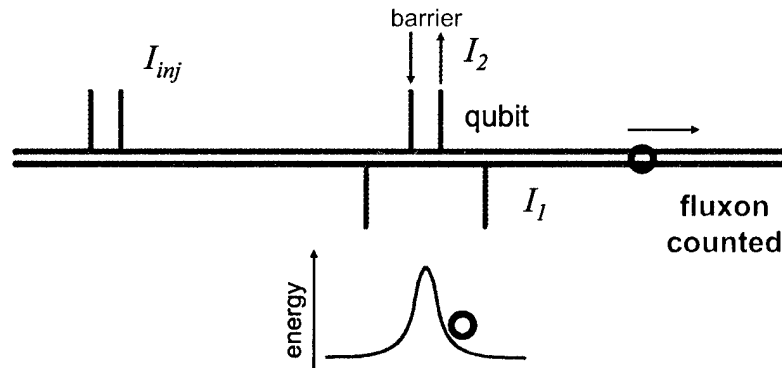


Figure 7. Scheme of the readout procedure.

The final state of the fluxon will be read by reducing potential U_1 to zero level and by switching on a small uniform bias current in the JTL, which try to move the fluxon in direction to the SFQ counter (see Fig.7). The fluxon will move there and hence counted only if it is located at the well B. If the fluxon is located in the well A, it will remain there due to the large potential barrier U_2 formed by current I_2 . The whole circuit is reset to original state by applying a negative bias current that removes the fluxon from well A through the RSFQ absorber the left boundary of the circuit.

Figure 8 presents the time diagram of the measurement cycle. At the time t_1 the fluxon gets locked in the potential well. The potential tilt is removed at $t=t_2$ by turning bias current to zero. The quantum superposition is switched on at $t=t_3$ and switched off at $t=t_4$. The bias current turned on at $t=t_5$, and if the fluxon is located at the well B, it will moves in direction to the counter. The current I_1 switches off at $t=t_6$ and removes the fluxon through the input buffer stage, thus resetting the system to the initial state.

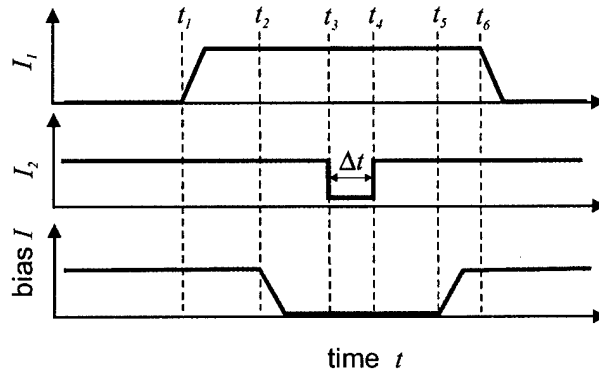


Figure 8. Time diagram of the measurement cycle.

Being repeated many times, these measurements reflect the probability of finding the fluxon in either state A or B as a function of Δt , thus sampling the Rabi oscillations. The oscillations decay probability as a function of Δt characterizes the decoherence time t_{dec} , which is important to prove the possible use of the superconducting electronics for quantum computing.

The above measurement scheme (based on magnetic flux states) is conceptually close to the one proposed by Nakamura et al. Their experiment demonstrated of the coherence of two charge states. We intend to measure similar effect, but instead of charge we will measure the “current” of magnetic by using an RSFQ counter.

LAYOUT AND CIRCUIT SIMULATION

The circuit layout that we developed for testing of the above described measurement scheme is shown in Fig. 9. The layout includes all required components for the experimental procedure described above. The purpose now is to test this measurement protocol at a temperature of 4.2 K and, after making it work, transfer this scheme to future measurement at mK temperatures. The total length of the device is about 690 μm and the width is 190 μm . The design is made according to the Hypres design rules.

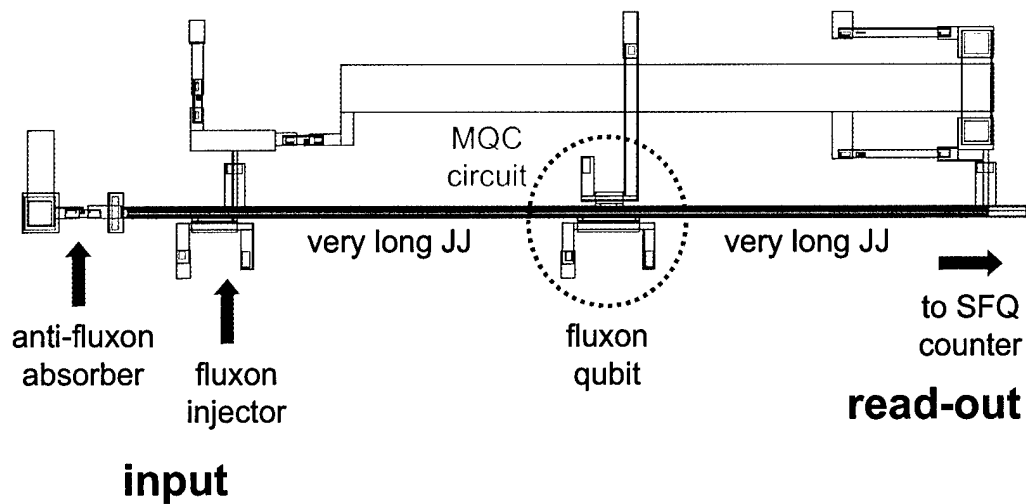


Figure 9. Layout of the designed test circuit.

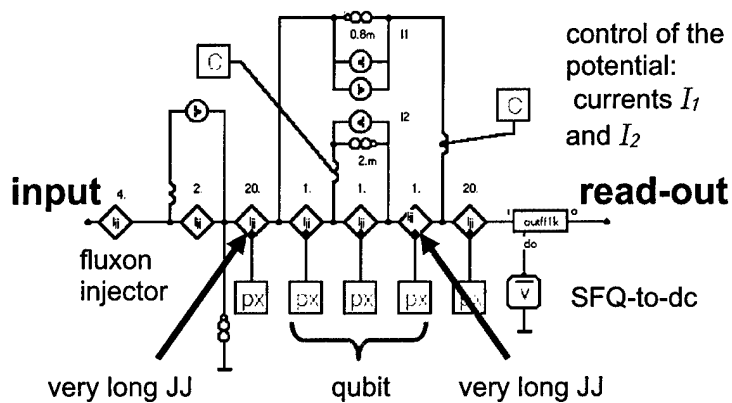


Figure 10. Symbolic scheme of the circuit used with WINS simulator.

Logic window	
R1 Resistor 1	90.0 90.0
I2 dc Current 17.454	14.8 17.2
I1 dc Current 6.806	24.8 45.7
P1 Programmable Pulse Generator	12.25.3 21.4
P2 Programmable Step Generator	1.6 90.0 90.0
P3 Programmable Pulse Generator	6.4 62.2 90.0
P4 Programmable Pulse Generator	16.49 32.3 38.3
I4 dc Current 1.76	90.0 90.0
P5 Programmable Step Generator	-13.5 90.0 74.9
I3 dc Current 8	46.1 43.9
rsff SubCircuit 1.32	29.2 31.6
Loss External Parameter 0.01	74.9 90.0
Len External Parameter 4	90.0 90.0

Figure 11. The optimization results table produced by WINS simulator.

In order to verify the functionality of the circuit, we performed its simulation and optimization using the Superconducting Schematic Editor and Simulator WINS (<http://www.kapl.tv>). The symbolic scheme used in this simulation is presented in Fig.10. The circuit was found successfully functioning with layout margins of about $\pm 29\%$ and bias current margins of $\pm 15\%$.

This layout for testing the circuit at 4.2 K includes 7 biased SFQ resistors and has no reset of SFQ flip-flops. This means that there will be two resistive Josephson junctions per SFQ register during the circuit operation. The total dissipated power is thus about 0.8 mW. For the future measurements in the quantum regime, we plan to put all resistors at 1 K pot of a dilution refrigerator. The design will be also modified to include SFQ flip-flops with reset, such that there will be no Josephson junctions in the non-zero voltage state. Thus, we will have no dissipation via resistors on the future quantum chip during its operation.

STATUS

The work performed within this project until now is described above. To summarize, it included

- calculation of the fluxon potential ;
- full circuit (RSFQ + fluxon qubit) simulation ;
- circuit optimization ;
- making a layout for 4.2 K .

The samples have been ordered at Hypres, Inc. in November 2001. In the final period of this 1-year project we will do:

- testing the circuits fabricated at Hypres ;
- exercising the proposed measurement protocol at 4.2 K ;
- making another design and test iteration if required .

Measurements in the quantum regime will be planned as a continuation of the current project beyond one-year period if the test results at 4.2 K are successful.

Alexey Ustinov, PhD

Professor of Experimental Physics

University of Erlangen-Nuremberg, Germany