A Prospective Approach to Energy Saving (Reversible) Computing

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Introductory Notes

Our "location" relative to discussed Entanglement issues

Entanglement – Qubits - Quantum Computing – Classical "Quantum" or Reversible Computing

Our Instruments

Theory – Numerical Simulations – Design Of Superconductor Integrated Circuit – Measurement at Helium Temperature

Our Immediate Goal

Demonstrate reversible digital circuit with specific energy dissipation below kBTln2 per one logic operation. (This is about million times lower than energy dissipation in modern semiconductor integrated circuits)

Our Mission

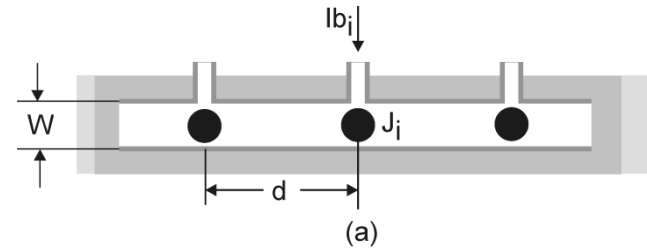**Help Quantum Computer researchers to move from basic science to practical circuitry (All QCs must operate in the reversible mode)**
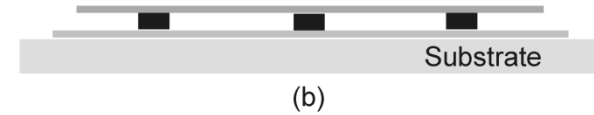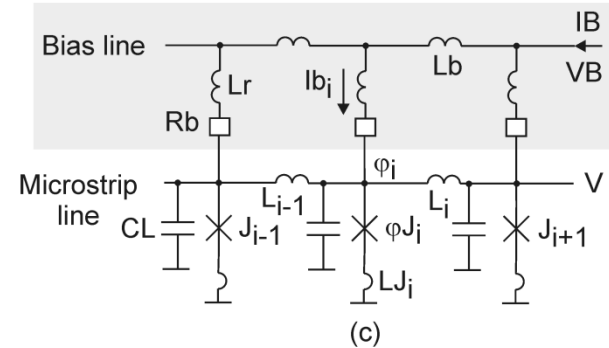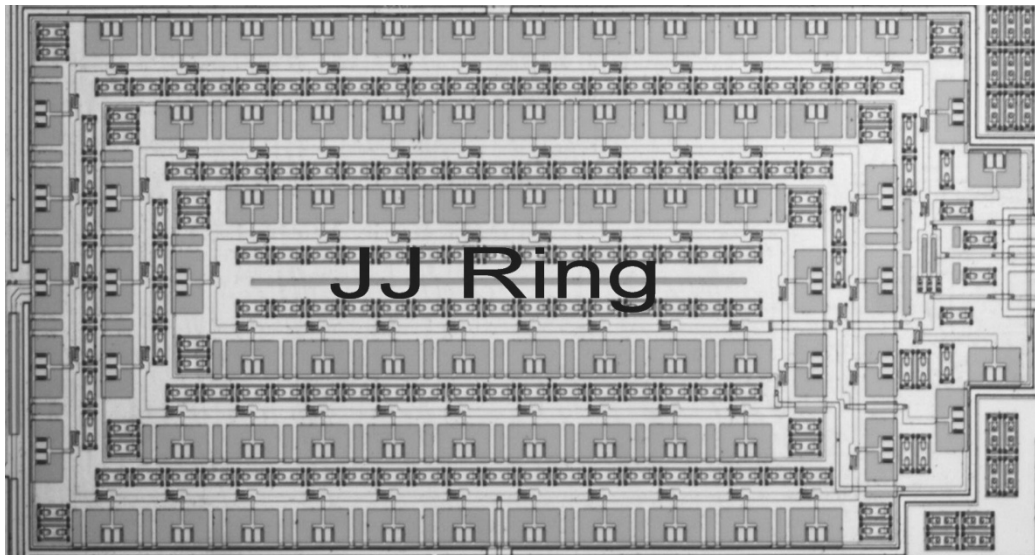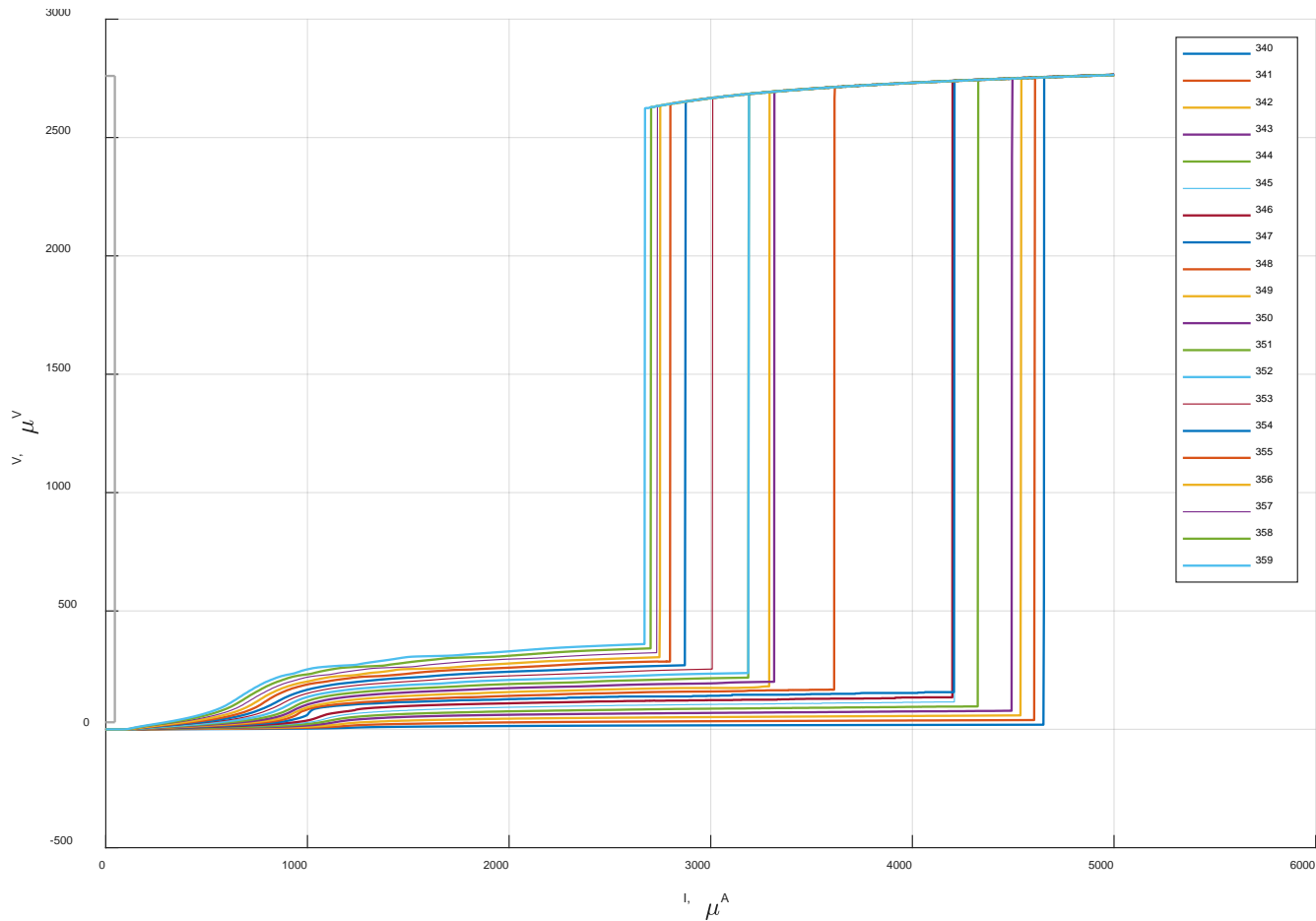
Long Josephson Junctions
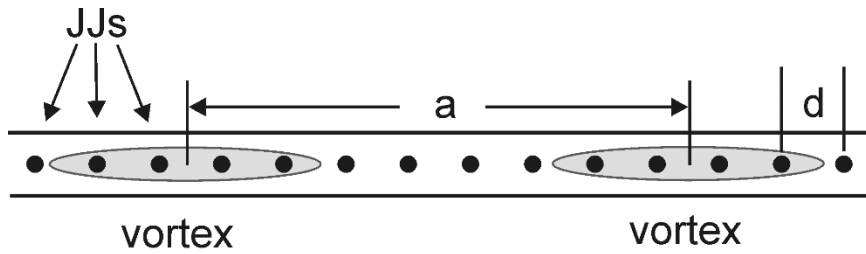
(a)

(b)

(a)

(b)
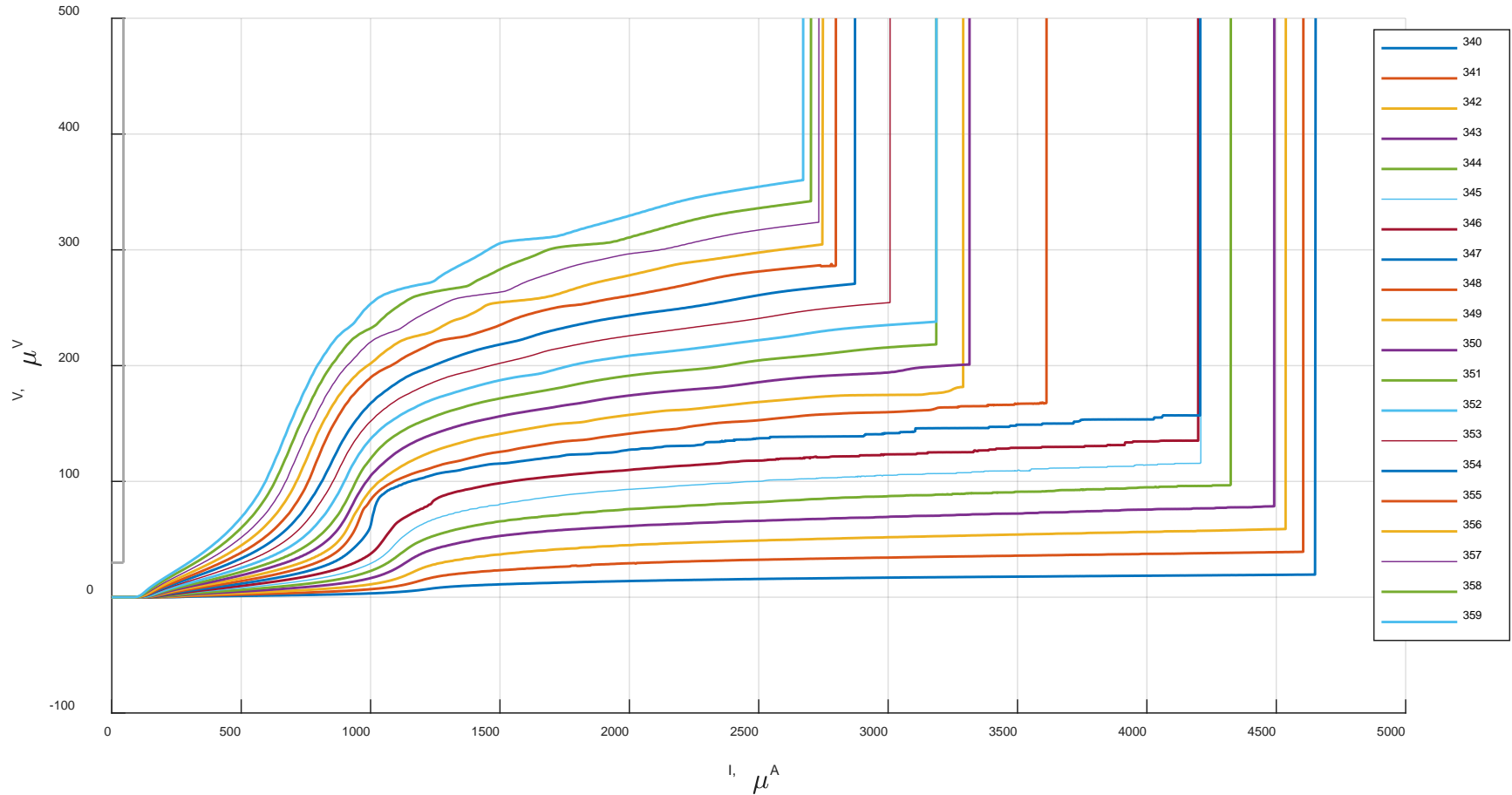
(c)

Ring with 77 Josephson junctions

Measured Propagation of Vortices Along Ring Josephson Junction with 256 Josephson Junctions I

$$C_0 \frac{d^2 \Phi_i}{dt^2} - \frac{\Phi_{i-1} - 2\Phi_i + \Phi_{i+1}}{L_0} + Ic \sin \varphi_i = 0$$

4

Propagation of Vortices Along
# Ring Josephson Junction II

Further Notes

- **Classical reversible computing is much closer to quantum computing than to conventional CMOS computing.**

- **Many people intuitively believe that quantum mode of reversible computing (or quantum computing) is more practical than classical reversible computing. In reality, classical reversible computing is much easier to implement. We are sure that demonstration of classical reversible circuits should be one of many intermediate stops on a very long road to any quantum computing.**

Reversible Computing at MIT and Lincoln Lab

It is widely accepted that for a long period of time Lincoln Lab and MIT played a very special role in the investigation and discoveries in the area of reversible computing. Here we would like to mention Edward Fredkin (currently with Carnegie Mellon University) and Tomasso Toffoli (currently with Boston University)
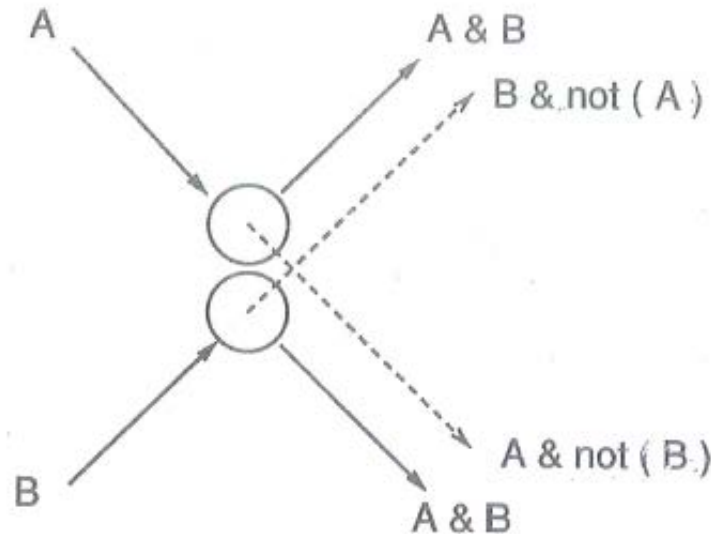
Mechanical billiard ball model for reversible computing

Highlights

- **Key theoretical discoveries in the area of Reversible Computing (RC) have been made in sixties and seventies by Landauer and Bennett. We closely followed their theoretical recommendations.**

- **Superconducting Josephson junction technology is the optimal choice for RC because it allows to eliminate static energy dissipation.**

- **Any prospective computing technology must satisfy a long list of requirements. Earlier suggestions for RC superconducting gates satisfied only a few of them. Our recent solution based on nSQUID gates is quite close to the requirement list. As a result, we experimentally approached the thermodynamic threshold.**

- **The most significant step was the elimination of multi-phase AC biasing schemes that are quite common for RC.**

- **The next important step could be a matching RC circuitry with a more conventional computing technology.**

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Competition for a Lower Energy Dissipation

(It has been discovered long ago that logic reversibility and thermodynamics set limitations for energy dissipation)

Only erasure of the information costs energy [R. Landauer]. This conclusion leads to the concept of logically reversible computation which avoids erasure of the information [C. Bennett].

Our goal was to experimentally approach and even cross thermodynamic threshold for energy dissipation per logic operation: $k_B T \ln 2$ (~4 $\cdot 10^{-23}$ J at T=4.2 K)

R. Landauer, "Irreversibility and heat generation in the computing process," *IBM J. of Res. and Devel.,* vol. 3, pp. 183-191, 1961.

C. Bennett, "Logical reversibility of computation", *IBM J. of Res. and Devel.*, vol. 17, p. 525, 1973

Impacts of Landauer Discoveries

The main paper
Title: Irreversibility and heat generation
in the computing process
Author: **Landauer R**
Source: IBM Journal of research and
development
Volume: 5   Issue: 3   Pages: 183-191
Published: 1961

Times Cited: **687**

With the so high number of citations it is possible to find papers of any kind, in particular those that give new proofs of Landauer principles and papers that explain why the principles are incorrect. However, about 2/3 of mentioned papers deal with reversible algorithms for Quantum Computing. This is because almost any Quantum Computer could be also termed as a Reversible Computer operating in a quantum mode.

This is quite strong an observation because it immediately leads to a natural question: Why QC researchers bypass a more simple classical mode of operation? Because it is more natural to start any big project from execution of simple tasks.
Probably we are the only group that tried to design and experimentally demonstrate Classical Reversible Computing.

Unprecedented Accuracy of R. Landauer Forecast
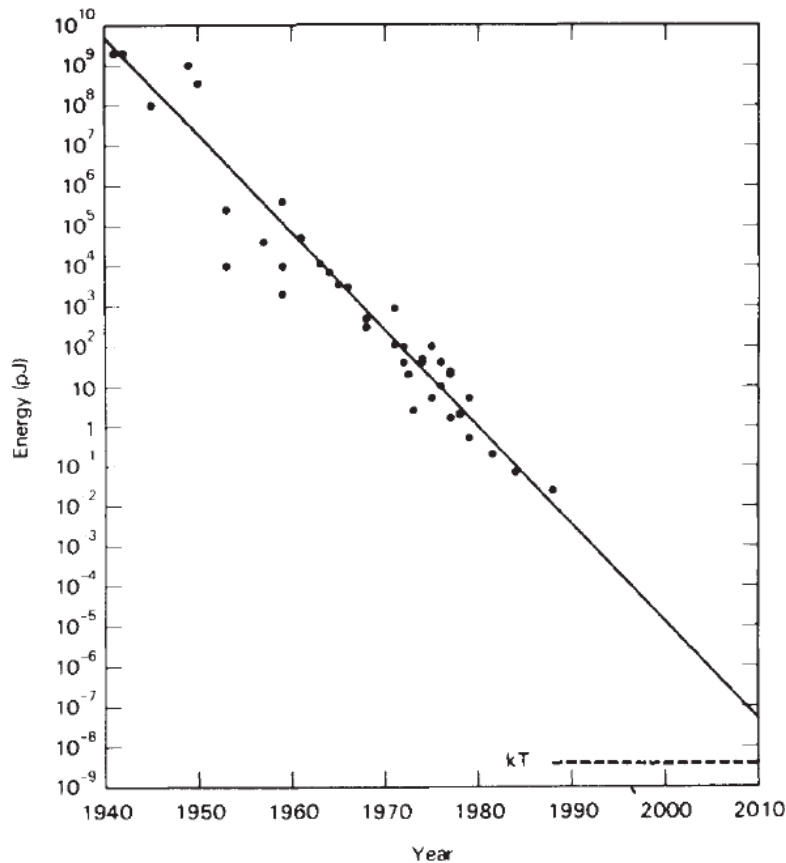
The decrease in energy dissipated per logic operation over recent decades.

In 1982 Landauer collected available data that are reasonably fitted by a simple exponential approximation. The fitting line hits kT threshold in 2014. We were on time to validate this forecast.

However, our circuit is too simple to be accepted as a model for universal circuits

Another Good Illustration For Reversible Computing
(Landauer 1991)

Must information be discarded in computation, communication and the measurement process? This question has physical importance because discarding a bit of information requires energy dissipation of order kT.
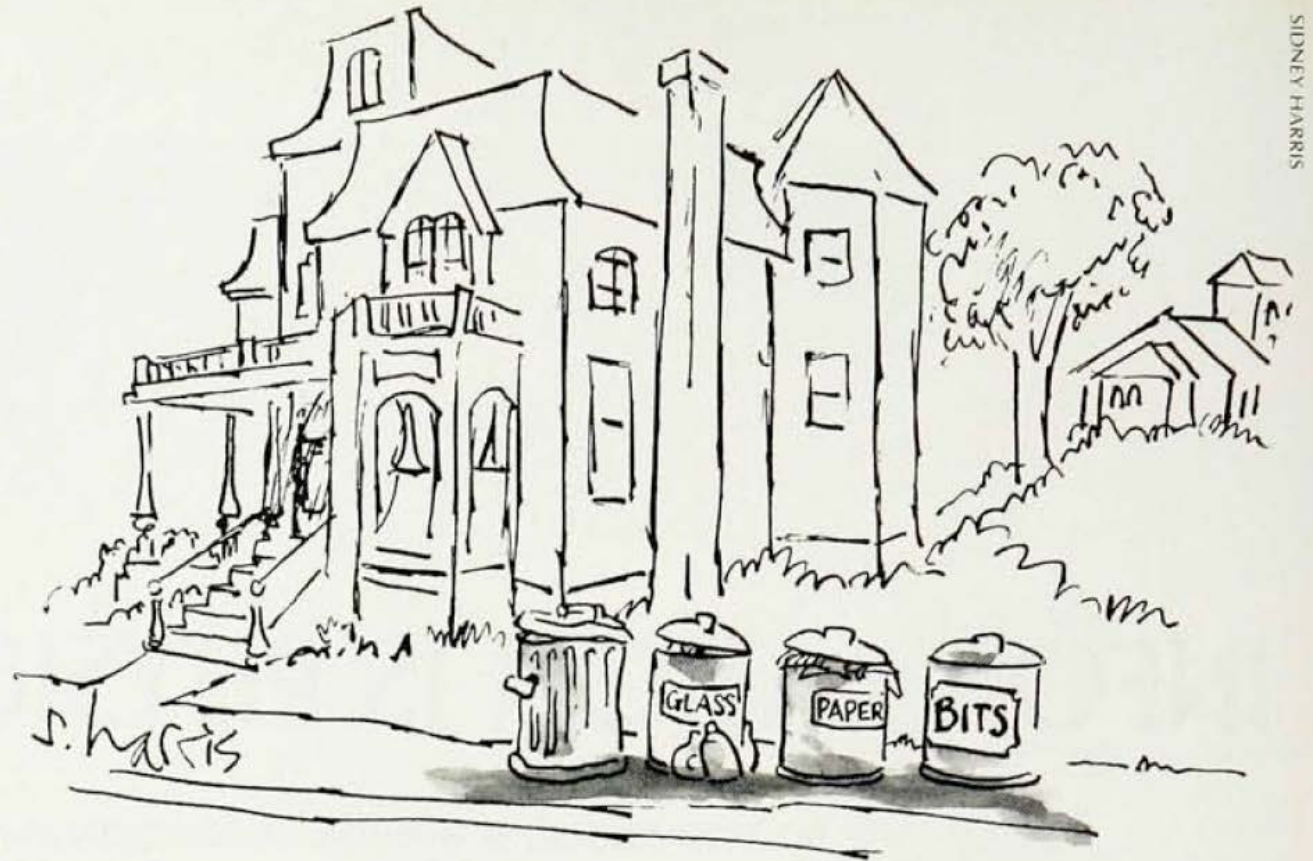
Introduction of Potentially Reversible Superconducting Circuits

-**No energy dissipation in superconducting state;**

-**Very convenient and accurate energy potential: $E(\varphi)=I_C\,(\varphi_{cl})\cdot\Phi_0\cdot\cos(\varphi)$;**

-**Developed technology: CAD tools, fabrication, measurement.**
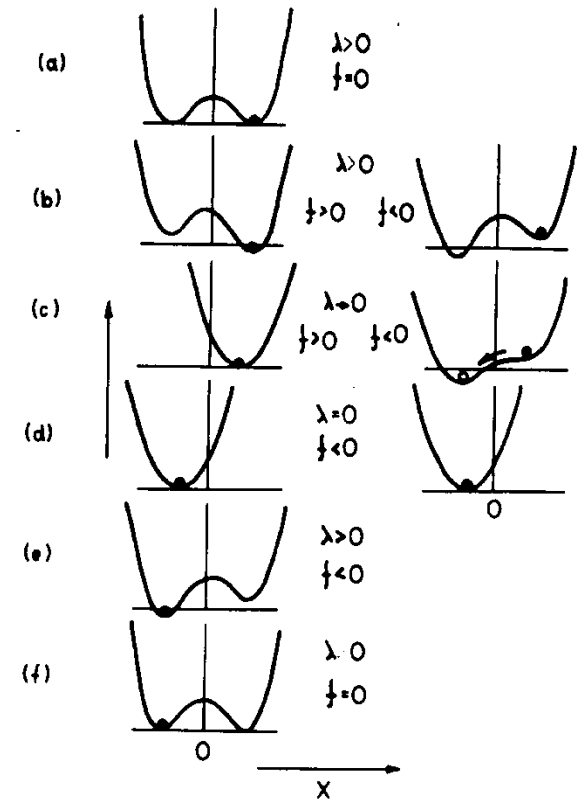
K.K. Likharev, "Classical and quantum limitations on energy consumption in computation," *Int. J. Theor. Phys.,* vol. 21, p. 311, 1982.

Circuit size is
about
4 mm x 2 mm
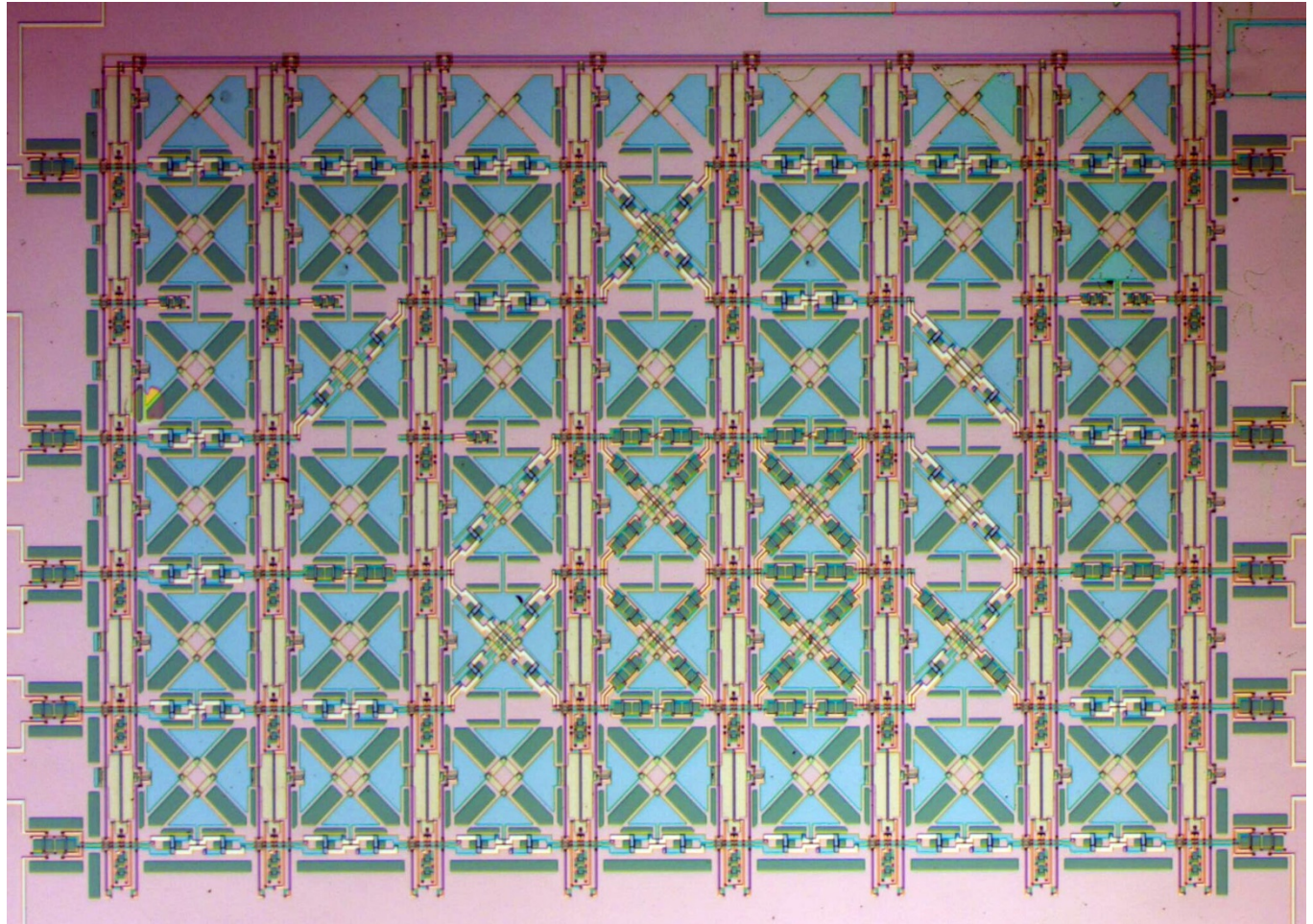
Grid of nSQUIDs
(2 x 2 nSQUID array)
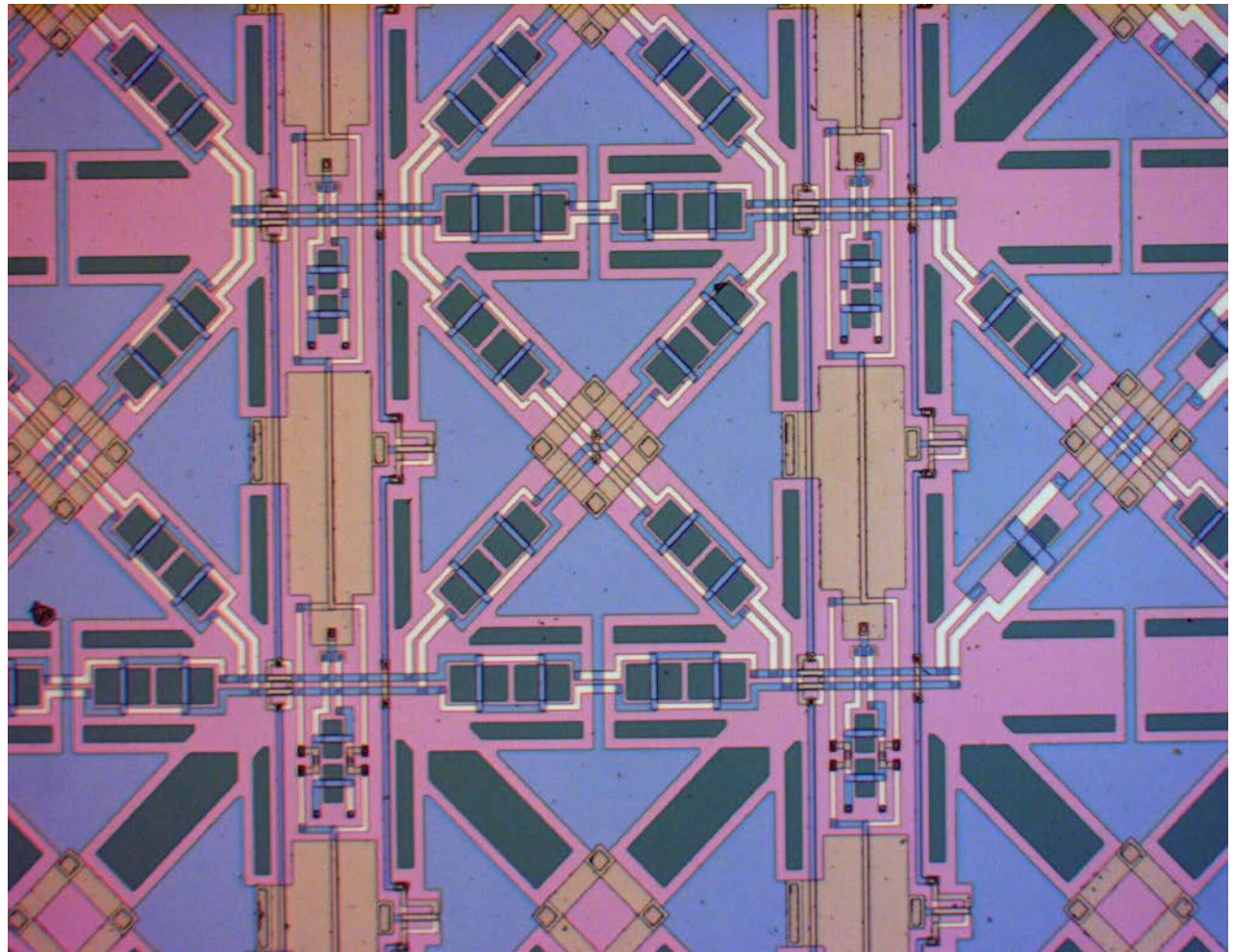
Grid of nSQUIDs
(one nSQUID)
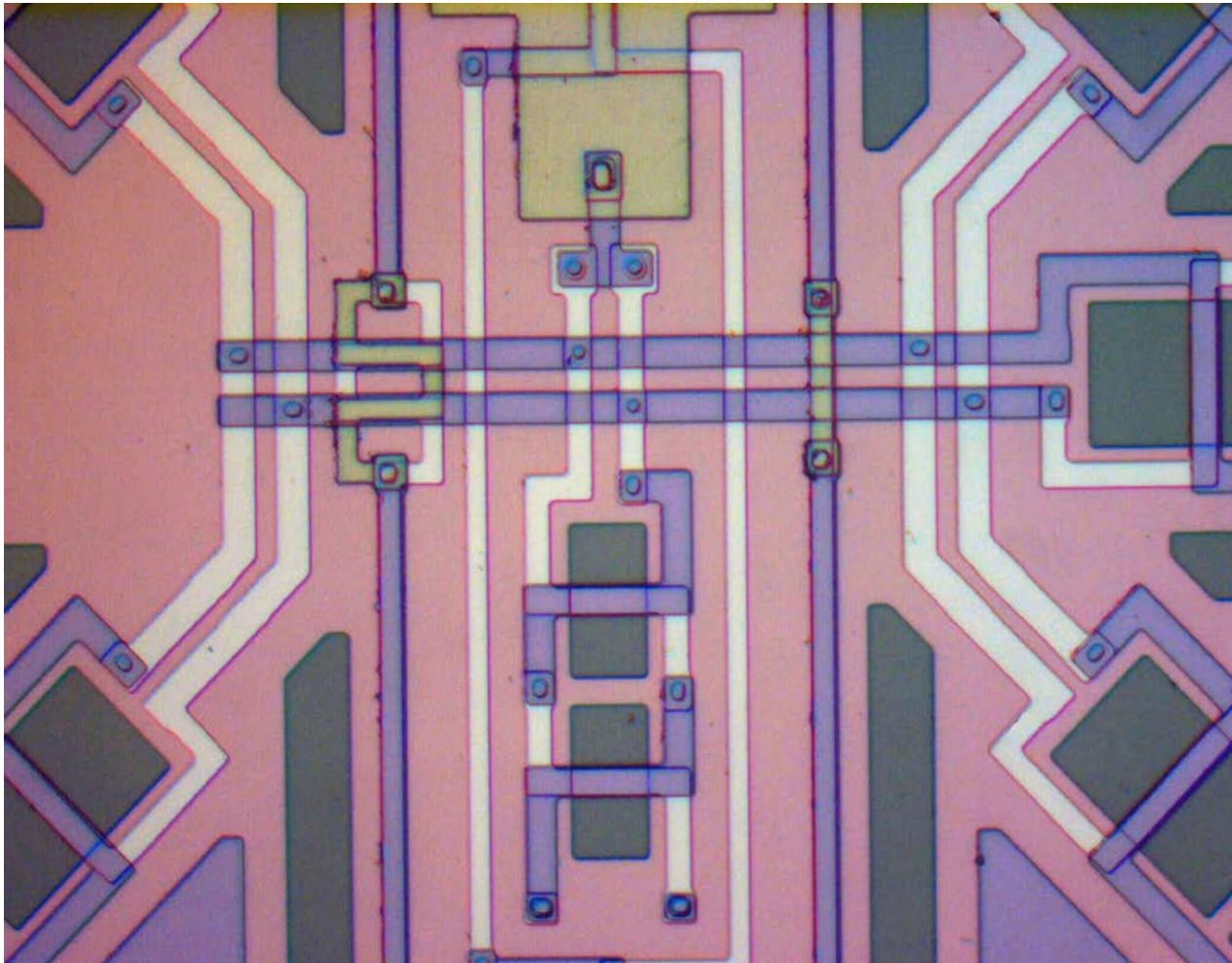
Parametric Quantron

also Known as Quantum Flux Parametron, Double SQUID, IN-SQUID, Flux and Ground-state Qubit

"Parametric Quantron", K.K. Likharev, and others 1985.
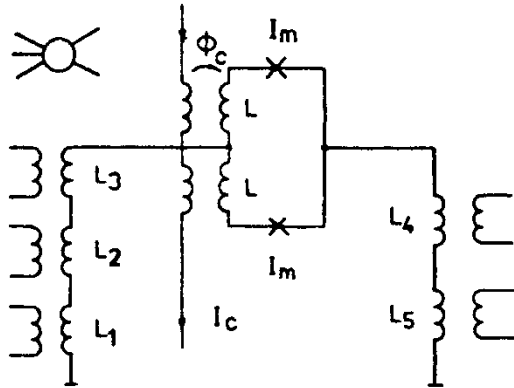
"DC or Quantum Flux Parametron", E.Goto and others, 1986
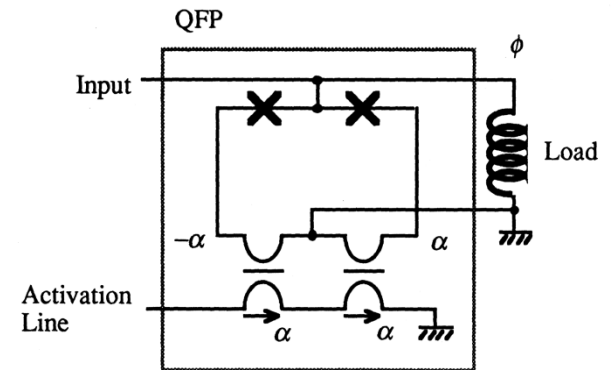
"IN-SQUID", J. Clarke and others, 2002
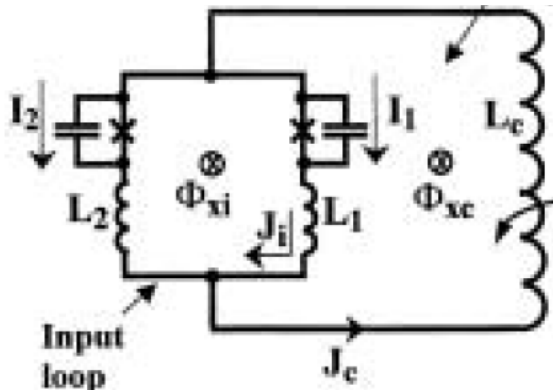
"Ground State Qubit", M. W. Johnson, and others, 2011.
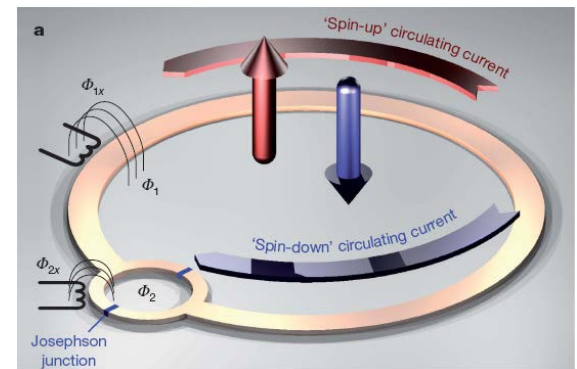
We mentioned only most common names given to almost identical devices that could be described as a superconducting inductance shorted by an externally controlled two-junction SQUID.

Properties of Inductance Shorted by Externally Controlled Two-Junction SQUID
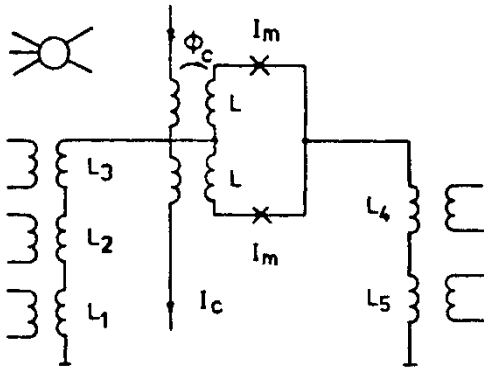
$$\frac{U(\varphi, \varphi_+)}{\Phi_0 I_m / 2\pi} =$$

$$\left(\frac{(\varphi_+ - \varphi_c)^2}{l} + \frac{(\varphi - \varphi_e)^2}{\Sigma l_i} \right) - 2\cos\varphi\cos\varphi_+$$
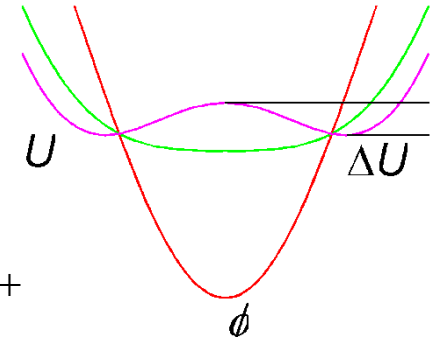
The effective critical current and therefore the energy profile of the device is controlled by an external current, Ic. This (AC) current delivers and takes energy to and from the cell. In other words, it serves as a bias current. At the same time it serves as a clock signal. **(In general, this is not good because several clock signals could be required to control complex logic circuits.)**

As an example, circuits developed in Goto group use 3-phase clocking scheme.
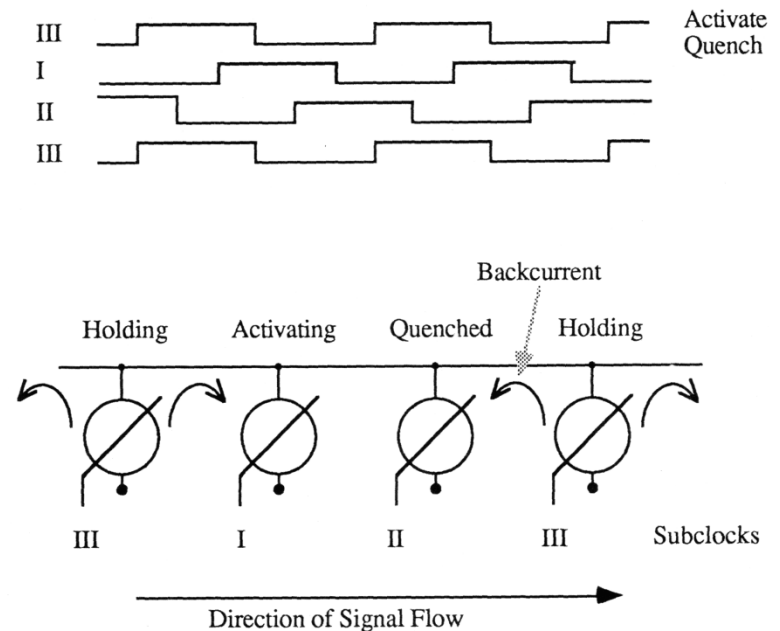
nSQUIDs (Basic Equations)
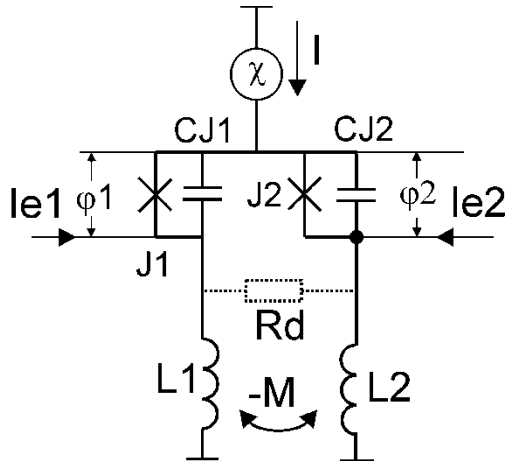
$$\varphi_+ = (\varphi_1 + \varphi_2)/2$$

$$\varphi = (\varphi_2 - \varphi_1)/2$$

$$\frac{U(\varphi_+, \varphi)}{\Phi_0 I_c / 2\pi} = \left(\frac{(\varphi_+ - \chi)^2}{1-k} + \frac{(\varphi - \varphi_e)^2}{1+k} \right) - 2\cos\varphi_+ \cos\varphi_-$$

$$\varphi e \sim (Ie1 - Ie2)/(1+k) \qquad k = |M|/L$$

Equivalent circuit of nSQUID string
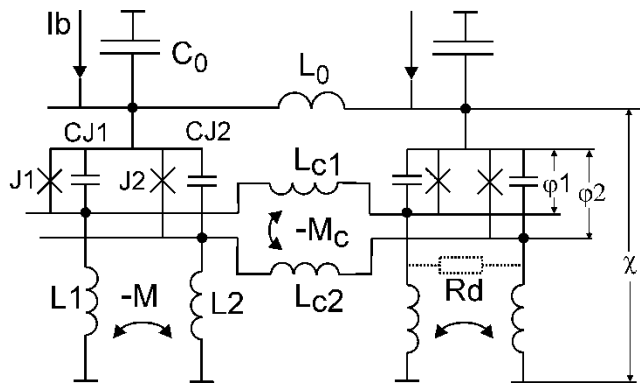
$$C_1 \frac{d^2\chi_i}{dt^2} - \frac{\chi_{i-1} - 2\chi_i + \chi_{i+1}}{L_0} + \frac{\Phi_0}{2\pi} Ic \sin\chi_i \cdot \cos\varphi_i = 0$$

$$C_2 \frac{d^2\varphi_i}{dt^2} - \frac{\varphi_{i-1} - 2\varphi_i + \varphi_{i+1}}{L1} + \frac{\varphi_i}{L2} + \frac{\Phi_0}{2\pi} Ic \sin\varphi_i \cdot \cos\chi_i = 0$$

Equivalent circuit of a string of nSQUID.

Numerical Solution

Sine Gordon Eq.

$$C_1 \frac{d^2 \chi_i}{dt^2} - \frac{\chi_{i-1} - 2\chi_i + \chi_{i+1}}{L_0} + \frac{\Phi_0}{2\pi} Ic\sin \chi_i \cdot \cos \varphi_i = 0$$

SQUID or Qubit Eq.

$$C_2 \frac{d^2 \varphi_i}{dt^2} - \frac{\varphi_{i-1} - 2\varphi_i + \varphi_{i+1}}{L1} + \frac{\varphi_i}{L2} + \frac{\Phi_0}{2\pi} Ic\sin \varphi_i \cdot \cos \chi_i = 0$$

Plots (top to bottom) show:
1 Common (Jos. Vortex) phase
2 Common current (blue) and effective
crit. current (green)
3 Differential Phase
4 Differential current (blue) and effective
crit. current (green)
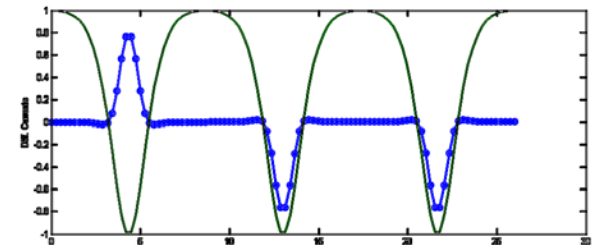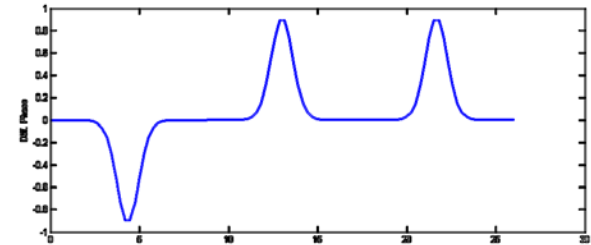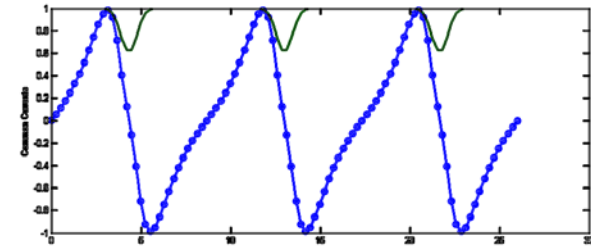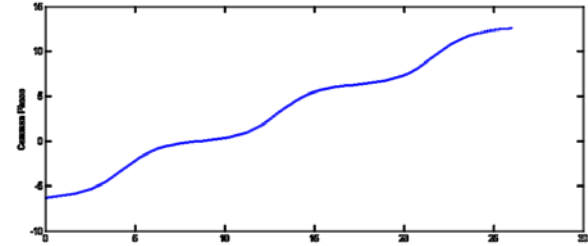
The First nSQUID Layout (ASC 2002)
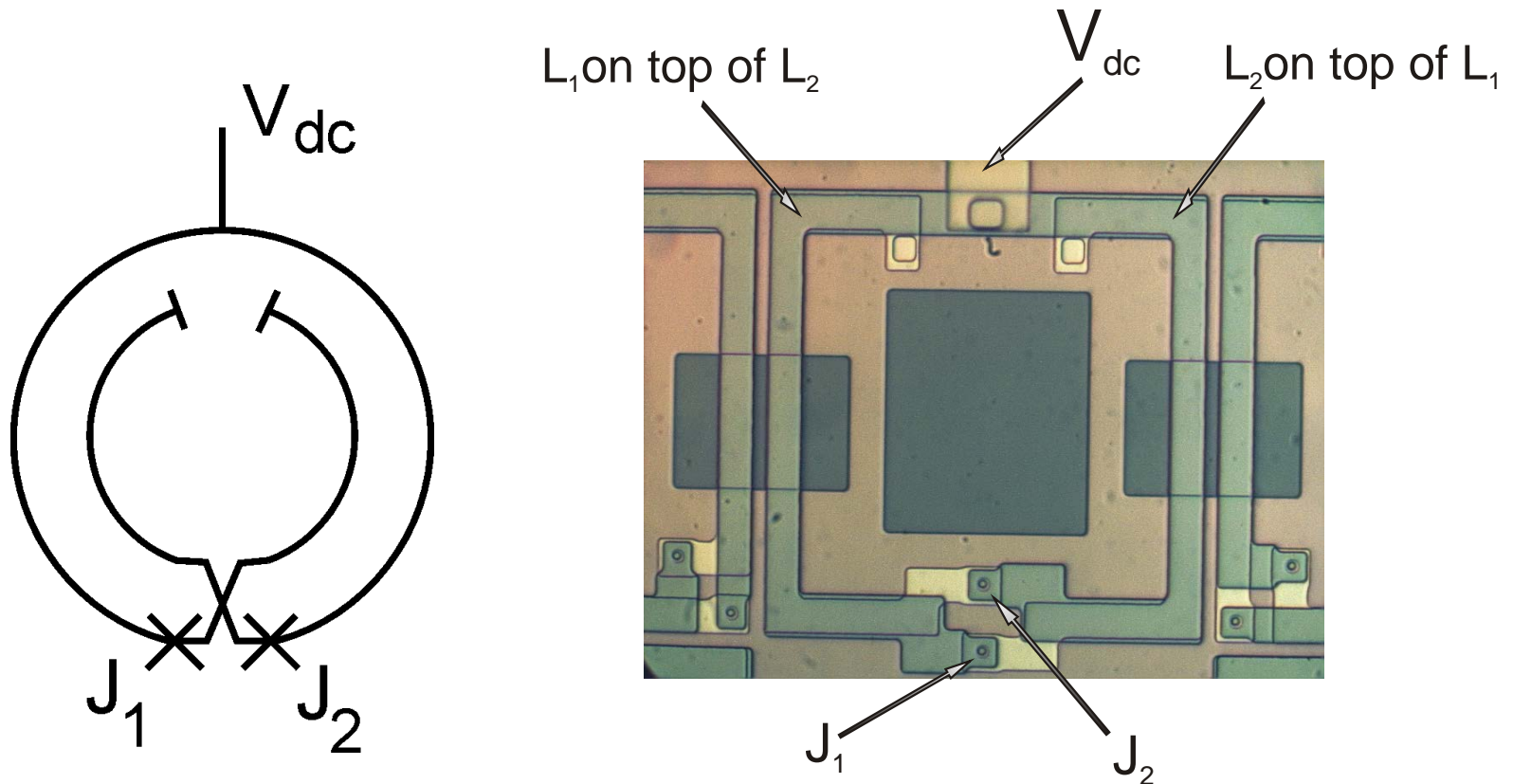
The circuit was fabricated at HYPRES, Inc. Target Ic = 0.015 mA. Dark areas are the ground plane moats. The left and right moats are used for magnetic coupling with other nSQUIDs

Schematics and Layouts of nSQUIDs with Galvanic Coupling
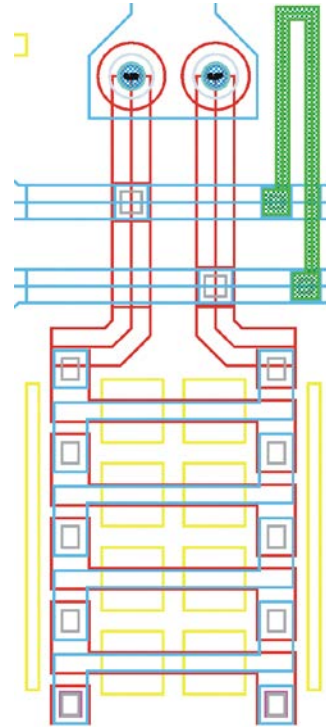
C
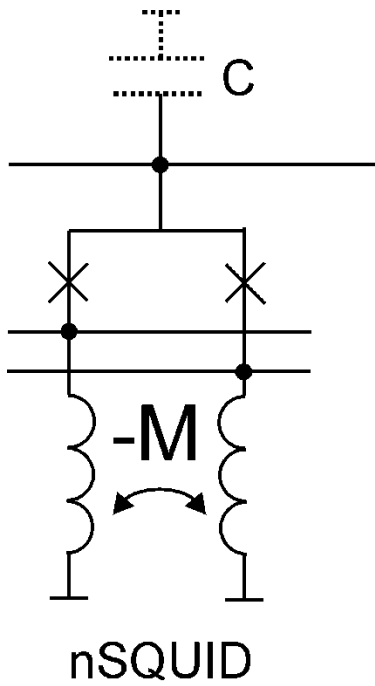
Clock line

Differential data lines

I_c= 0.01 mA
L=26 pH
M=-20 pH

-M
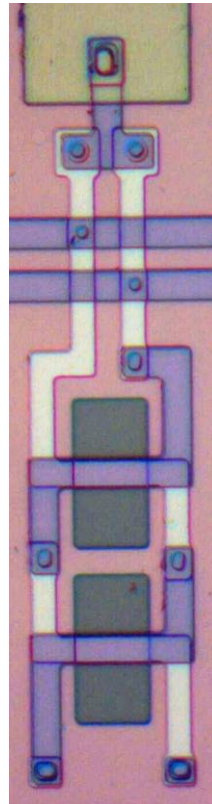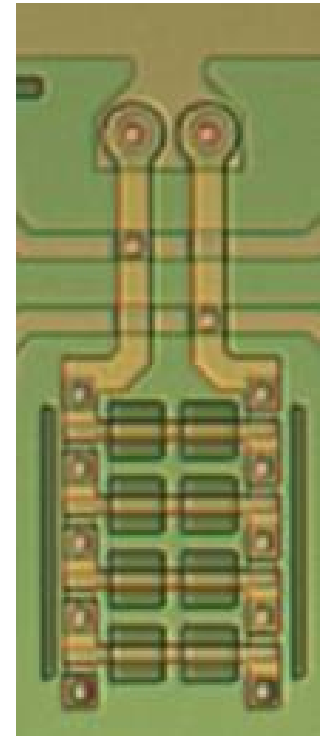
nSQUID

Year 2004

Year 2007-08

nSQUIDs as Building Blocks for Large Circuits
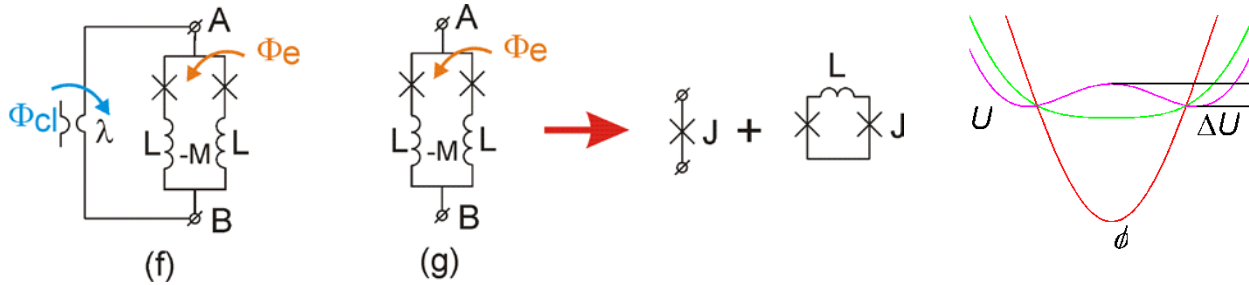
JJ phase drop controls (or clocks) the SQUID energy profile from mono-stable at $\phi_{cl}=0$ to bi-stable at $\phi_{cl}=\pi$

Long Josephson junction

Fluxons or Josephson vortices can freely move along long Josephson junctions with arbitrary speed V that depends only on initial and boundary conditions.
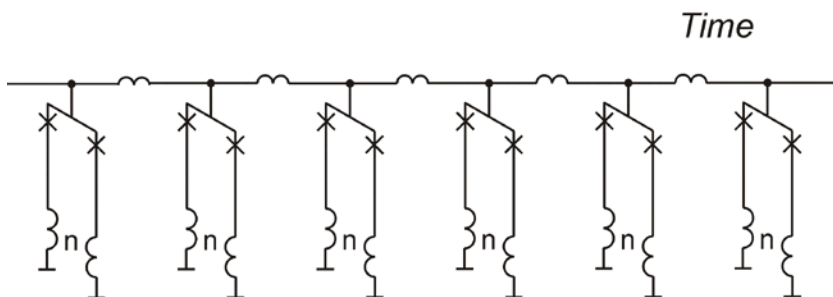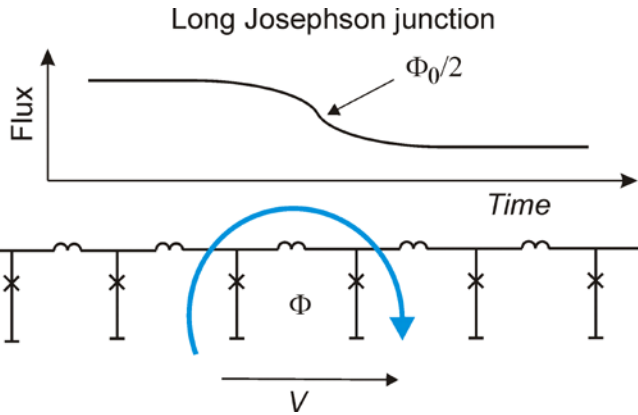
A long Josephson junction could be made of nSQUIDs. The SQUIDs located near the center of a moving or resting vortex have bistable energy profile and they should randomly "fall" into one of two energy minimums.
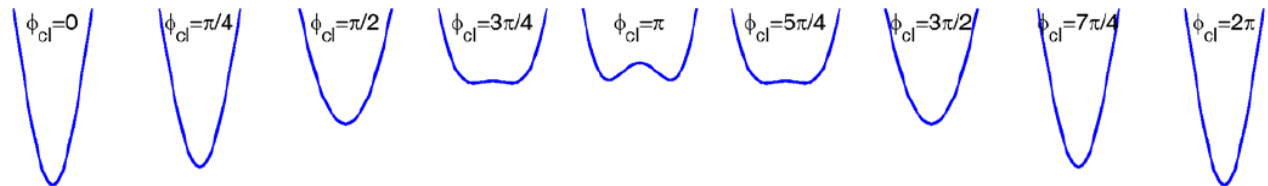
String of nSQUID is one of the Simplest Digital Circuits

Let us magnetically couple neighboring nSQUIDs. Such mutual biasing should force all nSQUIDs belonging to one Josephson vortex to select the same energy minimum.

Sketches below show energy profiles when one vortex occupies 8 nSQUIDs and the coupling is vanishingly low.
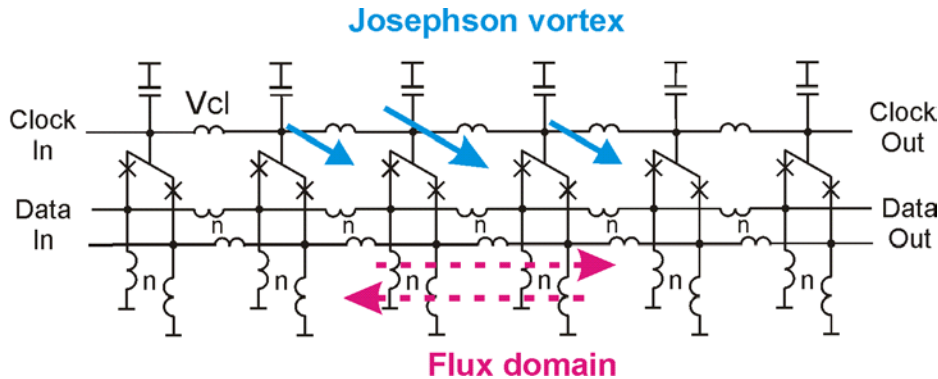
Energy profiles at $k=0$ -->
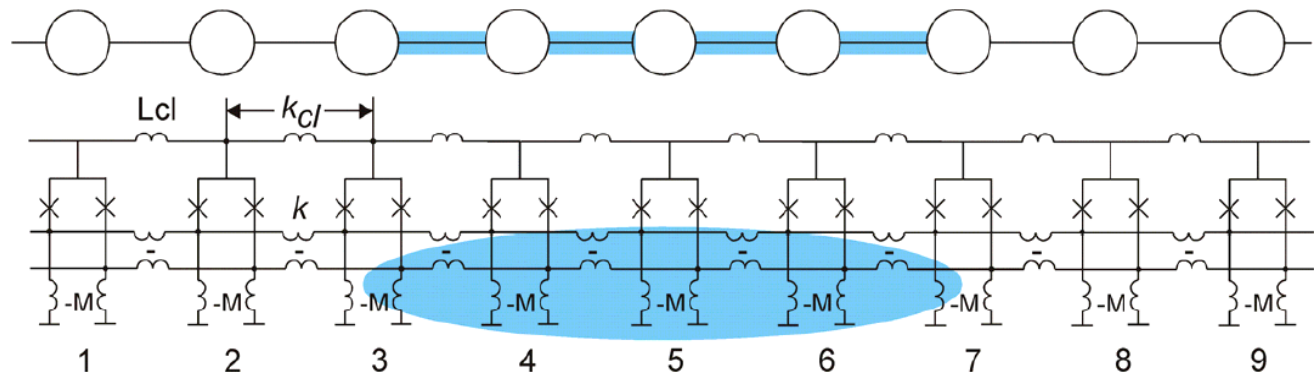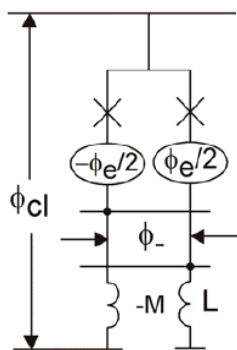
Integrated Circuit with
Two Reversible Shift Registers

We run 8 revisions of 5 mm x 5 mm design with 2 nSQUID shift registers sharing a common clock ring. Each shift register contains 8 nSQUIDs, 2 readout SQUIDs and 2 inputs/outputs.

Besides, the circuit contains "a magnetic bias" cell injecting into the clock ring 2 Josephson vortices (or $2\Phi_0$ phase shift) and a voltage (power) source.

The (bias) current flowing via the shift register is measured by a SQIF.

Two stand-alone cells (nSQUID and SQIF) are used for calibration.

$2\Phi_0$

2 Shift Registers

Voltage Source

Dummy cells

RC08

2 SQIFs (μA-meters)
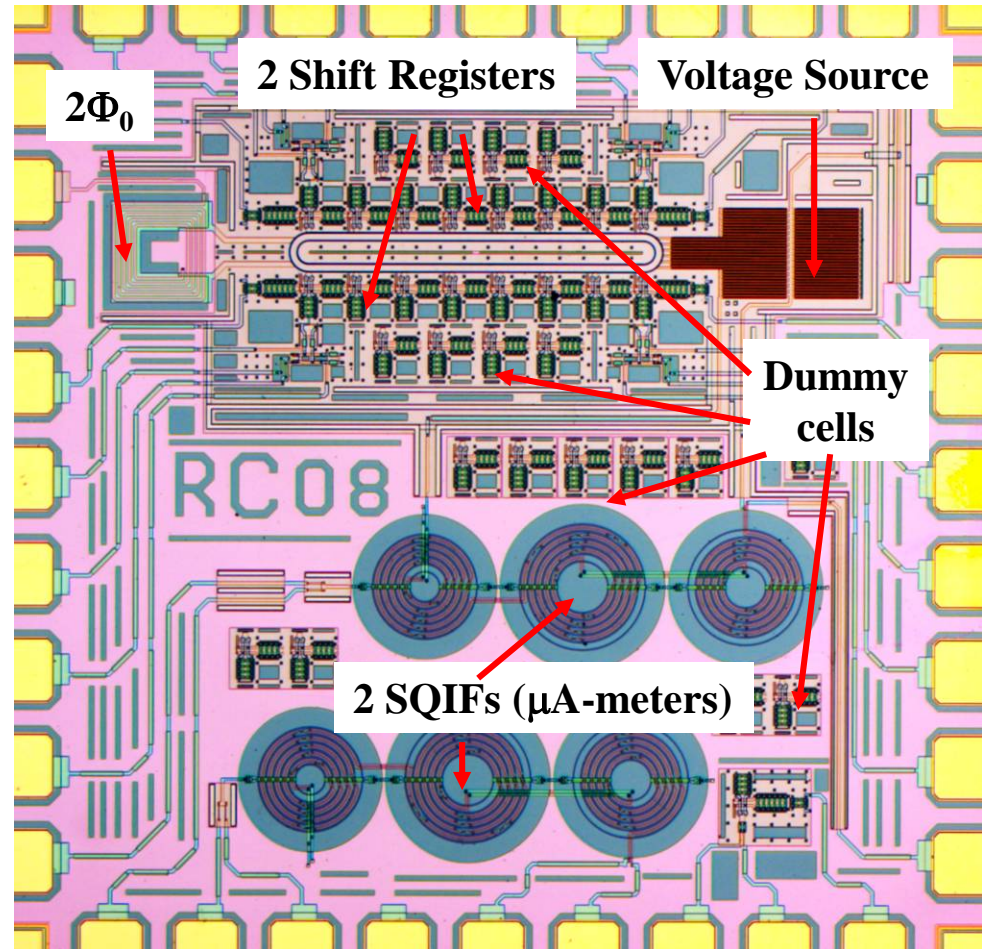
Two Shift Registers with a Common Clock Ring

Target critical current density jc=30 A/cm2;
Pitch – 170 μm,
Each register contains 8 nSQUIDs;
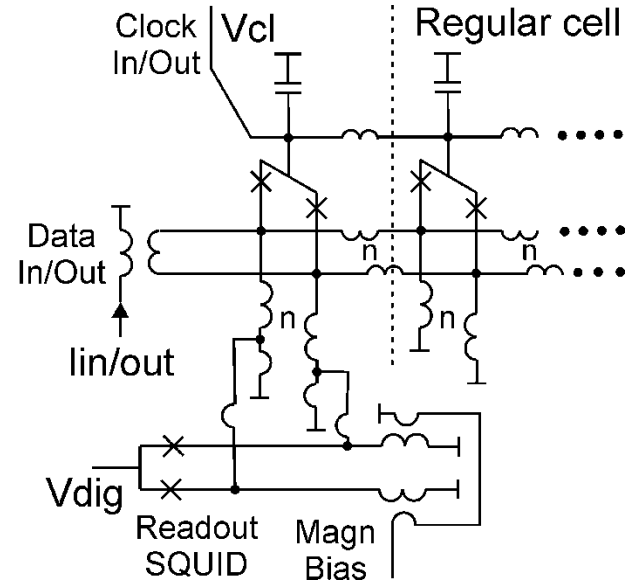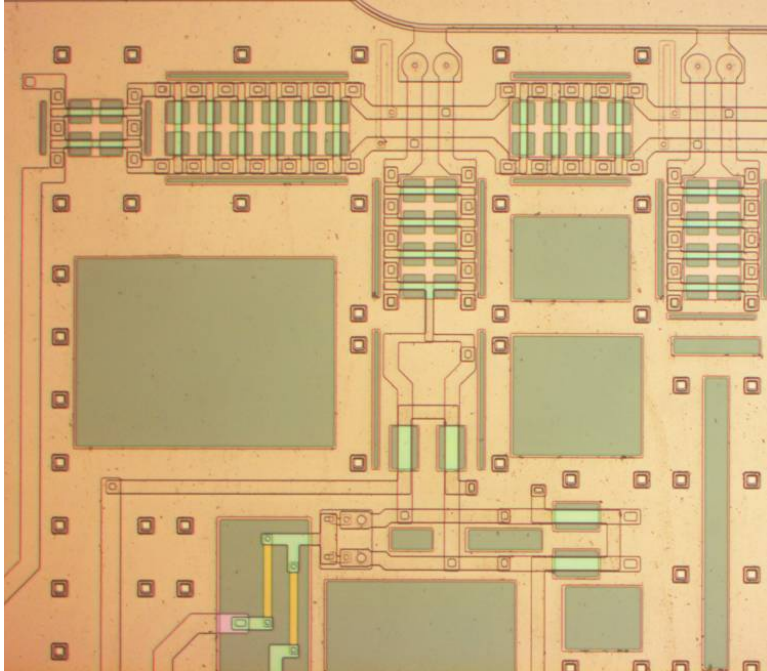Reading of data is provided by DC SQUIDs. (Coupling factor with the nSQUID is about 3 %.)

N Φ₀ generator

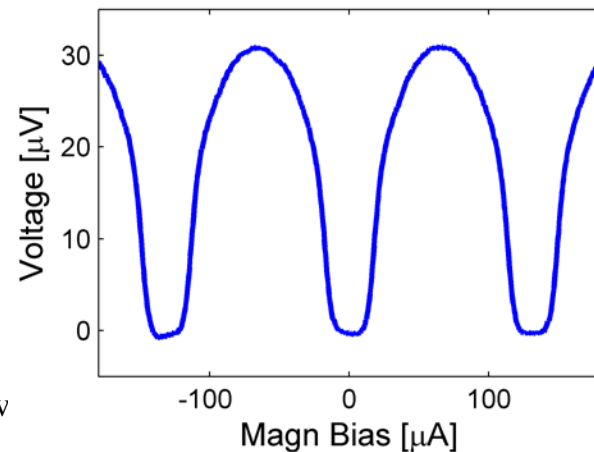External Magnetic Field

I_m

$2\Phi_0$
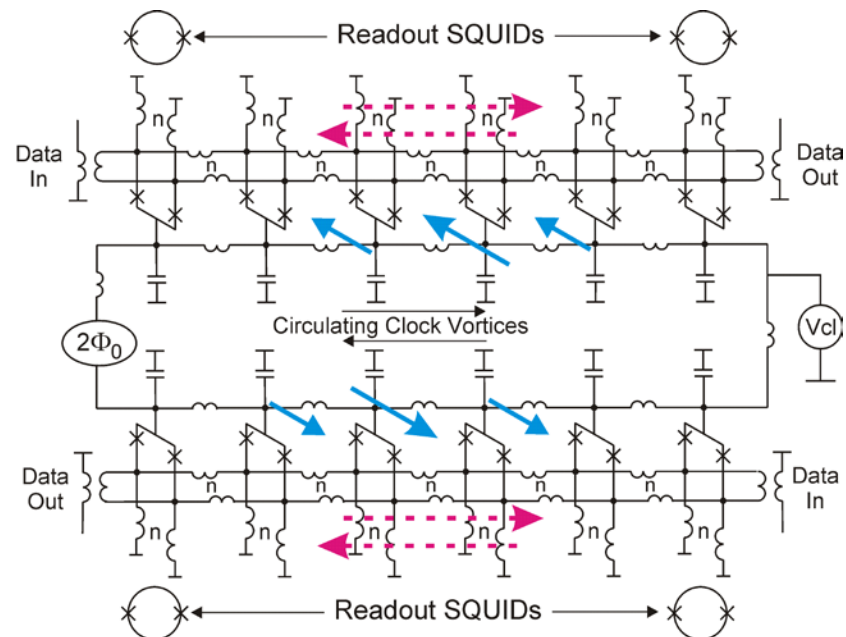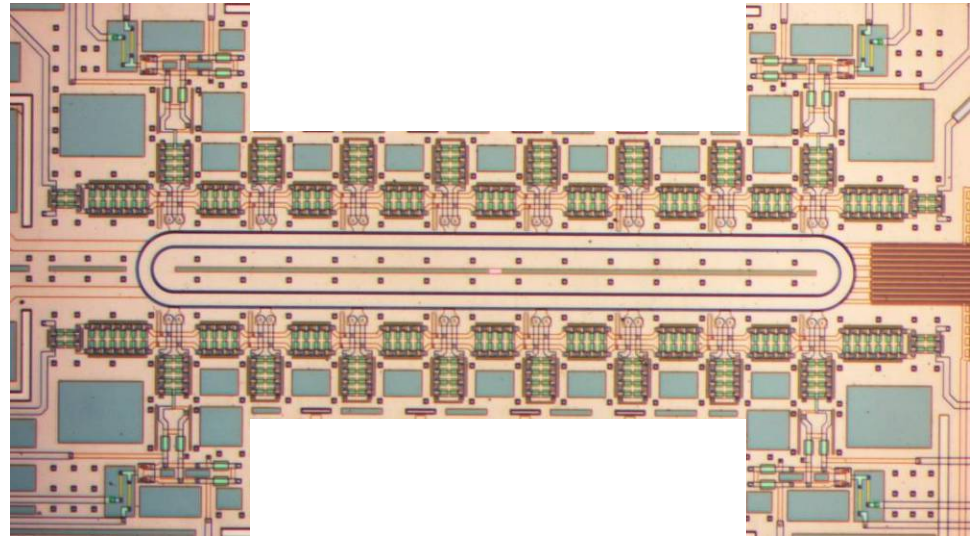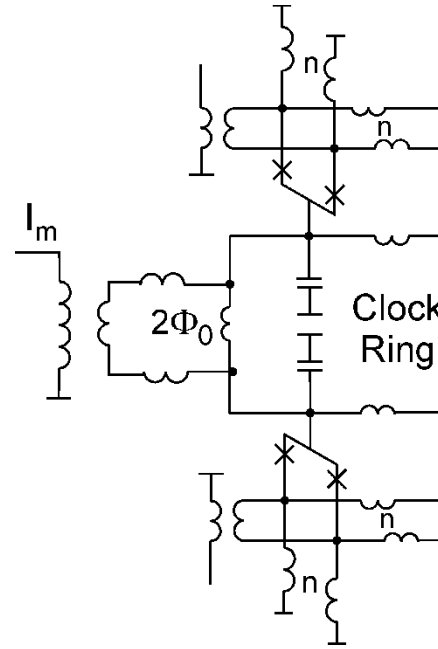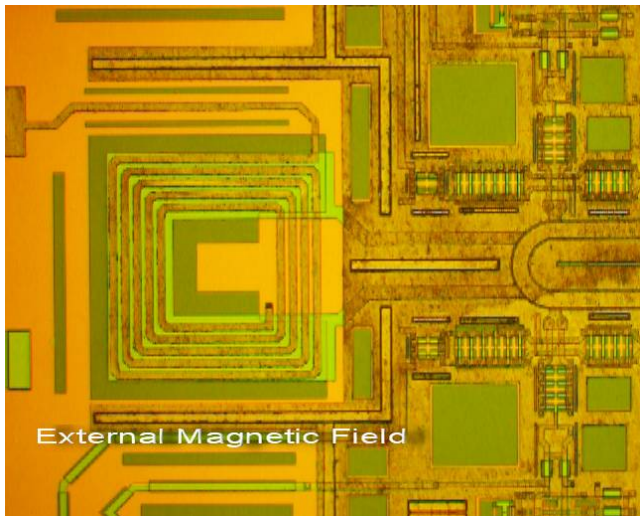
Clock Ring

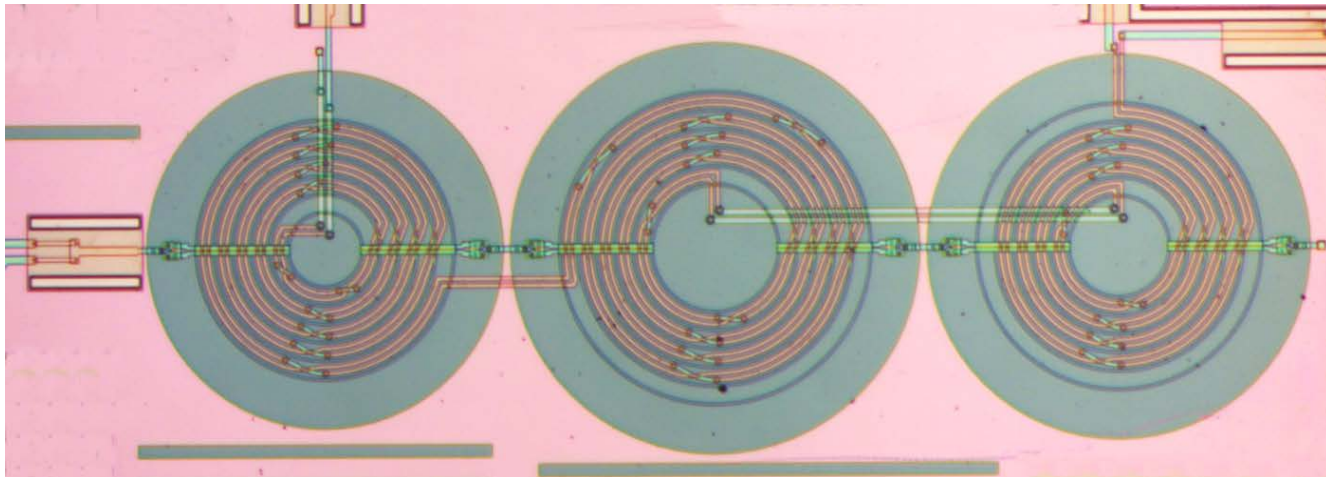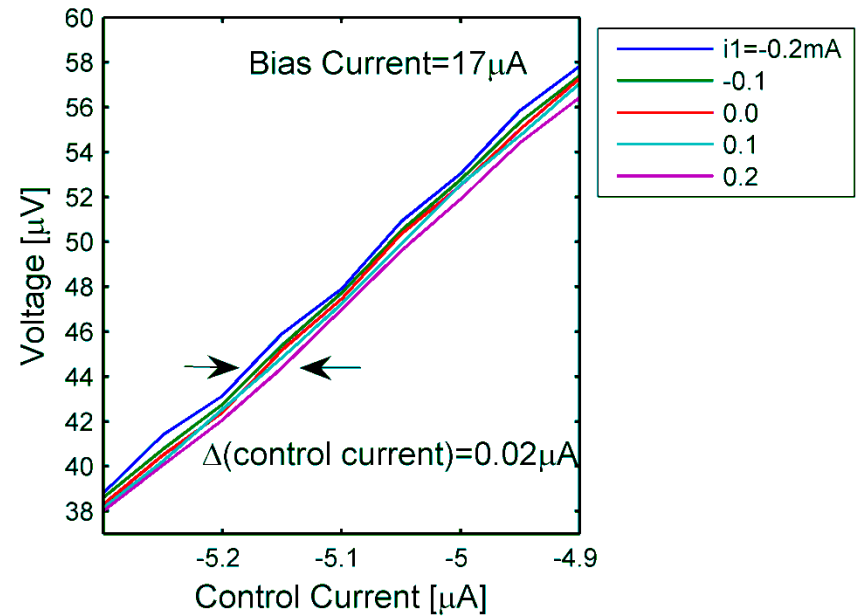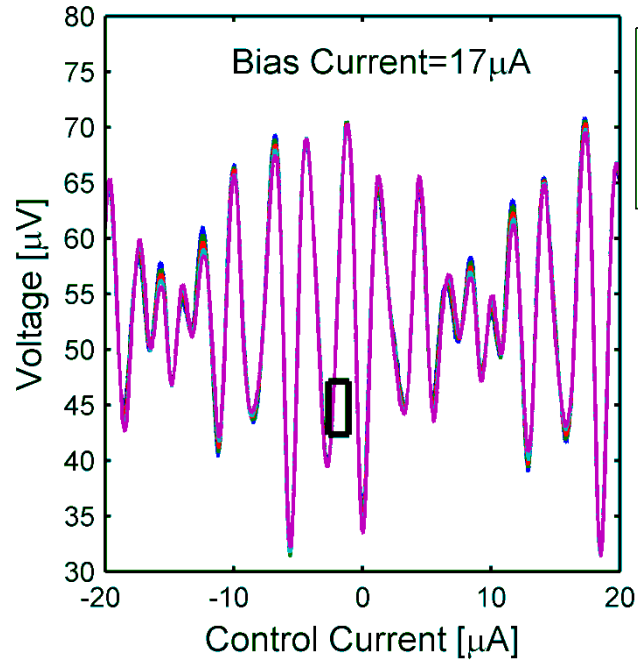Josephson vortices are "injected" into the clock ring by applying a corresponding magnetic flux to one of ring inductances.
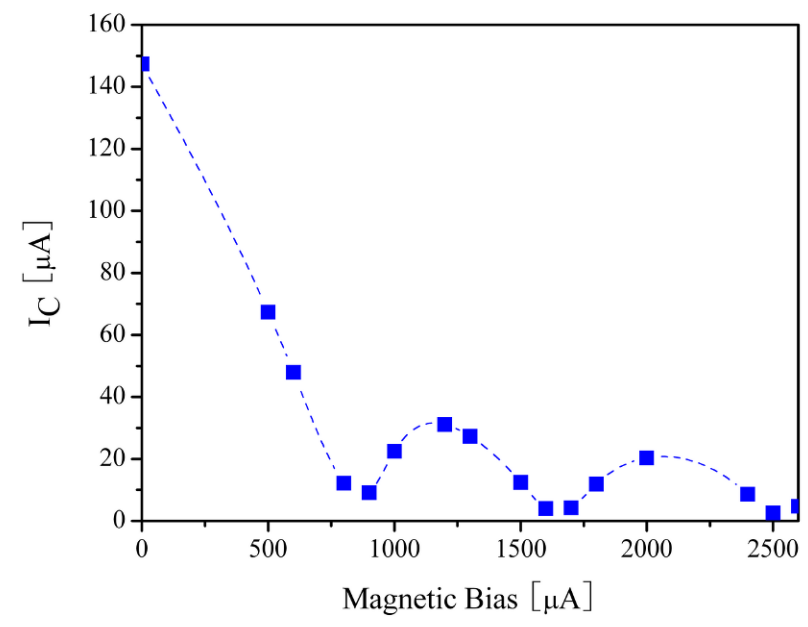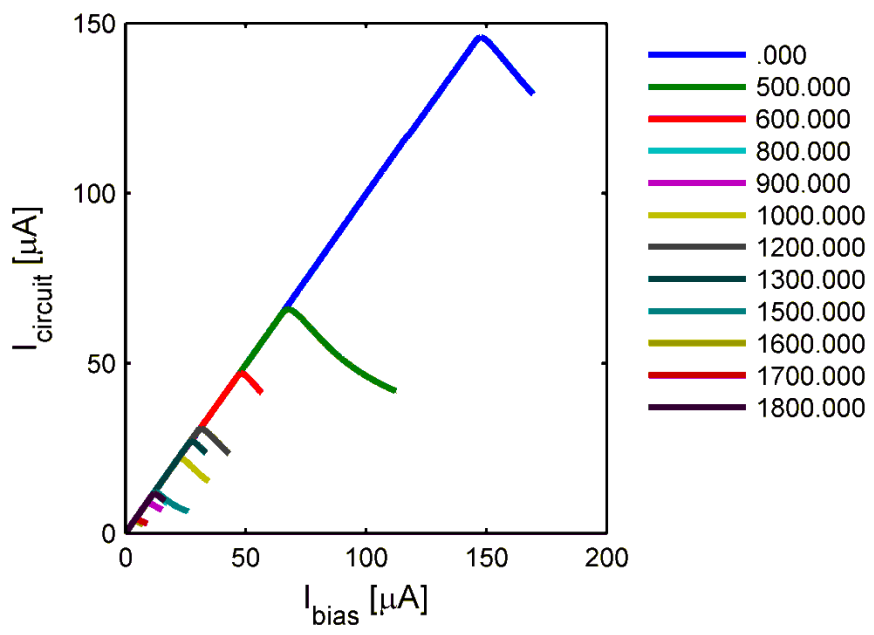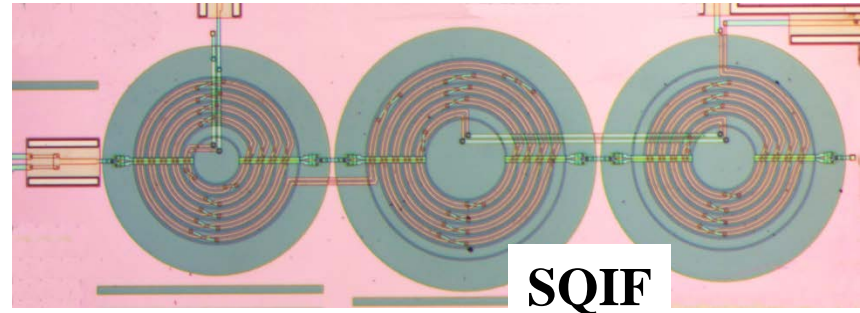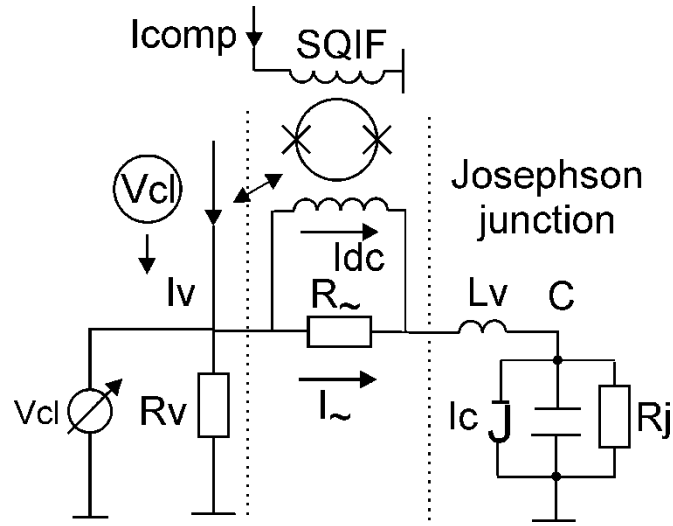
Data Input/Output and Readout SQUID

Differential phase of nSQUID is measured by a readout SQUID. (Effective coupling ~3%)

Vasili.Semenov

Superconductor (SQIF Based) micro Ampere-meter with a low crosstalk

Measurement of Bias Current I.

Icomp SQIF

Vcl

Iv

Idc

R~

I~

Vcl Rv

Lv C

Josephson junction

Ic J Rj

SQIF

—	.000
—	500.000
—	600.000
—	800.000
—	900.000
—	1000.000
—	1200.000
—	1300.000
—	1500.000
—	1600.000
—	1700.000
—	1800.000

$I_{circuit}$ [μA]

I_{bias} [μA]

I_C [μA]

Magnetic Bias [μA]

Measurements of Energy Dissipation

Due to DC biasing it is possible to reduce energy measurements to much simpler current measurements

$$E = V \cdot I \cdot Period$$

$$1/Period = (1/\Phi_0) \cdot V$$

$$E = \Phi_0 \cdot I$$

$$E_{th} = k_B T \ln 2$$

$$I_{th} = (\ln 2 / \Phi_0) \cdot k_B Temp$$

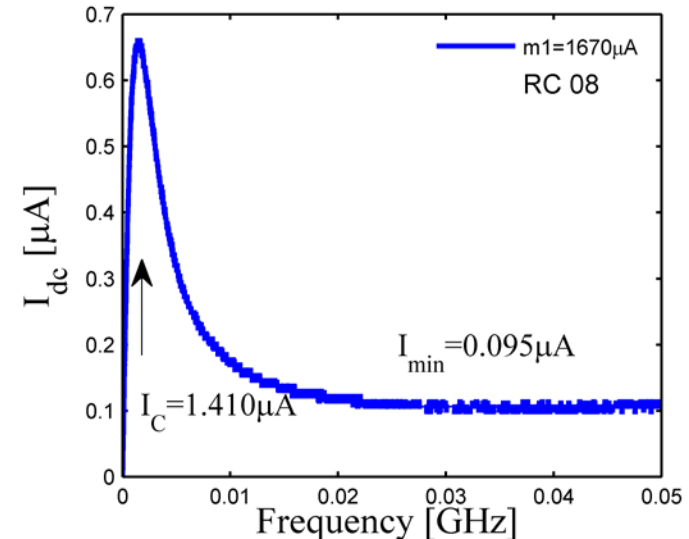At $Temp$=4.2 K $\qquad$ I_{th}=0.02μA

Measurement of the Energy Dissipation

Digitization of analog input magnetic flux and transfer it on about 2 mm distance, where the digitized signal is measured by a dc SQUID.
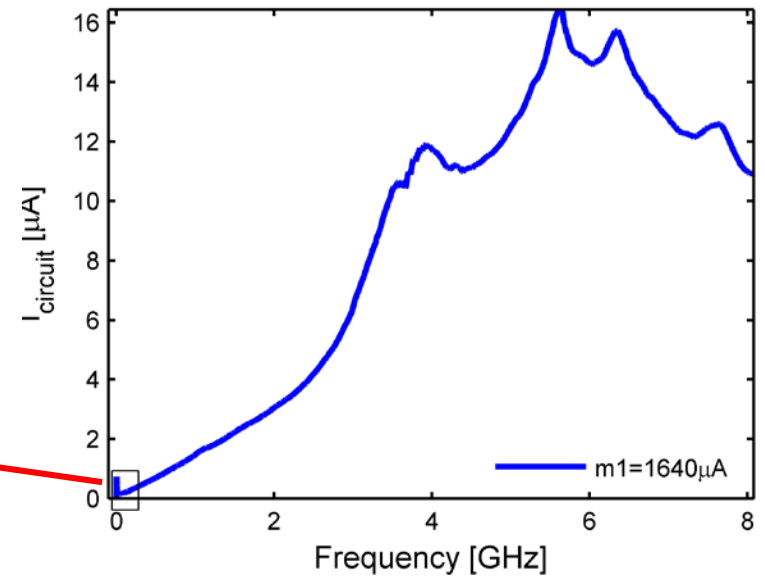
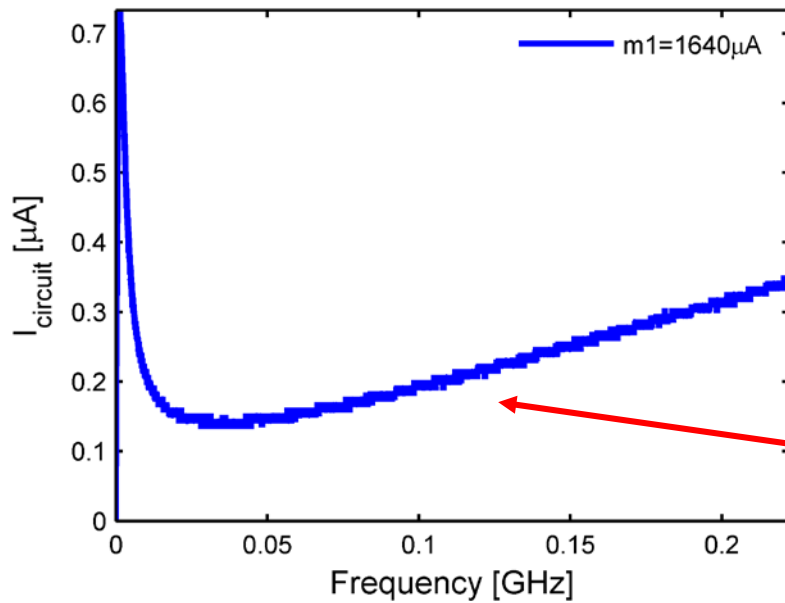**Legends show clock frequencies in GHz.**
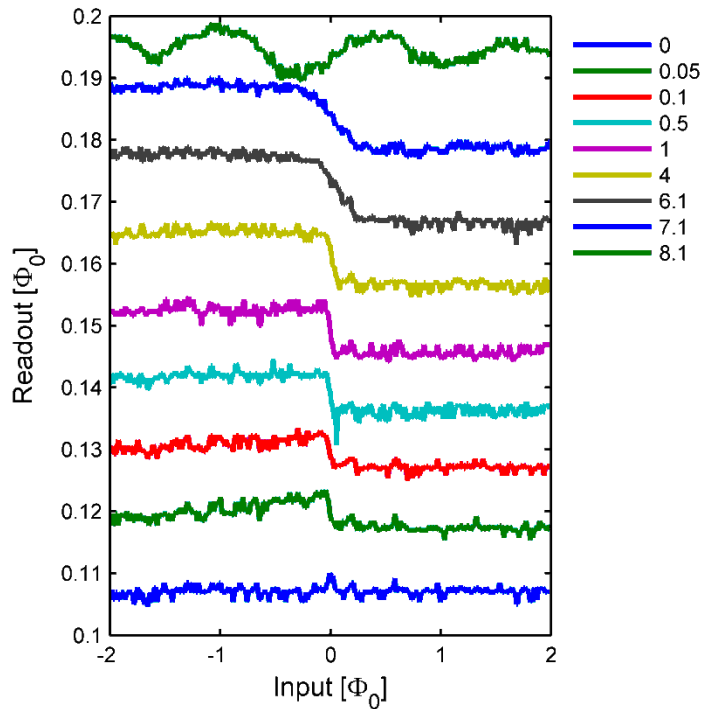
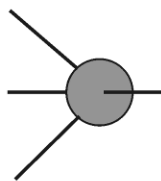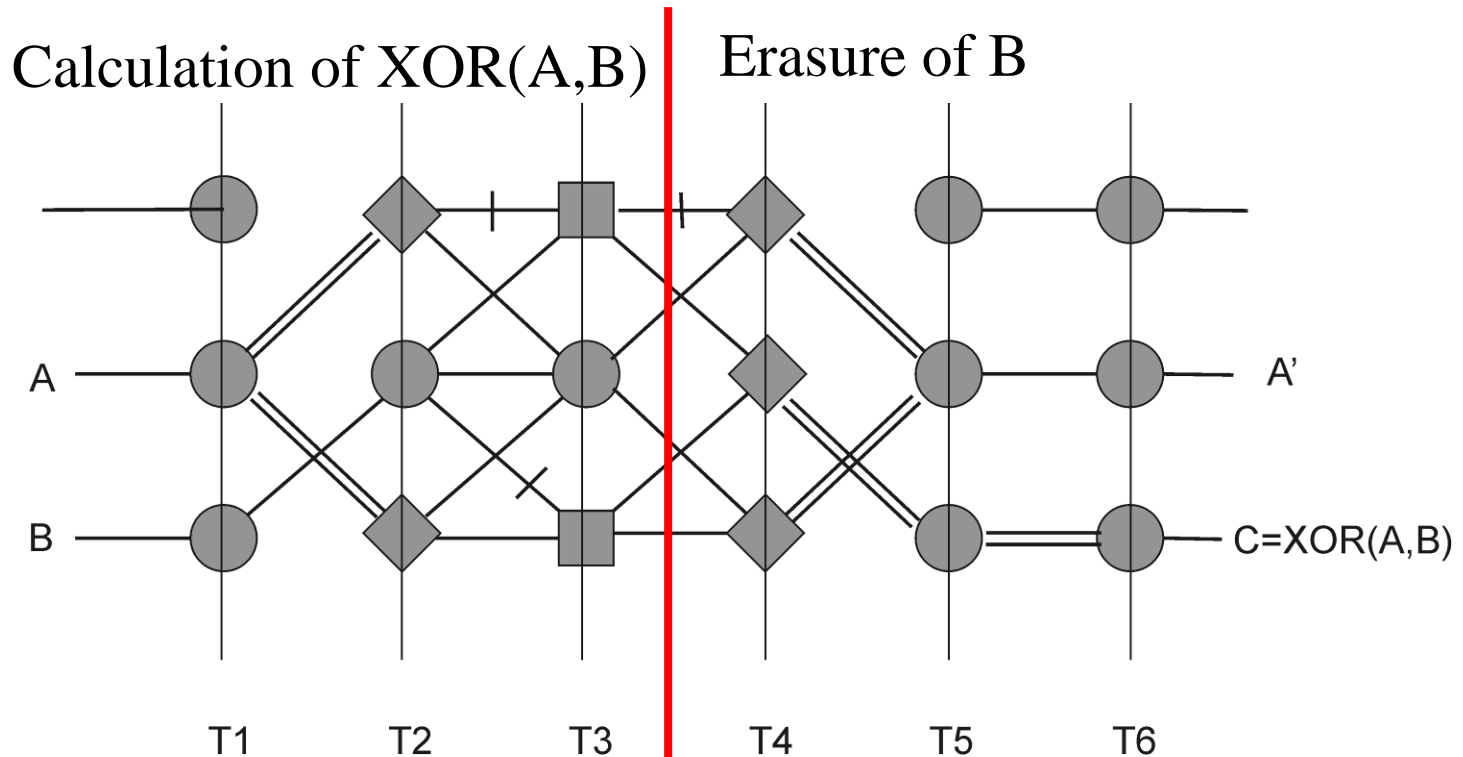2 vortices in the clock loop. Frequency range 0.05 GHz to 7.1 GHz

Measurement of the energy dissipation (in fact, dc current flowing via the circuit): the minimal observed current is about 2x the thermodynamic threshold value (0.04 μA).
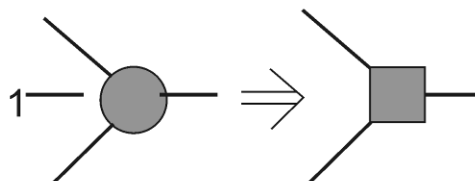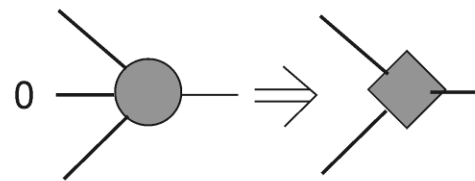
Measurement of Bias Current II.

Application of Bennett's Technique to Design of XOR Gate

Calculation of XOR(A,B)   Erasure of B
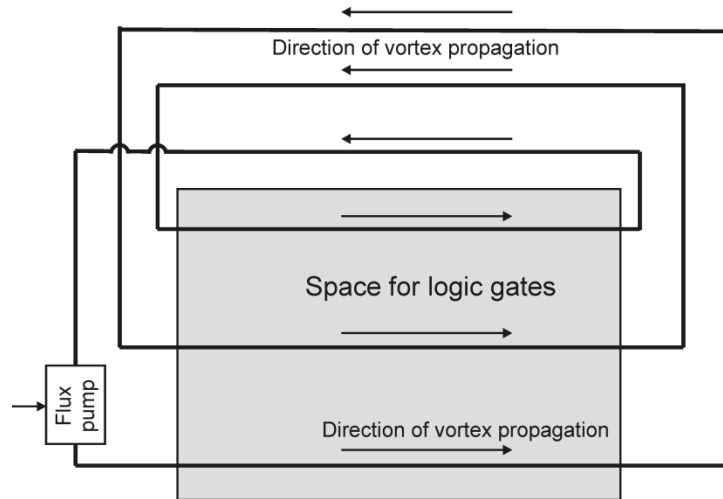
Architecture and System Issues: Timing Belt Clock Scheme

Two functionally similar "timing belts". One is composed of long Josephson junctions and nSQUID strings (both are shown as a black line) filled with vortices, while the other is a usual rubber timing belt used in cars.
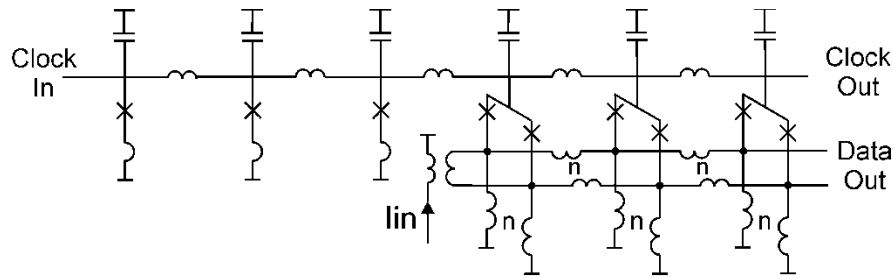
Timing Belt Serving Reversible XOR Gate Composed of Majority, OR and AND gates.

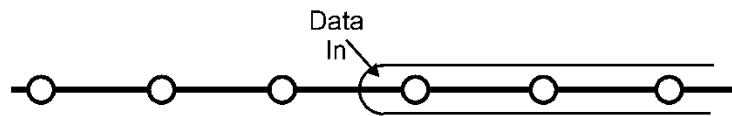(It can easy treated a kind of **superstring** composed of Josephson junctions)
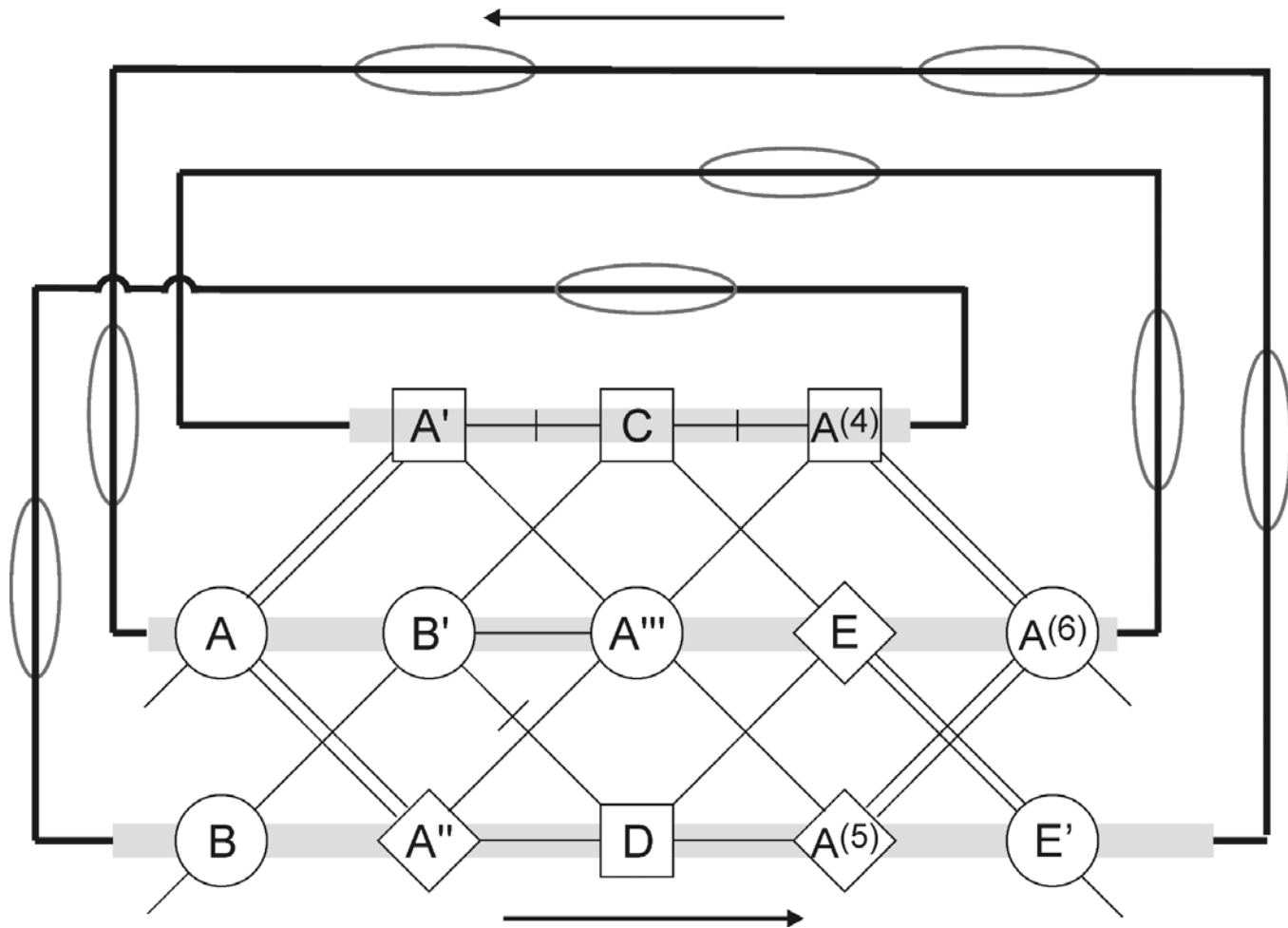
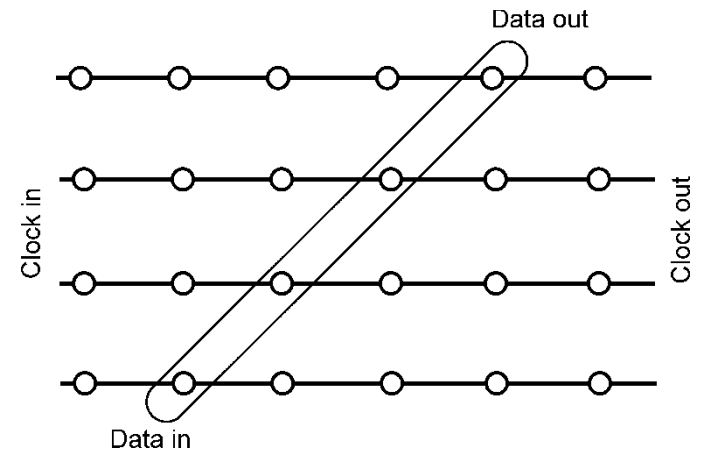# Important nSQUID Primitives

longJJ nSQUID Interface

(a)

(b)

Optional SQUID readout
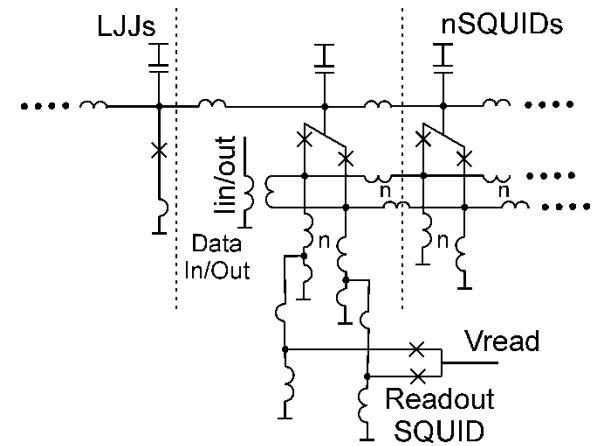
Copying and reversible Erasure of Data
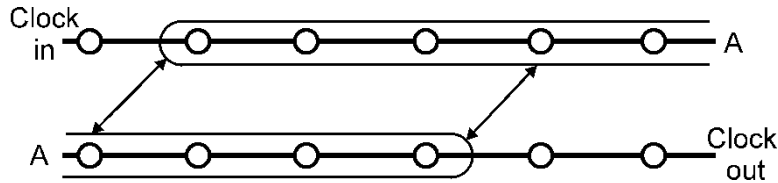
Possible implementation

Explanations taken from an old
Landauer paper   ===➔
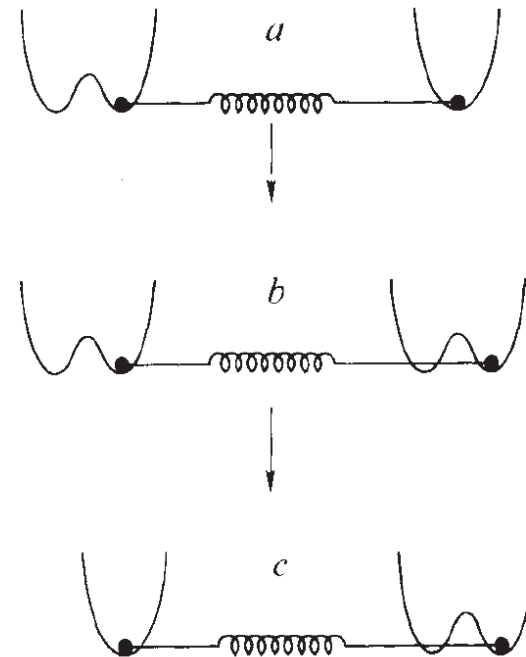
Coupled particles in time-dependent potential wells. In the transition from *a* to *b*, the information in the bistable well on the left sets the state of the one on the right. In the transition from *b* to *c* the well on the left is restored to a monostable state and is ready to receive new information.

Synchronization of nSQUID circuitry
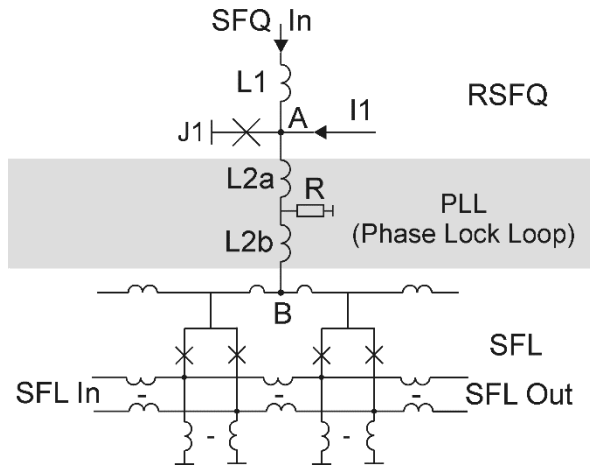
In fact, we need only a low-pass filter to smooth SFQ pulses. Numerical simulations were made by J. Ren.
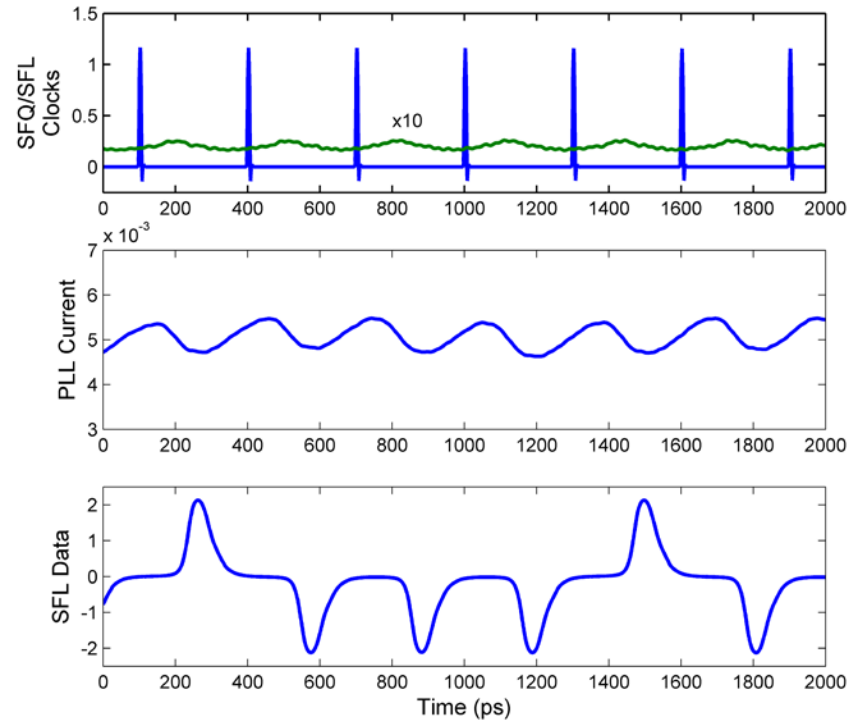
RSFQ Read Out of nSQUID Data

(a)

(b)
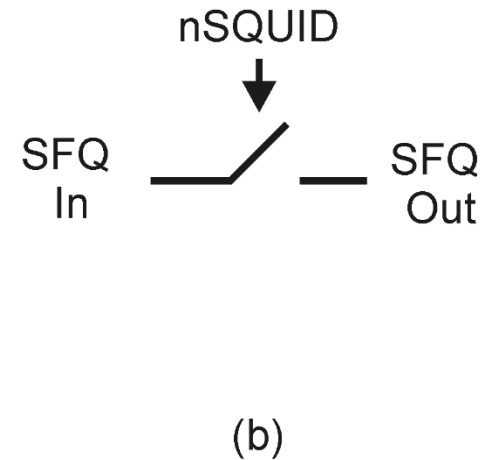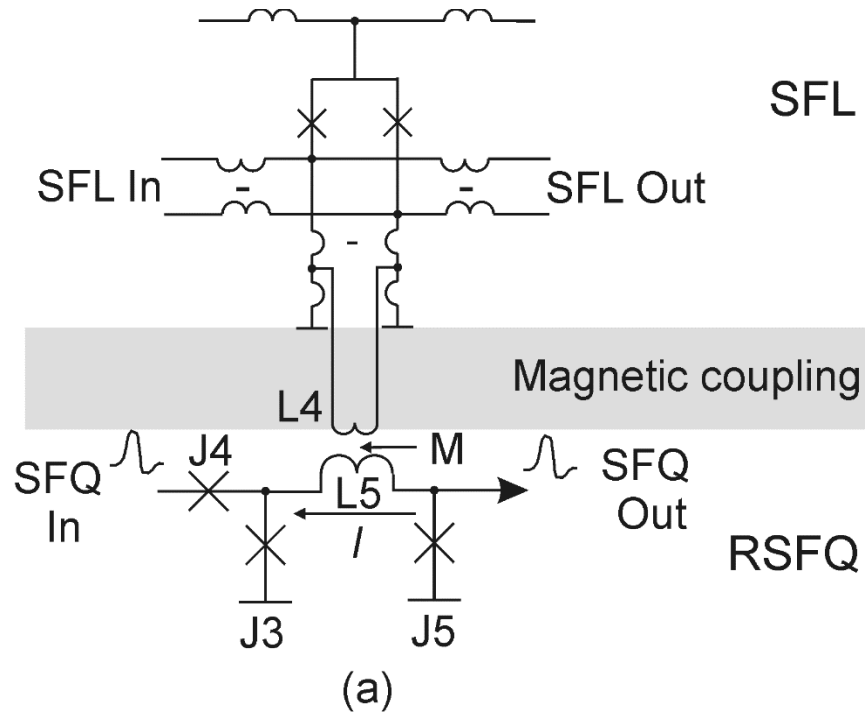
Details for clocked or digital SQUID (lower part in the sketch) could be found in V. Semenov, IEEE Trans. On Appl. Supercond., vol. 13, pp. 747-50, 2003

An Invitation to Analytically Investigate the System of Two Equations and join the bandwagon

$$C_1 \frac{d^2 \chi_i}{dt^2} - \frac{\chi_{i-1} - 2\chi_i + \chi_{i+1}}{L_0} + \frac{\Phi_0}{2\pi} Ic \sin \chi_i \cdot \cos \varphi_i = 0$$

$$C_2 \frac{d^2 \varphi_i}{dt^2} - \frac{\varphi_{i-1} - 2\varphi_i + \varphi_{i+1}}{L1} + \frac{\varphi_i}{L2} + \frac{\Phi_0}{2\pi} Ic \sin \varphi_i \cdot \cos \chi_i = 0$$
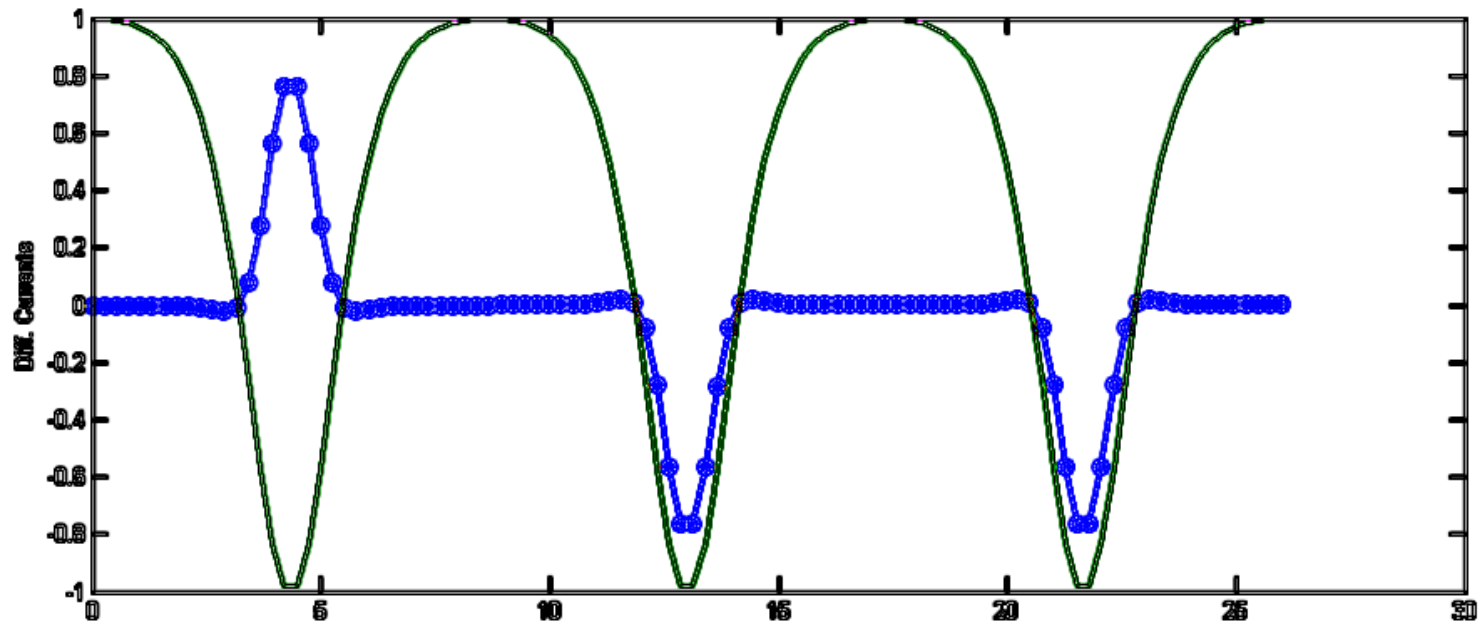
We started from a mathematical reversible computing model composed of two Sine-Gordon like differential equations.

Our PhD student Jie Ren designed and first time experimentally observed a circuit with specific energy dissipation about kBTln2 per a logic operation.

Currently she is the only member of the Chinese team with PhD degree in Superconductor Digital Electronics.

Proposed team funding for year of 2019 is unbelievable:

South China Morning Post on **Monday, 27 Aug 2018 asked a question**

"**Can China build a US$145 million superconducting computer that will change the world?**"

We can speculate that the fastest road to QC goes through the discussed superconductor reversible computing!

Conclusion

- It looks that we are able to provide experimental support for the theory of reversible computing developed by R. Landauer and C. Bennett.

- Experimentation with reversible circuits could bring several benefits.

- The technology could be practical if, indeed, the energy dissipation will be a really critical issue. Two evident examples are: small digital circuits operating at sub Kelvin temperatures and really huge digital systems, where for some reason the cost is less significant factor than the energy dissipation.

- Many features of nSQUIDs are quite similar to those of qubits. From academic point of view it would be exciting to run a contest for the lowest possible energy dissipation. Quantum effects will play important role when/if the energy dissipation is ~10^{-4} of $k_B T$. In this case a few nSQUIDs could be renamed into qubits and there is a chance that such circuits could be reconstructed and declared to be a quantum computer.

Thank you for your attention!