Reversible Josephson-Junction Circuits with SQUID Based Cells

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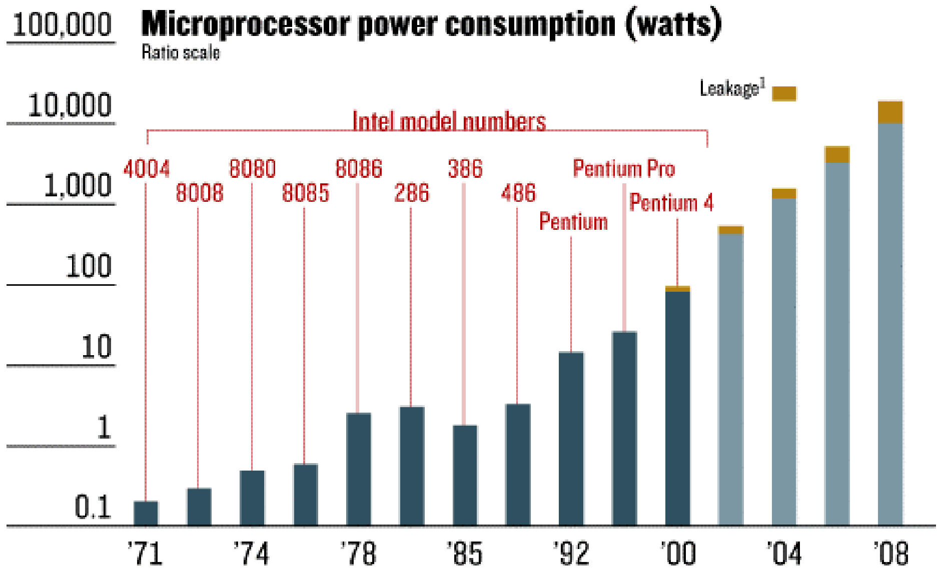
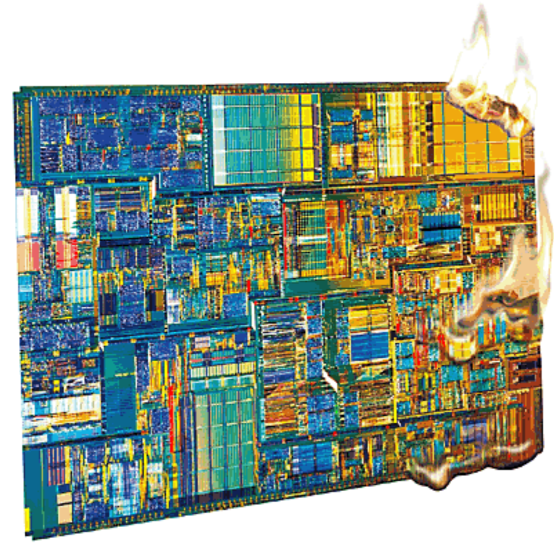
Practical Introduction

"Too High Electric Bill"

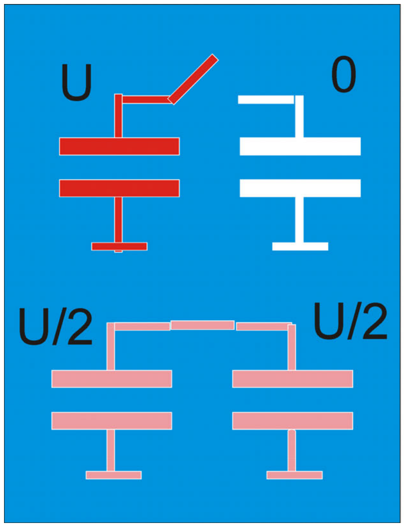




Electricity cost: 10 kW ×\$0.12/(kW·hour)=
= \$1.20/hour = \$29/day = \$870/month = \$10,560/year

Both figures after: Elizabeth Corcoran, "Too Hot to Handle", Forbes Magazine, Apr. 2, 2001

Irreversibility Is the Main Power Dissipation Channel in CMOS Circuits



$$E = C \times [U^2/2 + 0] = C \times U^2/2$$

$$E = C \times [(U/2)^2/2 + (U/2)^2/2) = C \times U^2/4$$

R.C. Merkle, *Nanotechnology,* vol. 4, p. 21, 1993.

A. De Vos, *Prog. Quant. Electron*., vol. 23, p. 1, 1999.

W. Athas *et al.*, *IEEE J. of Solid-State Circuits,* vol. 35, p. 1561, 2000.

M.P. Frank, *Comp. Science & Eng*. vol. 4, p. 16, 2002.

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Logic Reversibility and Thermodynamic Limitations on 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 real goals are:

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

- to detect the effect of logic reversibility on the energy dissipation

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

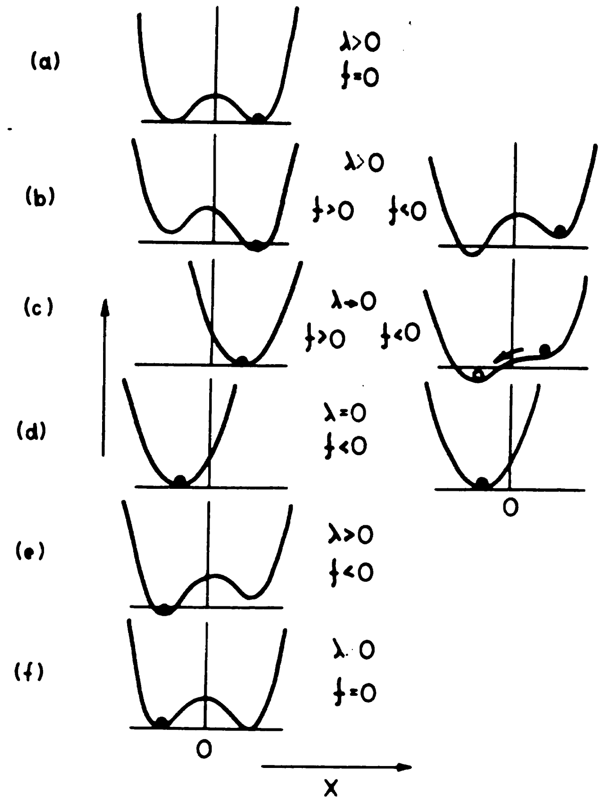
C. Bennett, "Logical reversibility of computation", *IBM J. of Res. and Devel.*, vol. 17, p. 525, 1973

Why Josephson Junction Technology?

-No energy dissipation in superconducting state;

-Very convenient and accurate energy potential:
$E(\varphi)=I_C\cdot\Phi_0\cdot\cos(\varphi)$;

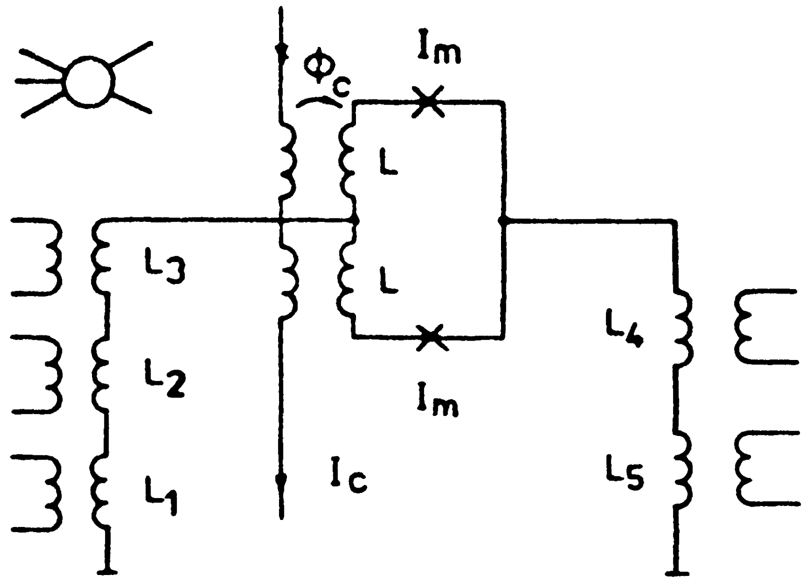
-Well developed technology: CAD tools, fabrication, measurement.



K.K. Likharev, “Classical and quantum limitations on energy consumption in computation,” *Int. J. Theor. Phys.*, vol. 21, p. 311, 1982.

The First Try: Externally (AC) Clocked Parametric Quantron

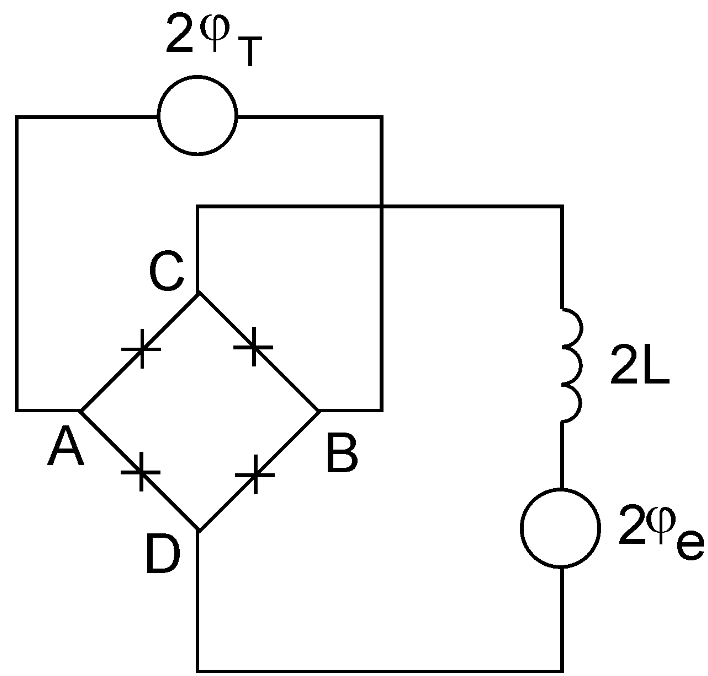
The energy flow in and out of a quantron through AC bias lines is about four order of magnitude larger than the proposed energy dissipation.



Unexceptionally high energy dissipation in AC power lines.

K.K. Likharev, S.V. Rylov, and V.K. Semenov,
***Reversible conveyer computation in arrays of parametric quantrons*,**
***IEEE Trans. on Magn.*, vol. 21, pp. 947-950, March 1985.**

The Second Try: 4JJ DC Biased Parametric Quantron



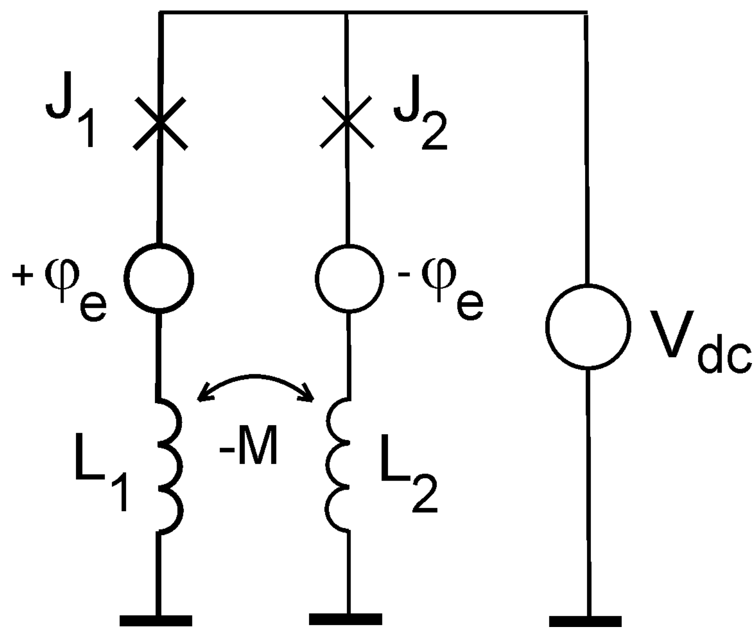
The circuit is too complex: it has an extra degree of freedom (corresponding to simultaneous switching of both upper or both lower junctions).

Parameter margins are unacceptably low.

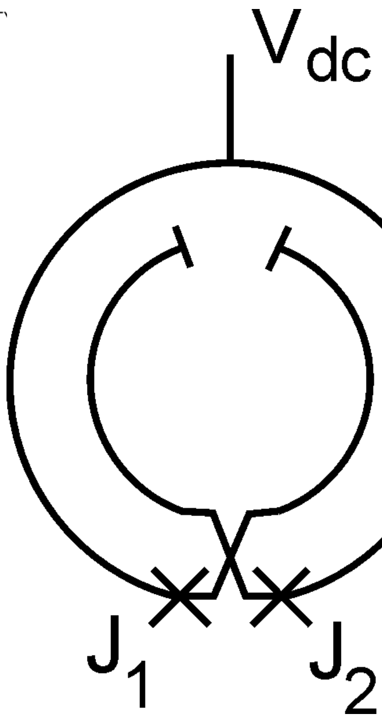
S.V. Rylov, V.K. Semenov, and K.K. Likharev, *DC powered parametric quantron,* Proc. of Int. Supercond. Electronics Conf. Pp.135-137, Aug. 1987.

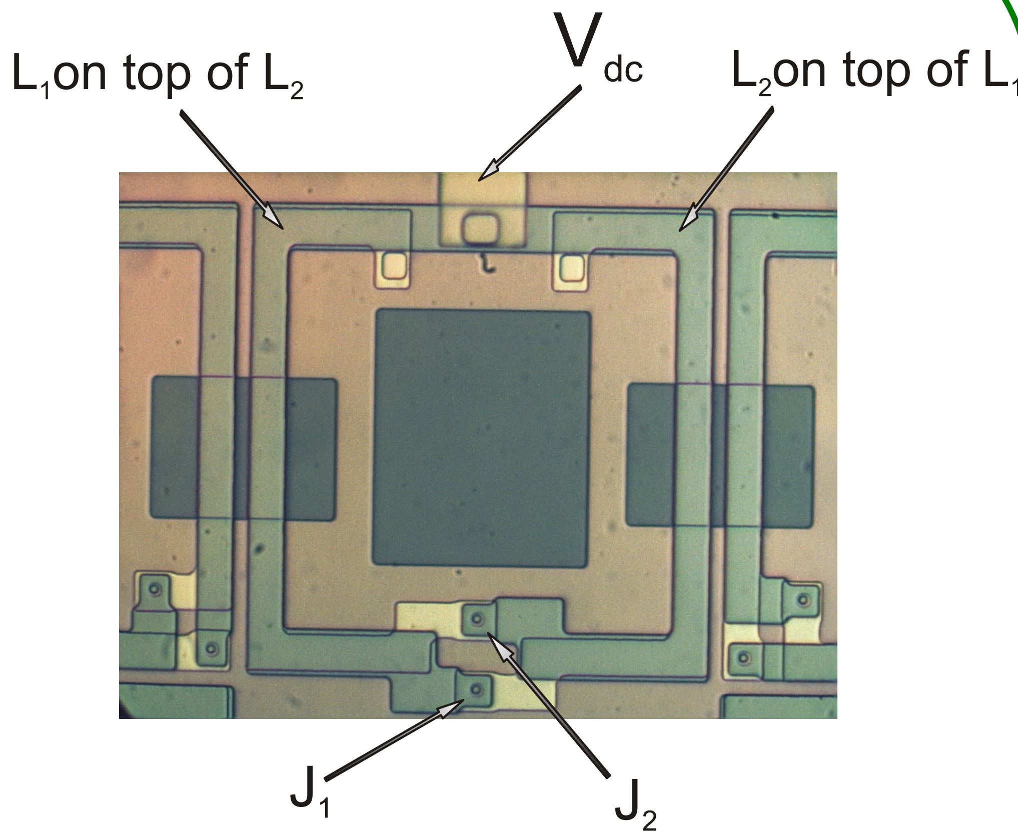
The new Solution: nSQUID: Basic Gate of Reversible JJ Circuits

The cell is a symmetric 2-junction SQUID. (Ic1=Ic2=Ic; L1=L2=L) The new features are obtained due to a negative mutual inductance M between the SQUID arms. The target value of this inductance is M=0.75xL.



Layout of nSQUID



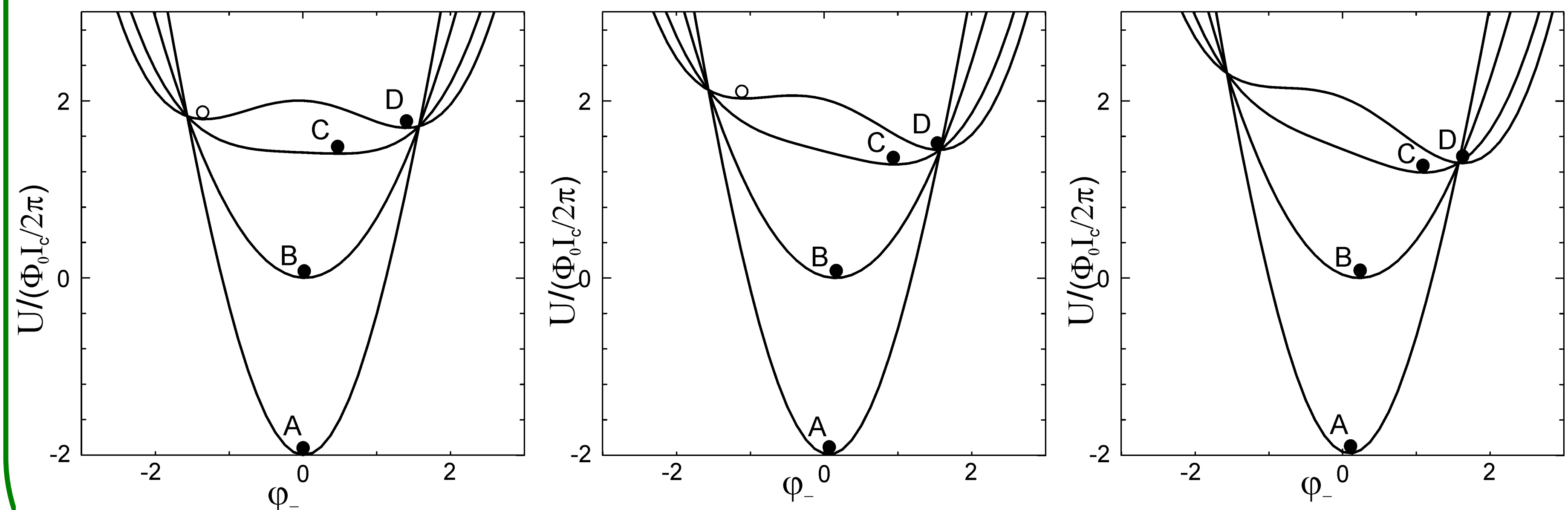


The circuit fabricated at HYPRES, Inc. Target Ic = 0.015 mA. Dark areas are the groundplane holes. The left and right holes are used for magnetic coupling with other nSQUIDs

Operation of nSQUID (Different Signals)

Different regimes of operation:

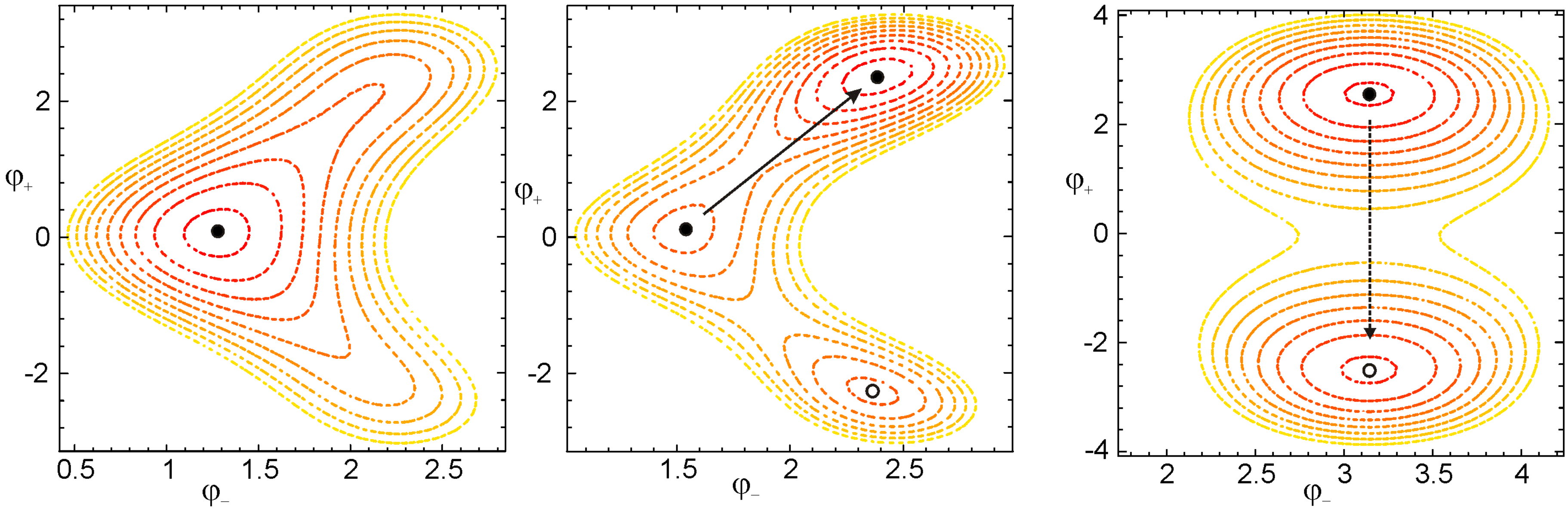
$$\beta_1 = 0.79, \qquad k = -0.77$$



φ_e=0.05 φ_e=0.30 φ_e=0.45

Irreversible (Incorrect) Mode of Operation

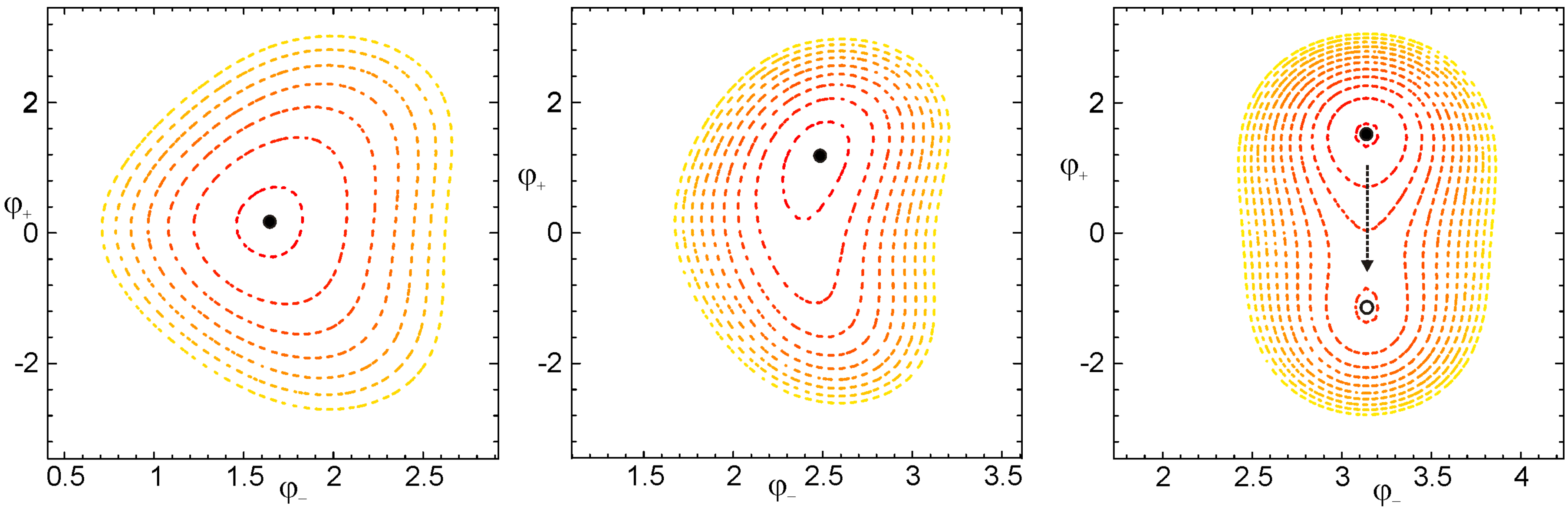
$\varphi_e = 0.05$



During a short period of time the monostable state (left plot) and bi-stable state (right plot) coexist (middle plot).
The jump (solid arrow) is irreversible.

Conventional Reversible Mode of Operation

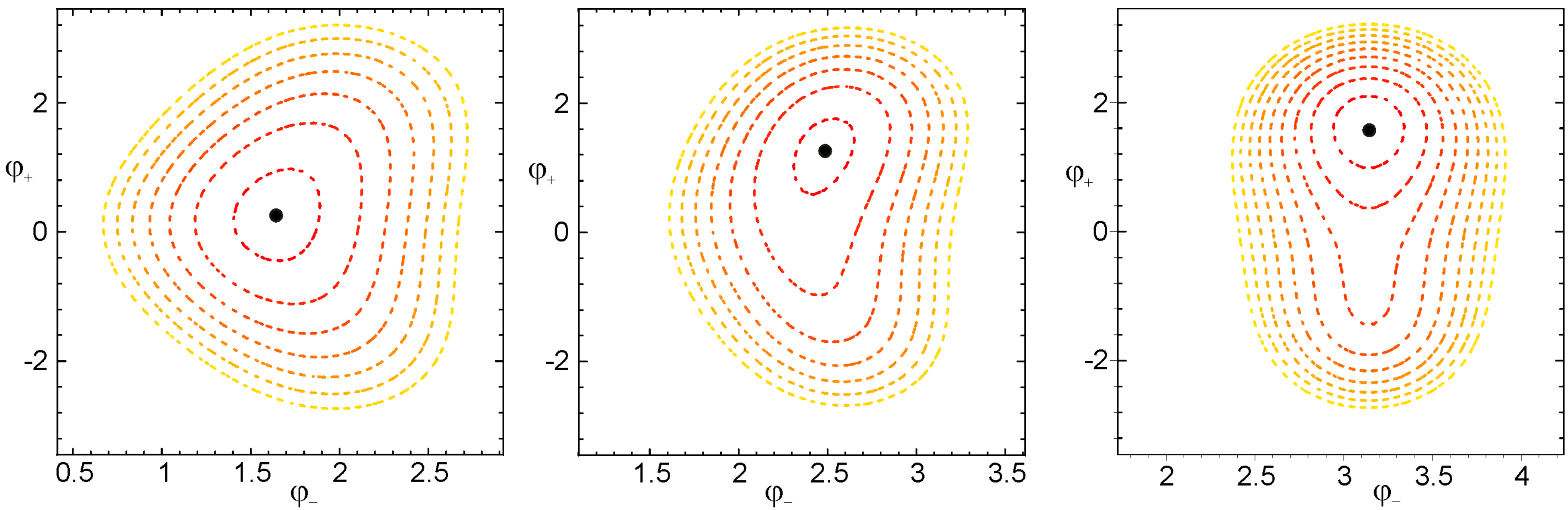
φ_e=0.30



The smooth transition between mono- and bi-stable states. However, there is a probability of a thermal (or quantum) transition to the second state. This is the major sourse of errors.

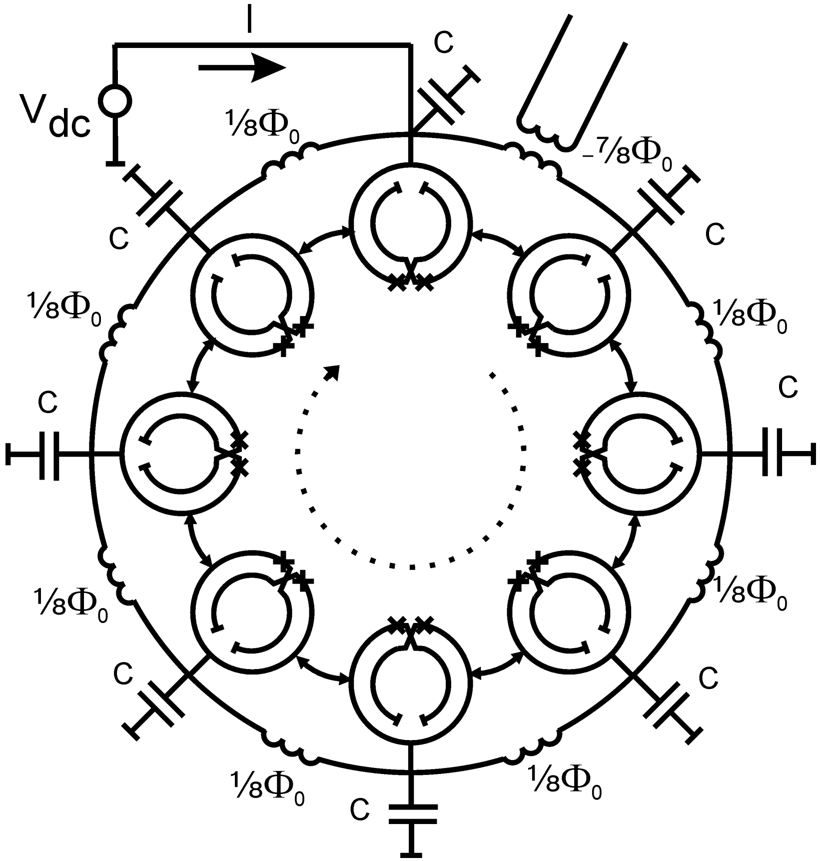
Single-Minimum (The Best) Mode of Operation

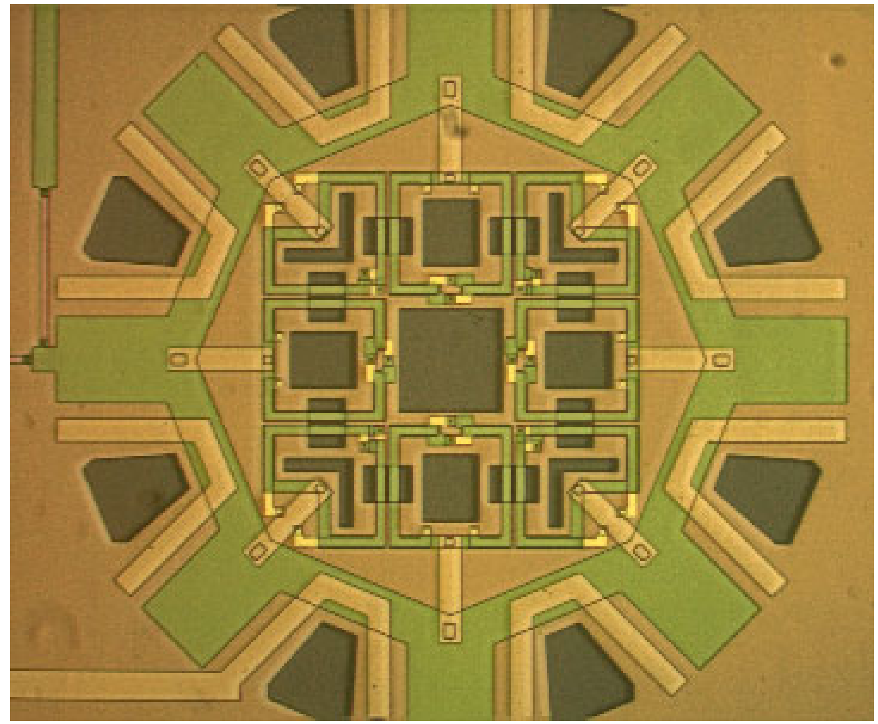
$\varphi_e = 0.45$



Due to a strong coupling of the nearest-neighbor nSQUIDs the second minimum in the potential profile is suppressed. In this collective regime the error rate should be much lower.

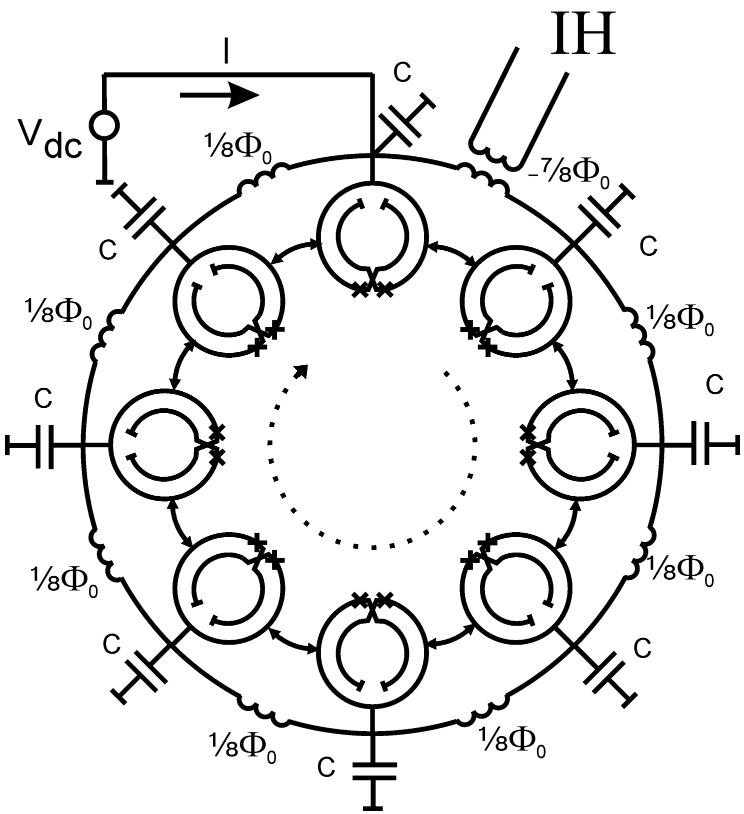
Eight-Cell Circular Shift Register with Magnetic Inter-Gate Coupling

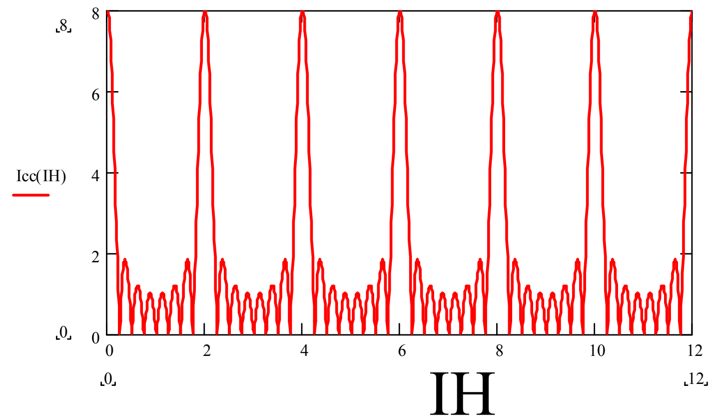


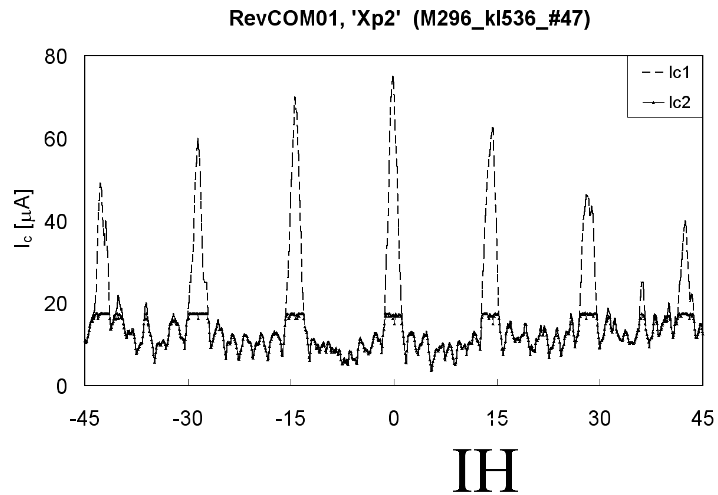


The circuit fabricated at HYPRES, Inc. (j_c=100 A/cm^2)

Experimentation With Shift Register







Dissipated Energy

E=P/f,

P=<I/N·V>,

$E=\langle I/N \cdot V/f\rangle = I \cdot \Phi_0$,

Dissipated energy does not depend on V!

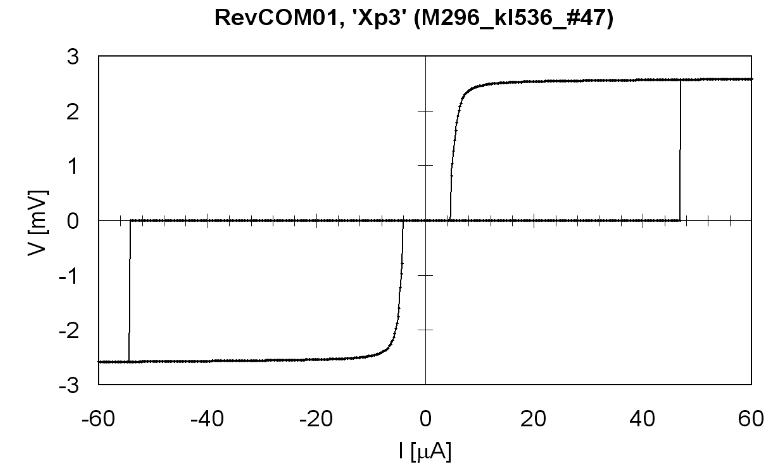
$E/k_BT\ln 2 = 0.7 \cdot I/N \cdot \Phi_0/k_BT$

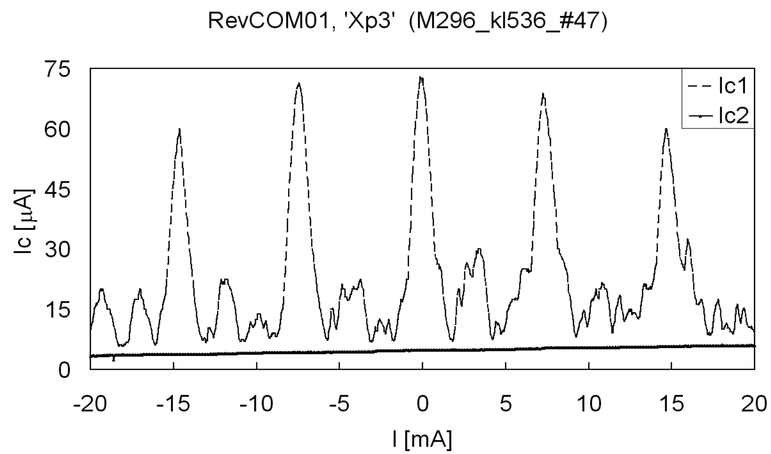
At T=4.2 K and N=8

$E/k_BT\ln 2 = I/0.32\mu A$

Minimal measured current I~5 μA

Demonstrated **$E/k_BT\ln 2 \sim 15$**

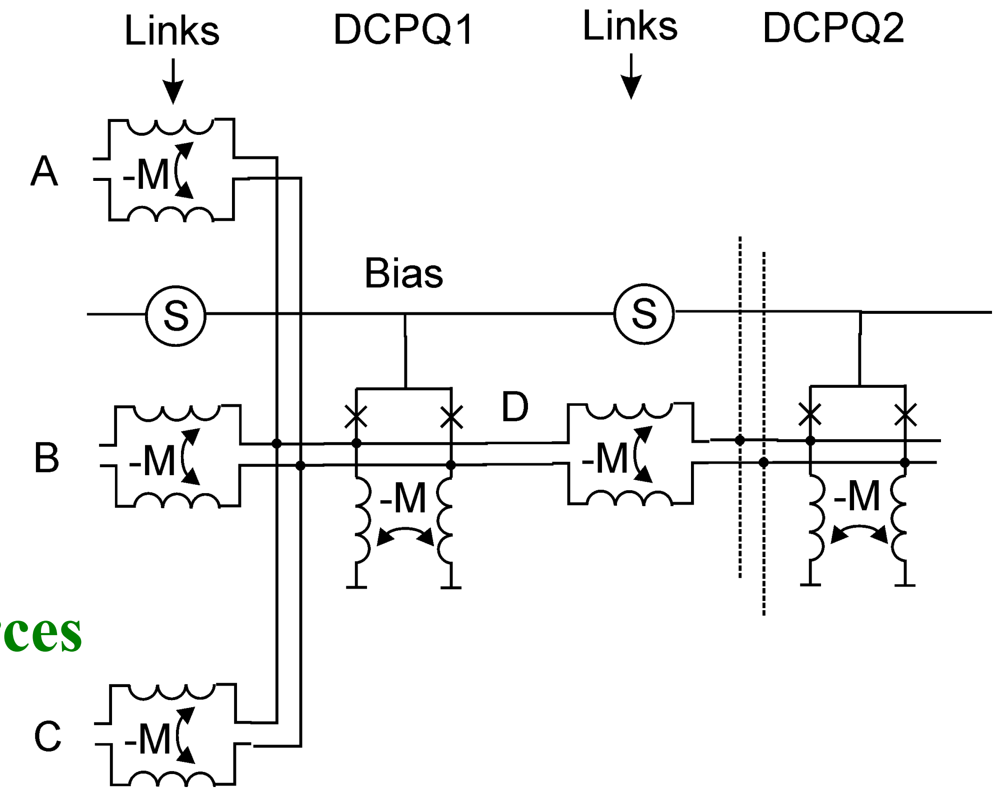




Direct Balanced Coupling of nSQUIDs

The plot illustrates that nSQUIDs (or DCPQs) could be directly coupled by pairs of wires with negative mutual inductances.

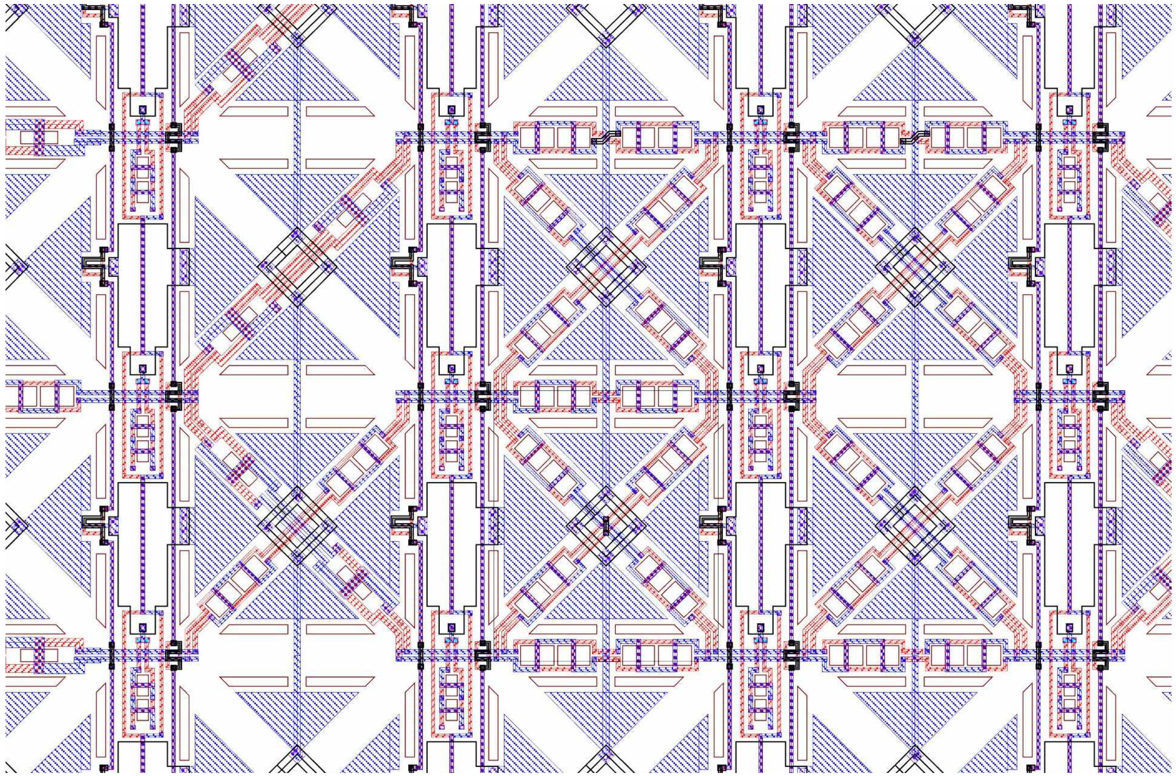
Multiphase timing is provided by DC flux sources (marked by symbol S).



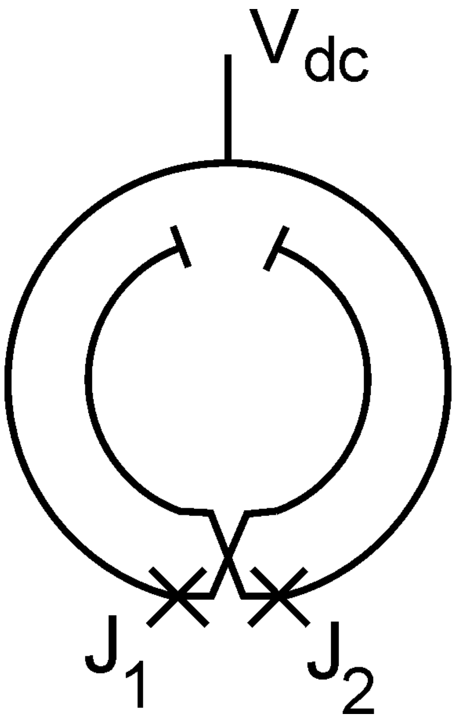
Grid of nSQUIDs.

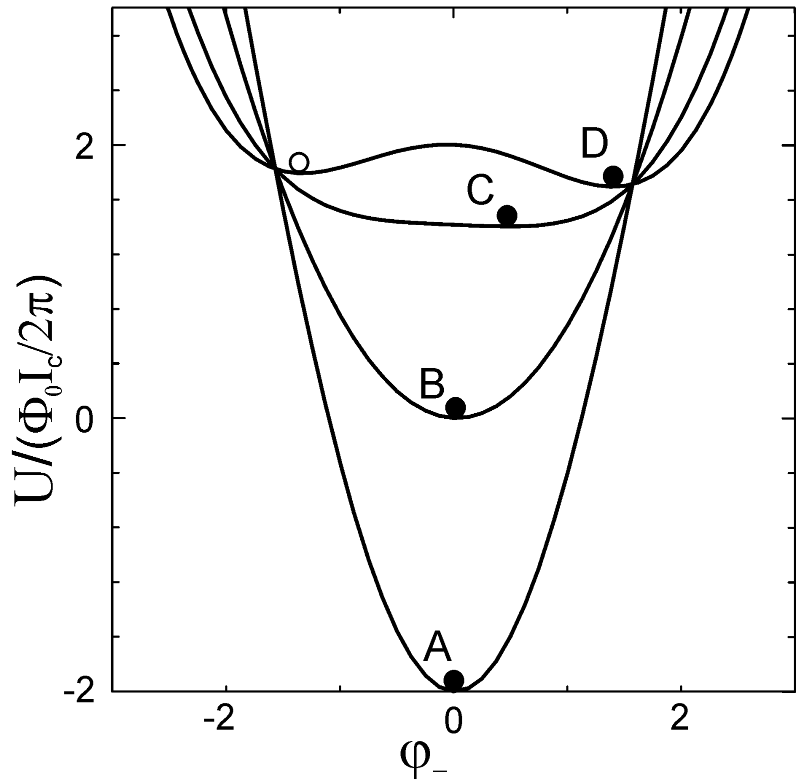
The functions are programmed by the presence, sign, and strength of corresponding links.

Test chip (small fragment of the reversible Fermat transform) designed at Stony Brook and fabricated at HYPRES, Inc.



Note: nSQUID Could Be Used as a Qubit





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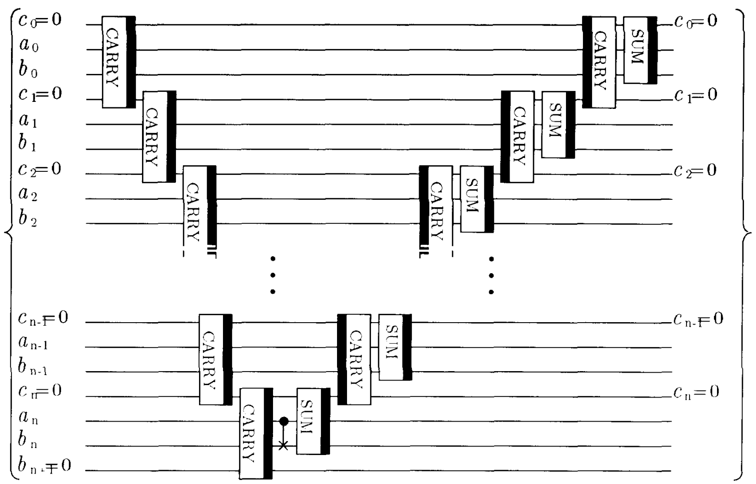
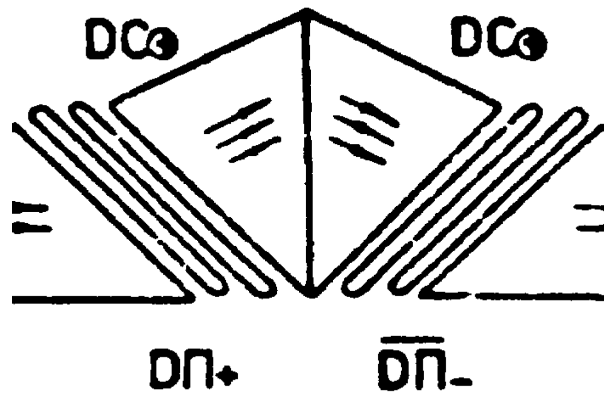
Quantum computers are inherently reversible devices.

The suggested large-scale architectures for quantum computers are surprisingly close to those suggested earlier for classical reversible computation.



V. Verdal, A. Barenco, and A. Ekert,
"*Quantum Networks for elementary Arithmetic Operations*,
Preprint 1995



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IEEE Trans. on Magn., vol. 21, pp. 947-950, March 1985.

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Conclusion

nSQUID is a promising elementary gate for implementation of the large-scale reversible Josephson-junction computing with the energy dissipation below $k_B T \ln 2$ per operation.

Large reversible circuits implementing quantum algorithms would serve as prototypes of multi-qubit quantum computers. Experiments with these circuits will speed-up the development of practical quantum computers.