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Superconducting Computing in Large-Scale Hybrid Systems*

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** Adapted in part from feature article with same title,*
IEEE Computer Magazine, Dec. 2015.

Abstract

- The past, present, and future of superconducting computing are discussed, based on the feature article in the December issue of IEEE Computer Magazine.

- Specific systems addressed include processors for supercomputers, digital radio receivers, quantum annealing, neural simulators, and ultra-low-power reversible computing.

Background on Superconductors

- Superconductors have zero resistance (R=0) when cooled below a critical temperature T_c.
- Unfortunately, requires deep cryogenic cooling.
  - For conventional low-temp. superconductors (LTS) such as niobium (Nb), $T_c \sim 9$ K = -264 ^{o}C. All present major applications based on LTS.
  - For newer high-temp. superconductors (HTS) such as $Y_1Ba_2Cu_3O_7$, $T_c \sim 90$ K = -183 ^{o}C. Complex ceramic crystalline materials, difficult to manufacture.
- Large-scale wire-based applications
  - Magnets for magnetic resonance imaging (MRI), high-energy physics accelerators.
- Also electronic applications
  - Based on “Josephson Junctions” (JJ), switching devices analogous to transistors.

Why Superconductors for Computing?

Advantages

- Low-energy switching of JJs < 10^{-18} J
- High-speed switching ~ 1 ps
- Thin-film IC technology based on Nb JJs
- Fast lossless ballistic signals on superconducting transmission lines at ~ c/2.

Disadvantages

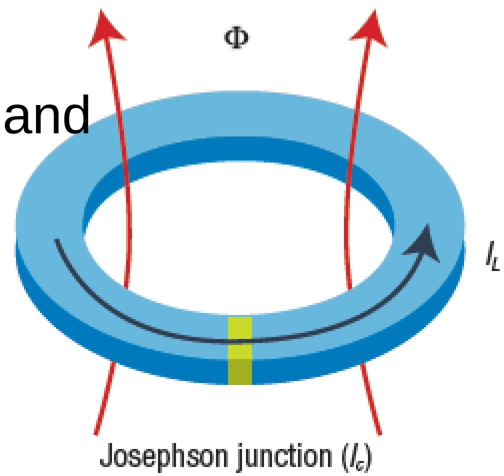
- Requires cooling to ~ 4 K for operation
- T and V/I levels not compatible with silicon.
- IC technology not as advanced as CMOS – 100 nm, 100K JJs.
- Not (yet) installed base of systems driving technology improvement
- Needs better scalable memory technology for large memories.

60 years of Superconducting Computing

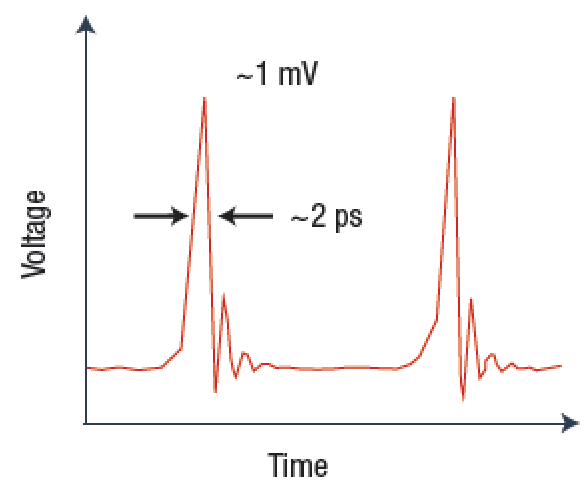
- 50s-60s:
  - Cryotrons at MIT – early thin-film magnetic switching – too slow.
- 70s-80s:
  - Josephson Computer Project at IBM – underdamped JJs, ~ 1 GHz, not fast enough
- 80s-90s
  - Nb JJ IC technology – Bell Labs, NEC
  - ps switching – Rapid Single-Flux-Quantum Logic (RSFQ) – Moscow State University
- 90s-present
  - Transfer of RSFQ to Stony Brook, Hypres, and TRW/NG
  - Hybrid Technology Multi-Threaded (HTMT) project (NSA, etc.) for supercomputers based on RSFQ – not continued
  - Also start of Superconducting Quantum Computing – D-Wave
  - IARPA Cryogenic Computing Complexity (C3) project

Single Flux Quantum Voltage Pulse

- Superconducting inductive loop stores quantized magnetic flux Φ_0 = h/2e =2x10^{-15} Wb
  - Φ_0 = LI = 2 pH-mA, corresp. to loop with L = 20 pH and I = 0.1 mA
  - Also known as Single Flux Quantum or SFQ



- JJ switches SFQ in or out of loop, generates SFQ pulse
  - Pulse height ~ 1 mV, width ~ 2 ps, area Φ_0 = 2 mV-ps
  - Pulse energy = Φ_0*I ~ 10^{-19} J
- RSFQ uses SFQ for logic and memory
  - Adds damping for greater control
  - Damped JJ to prevent "ringing"
  - Resistive power distribution network
  - Newer SFQ logic even lower power



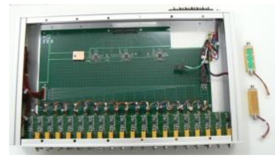
Present Superconducting Computing Sytems

- Not yet complete general-purpose computing systems
  - Custom processors for special purposes
- Superconducting digital receiver system – Hypres
  - Directly digitizes broadband radio-frequency signal, using 40 GHz RSFQ sampler
  - RSFQ logic for digital filters and first-stage processing
  - Fast FPGA at room temperature for remaining digital processing.
  - Complete turnkey systems now being operated in DoD labs.
- Superconducting quantum annealing processor – D-Wave
  - Type of analog quantum computer designed for optimization.
  - Uses array of ~ 1000 “flux qubits” cooled to ~ 0.02 K = 20 mK to reduce thermal fluctuations
  - Also low-power SFQ circuits for control and readout
  - Several systems at government labs and universities

Modular Multifunction Digital-RF Receiver*

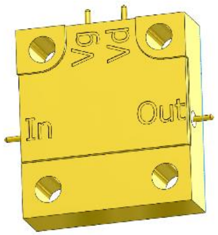
High-throughput Continuous Digital Data Recorder

FPGA Signal Processor



SCE-to-CMOS Interface Amps

Ambient (T =300K)

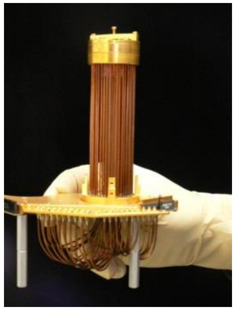


Cryo LNA

T= 40-100 K

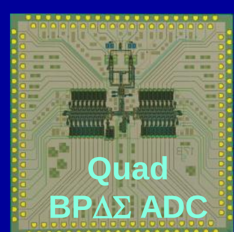
Variable-temperature Cryo-electronics Module

1st Stage (T =40K)



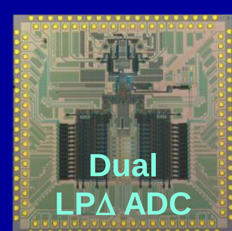
Chip Module

T= 4 K



Chip Module 2

T= 4 K



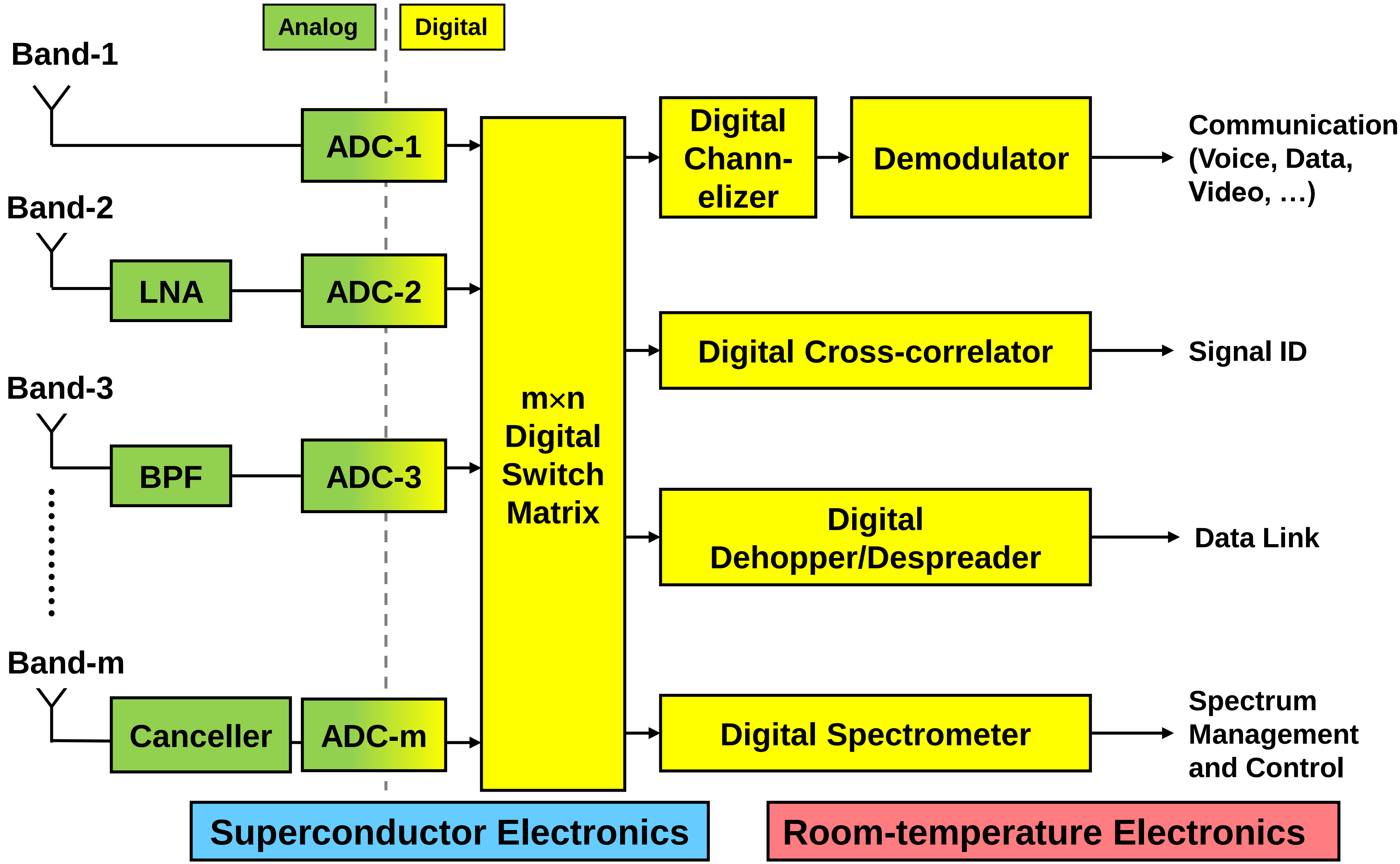
Chip Module 1

2nd Stage T = 4K

D. Gupta, D. E. Kirichenko, V. V. Dotsenko, et al., "Modular Multi-function Digital-RF Receiver Systems," IEEE Trans. Appl. Supercond., vol. 21, no. 3, pp. 883-890, June 2011.

**Courtesy of Dr. Deepnarayan Gupta, Hypres*

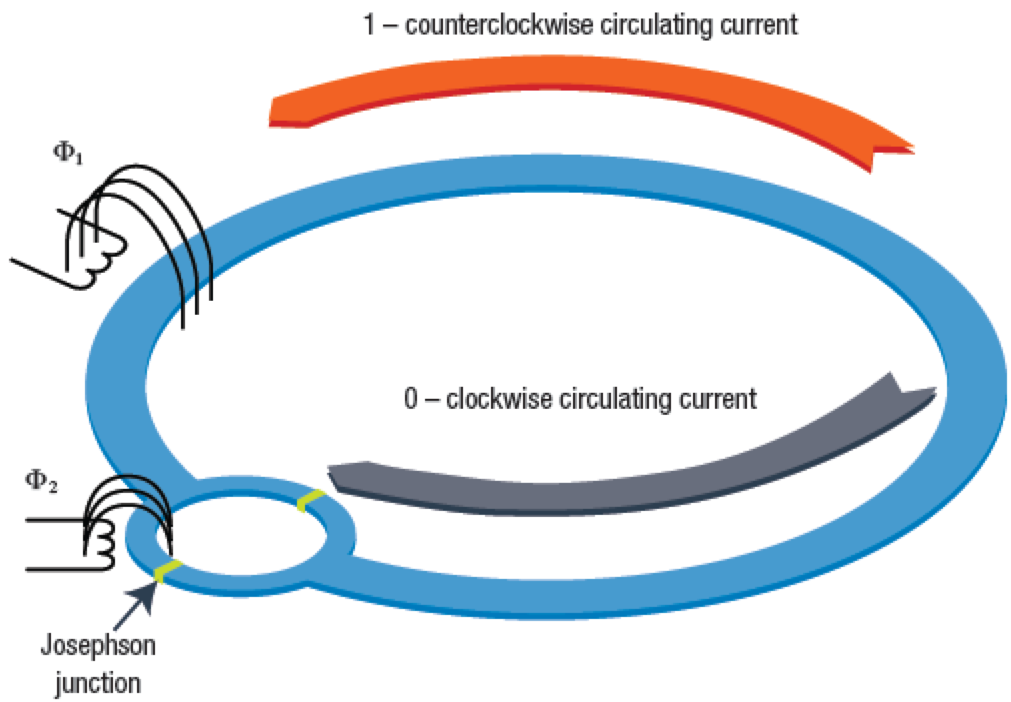
Block Diagram of Ultimate Digital-RF Receiver*



**Courtesy of Dr. Deepnarayan Gupta, Hypres*

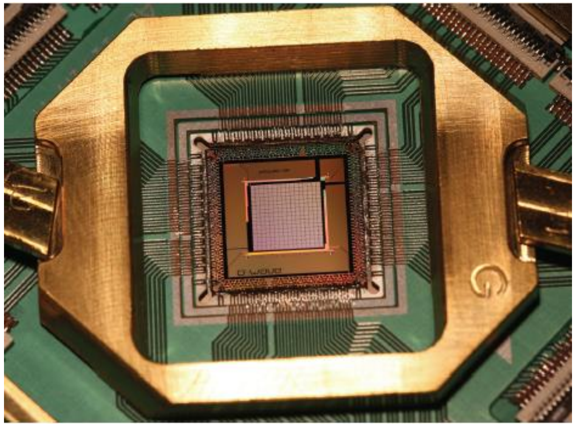
Quantum Computing: The Flux Qubit

- Bistable superconducting loop with JJs
  - Classically, loop can carry supercurrent in clockwise or counterclockwise, but not both at same time
  - In Flux Qubit, loop can be in "quantum superposition" of both states at the same time.
  - Coupling with external measurement can force system into one of two states



D-Wave Quantum Annealer

- Integrated circuit of 1000 flux qubits
  - Chip with 128,000 JJs, mostly classical superconducting circuits for programming and readout of qubits
- Complete turnkey system
  - Includes “dilution refrigerator” with T = 0.02K
  - Includes digital I/O lines for interfacing with room-temperature computer
- Designed to solve optimization problems
  - Also machine learning and protein folding.



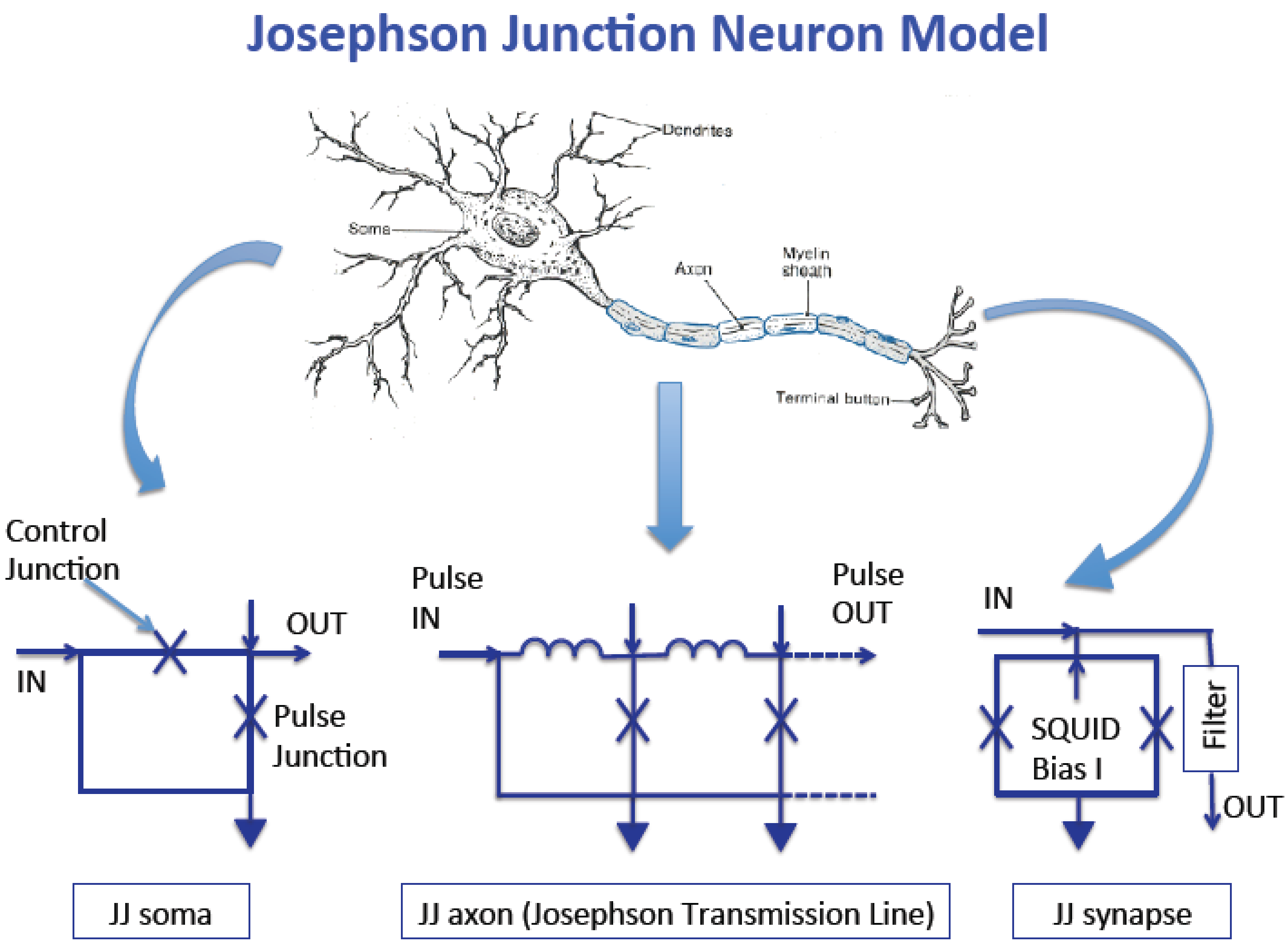
Future Superconducting Computing Systems

- Josephson microprocessor for accelerator and parallel supercomputer.
  - May operate up to 100 GHz clock speed.
  - Anticipated energy efficiency up to 100 better than current supercomputers for comparable performance
- Josephson neural simulator/neuromorphic computer
  - JJ naturally generates pulses, pulse rate can be modulated by other JJs
  - Directly analogous to neural operation, but much faster and lower power
- Josephson adiabatic/reversible computer
  - Extremely low power ~ kT per gate
- General-purpose Josephson quantum computer
  - Still in fundamental research, but massive quantum parallelism should enable factoring large numbers, for example.

Superconducting Exascale Supercomputing?

- Projected power for CMOS exascale much too large
  - If Moore's law has saturated, projected CMOS system will be enormous and impractical, ~ 1000 MW
- Superconducting approach much more energy efficient
  - JJ processors at 4 K, clocking at ~ 100 GHz, leads to ~ 1 MW for exascale system, *including* refrigeration power.
- *Potential Problems that need to be addressed*:
  - VLSI technology not quite mature.
  - Logic complexity not quite mature.
  - Memory density not mature.
  - Cryocoolers and packaging not quite mature.

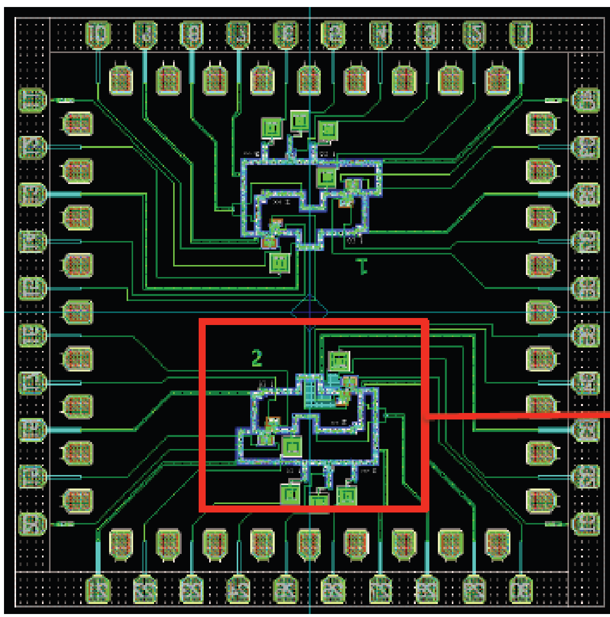
JJ Model for Neuron*



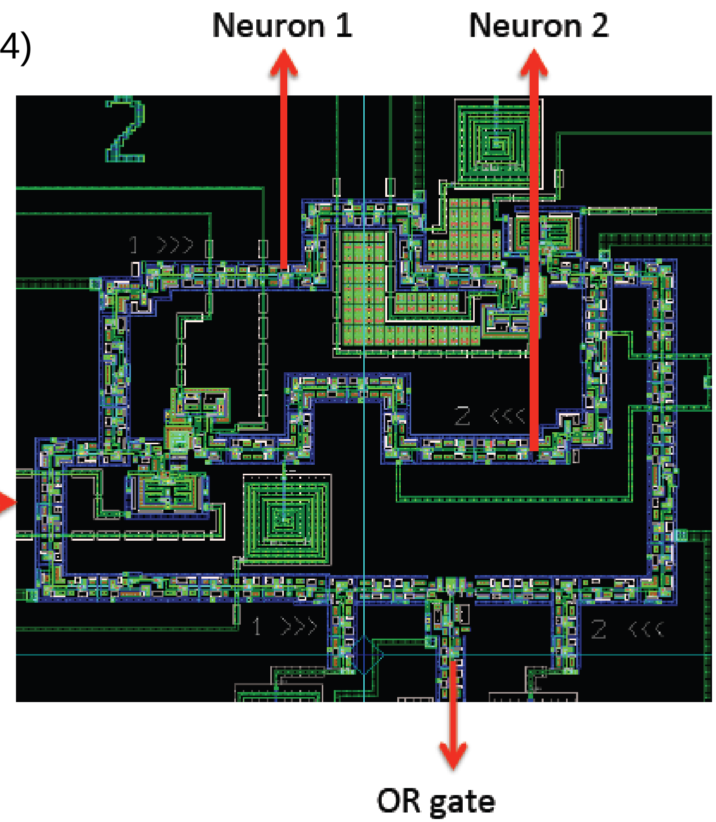
*Courtesy of Prof. Kenneth Segall, Colgate University

Josephson Circuit for Two Coupled Neurons

- Operates orders of magnitude faster and lower power than real neurons OR silicon-based neural simulators.
- Shows Phase-Flip bifurcation expected for coupled neurons
  - K. Segall et al. Physica B 455, 71 (2014)



Neuron IC chip with contains two coupled neuron samples



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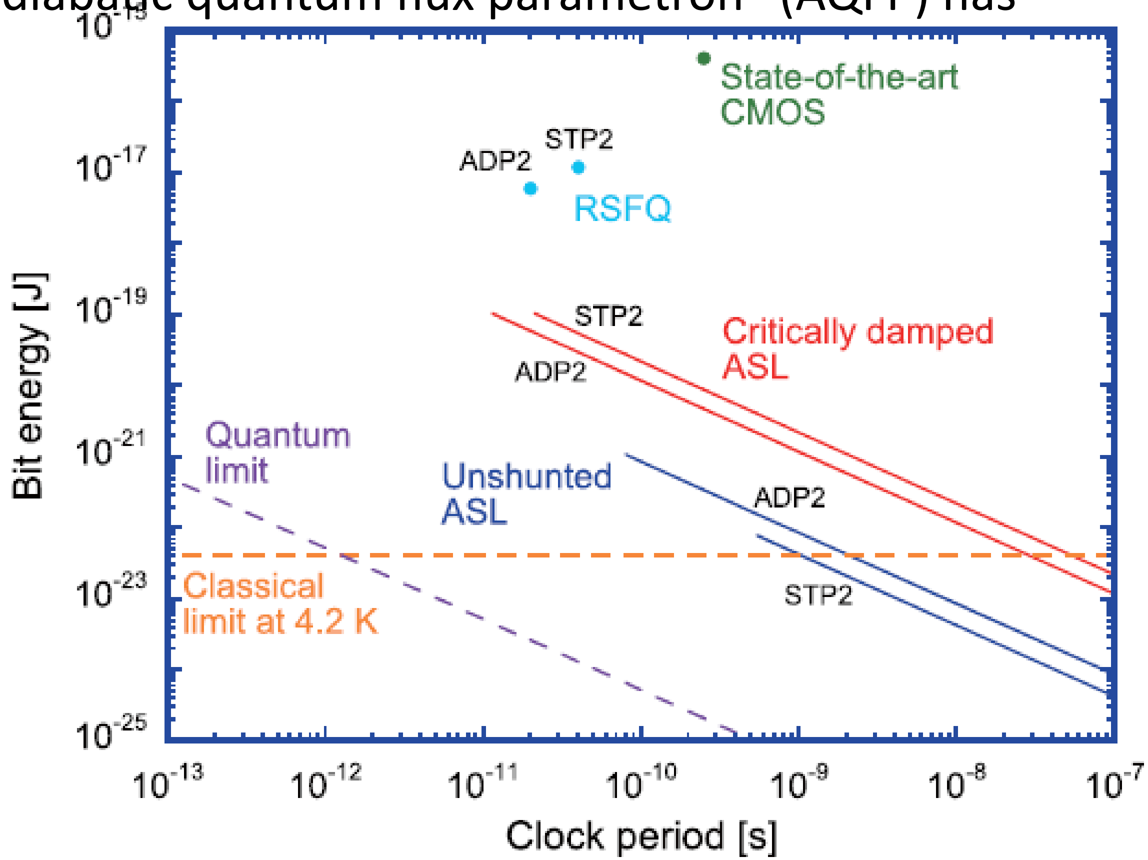
Ultra-low-power Superconducting Computing

- ❑ Landauer limit of kT *ln*(2) for energy/bit in conventional computing
  - ➢ Reversible Computing can get even lower
- ❑ But most conventional circuits are much more dissipative
  - ➢ A form of SFQ logic, “adiabatic quantum flux parametron” (AQFP) has been measured to have very low energy/bit.



*from Takeuchi, et al., Supercond. Sci. Technol. 28 (2015) 015003

Conclusions

- *Superconducting computing has been a background technology for decades, but may finally be coming to market as Moore's Law saturates.*
- *Superconducting Digital-RF Receivers and Quantum Annealers are already special-purposes processors, complete commercial turnkey systems.*
- *Future systems include microprocessors for supercomputers, neuromorphic and reversible processors, and general-purpose quantum computers.*