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Superconductivity Global Alliance (ScGA)

for

Greener, Healthier, Prosperous and Sustainable Future

Special Session

D. Scott Holmes

WG5 Electronics and Quantum Information Processing

Team:

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WG - Overview

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- **Sensing, computing, and communications** are key enablers of information economies
  - Superconductors have physics advantages that will allow major improvements in energy efficiency, speed, or security for these applications

- **Applications**:
  - **Sensors** and **Analogue signal processing**
  - **Digital computing**
  - **Artificial intelligence** (AI) and **Machine learning** (ML)
  - **Quantum computing** (QC) and **quantum communications**

- **Benefits**:
  - Optimization of complex logistics and control systems to create performance and efficiency in very large networks such as the IoT
  - Faster development of new materials, pharmaceuticals, and chemical processes
  - Energy-efficient artificial intelligence
  - Secure communications

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Market Opportunities

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- **Sensors** and **Analogue signal processing**
  - Small market, even including the encompassing systems
- **Digital computing**
  - Only large-scale, compute-intensive systems seem competitive
  - Large market with an entrenched competitor (CMOS)
- **Artificial intelligence** (AI) and **Machine learning** (ML)
  - Only large-scale, compute-intensive systems seem competitive
  - Large market
- **Quantum computing** (QC) and **quantum communications**
  - Large markets

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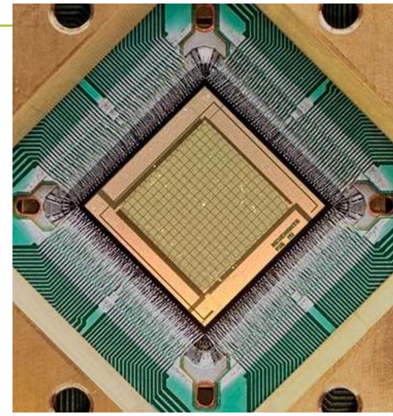
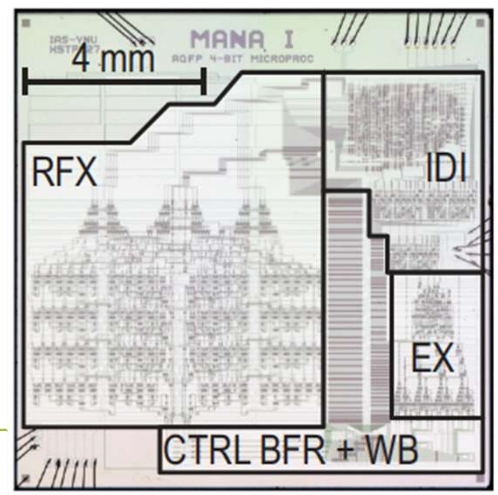
State of the Art (1)

- **Circuit complexity**
  - D-Wave Advantage, Pegasus P16 quantum processing unit (QPU) using superconductor electronics
  - 1 030 000 Josephson junctions (enabled by low I_C)
  - 5640 qubit array
  - 15 couplers per qubit
  - Active area: 8.4 mm × 8.4 mm
  - 15 to 20 mK operating temperature



https://en.wikipedia.org/wiki/D-Wave_Systems#Pegasus
https://www.dwavesys.com/solutions-and-products/systems/

- **Energy efficiency**
  - Microprocessor demonstration
  - Adiabatic quantum-flux-parametron (AQFP) logic
  - 21 460 Josephson junctions
  - 1.4 zJ switching energy
  - 15 aJ/op at 100 kHz (not including refrigeration)



Ayala+, 2021, doi: 10.1109/JSSC.2020.3041338

https://techxplore.com/news/2020-12-extremely-energy-efficient-microprocessor-superconductors.html

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State of the Art (2)

- **Artificial intelligence (AI) and machine learning (ML)**
  - Neuromorphic circuits using superconductor electronics
  - Natural spiking behavior of Josephson junctions
  - Possibly tolerant to variations in component parameter values
  - Promising, but scalability unproven

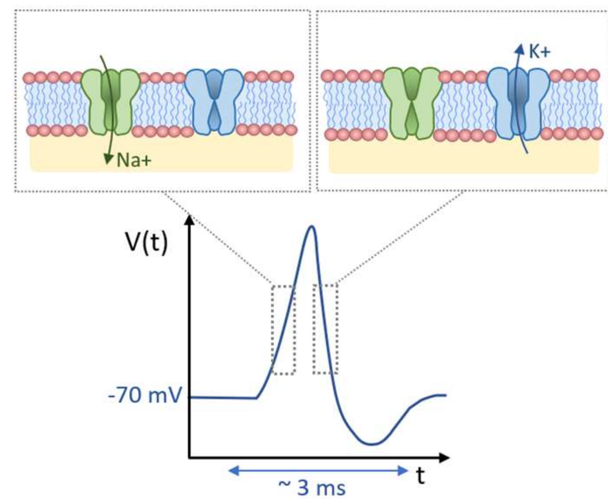


Fig. 3a. Spiking in biological neurons [1]

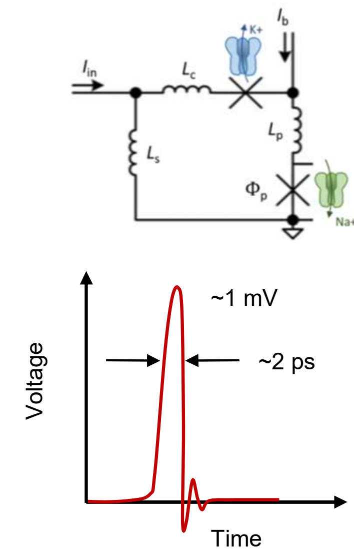
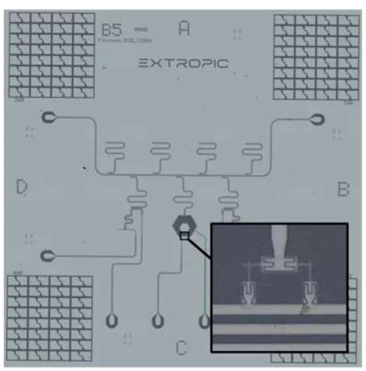


Fig. 4a. JJ neuron circuit [1]

[1] Schneider +, “**Supermind**” *Supercond. Sci. Technol.*, 2022, doi: 10.1088/1361-6668/ac4cd2



< Early superconducting neuron design with 2 JJs for a **probabilistic AI accelerator** (extropic.ai/future)

▸ Thursday: Ken Segall plenary 4PL1-01: Neuromorphic computing using SCE

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State of the Art (3)

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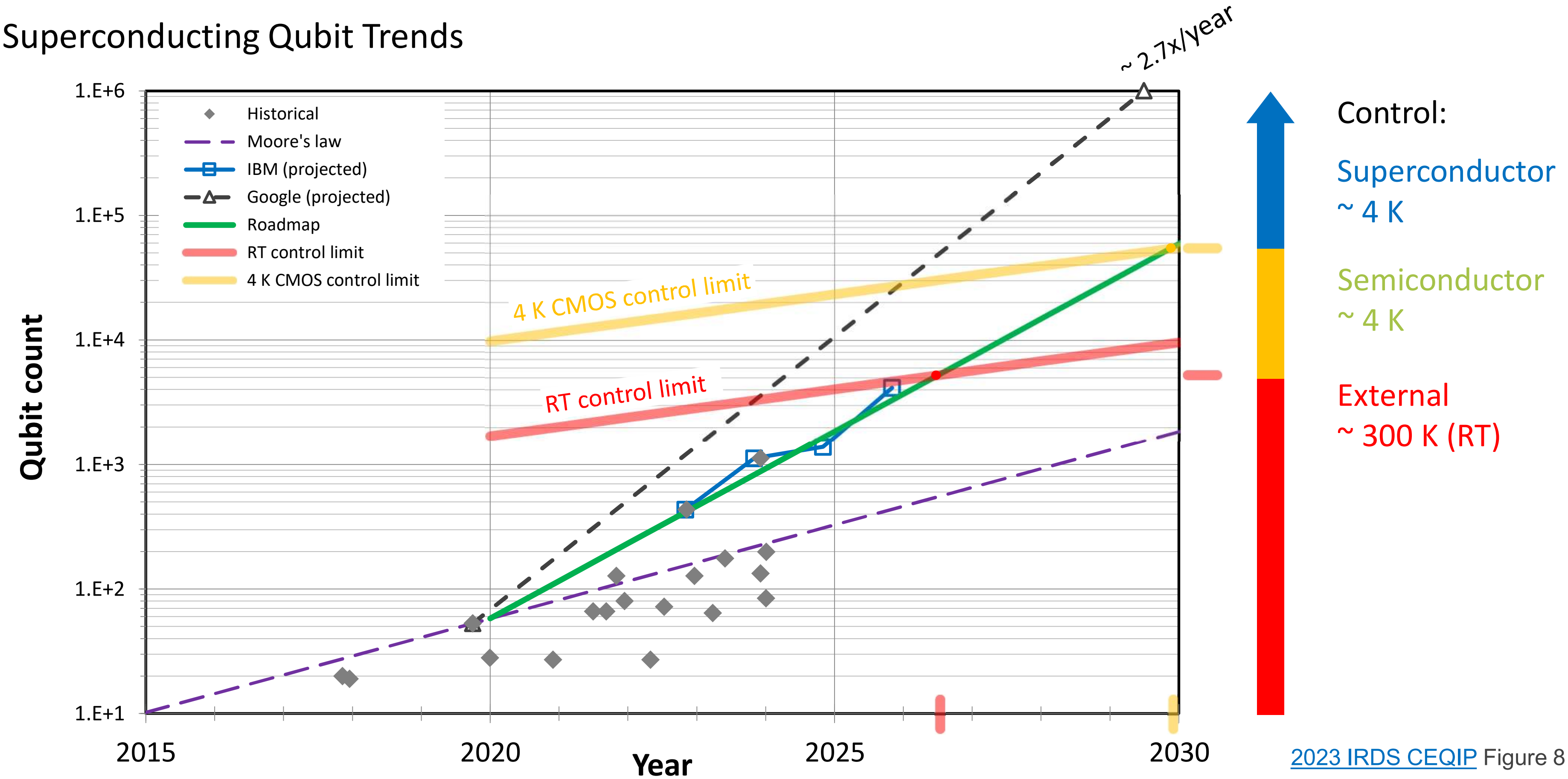
- Superconducting Qubit Trends



2023 IRDS CEQIP Figure 8

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TRL

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Area of concern	Current Status	Proposed Actions
Fabrication process		
Materials	TRL 6, but Nb only	Develop 300 mm process with NbN or NbTiN
0 junctions	TRL 6, but Nb/Al-AlO_x/Nb	Develop 300 mm process with higher J_C and less variation
π junctions	TRL 3, but Ni barrier	Develop junction compatible with NbTiN, 300 mm process
Capacitance layer	TRL 2	Demonstrate; develop 300 mm process

Supporting technologies or capabilities		
Electronic design tools	TRL 6, but missing capabilities	Shared database; support for logic block design
Cryogenics	TRL 9 but capacity gaps	Encourage development of mK refrigeration systems with higher capacity and better efficiency
Test facilities	Low speed	Community needs to decide if it can work together to avoid expensive redundancy
Workforce	Scarce at all levels	Development needed at graduate, technical and apprentice levels

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Strategic Roadmap (SCE + QIP)

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Theme	Unit	4 years	7 years	10 years
High performance computing (HPC)	EFLOP/s	0.1	20	100
	TFLOP/J	100	100	200
Neuromorphic computing	GSUPS	0.1	0.5	10
Quantum computing support system complexity	M JJ	10	100	1000

SUPS: synaptic updates per second

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Grand Challenges

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- Digital computer system
  - 100 EFlop/s performance
  - 200 TFlop/J computational energy efficiency
- Machine learning system
  - Train on MNIST within 1 second and perform inference with > 90% accuracy
- Quantum computing support system for 100,000 qubits
  - Provide control, readout, or quantum error correction support

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WP5 – Grand Challenges and Strategic Roadmap (SCE + QIP) (3 Challenges)

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1. Digital computer system
   - 100 EFlop/s performance
   - 200 TFlop/J computational energy efficiency
2. Machine learning system
   - Train on MNIST within 1 second and perform inference with > 90% accuracy
3. Quantum computing support system for 100,000 qubits
   - Provide control, readout, or quantum error correction support

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Potential Partnerships and Consortia

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Sustainable development of each application realm requires an economic ecosystem

- Electronic design automation (EDA) tools: ColdFlux, Synopsys, Cadence, Keysight
- IRDS: International Roadmap for Devices and Systems
- QED-C: The Quantum Economic Development Consortium

- Foundry for fabrication?
- Testing ?

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Impact Summary

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- Energy efficiency
  - Computing currently consumes about half of the power used for electronics. Energy efficient superconductor electronics is needed to enable computing at larger scale without increasing power requirements. The efficiency of large-scale computing systems is projected to improve by a factor of 10 to 100 with the application of superconductor electronics. Applications include data centres for digital computing, artificial intelligence (AI), and quantum information processing.
- Affordability
  - Superconductor electronics will enable existing market applications to grow in capacity at a fraction of the cost and 1% of the energy consumption, thus serving more people for less.
- Expanding scientific horizons
  - Superconductor strip photon detectors (SSPDs) capable of detecting single photons and superconducting transition edge sensors capable of measuring photon energies have enabled scientific discoveries in astrophysics. Arrays with fast processing will allow future discoveries.

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Call to Action

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- Digital superconductor electronics
  - Fabrication process and open foundry are needed
  - Testing facilities are needed

- Quantum computing
  - Strong investment from government and industry
  - QC support electronics, both digital and analogue, need development and investment
  - IRDS technology roadmap for superconducting QC predicts that superconductor electronic control and readout is needed by 2032 (DOI: 10.60627/042B-J892, section 4.3.3.1)

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