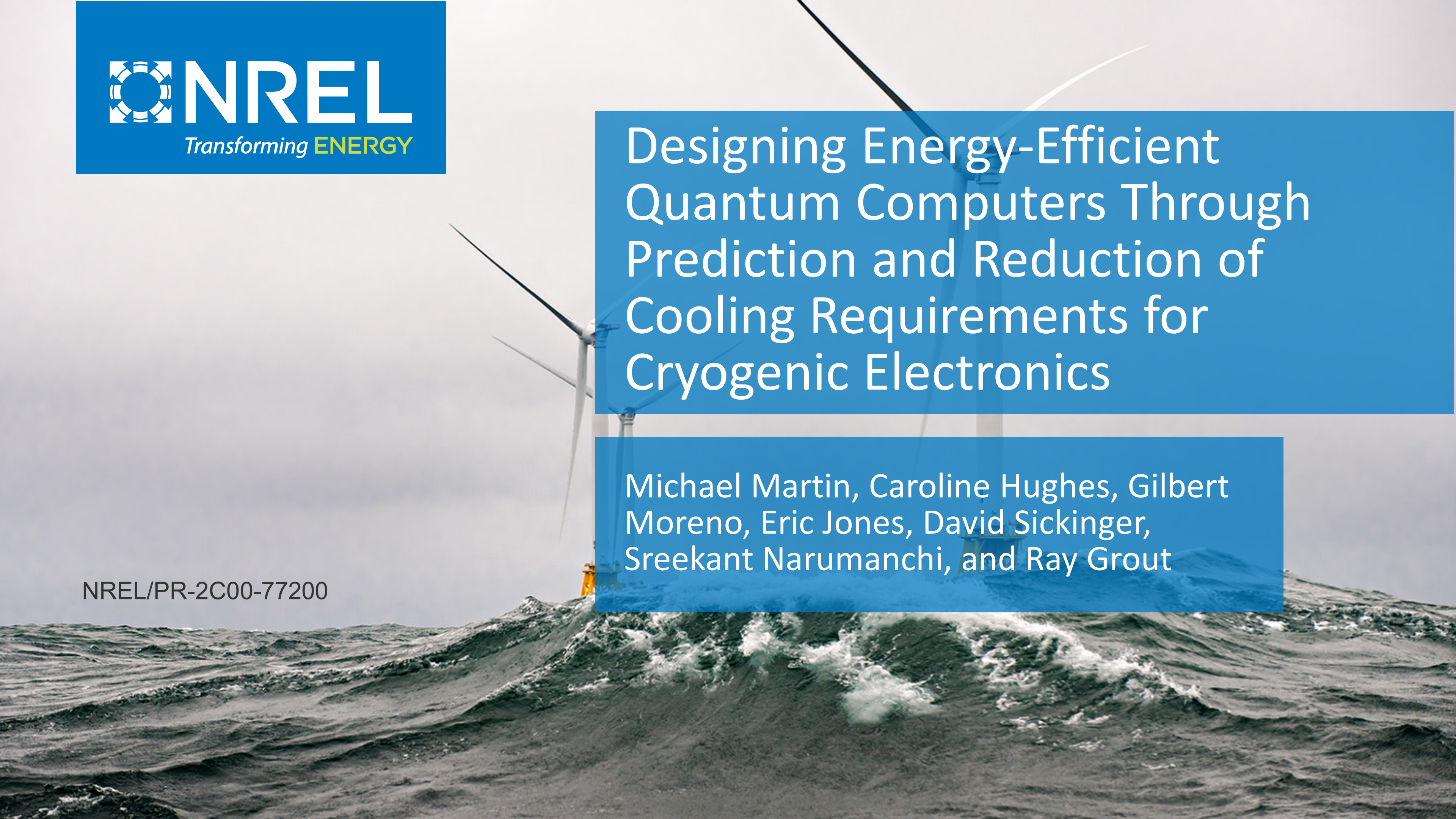

Designing Energy-Efficient Quantum Computers Through Prediction and Reduction of Cooling Requirements for Cryogenic Electronics

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Outline

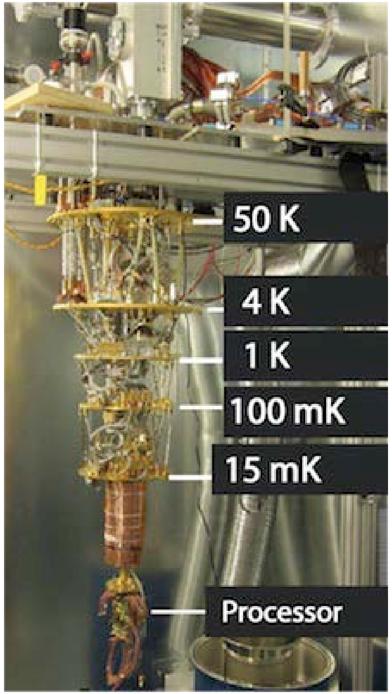
- QC and Energy Use: General Overview
- Model Development
- Ideal Results (No heat transfer)
- Results with heat transfer
- Conclusions

QC and Energy Use (1)

Quantum circuits operate at cryogenic temperatures.

- Operating temperatures determined by qubit type: superconducting qubits operate between 10-20 mK, while trapped-ion qubits operate at around 4 K.
- Development of low-temperature, low-energy conventional electronics to support QC an extremely active research area.

- Currently liquid helium and laser cooling are the only viable cooling technologies at these temperatures.



D-Wave Cooling System

QC and Energy Use (2)

Low temperature electronics *generally* use less energy than their higher-temperature counterparts, as shown by Landauer's principle, where the minimum energy cost of erasing a bit of information is given by:

$$E = k_b T_c ln(2).$$

However, the minimum cost of moving that heat out of a cryogenic chamber is given by the Carnot efficiency:

$$W = \frac{Q}{COP(T_c)|_c} = Q\left(\frac{T_o - T_c}{T_c}\right).$$

These two sets of physics drive *system-level* energy use in opposite directions.

QC and Energy Use (3)

Why should we care?

- Energy use in QC was identified by the International Energy Agency as a "wild card" in predicting national and global energy use.
- Because energy use is the dominant expense in data center operation, energy efficiency may limit QC deployment.
- If we understand how computer architecture will determine cryogenic cooling requirements, we may be able to design more energy-efficient quantum computers from the start.

Current quantum computers are 50 physical qubits: what happens when we get to 10,000+ qubits needed for Shor's Algorithm?

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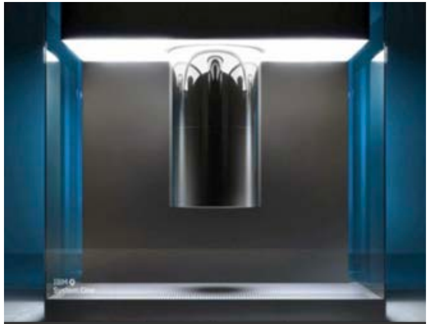
System Model for QC Energy Use (1)

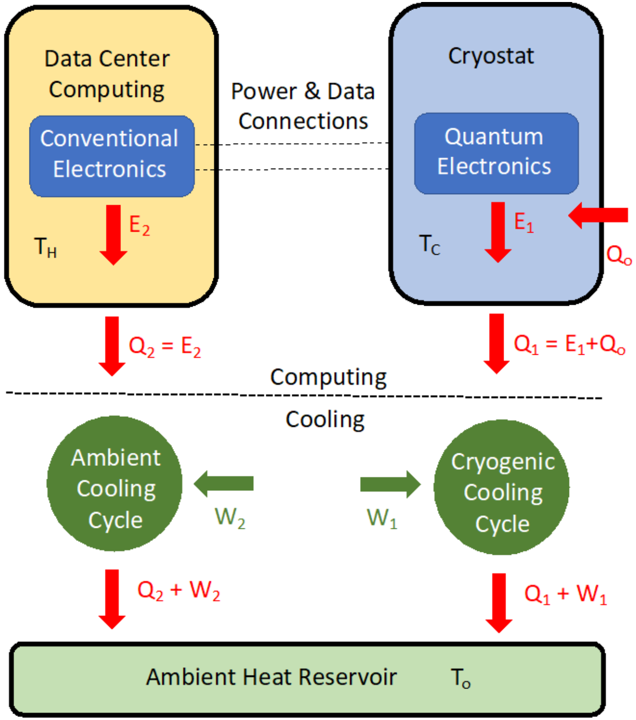
QCs are hybrid systems with multiple loads.

- E_1: Power used by electronics inside the cryostat.
- E_2: Power used by electronics outside the cryostat.
- Q_o: Heat entering the cryostat from ambient.
- W_1: Work to remove heat from cryostat.
- W_2: Work to remove heat from room temperature electronics

IBM quantum computer, showing adjacent packaging of room-temperature and cryogenic electronics.



https://newsroom.ibm.com/2019-01-08-IBM-Unveils-Worlds-First-Integrated-Quantum-Computing-System-for-Commercial-Use



Quantum Computer Energy Model

System Model for QC Energy Use (2)

Electronic heat loads scale with the number of physical qubits n_p, with q = total power used per qubit, and ϕ the energy is split between the data center and cryostat

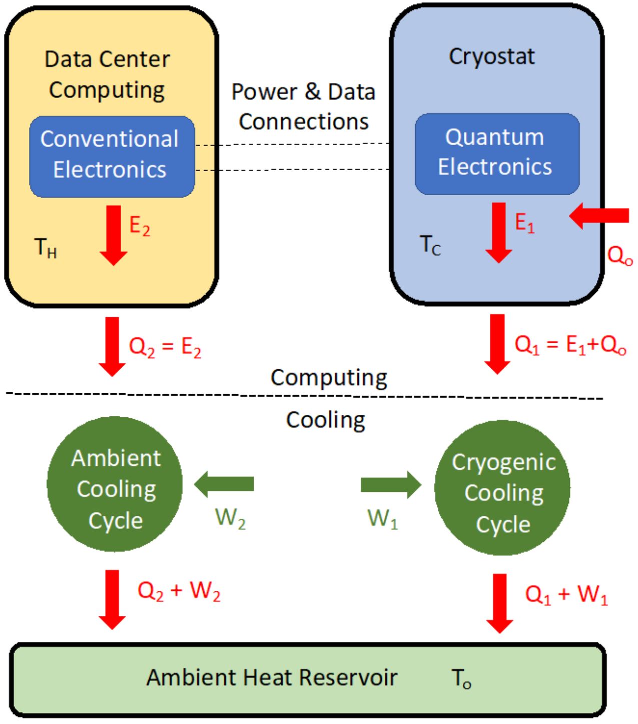
$$E_1 = \phi n_p q \text{ and } E_2 = (1-\phi) n_p q$$

Q_o, the heat entering the cryostat, will be:

$$Q_o = UA(T_o - T_c) \approx UC_1 T_o v_q^{2/3} n_p^{2/3}.$$

W_1 and W_2 based on cooling system efficiencies:

$$W_1 = \frac{E_1 + Q_o}{\eta_c COP(T_c)|_C} \qquad W_2 = Q_2/FOM(T_o).$$



Quantum Computer Energy Model

System Model for QC energy use (3)

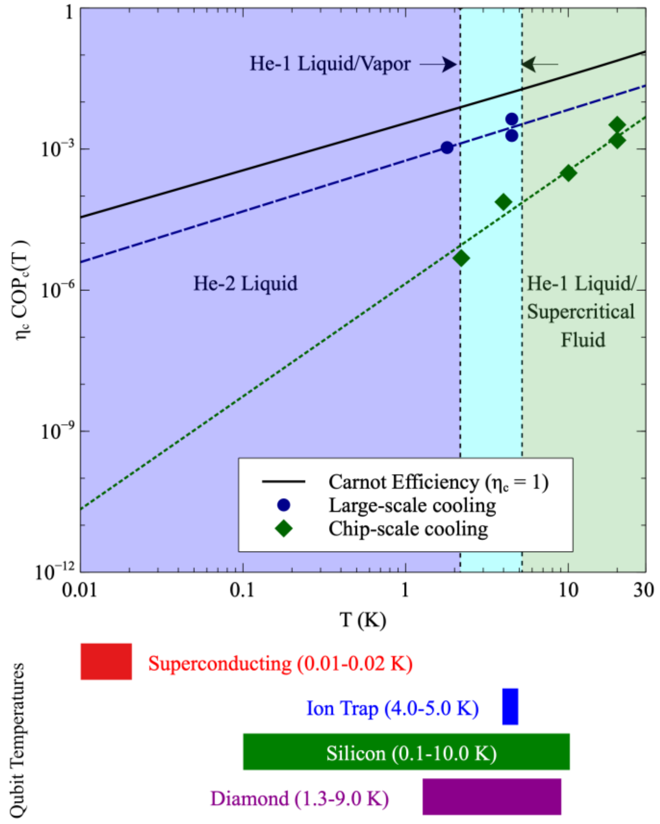
Put all of this together, and we know the total data center energy use:

$$E_T = n_p q \left[1 + \phi \left(\frac{1 + \beta n_p^{-1/3}}{\eta_c COP(T_c)|_C} \right) + \left(\frac{1 - \phi}{FOM(T_o)} \right) \right]$$

Electronics Energy | Cryogenic Cooling | Ambient Cooling

where $\beta = U C_1 T_o v_q^{2/3} / q$

While many of these parameters are unknown, we know enough to begin realistic scaling.



System Model for QC energy use (4)

This equation contains many factors that we just can't predict since technology will evolve.

$$E_T = n_p q \left[1 + \phi\left(\frac{1 + \beta n_p^{-1/3}}{\eta_c COP(T_c)|_C}\right) + \left(\frac{1-\phi}{FOM(T_o)}\right)\right]$$

Factoring out q to get $E_T{}^*$:

$$E_T^* = n_p \left[1 + \phi\left(\frac{1 + \beta n_p^{-1/3}}{\eta_c COP(T_c)|_C}\right) + \left(\frac{1-\phi}{FOM(T_o)}\right)\right]$$

We can also look at the Power Usage Efficiency (PUE), the ratio of total power compared to power used for computation.

$$PUE = \left[1 + \phi\left(\frac{1 + \beta n_p^{-1/3}}{\eta_c COP(T_c)|_C}\right) + \left(\frac{1-\phi}{FOM(T_o)}\right)\right]$$

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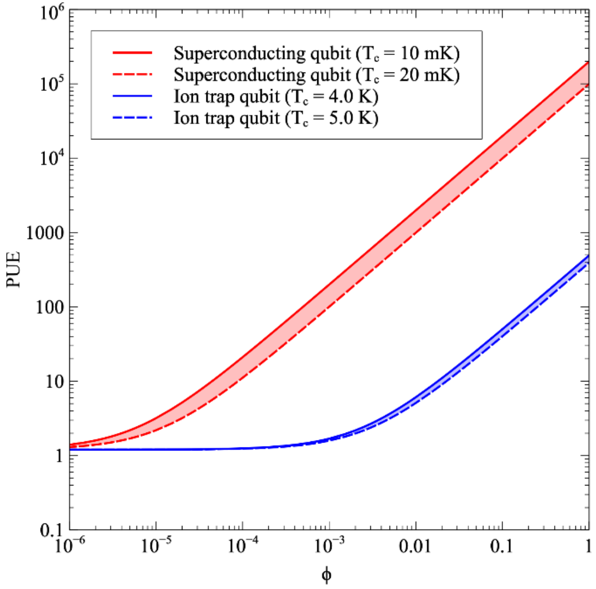
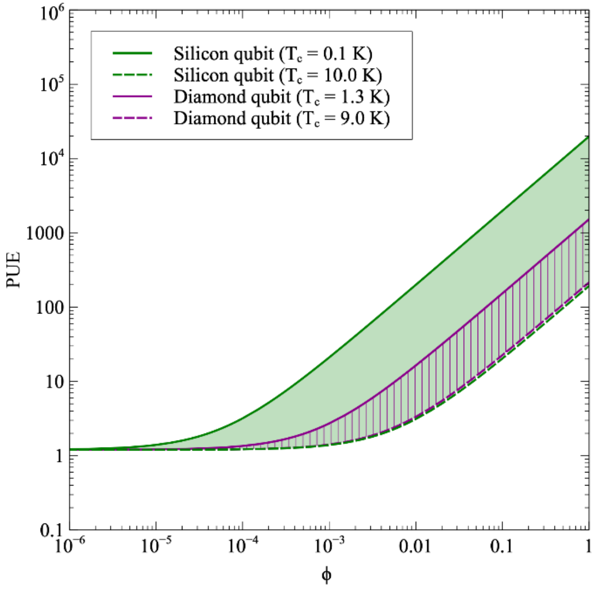
Ideal Results

We can look at the Power Usage Efficiency (PUE) as a function of ϕ when β=0: Results are independent of size.

Cooling power use dominates total power use and is *extremely* sensitive to computing architecture.





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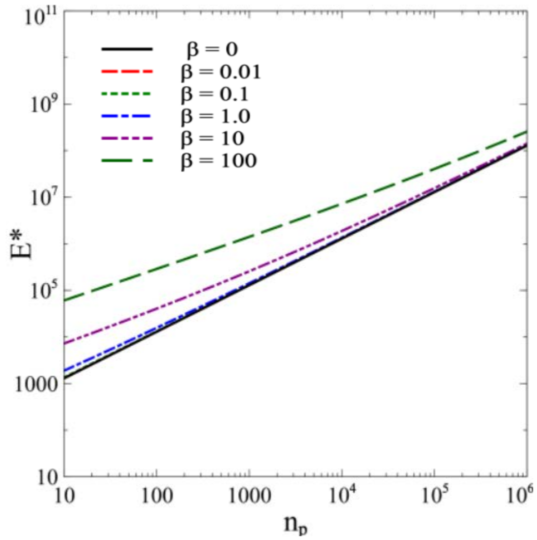
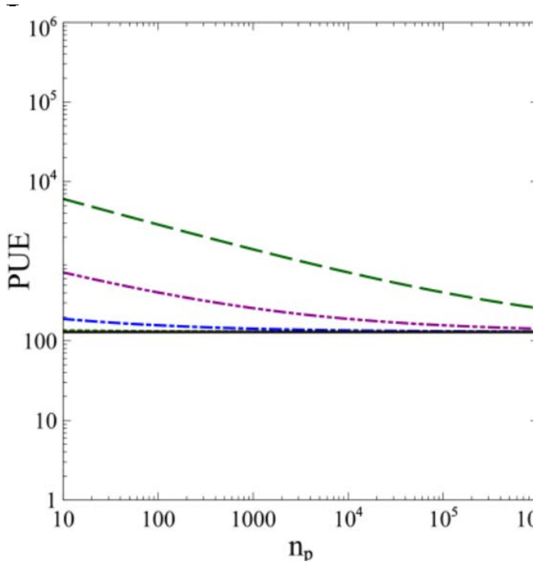
Results with heat transfer (1)

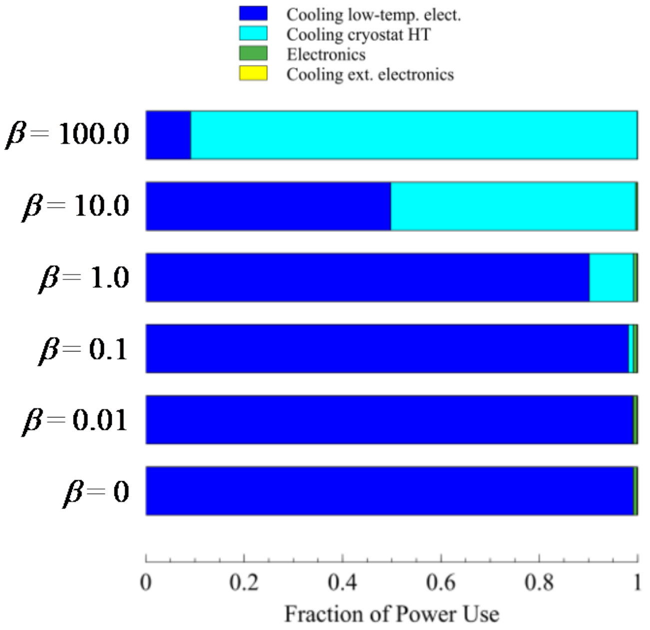
Begin by looking at a superconducting system with $\phi = 0.001$, $T_c = 15$ mK.



$E^* = E/q$



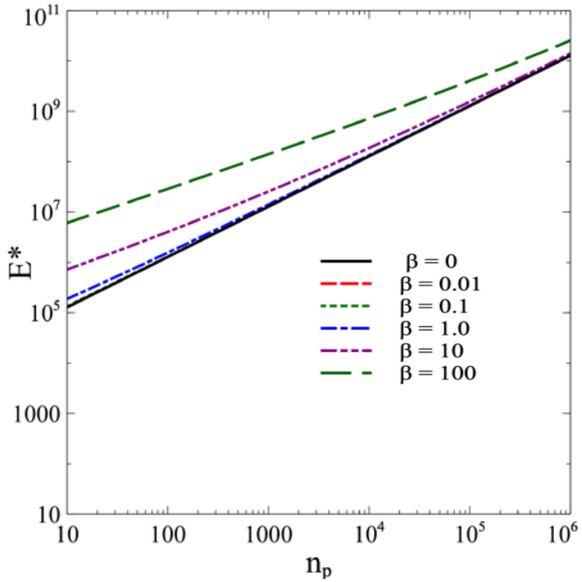
PUE



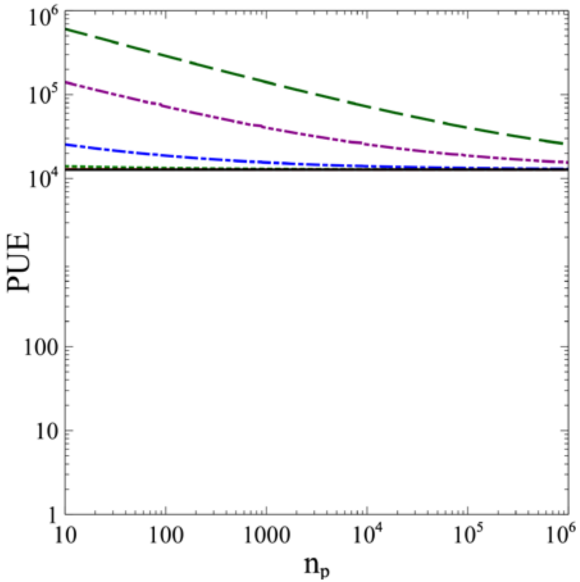
Power Usage for $n_p = 1000$

Results with heat transfer (2)

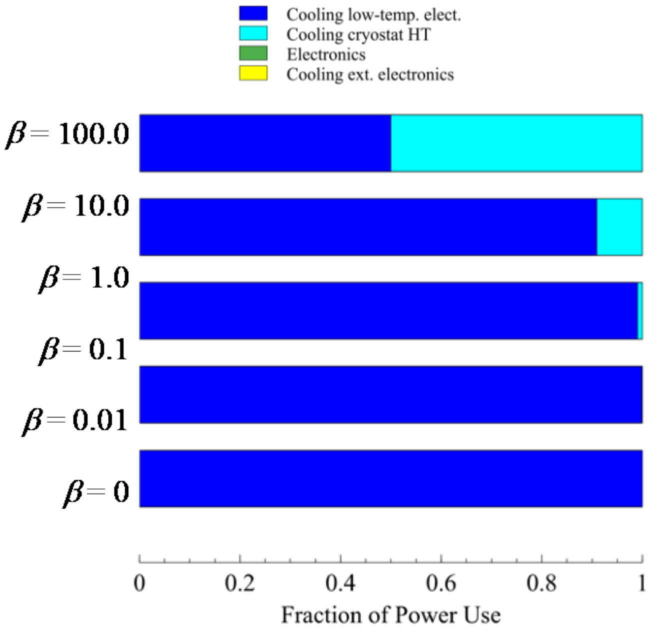
Compare to a superconducting system with $\phi = 0.1$, T_c= 15 mK.



$E^* = E/q$



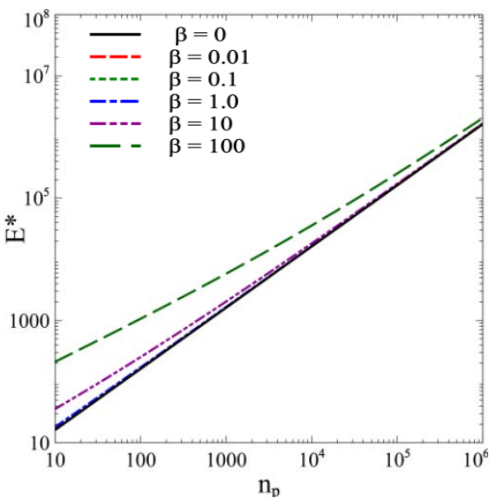
PUE



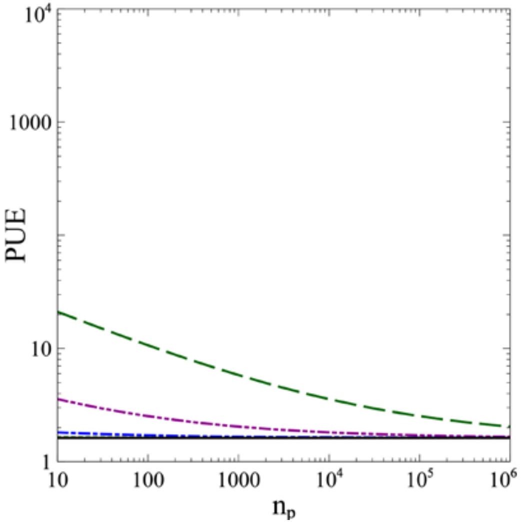
Power Usage for n_p = 1000

Results with heat transfer (3)

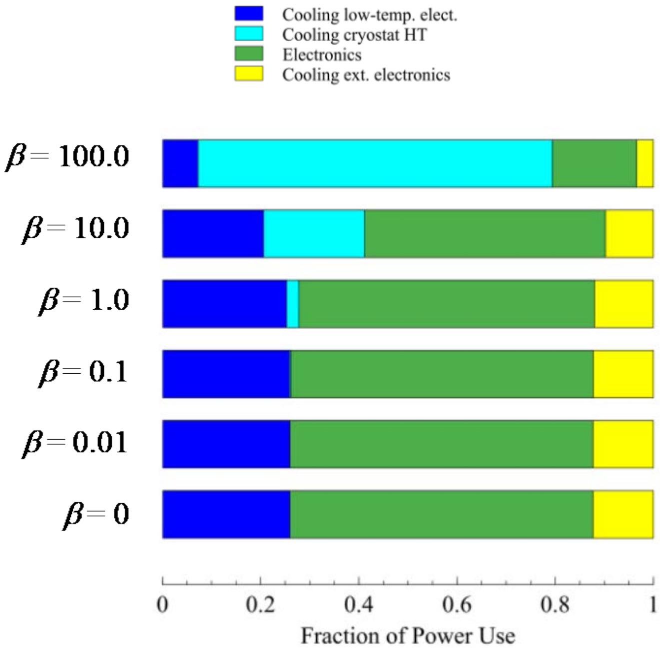
Results are very different for a trapped-ion system with $\phi = 0.001$, $T_c = 4$ K.



$E^* = E/q$



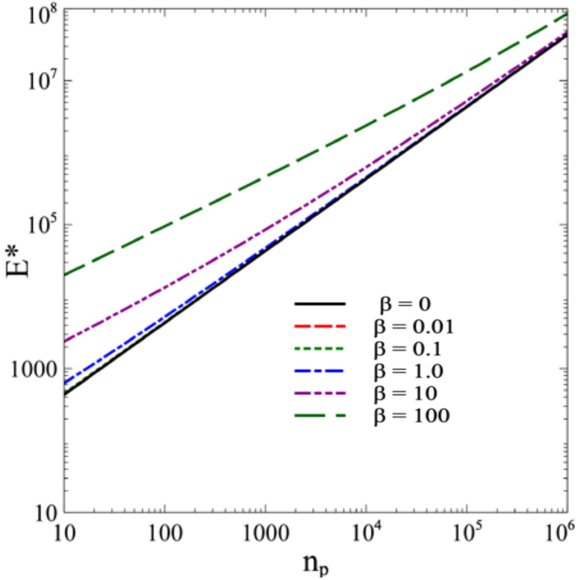
PUE



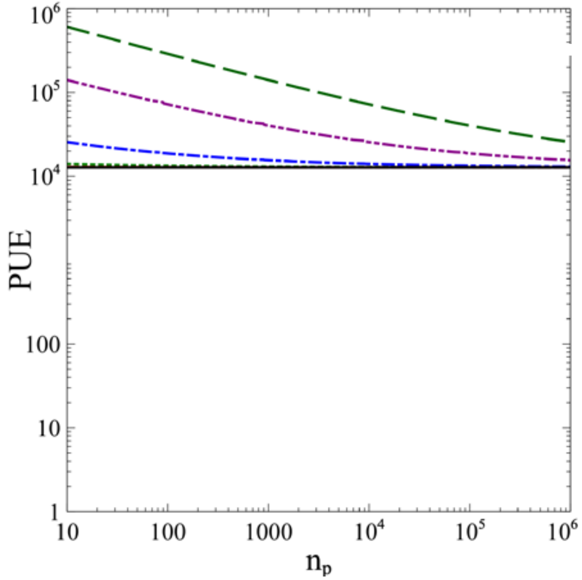
Power Usage for $n_p = 1000$

Results with heat transfer (4)

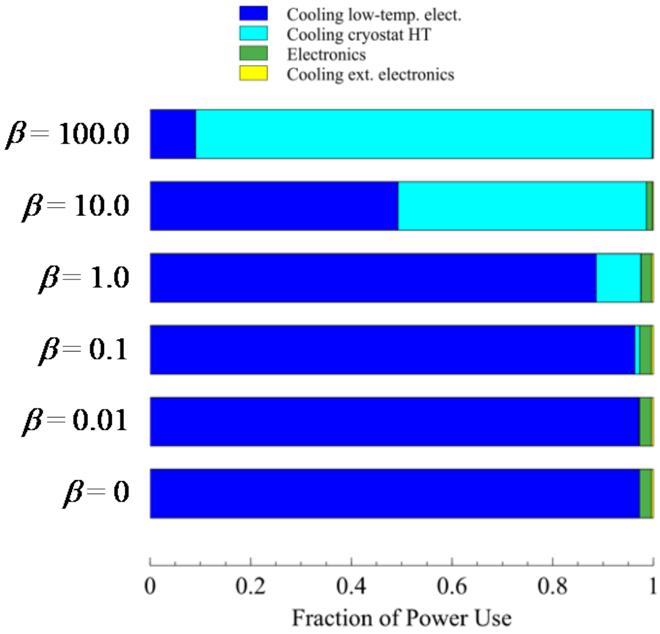
Results are very different for a trapped-ion system with $\phi = 0.1$, $T_c = 4$ K.



$E^* = E/q$



PUE



Power Usage for $n_p = 1000$

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Conclusions

Even without knowing details of QC architecture, we can scale QC energy use.

- Cooling dominates overall power usage, a reversal from classical computing where cooling is 2-20% of power usage.
- The power usage is sensitive to the computer architecture: more power dissipated in the cryostat, lower qubit temperatures, and physically larger systems all drive up power usage

We can *design* systems for lower power by taking these effects into account.

Questions?

Questions?

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Computing power vs power (1)

No clear metric for computing power in QC, but we can look at how the Hilbert space *C* scales with the number of *computational qubits* n_c:

$$C \propto 2^{n_c} = 2^{n_p/N}.$$

N depends on the error rate. An error rate of of 10^{-3} gives N = 15,313, an error rate of 10^{-6} gives N=1,013, and an error rate of 10^{-9} gives N=313.

Scale C^* as the Hilbert space divided by the Hilbert space given by 1,000 computational qubits.

C^*	N = 100	N = 1,000	N = 10,000
0.01	9.9336×10^4	9.9336×10^5	9.9336×10^6
0.1	9.9668×10^4	9.9668×10^5	9.9668×10^6
1.0	1.0×10^5	1.0×10^6	1.0×10^7
10.0	1.0033×10^5	1.0033×10^6	1.0033×10^7
100.0	1.0067×10^5	1.0067×10^6	1.0067×10^7

Computing power vs power (2)

The previous scaling suggests we want as many qubits as possible to maximize computational power.

We can look at how providing the computational power of 1,000 computational qubits changes with *N* and with qubit type. The error rate impacts energy efficiency…