Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Superconducting qubit studies at NEXUS

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New Perspectives 2022

June 22, 2022

FERMILAB-SLIDES-22-053-AD

Superconducting qubits

- Type of "artificial atom," an anharmonic oscillator that serves as a two-level system
- Superconducting qubits are just one of many kinds of qubits
- Josephson junction is used as a nonlinear inductor to build the anharmonic circuit
- Can be designed for specific transition frequencies, different degrees of anharmonicity, etc.
- Qubit is coupled to a circuit or 3D cavity for readout and control: qubit state affects cavity and vice versa
- Lifetime of qubit state is limited by relaxation and decoherence

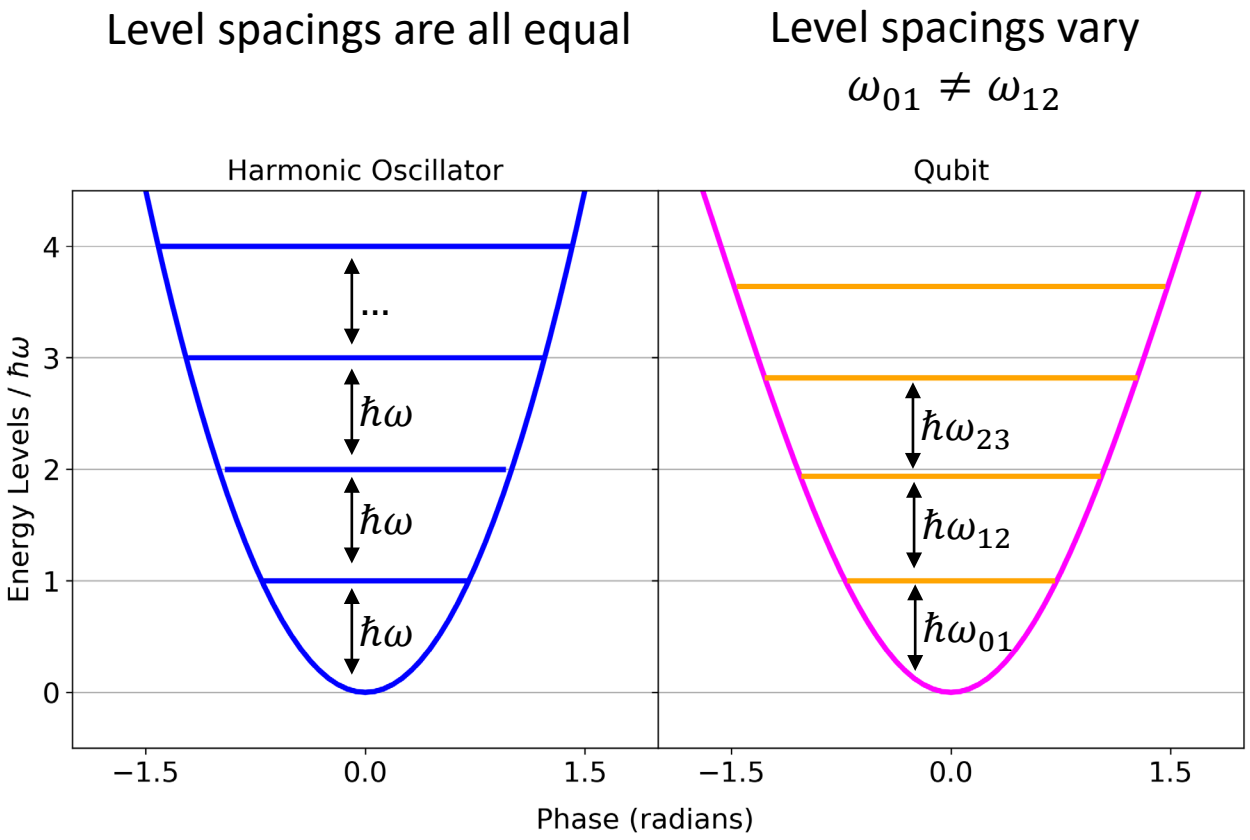

Figure from D. Bowring

Applications of qubits

Quantum computing/information

- Used as bits with $|0\rangle$ and $|1\rangle$ states, but also superpositions of those states
- Qubits can be entangled with other qubits
- Quantum computers: utilize large arrays of entangled qubits to perform computations, encode information
- Errors can arise just as in normal computing, requiring error correction code
- Leading error correction methods require no spatial correlation of errors

Quantum sensing

- Used for low noise experiment readout, e.g. axion dark matter haloscopes
- Linear amplification: fundamental lower bound on the noise of a measurement of two quadratures, the Standard Quantum Limit
- Single photon counting: measure only one quadrature (number) and throw away all information on second quadrature (phase)
- Can measure the same photon many times: quantum nondemolition (QND) measurement
- Errors could result in false positives

Understanding qubit errors is critical for both applications.

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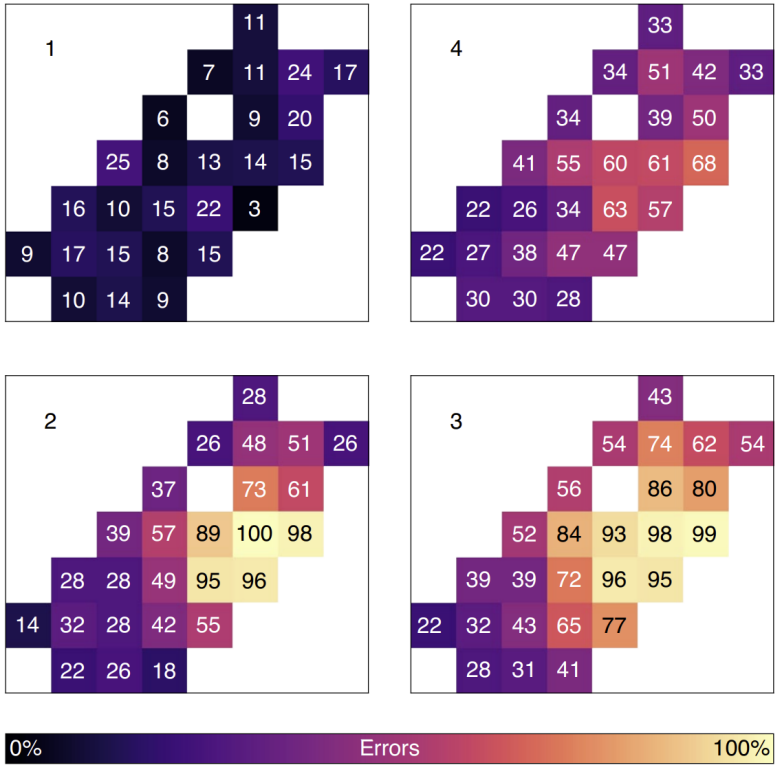
Qubit errors

- Multiple experiments have observed qubit errors and limitations on coherence associated with ionizing radiation
- Suspected mechanism: phonons generated by energy deposition break superconducting Cooper pairs, creating quasiparticles
- These errors have been found to be correlated across multiple qubits on a chip:
  - M. McEwen *et al.* found "catastrophic error bursts" looking at 26 qubits in their Google Sycamore processor on much faster timescales than what's required for computations
  - Wilen *et al.* found a spatial correlation of charge errors over a length scale of 600 µm in a 4 qubit device

McEwen 2022



Relevant literature:

A. P. Vepsäläinen, *et al.* Impact of ionizing radiation on superconducting qubit coherence, *Nature* **584** (2020).

L. Cardani, *et al.* Reducing the impact of radioactivity on quantum circuits in a deep-underground facility, *Nature Communications* **12** (2021).

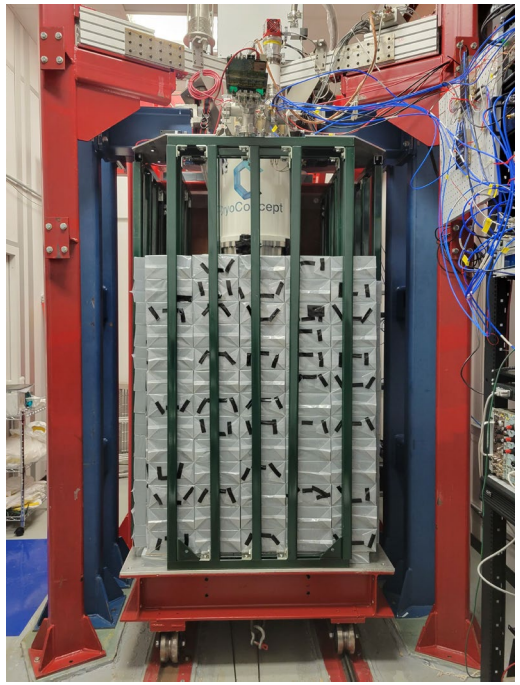
M. McEwen, *et al.* Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits, *Nature Physics* **18** (2022).

C. Wilen, *et al.* Correlated charge noise and relaxation errors in superconducting qubits, *Nature* **594** (2021).

Program at NEXUS

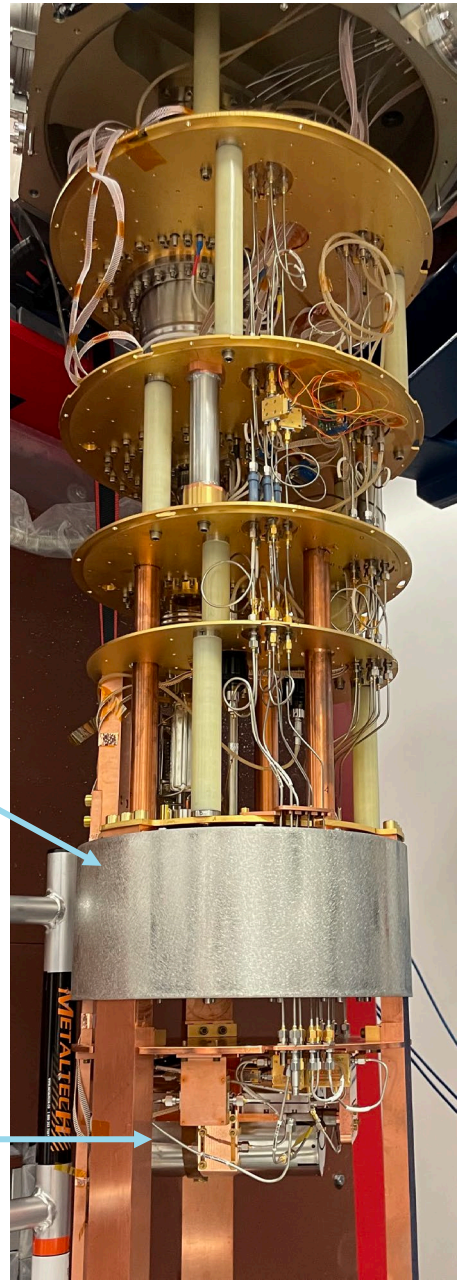
- Taking the same 4 qubit device underground to repeat charge noise study in the low-background environment at NEXUS (D. Temples talk)
- Underground: shielding from cosmic rays
- Lead shielding inside fridge, above RF mixing chamber plate
- Removable lead shield around fridge
- Thoroughly-characterized radiation background

Lead shield photos by B. Schmidt



Lead inside fridge, surrounded by magnetic shield

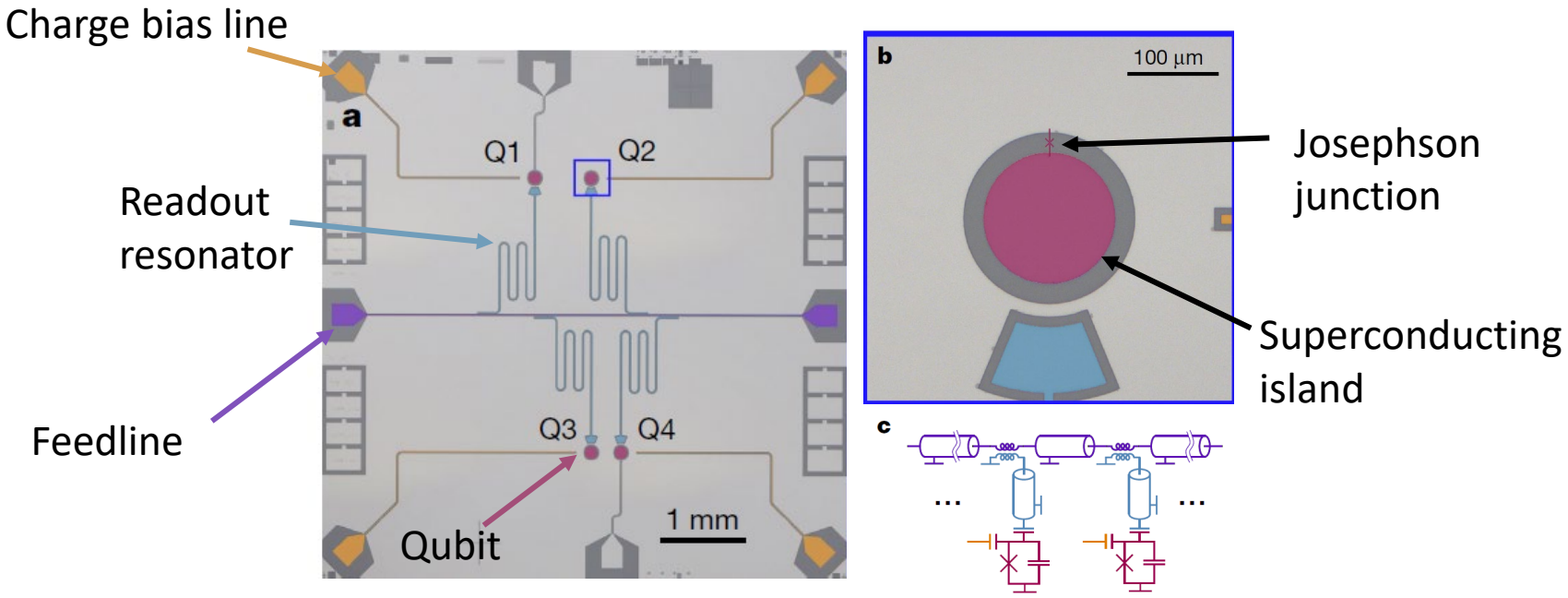
Magnetic shield containing qubit package



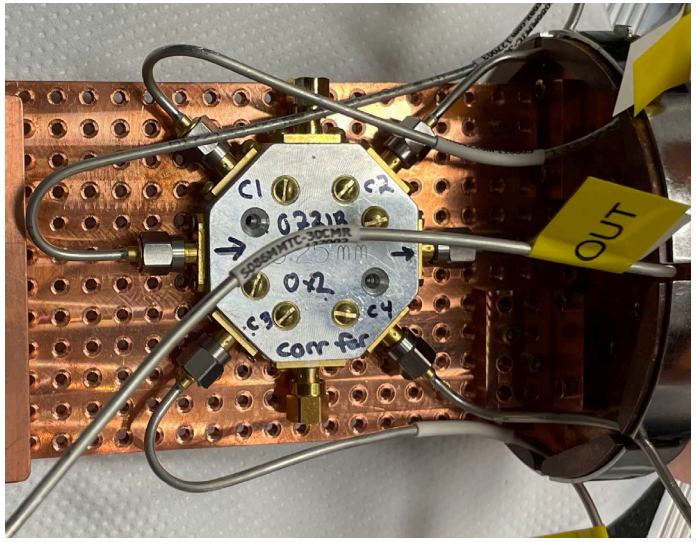
*C. Macklin, *et al.* Science **350**.6258 (2015)

Qubit device and electronics

- Array of 4 weakly charge-sensitive transmon qubits, each with their own resonator and charge bias and a common feedline
- Mounted in an mumetal magnetic shield
- Readout line uses a Traveling Wave Parametric Amplifier (TWPA)* and a HEMT
- Two readout systems: continuous wave (CW) and pulsed

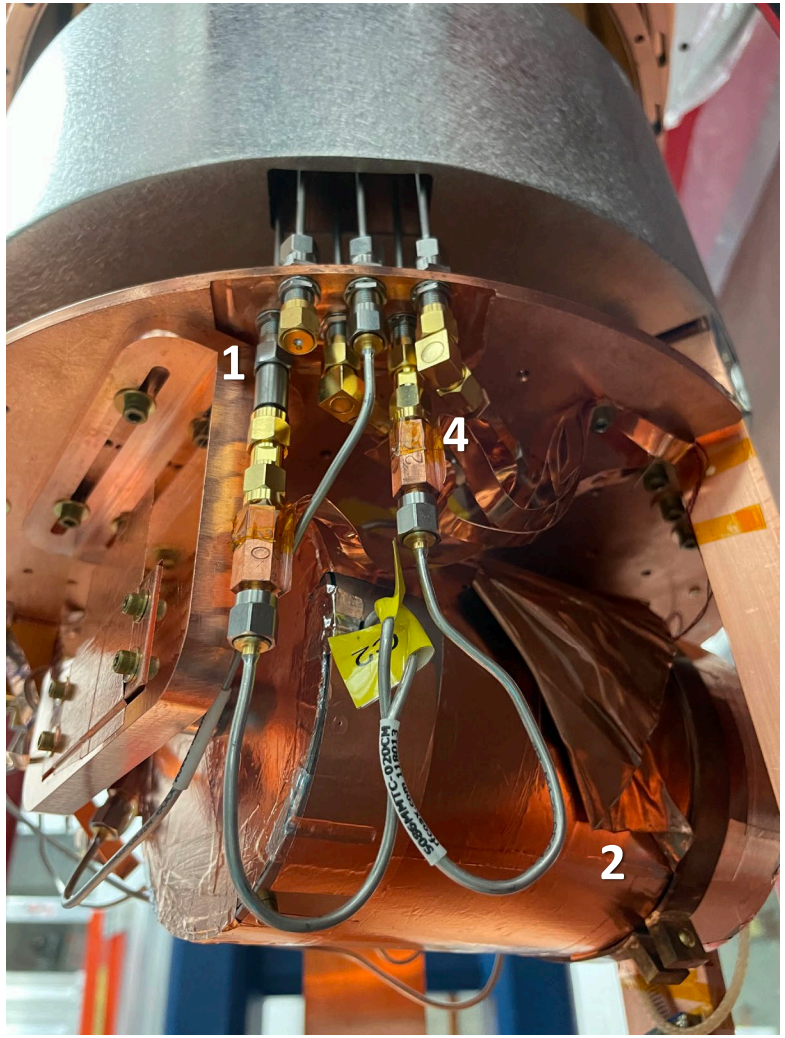


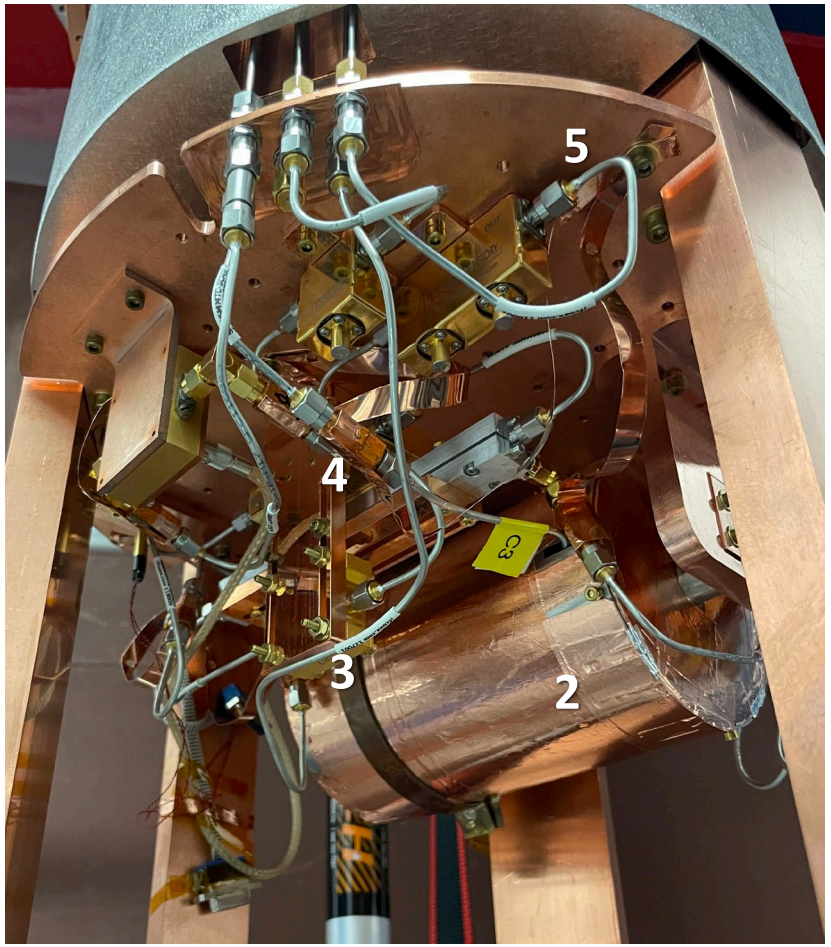
Wilen *et al.*, Nature (2021)

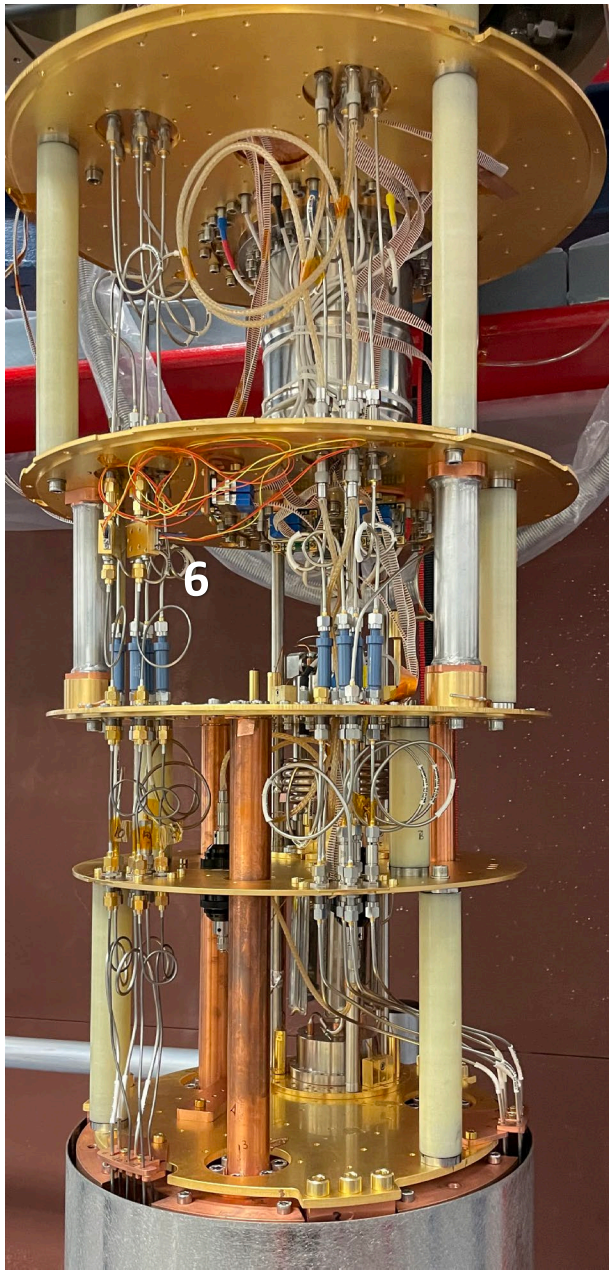


Qubit device and electronics

1. Input line
2. Magnetic shield
3. TWPA
4. Eccosorb filter
5. Output line
6. HEMT





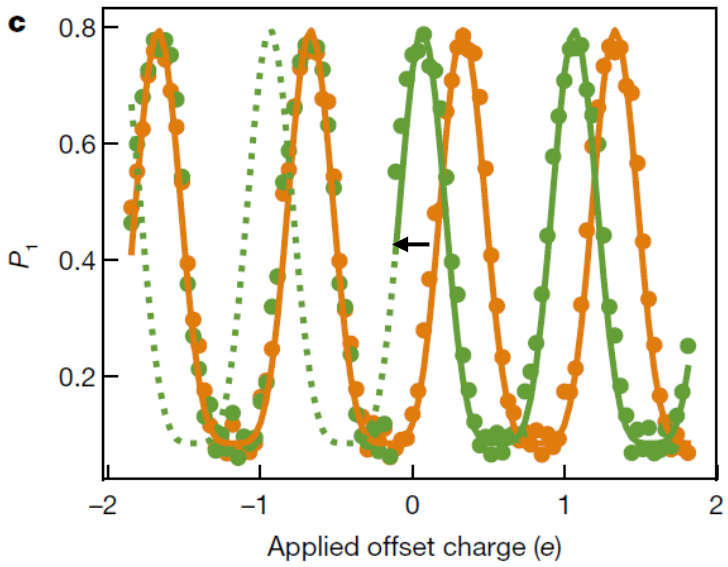


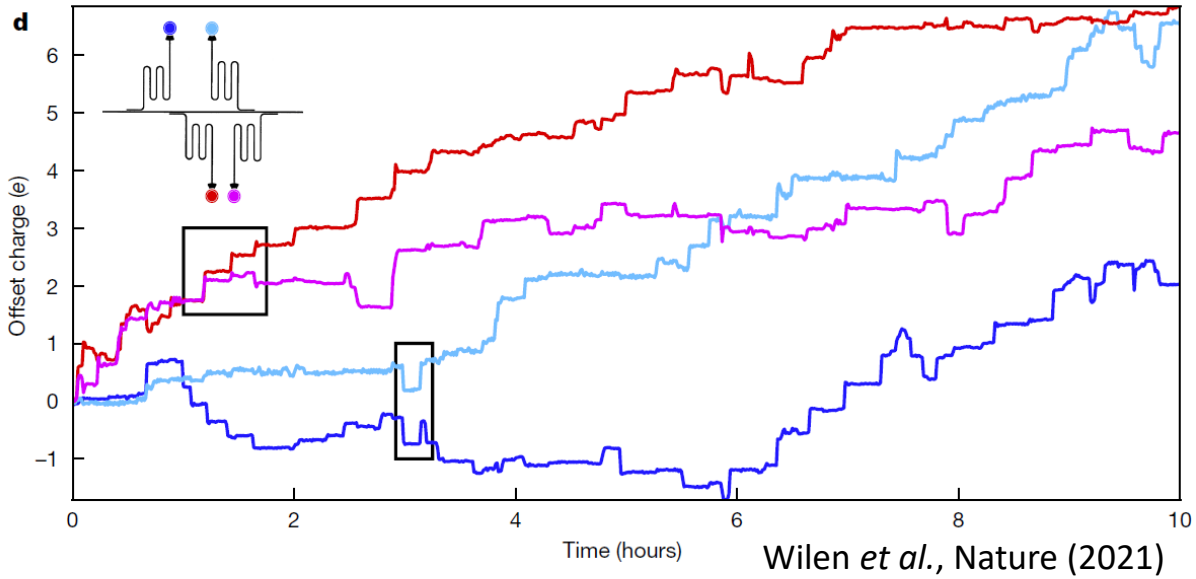
Measurement goals

- Perform Ramsey tomography on the qubits: measuring qubit state as a function of applied offset charge, expect predictable oscillation
- Looking for sudden deviation from prediction
- Simultaneous monitoring of multiple qubits for these unexpected charge jumps (errors) to determine the error rate

- **Goal:** determine the impact of shielding on the error rate, compare with Wilen results
- Long term:
  - Additional measurements in a local above ground fridge for additional comparison
  - Analysis of backgrounds for qubit-based dark matter searches
  - Guidance about device construction, material choice, and shielding to mitigate errors

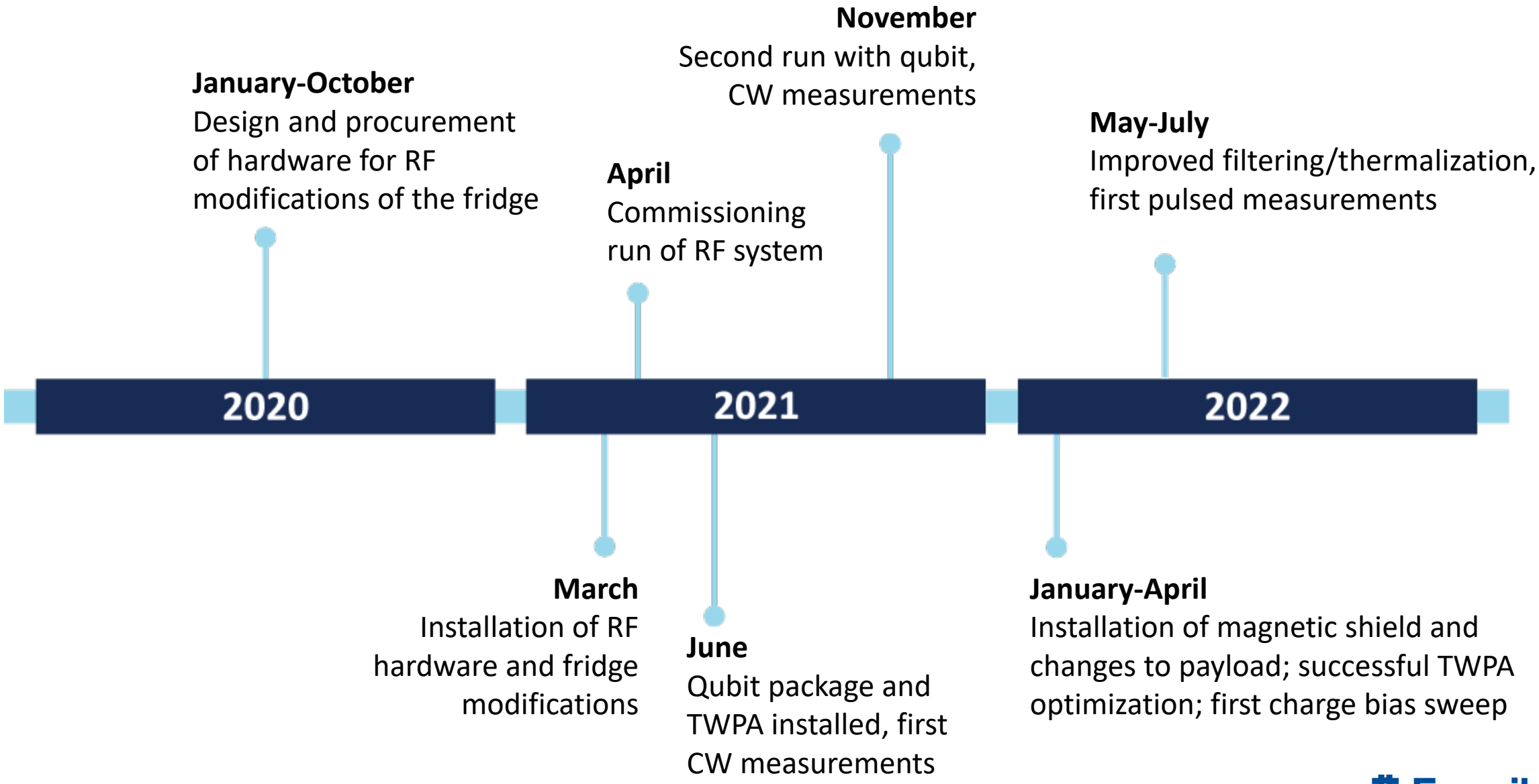
Green vs orange: jump from expected oscillation





Wilen *et al.*, Nature (2021)

Timeline and work so far

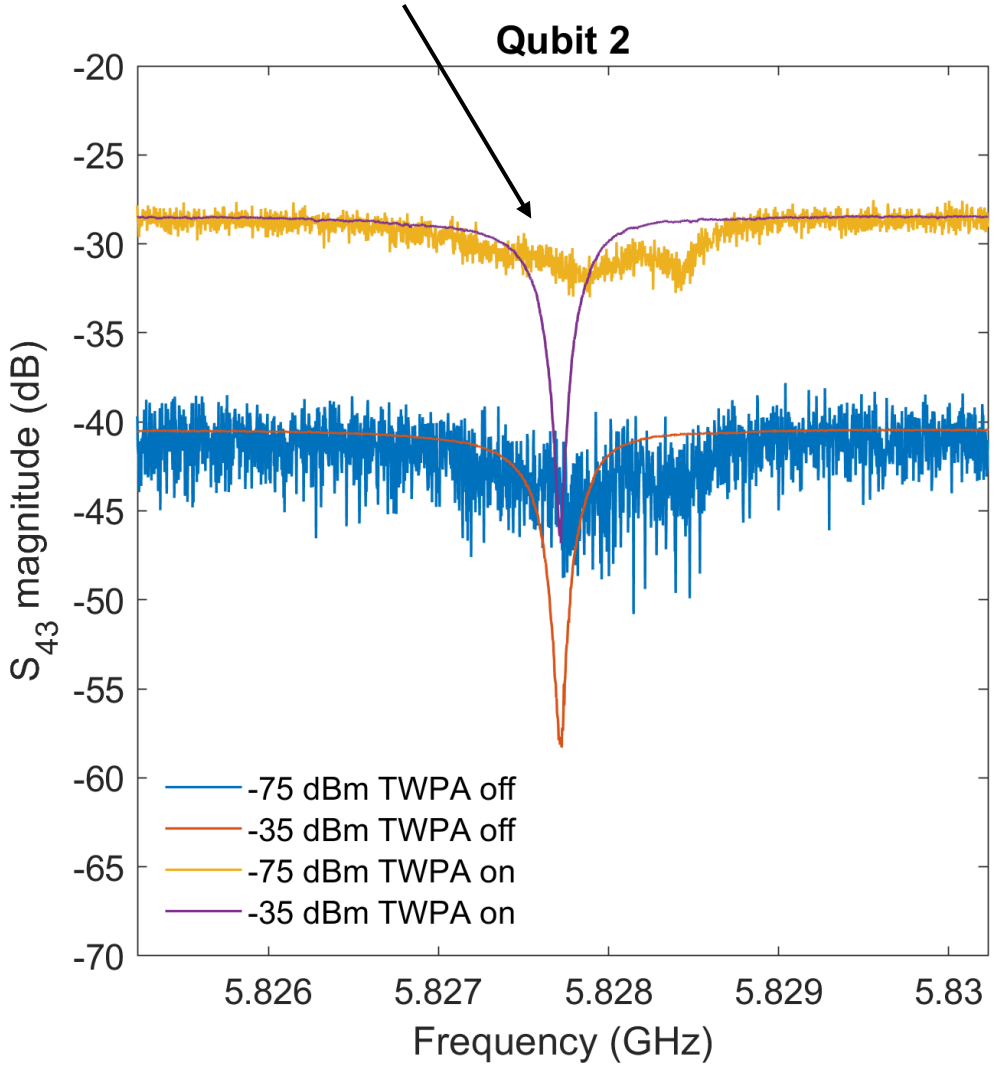


Progress in previous runs

- Cavity and qubit spectroscopy performed with CW measurement system; optimization of TWPA
- Initial measurements performed to measure qubit spectroscopy as a function of charge bias: first step for correlated charge noise study
- Initial CW measurements to understand qubit temperature (Stark calibration)
- Commissioning of hardware on warm side, development of code-base for hardware control

- One limitation in previous runs: qubits were hot

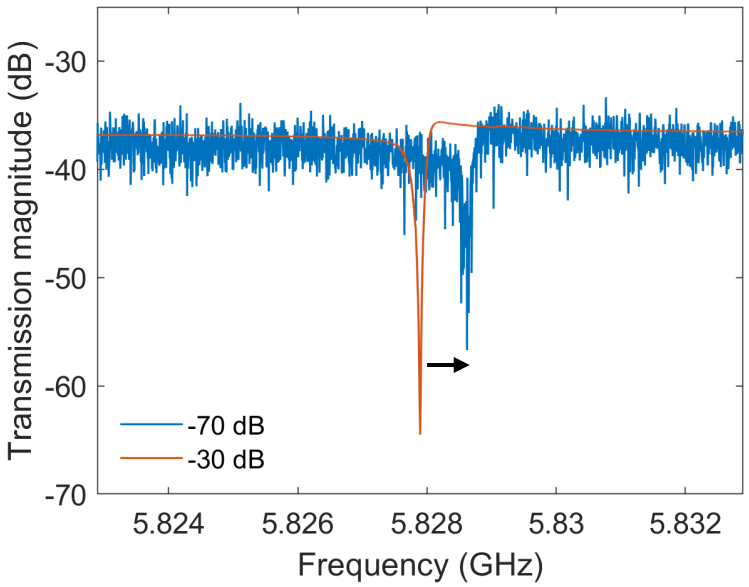
Multiple peaks in low power state, indicative of extra power reaching device

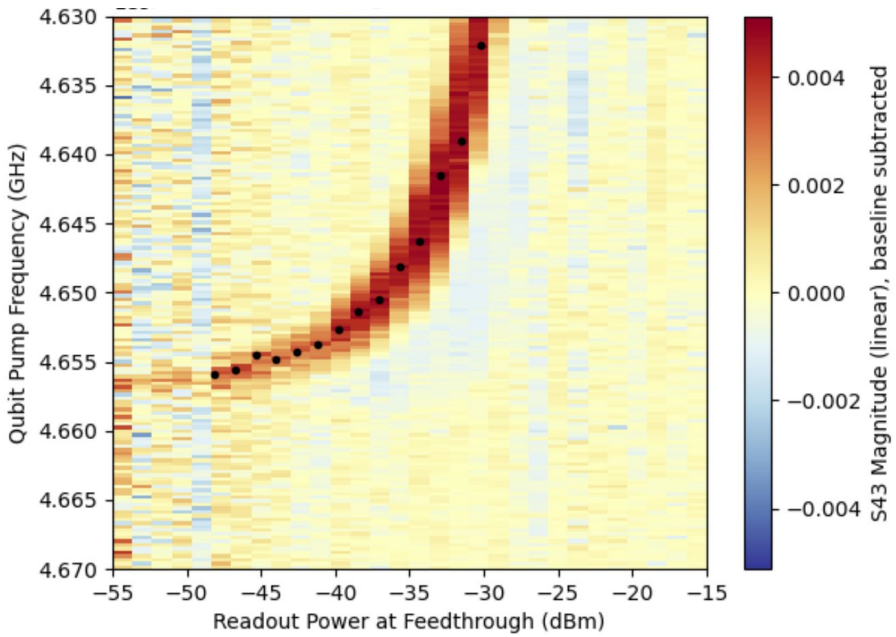


Work in NEXUS Run 14 (ongoing)

- Improved qubit temperature by adding Eccosorb filters and additional attenuation
- Repeated previous measurements to confirm changes improved qubit temperature
- Initial measurements performed with the pulsed setup, first pulsed operation of the qubit device!
- Ongoing: fine-grain measurements of qubit spectroscopy versus charge bias, planned with and without lead shielding
- Upcoming: additional pulsed measurements for charge noise study

Clear shift from high to low power





Shift in qubit frequency as a function of readout power, can get photon number in cavity (AC Stark shift)

Thank you!

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Daniel Bowring
Matt Hollister
Samantha Lewis
Jialin Yu
Alexander Novara (SULI 2021)
Hannah Magoon

Northwestern

Enectali Figueroa-Feliciano
Valentina Novati
Benjamin Schmidt
Grace Bratrud (SULI 2021)

SLAC NATIONAL ACCELERATOR LABORATORY

Noah Kurinsky
Taj Dyson

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON

Robert McDermott
Chris Wilen
Sohair Abdullah
Gabe Spahn (SULI 2019, NEXUS intern 2020)

Northwestern NEXUS Experimental Underground Site @Fermilab

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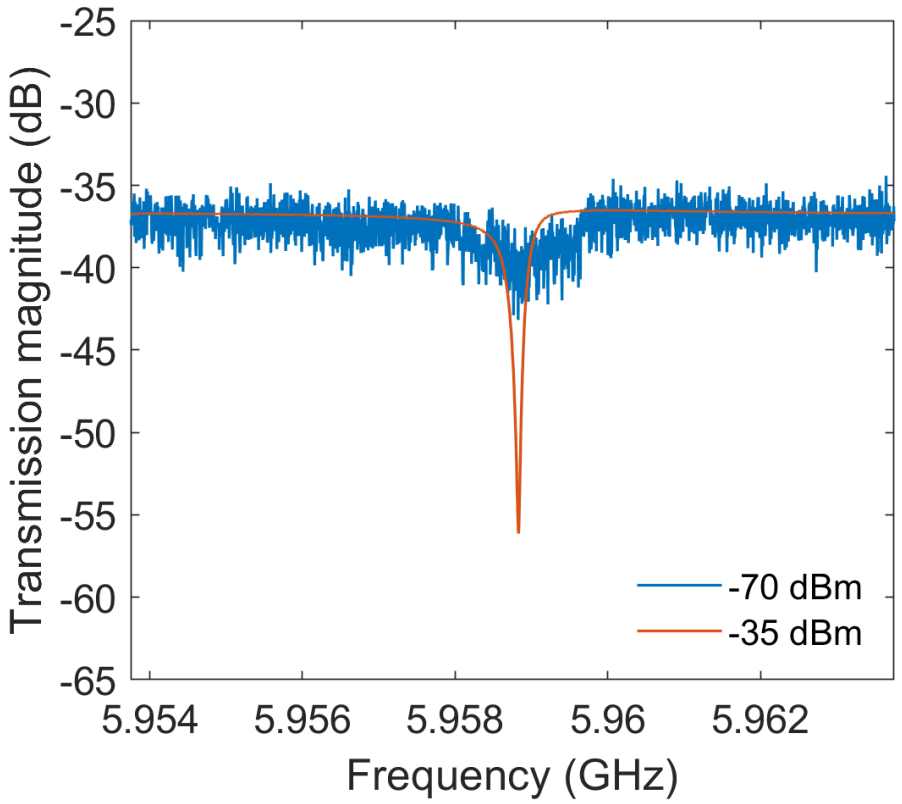
TWPA: C. Macklin, *et al.* Science **350**.6258 (2015)

Backup slides

Change in cavity spectroscopy Run 13 to Run 14

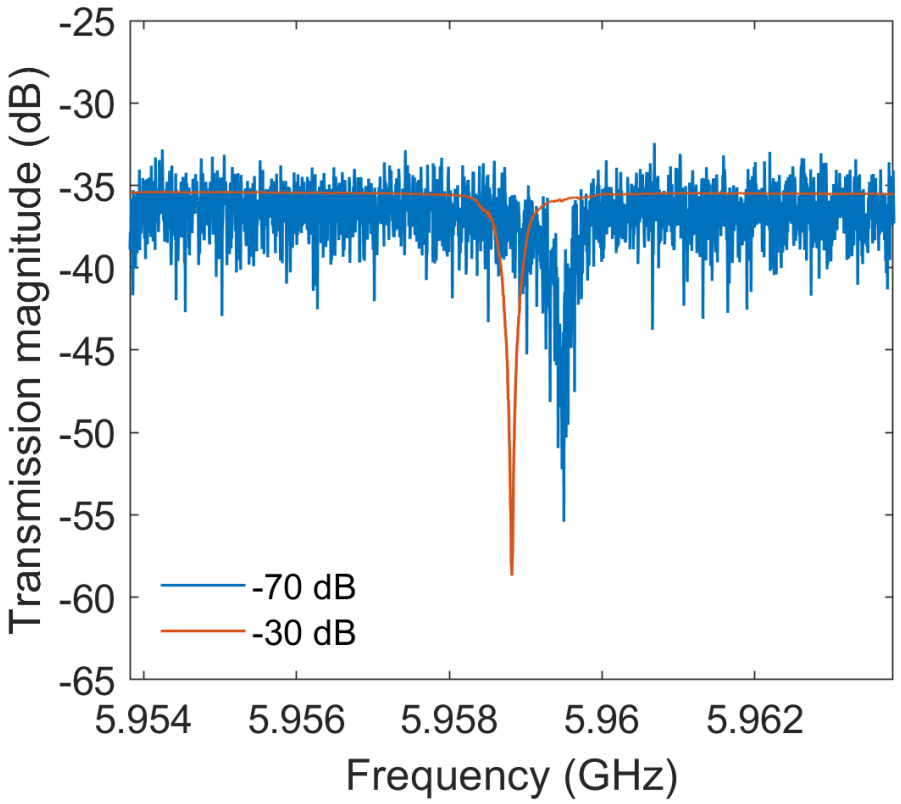
Run 13

Shifted peak not visible in lowest power state



Run 14

Clear shifted peak at same low power, half the number of averages as other case



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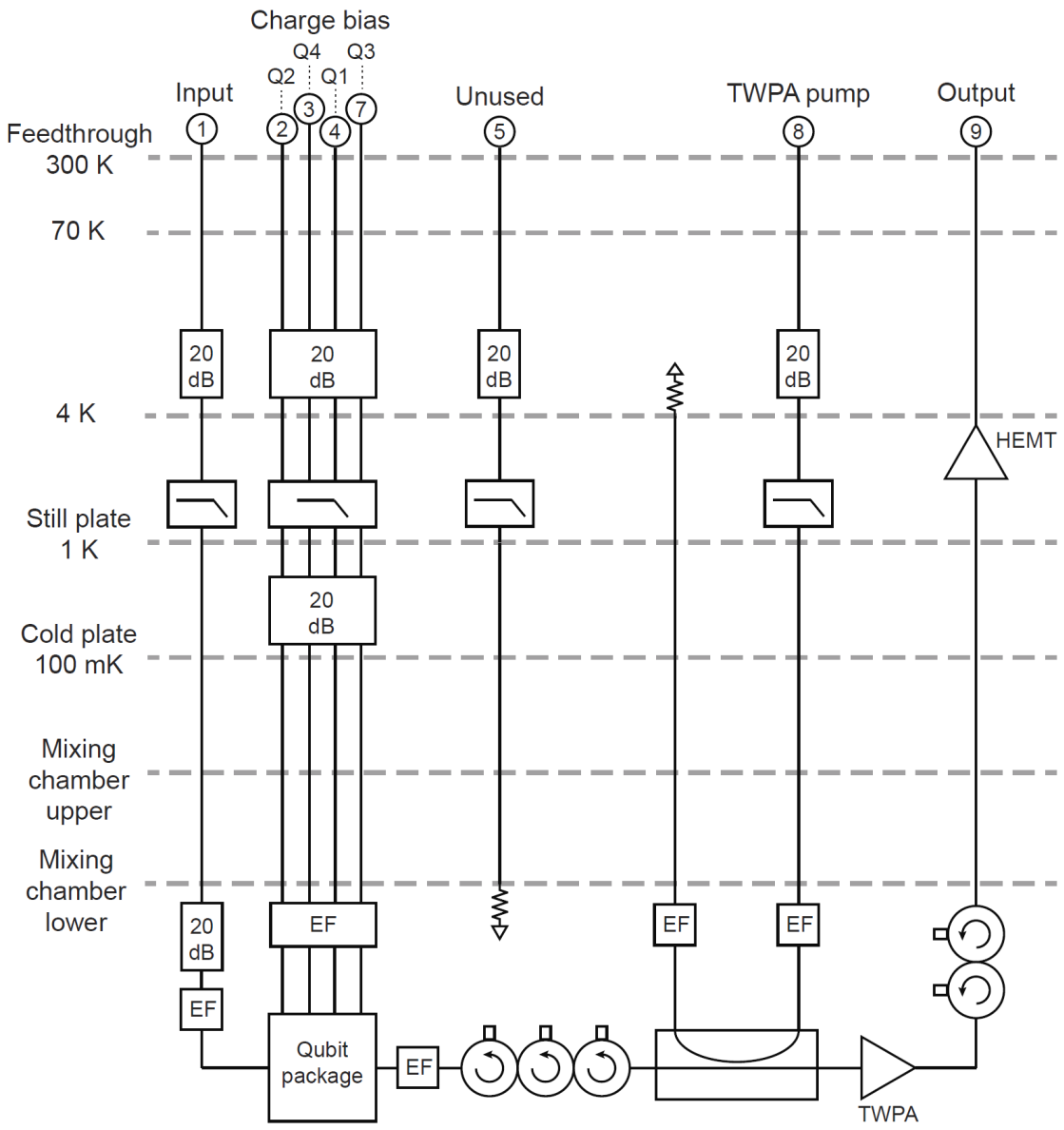
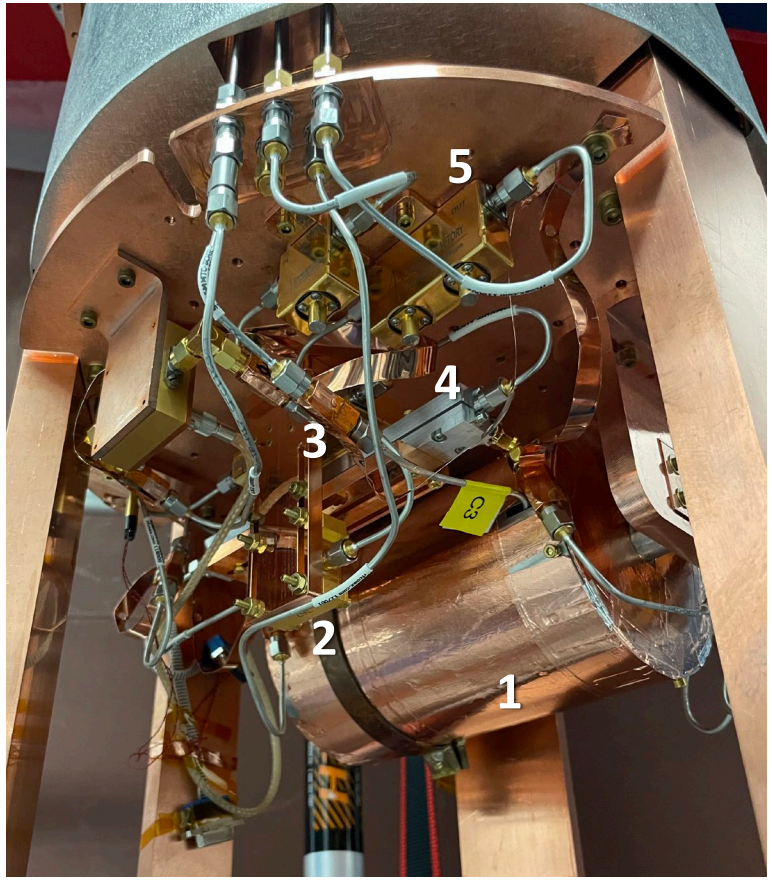
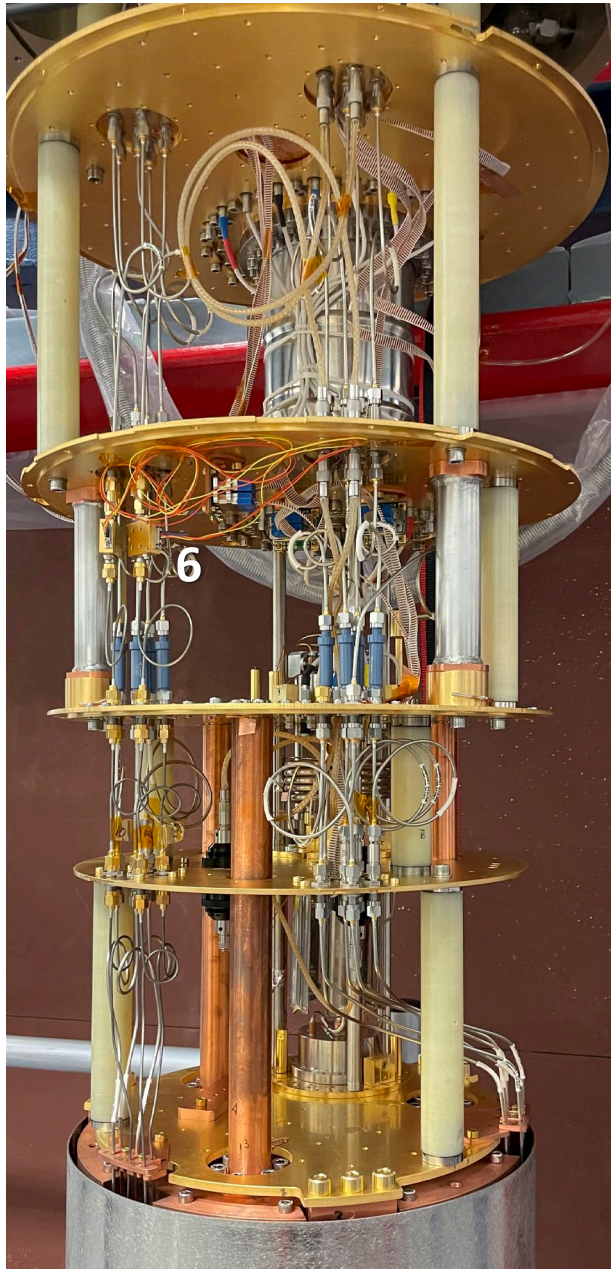


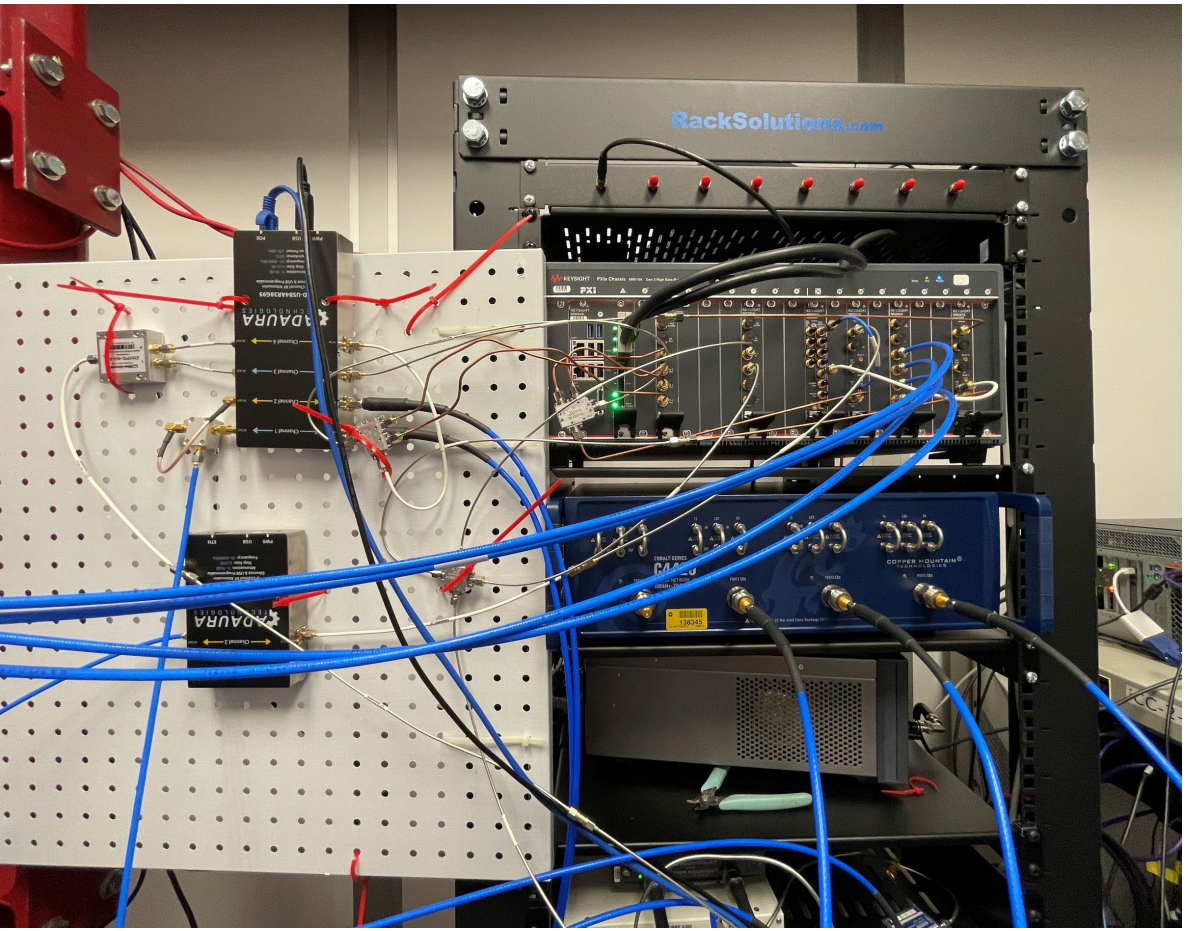


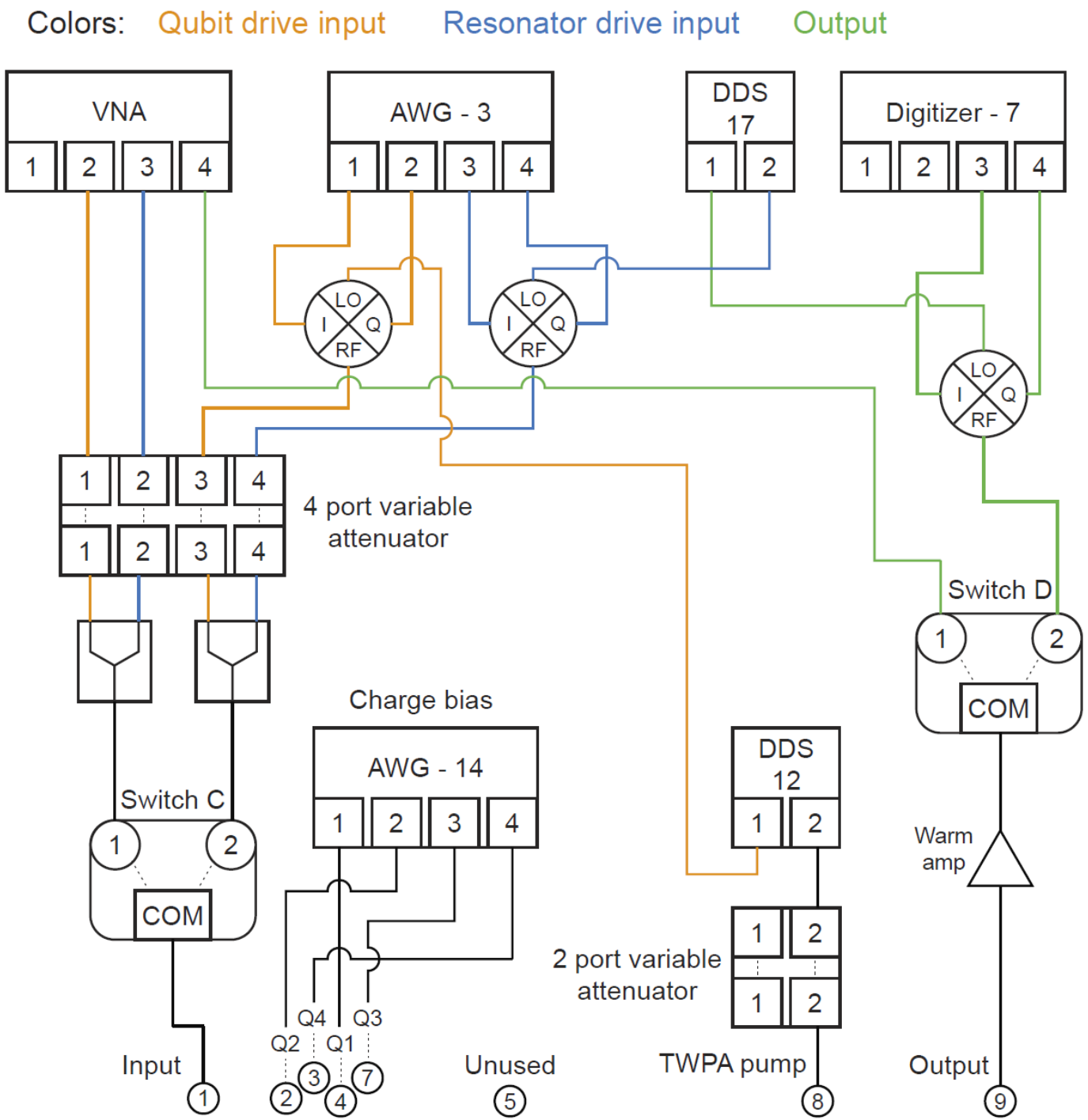


1. Magnetic shield
2. TWPA
3. Eccosorb filter
4. Directional coupler
5. Double junction isolator
6. HEMT

Warm wiring

- Continuous wave readout using a Copper Mountain Technologies Vector Network Analyzer
- Pulsed readout with a Keysight PXIe system





Jaynes-Cummings Hamiltonian

- Describes the two-level qubit system coupled to a cavity (harmonic oscillator)

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2 + \frac{\hbar g^2}{\Delta}(a^\dagger a + 1/2)\sigma_z$$

$$H = \hbar\left(\omega_r + \frac{g^2\sigma_z}{\Delta}\right)(a^\dagger a + 1/2) + \hbar\omega_q\sigma_z/2$$

so $\omega_r \to \omega_r \pm g^2/\Delta$. Or, similarly,

$$H = \hbar\omega_r(a^\dagger a + 1/2) + \frac{\hbar}{2}\left(\omega_q + 2\frac{\hbar g^2}{\Delta}a^\dagger a + \frac{g^2}{\Delta}\right)\sigma_z.$$

This is effectively an AC Stark shift in the atom transition frequency $\omega_q \to \omega_q + 2\bar{n}g^2/\Delta$.

Math from D. Bowring

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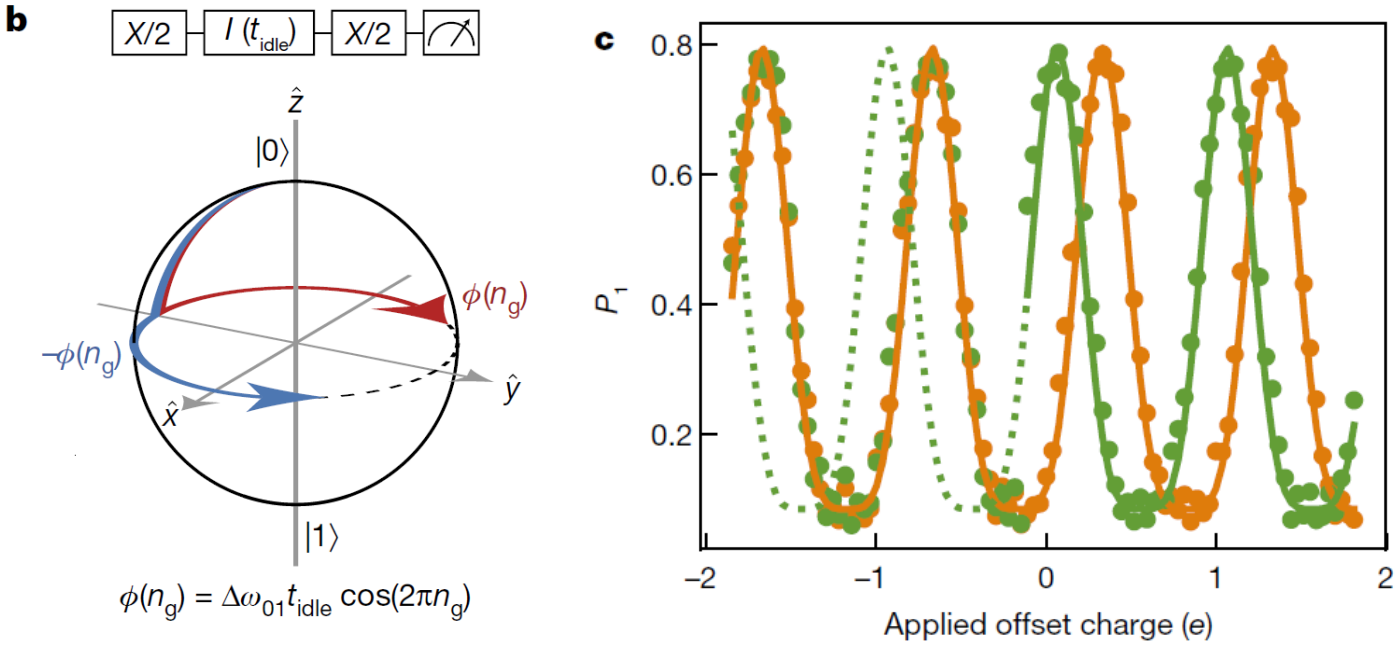
Ramsey tomography

- Send X/2 pulse to begin rotation around Block sphere
- Wait for an idle time
- Send a second X/2 pulse to rotate back to the Z axis
- Phase of rotation is determined by offset charge
- Measure the state of the qubit, map to P_1 for applied offset charge



Wilen *et al.*, Nature (2021)