Single-ion Heisenberg-limited Quantum Phase Sensors

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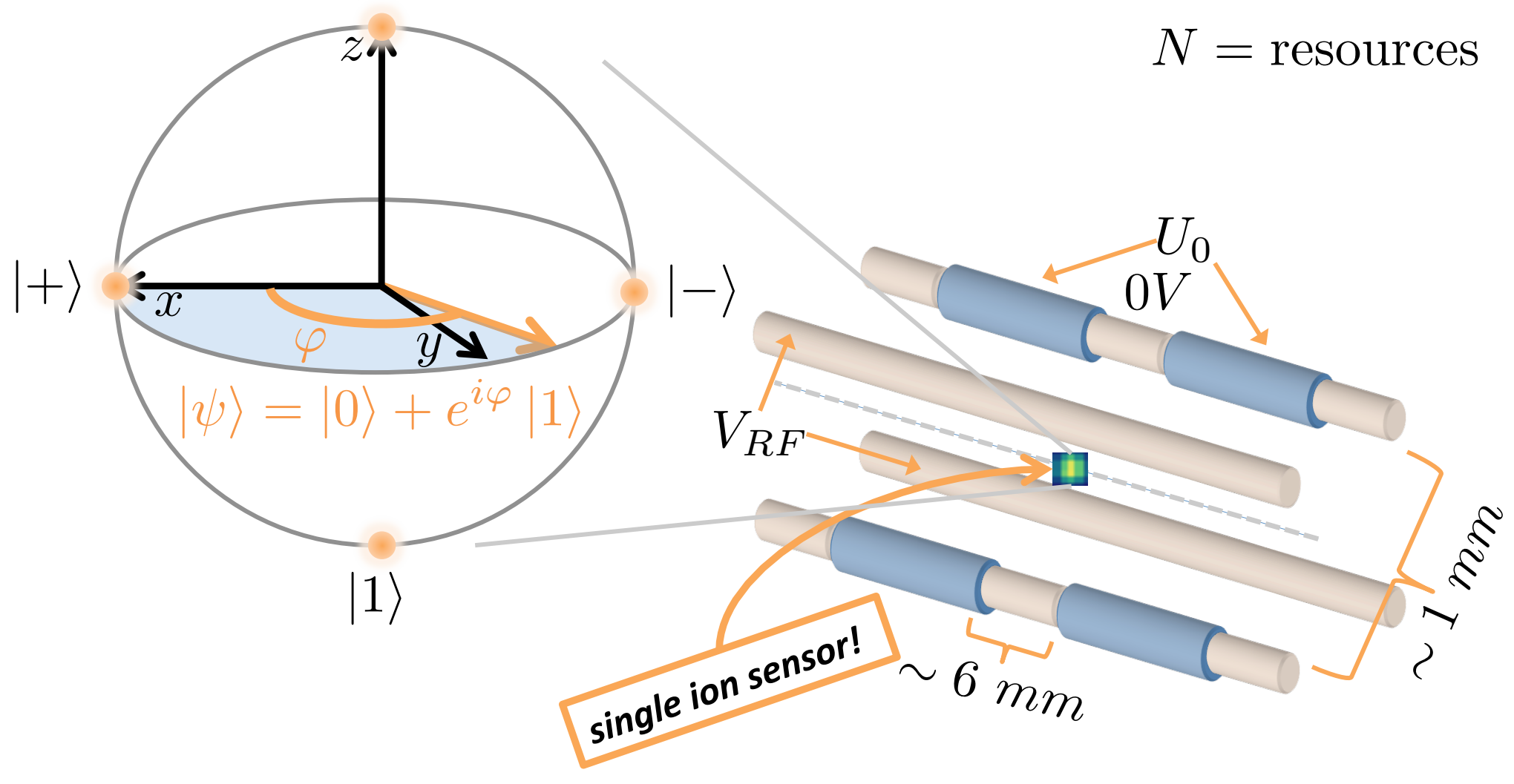
We report on our efforts to construct a single-ion-qubit sensor capable of Heisenberg limited detection of external fields that can be efficiently coupled to the ion qubit. Based on a single-qubit iterative phase estimation algorithm (IPEA)[3], a quadratic enhancement in quantum phase estimation precision is achieved when compared to standard shot-noise limited measurement protocols without using any entanglement. This approach also has the advantage that it does not require an understanding of the quantum Fourier transform, and it is readily related to more conventional approaches for measuring phases. The bit-by-bit estimation of an unknown phase only requires standard quantum information processing (QIP) protocols in addition to the use of single-qubit rotations that are each of a relative phase that is conditioned on all previous classical outcomes in the measurement sequence. Successful implementation of the IPEA will demonstrate a working quantum circuit with relatively immediate and useful applications in basic science, remote sensing, and clock synchronization. We also describe the potential application of novel ion trap architectures previously put forth[4,5] to the problem of miniaturizing the IPEA experiment as well as other single- and multi-qubit quantum enhanced metrology experiments. While these architectures were initially conceived in the context of large-scale QIP and quantum simulation, we face similar technical challenges in developing deployable ion trap based quantum sensors. This provides further impetus for developing relevant enabling technologies with both long- and short-term applications.

A single ion-qubit sensor . . .

$$\sim \frac{1}{\sqrt{N}} = \text{shotnoise scaling (i.e., SQL)}$$

$$\sim \frac{1}{N} = \text{Heisenberg scaling}$$

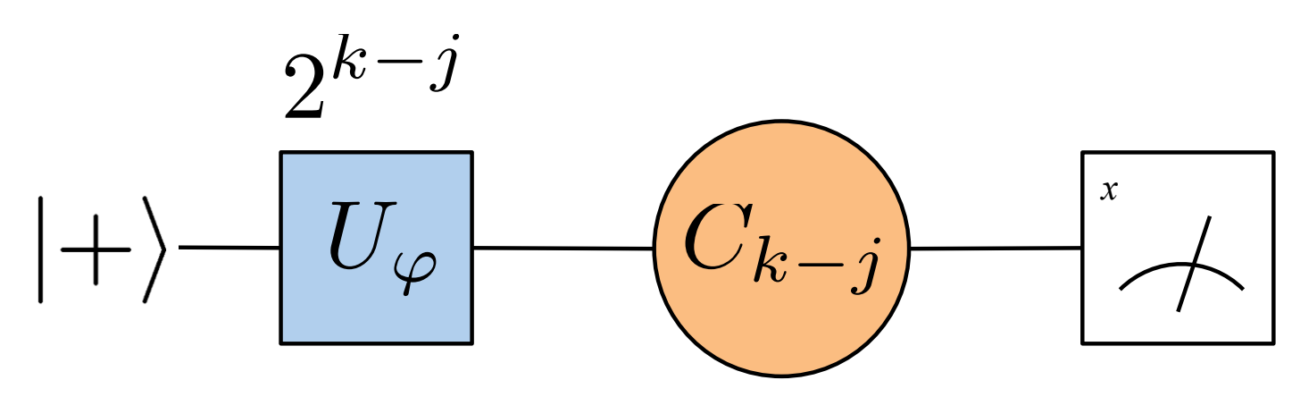
$$N = \text{resources}$$



① Single ion probe for measuring a parameter of an applied field.
② Measure phase φ induced by the applied (i.e., the measured) field.
③ Use QIP techniques; "+"-state ↔ "0"-state, and "-"-state ↔ "1"-state.
④ Use coherent feedforward on φ in sequential measurements to achieve HL scaling.

The Iterative Phase Estimation Algorithm (IPEA)[3] . . .

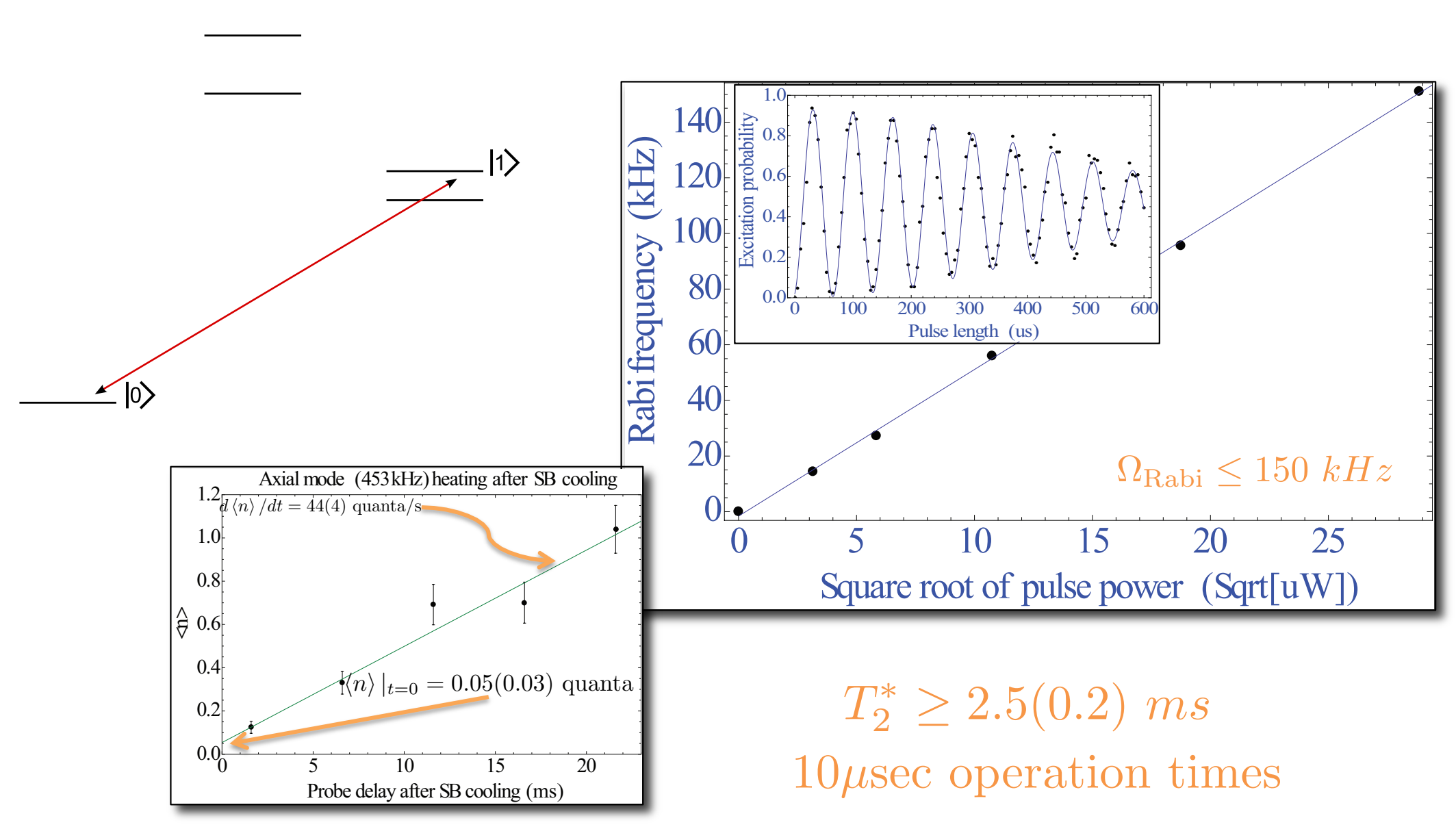
A total of *k* iterations for *k* bits of precision, where *j* runs from 1 through *k*.



① Repump to "0"-state and then prepare "+"-state with π/2 pulse.
② Sample the external (applied) field.
③ Perform feedforward rotation to modify φ conditioned on all previous outcomes.
④ Map the internal state (in the x-direction) to the logical basis and readout.

① Estimate bits from the LSB (b_k) to the MSB (b_1); robust against initial errors.
② The number *N* of resources utilized scales as 2^k for *k* bits of precision.
③ Precision scales as *$1/2^k$ (or 1/N)*, with a nominal increase for high confidence.
④ The QFT is implemented sequentially on a single qubit.
⑤ The classically conditioned "feedforward" depends on all previous measurements in the sequence, and it enhances the accuracy of the obtained bit.
⑥ No entanglement (i.e., only one qubit) is required, differing from other PEA's, but there is a trade-off in the time required to perform the measurement sequence for this simplicity.

Technical readiness . . .

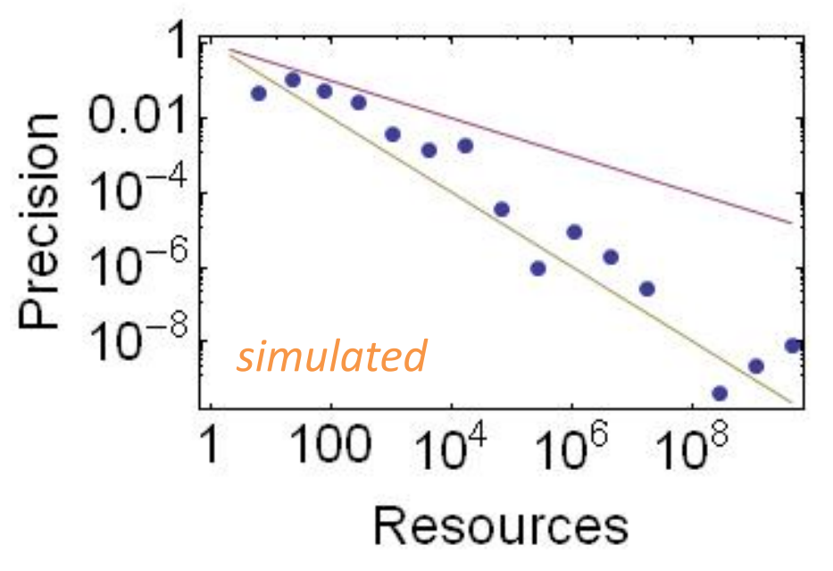


$$T_2^* \geq 2.5(0.2)\ ms$$

10μsec operation times

① Can obtain a minimum 2.5 ms coherence time with spin-echo recovery techniques.
② Maximum achieved Rabi frequency is 150 kHz with ~ 10 microsecond operations.
③ Only single qubit rotations required for iterative phase estimation algorithm (IPEA).
④ The necessary coherent control of a single qubit has been achieved.

Expected performance . . .

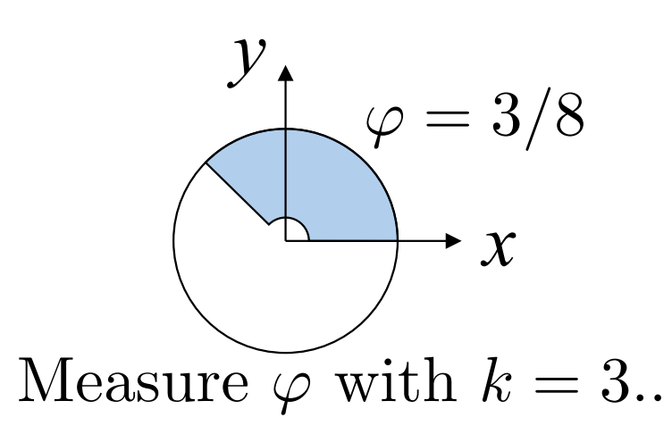


① We expect modest gains initially with precisions at the percent level.

② The ultimate precision allowed with the present apparatus remains to be seen.

③ Currently considering designs for a miniaturized version of the IPEA sensor for magnetic field sensing applications. Expect to use more robust microwave-based coherent manipulation methods (see below) and a resulting increase in ultimately attainable precision.

Using the IPEA in an example . . .

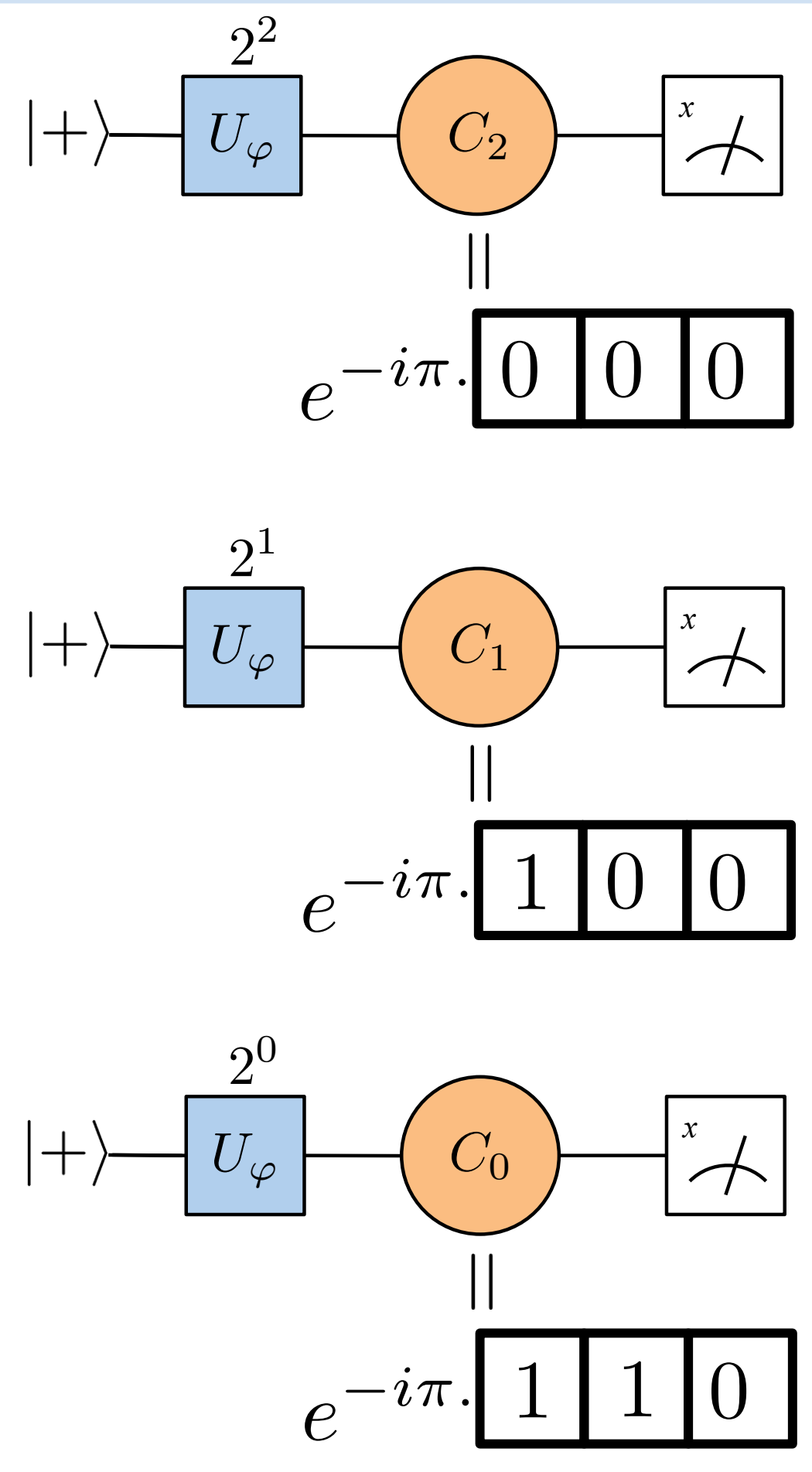


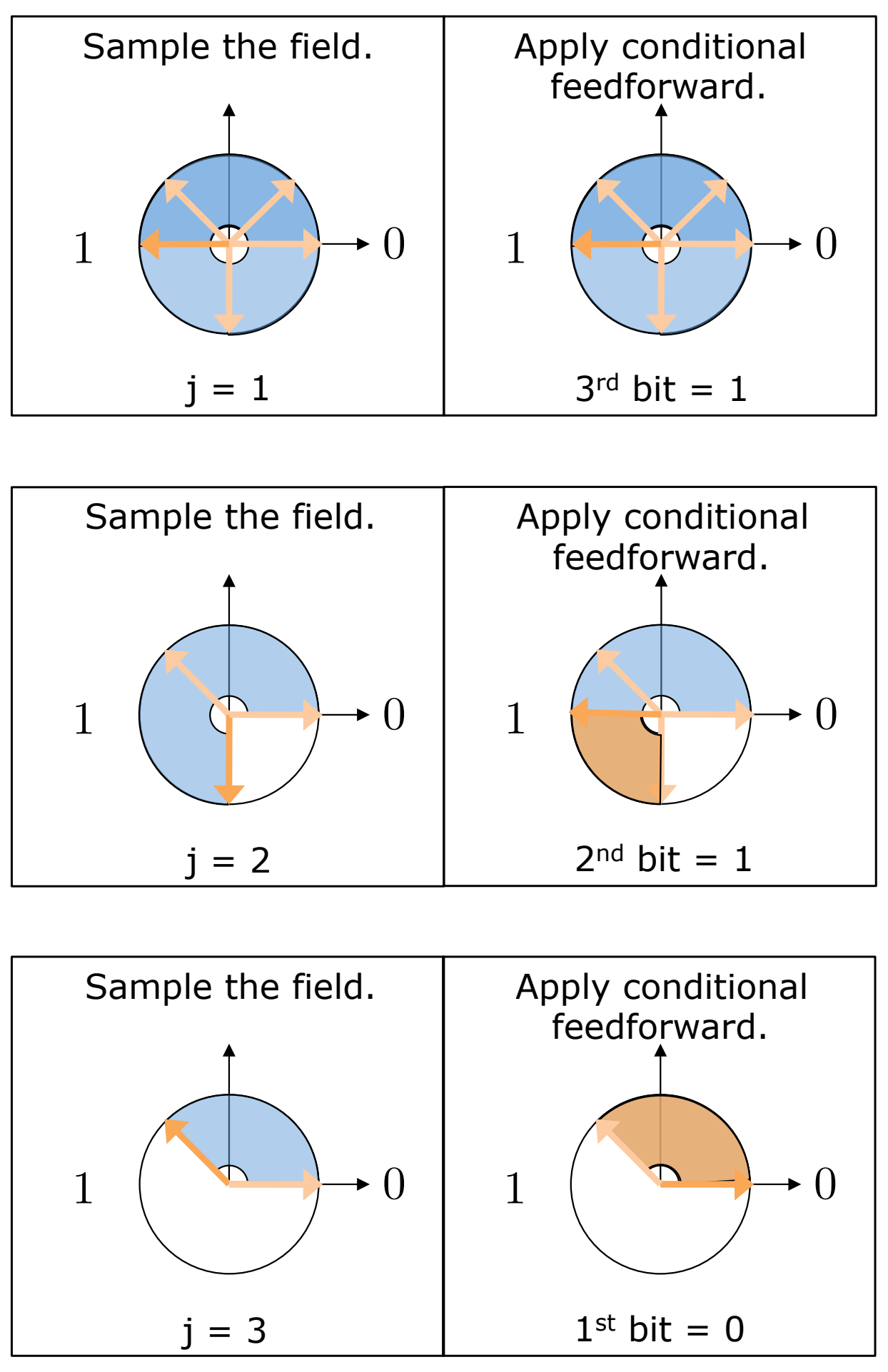
Measure φ with $k = 3$...

- ☐ Feedforward "cancels out" less sig. bits of ϕ
- ☐ more-sig. bits obtained with higher accuracy

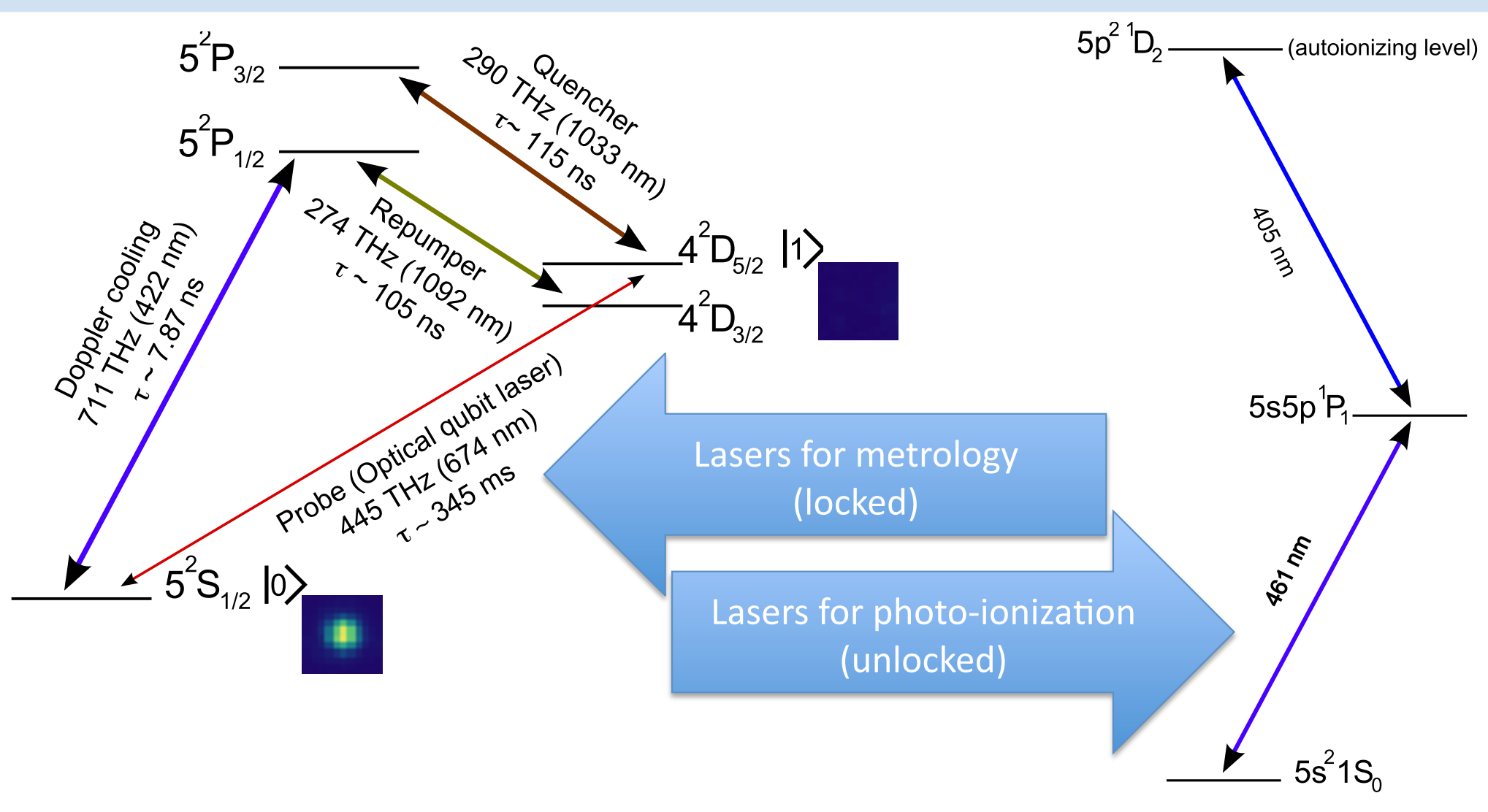
$$\varphi_{\rm estimate} = 2\pi.\boxed{0}\boxed{1}\boxed{1}$$

$$= 2\pi\left(0\times\frac{1}{2}+1\times\frac{1}{4}+1\times\frac{1}{8}\right)$$



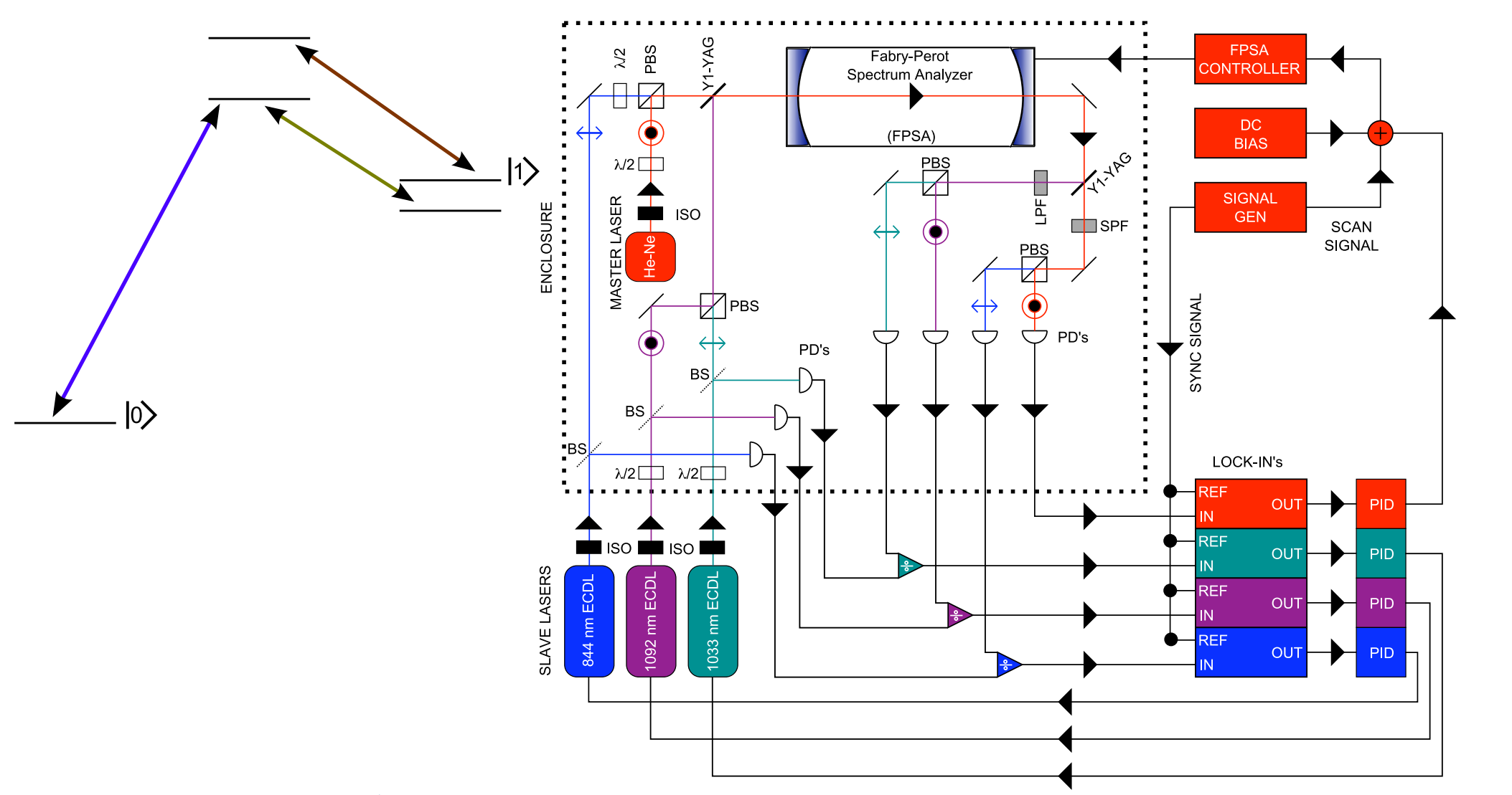


Relevant ^{86,88}Sr$^+$ laser systems . . .



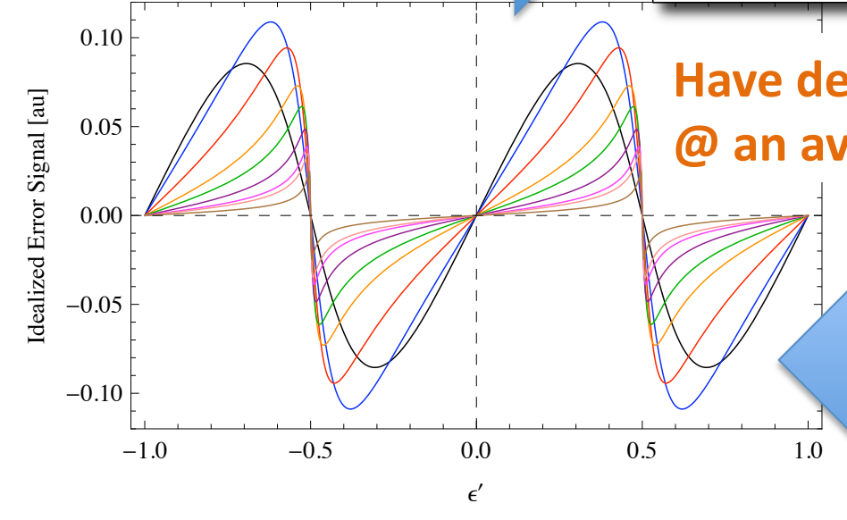
① 422 & 1092 for Doppler cooling and qubit state readout, ~100% readout efficiency.
② 674 & 1033 for resolved motional sideband cooling to near motional ground state.
③ 674 for coherent operations on the optical qubit.
④ 2-photon ionization loading process; have some isotope selectivity.
⑤ The 405 is a bare diode laser, and the system works with only 2 μW of 461.

Frequency stability of the lasers . . .



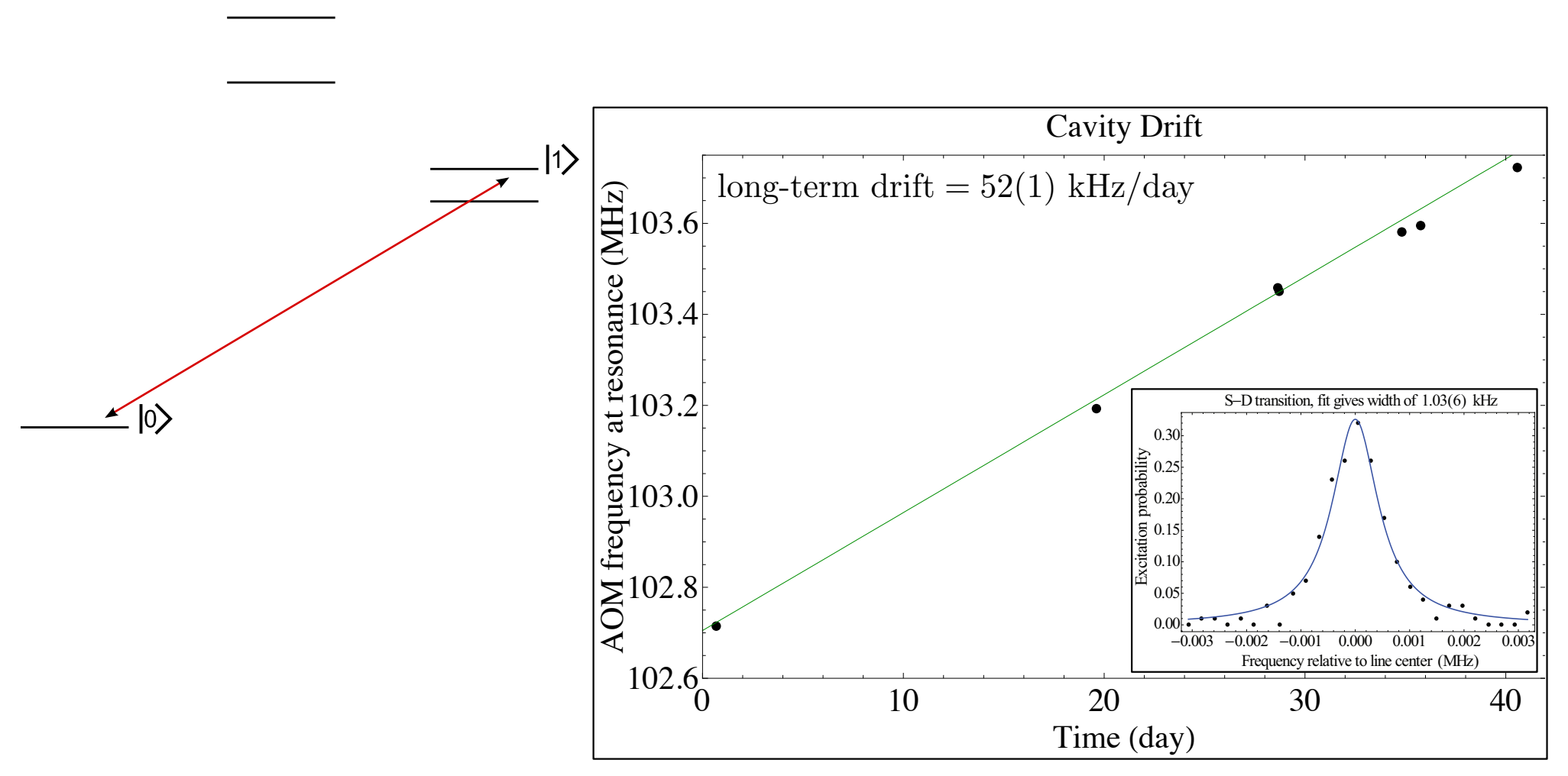
Sub-MHz long-term stability for all lasers!

Loop	Bandwidth [Hz]	Drift Rate [MHz/min]	Locked RMS [kHz]
844 nm (422 nm)	< 350	> 5/2 > 5	< 400 kHz < 800 kHz
1033 nm	< 157	> 3/2	< 400 kHz
1092 nm	< 151	> 30	< 500 kHz
SSTC	< 362	> 2	< 250 kHz



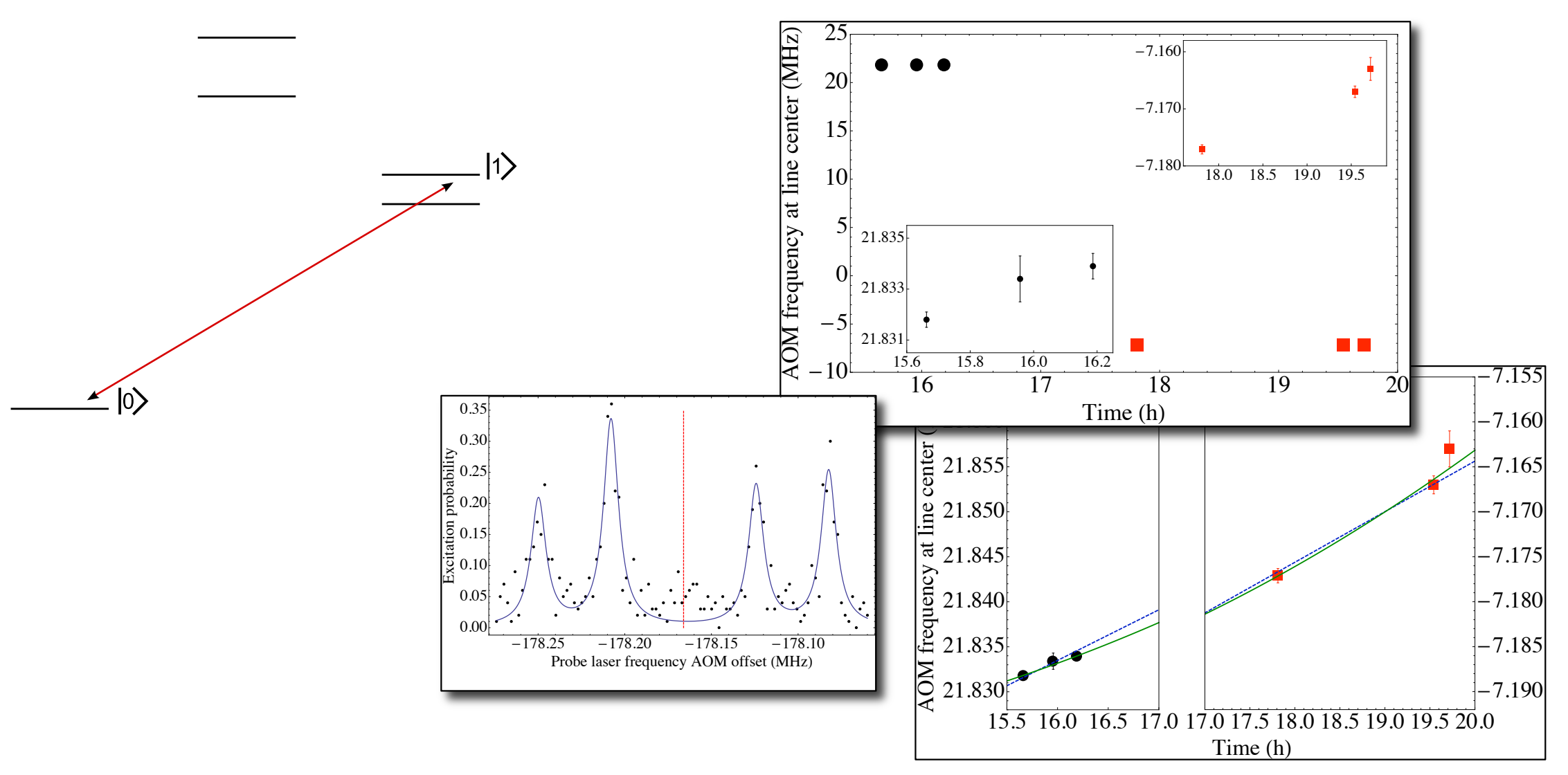
Have demonstrated a minimum Allan deviation of 60 kHz @ an averaging time of ~ 60 sec w/ the 422 nm laser.

Found error signals to be more ideal for low cavity finesse.



① Qubit laser locked to an ultra low expansion (ULE) cavity using the PDH technique.
② ULE cavity temperature stable to within ~ 1 mK over 24 hour period.
③ Long-term drift is 52 kHz/day; short-term nonlinear drifts ≤ 6 times long-term drift.
④ Qubit laser ~ 1 kHz wide on few minute timescale for performing spectroscopy.

A high precision isotope shift measurement on the qubit transition . . .



$$\Delta\nu_{\rm meas}^{88,86} = 570.281(4)\ MHz$$

arXiv:1009.0883; also to appear in Phys. Rev. A

On-chip excitation microcoils[4,5] + the Field Programmable Trap Array (FPTA)[5] = the quantum Field Programmable Gate Array (q-FPGA)[5] . . .

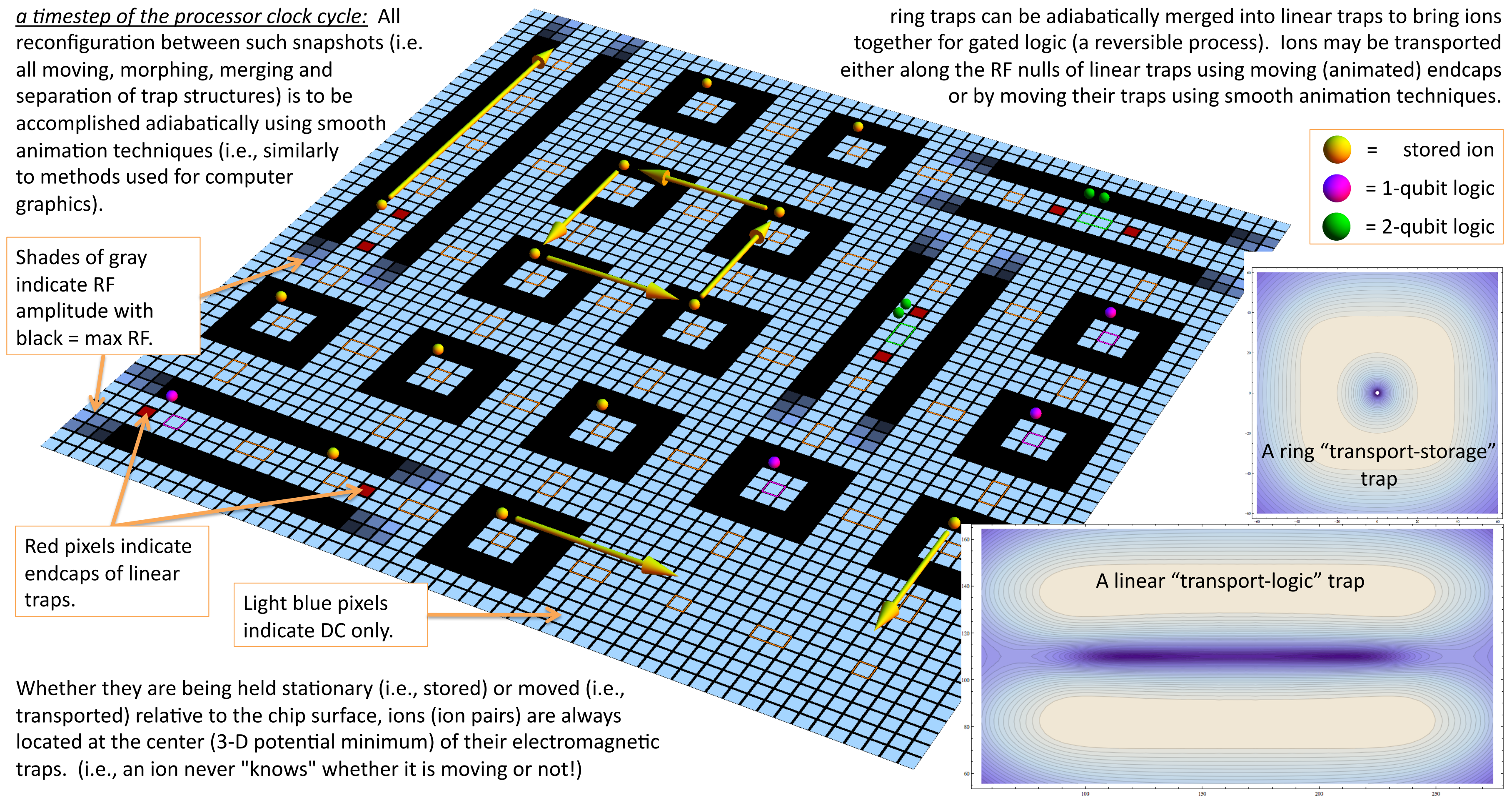
***Excitation microcoils to enable Logic Scaling*[4,5] . . .** [PRA 77, 022324 (2008)]
- ☐ Virtually eliminates decoherence from spontaneous scattering.
- ☐ Allows laserless coherent operations.
- ☐ Simplified optics.
- ☐ Reduces engineering complexity.

***Field Programmable Trap Arrays (FPTA's) to enable qubit array scaling*[5] . . .**
[*Publication forthcoming.*]
- ☐ Fully dynamically configurable array of surface-electrode pixels w/ a designer superposition of RF & DC applied to each pixel in each processor clock cycle.
- ☐ Dynamically build and rebuild (i.e., "draw" and "re-draw" w/ pixels) a quantum processor to suit a given algorithm.
- ☐ Designed to be compatible (integrable) with our microcoil concept.
- ☐ Enables deterministic ion qubit transport and reordering without RF heating or dephasing, without using junctions.

Potential Applications . . .
- ☐ Scalable quantum computing
- ☐ Scalable linear and nonlinear sensing
- ☐ Scalable cold quantum chemistry
- ☐ Cat-state metrology (Diego Dalvit)[6]
- ☐ Integrate with atom chip tech?

A snapshot of the quantum processor during a timestep of the processor clock cycle: All reconfiguration between such snapshots (i.e. all moving, morphing, merging and separation of trap structures) is to be accomplished adiabatically using smooth animation techniques (i.e., similarly to methods used for computer graphics).

Ions are always held in ring (0-D) or linear (quasi-1-D) traps. Neighboring ring traps can be adiabatically merged into linear traps to bring ions together for gated logic (a reversible process). Ions may be transported either along the RF nulls of linear traps using moving (animated) endcaps or by moving their traps using smooth animation techniques.



Shades of gray indicate RF amplitude with black = max RF.

Red pixels indicate endcaps of linear traps.

Light blue pixels indicate DC only.

Whether they are being held stationary (i.e., stored) or moved (i.e., transported) relative to the chip surface, ions (ion pairs) are always located at the center (3-D potential minimum) of their electromagnetic traps. (i.e., an ion never "knows" whether it is moving or not!)

Status and outlook . . .

Quantum phase estimation . . .
- ☐ Old trap developed an endcap-sleeve to RF short. Building a new trap.
- ☐ Also upgrading the imaging system.
- ☐ A novel application of quantum information processing techniques to metrology.
- ☐ Will be a novel demonstration of a practical quantum circuit.

The FPTA and q-FPGA . . .
- ☐ Currently designing and considering fabrication methods for constructing proof-of-principle prototypes.
- ☐ Continuing to refine initial models and to explore the possibilities and pitfalls allowed by a large parameter space.
- ☐ Working to determine the most optimal electrode scalings for integration of the microcoils with the FPTA. (i.e., working to determine the most optimal configuration when considering design constraints imposed by the scaling laws inherent to these two technologies.)
- ☐ Also considering the advantages and disadvantages of multiple pixel-electrode and pixel-lattice geometries.

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