Neutral-Atom QC: Equipment and Operation, Part A

Companies, array architectures, lasers, environmental control, control loops, error correction, interconnects and hologram design

October 26, 2026 · D. Hakala

> **About this version.** A cleaned-up copy of Equipment_and_Operation_A.docx . The text sketches are redrawn as diagrams, the inline maths are typeset, and four short equations are added where the source described the maths in words. The stock photo is removed, and the numbered web citations are replaced by the source's name in brackets, with the links listed at the end. The content is otherwise as in the source; statements that conflict with published papers are listed in Section 16 for future follow up.

1. Neutral-atom QC companies

The leading full-stack neutral-atom companies trap individual atoms (such as rubidium or cesium) as qubits in tightly focused laser beams called optical tweezers (YouTube overviews).

Pure-play hardware developers

- **QuEra Computing:** spun out of Harvard and MIT research. Launched the 256-qubit Aquila analog system (public on Amazon Braket) and is working towards commercial fault-tolerant machines (SpinQ, The Quantum Insider).
- **Atom Computing:** gate-based machines using alkaline-earth atoms; built a 1,200+ qubit system and works with Microsoft on on-premises and cloud fault-tolerant machines.
- **Pasqal:** French, founded on Nobel Prize-winning research; dual analog–digital processors deployed in HPC centres (Pasqal).
- **Infleqtion:** formerly ColdQuanta, listed on NYSE as INFQ; builds the Sqale computer, neutral-atom sensors, clocks and the Superstaq software platform (Infleqtion, CB Insights).
- **planqc:** German start-up storing qubits in single atoms in 2D/3D arrays and driving gates with precision laser pulses (VentureRadar).

Emerging start-ups and regional players

- **Oratomic (USA):** fault-tolerant neutral-atom systems combined with AI-driven research automation.
- **Q-Factor (Israel):** new architectures aimed at hardware scaling bottlenecks.
- **Atom Quantum Labs and OpenQuantum:** system integration and market solutions (Yahoo Finance, VentureRadar).

Large technology companies

- **Google Quantum AI:** has added a neutral-atom program alongside its superconducting work (YouTube, Reddit).
- **Microsoft:** Azure Quantum cloud, qubit-virtualization software and infrastructure behind Atom Computing's machines (Reddit).
- **Amazon Web Services:** public access to QuEra through Amazon Braket (YouTube, Reddit).

2. How each company builds and runs its array

All the platforms share one physics stack: optical tweezers to hold single atoms, an ultra-high-vacuum chamber to isolate them, and precise laser pulses that excite atoms to Rydberg states for gates. They differ in geometry, optics and how they manipulate states.

QuEra: reconfigurable 2D arrays and analog dynamics

- **Creation:** a laser is phase-shaped by a spatial light modulator (SLM) into a dense, arbitrary 2D grid of hundreds of tweezers.
- **Maintenance (defect-free sorting):** loading leaves about half the traps empty. A camera images the grid, an algorithm plans the moves, and moving tweezers from an RF-driven acousto-optic deflector (AOD) carry atoms into a defect-free pattern.
- **Manipulation:** the AOD tweezers move atoms mid-computation (coherent shuttling), and a global laser pulse excites atoms to Rydberg states, where the Rydberg blockade forms the entangling gate.

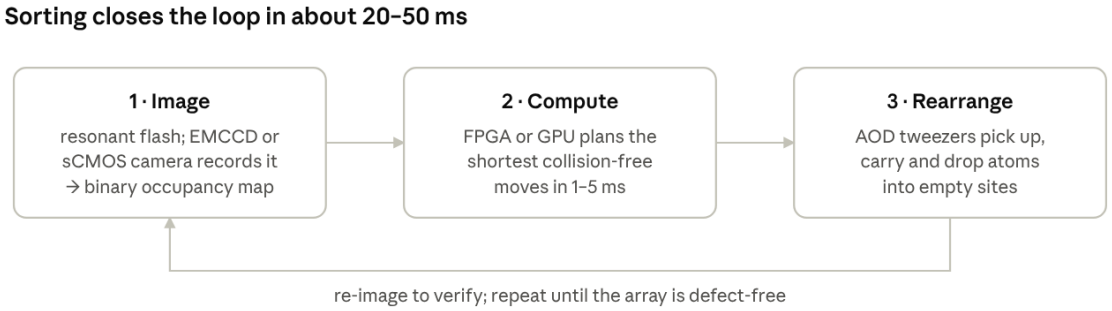

Figure 1. Sorting loop: image, compute moves, rearrange, re-image (reused from the Oct 22 notes).

Atom Computing: 1,000+ qubit 3D optical lattices (as described in the source)

- **Creation:** counter-propagating beam pairs intersect to form a 3D interference lattice, stacking layers of atoms to hold more than 1,200 qubits.
- **Maintenance:** ^{171}Yb stores the qubit in its nuclear spin, shielded from stray fields; a magic-wavelength trap holds the atom without shifting the qubit frequency.
- **Manipulation:** narrow-linewidth lasers drive single-qubit rotations; UV lasers briefly excite the atoms to Rydberg states for entangling gates.

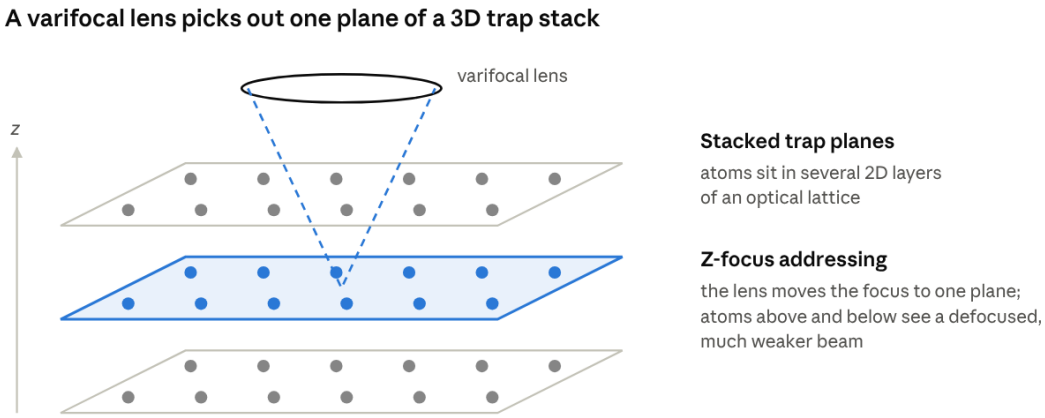

Figure 2. Stacked trap planes with a varifocal lens addressing one plane (the source's 3D-lattice sketches, reused from the Oct 22 notes). See Section 16 for how this compares with Atom Computing's published hardware.

Pasqal: custom geometries and dual analog–digital operation

- **Creation:** high-resolution SLMs place Rb atoms in layouts that match the problem, for example the lattice of a crystal being simulated.
- **Maintenance:** vacuum chambers integrated with HPC server racks; vacuum pressure optimized against collisions; retro-reflectors to raise trap depth and lifetime.
- **Manipulation:** analog mode drives the whole array as a quantum simulator; digital mode uses tightly focused beams on single atom pairs for site-specific gates.

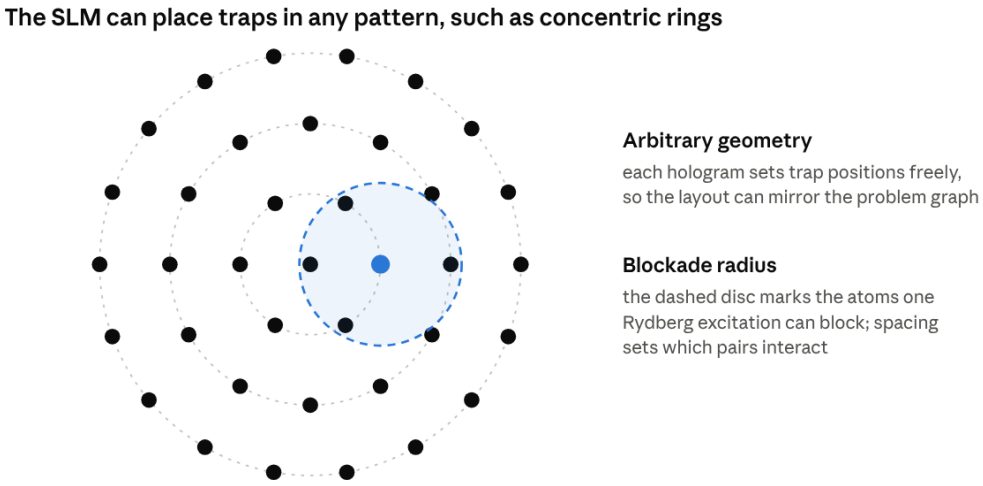

Figure 3. An SLM can place traps in any pattern, such as concentric rings.

planqc: clock atoms

- **Creation:** strontium atoms in optical lattices that give uniform potentials over thousands of sites.
- **Maintenance:** two-stage cooling, a broad transition for fast cooling and then a narrow line to reach the lowest vibrational state.
- **Manipulation:** trapping and computing are separated: trap light holds the atom while a localized, phase-modulated beam drives the qubit.

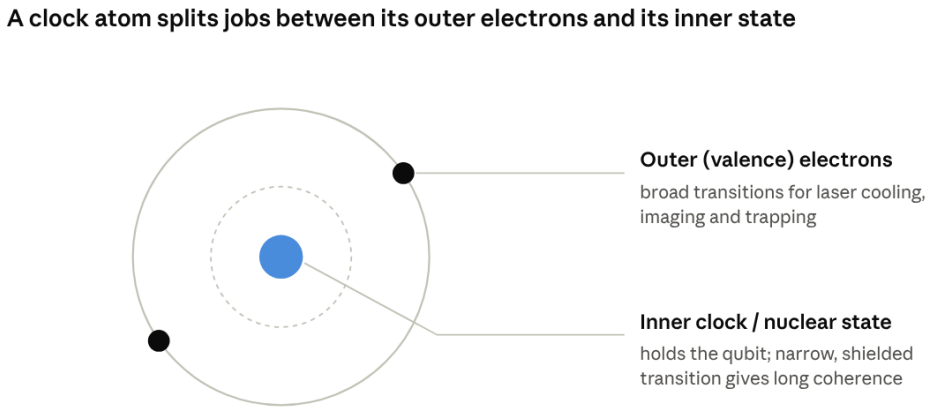

Figure 4. A clock atom splits jobs between its outer electrons (cooling, imaging, trapping) and its inner state (the qubit).

3. QuEra: moving atoms mid-computation

Coherent shuttling lets any qubit interact directly with any other, so no SWAP gates are needed. During one calculation, control passes between static and moving traps:

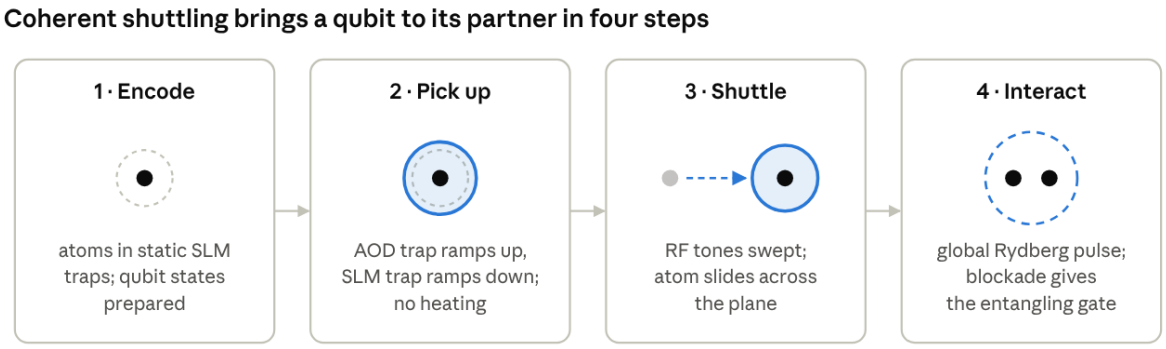

Figure 5. Coherent shuttling in four steps.

1. **Initialization:** atoms sit in the static SLM grid; single-qubit or local entangling operations are applied.
2. **Hand-off:** AOD traps are switched on over selected static traps; the AOD trap ramps up while the static trap ramps down, transferring the atom without heating or decoherence.
3. **Shuttling:** the RF frequencies driving the AOD crystals are swept, changing the deflection angle and sliding the atoms across the plane.
4. **Gate and drop-off:** atoms arrive beside their partners; a global pulse excites Rydberg states and the blockade produces the entangling gate. Atoms can then return or move on.

Optical engine

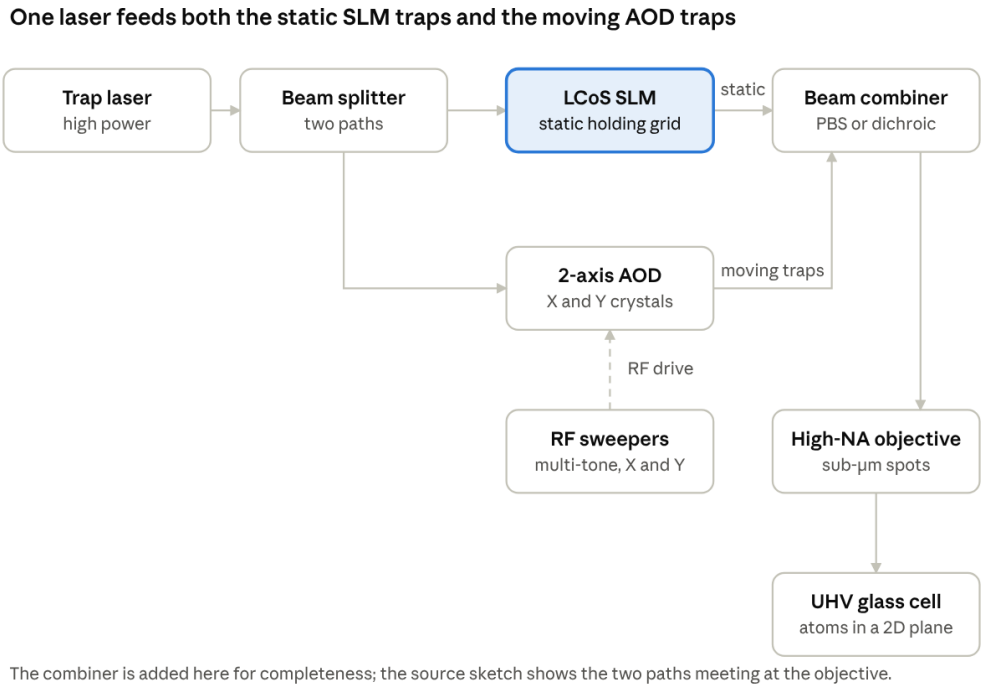

Figure 6. One laser feeds both the static SLM traps and the moving AOD traps.

- **Two-axis AODs:** crystals such as tellurium dioxide driven by RF synthesizers act as tunable diffraction gratings; sweeping the RF steers the beams in X and Y.
- **High-NA objective:** just outside the vacuum window, it focuses the beams to sub-micron spots so the traps are deep enough to hold atoms during acceleration and deceleration.

4. Atom Computing: 3D selection by fill-and-discard (as described in the source)

Instead of moving atoms between sites, the source describes overfilling a 3D lattice and removing the surplus:

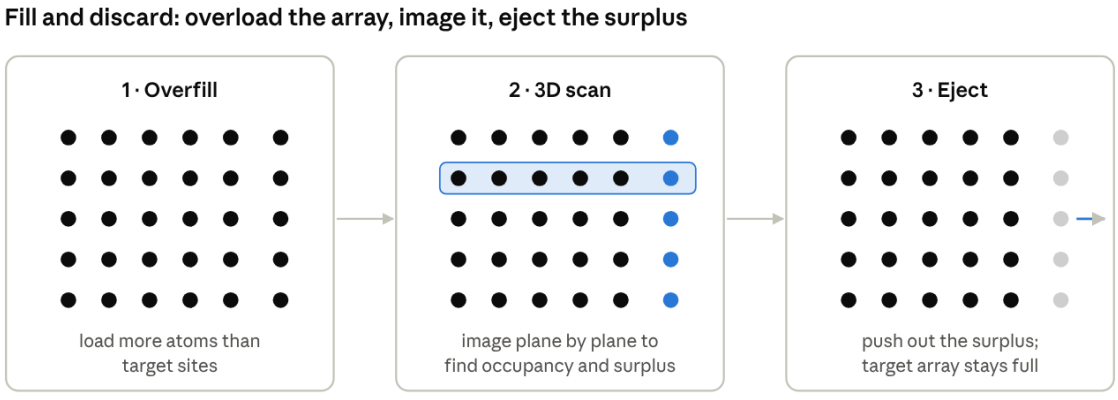

Figure 7. Fill and discard: overload the array, image it, eject the surplus.

1. **Stochastic loading:** a dense ^{171}Yb cloud loads the 3D lattice at about 50 % occupancy.

2. **Depth imaging:** the camera changes focus (or uses multi-plane imaging) to image planes Z_1, Z_2, Z_3, building a 3D occupancy map.
3. **Targeted ejection:** a fully occupied sub-block (for example 10 × 10 × 10) is chosen and focused pulses kick the surplus atoms out.

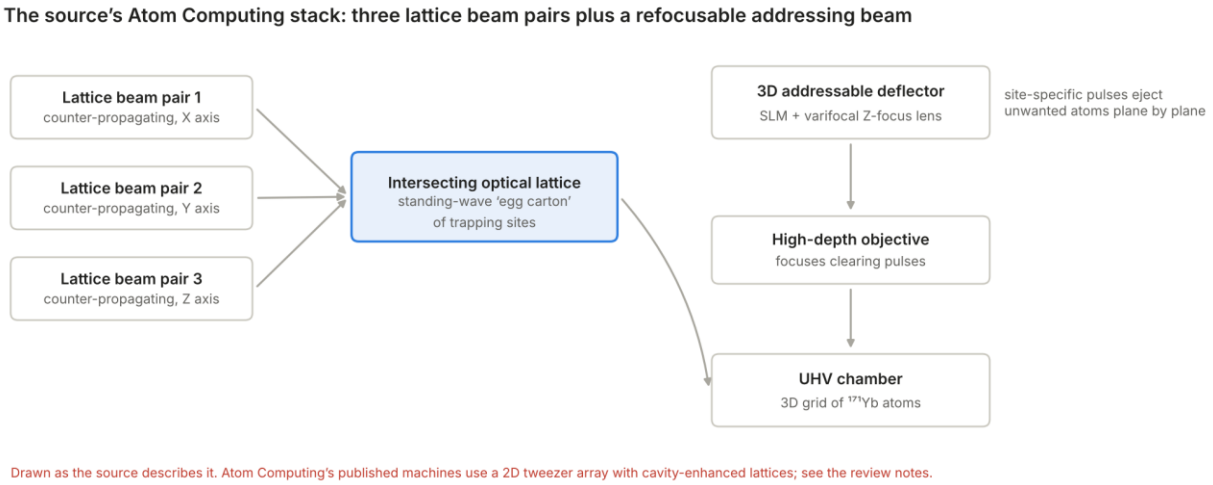

Figure 8. The hardware stack as the source describes it: three lattice beam pairs and a refocusable addressing beam.

- **Counter-propagating lattice lasers:** three orthogonal beam pairs form an 'egg-carton' lattice that holds atoms in vertical stacks.
- **Varifocal focusing:** fast variable-focus lenses or electro-optic devices move the addressing focus between planes in microseconds without moving the objective.

Feature	QuEra (2D shuttling)	Atom Computing (3D selection, per source)
Array dimension	Single dense 2D plane	Stacked 3D layers
Primary method	Atoms moved mid-calculation	Excess atoms ejected to leave a full core
Core equipment	Two-axis AODs + RF sweepers	3D counter-propagating lattice + varifocal Z optics
Benefit	Connectivity can be rewritten mid-algorithm	Many qubits in a small volume

5. Laser wavelengths and linewidths

Control divides into trapping and cooling (high power, broad linewidth) and quantum gates (narrow linewidth, low noise).

Company	Atom	Operation	Wavelength	Typical linewidth
QuEra, Pasqal	^{87}Rb	Laser cooling (D2)	780 nm	~1 MHz
QuEra, Pasqal	^{87}Rb	Optical tweezers	850 nm	broadband (> 10 GHz)
QuEra, Pasqal	^{87}Rb	Ground-state qubit control (D1)	795 nm	< 100 kHz
QuEra, Pasqal	^{87}Rb	Rydberg excitation (two-photon)	420 nm + 1013 nm	< 10 kHz
Atom Computing	^{171}Yb	Laser cooling (broad line)	399 nm	~30 MHz

Company	Atom	Operation	Wavelength	Typical linewidth
Atom Computing	^{171}Yb	Magic-wavelength lattice	759 nm	broadband
Atom Computing	^{171}Yb	Qubit clock rotation	578 nm	< 1 Hz
Atom Computing	^{171}Yb	Rydberg transition	302 nm (UV)	< 5 kHz
planqc	^{87}Sr	Main cooling (blue line)	461 nm	~32 MHz
planqc	^{87}Sr	Narrow cooling (red line)	689 nm	~7 kHz
planqc	^{87}Sr	Magic-wavelength trapping	813.4 nm	broadband
planqc	^{87}Sr	Qubit clock gate	698 nm	< 1 Hz

The ~30 MHz, ~32 MHz and ~7 kHz entries are the natural linewidths of those atomic transitions, not laser linewidths.

6. Beam geometry

Cooling and loading (all platforms)

Three orthogonal pairs of counter-propagating cooling beams form a magneto-optical trap (MOT) that slows hot atoms to microkelvin temperatures so the tweezers can capture them.

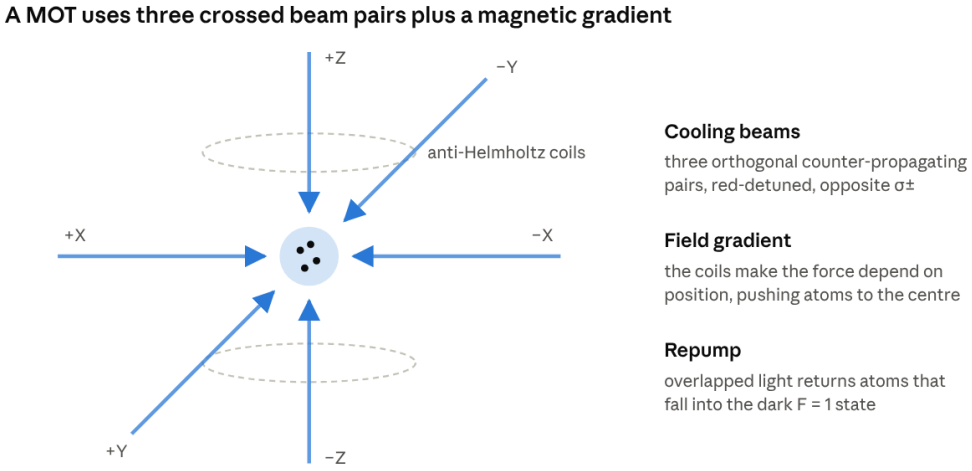

Figure 9. A MOT uses three crossed beam pairs plus a magnetic gradient.

2D addressing layout (QuEra, Pasqal)

The static tweezer array comes up through the objective from below, a global Rydberg beam (420 nm + 1013 nm) covers the whole array, and an AOD-steered 795 nm Raman beam targets single qubits.

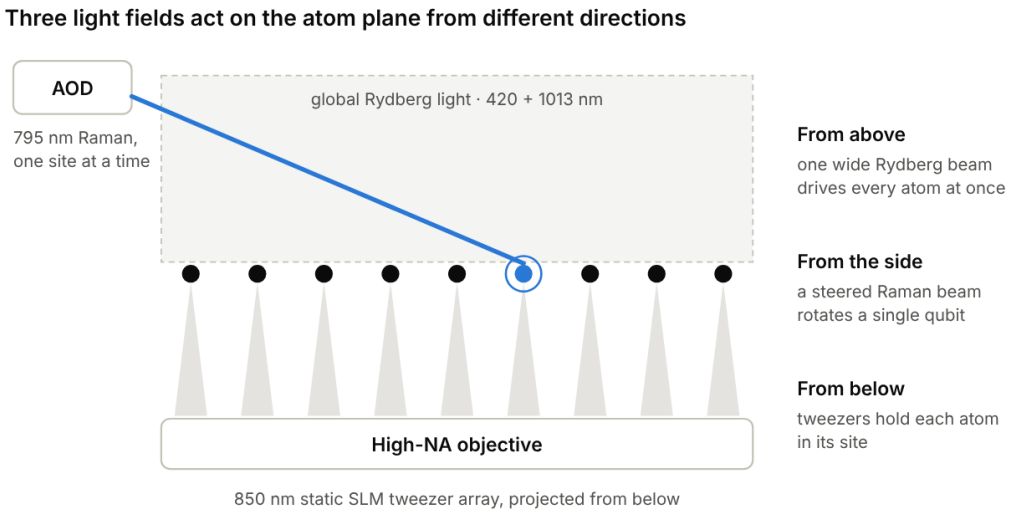

Figure 10. Three light fields act on the atom plane from different directions.

3D lattice and Z-focus (Atom Computing, planqc, per source)

Three retro-reflected beam pairs form the standing-wave lattice, and a varifocal lens moves the vertical addressing beam between planes (Figure 2).

Key engineering points

- **Why sub-hertz linewidths:** the Sr and Yb clock transitions are 'forbidden' and extremely narrow; laser phase noise makes the laser drift out of step with the atom and the rotation fails (Physics World).
- **Magic wavelength:** trap light normally shifts atomic levels (AC Stark shift). At the magic wavelength (759 nm for Yb, 813.4 nm for Sr) both levels shift equally, so the atom is held without disturbing the qubit (ADS).

7. Laser generation and frequency conversion

Few lasers emit directly at the short wavelengths needed, such as 302 nm (Atom Computing's Rydberg line) or 461 nm (strontium cooling). Instead, a stable near-infrared laser is amplified and frequency-doubled in a nonlinear crystal (second-harmonic generation, SHG).

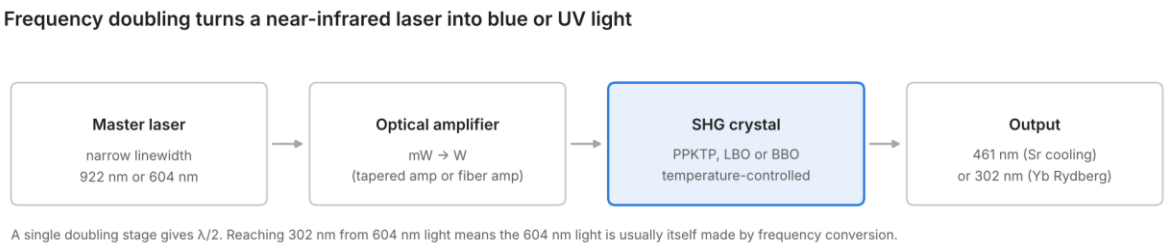

Figure 11. The frequency-doubling chain.

In the crystal, two photons at frequency ω combine into one photon with twice the energy and frequency and half the wavelength:

$$E_{out} = 2\,\hbar\omega, \qquad \omega_{out} = 2\omega, \qquad \lambda_{out} = \frac{\lambda}{2} \tag{1}$$

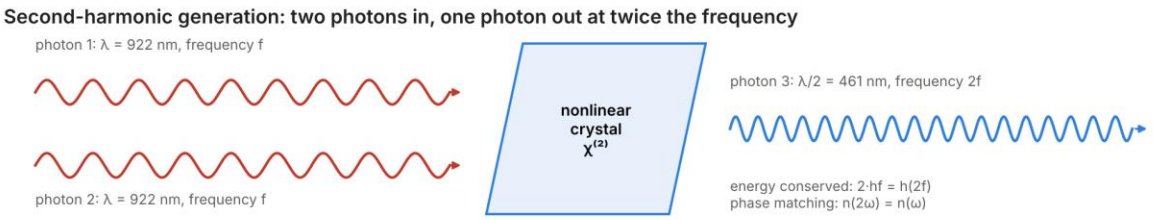

Figure 12. Second-harmonic generation at the photon level (922 nm → 461 nm).

Sub-hertz clock lasers

For the 578 nm (Yb) and 698 nm (Sr) clock lines the laser is locked to an ultra-low-expansion (ULE) glass reference cavity in its own vacuum housing. Light circulates thousands of times between high-reflectivity mirrors; a feedback loop compares the laser phase with the cavity and corrects the laser, narrowing its linewidth from megahertz to below one hertz.

8. Vibration isolation

A tweezer is about 1 µm across and the trap is shallow. Floor motion of a few hundred nanometres from traffic, air handling or sound can make the beam move relative to the chamber, heating the atom out of its trap or dephasing the qubit. Machines therefore use a layered isolation stack.

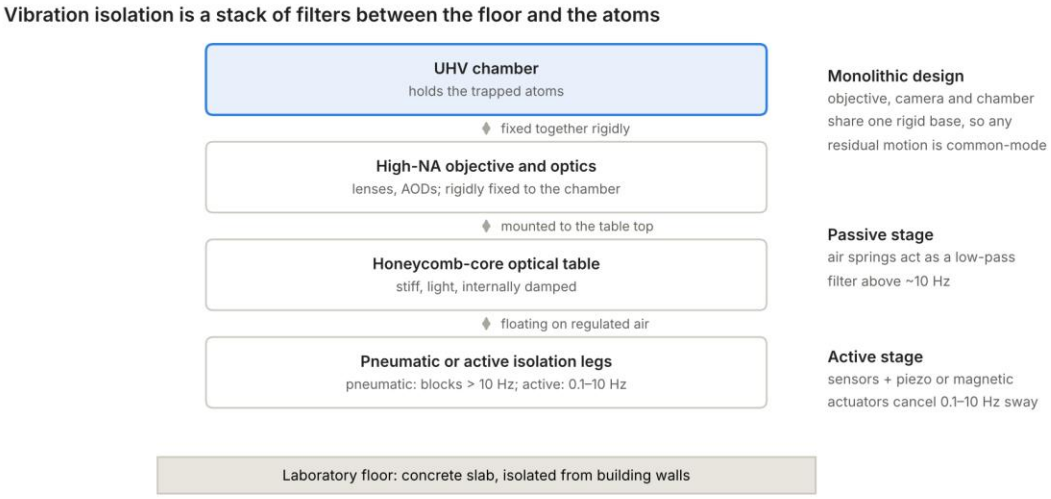

Figure 13. The structural isolation hierarchy.

- **Pneumatic and active legs:** air-filled legs are soft springs that filter floor noise above about 10 Hz; for 0.1–10 Hz building sway, sensors and piezo or magnetic actuators push back in real time.
- **Honeycomb-core table:** steel skins separated by a honeycomb core are stiff for their mass and damp acoustic vibration (Figure 14).
- **Monolithic optomechanics:** objectives are clamped with heavy invar or stainless brackets to the same base as the vacuum chamber, so any residual motion moves camera, lenses and chamber together.

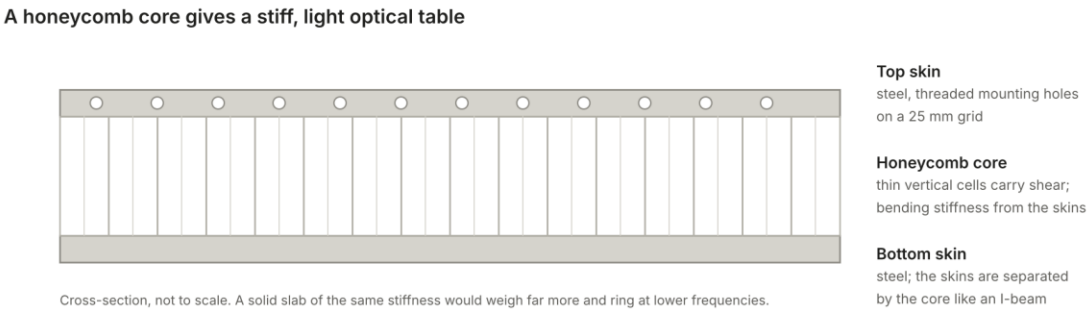

Figure 14. Honeycomb-core optical table, cross-section.

9. Magnetic shielding

Stray fields shift atomic levels (Zeeman effect) and scramble the qubit. Alkali atoms are the most sensitive because their qubits sit in electron-spin states. Machines combine passive and active shielding.

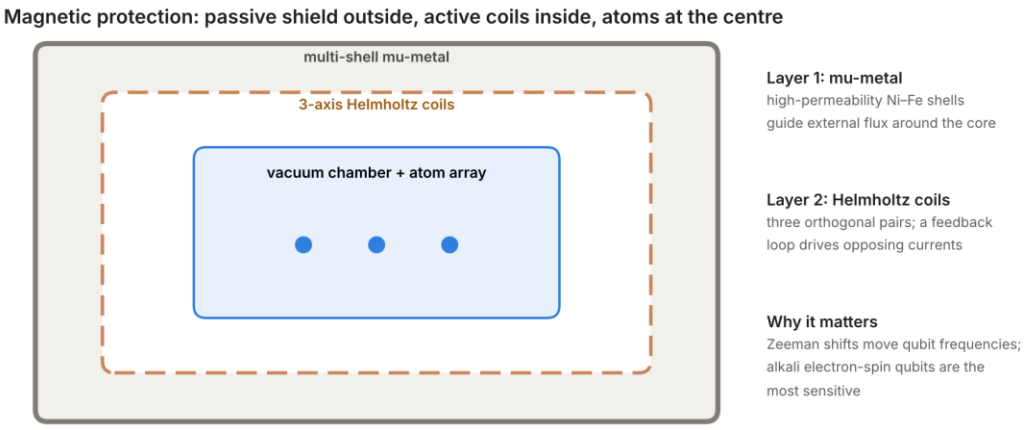

Figure 15. The shielding hierarchy described in the source.

- **Mu-metal enclosures:** nested boxes of a high-permeability Ni–Fe alloy do not block field so much as guide it: flux is drawn into the walls and routed around the interior (Figure 16).
- **Active Helmholtz coils:** three orthogonal coil pairs cancel what the shield misses. Fluxgate magnetometers outside the chamber measure the field, and a feedback controller drives opposing currents.

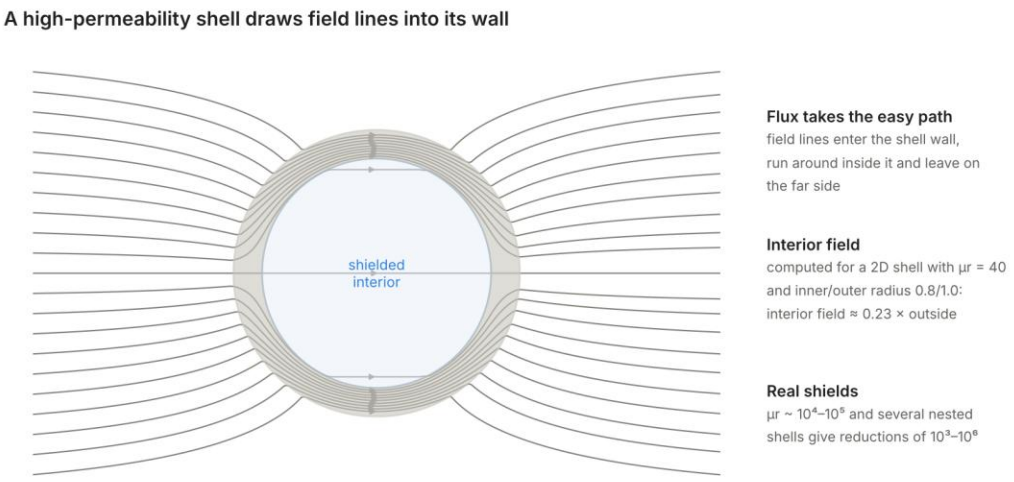

Figure 16. Field lines around a high-permeability cylindrical shell, computed from the analytic 2D solution (μr = 40 for visibility).

10. Thermal management

Watts of laser light pass through modulators, crystals and mirrors; the small fraction absorbed heats them, and the expansion makes beams drift off the atoms. The heat sources are therefore kept away from the processor.

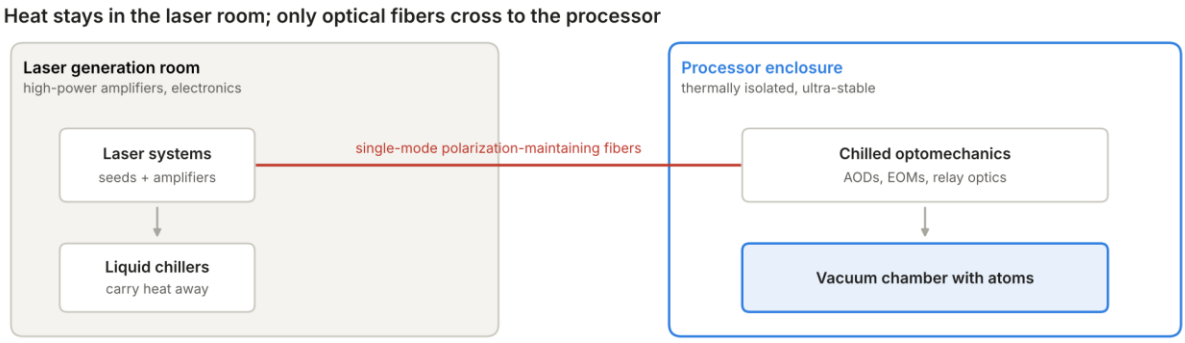

Figure 17. Laser room and processor enclosure joined only by fibers.

- **Fiber decoupling:** lasers, amplifiers and supplies sit on a separate bench or in another room; single-mode polarization-maintaining fibers carry the light to the processor table.
- **TECs and water cooling:** components that must sit near the atoms (AODs, EOMs) use thermoelectric coolers on water-cooled copper blocks (Figure 18), holding the component to about ±0.01 °C.
- **Enclosures:** the table is sealed in a rigid enclosure with laminar filtered air, holding the table to about ±0.1 °C over the day.

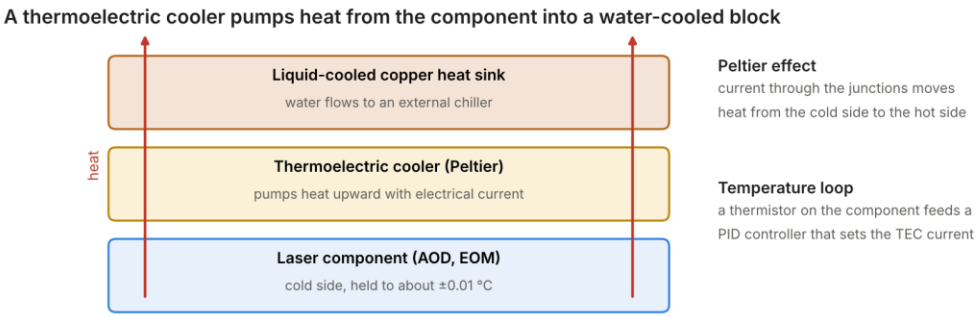

Figure 18. Thermoelectric cooler stack.

11. Cryogenic neutral-atom systems

Neutral atoms normally run in room-temperature glass cells, but cooling the vacuum system to 4 K (liquid-helium temperature) attacks the main lifetime limit: background gas collisions. At 4 K residual gas freezes onto the walls, and the source says trap lifetime rises from about 10 s to hours, enough for long error-correction runs. The source names Pasqal as moving in this direction.

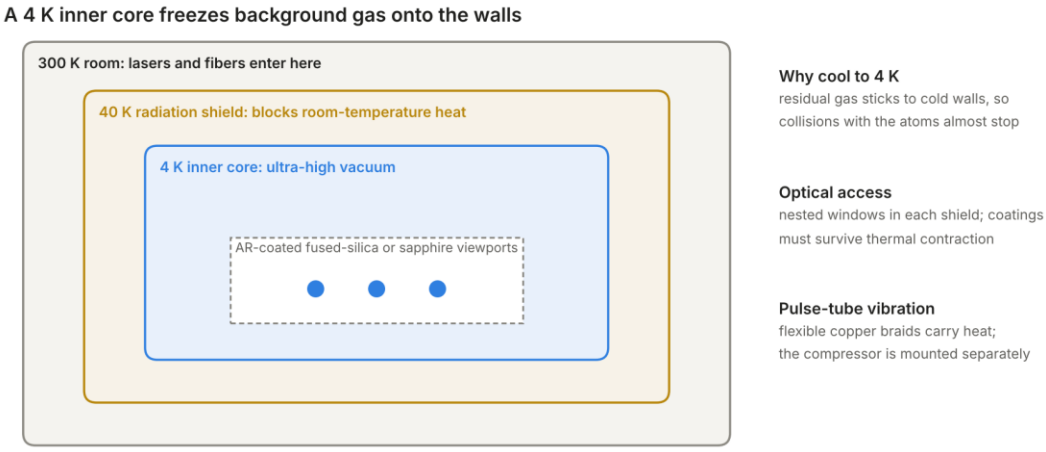

Figure 19. Nested cryogenic shields.

- **Optical access:** nested viewports of fused silica or sapphire with anti-reflection coatings that survive thermal contraction without distorting the wavefront.
- **Pulse-tube vibration:** the cryocooler compressor shakes; flexible copper braids carry heat while separate damping structures absorb the vibration.

12. Software control loops

A master control system runs several feedback loops at once, each matched to the speed of the disturbance it corrects.

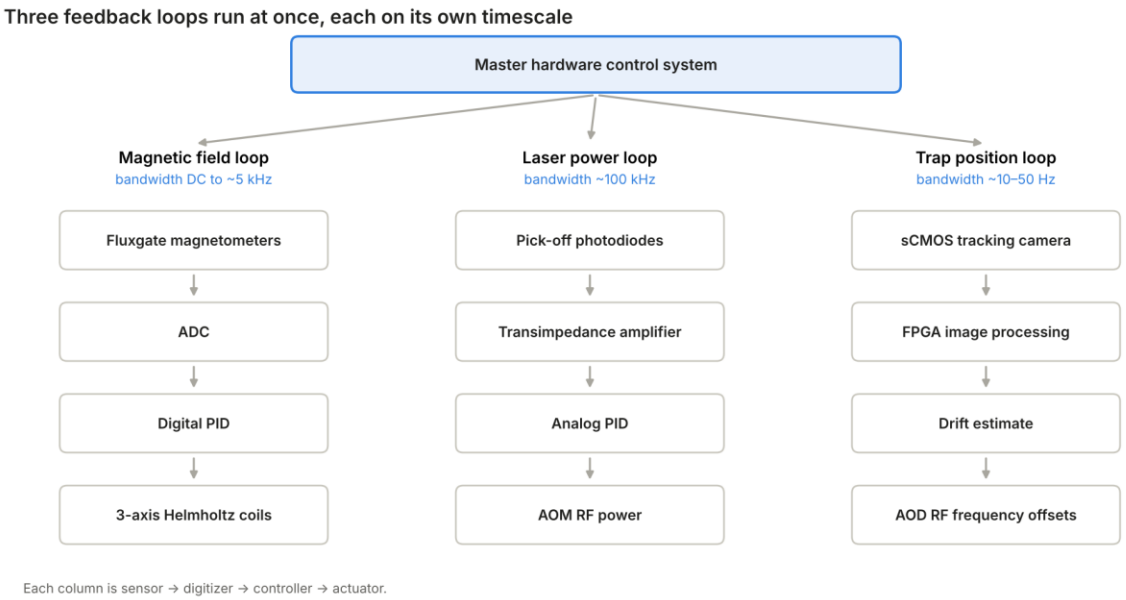

Figure 20. Magnetic, laser-power and position loops.

- **Magnetic loop (DC to ~5 kHz):** fluxgate sensors on the outer shield feed a fast digital PID controller, which drives DACs on the Helmholtz coils to cancel, for example, a nearby elevator before the atoms dephase.
- **Laser power loop (~100 kHz):** pick-off photodiodes sample about 1 % of each beam before the chamber; an analog loop adjusts the RF power to an AOM to flatten amplifier intensity noise.
- **Position loop (~10–50 Hz):** a tracking camera watches reference marks; as the structure drifts with temperature, small frequency offsets on the AOD RF drive steer the traps to follow.

13. Real-time quantum error correction

Thousands of physical qubits are grouped by codes such as the surface code or quantum LDPC codes into logical qubits. The hardware has to measure errors and decode them before the logical information is lost.

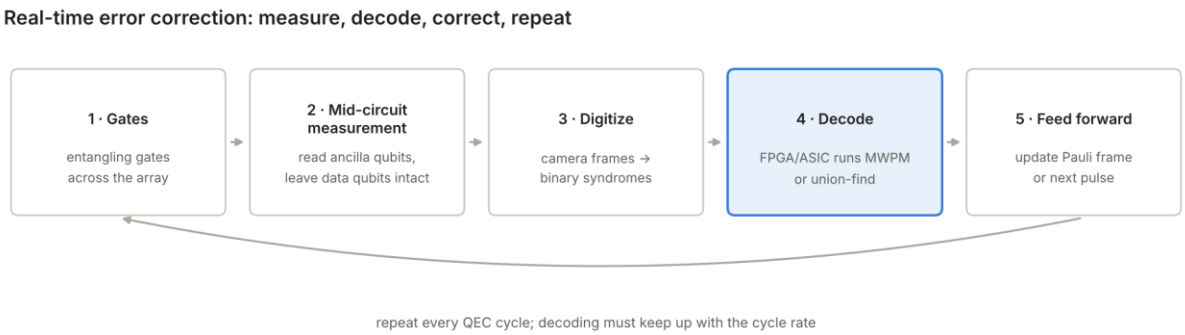

Figure 21. The real-time QEC loop.

- **Mid-circuit measurement:** ancilla qubits are read out while data qubits keep their state. The source says that in alkaline-earth systems the data qubits are shelved into a dark state while the ancillas are imaged.

- **Decoding bottleneck:** decoding must keep pace with the machine; FPGAs placed next to the camera outputs run the decoder to avoid processing delays.

14. Modular photonic interconnects

The source puts the practical limit of one vacuum module at 1,000–10,000 atoms (optical crowding, laser power, window size). Larger machines link modules with optical fiber.

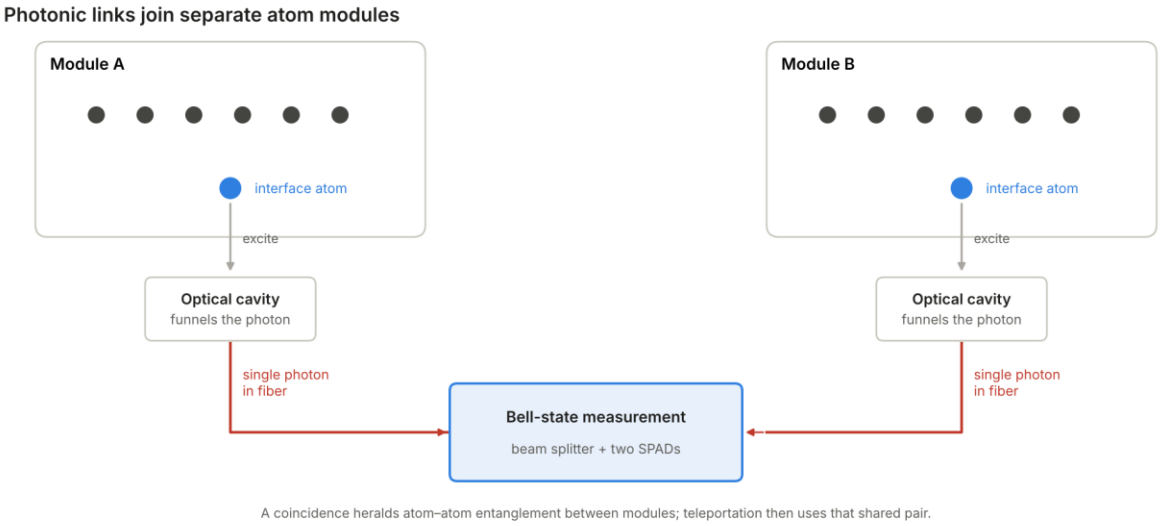

Figure 22. Two modules linked through a Bell-state measurement station.

1. **Atom–photon entanglement:** a laser pulse makes an interface atom emit one photon whose polarization is entangled with the atom's spin.
2. **Optical cavities:** a high-finesse micro-cavity around the interface atom directs most emitted photons into a single-mode fiber.
3. **Bell-state measurement:** photons from the two modules interfere on a beam splitter in front of single-photon detectors (SPADs); a coincidence heralds entanglement between the two atoms, linking the modules.

15. Gerchberg–Saxton hologram design

The Gerchberg–Saxton (GS) algorithm and its variants compute the phase patterns written to an SLM to split one laser beam into hundreds of tweezers. A phase-only SLM cannot change the amplitude of the light, only its phase, and a lens performs a Fourier transform, so finding the SLM phase that produces a target pattern (for example a 10 × 10 square or a kagome lattice) is a phase-retrieval problem.

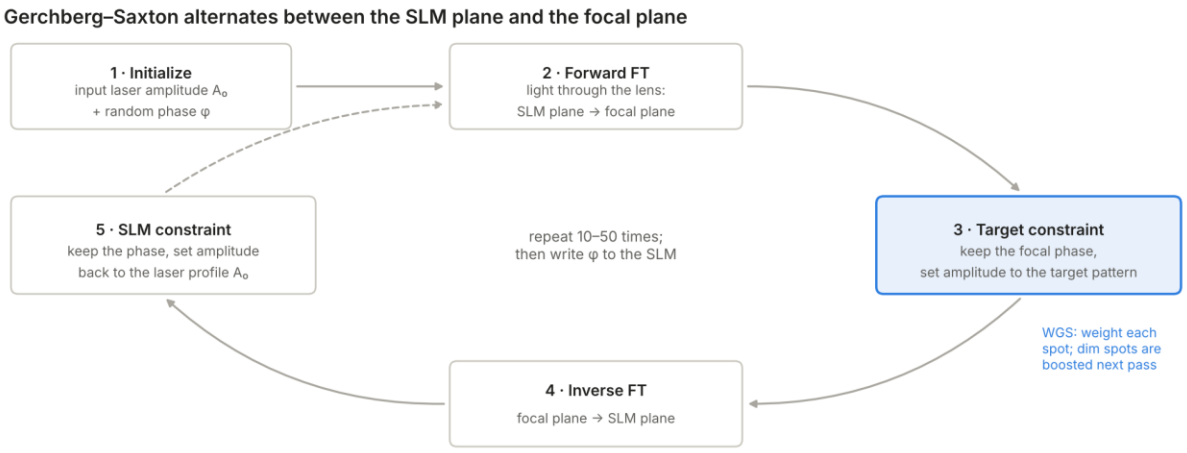

Figure 23. The GS iteration between SLM plane and focal plane.

In symbols, with input amplitude A_0, target amplitude A_T and SLM phase ϕ, iteration k computes the focal field and the new SLM phase:

$$E_f^{(k)} = \mathrm{FT}\left\{A_0\, e^{i\phi^{(k)}}\right\} \tag{2}$$

$$\phi^{(k+1)} = \arg \mathrm{IFT}\left\{A_T\, e^{i\arg E_f^{(k)}}\right\} \tag{3}$$

The loop usually converges in 10–50 iterations. Plain GS leaves the spot intensities uneven, which gives atoms different trap depths, heating rates and gate errors. Weighted GS (WGS) rescales each target spot every iteration so that dim spots are pushed up:

$$A_{T,j}^{(k)} = w_j^{(k)} A_{T,j}, \qquad w_j^{(k)} = w_j^{(k-1)}\, \frac{\langle |E_f^{(k)}| \rangle}{|E_{f,j}^{(k)}|} \tag{4}$$

where ⟨|E_f|⟩ is the mean spot amplitude and j labels the spots.

Variant	Modification	Benefit
Weighted GS (WGS)	Per-spot weight factor updated each iteration (equation 4)	Near-identical trap depths (the source says > 99 % uniformity)
Offset GS (OGS)	Shifts ghost images and interference noise outside the trapping region	Less stray light near the qubits
GPU-accelerated WGS	Parallel 2D FFTs on graphics hardware	Milliseconds per hologram, so new layouts can be computed on the fly

16. Review notes: claims to check before relying on them

The source cites mostly vendor pages, videos and forum threads. These statements conflict with published work or look unsupported:

Claim in the source	Concern
Atom Computing uses a 3D optical lattice and fill-and-discard ejection (Sections 2, 4, 6)	Atom Computing's 1,225-site machine is a 2D 35 × 35 array at 3.3 µm pitch, filled by AOD rearrangement; cavity-enhanced lattices are used for loading and imaging (Norcia 2024). The 3D workflow appears unsupported.
Atom Computing traps at 759 nm (magic lattice)	Its published target tweezers are at 459.6 nm and 423.3 nm (clock-magic), with 483 nm reservoir tweezers and 783.8 nm cavity lattices (Norcia 2024). 759 nm is the Yb clock-magic wavelength used in optical clocks.
Single-qubit rotations use the clock laser 'within the ground-state manifold'	Atom Computing drives single-qubit gates with 556 nm Raman beams detuned from $^3P_1$; the 578 nm clock laser shelves $\|1\rangle$ for the CZ gate (Muniz 2024).
Mid-circuit measurement shelves data qubits into a dark state	Atom Computing hides data qubits with 459.6 nm light that shifts their $^3P_1$ level by 74 MHz while ancillas are imaged on 556 nm (Norcia 2023).
planqc stores the qubit in a nuclear spin; cooling to the ground state uses the clock line	^{88}Sr has no nuclear spin; the Munich work behind planqc encodes a fine-structure qubit in metastable ^{88}Sr (arXiv:2401.11054). Narrow-line cooling uses the 689 nm line, not the 698 nm clock line.
QuEra's global Rydberg pulse is 'ultraviolet'	For ^{87}Rb the Rydberg light is 420 nm + 1013 nm (Section 5),equivalent energy of photons together corresponds to UV, but no UV photon appears to be used; UV (302 nm) applies to Yb.
SHG chain uses an EDFA to amplify 922 nm or 604 nm light	Erbium-doped fiber amplifiers work only near 1.53–1.57 µm. 922 nm is usually amplified with a tapered amplifier; 302 nm is usually reached by doubling twice from about 1.2 µm.
Cryogenic cooling raises lifetime from ~10 s to hours	Room-temperature machines already reach > 150 s (Chiu 2025); a cryogenic Rydberg-array system reported a 3000 s trap lifetime (arXiv:2412.09780).
Decoding must finish within the atoms' coherence, 'typically under 5–10 ms'	Nuclear-spin coherence is seconds (Barnes 2022, Norcia 2023). The practical limit is the QEC cycle time: the decoder must keep pace with repeated cycles.
A Bell-state measurement 'instantly teleports' the quantum state	The measurement heralds remote entanglement; teleporting a state then needs a further measurement and classical feed-forward.
'Offset GS (OGS)'	Not a standard algorithm name; common variants are WGS, phase-fixed WGS, conjugate-gradient methods and camera or atom feedback.
Infleqtion trades as NYSE: INFQ	Plausible but not checked here.

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