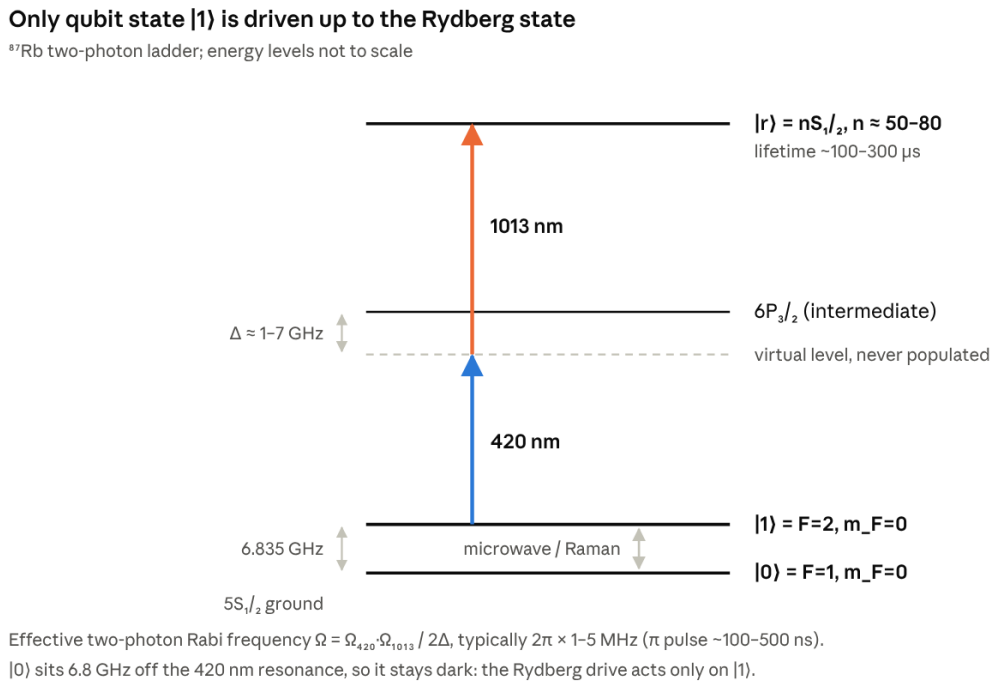
Rb-87 Rydberg Qubits and Gates

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In most ^{87}Rb processors the qubit lives in two long-lived ground hyperfine states. The Rydberg state is an auxiliary level each atom visits for well under a microsecond, only during two-qubit gates.

Generating a Rydberg state

A Rydberg state has the valence electron in a very high orbit (n ≈ 50–80, versus n = 5 in the ground state). It is reached with a two-photon ladder: 420 nm drives $5S_{1/2} \rightarrow 6P_{3/2}$, and 1013 nm drives $6P_{3/2} \rightarrow nS_{1/2}$ (for example 70S or 53S) or nD.



Rb-87 level diagram · qubit states and the 420 + 1013 nm Rydberg ladder

- **Detuning:** both lasers sit ~1–7 GHz from the 6P intermediate state, so the atom almost never occupies 6P and scattering from it is suppressed.
- **Effective drive:** the atom sees one two-photon Rabi frequency, $\Omega \approx \frac{\Omega_{420}\,\Omega_{1013}}{2\Delta}$, typically 2π × 1–5 MHz. A π pulse, which takes the atom fully from ground to Rydberg, lasts about 100–500 ns.
- **Counter-propagating beams:** the 420 and 1013 nm beams travel in opposite directions, so their Doppler shifts largely cancel.
- **Locking:** both lasers are locked to the ULE cavity; their combined phase noise sets the coherence of the ground–Rydberg transition.
- **Traps off:** tweezer light repels Rydberg atoms, so traps are switched off for a few microseconds during the pulse. At 10 µK the atoms barely move in that time.

Property	Scaling with n	Typical at n ≈ 70	Why it matters
Orbit size	n^2	~0.3–0.5 μm	Huge, so easily perturbed
Interaction strength C_6 (van der Waals)	$\sim n^{11}$	Strong at several μm	Enables the blockade
Lifetime (300 K, with blackbody radiation)	$\sim n^3$	~100–300 μs	Long compared with ~1 μs gates
Polarizability	$\sim n^7$	Very large	Sensitive to stray electric fields, so electrodes null them

How it works as a qubit

The standard choice is the hyperfine "clock" qubit. The Rydberg level is a conditional helper, not the stored state.

Qubit type	$\|0\rangle$	$\|1\rangle$	Lifetime / coherence	Typical use
Hyperfine clock (standard)	$\|F=1, m_F=0\rangle$	$\|F=2, m_F=0\rangle$ (6.835 GHz above)	Ground states, effectively infinite lifetime; T_2^* ~1–10 ms, ~1 s with dynamical decoupling	Digital QC
Ground–Rydberg	5S	$\|r\rangle$	Decays in ~100 μs; untrapped	Analog quantum simulation

- **Why m_F = 0:** these states are insensitive to magnetic fields to first order.
- **What limits coherence:** trap-induced differential light shifts, the same nonuniformity the SLM feedback works to reduce.
- **Rydberg as a helper:** only $|1\rangle$ is coupled to $|r\rangle$. $|0\rangle$ is 6.8 GHz off resonance and stays dark, so the Rydberg laser acts conditionally on the qubit state. That is the key to two-qubit gates.
- **Initialize:** optical pumping into $|F=2, m_F=0\rangle$ with π-polarized light on F=2→F′=2 (the target is a dark state) plus repump; a microwave π pulse maps the atom to $|0\rangle$ if needed.
- **Read out:** a resonant push-out pulse removes atoms in $|1\rangle$ (F=2), then the camera images the survivors. Atom present means $|0\rangle$; atom missing means $|1\rangle$.

Single-qubit gates

A single-qubit gate is a controlled rotation R(θ, ϕ) between $|0\rangle$ and $|1\rangle$. The rotation angle $\theta = \Omega \times t_{\text{pulse}}$, set by AOM or switch timing. The axis ϕ is the drive's phase, set digitally by the DDS or AWG. Typical fidelity is 99.5–99.9% per gate.

Method	How	Speed (π pulse)	Strength	Cost

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Global microwave	6.835 GHz horn drives every atom	~5–50 μs (Rabi ~2π × 10–100 kHz)	Extremely uniform, simple	Slow; global only
Raman	Two laser beams 6.835 GHz apart, detuned from the D lines	~1 μs	Fast; can be focused for local gates	Photon scattering; needs a phase-stable beam pair
Virtual Z	Control software shifts the phase reference of all later pulses	Zero time	No error	Z axis only
Physical Z	Local light shift applied for a set time	μs scale	Site-selective	Needs the addressing beam

Local gates on chosen atoms: a global rotation is combined with the local light-shift beam. Shifted atoms are off resonance and skip the rotation, or the shifted atoms alone get a Z rotation. Composite pulses such as BB1 cancel errors from intensity variation across the array.

Keeping the qubit healthy between gates:

- A bias field of a few gauss fixes the quantization axis.
- Spin-echo or XY-type decoupling pulses cancel slow dephasing from trap-depth nonuniformity. This is where the SLM uniformity spec pays off.

Two-qubit gate: CZ via Rydberg blockade

Two Rydberg atoms within the blockade radius cannot both be excited, and that conditional behavior entangles them. One global pulse can run hundreds of CZ gates in parallel, at ~99.5% fidelity with current protocols.

The blockade

- Two Rydberg atoms at distance r interact with energy $V = \frac{C_6}{r^6}$.
- Inside the blockade radius $R_b = \left(\frac{C_6}{\hbar\Omega}\right)^{1/6}$, about 5–10 μm, V is much larger than the laser coupling. The doubly excited state $|rr\rangle$ is shifted far off resonance and can't be reached.
- If one atom is excited, its neighbor cannot be.

What a global Rydberg pulse does to each input state

Input	Rydberg coupling	Outcome
$\|00\rangle$	Neither atom couples	Nothing happens
$\|01\rangle$, $\|10\rangle$	One atom cycles $\|1\rangle \rightarrow \|r\rangle \rightarrow \|1\rangle$	Returns with phase ϕ_1

Input	Rydberg coupling	Outcome
$\|11\rangle$	Blockaded: the pair couples collectively to $\frac{\|1r\rangle+\|r1\rangle}{\sqrt{2}}$ at $\sqrt{2}\cdot\Omega$ and never reaches $\|rr\rangle$	Returns with phase ϕ_{11}

Pulse parameters are chosen so that $\varphi_{11} = 2\varphi_1 + \pi$. After single-qubit Z corrections remove ϕ_1, the result is exactly a controlled-Z (CZ). A CNOT is CZ with Hadamard gates on the target before and after.

Pulse protocols

Protocol	Pulse sequence	Local addressing needed	Notes
Jaksch et al. (2000)	π on control, 2π on target, π on control	Yes	Original scheme: a control in $\|r\rangle$ blocks the target, which picks up no phase
Levine et al. (2019)	Two global pulses with a laser phase jump between them	No	First high-fidelity global gate
Time-optimal smooth phase (Jandura–Pupillo; Evered et al. 2023)	One global pulse with a continuously varying laser phase	No	~99.5% fidelity, current state of the art

Setting up the gate in the machine

1. **Arrange pairs:** the AOD mover places the two atoms of each pair ~2 μm apart, well inside R_b, with different pairs ≥10 μm apart, well outside it. Many designs use a dedicated gate zone, with atoms shuttled in from storage.
2. **Prepare:** cool, initialize the qubits, apply any single-qubit gates, and null stray electric fields.
3. **Pulse:** turn the traps off for ~1–3 μs, apply the 420 + 1013 nm pulse (~250–500 ns) with the computed phase profile, and turn the traps back on.
4. **Correct:** apply virtual Z corrections, add echo pulses if needed, and continue the circuit.

Error budget

Error source	Mitigation
Rydberg decay during the pulse	Higher n, shorter gates
Scattering from 6P	Larger intermediate detuning Δ, at the cost of laser power
Laser phase and intensity noise	ULE-cavity lock, intensity servos
Atom temperature and Doppler shifts	Better cooling, counter-propagating beams

Error source	Mitigation
Uneven Rydberg beam intensity across the array	Beam shaping, flat-top profiles
Imperfect blockade at the pair spacing	Tighter pair spacing
Atom loss when left in $\|r\rangle$ (untrapped)	Accurate pulse calibration

The numbers in this doc (n, Ω, lifetimes, fidelities) are typical literature values, not checked against sources here. Verify against Jaksch et al. (PRL 2000), Levine et al. (PRL 2019) and Evered et al. (Nature 2023).

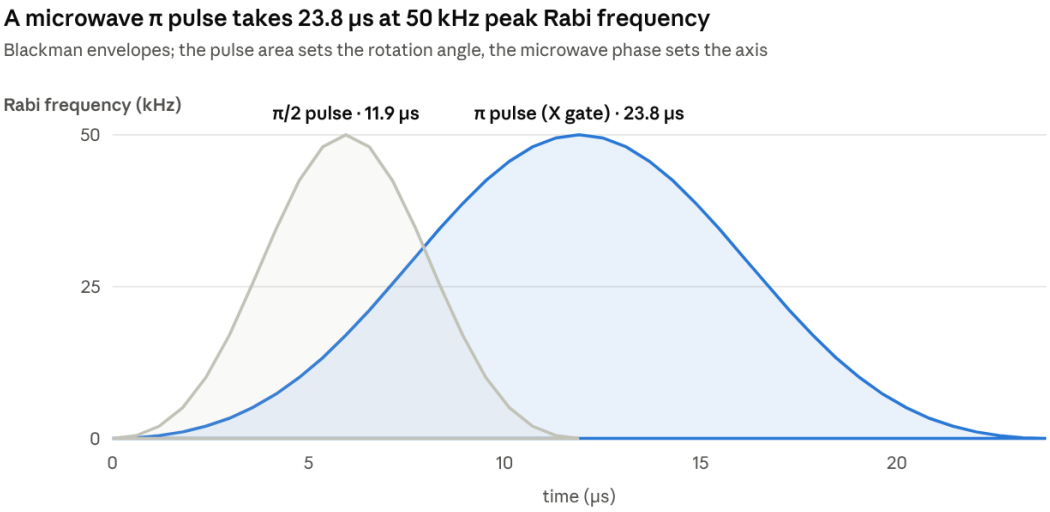
Pulse waveforms

Every operation is a shaped microwave or laser pulse defined by three things: amplitude envelope, phase and detuning. The CZ parameters below were checked by simulating the gate (blockaded-pair model: perfect blockade, no Rydberg decay or 6P scattering). Times assume a Rydberg Rabi frequency $\Omega = 2\pi \times 4.6$ MHz.

Operation	Drive	Amplitude envelope	Phase / detuning	Duration	Check
X (π) gate	6.835 GHz microwave	Blackman, peak Rabi $2\pi \times 50$ kHz	Constant; phase sets the rotation axis	23.8 μs	Pulse area π
π/2 gate	6.835 GHz microwave	Blackman, same peak	Constant	11.9 μs	Pulse area π/2
X (π) gate, Raman	Raman beam pair	Blackman, peak $2\pi \times 1$ MHz	Constant	1.19 μs	Pulse area π
Z rotation	None (virtual)	None	Offset added to the phase of all later pulses	0	Exact
CZ, Jaksch	Local Rydberg beams	Square: π (control), 2π (target), π (control)	Resonant	~435 ns	Not simulated here
CZ, two-pulse (Levine)	Global 420 + 1013 nm	Square, constant Ω	$\Delta = 0.377\,\Omega$; phase jump 3.902 rad at the midpoint	297 ns	Simulated F = 0.999999
CZ, time-optimal	Global 420 + 1013 nm	Square, constant Ω	$\Delta = 0$; smooth phase $\phi(t)$	263 ns	Simulated $1 - F = 1.5 \times 10^{-8}$

The sign of the Levine phase jump depends on the Hamiltonian's phase convention; with the other sign the gate fails (simulated F = 0.67), so calibrate it on the machine. The time-optimal profile here is one valid solution found by optimization; published papers use different but equivalent parameter sets.

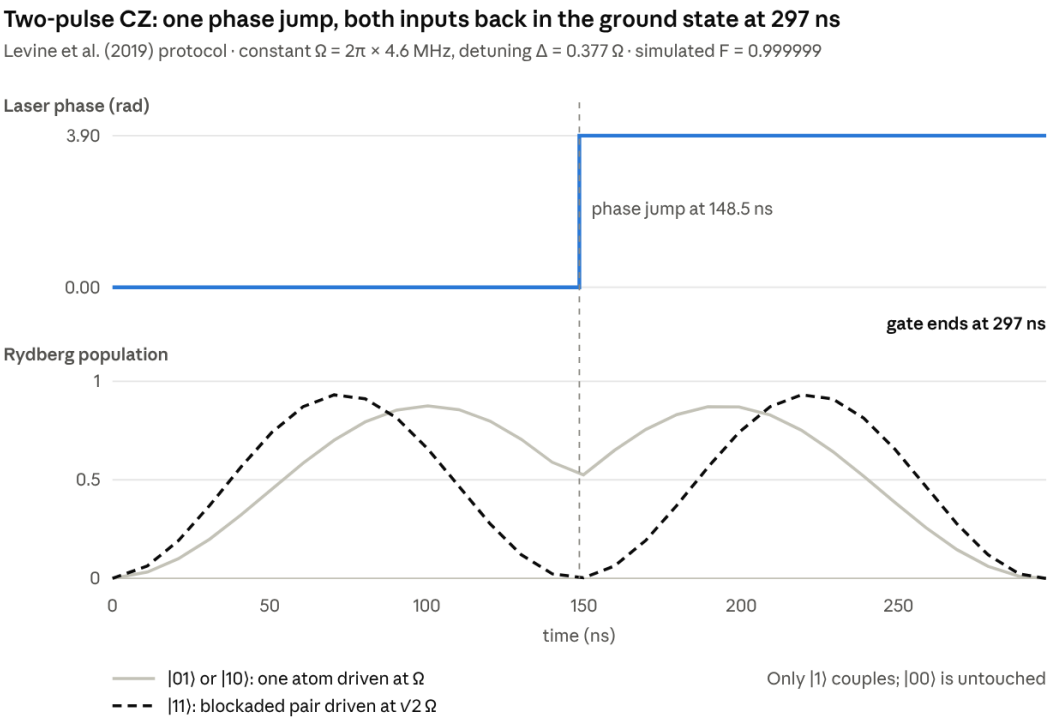
Single-qubit pulses



computed: Blackman envelope, peak Rabi $2\pi \times 50$ kHz, area π and $\pi/2$

A Blackman envelope (rather than a square pulse) keeps the spectrum narrow, so neighboring transitions are not driven. The Raman version has the same shape, 20× faster at $2\pi \times 1$ MHz peak.

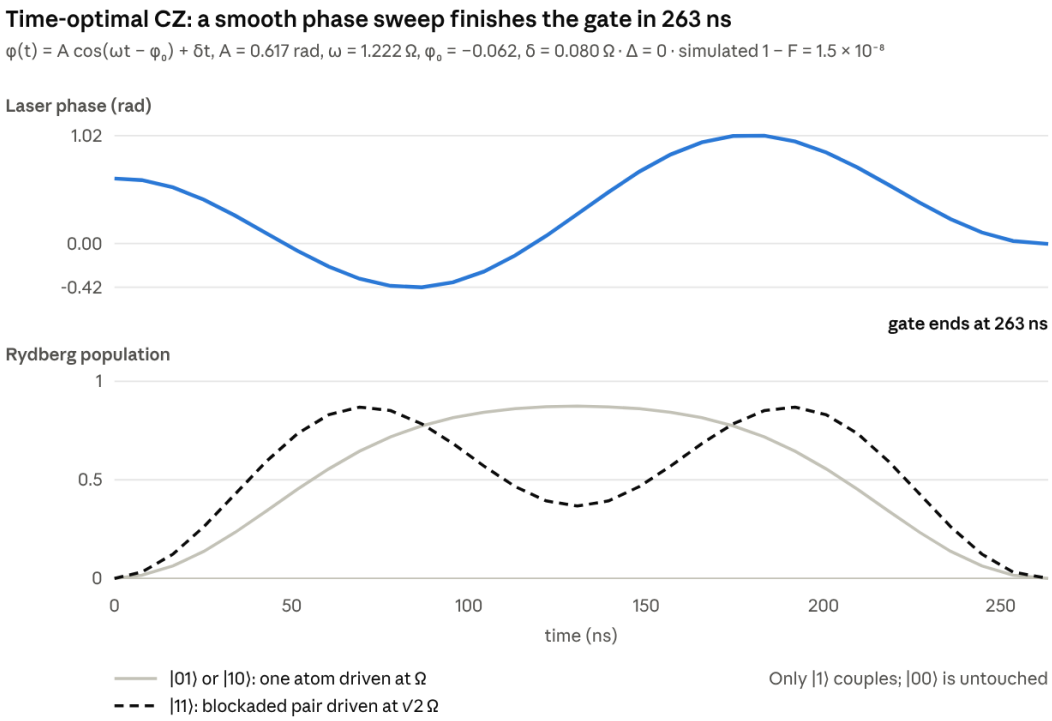
CZ: two-pulse protocol (Levine et al.)



simulated: blockaded-pair model, $\Omega = 2\pi \times 4.6$ MHz, Levine et al. (2019) parameters

Amplitude and detuning stay constant for both pulses; only the laser phase changes, in one jump at the midpoint. The single atom's detuned Rabi cycle does not close after the first pulse; the phase jump steers it back, while the blockaded pair (driven √2 faster) completes two full cycles. Both end in the ground state with the CZ phase relation.

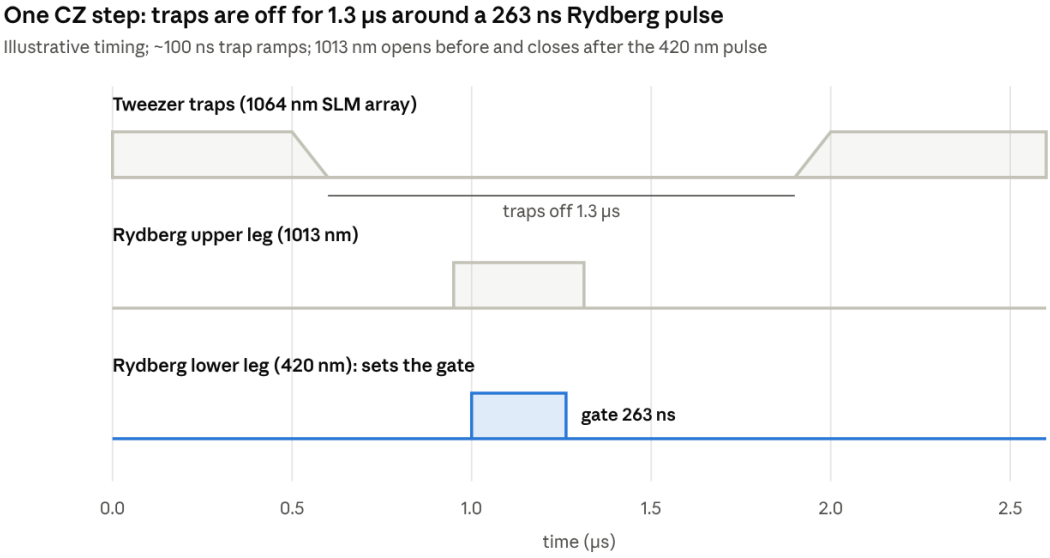
CZ: time-optimal protocol



simulated: blockaded-pair model, Ω = 2π × 4.6 MHz, phase profile fitted here

One continuous pulse at constant amplitude and zero detuning; all the control is in the laser phase, which the AWG writes onto the 420 nm beam's AOM. It is ~11% shorter than the two-pulse gate, so less time is spent in the decaying Rydberg state.

Timing of one CZ step



illustrative timing; gate length from the time-optimal pulse above

The 420 nm pulse alone defines the gate; the 1013 nm beam brackets it, so its own switching edges don't land inside the gate. Traps are released before and recaptured after, because the trap light repels atoms in the Rydberg state.

Real pulses add ~10–20 ns rise and fall edges, and the ideal-model fidelities above leave out Rydberg decay, 6P scattering and laser noise; see the error budget above.