

# Improving Rydberg Gate Fidelity

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How can we improve the fidelity of gates created by the interaction of excited Rydberg state atoms. The baseline design sits near 99.7% CZ fidelity. Most of the remaining error is 6P scattering and Rydberg decay, both reduced by more laser power, so laser power and phase-noise filtering come first; robust pulses, uniform illumination and colder atoms take it toward ~99.9%, and cryogenics or new gate types toward 99.95%.

## Where the error comes from

Numbers come from the gate simulation built earlier (time-optimal CZ,  $\Omega = 2\pi \times 4.6$  MHz, gate time 263 ns) plus standard  $^{87}\text{Rb}$  values.

| Error source                  | What was computed or assumed                                                                                          | Typical error per CZ                                  |
|-------------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|
| 6P scattering                 | Error $\approx 3.8 \Gamma_{6p}/\Delta$ ; about $2.7 \times 10^{-3}$ per driven atom at $\Delta = 2\pi \times 2$ GHz   | $\sim 1.3 \times 10^{-3}$ averaged over inputs        |
| Rydberg decay                 | Average time in the Rydberg state $2.96/\Omega$ (simulated); lifetime $\sim 150 \mu\text{s}$ at room temperature      | $6.8 \times 10^{-4}$                                  |
| $\Omega$ error from intensity | 1% $\Omega$ error $\rightarrow 3.5 \times 10^{-4}$ ; 2% $\rightarrow 1.4 \times 10^{-3}$ (simulated)                  | $10^{-4}$ – $10^{-3}$                                 |
| Laser phase noise             | 1 kHz effective linewidth, no servo bumps                                                                             | $\sim 1 \times 10^{-4}$ , often 10× worse in practice |
| Doppler shift                 | At 10 $\mu\text{K}$ the spread is 0.94% of $\Omega$ ; a 0.01 $\Omega$ detuning costs $1.3 \times 10^{-4}$ (simulated) | $\sim 1 \times 10^{-4}$                               |

These sum to roughly  $2.5$ – $3.5 \times 10^{-3}$ , about 99.65–99.75% fidelity, which is where the best labs are. The two largest terms both shrink with more laser power.

## 1. Reduce laser noise and add power

The effective two-photon Rabi frequency sets the trade-off:

$$\Omega = \frac{\Omega_{420} \Omega_{1013}}{2\Delta}$$

- **Larger detuning:** at fixed  $\Omega$ , scattering error falls as  $1/\Delta$ , but  $\Delta$  can only grow if  $\Omega_{420} \cdot \Omega_{1013}$  grows. Quadrupling the power in both beams raises  $\Delta$  4× and cuts scattering 4×.
- **Faster gate:** at fixed  $\Delta$ , more power raises  $\Omega$ , shortening the gate and reducing Rydberg-decay error proportionally.

## How to get the power

- **Per-beam Rabi frequency:**  $\Omega_{420}$  and  $\Omega_{1013}$  each need  $\sim 2\pi \times 100\text{--}250$  MHz to support  $\Delta \approx 2\pi \times 2\text{--}7$  GHz at  $\Omega \approx 2\pi \times 5$  MHz.
- **1013 nm:** a narrow ECDL seed plus a ytterbium fiber amplifier at several watts. Straightforward.
- **420 nm (the harder leg):** frequency-double an 840 nm diode + tapered amplifier in a resonant SHG cavity, or injection-lock direct 420 nm diodes to a stable seed. Expect hundreds of mW to  $\sim 1$  W.
- **Beam size:** make it only as large as the active zone, or use the multi-spot approach in option 3.

## Phase noise

- **Linewidth:** Pound–Drever–Hall lock both lasers to the ULE cavity for Hz–kHz linewidth.
- **Servo bumps:** the lock pushes noise to  $\sim 0.5\text{--}2$  MHz, exactly where a gate at  $\Omega \approx 2\pi \times 5$  MHz is most sensitive. This usually dominates the phase-noise error.
- **Fix for servo bumps:** use the light *transmitted* through the cavity, which is filtered, to injection-lock a slave diode or seed the amplifier, so the high-power beam inherits the clean spectrum. This is how the 99.5% results were achieved.
- **Measuring it:** self-heterodyne or beat-note against a second cavity; on the atoms, phase noise appears as Rydberg Rabi dephasing faster than decay alone explains.

## Targets

- $\Delta \geq 2\pi \times 5$  GHz
- Phase-noise power spectral density below  $\sim 1$  Hz<sup>2</sup>/Hz in the 0.1–5 MHz band, with no visible servo bumps
- Intensity noise below 0.1% RMS during the gate

## 2. Use robust optimal-control pulses

The time-optimal pulse is fast but error-sensitive: in simulation a 1%  $\Omega$  error costs  $3.5 \times 10^{-4}$  and a 0.01  $\Omega$  detuning costs  $1.3 \times 10^{-4}$ , both growing with the square of the error.

- **Optimize over a range of errors:** optimize the laser phase  $\phi(t)$ , and optionally the amplitude  $\Omega(t)$ , with the cost averaged over a spread of  $\Omega$  errors (say  $\pm 2\%$ ) and detunings ( $\pm 0.03 \Omega$ ). This is ensemble or robust GRAPE.
- **Or cancel first-order sensitivity:** add derivative terms that force the gate's sensitivity to zero at the nominal point.
- **Trade-off:** robust pulses are typically 10–30% longer, adding a little decay error; the right balance depends on the measured noise.
- **Smooth edges:**  $\sim 10\text{--}20$  ns amplitude ramps so AOM and amplifier bandwidth don't distort the pulse.

## Best way to achieve it

1. Extend `rydberg_cz_pulse_sim.py` with a robust cost function (a small change).
2. Include the measured laser noise spectrum and beam-intensity map in the model.

3. Calibrate on the machine with closed-loop optimization of a few pulse parameters (for example Bayesian optimization of the phase-profile coefficients) against measured CZ fidelity.

**Target:** error from  $\pm 1\% \Omega$  and  $\pm 0.02 \Omega$  detuning below  $10^{-4}$ .

### 3. Make the Rydberg illumination uniform

A Gaussian global beam 1% weaker at the edge sites adds  $\sim 3.5 \times 10^{-4}$  error there. Because  $\Omega \propto \sqrt{I_{420} \cdot I_{1013}}$ , each beam needs about 1% uniformity to hold the  $\Omega$  error near 1%.

| Approach                             | How                                                                                                       | Strength                                                                                                                                    | Limitation                                                                                                                                                                  |
|--------------------------------------|-----------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Multi-spot Rydberg beams (preferred) | One 420 and 1013 nm spot per atom, from the same kind of hologram as the trap array                       | 5–20× more intensity per atom at the same power (feeds option 1); uniformity fixed by the weighted Gerchberg–Saxton feedback used for traps | Spots must track the atom positions                                                                                                                                         |
| Flat-top beam                        | Refractive beam shaper ( $\pi$ Shaper type) or static diffractive element designed with the hologram code | Simple and stable                                                                                                                           | Wastes power outside the atoms                                                                                                                                              |
| LCOS SLM directly at 420 nm          | Same SLM optics at the blue wavelength                                                                    | Reconfigurable                                                                                                                              | Organic alignment and LC degrade under blue light (oblique-SiO <sub>2</sub> alignment is the robust choice); dielectric mirror must suit 420 nm; check response and flicker |

Many groups use the SLM to design and test the pattern, then fabricate a static fused-silica element for the production machine.

### Calibration and specs

- Measure each site's Rydberg Rabi frequency (or each beam's light shift) on the atoms and feed it back into the hologram weights until the spread is under 0.5%.
- Pointing stability below 1% of the spot size.
- Pure polarization, so the coupling strength is identical at every site.

### 4. Use colder atoms

At 10  $\mu$ K the Doppler spread is 0.94% of  $\Omega$  ( $\sim 1 \times 10^{-4}$  error); thermal position spread adds a little more through intensity variation across each spot and variation in atom spacing.

1.  **$\Lambda$ -enhanced gray molasses on D1 (795 nm)** after loading reaches  $\sim 5\text{ }\mu\text{K}$ . Cheap: mostly AOM and EOM work on light already available.
2. **Adiabatic trap lowering** over  $\sim 1\text{ ms}$  just before the gate reduces temperature roughly in proportion to the trap frequency.
3. **Raman sideband cooling** to the motional ground state gives the lowest temperature. Needs a Raman beam pair and resolved trap sidebands; worthwhile if Raman beams already serve single-qubit gates.
4. **Counter-propagating 420 and 1013 nm beams** reduce the effective wavevector that drives the Doppler shift; keep that geometry.

**Targets:**  $\leq 5\text{ }\mu\text{K}$  at gate time (halves the Doppler term), and pair spacing chosen so the blockade strength  $V/\Omega > 50$  even at the edges of the thermal spread.

## 5. Convert errors into erasures

If most errors leave a detectable trace, the decoder knows where they happened, and a surface code tolerates several times more physical error: Wu, Kolkowitz, Puri and Thompson (2022) estimated the threshold rises from  $\sim 1\%$  to  $\sim 4\%$  when about 98% of errors are erasures.

### How it works in $^{171}\text{Yb}$

- The qubit sits in the metastable  $^3\text{P}_0$  state (nuclear-spin states  $m_I = \pm 1/2$ ).
- Most Rydberg decays end up outside the qubit subspace, mainly in the  $^1\text{S}_0$  ground state.
- Imaging on a  $^1\text{S}_0$  transition reveals those atoms without disturbing the  $^3\text{P}_0$  qubits.
- The MPQ  $^{88}\text{Sr}$  work converted about 91% of leakage into detected erasures this way.

### What $^{87}\text{Rb}$ can do (part of the benefit)

- **Detect atom loss mid-circuit:** occupancy-only imaging, with missing atoms treated as erasures. Harvard's 2025 below-threshold result used this.
- **Pump out leftover Rydberg population** after each gate, so it becomes clean loss rather than a hidden error.
- **Detect leakage** to other hyperfine sublevels with state-selective imaging.

### Decision point

Full erasure conversion means moving to Yb or Sr, with new lasers (399, 556 and 578 nm, plus Rydberg UV) and a magic trap wavelength that also removes trap-induced dephasing. It is the biggest long-term lever, but it is a species choice, not an upgrade.

## 6. Pushing past 99.9%

| Option                                      | How it works                                                  | Benefit                                                                                                                                                                                    | Cost or status                                                        |
|---------------------------------------------|---------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------|
| Cryogenic environment ( $\sim 4\text{ K}$ ) | Removes blackbody-driven Rydberg transitions; improves vacuum | Rydberg lifetime 2–4 $\times$ longer: decay error $6.8 \times 10^{-4}$ (150 $\mu\text{s}$ ) $\rightarrow$ $2.6 \times 10^{-4}$ (400 $\mu\text{s}$ ), simulated; trap lifetime $\sim 6,000$ | Cryostat with optical access, vibration control, trap-laser heat load |

| Option                         | How it works                                                                                        | Benefit                                                                                       | Cost or status                                                                    |
|--------------------------------|-----------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| Choice of Rydberg level $n$    | Lifetime grows as $n^3$ , stray-field sensitivity as $n^7$                                          | Cheap tuning knob; $n \approx 50\text{--}80$ is the usual sweet spot                          | Needs electrodes to null stray fields and Rydberg spectroscopy to check stability |
| Förster-resonance gates        | A small DC field makes two pair states degenerate; interaction switches from $C_6/r^6$ to $C_3/r^3$ | Stronger, longer-range blockade, less sensitive to atom spacing                               | Precise field control                                                             |
| Dipolar iSWAP / exchange gates | Two different Rydberg states exchange energy through dipole coupling                                | Native iSWAP or parametrized exchange gates; proposed to reach 99.9% (Ildefonso et al., 2025) | Simulation only, not yet demonstrated                                             |

## Recommended order

| Step           | Action                                                                  | Expected CZ error after                                                      |
|----------------|-------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Baseline       | Current design                                                          | $\sim 3 \times 10^{-3}$ (99.7%)                                              |
| + 1            | $\Delta \geq 2\pi \times 5$ GHz, filtered phase noise                   | $\sim 1.5 \times 10^{-3}$                                                    |
| + 2, 3         | Robust pulses; multi-spot Rydberg beam with atom feedback               | $\sim 1 \times 10^{-3}$                                                      |
| + 4            | $\leq 5$ $\mu$ K at gate time                                           | $\sim 8 \times 10^{-4}$                                                      |
| + 6            | Cryogenics or Förster gates                                             | $\sim 4\text{--}5 \times 10^{-4}$ (99.95%)                                   |
| 5, in parallel | Loss detection and Rydberg pump-out (Rb), or erasure conversion (Yb/Sr) | Raises what the error-correction code tolerates rather than the raw fidelity |

These are estimates; real machines usually show extra error sources (stray fields, crosstalk, calibration drift) that only appear during commissioning.

- ☐ Extend the pulse simulation with a robust cost function and compare sensitivity curves with the time-optimal pulse

## Sources

- Simulated values in this note: `rydberg_cz_pulse_sim.py` (C:\LCoS\Neutral Atom QC)
- [Universal gates for a metastable qubit in Sr-88 \(arXiv 2506.10714\)](#)
- [Native iSWAP and exchange gates from dipolar Rydberg interactions \(arXiv 2512.05037\)](#)
- [Architectural mechanisms of a universal fault-tolerant quantum computer \(arXiv 2506.20661\)](#)

- [Neutral Atom Quantum Computing: Principles, Routes, Progress, and Challenges \(arXiv 2608.05010\)](#)
- The  $2.95/\Omega$  time-in-Rydberg result (Jandura & Pupillo 2022; Evered et al. 2023), the erasure threshold (Wu et al., *Nat. Commun.* 13, 4657, 2022), and the  $^{87}\text{Rb}$   $6P_{3/2}$  lifetime ( $\sim 112$  ns).