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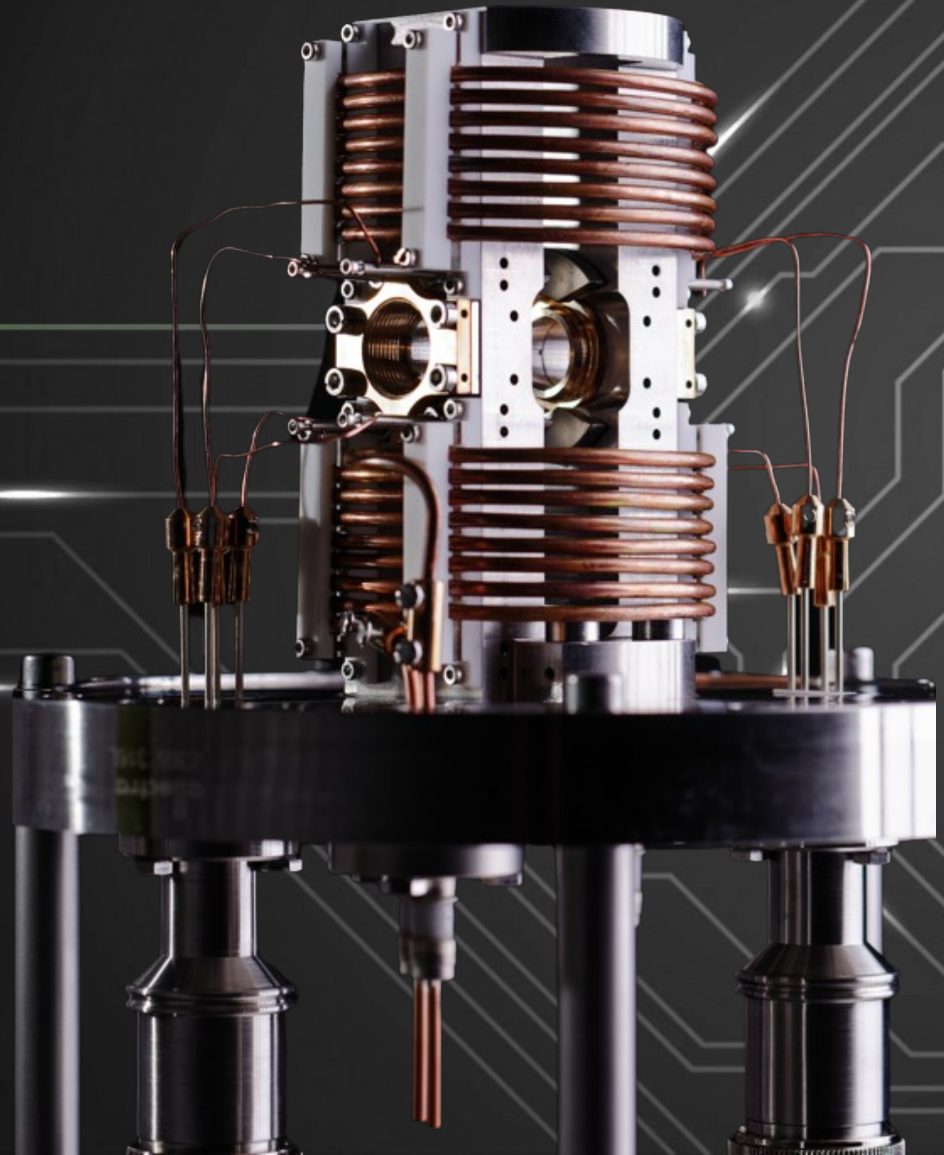
Pulse-level Programming of Neutral-Atom Devices with Pulser



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Practical Quantum Computing School | November 23, 2021

Outline

Morning Session

(9h30 - 10h45) Introduction to Pulser + Installation

(10h45-11h15) Break

(11h15-12h00) Pulse sequence design: Bell state preparation

(12h00-13h00) Lunch Break

Afternoon Session

(13h00-14h30) AFM state preparation, Parametrized Sequences and Optimal Control

(14h30-15h00) Break

(15h00-16h30) Noisy Simulations + Maximum-Independent-Set Problem with Noise

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Understanding Neutral-Atom Quantum Devices

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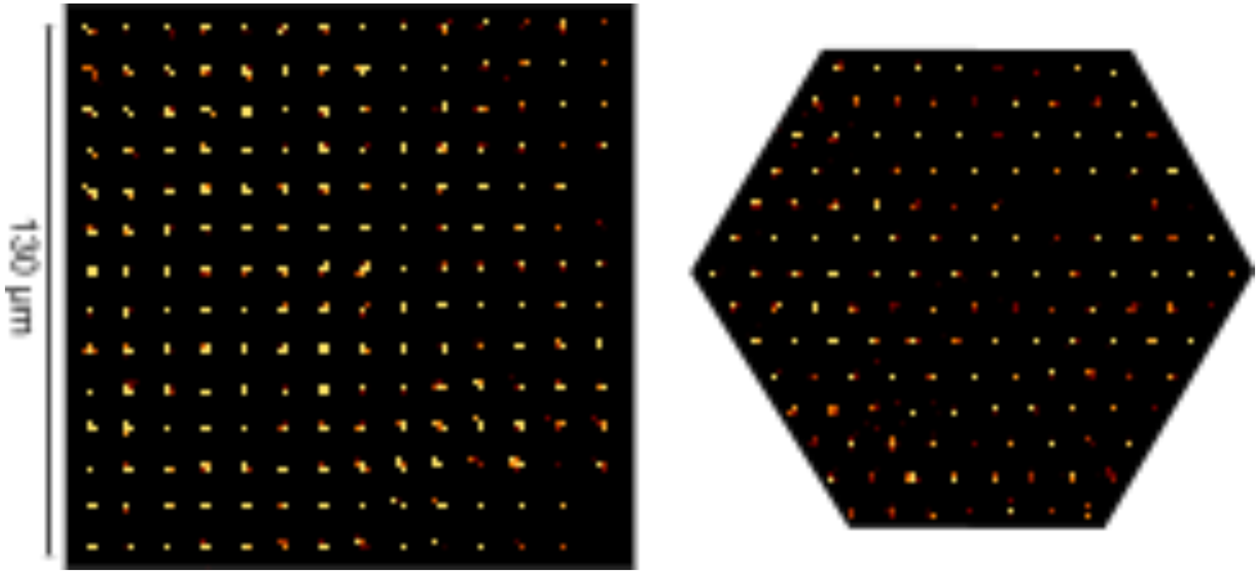
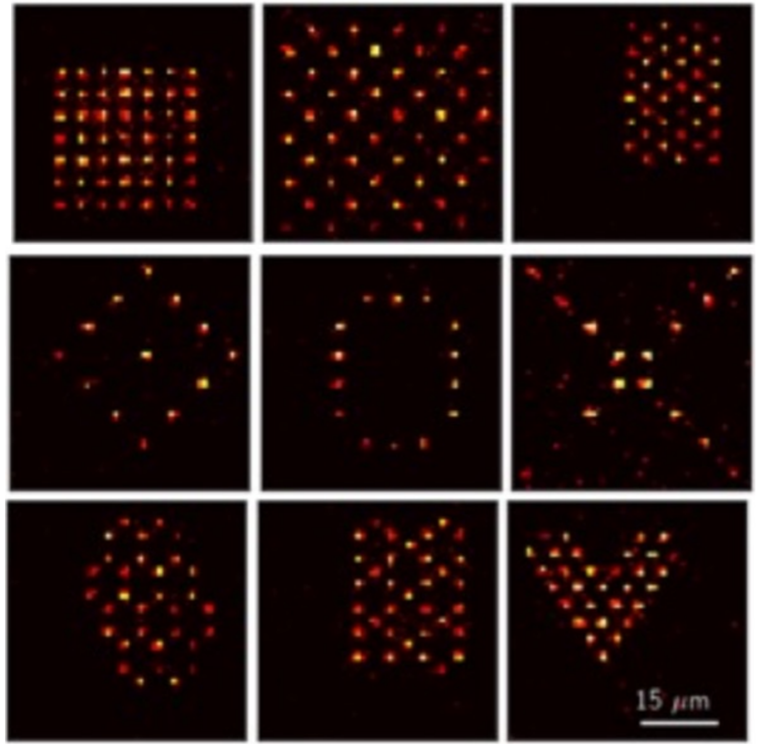
Neutral Atoms as Qubits



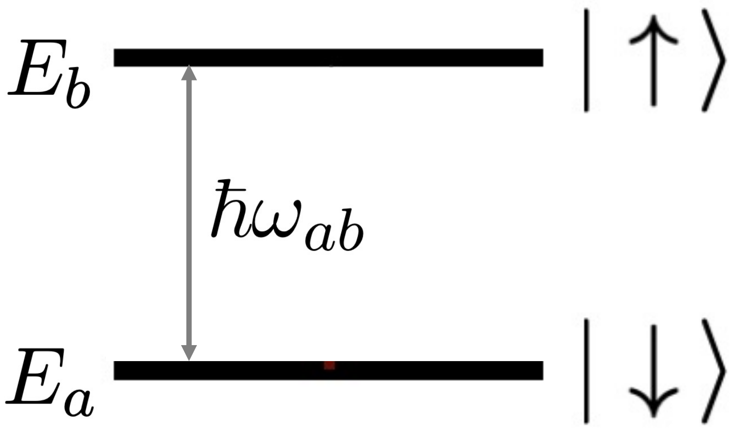
196 qubits arranged in a square or triangular lattice.



Each qubit is an individual neutral atom, trapped in an array of optical tweezers.

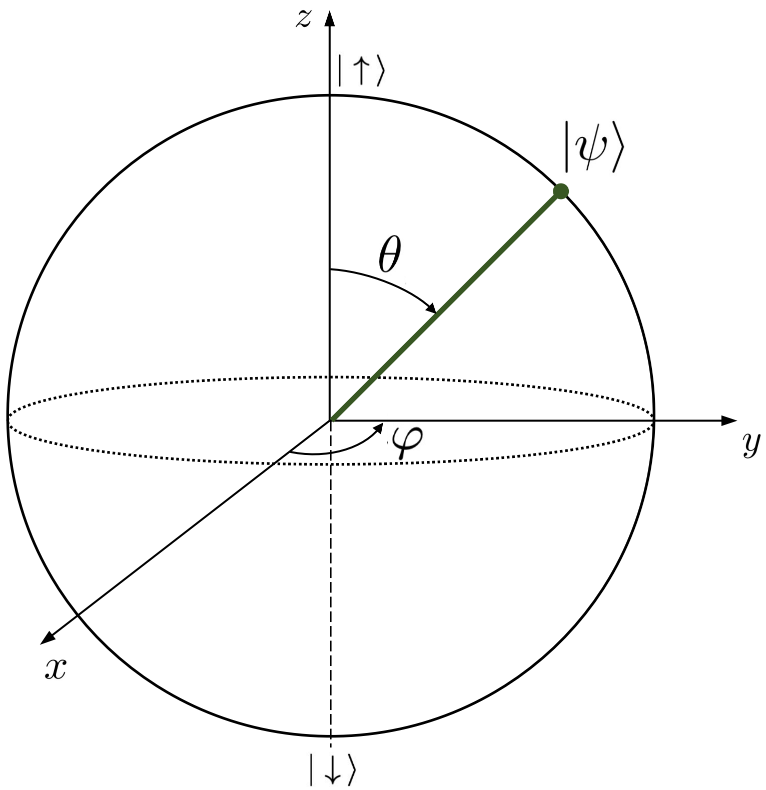
High flexibility: The atoms can be laid out in arbitrary, user-defined patterns.

Neutral Atoms as Qubits



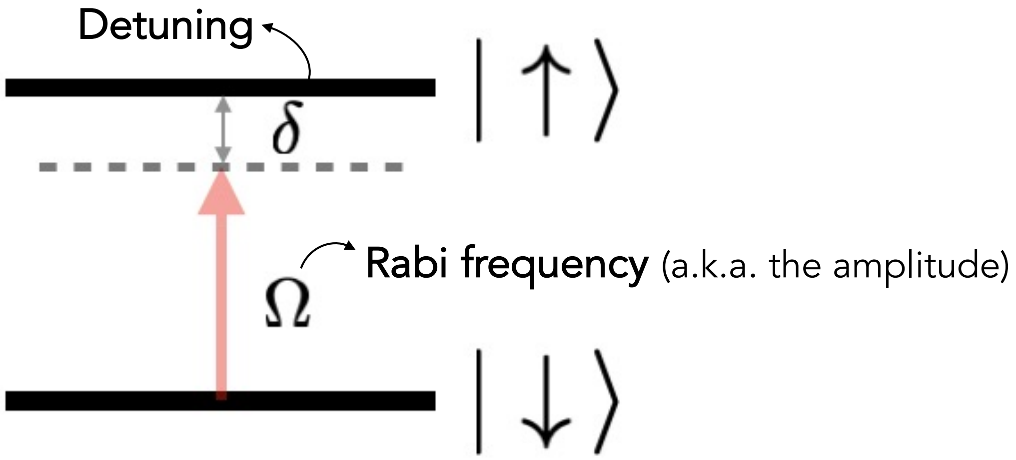
$$|\psi\rangle = \cos(\theta/2)\,|\uparrow\rangle + e^{i\varphi}\sin(\theta/2)\,|\downarrow\rangle$$

A qubit state can be encoded in two energy levels of the atom.



The quantum state on the Bloch sphere.

Manipulating a qubit's state



$$H^D(t) = \frac{\hbar}{2}\mathbf{\Omega}(t)\cdot\boldsymbol{\sigma}$$

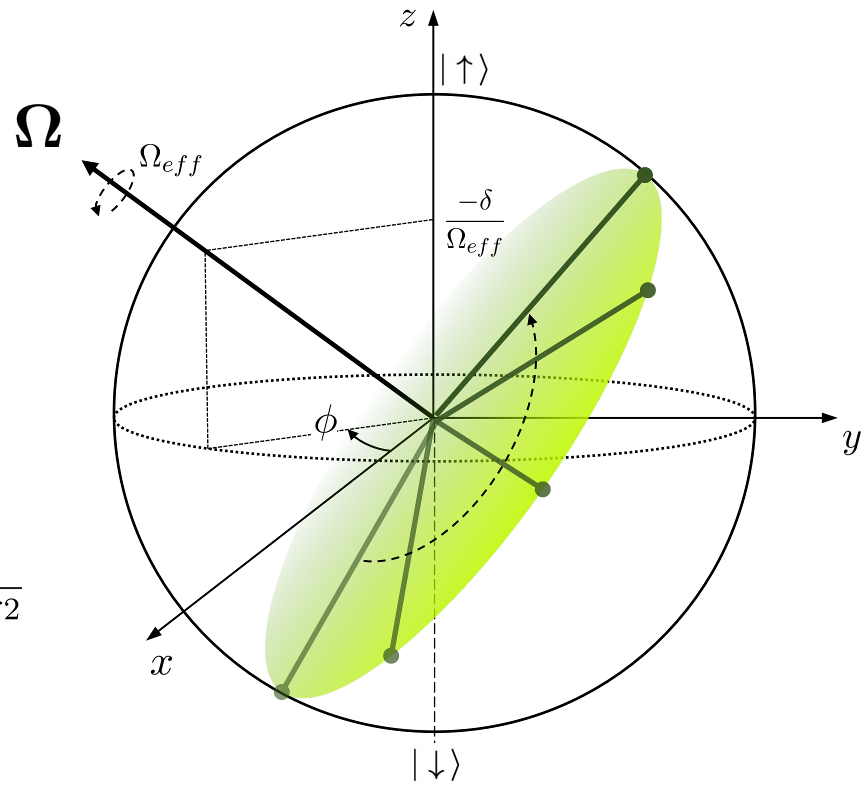
Driving Hamiltonian

$$\mathbf{\Omega}(t) = \begin{pmatrix} \Omega(t)\cos(\phi) \\ -\Omega(t)\sin(\phi) \\ -\delta(t) \end{pmatrix}$$

"Angular velocity" vector

$$\Omega_{eff} = |\mathbf{\Omega}| = \sqrt{\Omega^2 + \delta^2}$$

Effective Rabi frequency



Describes a rotation around $\mathbf{\Omega}$
with angular velocity Ω_{eff}

A laser is tuned to drive a coherent transition between the two energy levels.

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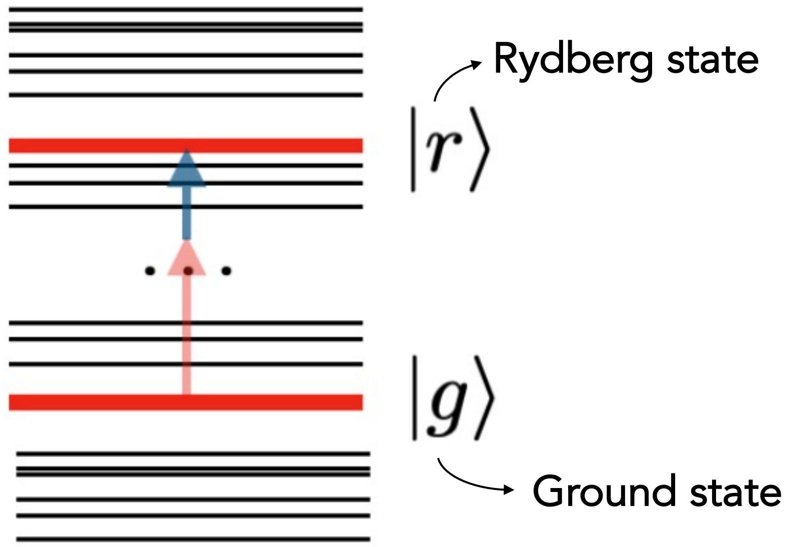
Rydberg states



Driving Hamiltonian

Interaction strength (depends on the Rydberg level)

$$\mathcal{H}^{gr}(t) = \sum_i \left(H_i^D(t) + \underbrace{\sum_{j<i} \frac{C_6}{(R_{ij})^6} \hat{n}_i \hat{n}_j}_{\text{Interaction term}} \right)$$

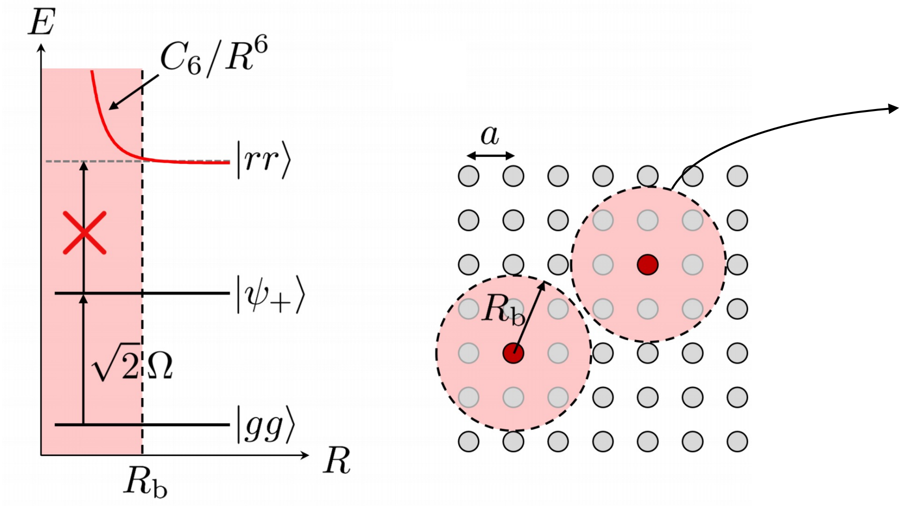
R_{ij} : Distance between atoms *i* and *j*

$\hat{n}_i \equiv |r\rangle\langle r|_i$: Rydberg state occupancy operator for atom *i*

Rydberg states are highly excited electronic states.

When in the Rydberg state, the atoms exhibit a very large electric dipole moment that makes **neighboring atoms interact.**

The Rydberg Blockade



Source: Nature Physics 16, 132 (2020)

- Resonant pulse of Rabi frequency Ω
- $|gg\rangle \rightarrow |rr\rangle$ is shifted out of resonance
- $|gg\rangle$ is coupled to the **entangled state**

$$|\psi_+\rangle = \frac{|gr\rangle + |rg\rangle}{\sqrt{2}}$$

with Rabi frequency $\sqrt{2}\Omega$

The interaction strength is only meaningful between Rydberg atoms at a distance smaller than

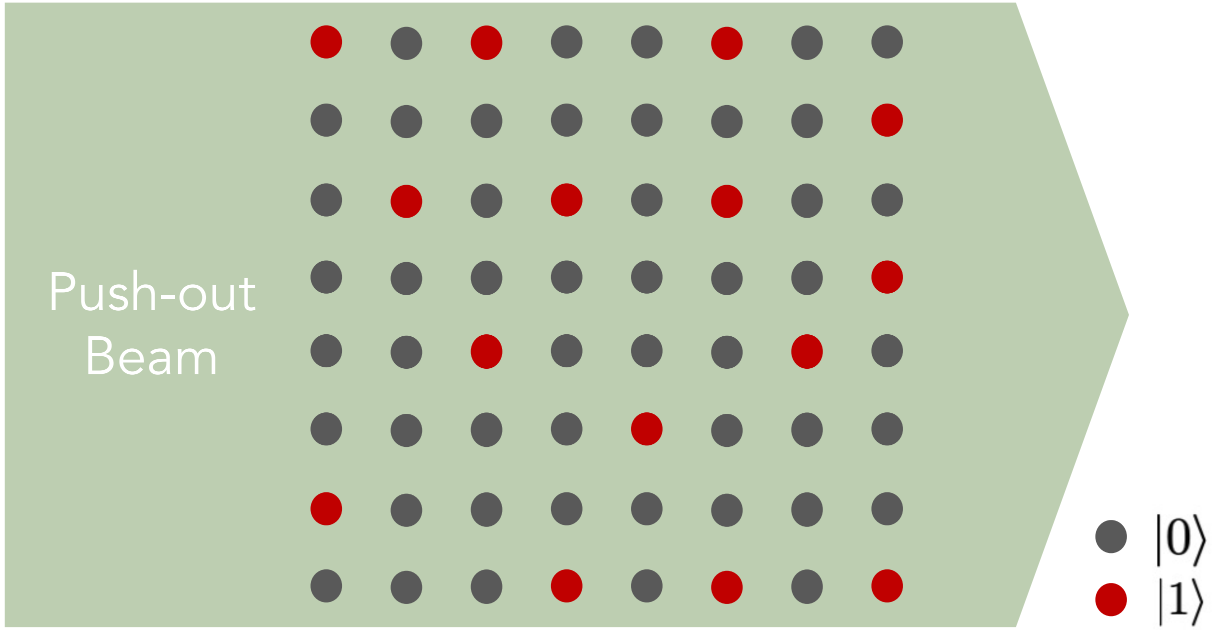
$$R_b = \left(\frac{C_6}{\hbar\Omega}\right)^{1/6}$$

called the **Rydberg blockade radius.**

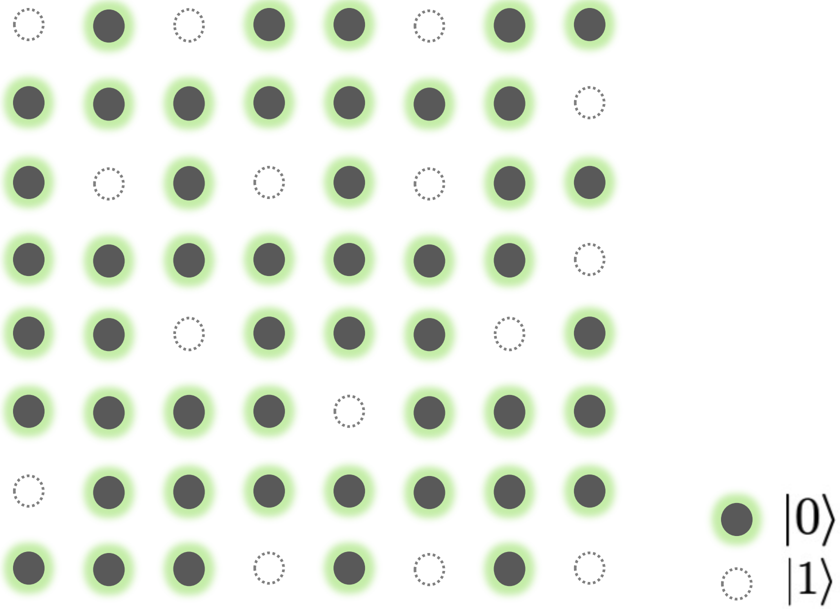
Similarly, an individual atom's transition from the ground to the Rydberg state will be suppressed if it is close to an atom already in the Rydberg state.

This is the mechanism behind the implementation of **multi-qubit gates.**

Measurement



State at the end of a run



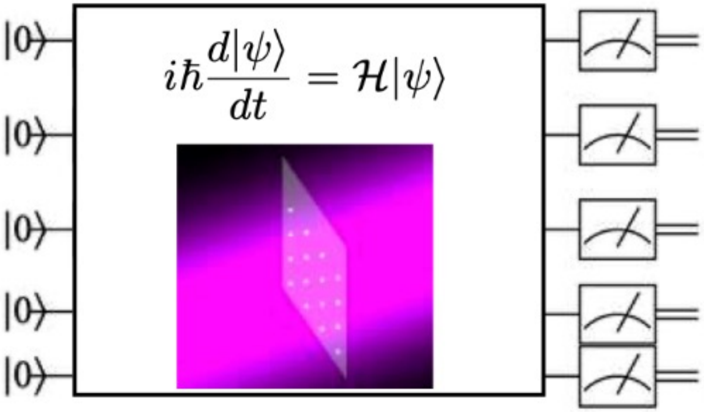
Fluorescence image

Modes of Operation

Overview: Analog vs. Digital

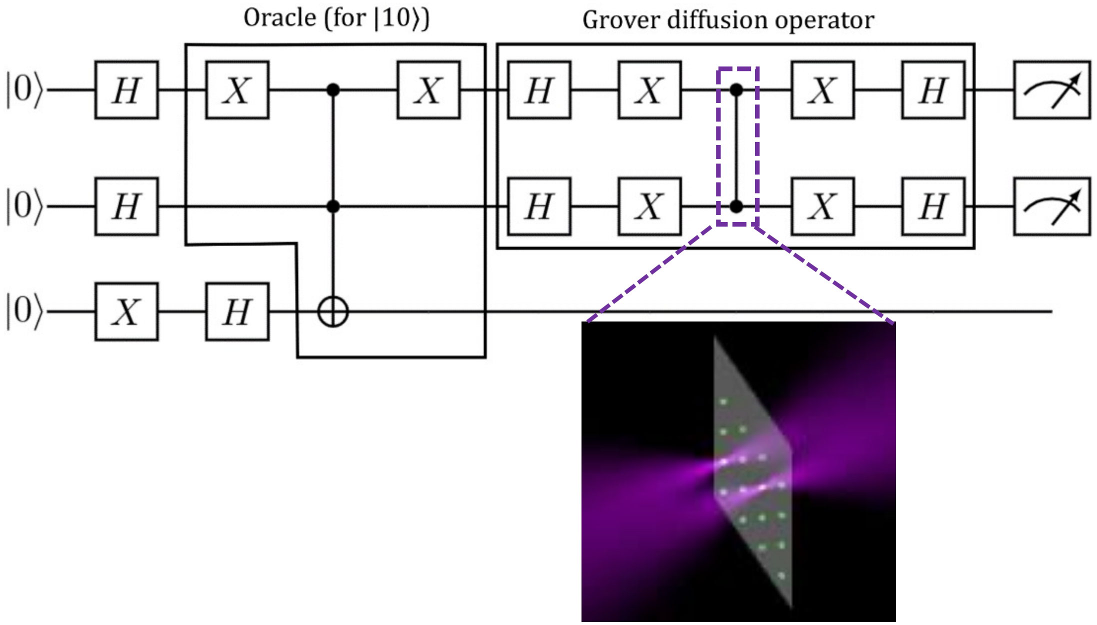
Analog Approach

$$\mathcal{H}(t) = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_i^x - \hbar\delta(t)\hat{n}_i + \sum_{j<i} \frac{C_6}{(R_{ij})^6}\hat{n}_i\hat{n}_j \right)$$



One Hamiltonian with **continuously controlled parameters** dictates the dynamics of the whole system.

Digital Approach



Each gate is done in isolation, by acting locally only on the involved qubits.

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Analog Approach

A tunable Ising Hamiltonian

Transverse field

Ising couplings: $J_{ij} \propto 1/R_{ij}^6$

$$\mathcal{H}(t) = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_i^x - \hbar\delta(t)\hat{n}_i + \sum_{j<i} \frac{C_6}{(R_{ij})^6}\hat{n}_i\hat{n}_j \right)$$

$$\hat{n}_i = \frac{1+\sigma_i^z}{2}$$

Quantum Simulation

Permits the simulation of quantum many-body systems far beyond the limits of classical computers, allowing, for example, the:

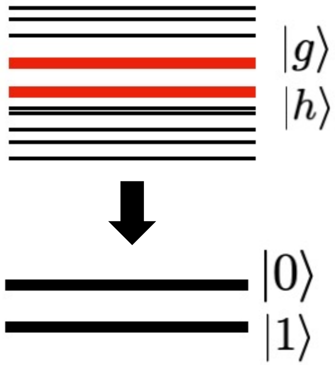
- Observation of out-of-equilibrium dynamics
- Adiabatic preparation of ground states

Solving hard combinatorial optimization problems

Some of these problems don't have a satisfactory classical solution but are mappable to the Ising Hamiltonian. Examples include:

- The Max-k-Cut problem
- The Maximum Independent Set problem

Basis states



Hamiltonian

$$H^D(t) = \frac{\hbar}{2}\mathbf{\Omega}(t) \cdot \boldsymbol{\sigma}$$

$$\mathbf{\Omega}(t) = \begin{pmatrix} \Omega(t)\cos(\phi) \\ -\Omega(t)\sin(\phi) \\ -\delta(t) \end{pmatrix}$$

In the digital approach, the qubits are encoded in two hyperfine ground states of the system.

The atoms don't interact when not in a Rydberg state, so their dynamics are determined solely by the driving Hamiltonian.

Digital Approach: Single-qubit gates

Time-evolution with a pulse of duration τ :

$$H^D(t) = \frac{\hbar}{2}\boldsymbol{\Omega}(t)\cdot\boldsymbol{\sigma} \longrightarrow U(\boldsymbol{\Omega},\tau) = \exp\left[-\frac{i}{2}\int_0^\tau \boldsymbol{\Omega}(t)\cdot\boldsymbol{\sigma}\mathrm{d}t\right]$$

For a resonant pulse ($\delta = 0$) of phase φ :

$$\theta = \int_0^\tau \Omega(t)\mathrm{d}t$$

Rotation angle

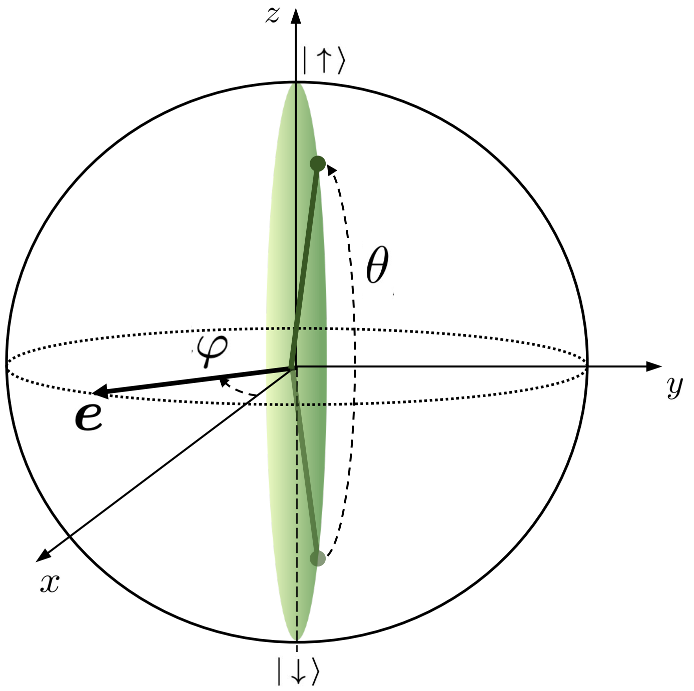
$$\boldsymbol{e}(\varphi) = (\cos\varphi, -\sin\varphi, 0)$$

Rotation axis

Rotation of θ around $\boldsymbol{e}(\varphi)$:

$$R_{\boldsymbol{e}(\varphi)}(\theta) = R_z(-\varphi)R_x(\theta)R_z(\varphi)$$

Any resonant pulse can be described as a sequence of these three rotations.



Digital Approach: Single-qubit gates

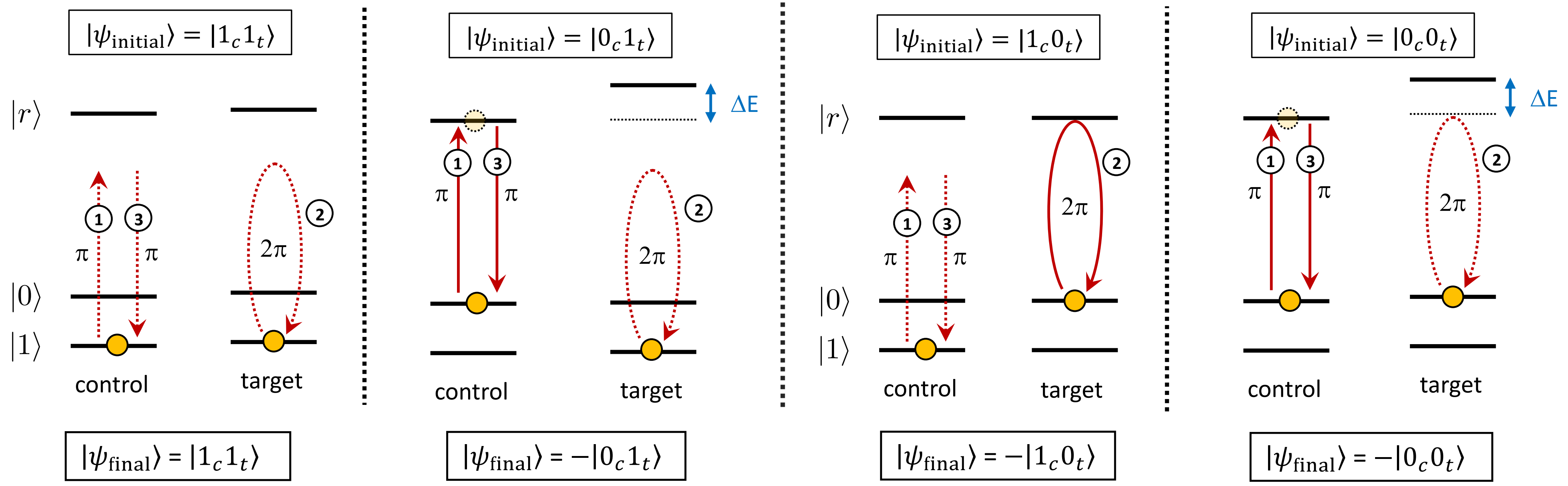
Resonant-laser pulse rotation: $R_{\mathbf{e}(\varphi)}(\theta) = R_z(-\varphi)R_x(\theta)R_z(\varphi)$

With a resonant pulse followed by a *z*-rotation, we can execute any single-qubit gate.

Arbitrary single-qubit gate: $U(\gamma, \theta, \varphi) = R_z(\gamma + \varphi)R_{\mathbf{e}(\varphi)}(\theta) = R_z(\gamma)R_x(\theta)R_z(\varphi)$

Since the *z*-rotations can be achieved "virtually" by changing the phase reference frame, we **only need one resonant pulse** to perform **any single-qubit gate.**

Digital Approach: The Controlled-Z gate



To perform multi-qubit gates, an interaction between the involved qubits is required. Thus, the atoms are brought briefly to the Rydberg state to exploit the **Rydberg state** to exploit the **Rydberg blockade.**

Digital Approach: The Controlled-Z gate

Possible outcomes:

Initial state	$\|00\rangle$	$\|01\rangle$	$\|10\rangle$	$\|11\rangle$
Final state	$-\|00\rangle$	$-\|01\rangle$	$-\|10\rangle$	$\|11\rangle$

Corresponding matrix:

$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} = e^{i\pi} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = e^{i\pi}\mathrm{CZ}$$

∴ The procedure describes the CZ gate (up to a global phase of π).

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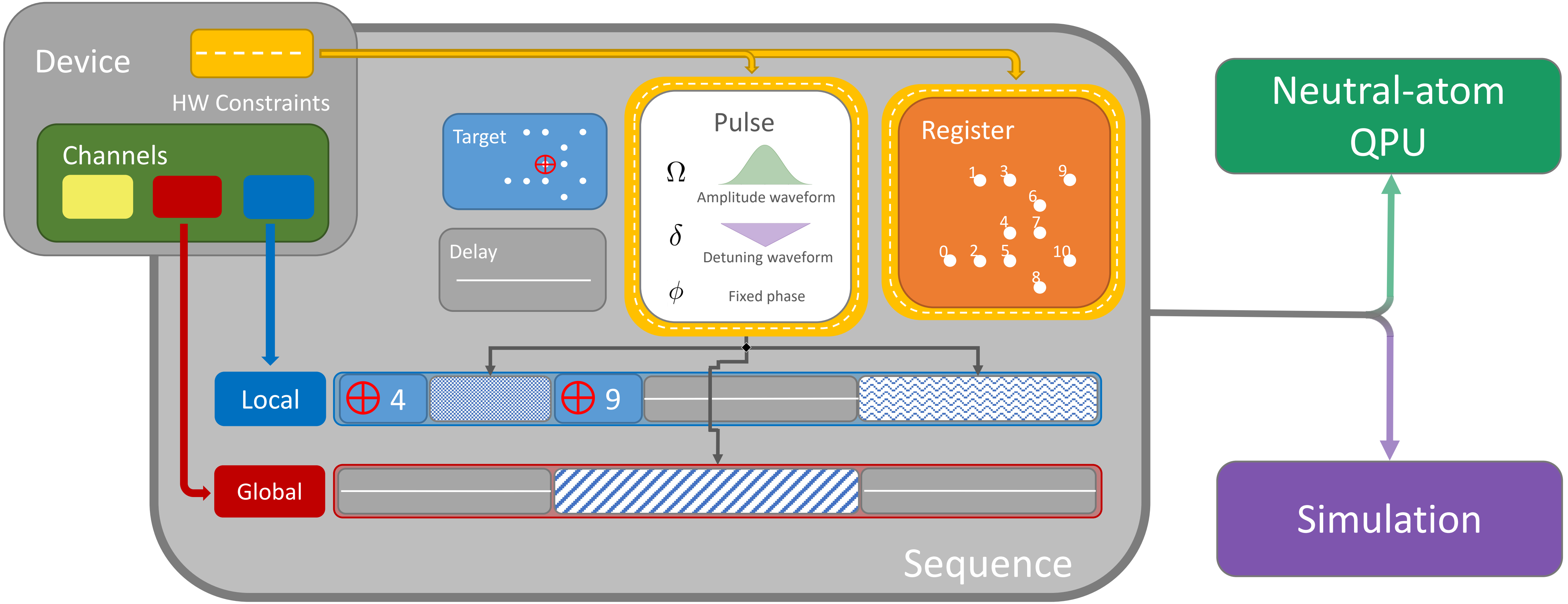
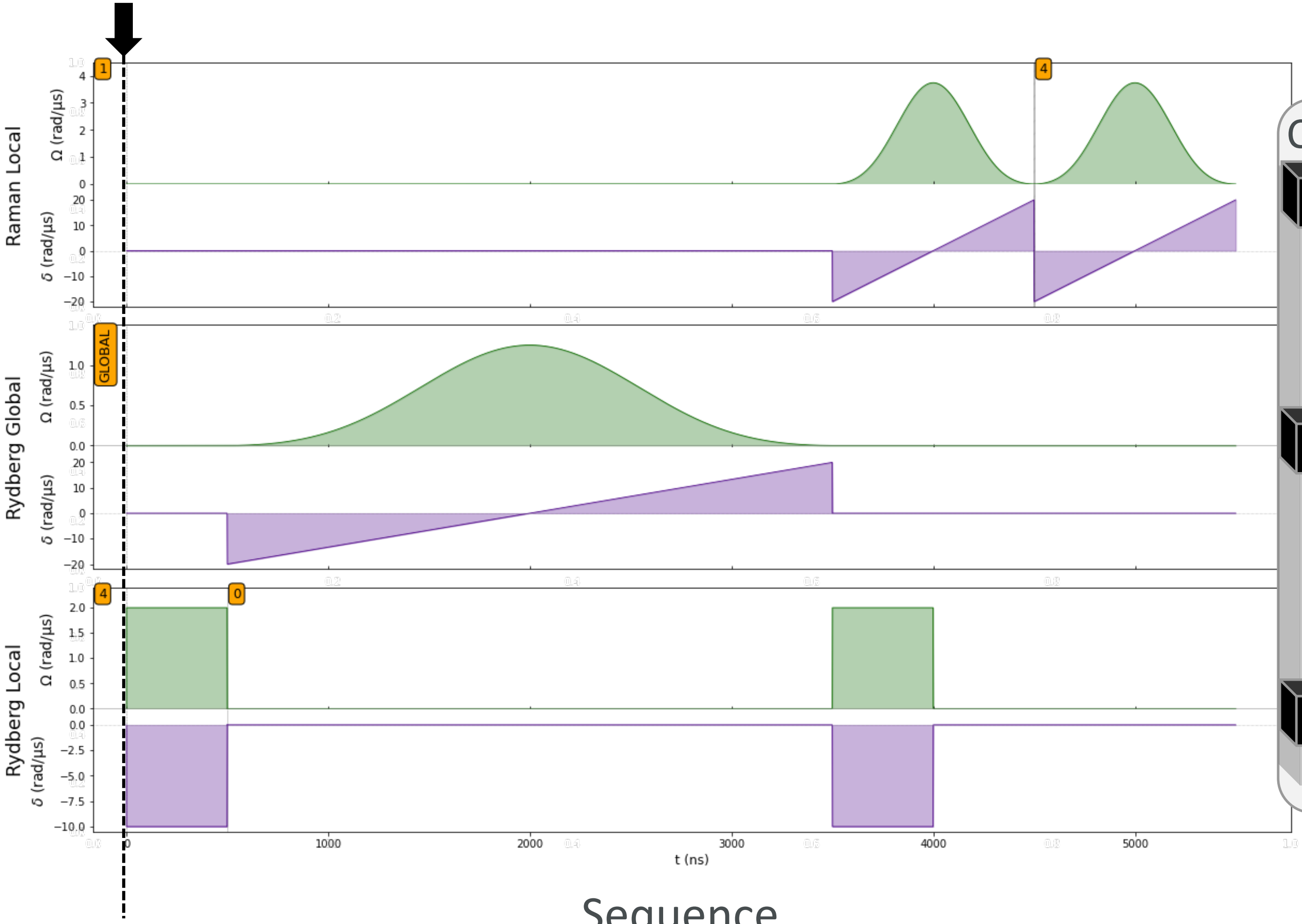
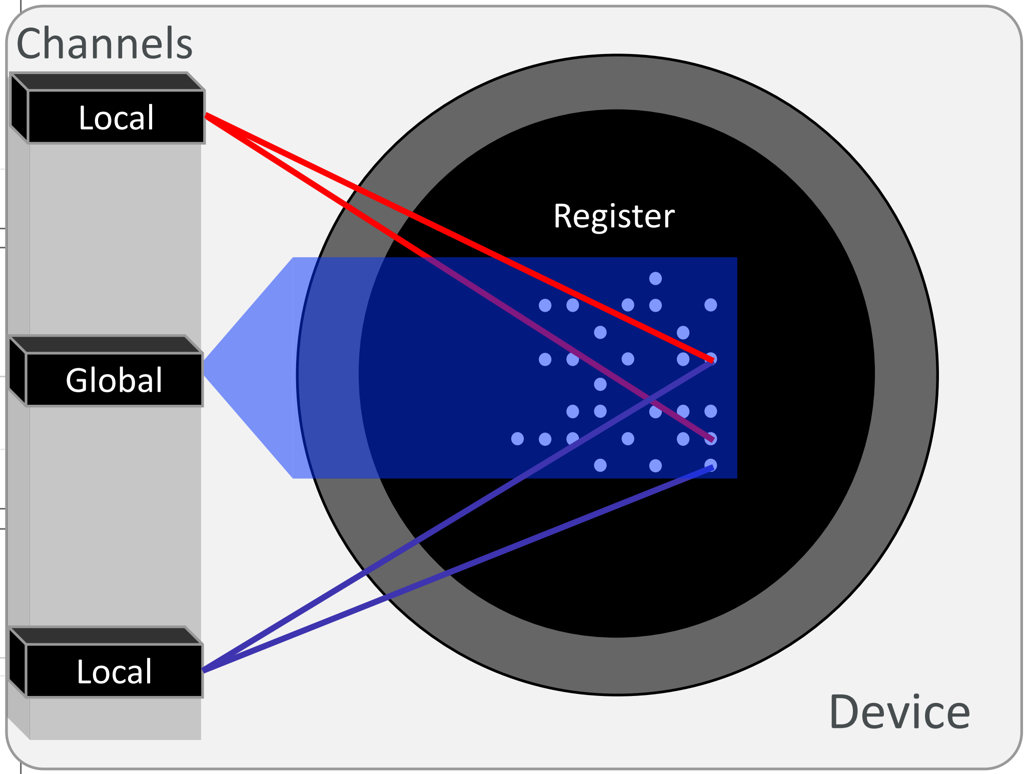
Architecture



Execution of a Pulse Sequence



Sequence



Resources

Installation: `pip install pulser`

Pre-requisites:

- ✓ Python 3.7 or higher
- ✓ Recommended: Jupyter Notebook installed

GitHub Repository: https://github.com/pasqal-io/Pulser

Documentation: https://pulser.readthedocs.io/

Tutorials for today: https://github.com/pasqal-io/CINECAxIFAB-PQCS