

IQuEra>

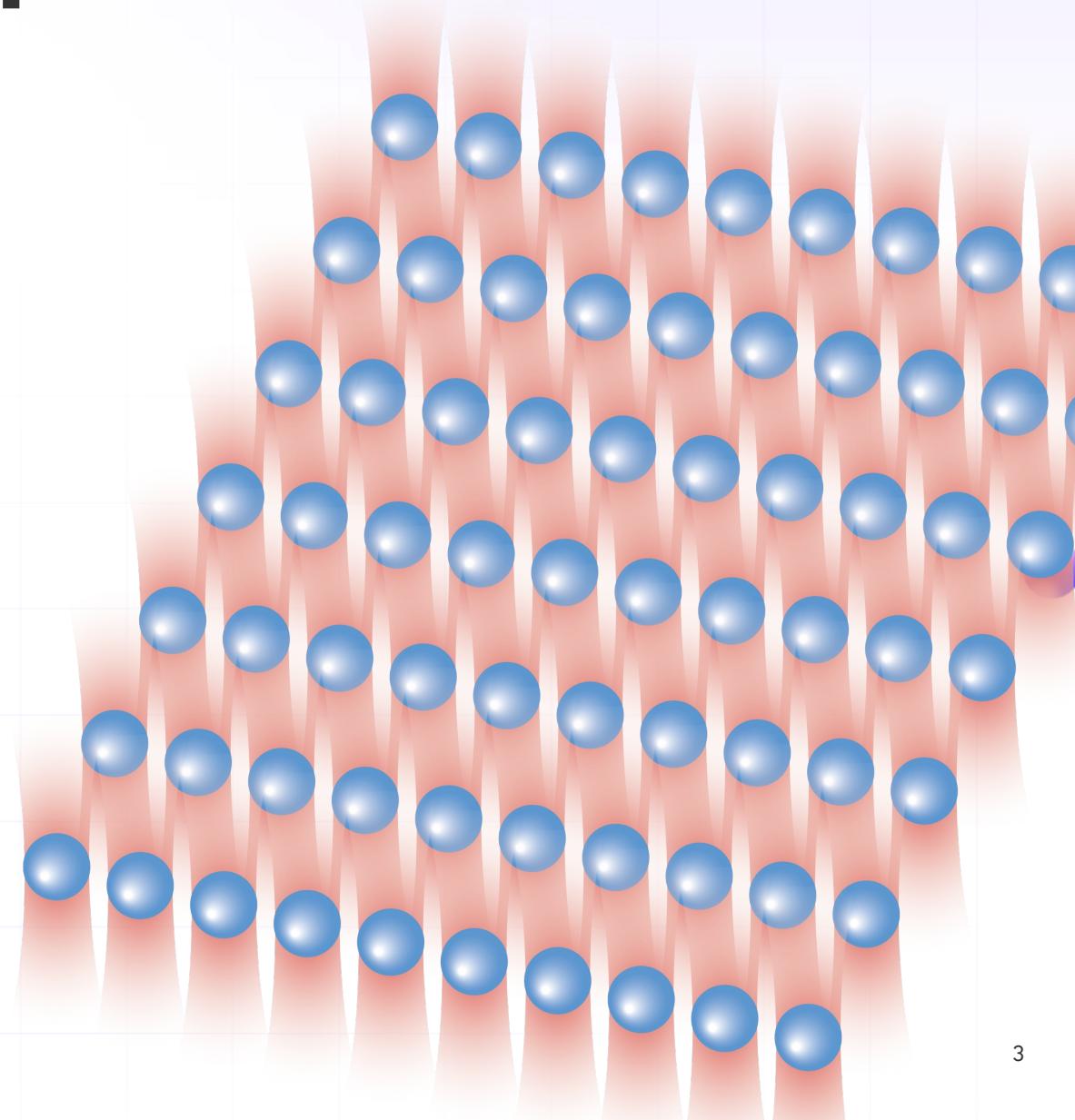
Session I: Basics

House rules (if you want to get the most of this activity)

- Videos on
- Mics muted (unless want to speak)
- Interrupt facilitator as much as possible! (raise hands or unmute and speak at will)

Neutral-atom quantum processor

- Densely packed qubits (atoms)
- Efficient qubit control
- Flexible problem encoding
- New ways to think quantum computing!

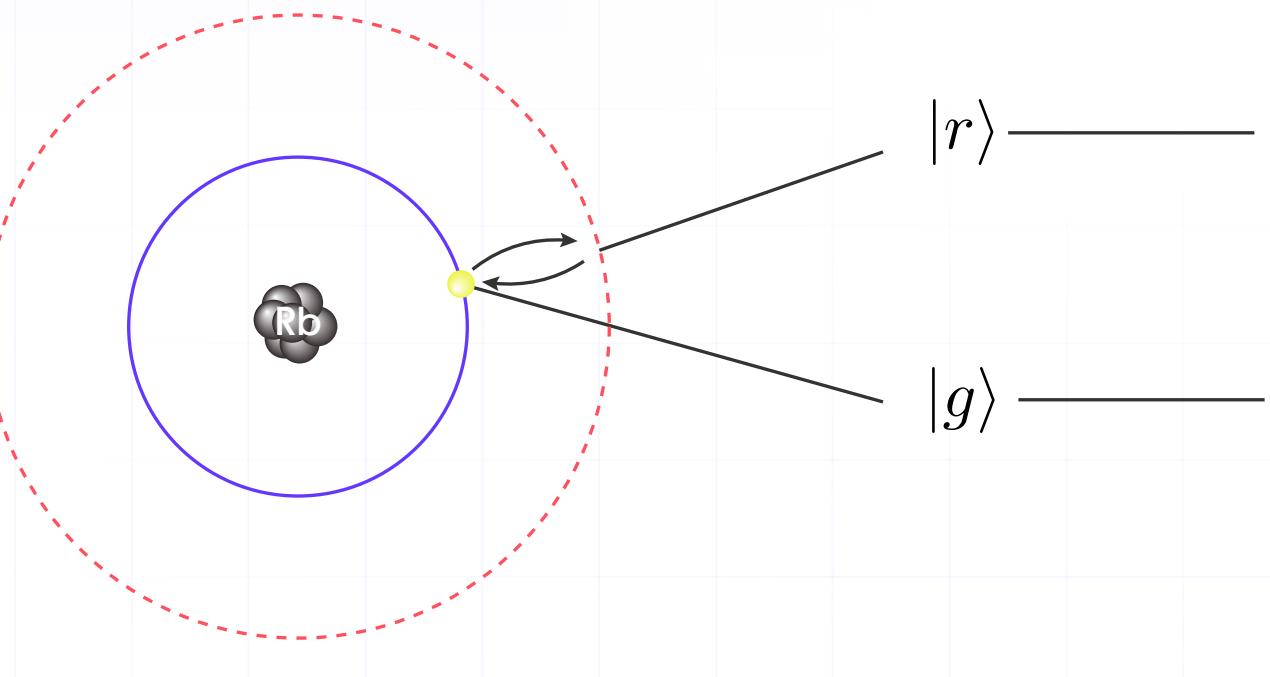


Learning objectives

By the end of the session, you will be able to:

- **Explain** how **neutral atoms** can be used as a **platform** for quantum computing
- **Distinguish** **analog** and **digital** (gate-based) quantum computing
- **Define** **field-programmable qubit arrays** and **exemplify** some of their **advantages**
- **Describe** Aquila's **programming** range
 - its Hamiltonian and controllable parameters, limitations of service

Qubits by puffing atoms



Periodic Table of the Elements

Periodic Table of the Elements

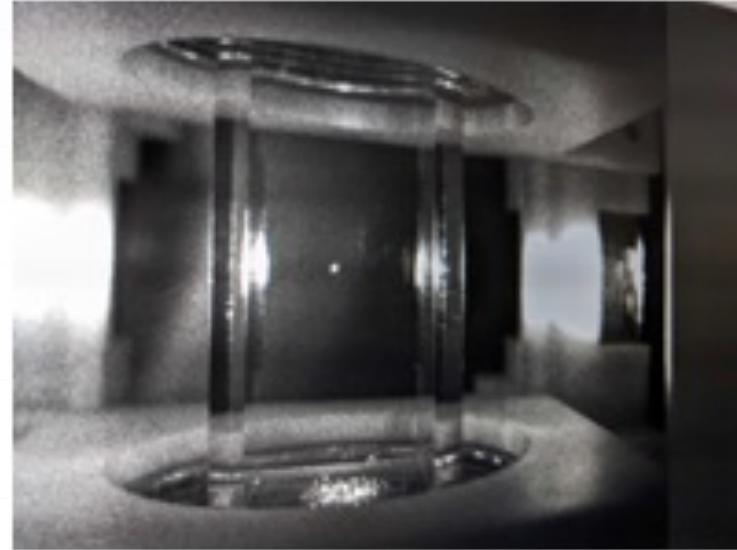
The table includes the following information for each element:

- Atomic Number**: The element's position in the periodic table.
- Symbol**: The standard two-letter symbol for the element.
- Name**: The element's name.
- Atomic Weight**: The element's mass number.
- Electrons per shell**: The number of electrons in each shell, represented by a sequence of numbers (e.g., 2, 8, 8, 2 for Helium).
- State of matter [color of name]**: The element's state of matter at room temperature and its color.
- Subcategory in the metal-metalloid-nonmetal trend (color of background)**: Categories include Alkali metals (red), Alkaline earth metals (blue), Lanthanides (light blue), Actinides (pink), Transition metals (yellow), Post-transition metals (orange), Metalloids (green), Nonmetals (purple), and Noble gases (pink).
- Unknown chemical properties**: Indicated by a grey question mark icon.

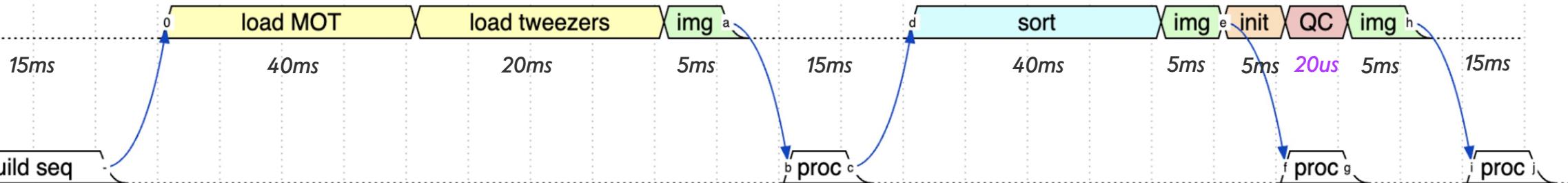
Group	Element	Symbol	Atomic Number	Atomic Weight	Electrons per shell	State of matter [color of name]	Subcategory in the metal-metalloid-nonmetal trend (color of background)
1	Hydrogen	H	1	1.008	1	GAS	Alkali metals
2	Helium	He	2	4.003	2	LIQUID	Alkaline earth metals
3	Lithium	Li	3	6.941	2, 1	SOLID	Lanthanides
4	Beryllium	Be	4	9.012	2, 2	SOLID	Actinides
5	Boron	B	5	10.81	2, 3	SOLID	Transition metals
6	Carbon	C	6	12.011	2, 4	SOLID	Post-transition metals
7	Nitrogen	N	7	14.007	2, 5	SOLID	Metalloids
8	Oxygen	O	8	15.999	2, 6	SOLID	Nonmetals
9	Fluorine	F	9	18.998	2, 7	SOLID	Noble gases
10	Neon	Ne	10	20.180	2, 8	SOLID	
11	Sodium	Na	11	22.989	2, 8, 1	SOLID	
12	Magnesium	Mg	12	24.321	2, 8, 2	SOLID	
13	Aluminum	Al	13	26.982	2, 8, 3	SOLID	
14	Silicon	Si	14	28.085	2, 8, 4	SOLID	
15	Phosphorus	P	15	30.973	2, 8, 5	SOLID	
16	Sulfur	S	16	32.065	2, 8, 6	SOLID	
17	Chlorine	Cl	17	35.45	2, 8, 7	SOLID	
18	Argon	Ar	18	39.948	2, 8, 8	SOLID	
19	Potassium	K	19	39.098	2, 8, 8, 1	SOLID	
20	Calcium	Ca	20	40.08	2, 8, 8, 2	SOLID	
21	Scandium	Sc	21	44.956	2, 8, 8, 2	SOLID	
22	Titanium	Ti	22	47.88	2, 8, 8, 2	SOLID	
23	Vanadium	V	23	50.944	2, 8, 8, 2	SOLID	
24	Chromium	Cr	24	51.996	2, 8, 8, 2	SOLID	
25	Manganese	Mn	25	54.938	2, 8, 8, 2	SOLID	
26	Iron	Fe	26	55.845	2, 8, 8, 2	SOLID	
27	Cobalt	Co	27	58.93	2, 8, 8, 2	SOLID	
28	Nickel	Ni	28	58.69	2, 8, 8, 2	SOLID	
29	Copper	Cu	29	63.55	2, 8, 8, 2	SOLID	
30	Zinc	Zn	30	65.40	2, 8, 8, 2	SOLID	
31	Gallium	Ga	31	69.723	2, 8, 8, 2	SOLID	
32	Silicon	Ge	32	72.61	2, 8, 8, 2	SOLID	
33	As	As	33	74.92	2, 8, 8, 3	SOLID	
34	Se	Se	34	78.91	2, 8, 8, 4	SOLID	
35	Br	Br	35	79.904	2, 8, 8, 4	SOLID	
36	Kr	Kr	36	83.81	2, 8, 8, 8	SOLID	
37	Rubidium	Rb	37	85.467	2, 8, 8, 2, 1	SOLID	
38	Sr	Sr	38	87.62	2, 8, 8, 2, 2	SOLID	
39	Yttrium	Y	39	88.905	2, 8, 8, 2, 2	SOLID	
40	Zirconium	Zr	40	91.224	2, 8, 8, 2, 2	SOLID	
41	Nickel	Nb	41	92.906	2, 8, 8, 2, 2	SOLID	
42	Molybdenum	Mo	42	95.94	2, 8, 8, 2, 2	SOLID	
43	Techneium	Tc	43	96.903	2, 8, 8, 2, 2	SOLID	
44	Ruthenium	Ru	44	101.07	2, 8, 8, 2, 2	SOLID	
45	Rhenium	Rh	45	102.905	2, 8, 8, 2, 2	SOLID	
46	Palladium	Pd	46	106.44	2, 8, 8, 2, 2	SOLID	
47	Technetium	Tc	47	107.87	2, 8, 8, 2, 2	SOLID	
48	Cadmium	Cd	48	114.82	2, 8, 8, 2, 2	SOLID	
49	Indium	In	49	115.71	2, 8, 8, 2, 2	SOLID	
50	Gallium	Ga	50	117.60	2, 8, 8, 2, 2	SOLID	
51	Selenium	Se	51	121.76	2, 8, 8, 2, 2	SOLID	
52	Te	Te	52	127.60	2, 8, 8, 2, 2	SOLID	
53	Iodine	I	53	131.29	2, 8, 8, 2, 2	SOLID	
54	Xe	Xe	54	131.29	2, 8, 8, 2, 2	SOLID	
55	Cesium	Cs	55	132.91	2, 8, 8, 2, 2, 1	SOLID	
56	Ba	Ba	56	137.33	2, 8, 8, 2, 2, 2	SOLID	
57	Lanthanum	La	57	138.91	2, 8, 8, 2, 2, 2	SOLID	
58	Cerium	Ce	58	140.11	2, 8, 8, 2, 2, 2	SOLID	
59	Praseodymium	Pr	59	140.914	2, 8, 8, 2, 2, 2	SOLID	
60	Neodymium	Nd	60	144.24	2, 8, 8, 2, 2, 2	SOLID	
61	Promethium	Pm	61	147.94	2, 8, 8, 2, 2, 2	SOLID	
62	Samarium	Sm	62	150.919	2, 8, 8, 2, 2, 2	SOLID	
63	Europeum	Eu	63	151.96	2, 8, 8, 2, 2, 2	SOLID	
64	Gadolinium	Gd	64	157.91	2, 8, 8, 2, 2, 2	SOLID	
65	Dysprosium	Dy	65	162.50	2, 8, 8, 2, 2, 2	SOLID	
66	Terbium	Tb	66	164.93	2, 8, 8, 2, 2, 2	SOLID	
67	Holmium	Ho	67	167.26	2, 8, 8, 2, 2, 2	SOLID	
68	Erbium	Er	68	169.93	2, 8, 8, 2, 2, 2	SOLID	
69	Dysprosium	Dy	69	170.94	2, 8, 8, 2, 2, 2	SOLID	
70	Thulium	Tm	70	173.04	2, 8, 8, 2, 2, 2	SOLID	
71	Lutetium	Lu	71	174.97	2, 8, 8, 2, 2, 2	SOLID	
72	Actinium	Ac	72	172.21	2, 8, 8, 2, 2, 2	SOLID	
73	Thorium	Th	73	178.4	2, 8, 8, 2, 2, 2	SOLID	
74	Protactinium	Pa	74	199.93	2, 8, 8, 2, 2, 2	SOLID	
75	Uranium	U	75	238.03	2, 8, 8, 2, 2, 2	SOLID	
76	Nepalium	Np	76	237.0	2, 8, 8, 2, 2, 2	SOLID	
77	Plutonium	Pu	77	239.0	2, 8, 8, 2, 2, 2	SOLID	
78	Americium	Am	78	243.0	2, 8, 8, 2, 2, 2	SOLID	
79	Curium	Cm	79	247.0	2, 8, 8, 2, 2, 2	SOLID	
80	Berkelium	Bk	80	250.0	2, 8, 8, 2, 2, 2	SOLID	
81	Cf	Cf	81	251.0	2, 8, 8, 2, 2, 2	SOLID	
82	Es	Es	82	257.0	2, 8, 8, 2, 2, 2	SOLID	
83	Fm	Fm	83	258.0	2, 8, 8, 2, 2, 2	SOLID	
84	Md	Md	84	259.0	2, 8, 8, 2, 2, 2	SOLID	
85	No	No	85	259.0	2, 8, 8, 2, 2, 2	SOLID	
86	Radon	Rn	86	259.0	2, 8, 8, 2, 2, 2	SOLID	
87	Atmospheric	At	87	259.0	2, 8, 8, 2, 2, 2	SOLID	
88	Lanthanide	Lu	88	259.0	2, 8, 8, 2, 2, 2	SOLID	

QPU cycle

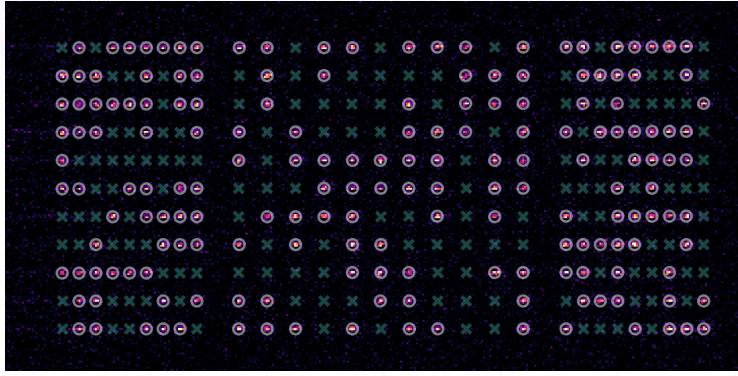
*~100k atoms
in a Rb-87 MOT*



QPU

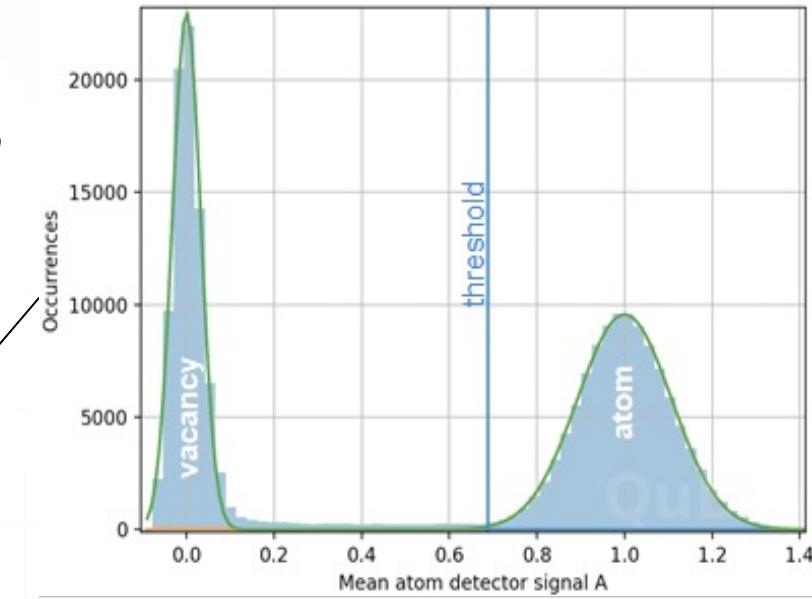


QPU cycle

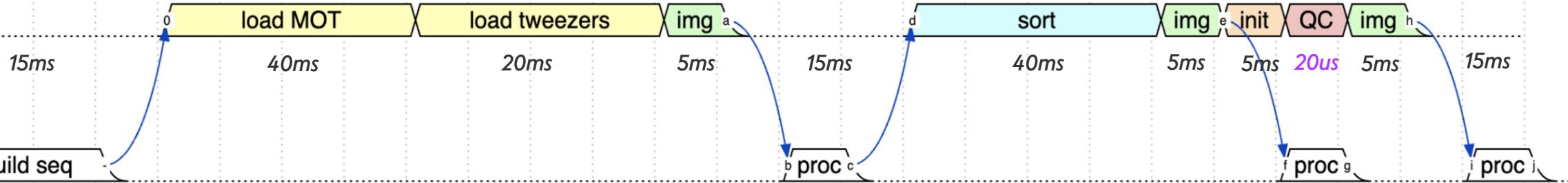


*Loading
occupation
~60%*

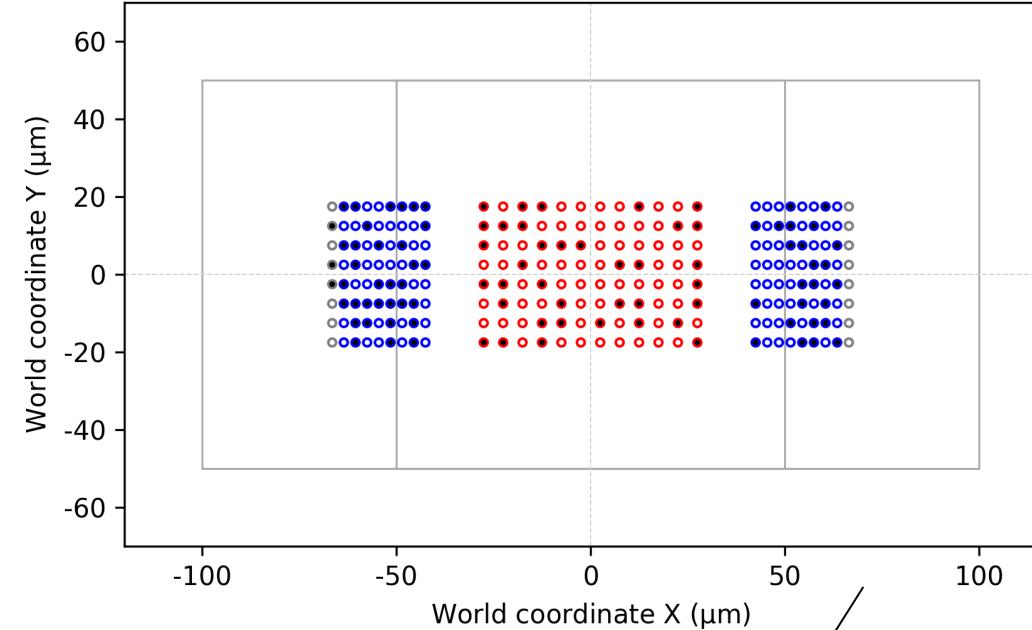
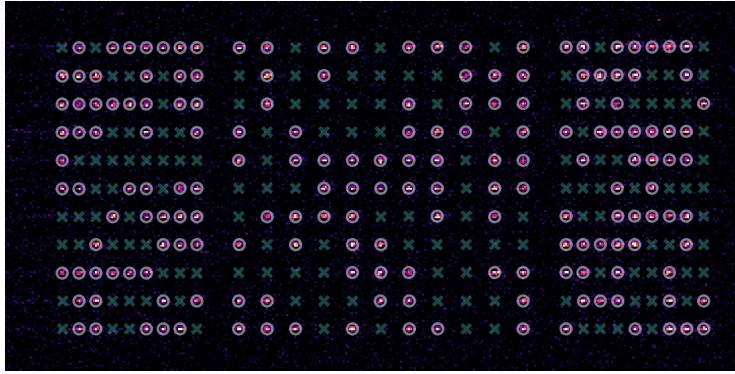
*Atom
detection
99.9%*



QPU

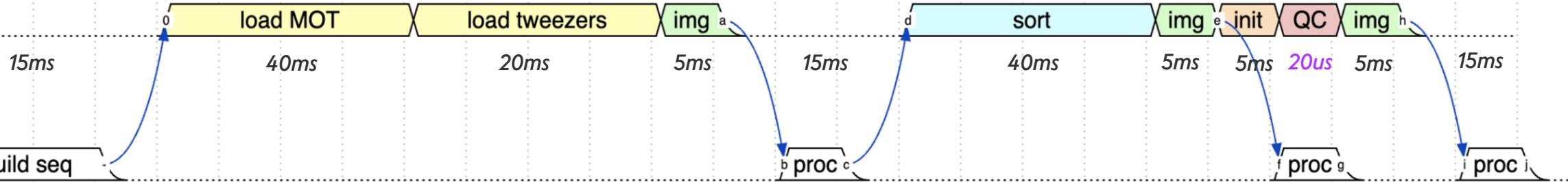


QPU cycle



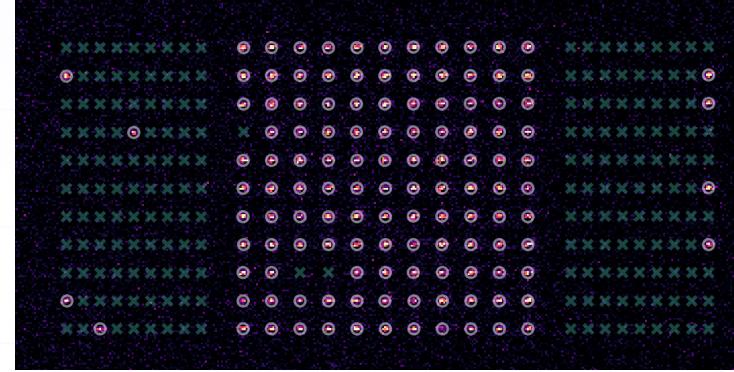
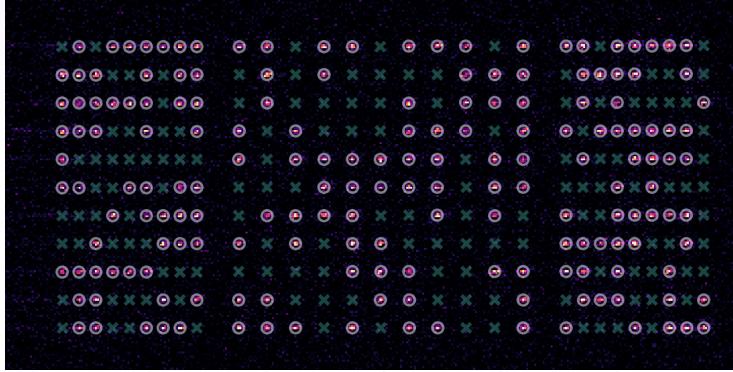
Rearrangement fidelity
99.5% / atom

QPU



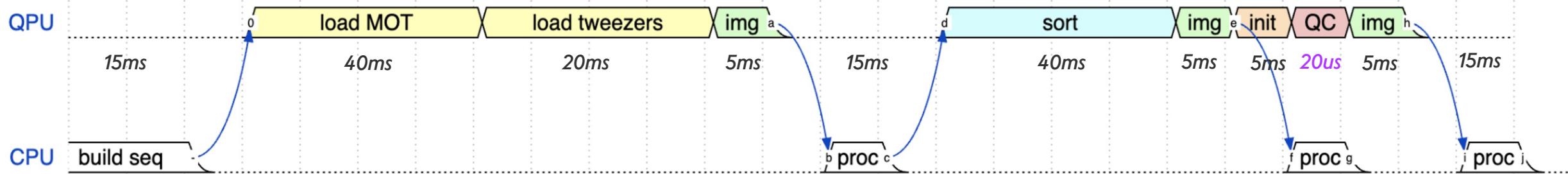
IQUERA >

QPU cycle

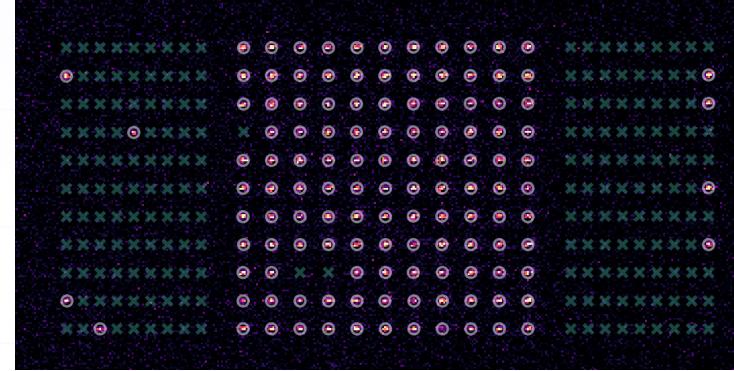
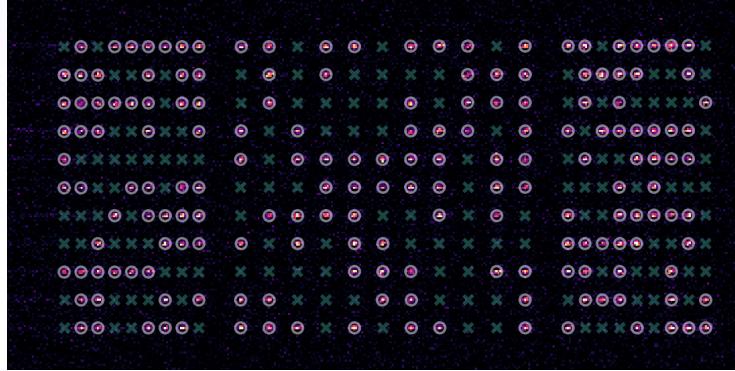


Rearrangement fidelity
99.5% / atom

Atom detection
99.9%

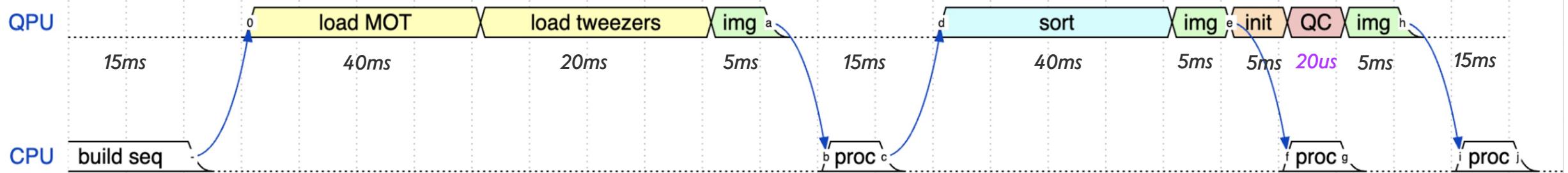


QPU cycle

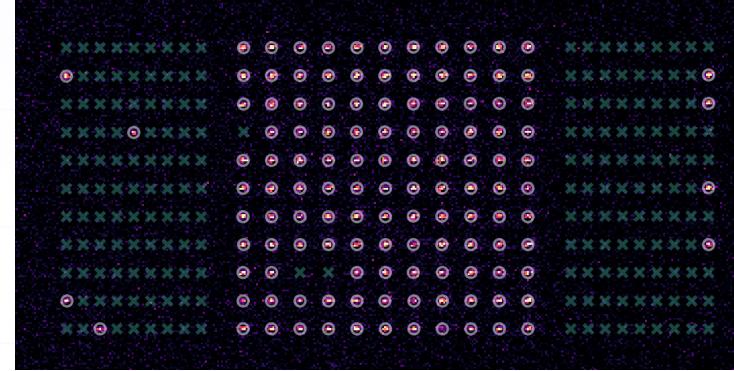
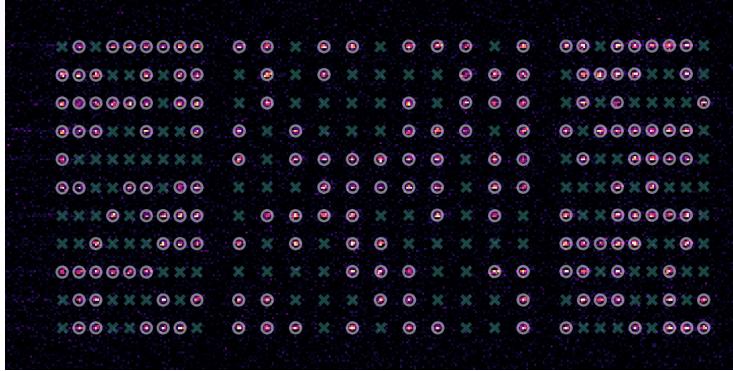


Cooling to
 $<10\text{uk}$

Optical pumping
 $> 99\%$

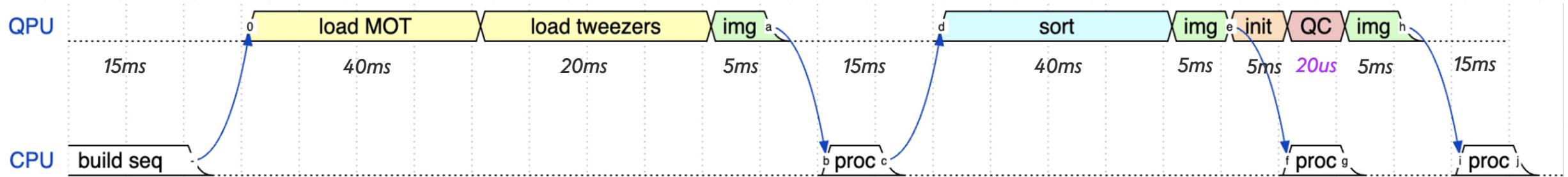


QPU cycle

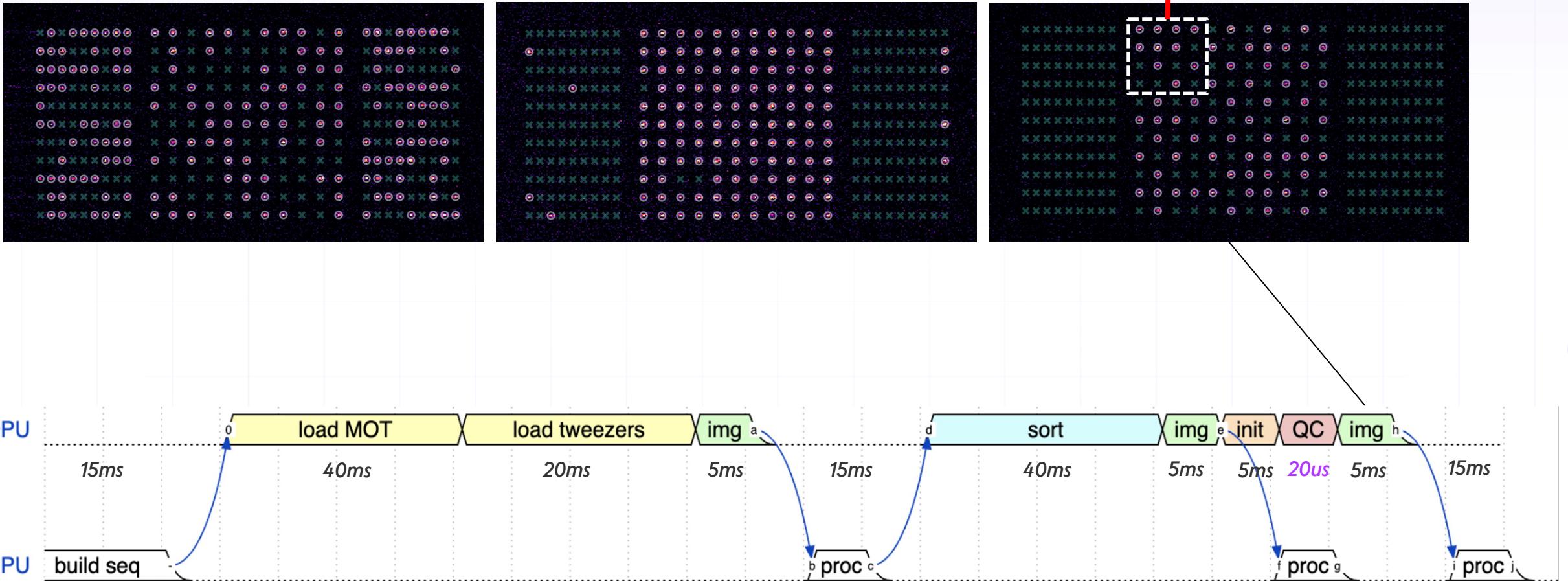


Coherent evolution

$$i \frac{\partial}{\partial t} |\psi\rangle = H |\psi\rangle$$



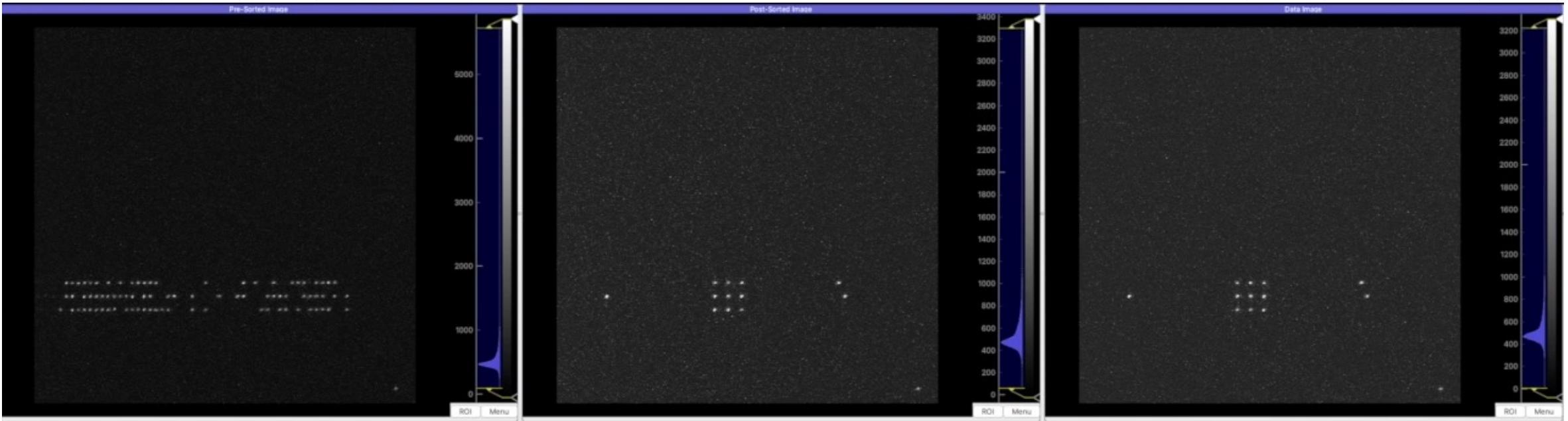
QPU cycle



Sneak peak into the running engine

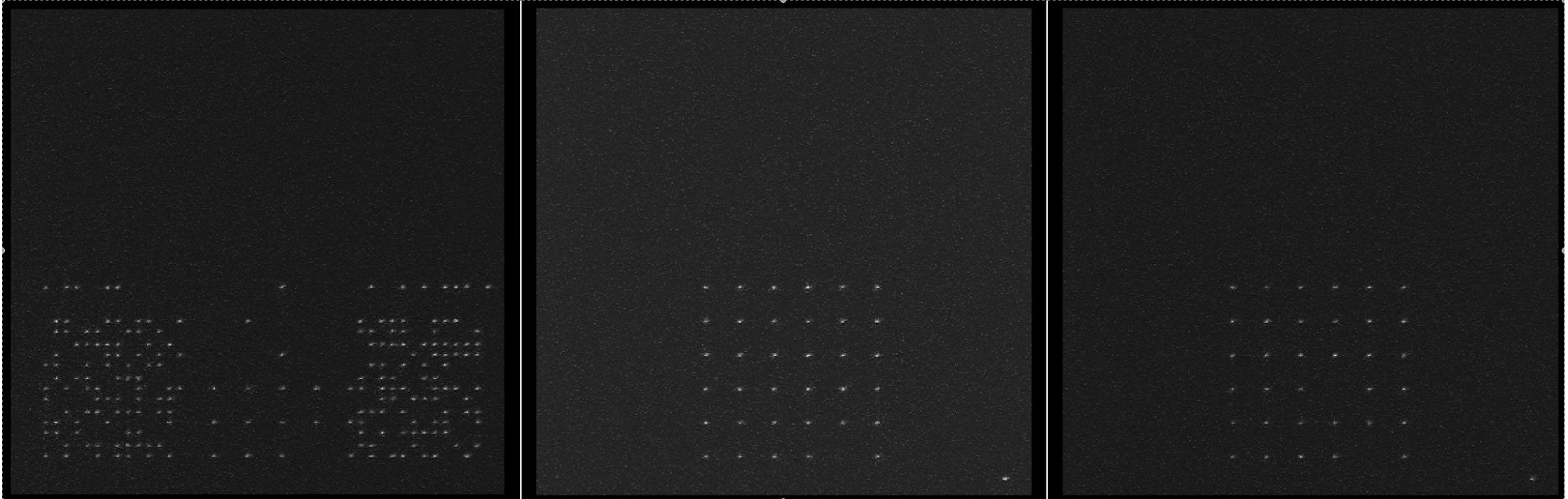
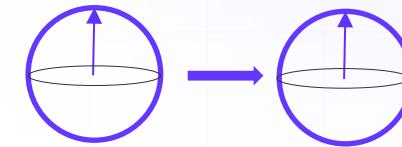


Sneak peak into the running engine



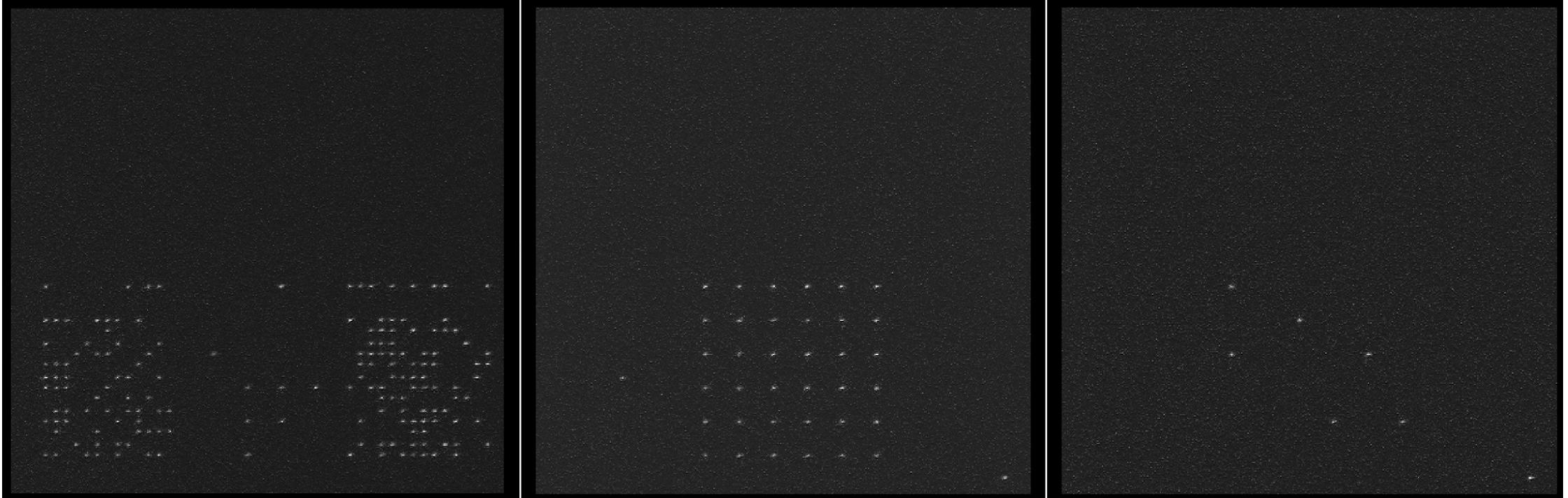
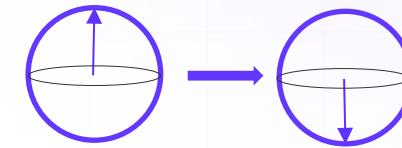
What qubit control really looks like:

2π pulse



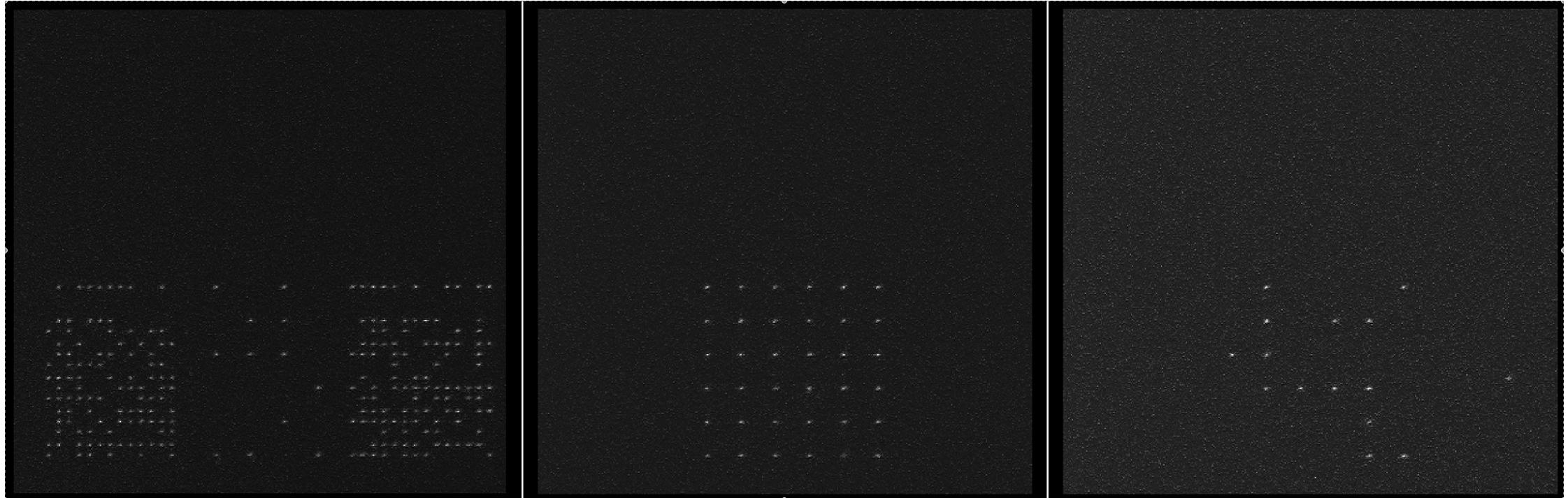
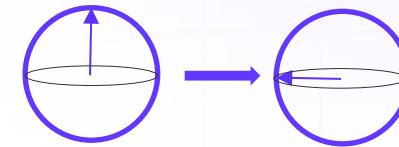
What qubit control really looks like:

π pulse

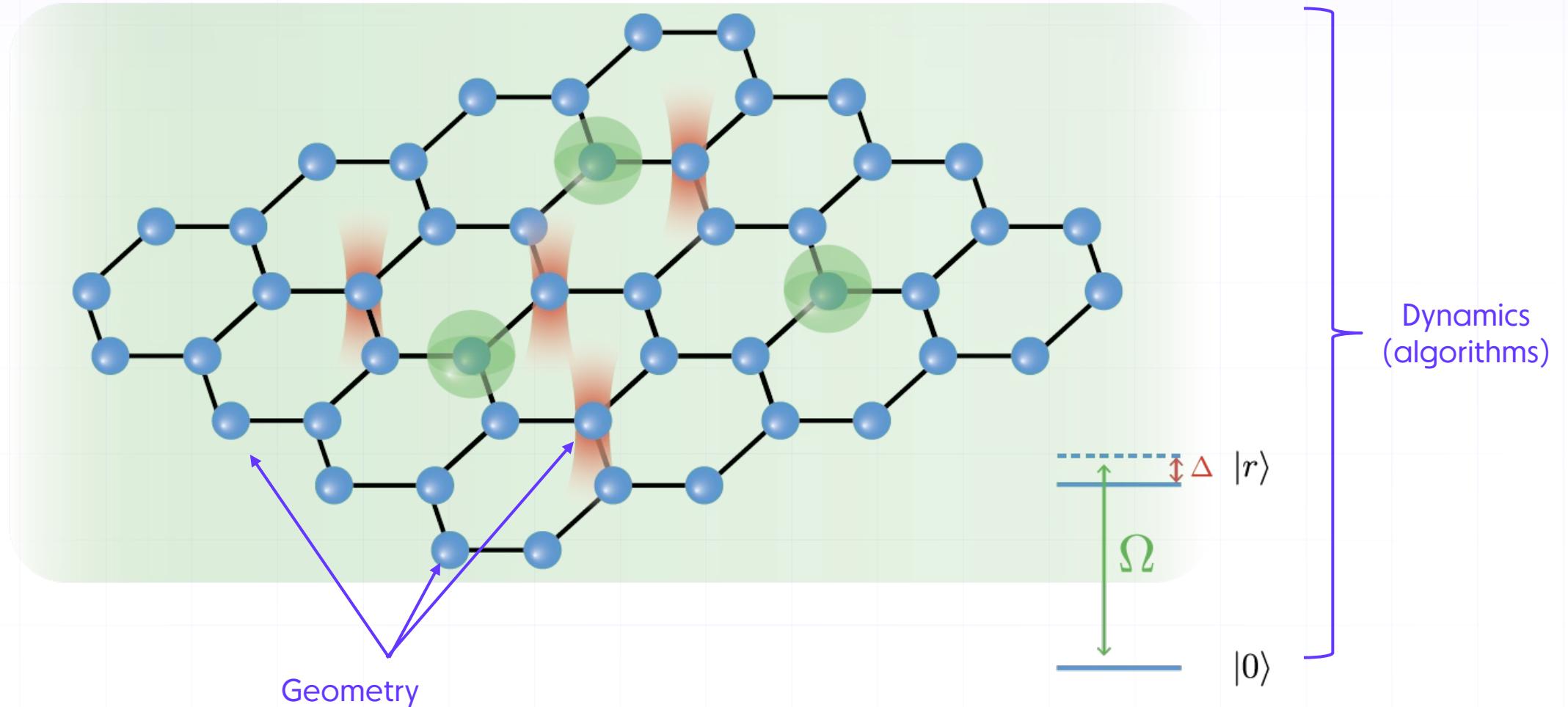


What qubit control really looks like:

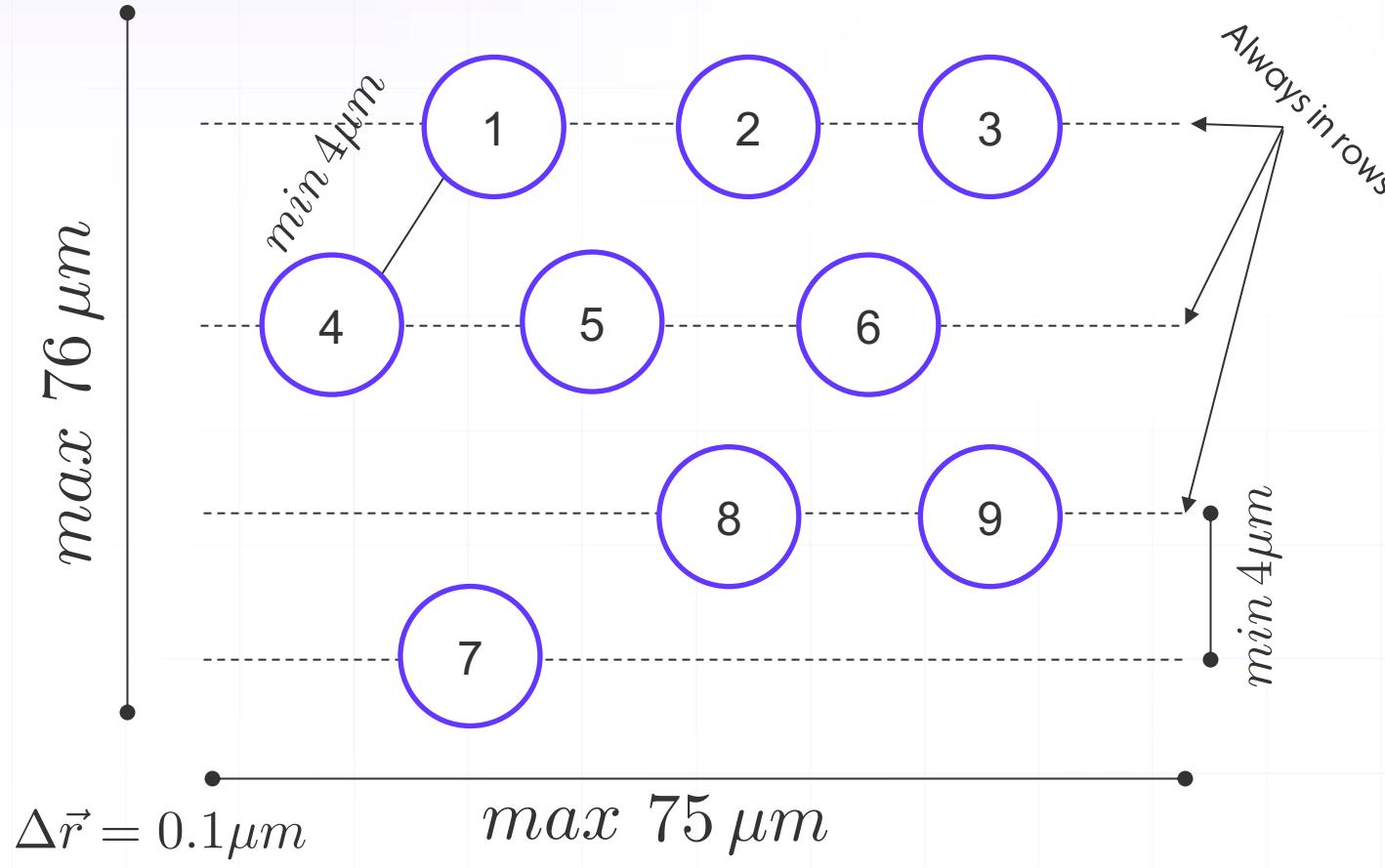
$\pi/2$ pulse



A neutral-atom quantum processor



Hardware constraints: Geometry



Activity 1:

Think-pair-share. What do you think is the origin of each of these constraints?

Activity 2:

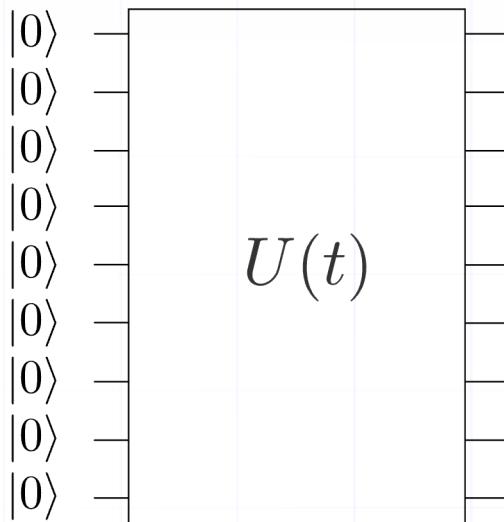
defining qubit positions on Bloqade

More details @

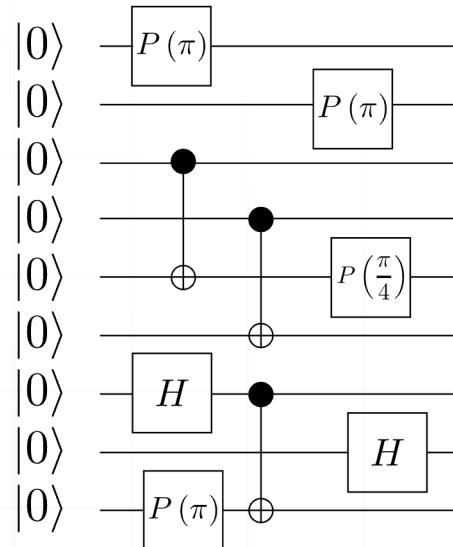
<https://queracomputing.github.io/Bloqade.jl/dev/capabilities/>

Information processing: Analog computing

Analog operation



Digital operation



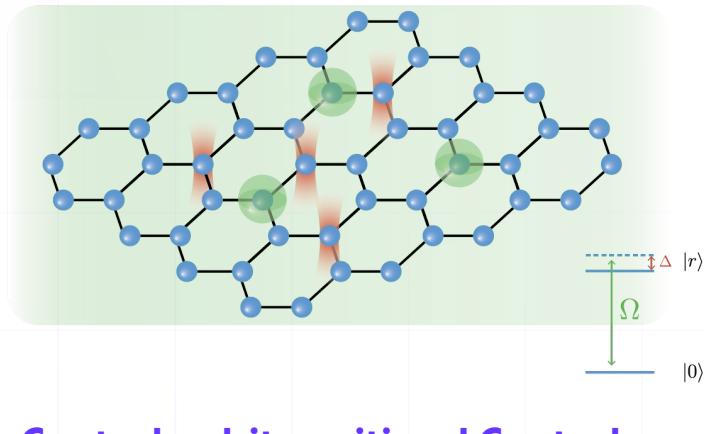
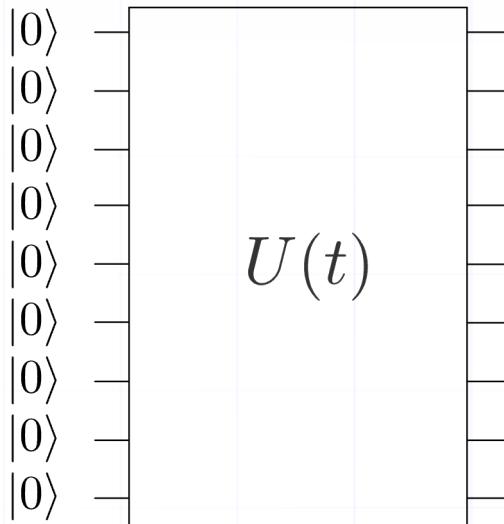
Designed for the early stage of maturity of the quantum computing resources of today...

- ✓ Robustness to errors
- ✓ Efficient control
- ✓ Single-step large entanglement
- ✗ Universal applicability

More on analog processors:
[Nature volume 607](#), p. 667–676 (2022)

Field Programmable Qubit Arrays (FPQAs)

Analog operation



**Control qubit positions! Control
qubit connectivity!**

⇒ Many possibilities!

Designed for the early stage of maturity of the quantum computing resources of today...

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- ✓ Single-step large entanglement
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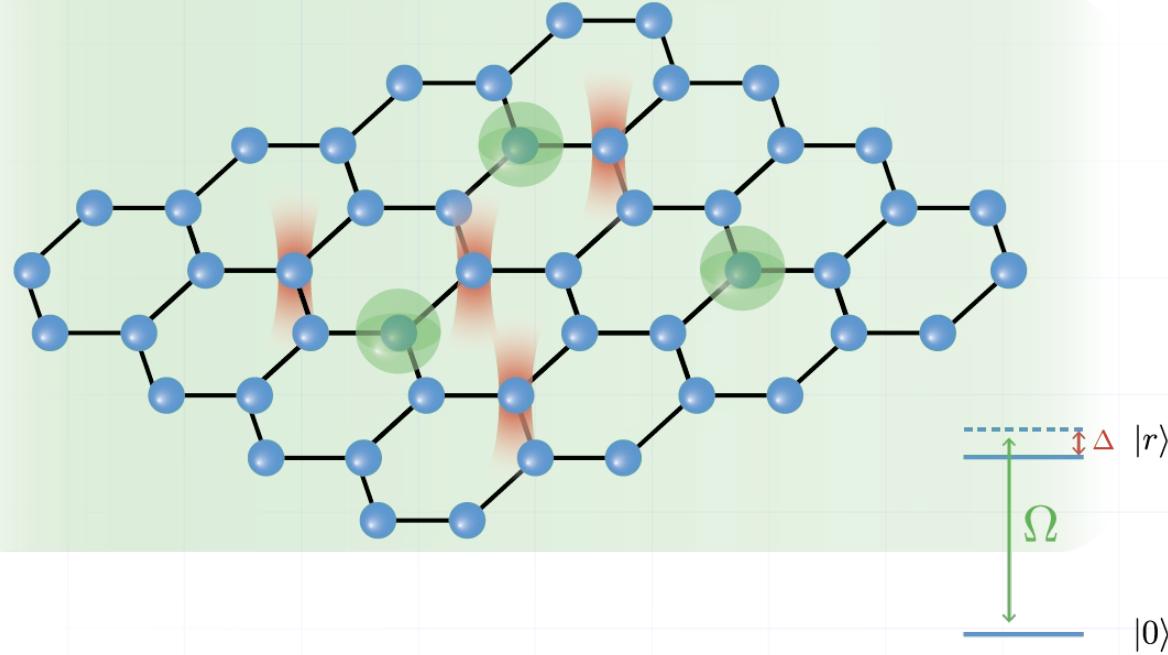
More on analog processors:
[Nature volume 607](#), p. 667–676 (2022)

Algorithm = time evolution

$$i \frac{\partial}{\partial t} |\psi\rangle = \boxed{H} |\psi\rangle$$

Analog quantum dynamics control

$$H = \sum_i \frac{\Omega(t)}{2} (e^{i\phi(t)} |g_i\rangle\langle r_i| + e^{-i\phi(t)} |r_i\rangle\langle g_i|) - \sum_i \Delta(t) n_i + \sum_{i < j} V_{ij} n_i n_j$$

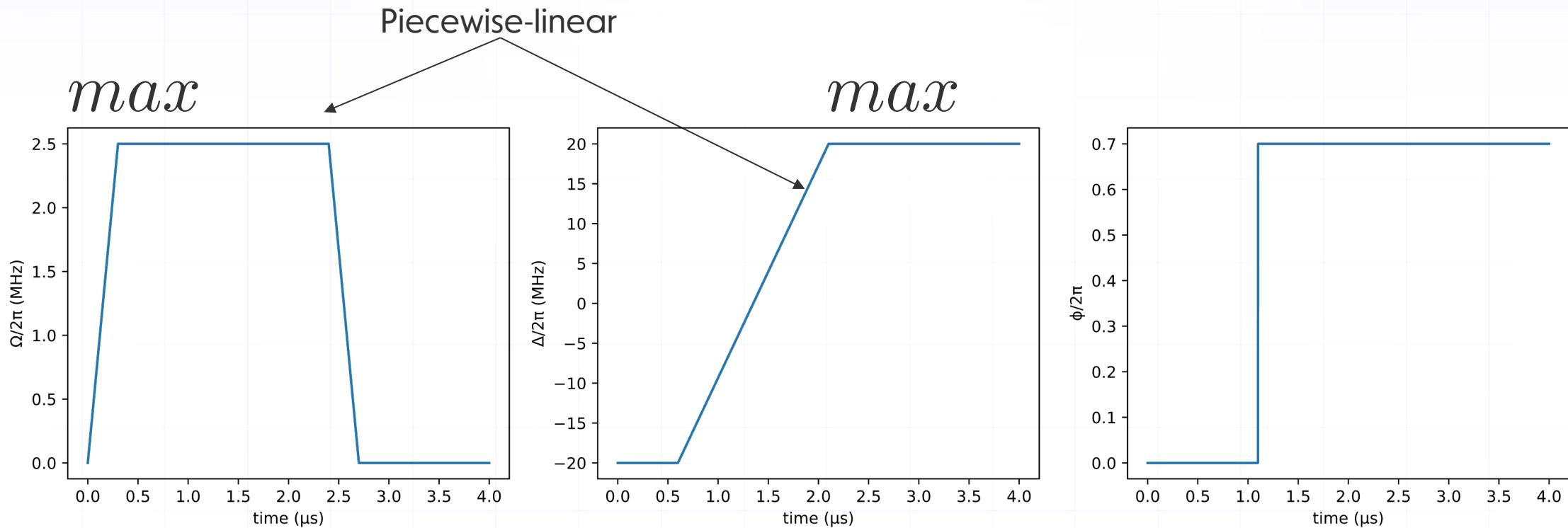


$$n_i = 1 * |r_i\rangle\langle r_i| + 0 * |g_i\rangle\langle g_i|$$

$$V_{ij} \sim d_{ij}^{-6}$$

Hardware constraints: dynamics

Activity: Encoding waveforms on Bloqade

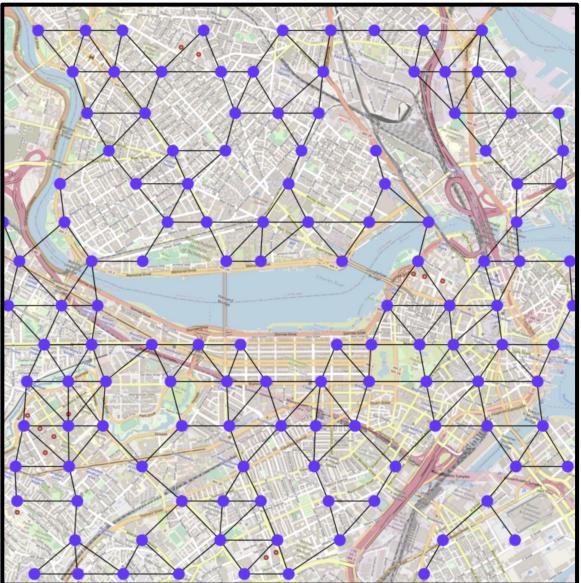


$$t_{max} = 4 \mu s$$

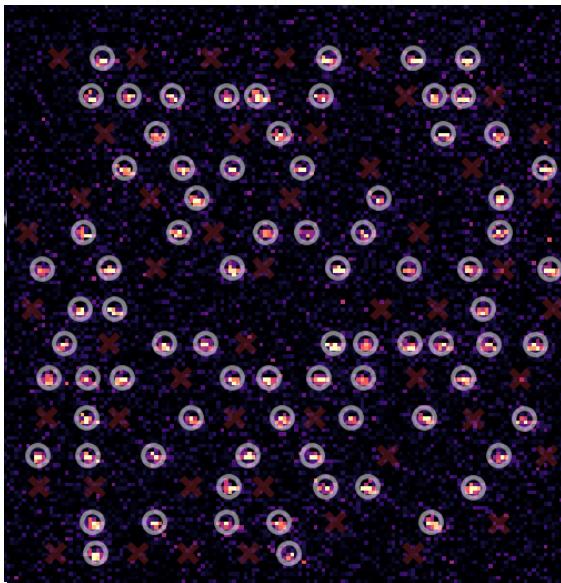
Piecewise-constant

FPQA = Efficient Problem Encoding

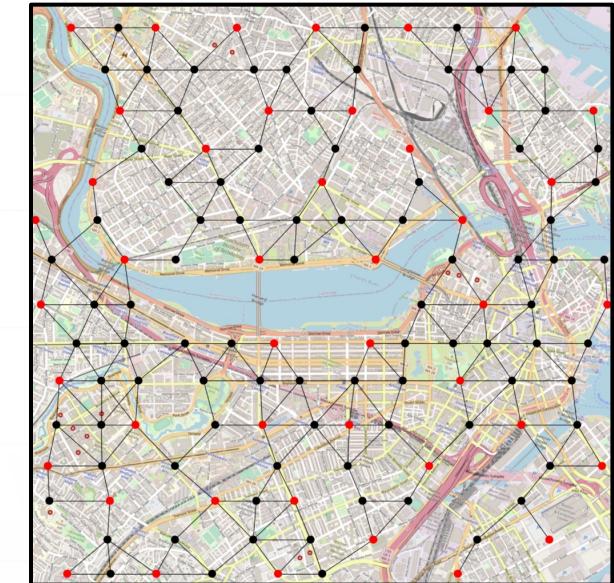
Choose possible locations



Create an atomic twin

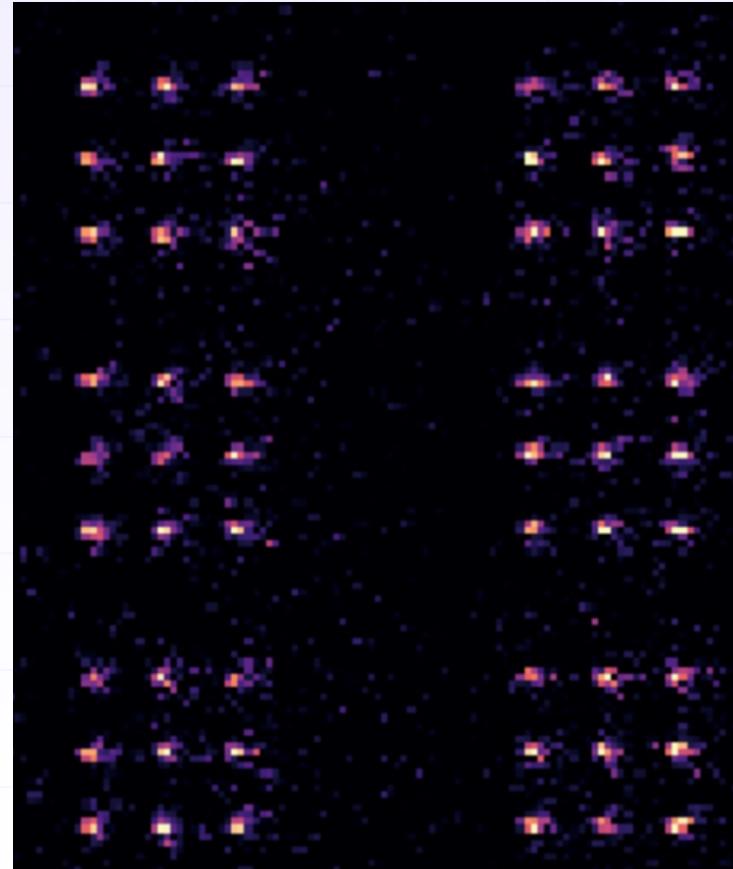
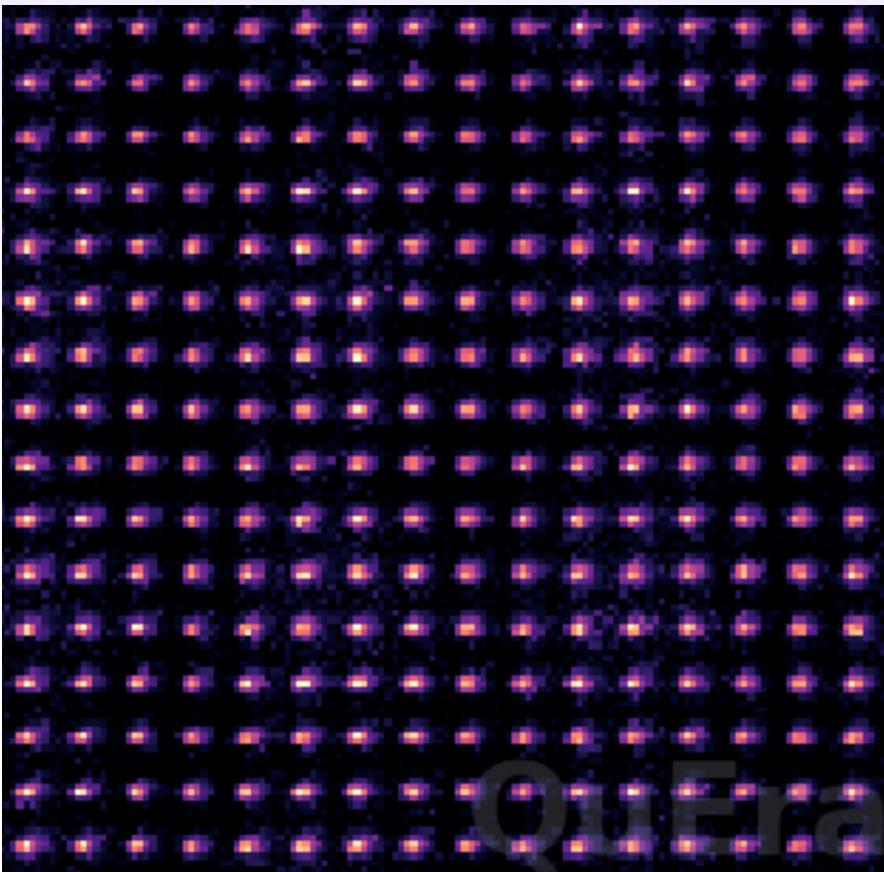


Excite atoms to find answer!



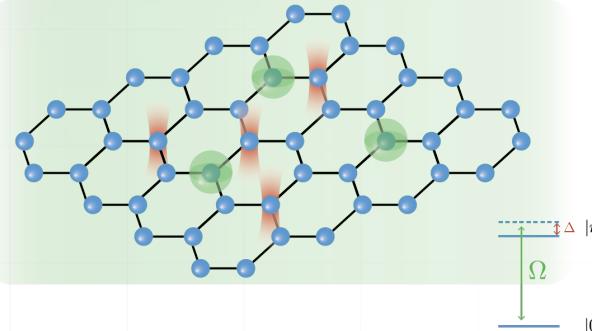
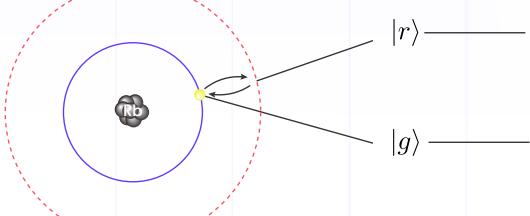
How to optimally cover Boston with coffee shops?

FPQA = Parallelization

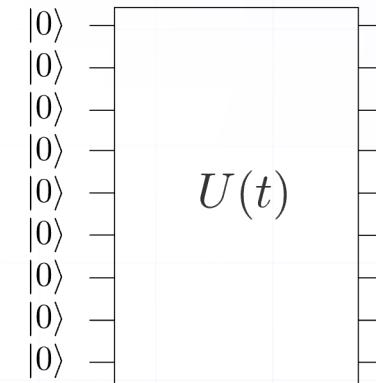


Summary

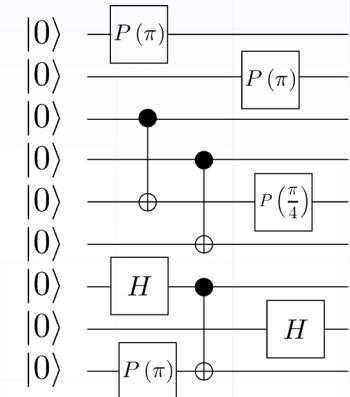
Architecture



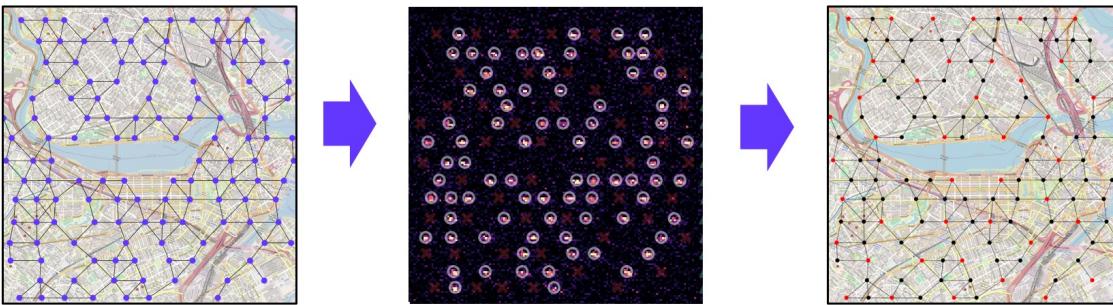
Analog operation



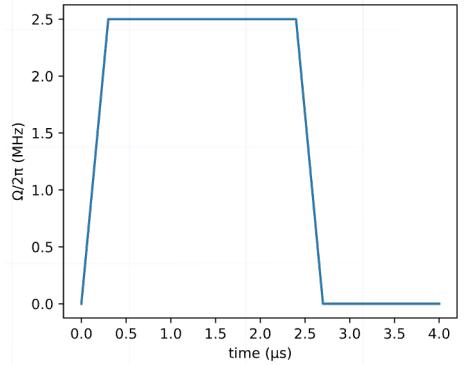
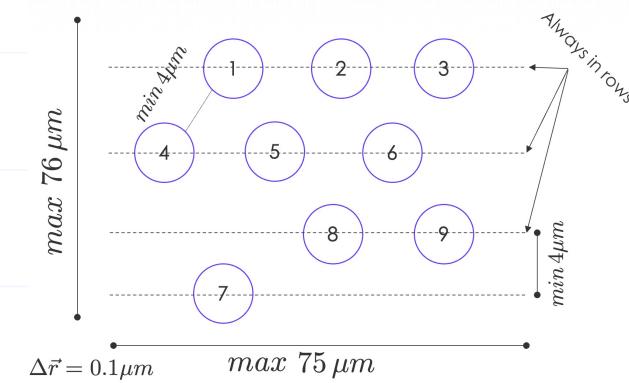
Digital operation



FPQA paradigm



Hardware constraints



Learning objectives

Now you are able to:

- **Explain** how **neutral atoms** can be used as a **platform** for quantum computing
- **Distinguish** **analog** and **digital** (gate-based) quantum computing
- **Define** **field-programmable qubit arrays** and **exemplify** some of their **advantages**
- **Describe** Aquila's **programming** range
 - its Hamiltonian and controllable parameters, limitations of service