Compact Ion-Trap Quantum Computing Demonstrator

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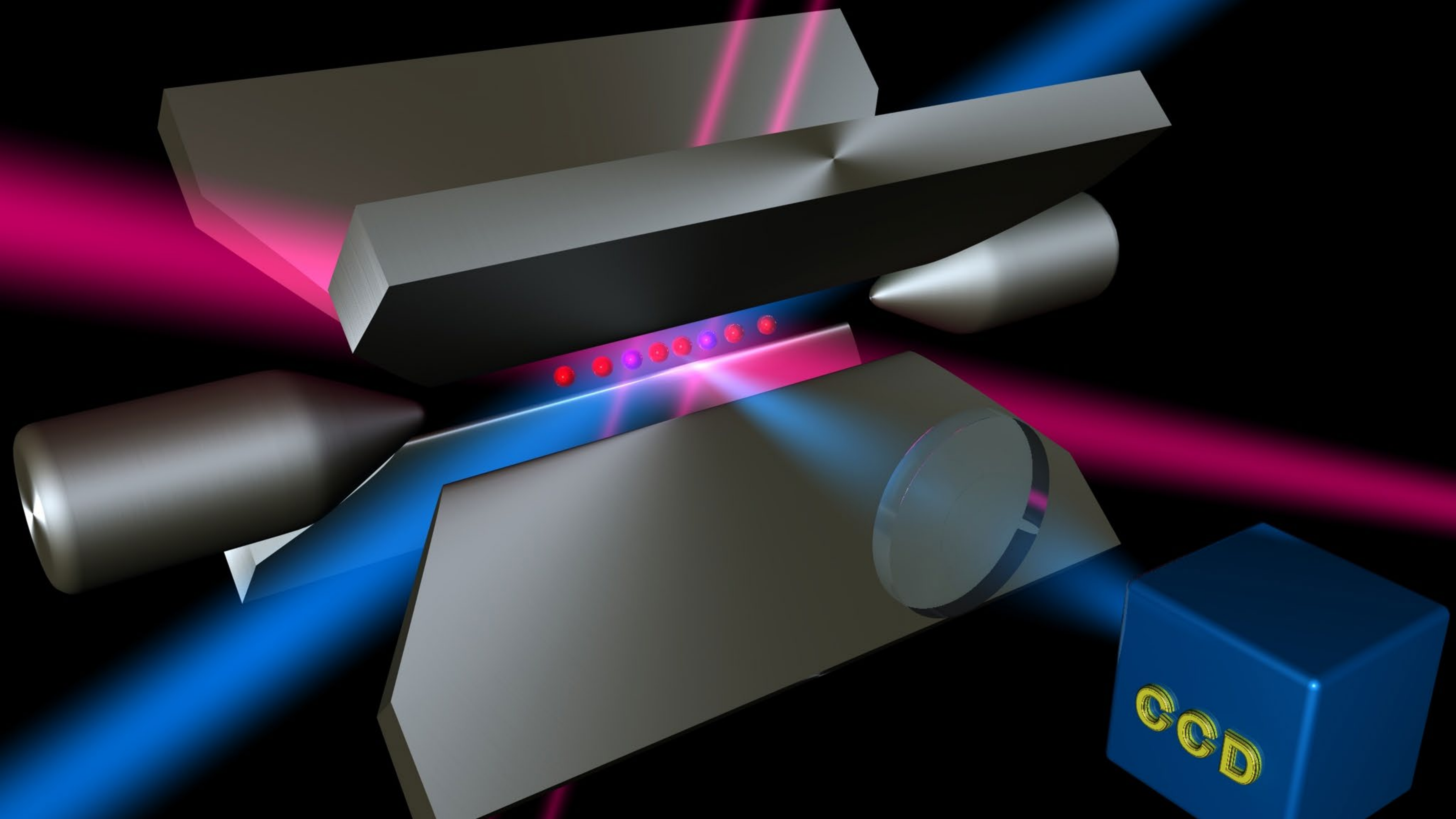
universität innsbruck

AQTION

IQI

FFG Promoting Innovation.

FWF Der Wissenschaftsfonds.


CCD

Outline

1. Trapping
2. State manipulation
   - $^{40}Ca^+$
   - Optical pumping
   - Sideband cooling
   - Detection
3. Qubit manipulation
   - Single qubit gate
   - MS gate
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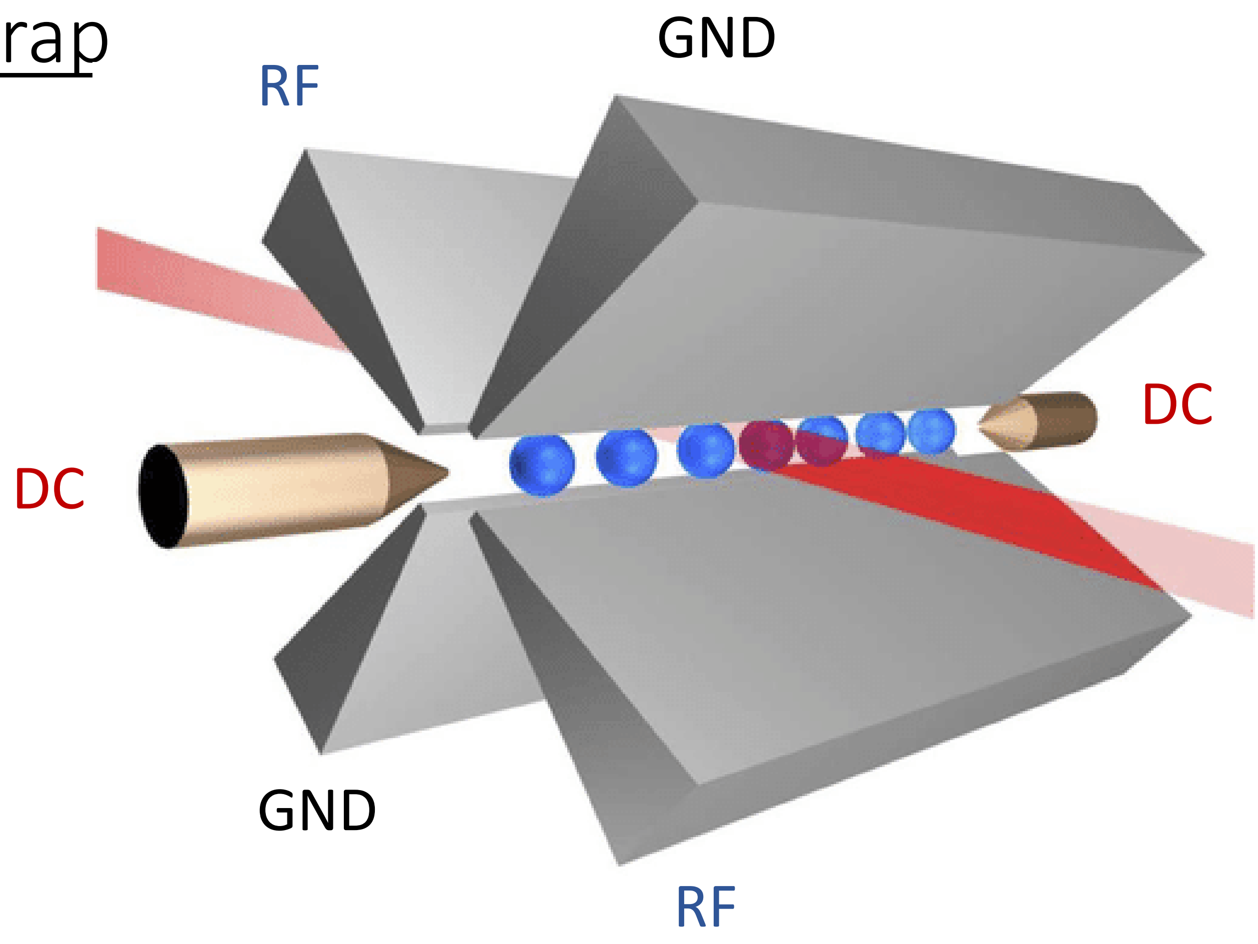
   - Compact optics
   - Trap drawer
   - Vibrations
   - Addressing
7. Automation
   - Keeping constant fidelity
8. Performance
   - Benchmarking
   - Quantum volume

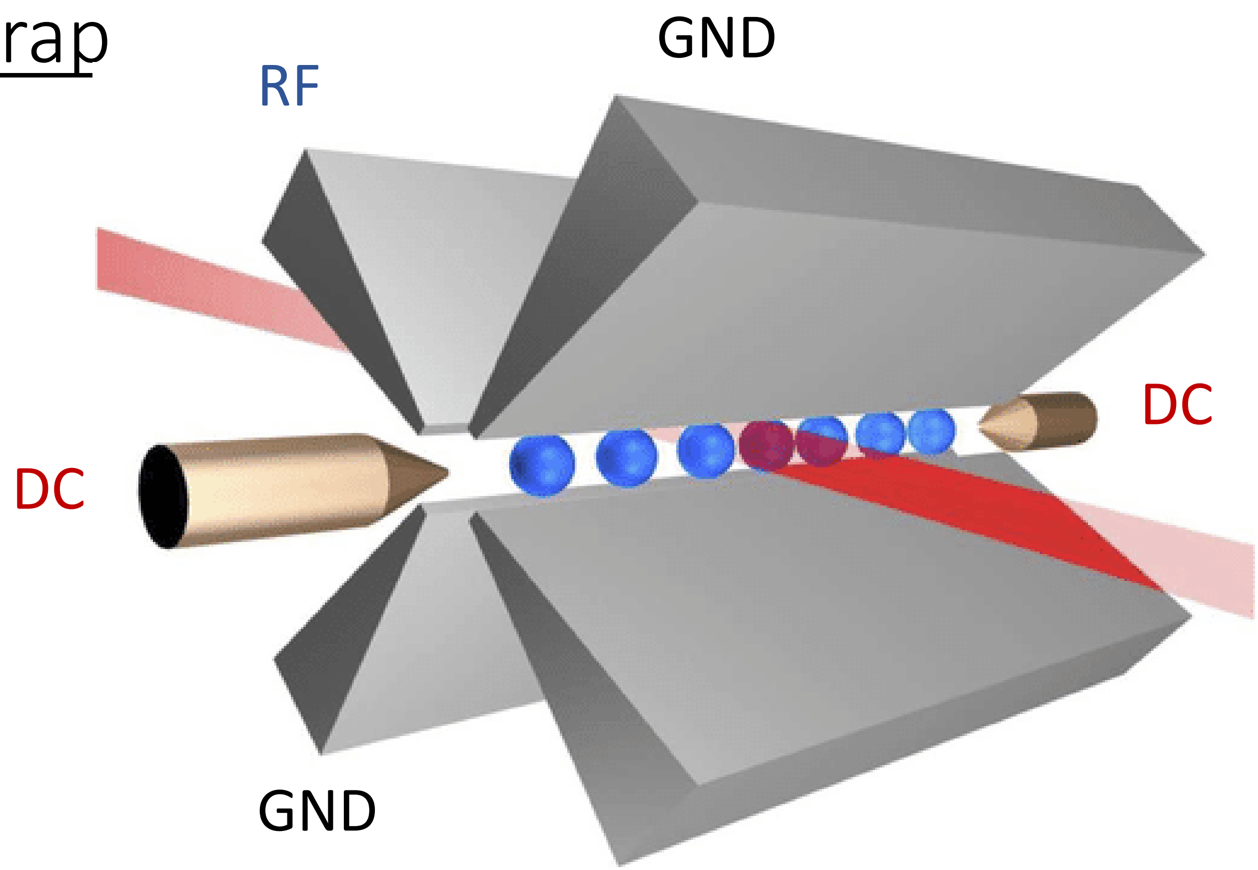
Paul trap



RF – 10 W @ 25 MHz

DC – 1000 V

Paul trap



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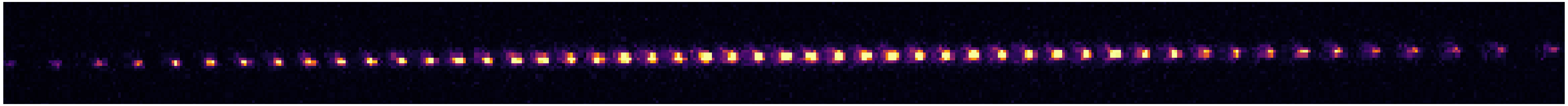

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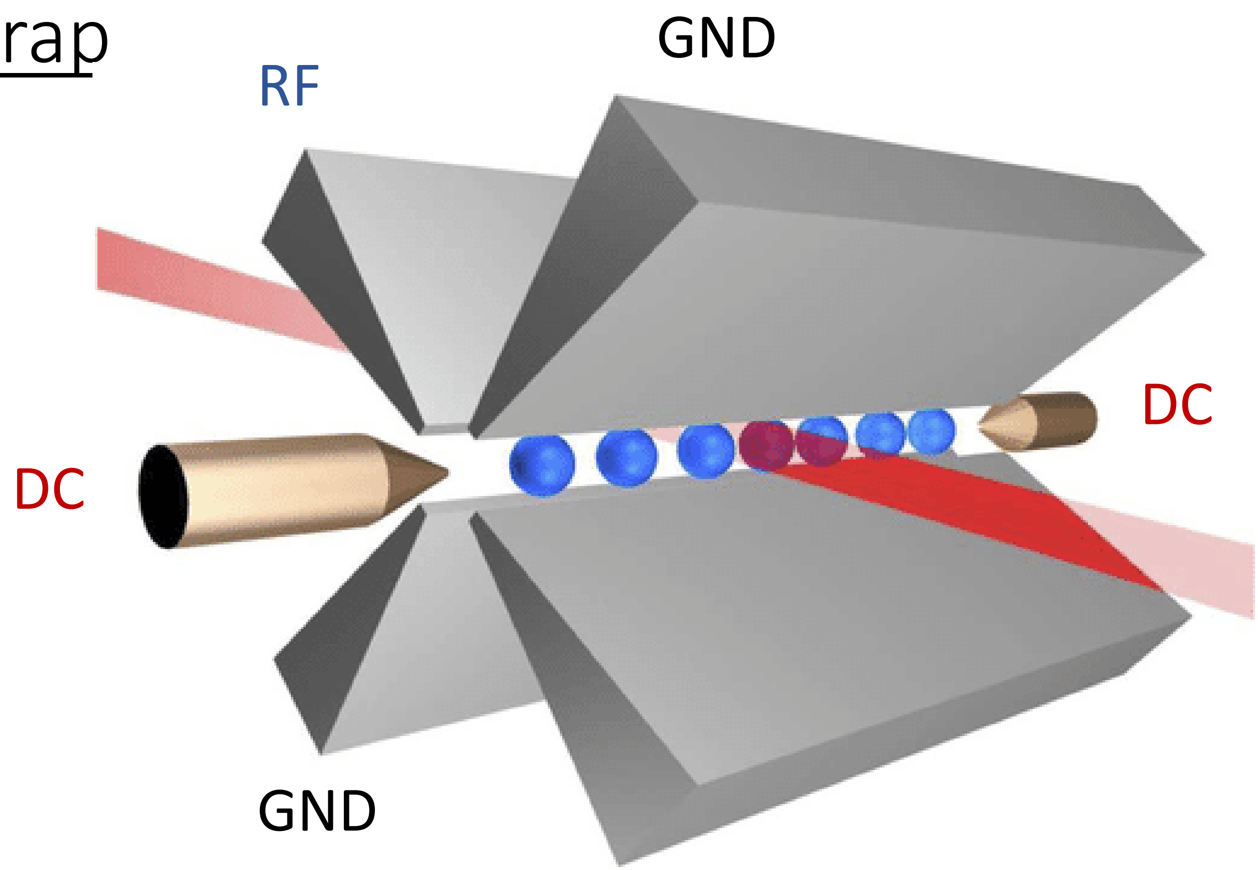

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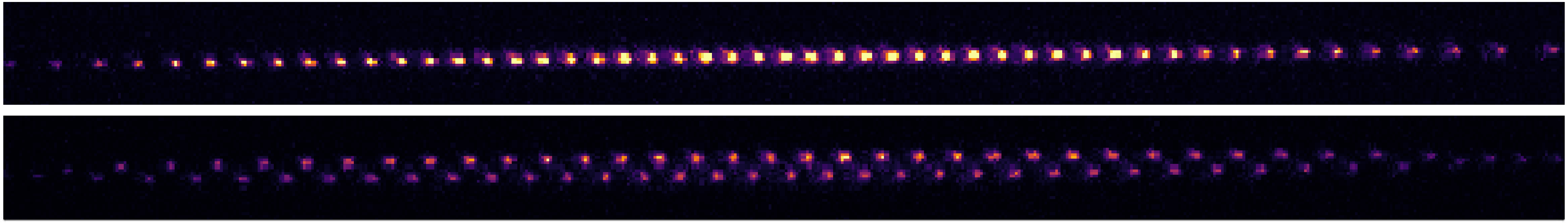

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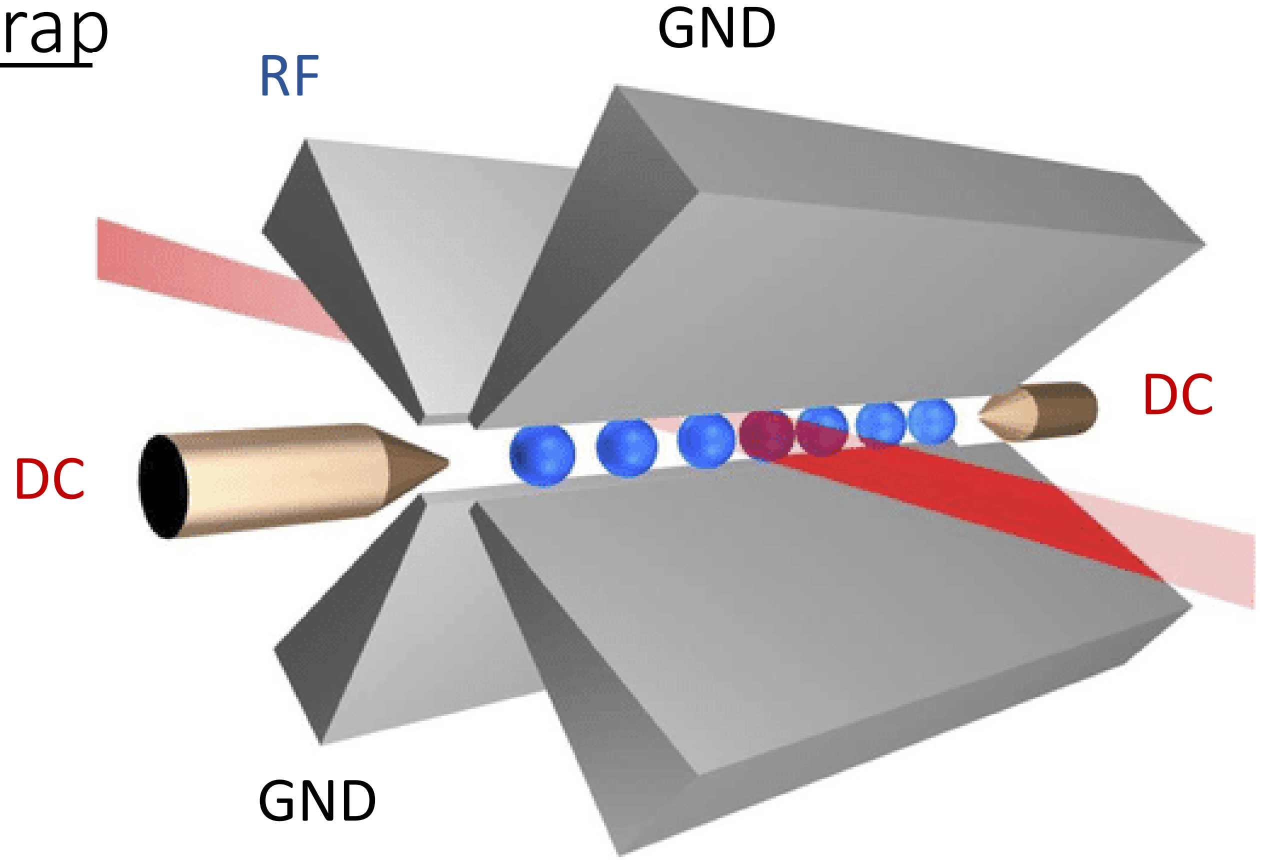

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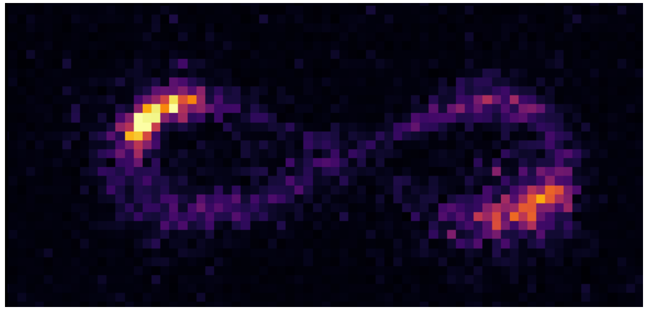

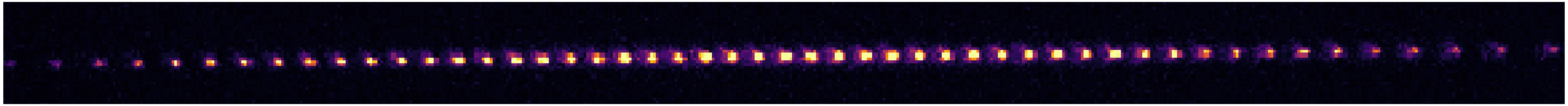

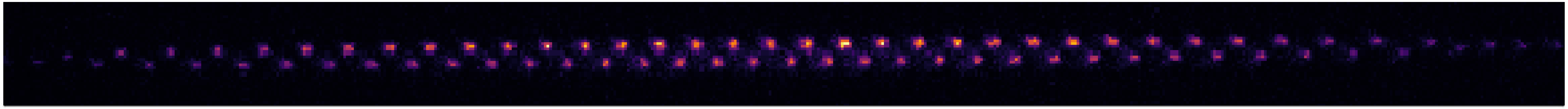

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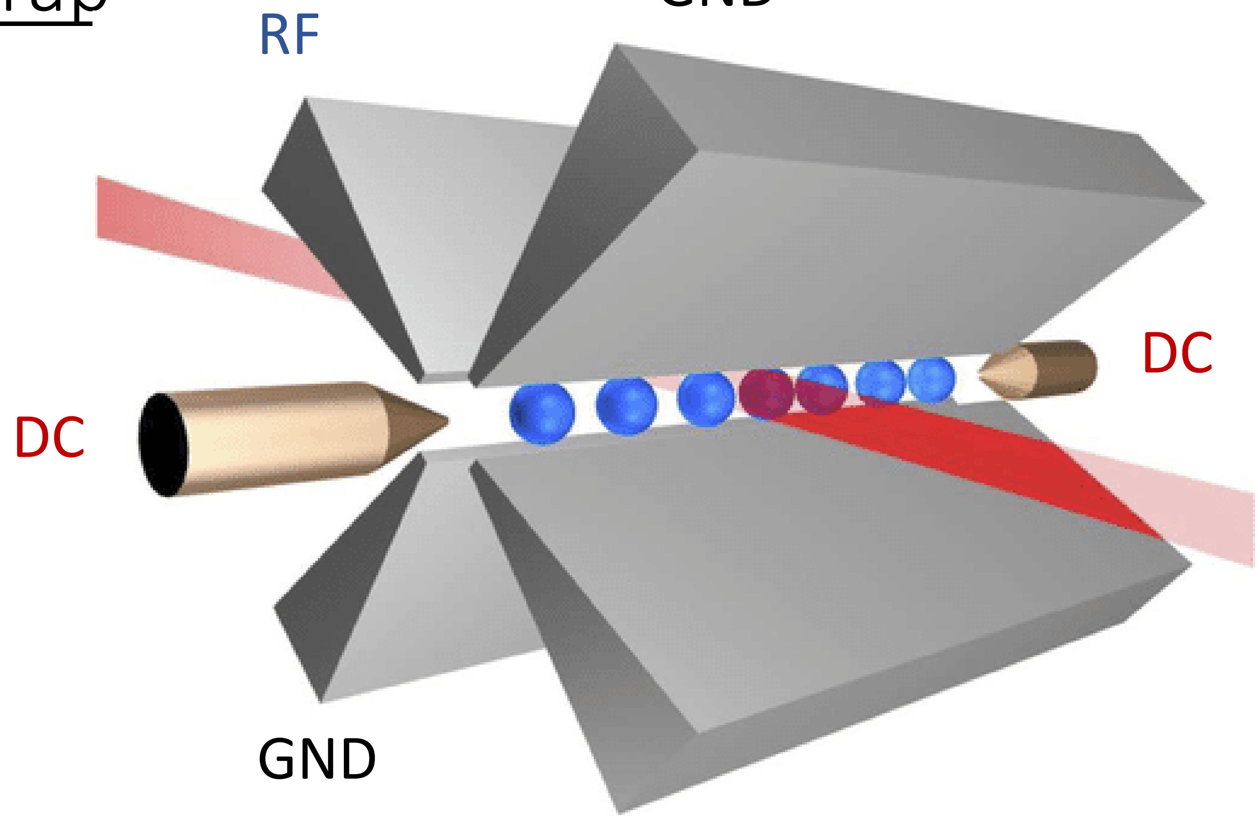

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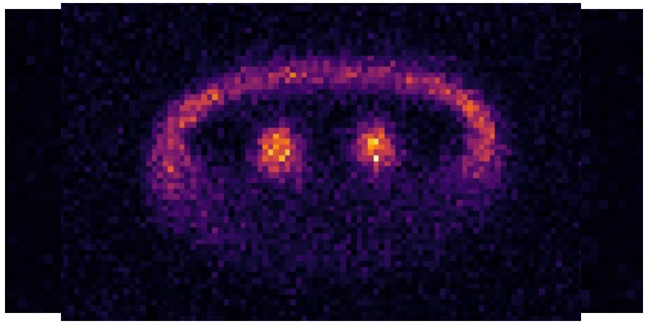

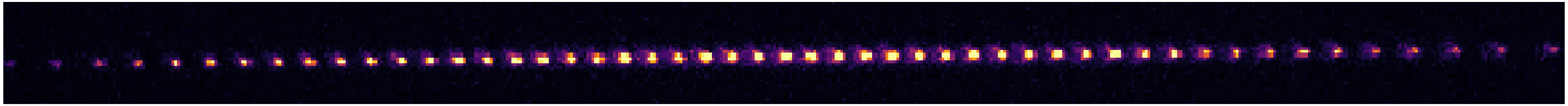

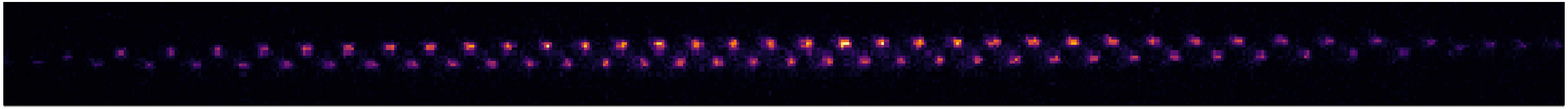

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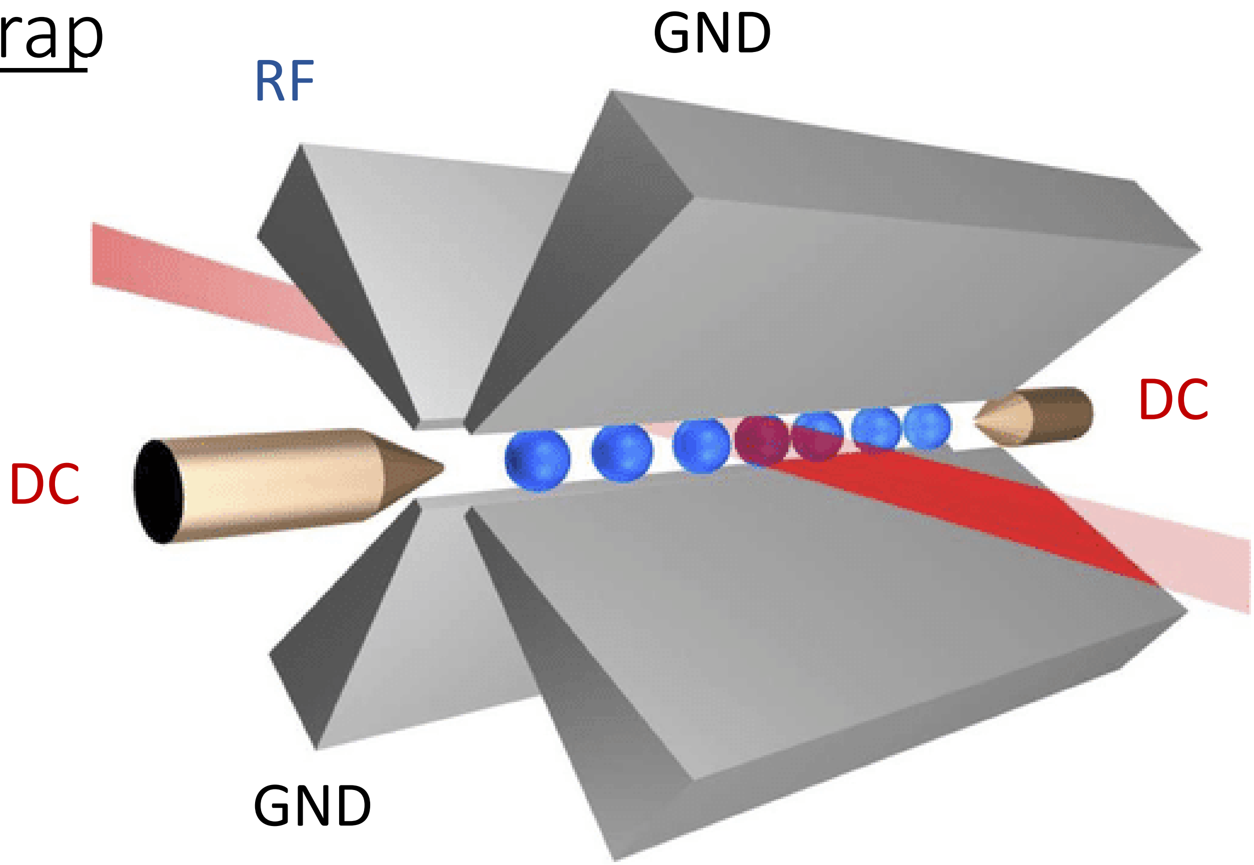

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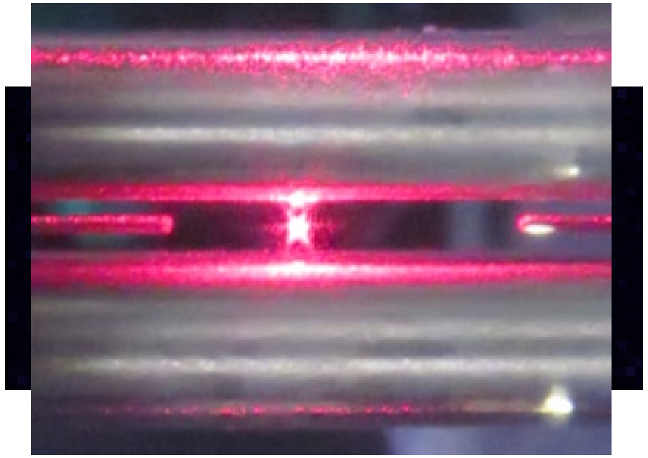
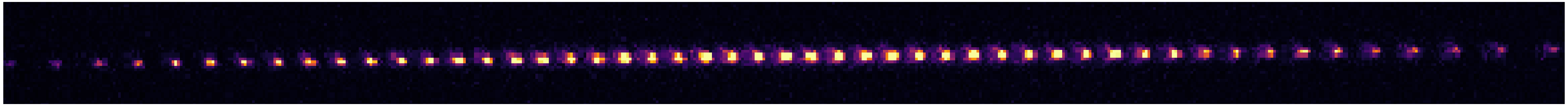
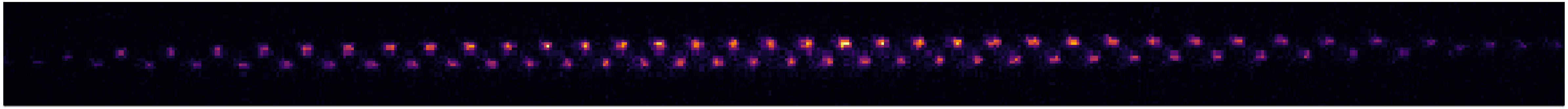
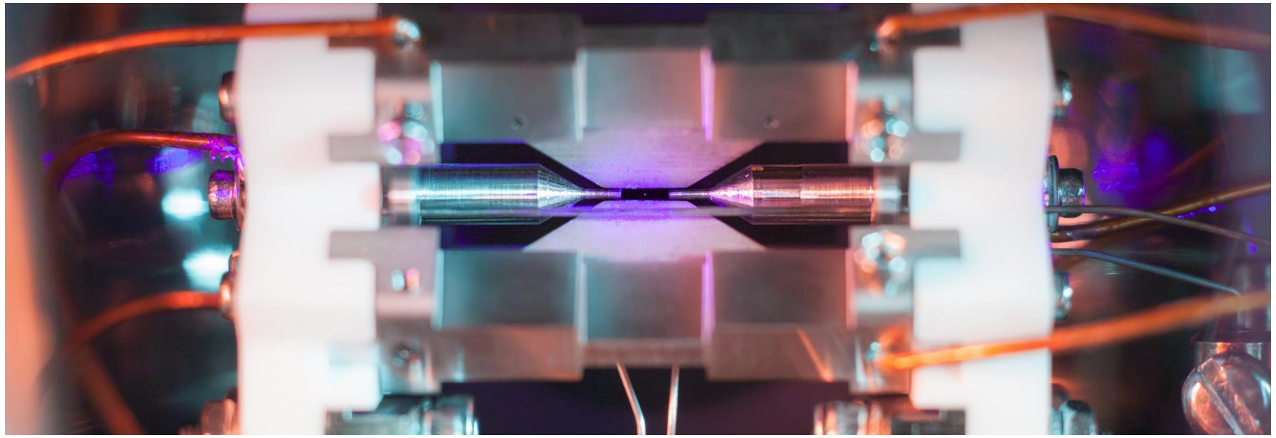
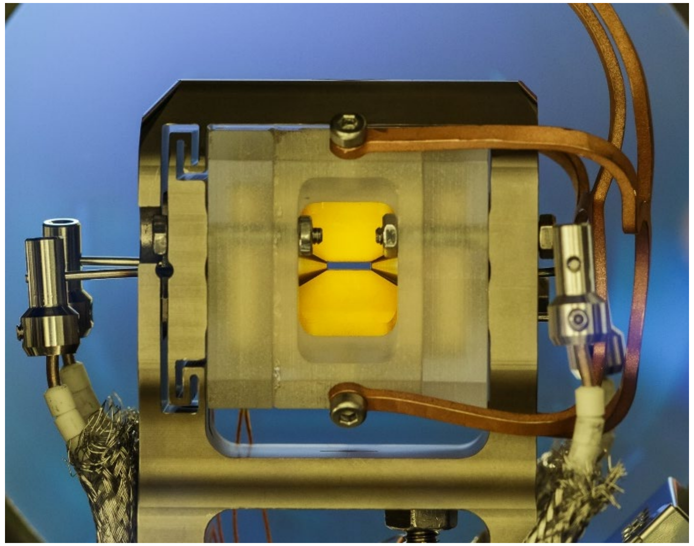


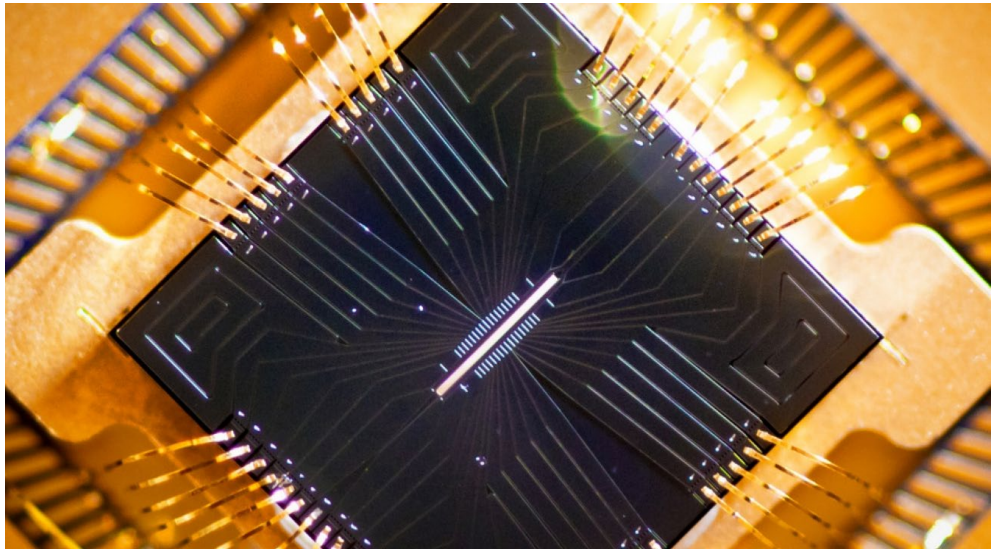


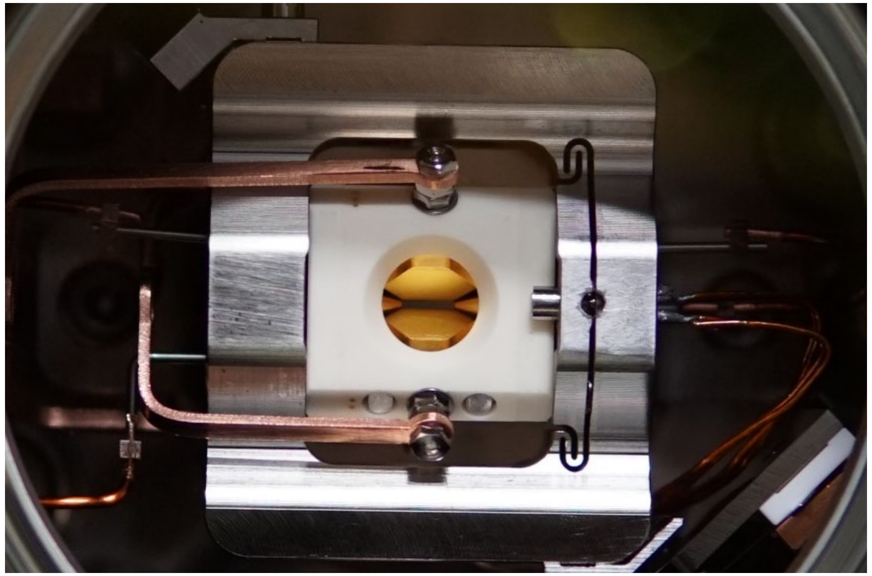


Real traps

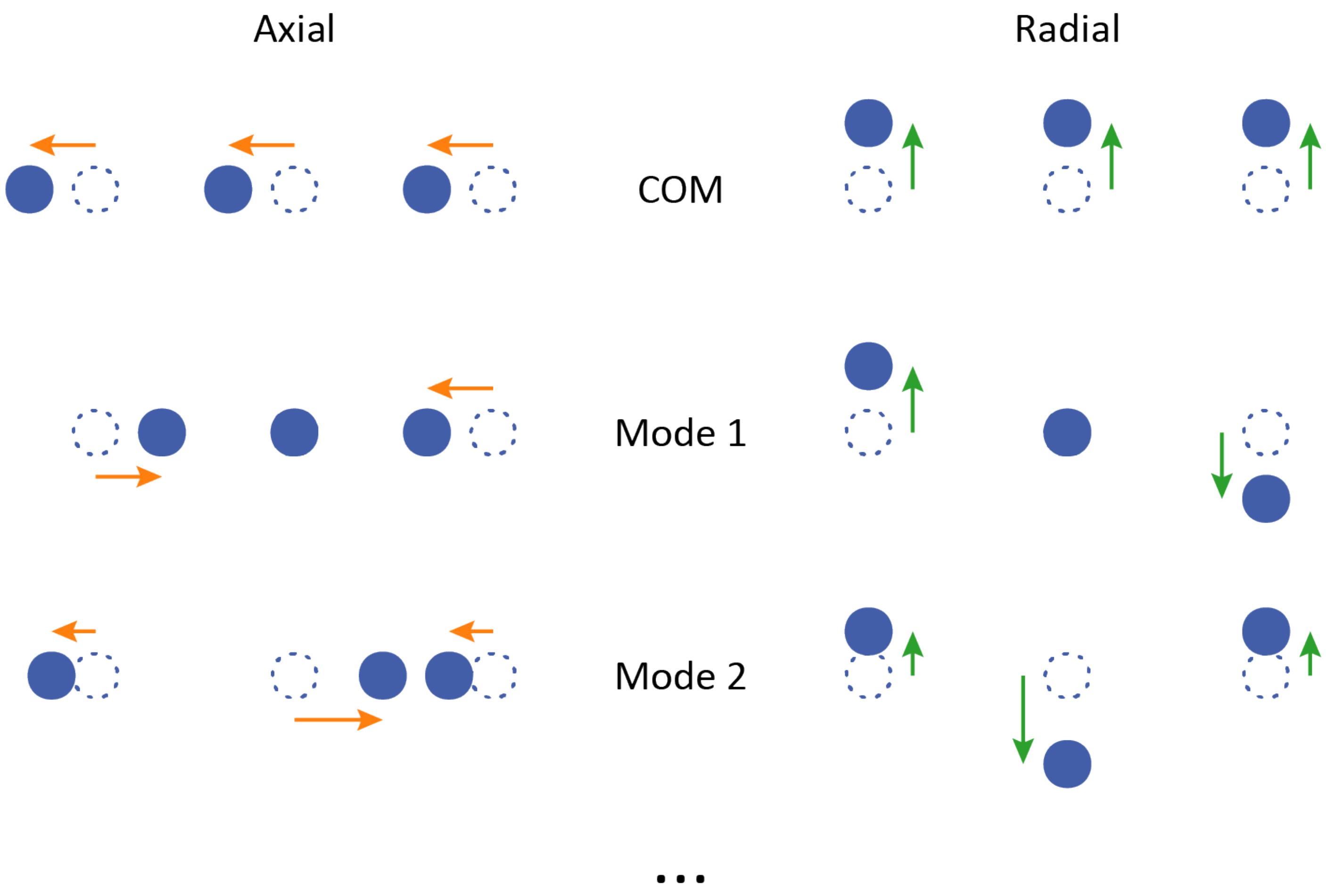


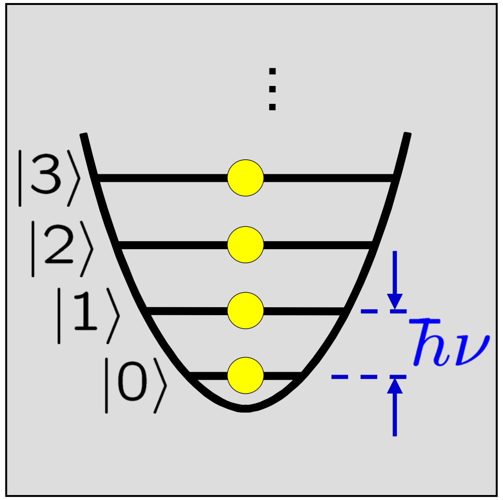






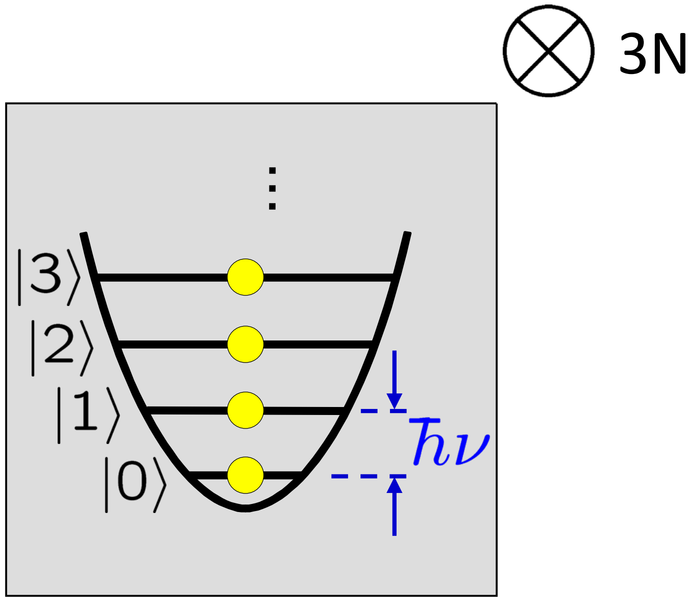
Trap: motional modes





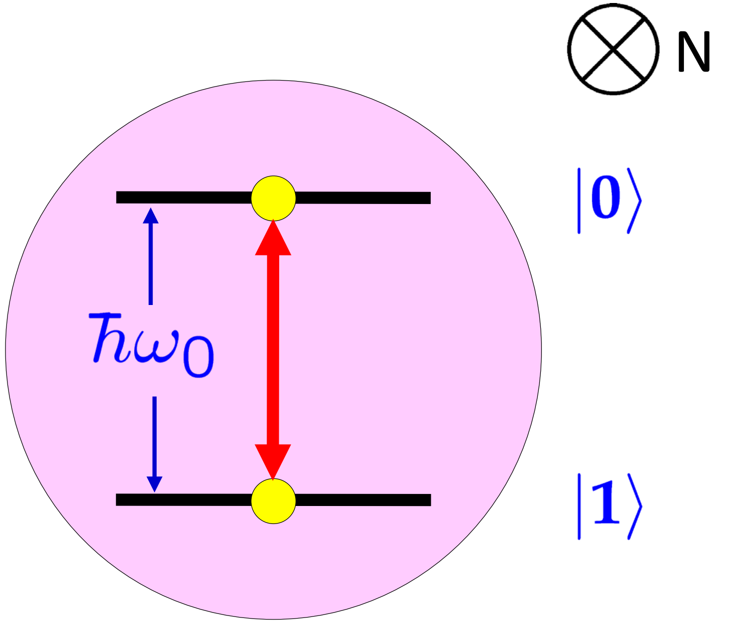
100 – 3000 kHz

System state



0.1 – 3 MHz

$\otimes$



10 MHz – 400 THz

(various qubit types)

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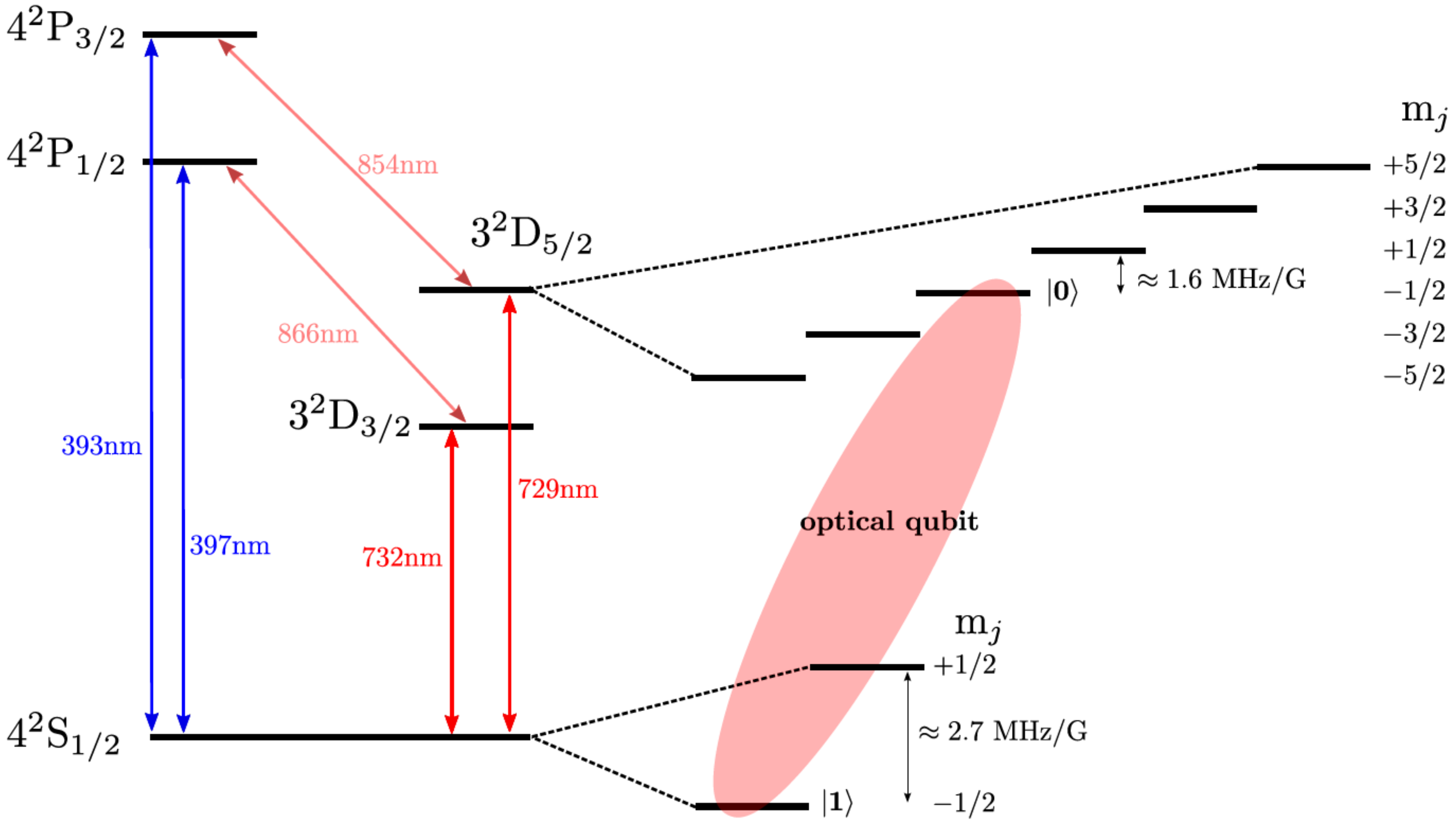
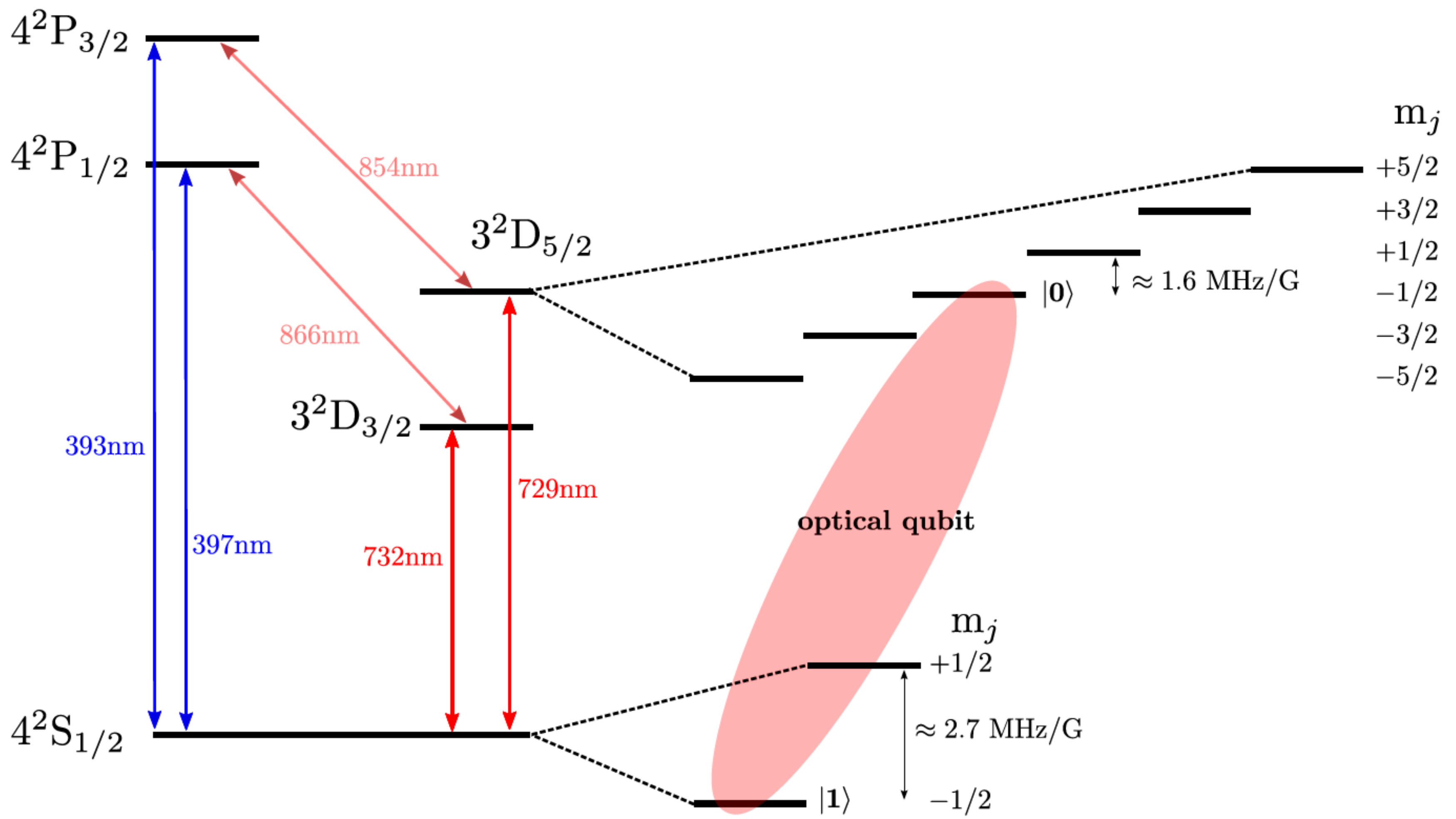
$^{40}Ca^{+}$



$4^2P_{3/2}$
$4^2P_{1/2}$
854nm
866nm
$3^2D_{5/2}$
$3^2D_{3/2}$
393nm
397nm
732nm
729nm
$4^2S_{1/2}$
m_j
+5/2
+3/2
+1/2
−1/2
−3/2
−5/2
$|0\rangle$
$\approx$ 1.6 MHz/G
optical qubit
m_j
+1/2
$\approx$ 2.7 MHz/G
$|1\rangle$
−1/2

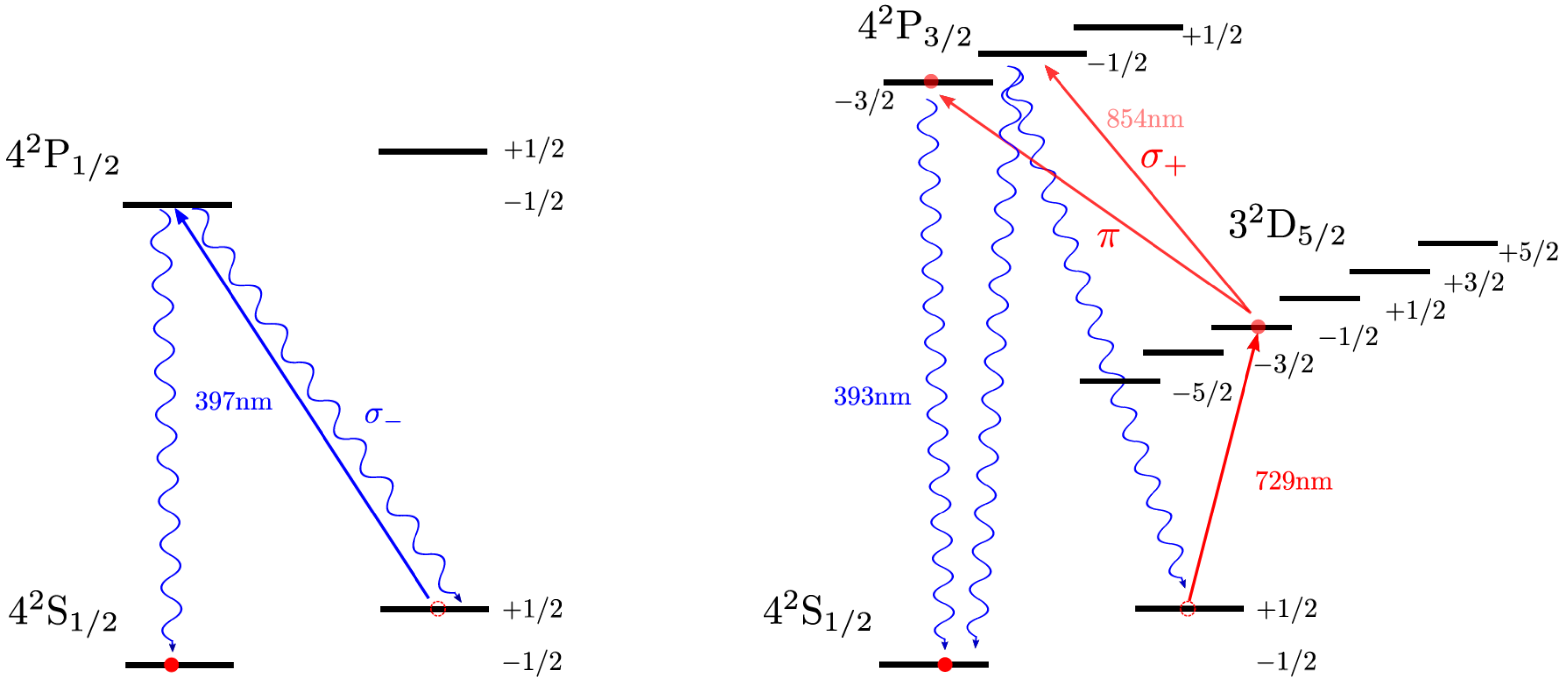
$^{40}Ca^{+}$



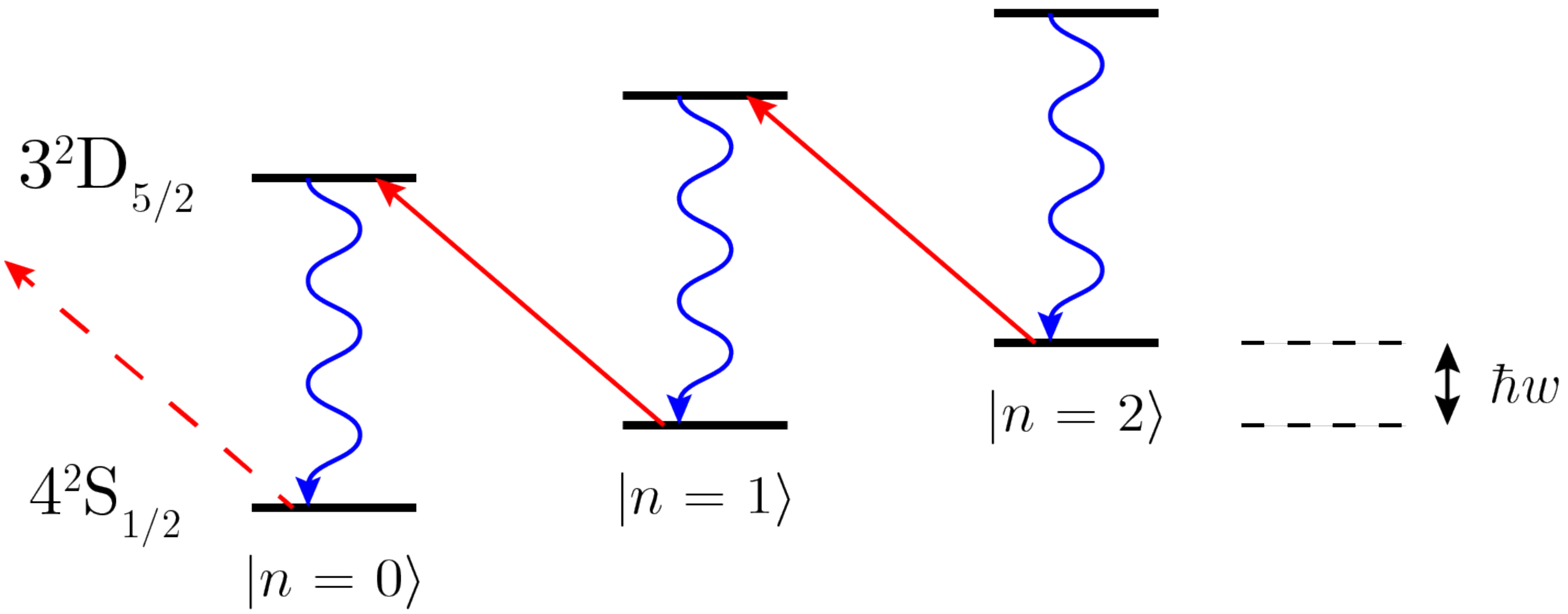
Qubit types:

- **Optical**
- Zeeman
- Hyperfine

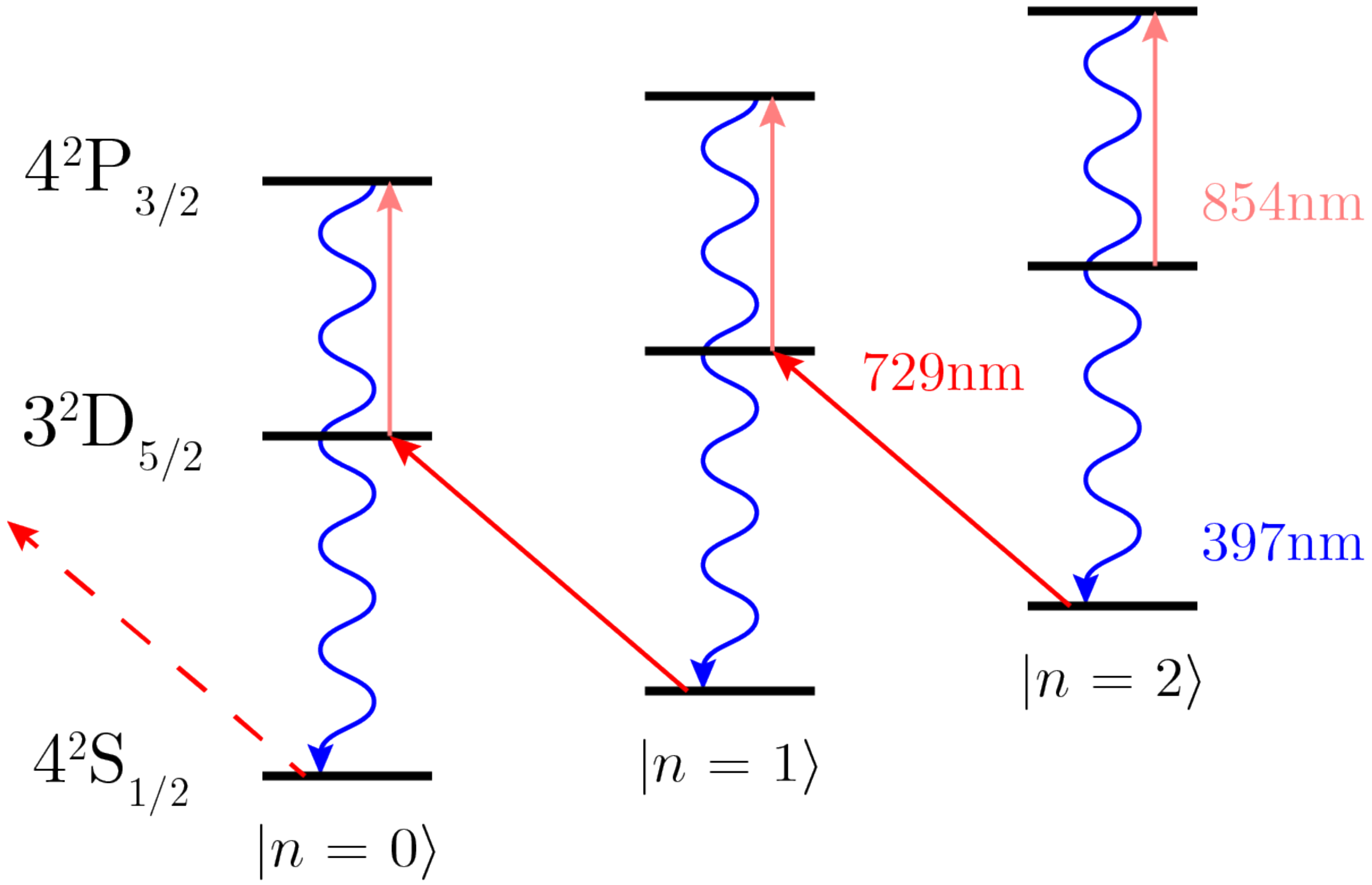
Optical pumping



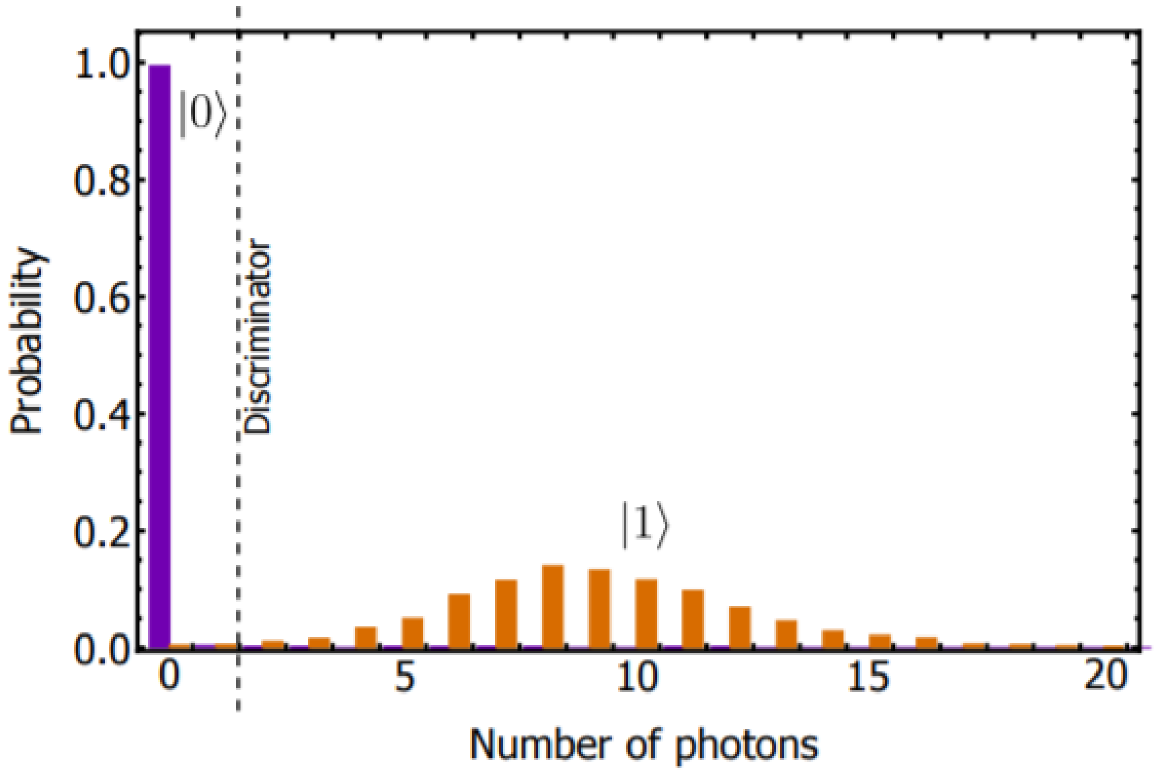
Sideband cooling



Sideband cooling



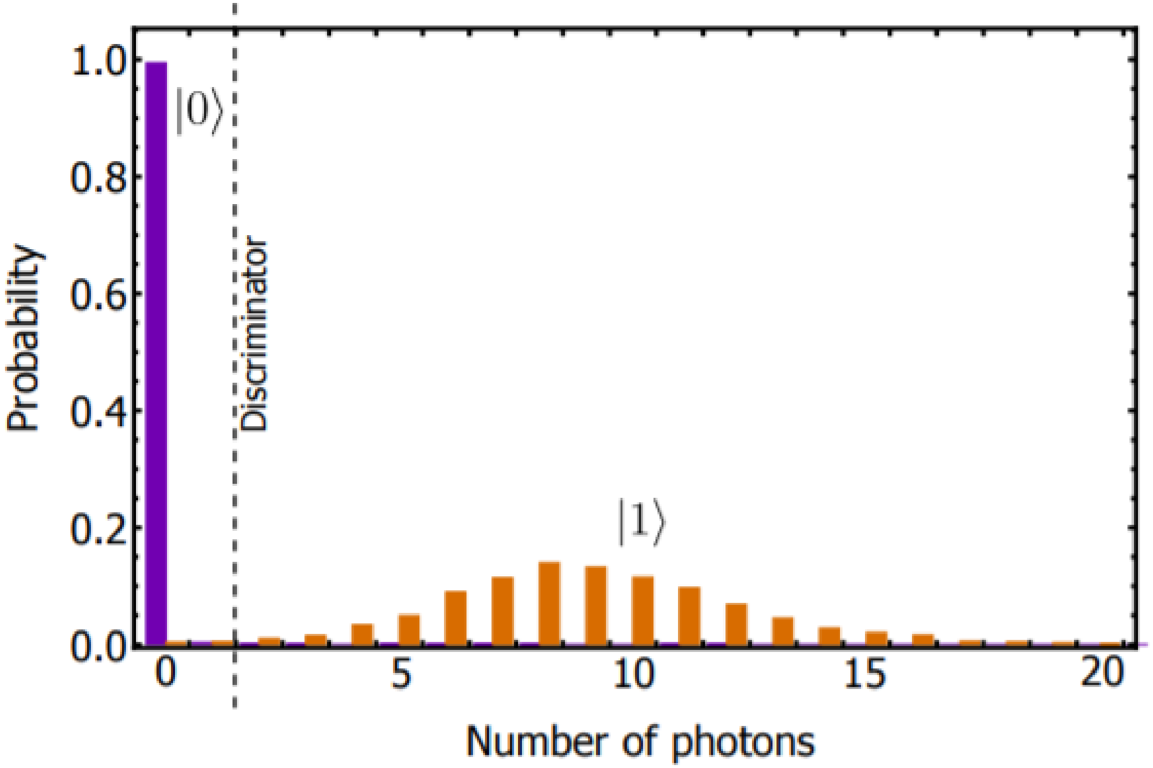
Detection



A Programmable Five Qubit Quantum Computer
Using Trapped Atomic Ions

Shantanu Debnath, Doctor of Philosophy, 2016

Detection



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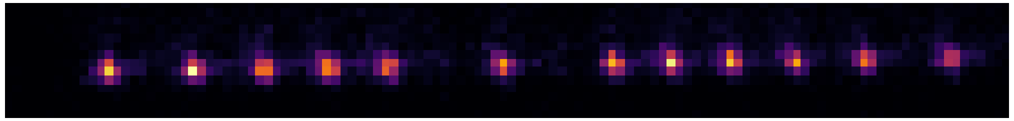

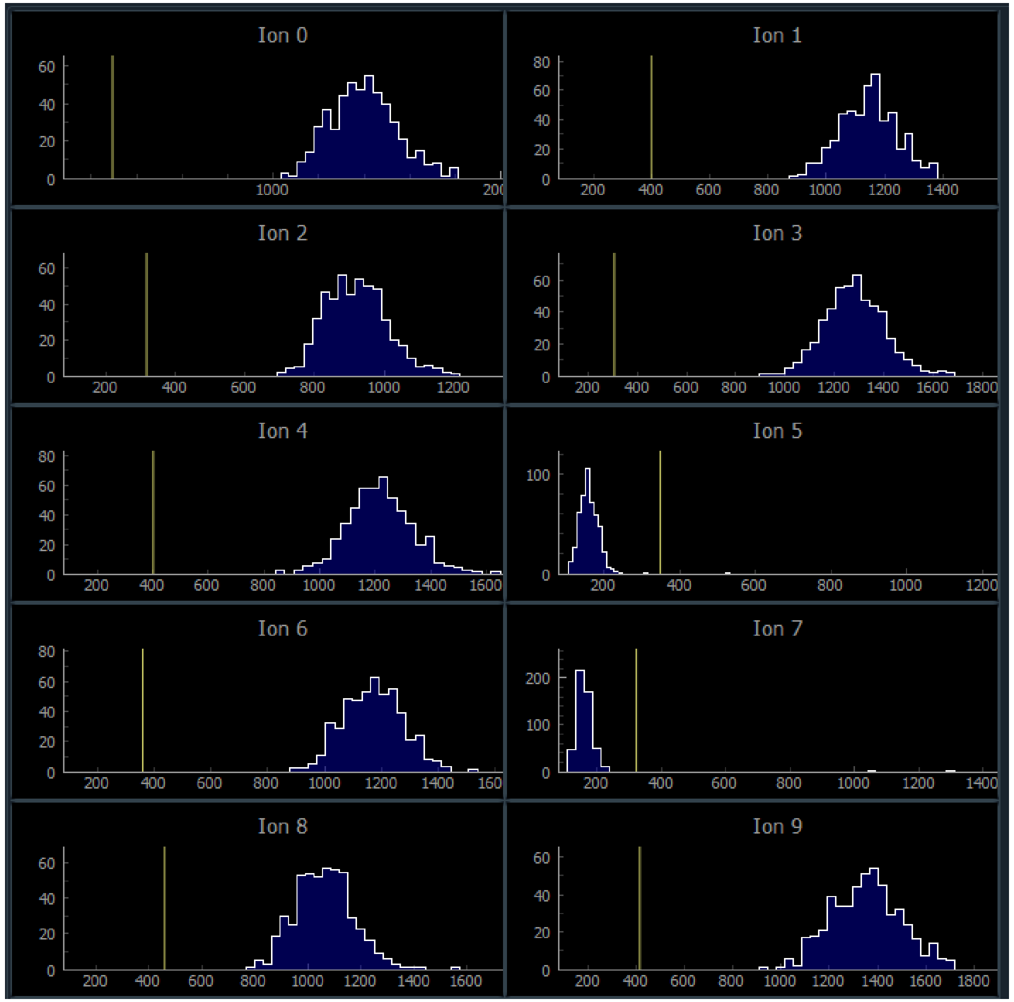

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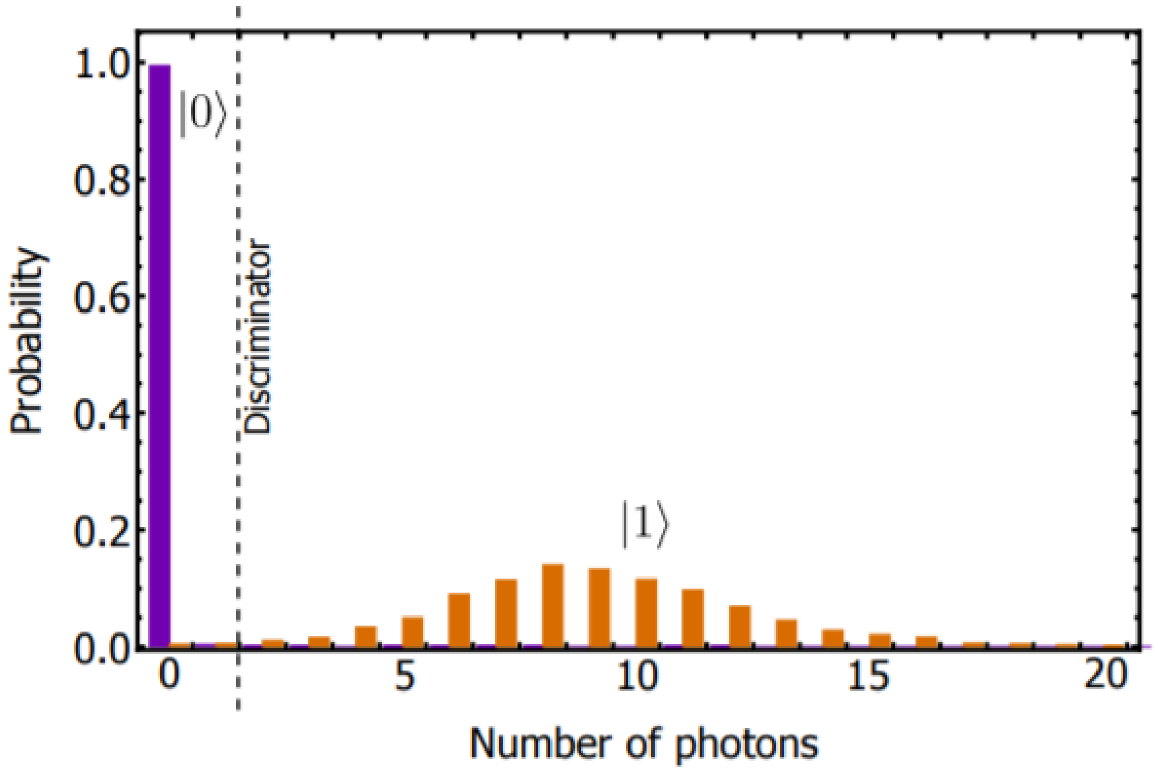

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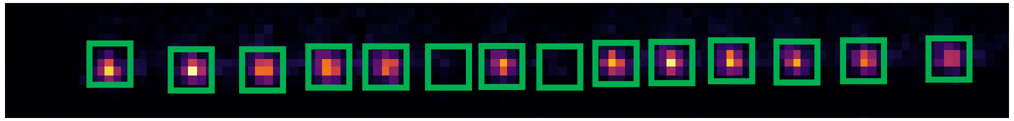

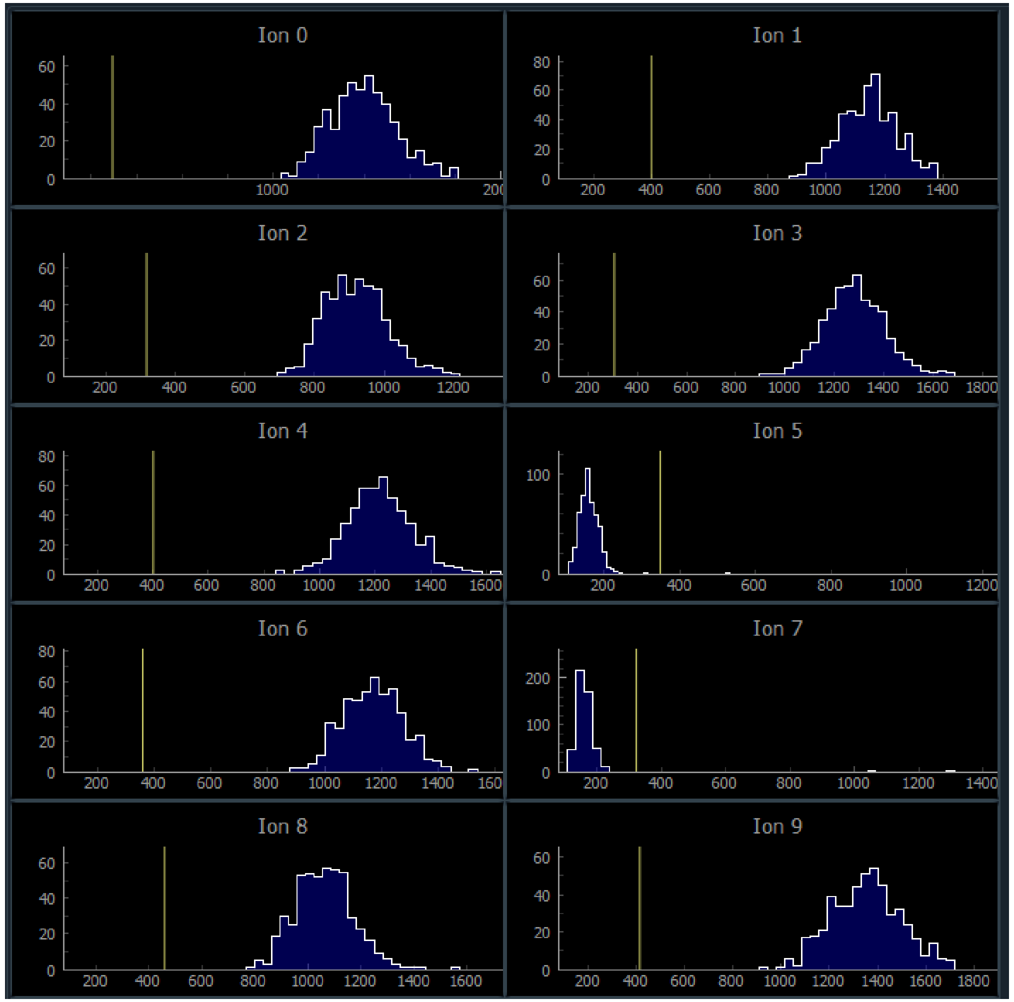

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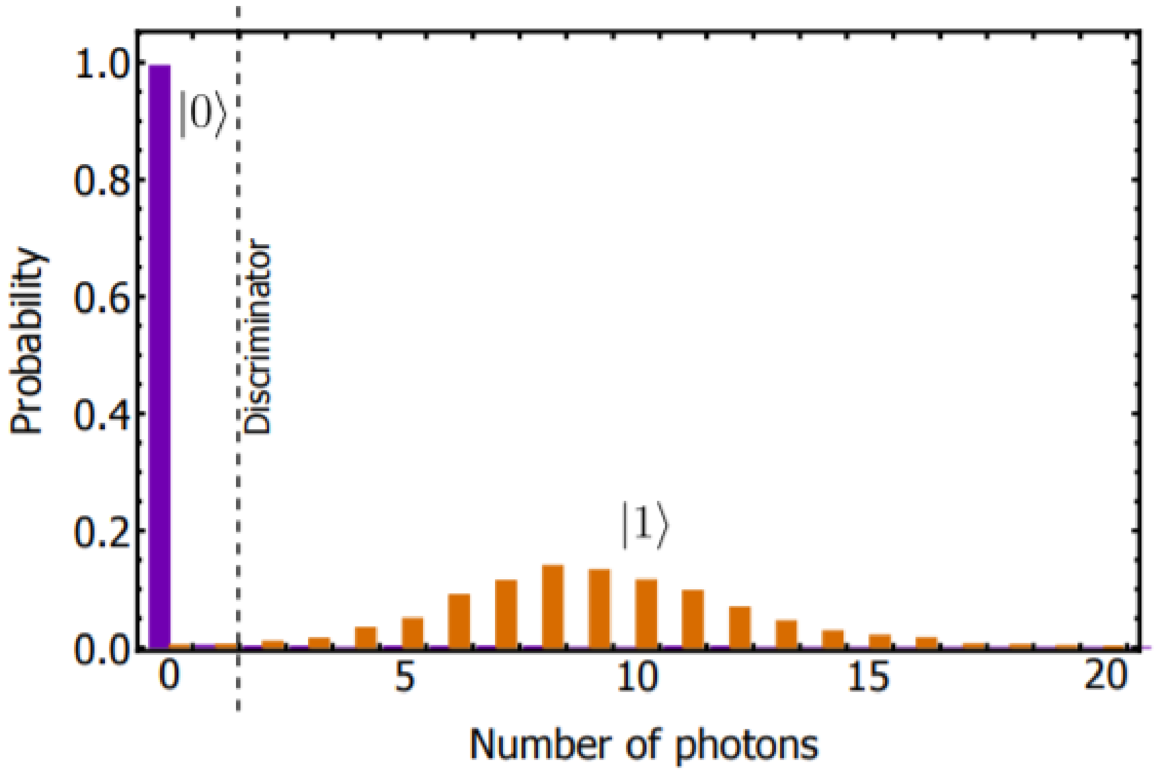

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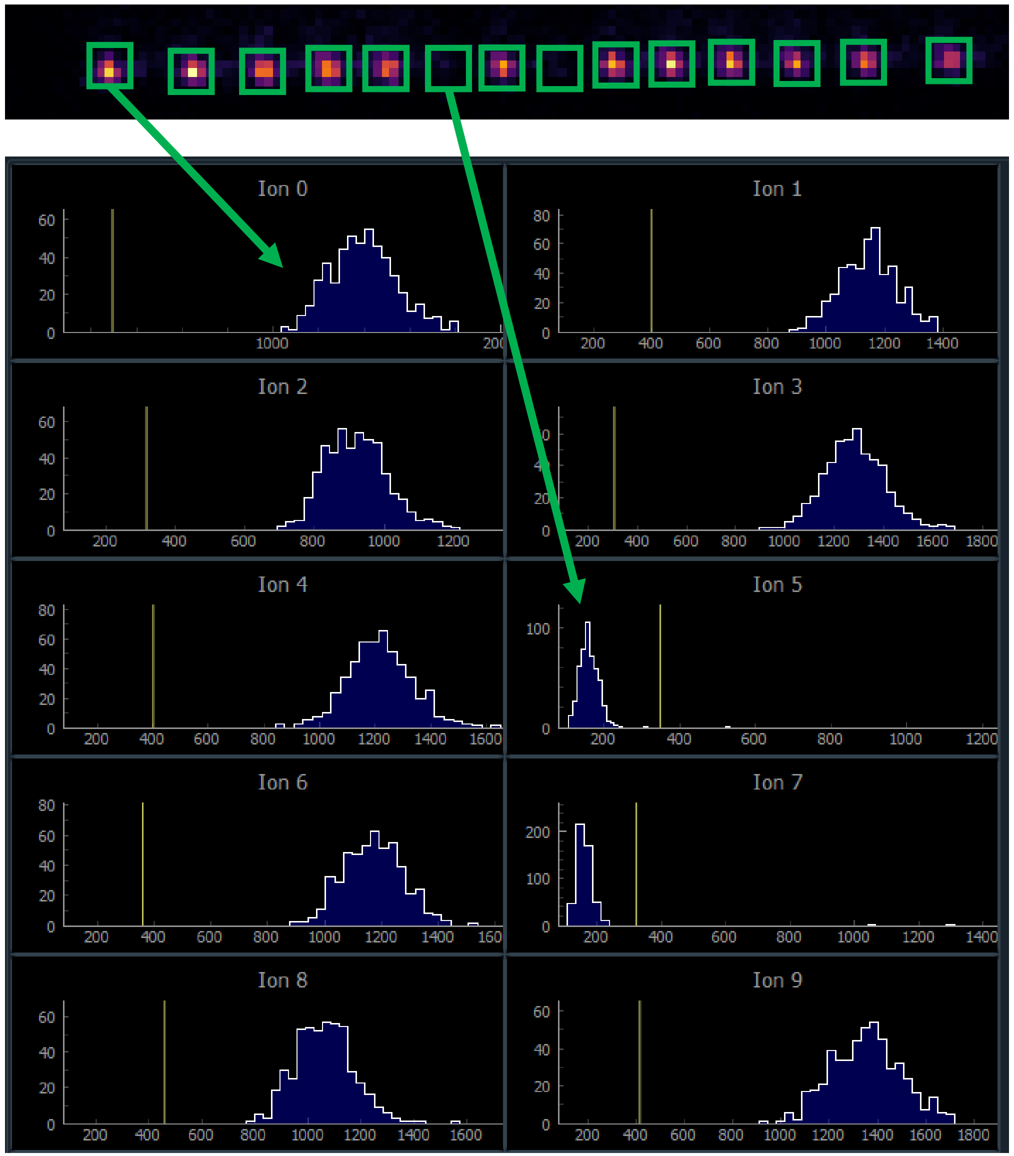

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Single qubit gates

$$R(\theta) = e^{-i\frac{\theta}{2}\vec{n}\cdot\vec{\sigma}}$$

Single qubit gates

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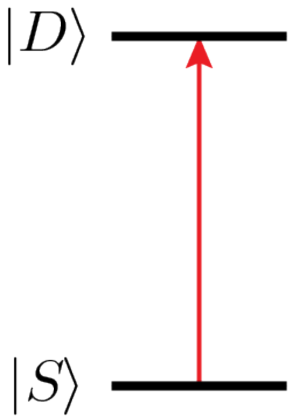
Resonant

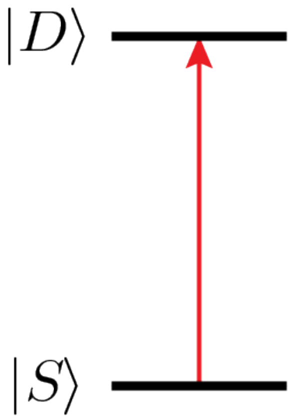


$$R_{xy}(\theta, \phi) = e^{-i\frac{\theta}{2}(\sigma_x \cos\phi + \sigma_y \sin\phi)}$$

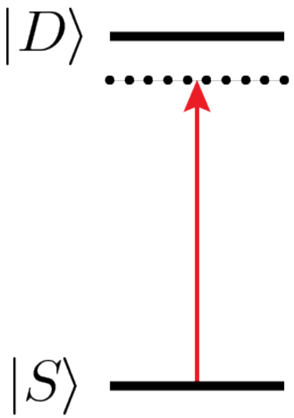
Single qubit gates

$$R(\theta) = e^{-i\frac{\theta}{2}\vec{n}\cdot\vec{\sigma}}$$

Resonant



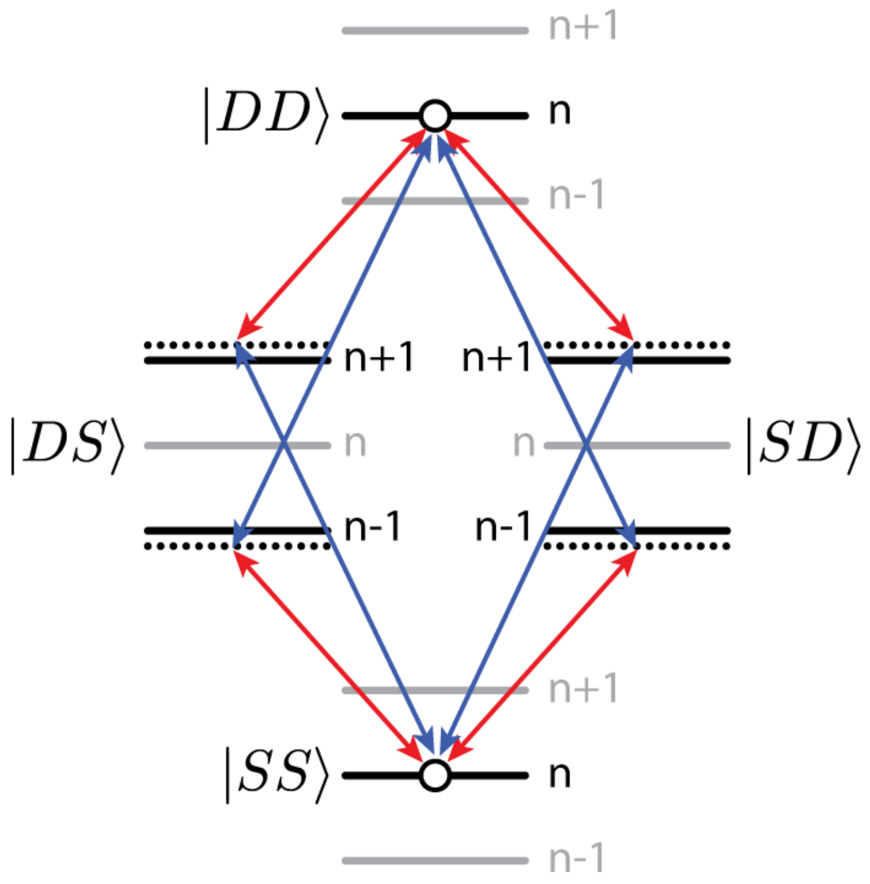
Off-resonant

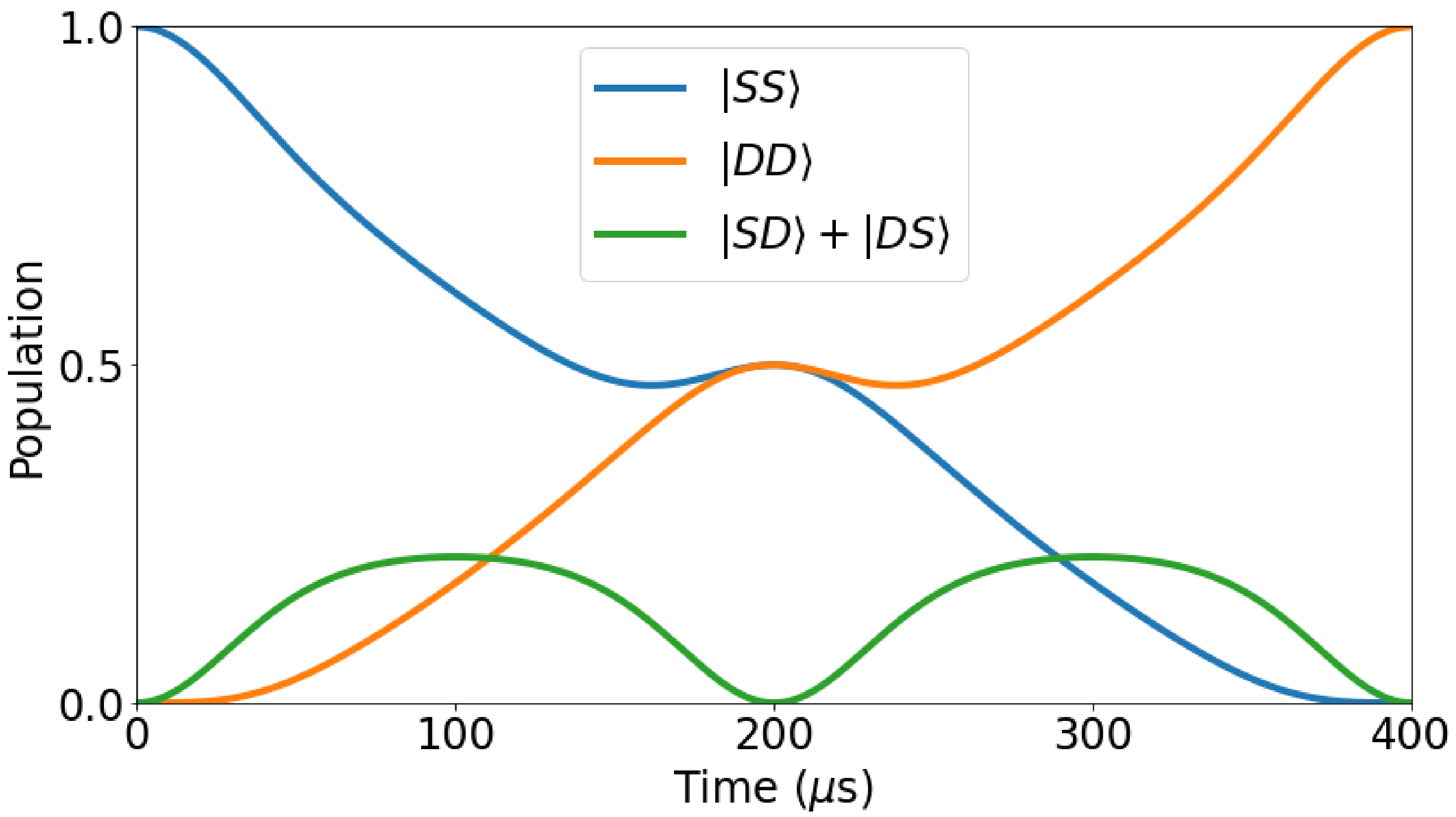


$$R_{xy}(\theta,\phi) = e^{-i\frac{\theta}{2}(\sigma_x\cos\phi + \sigma_y\sin\phi)}$$

$$R_z(\theta) = e^{-i\frac{\theta}{2}\sigma_z}$$

MS gate





$$XX(\chi) \approx e^{-i\chi\sigma_x \otimes \sigma_x}$$

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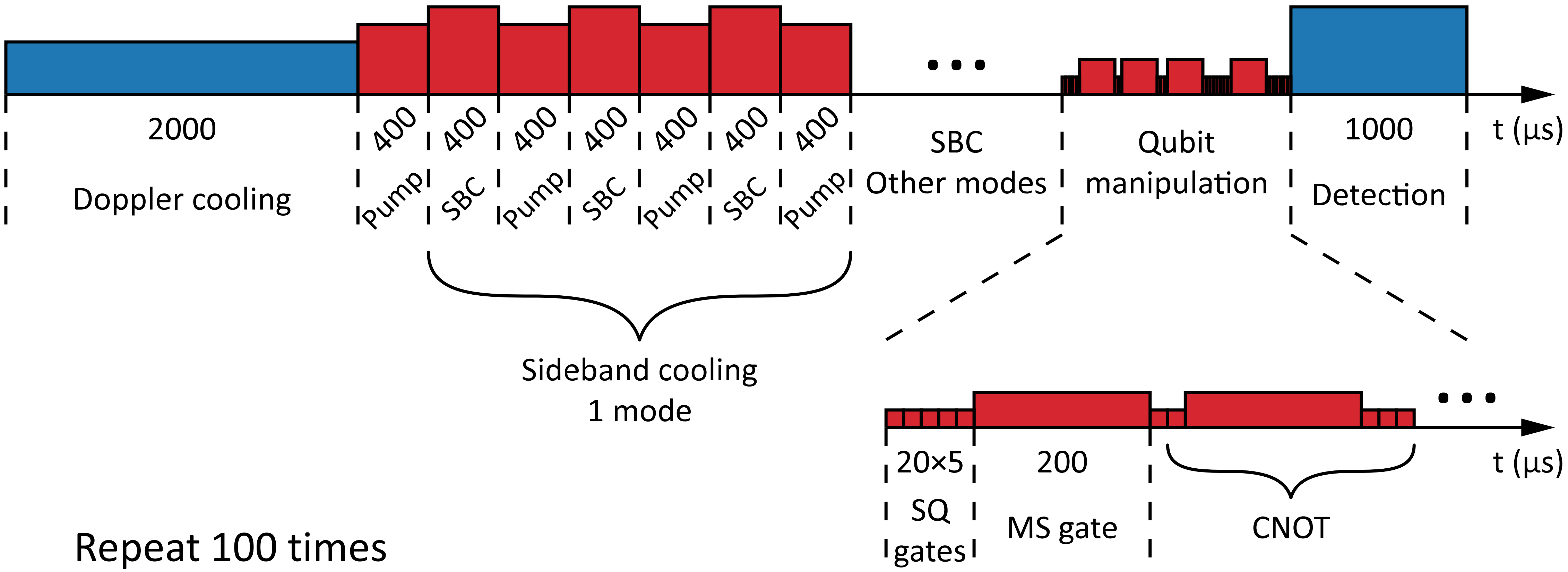
Pulse sequence



Repeat 100 times

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Scaling: long chain

With longer chains:

- More RF power
- Harder to address

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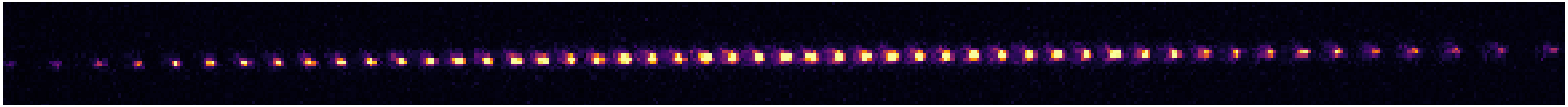
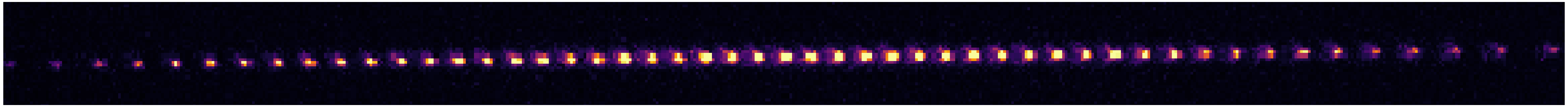
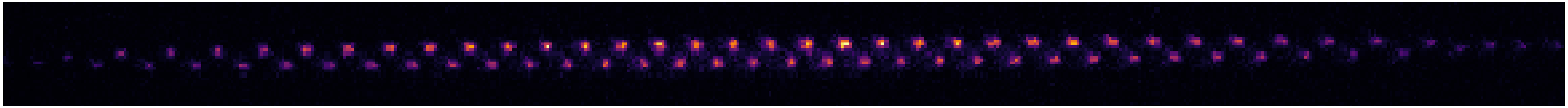


Scaling: long chain

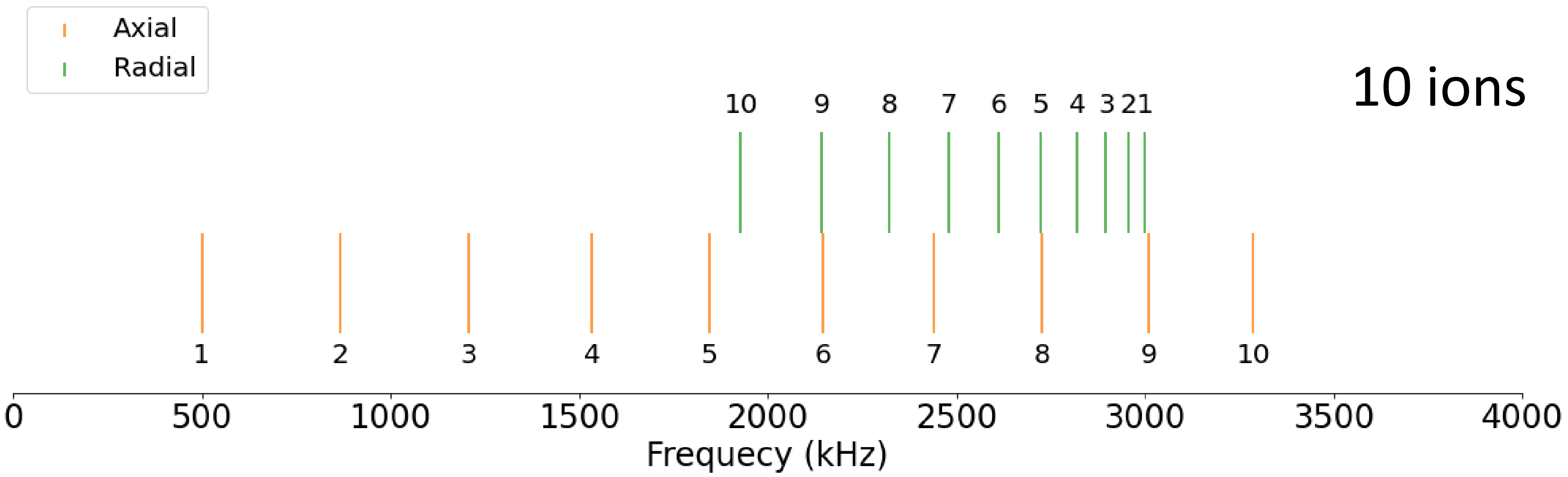
With longer chains:

- More RF power
- Harder to address



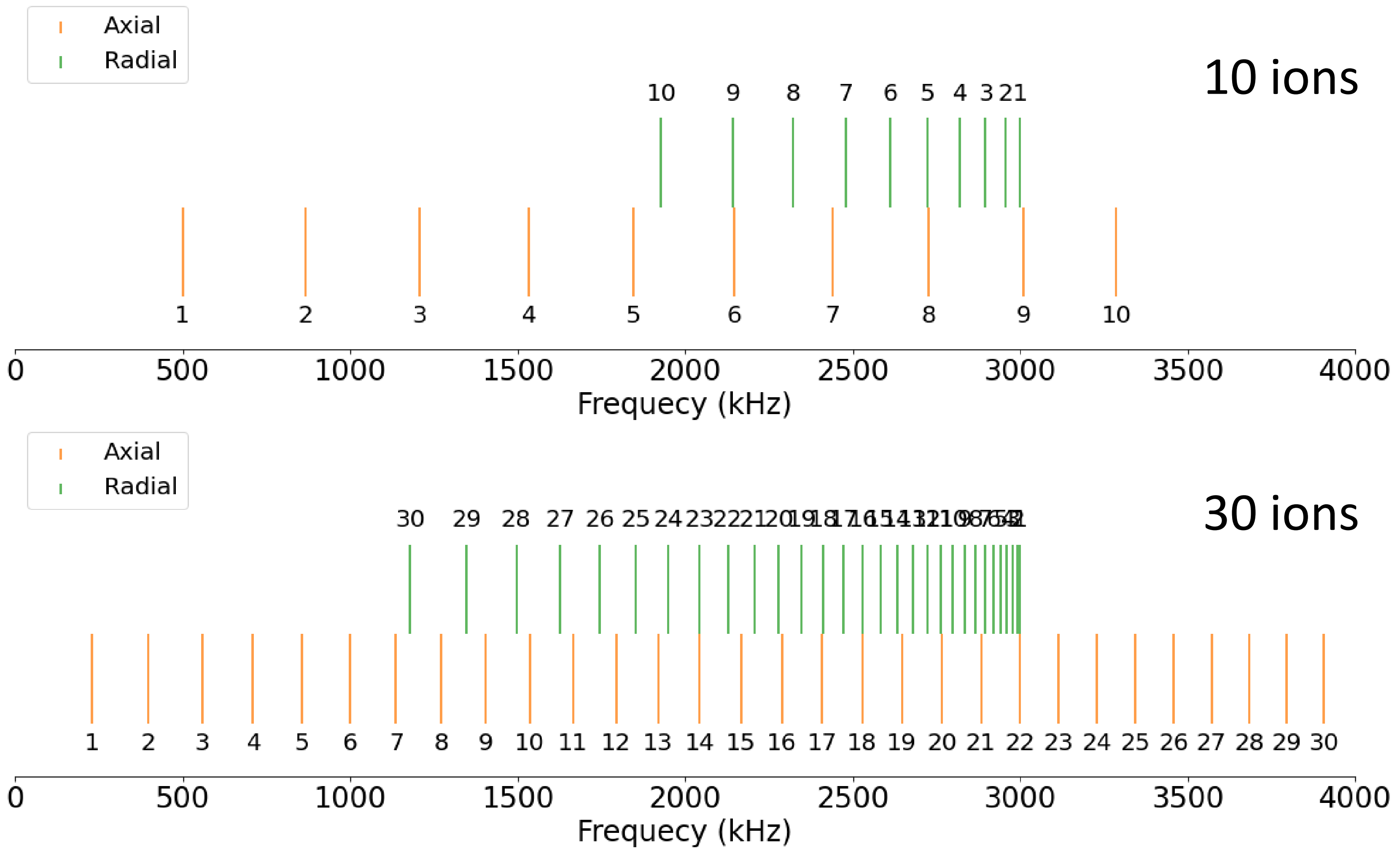


Scaling: spectrum



10 ions

Scaling: spectrum



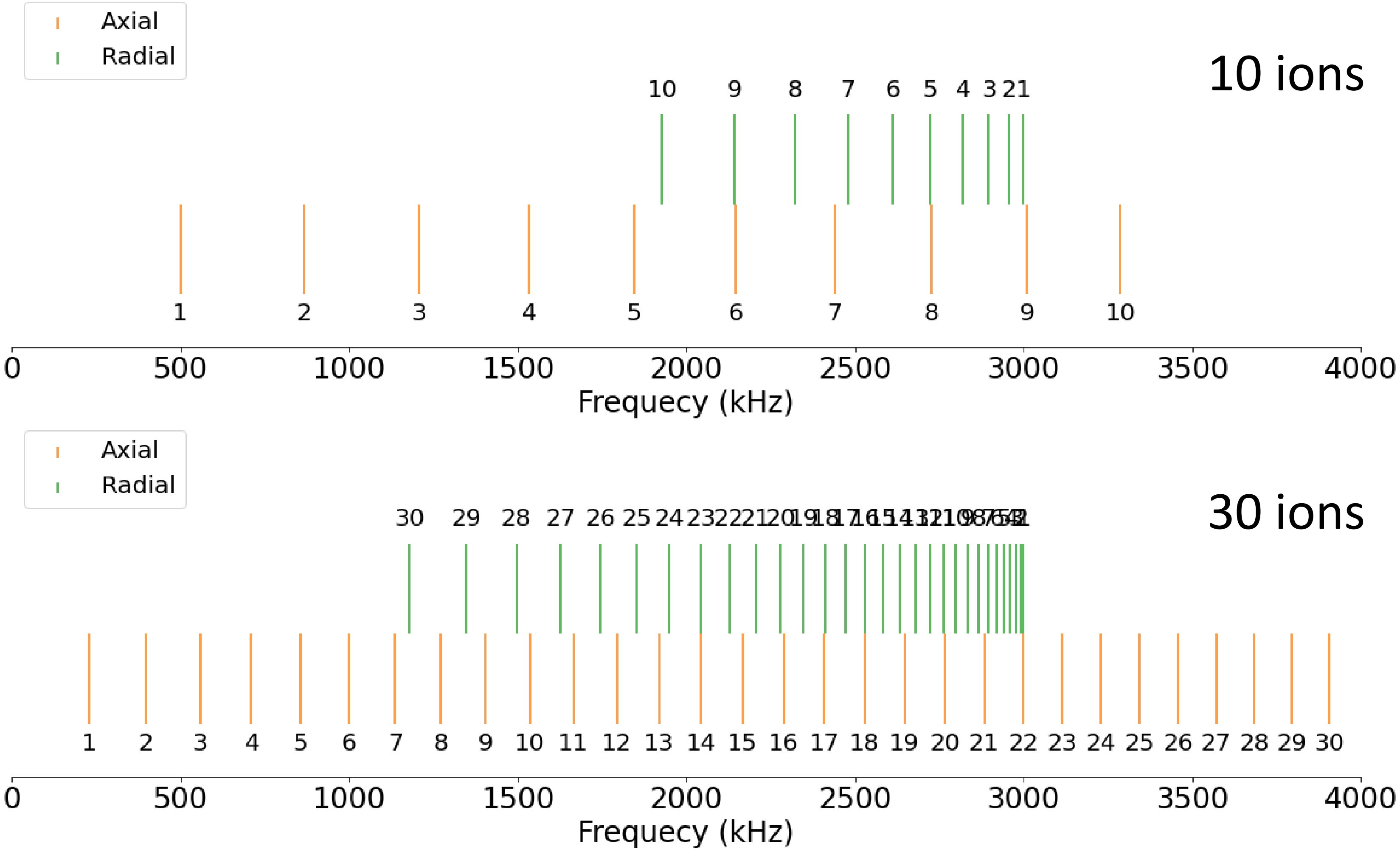
Scaling: spectrum

Axial:

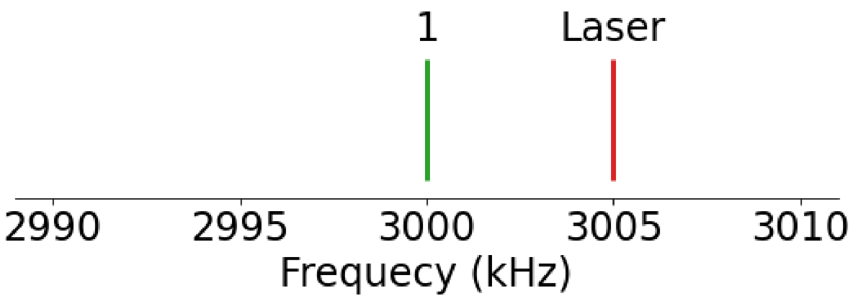
- More cross-talk
- Higher heating rates

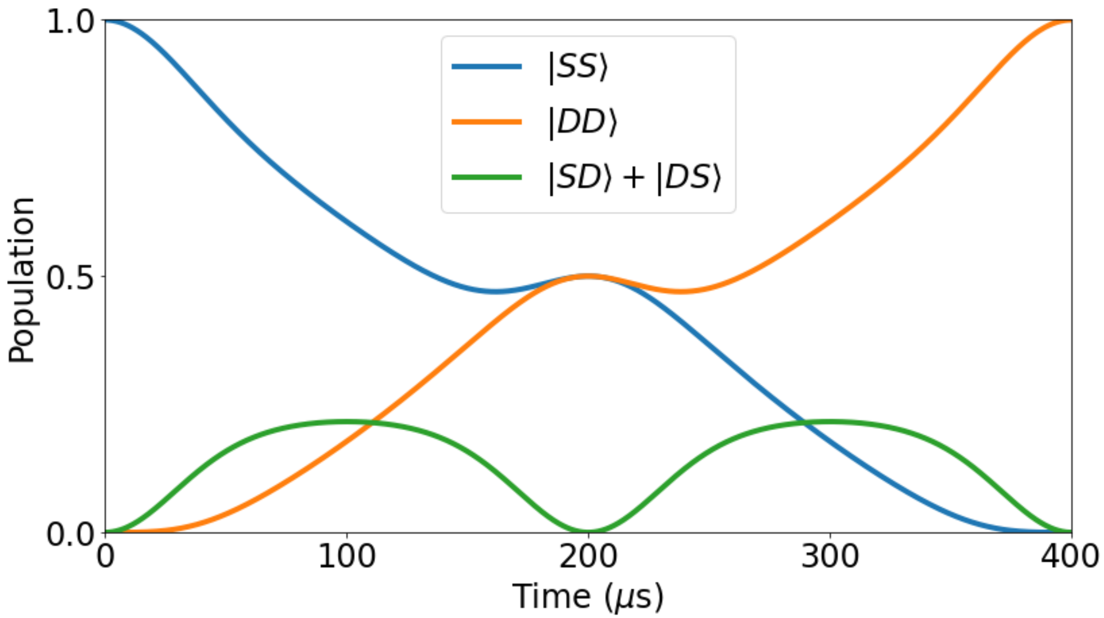
Radial:

- Modes are too close
- Axials are too hot



Scaling: spectrum – MS gates





1

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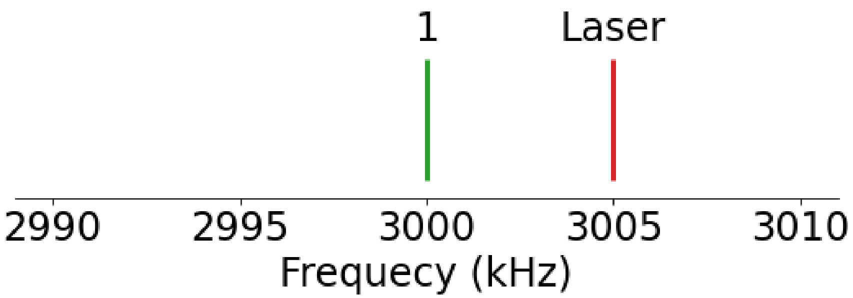
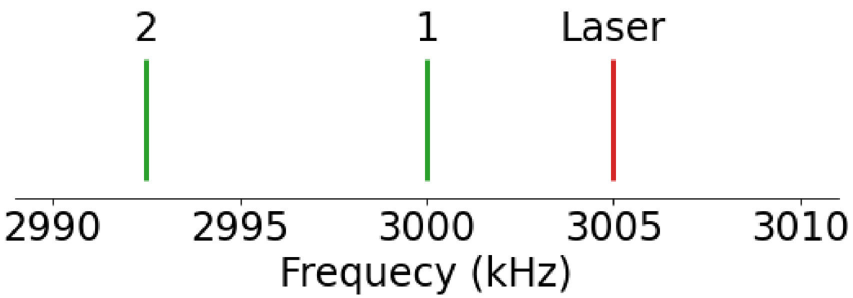
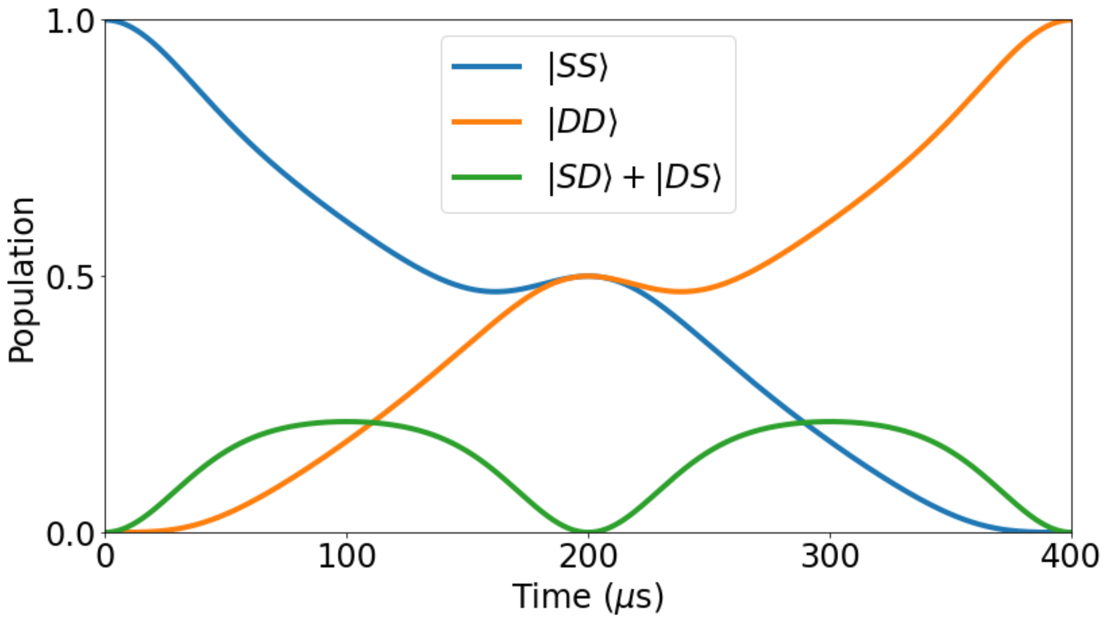
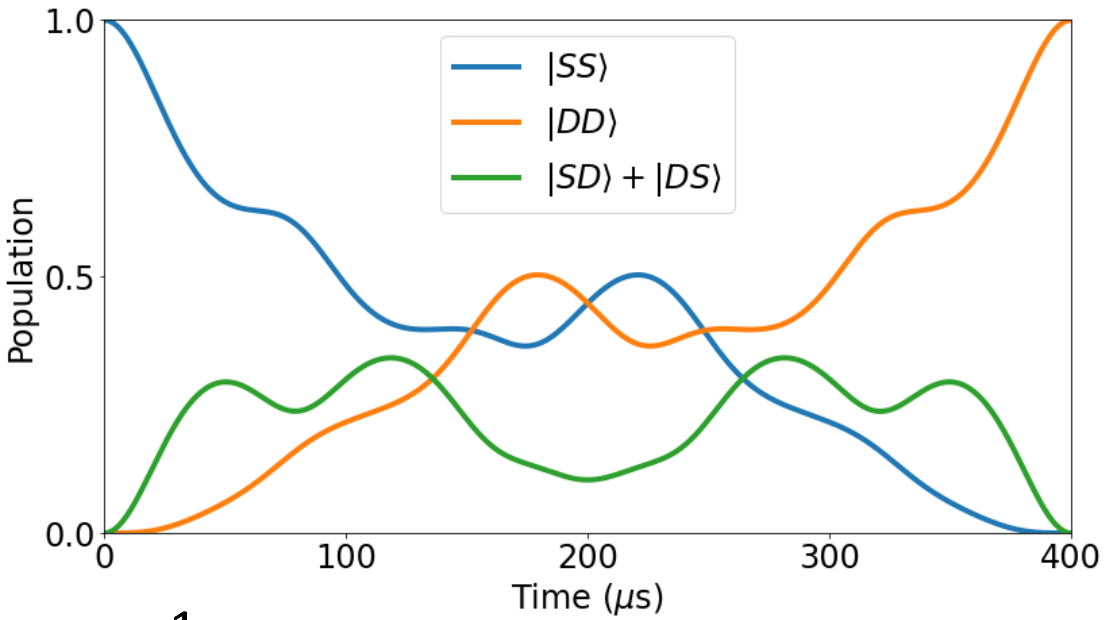


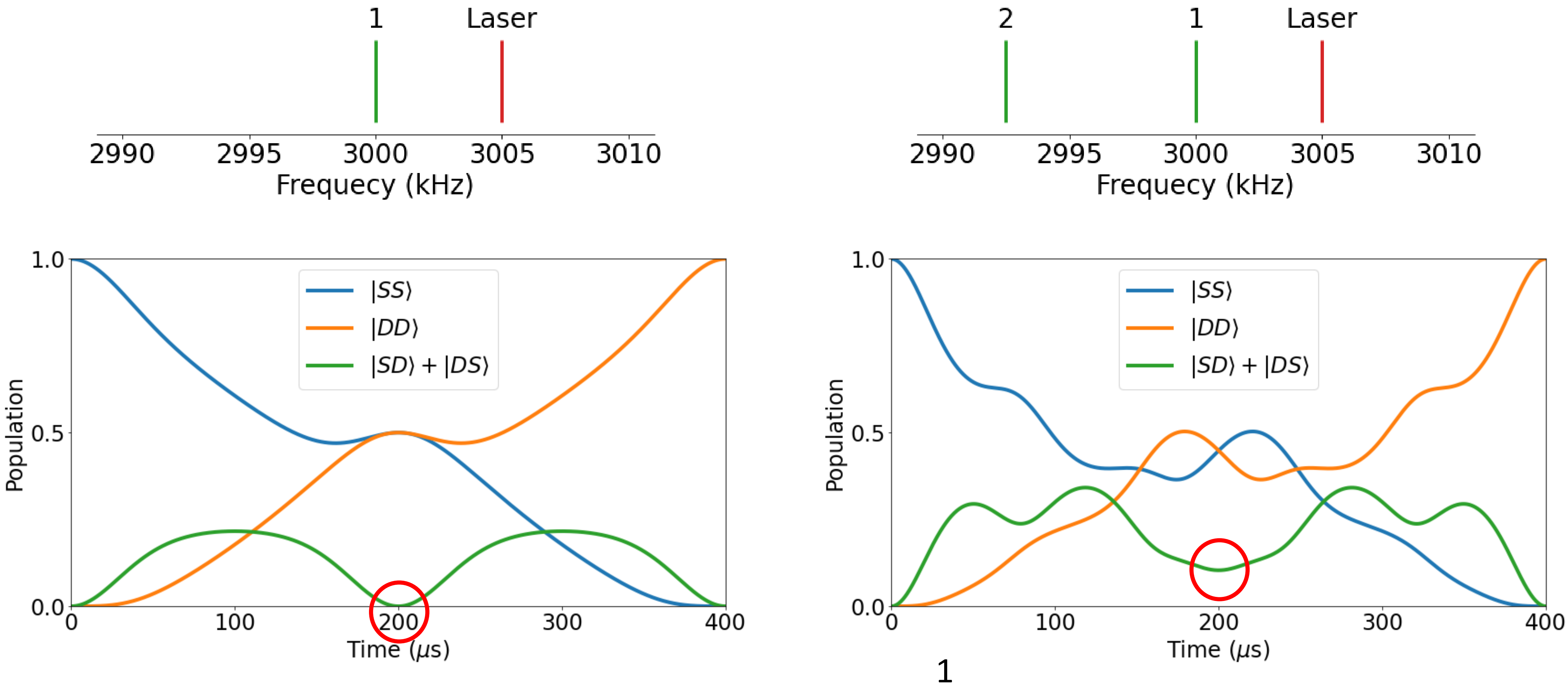






1

Scaling: spectrum – MS gates



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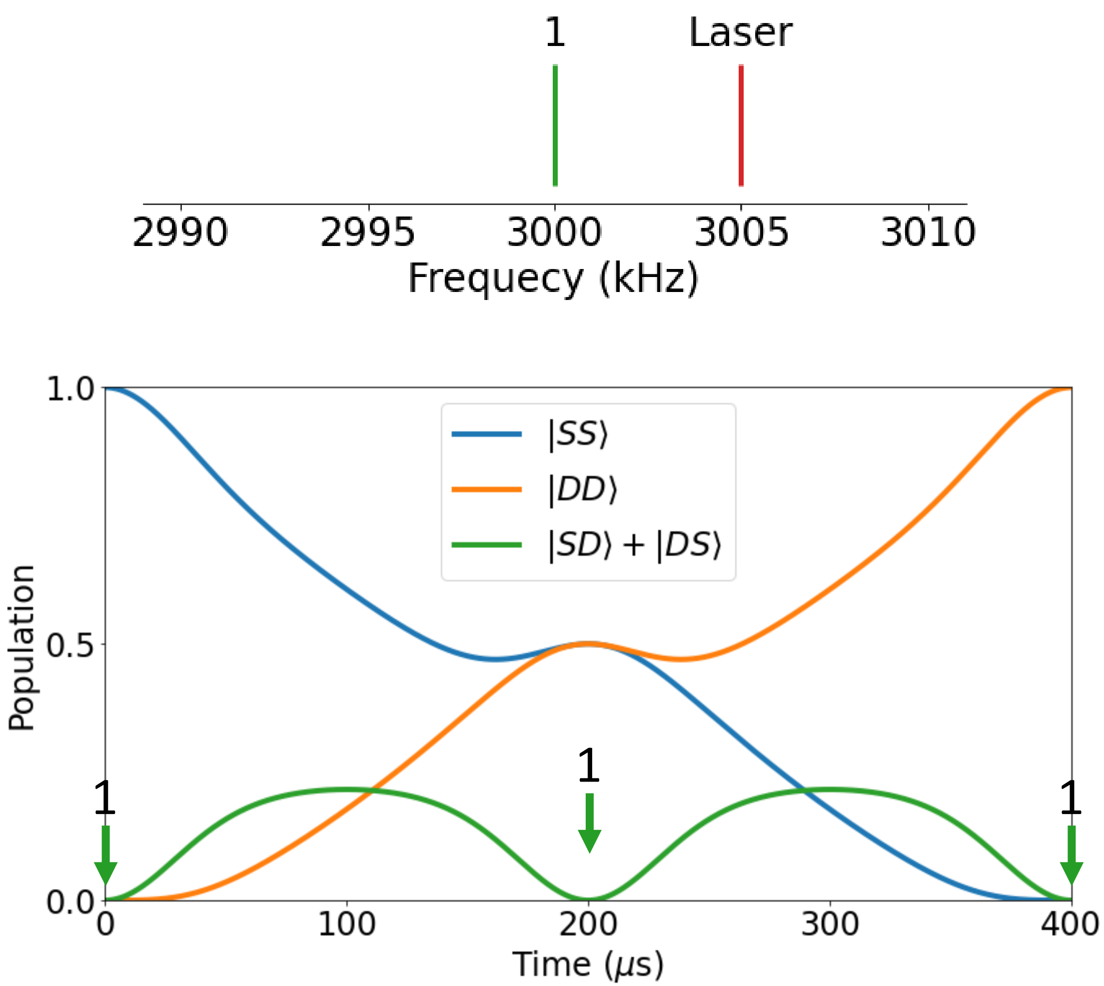
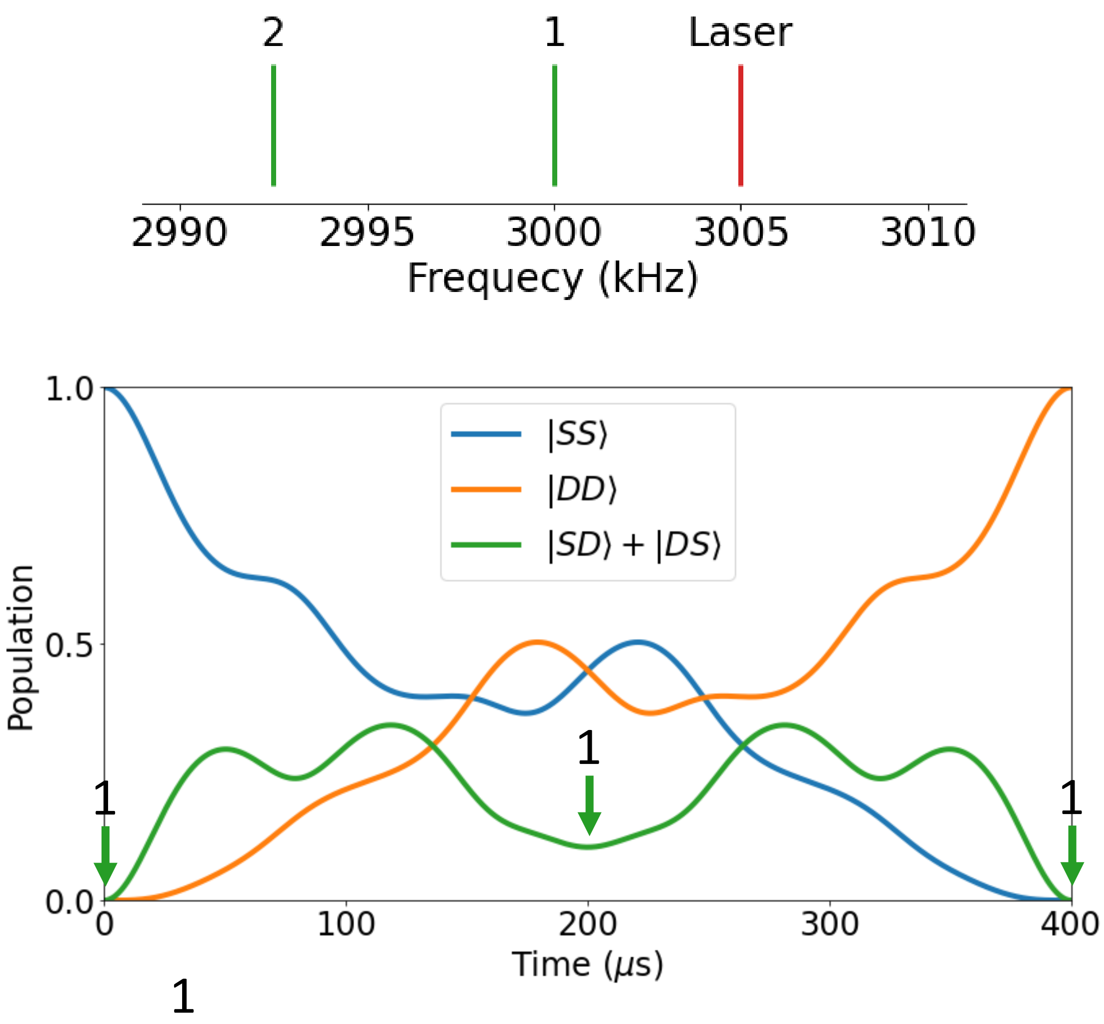
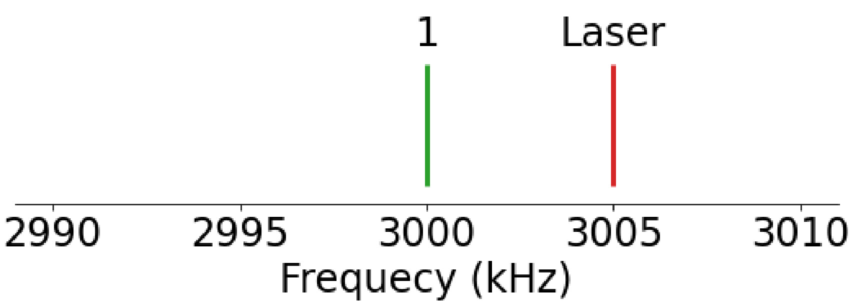
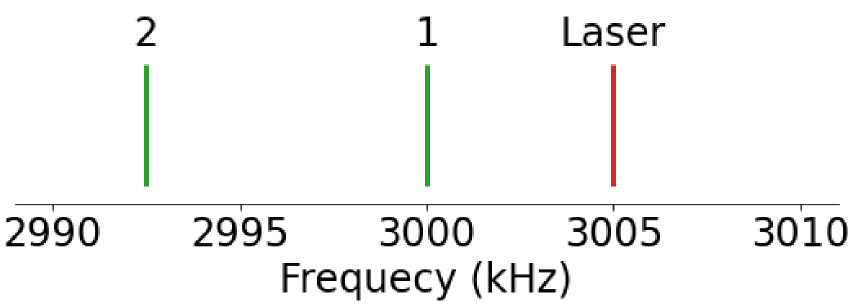
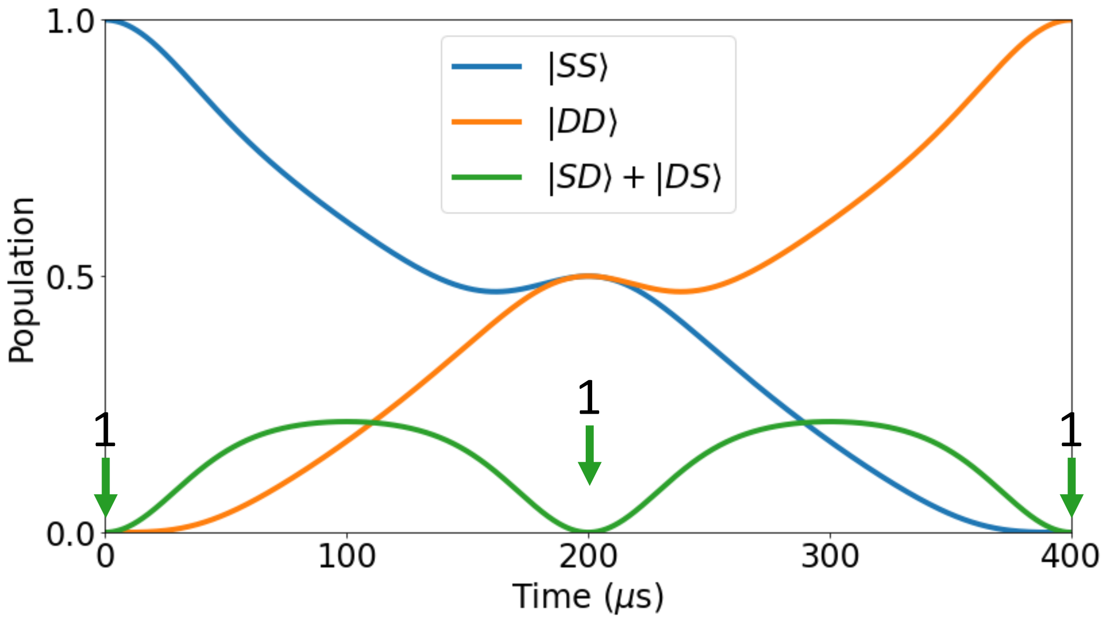


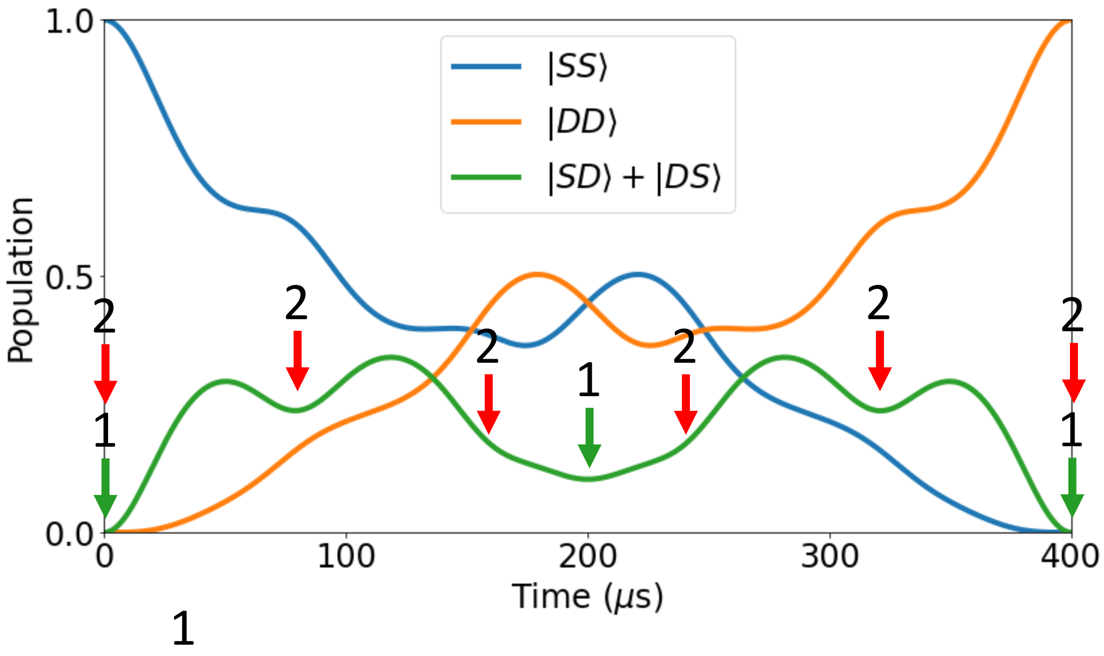


Scaling: spectrum – MS gates

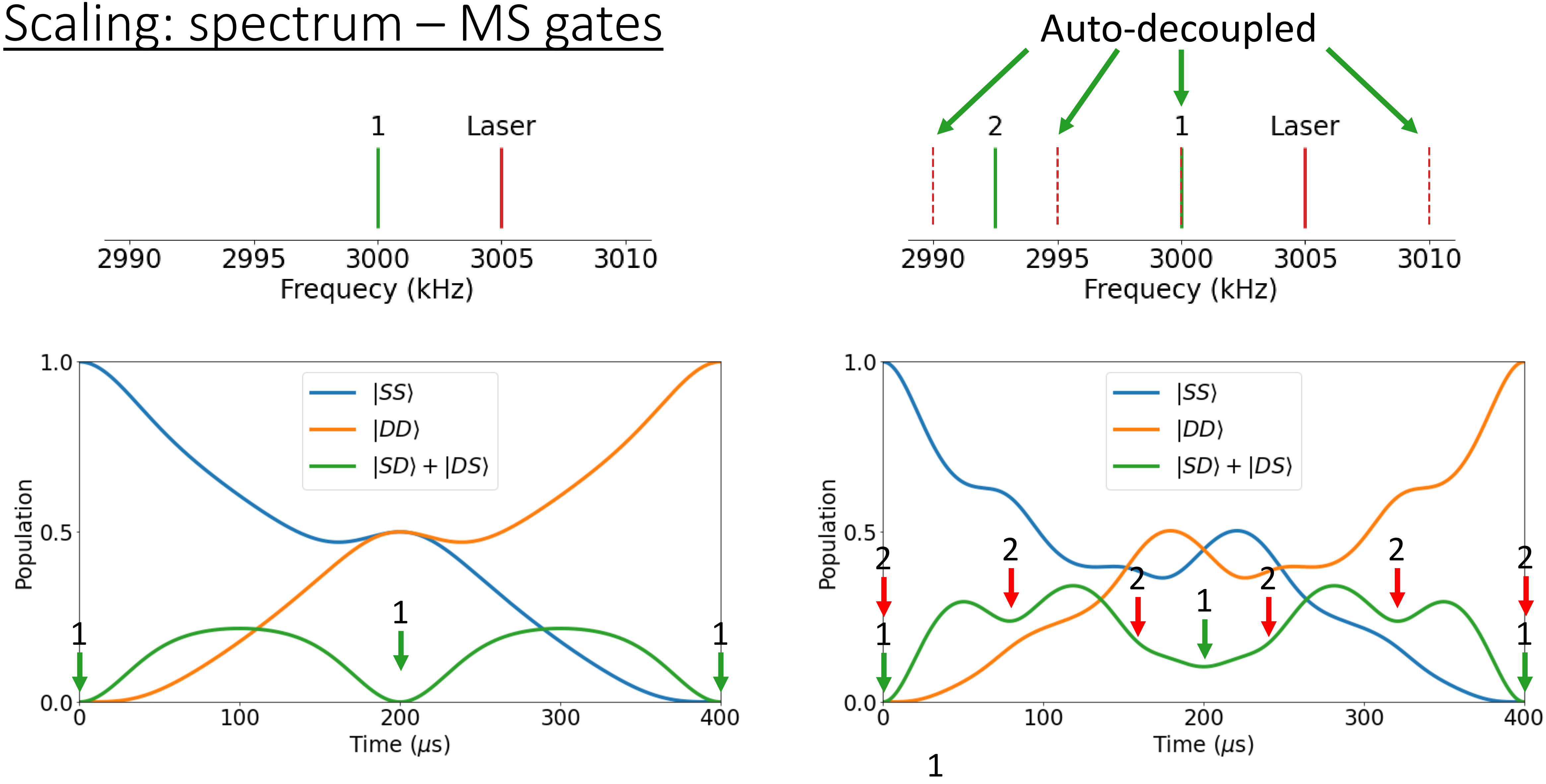




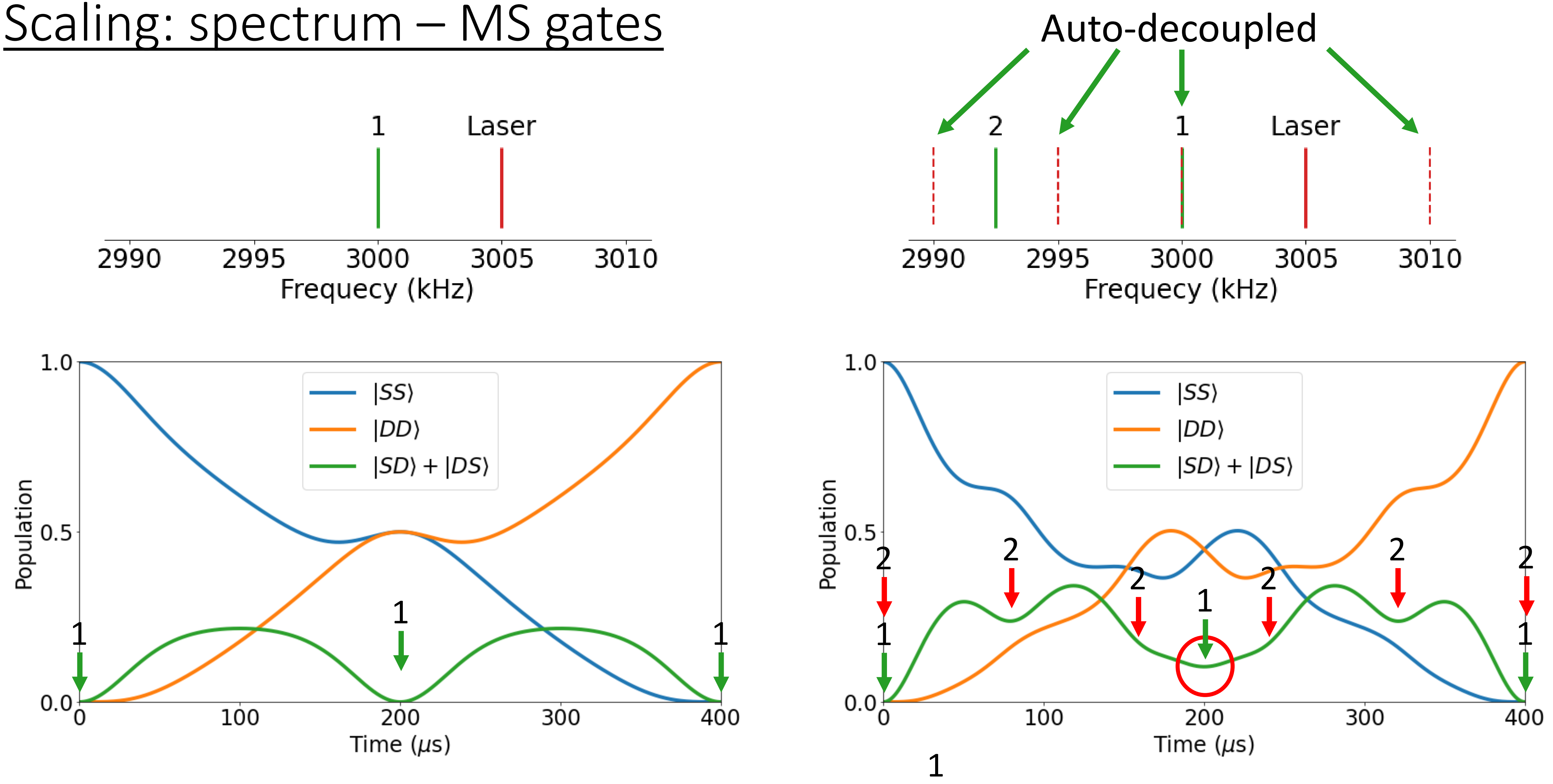




Scaling: spectrum – MS gates

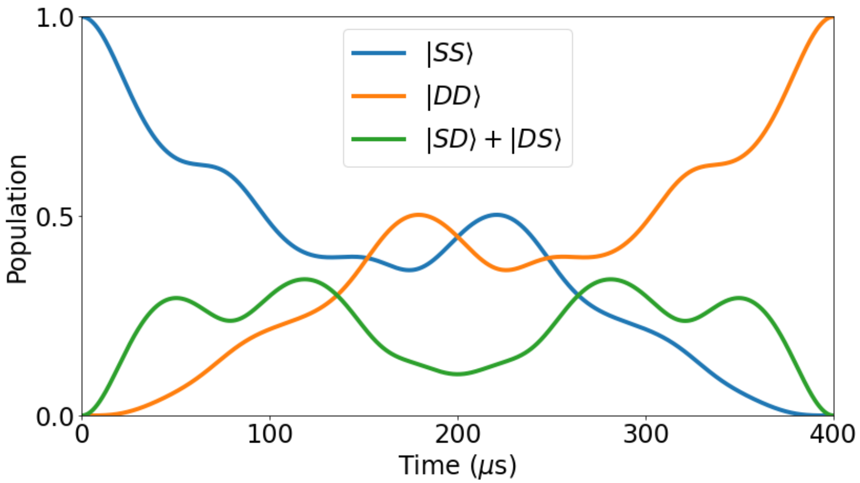


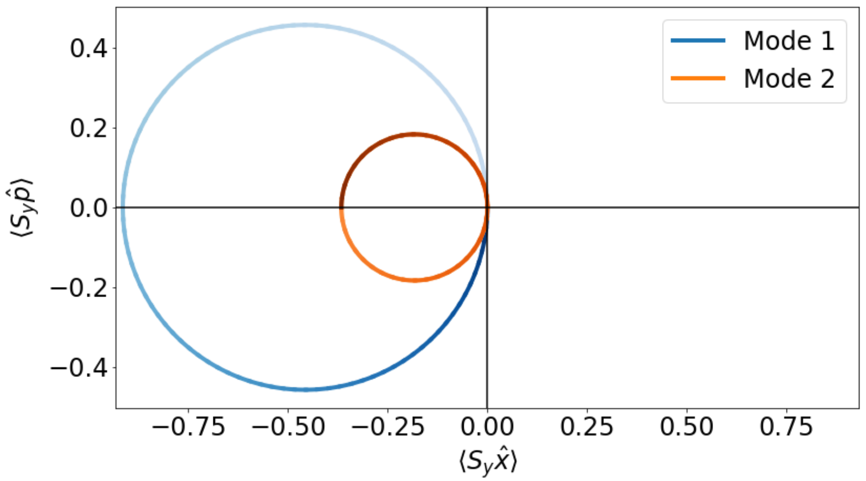
Scaling: spectrum – MS gates



Modulated MS gate

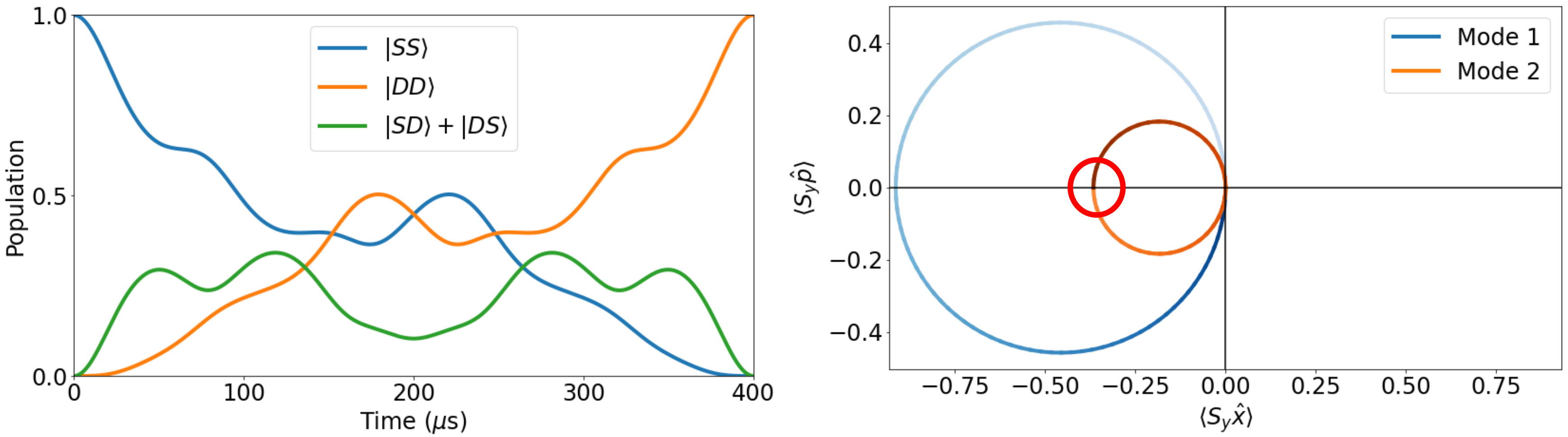
Unmodulated





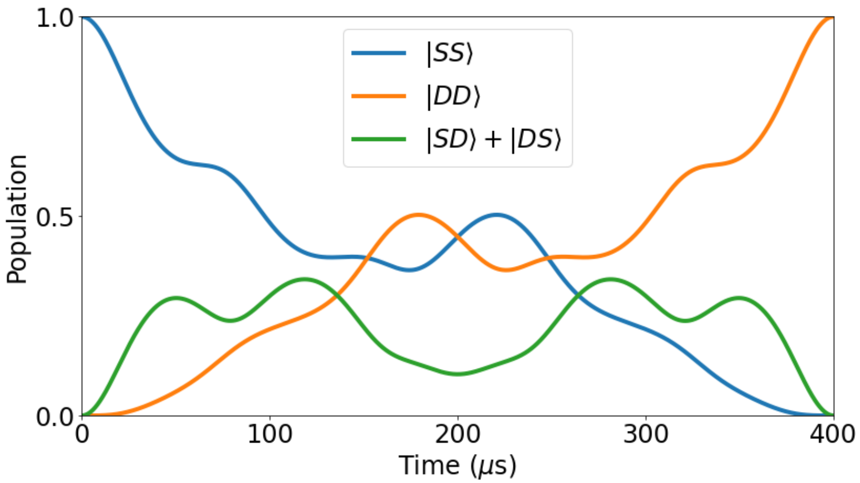
Modulated MS gate

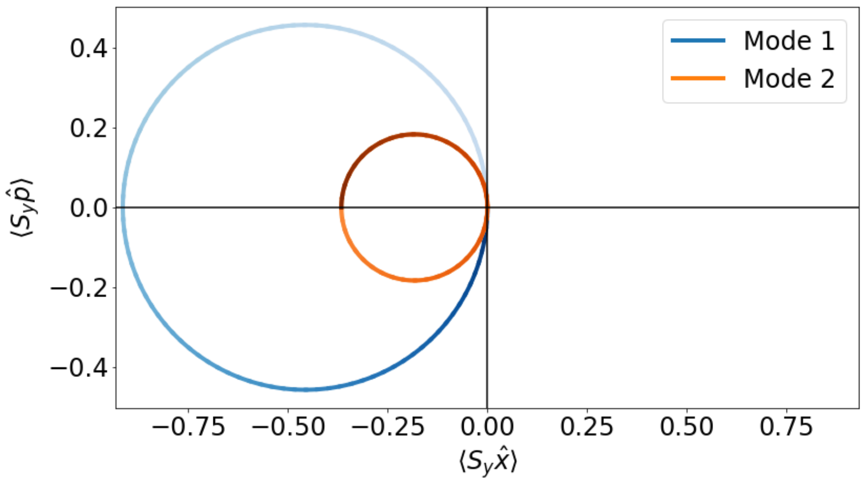
Unmodulated



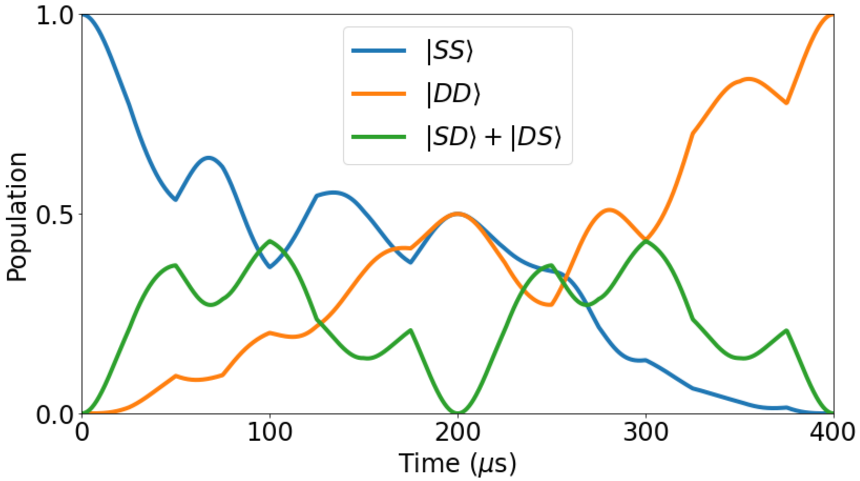
Modulated MS gate

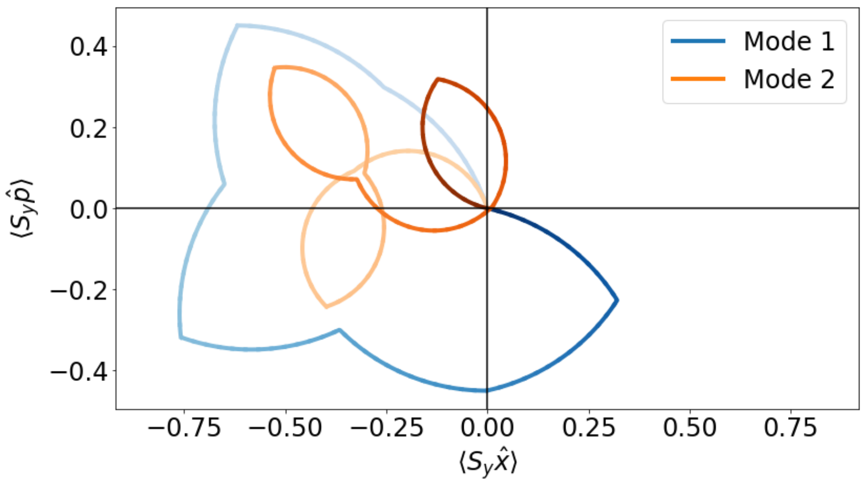
Unmodulated



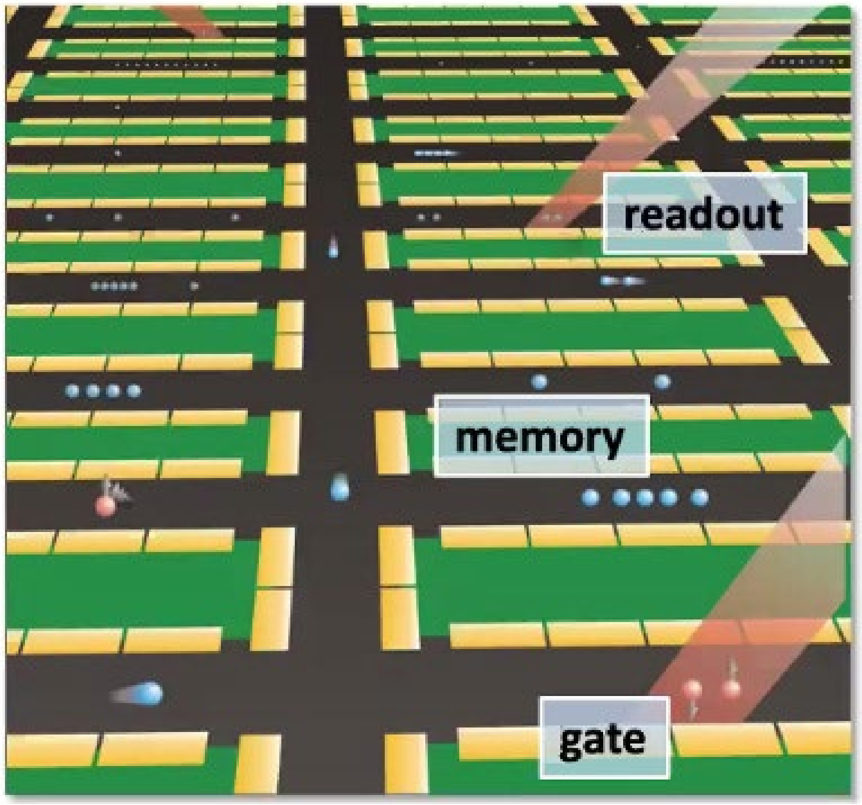


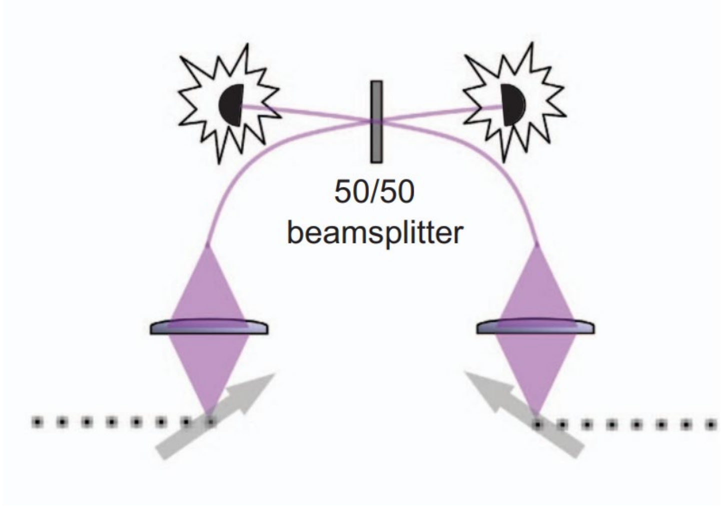
Phase modulated

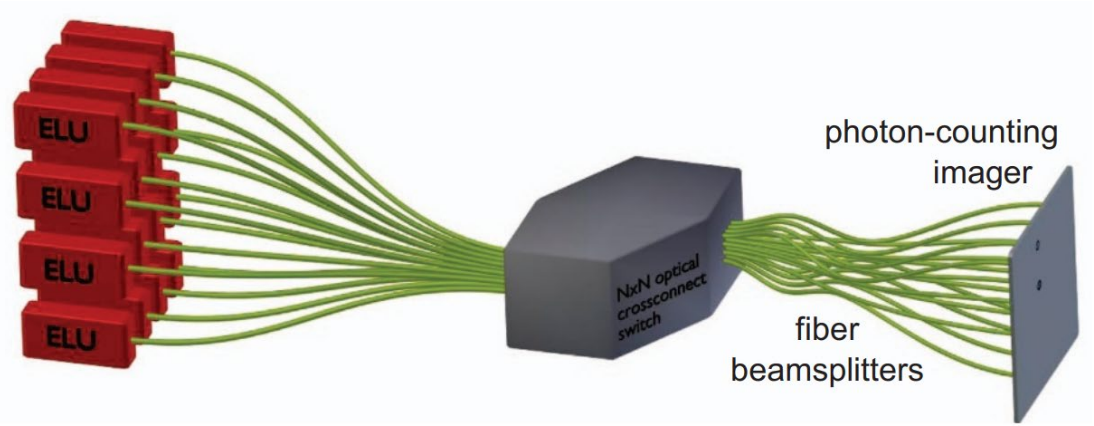




‘Scalable solutions’







Daniel Slichter, NIST/OSA Quantum 2.0 Conference

Brown, K et al. npj Quantum Inf 2, 16034 (2016)

Outline

1. Trapping
2. State manipulation
   - $^{40}Ca^{+}$
   - Optical pumping
   - Sideband cooling
   - Detection
3. Qubit manipulation
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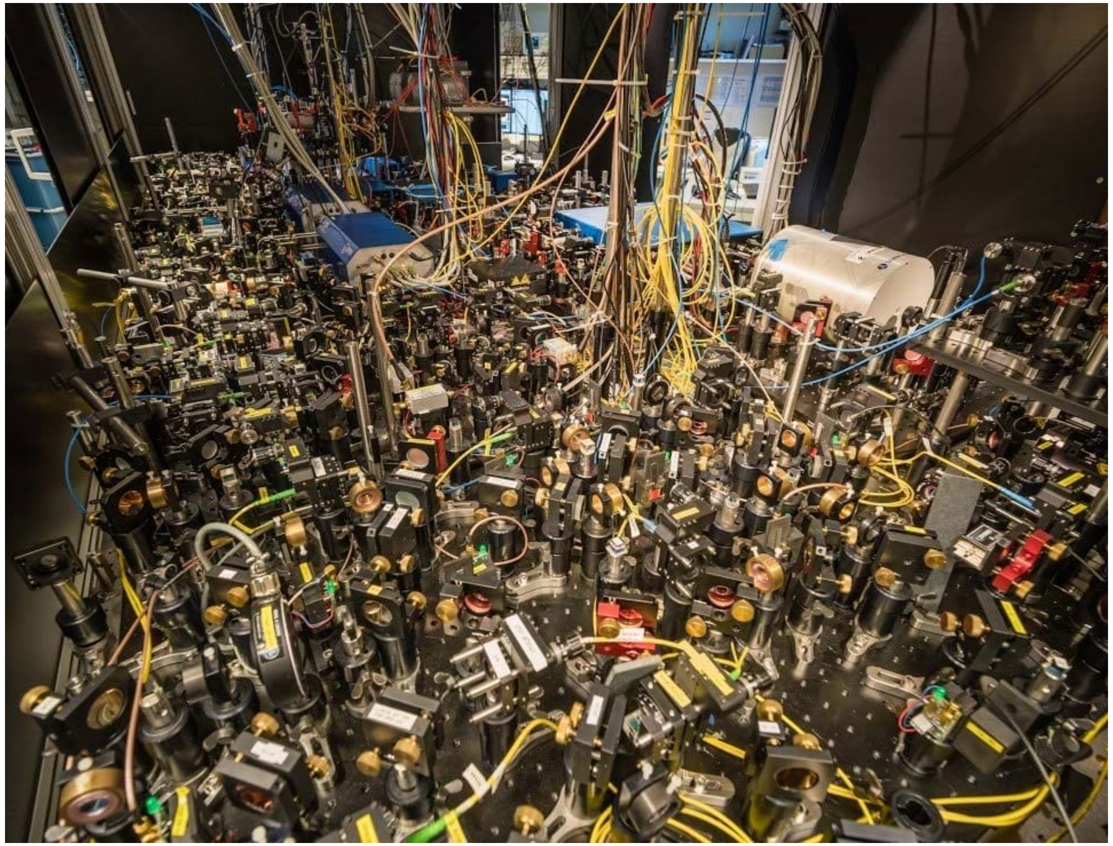
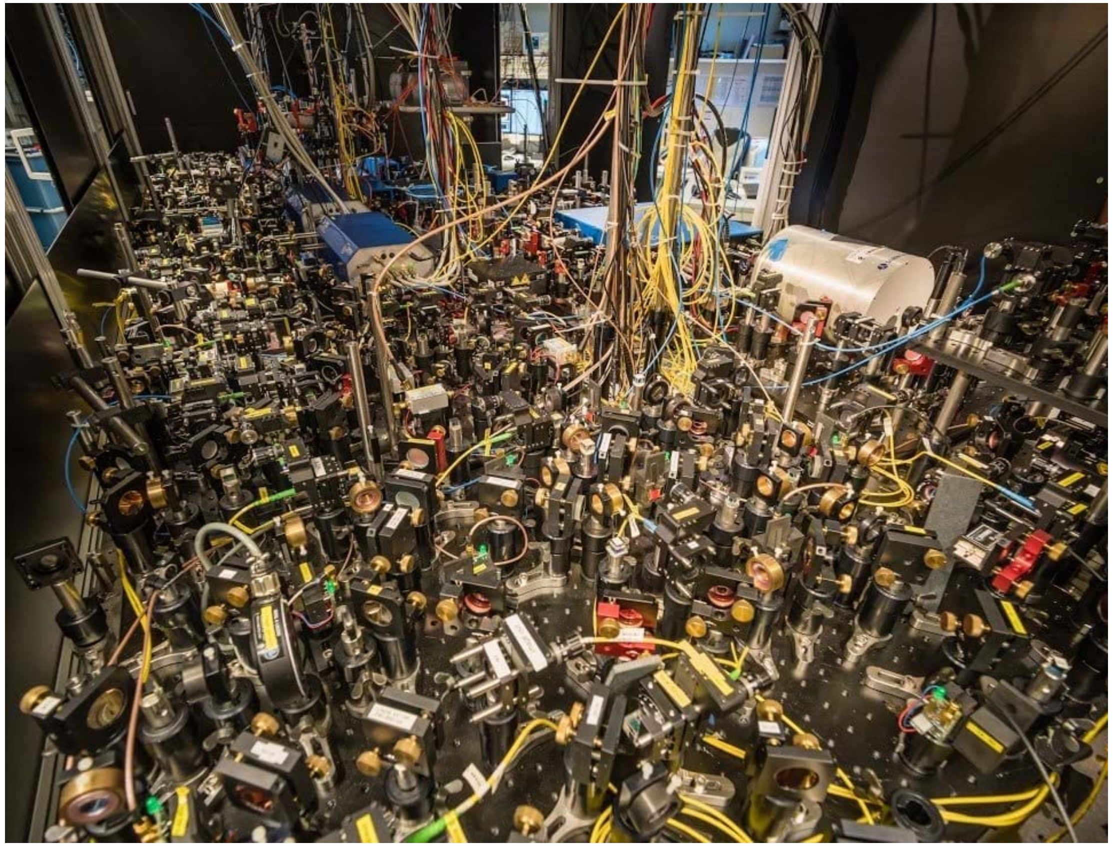
   - Compact optics
   - Trap drawer
   - Vibrations
   - Addressing
7. Automation
   - Keeping constant fidelity
8. Performance
   - Benchmarking
   - Quantum volume

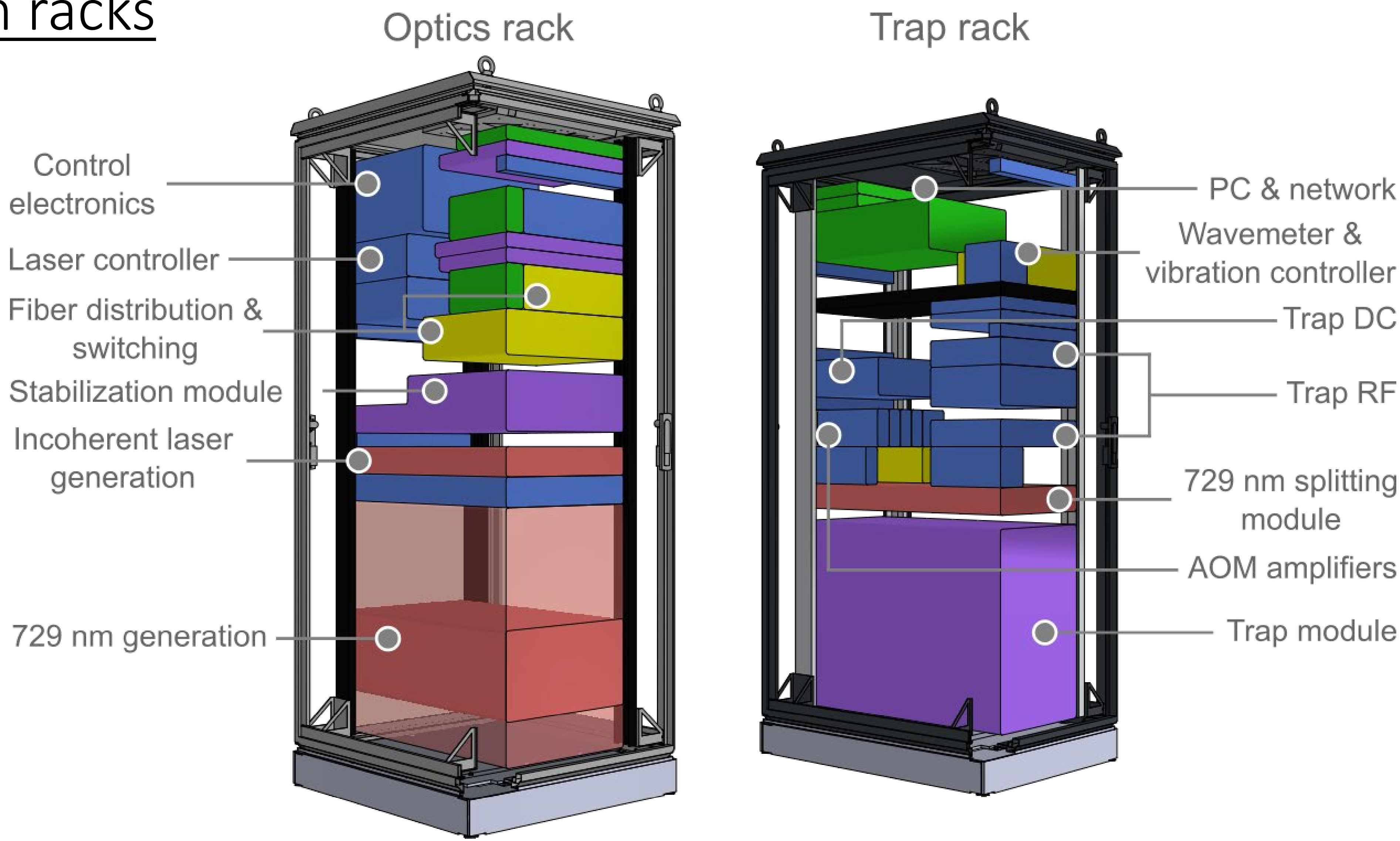
AQTION project (not AQT)



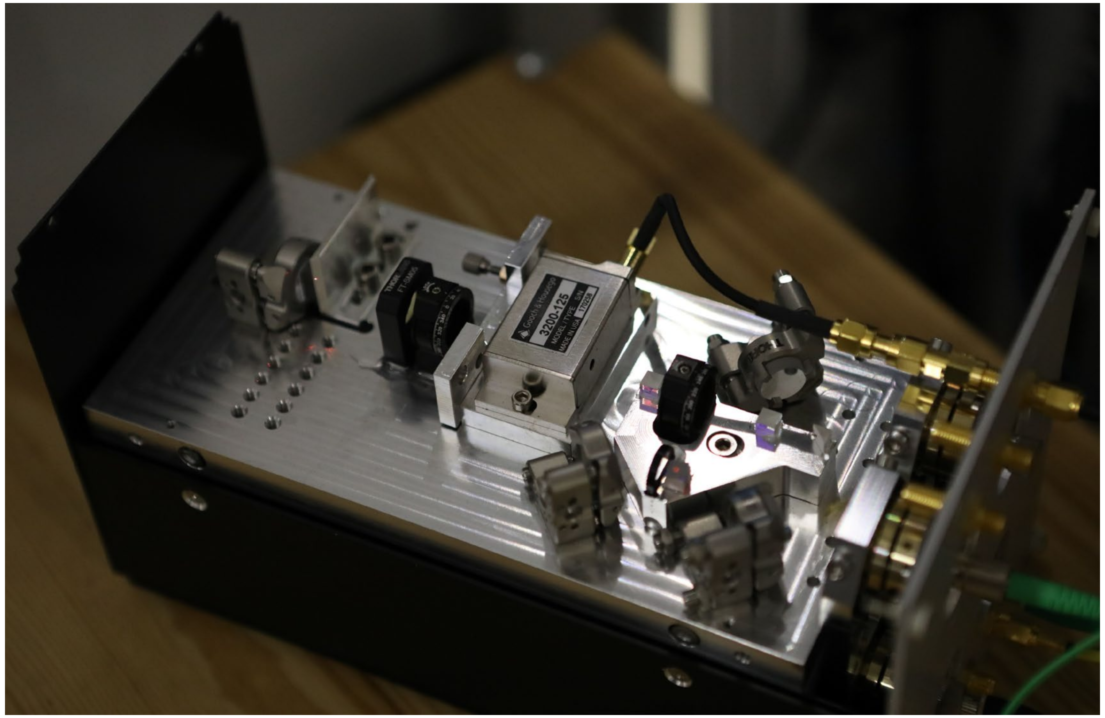
AQTION project (not AQT)

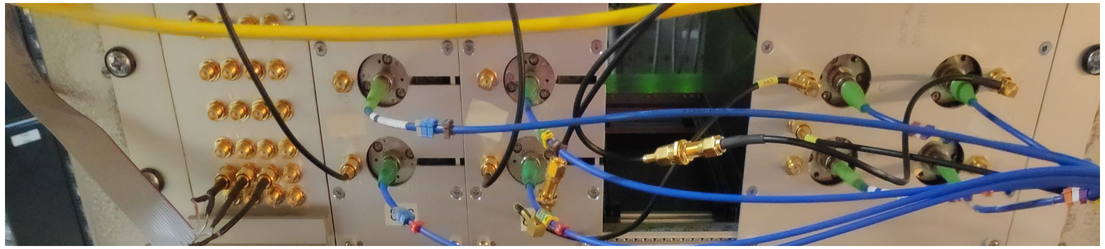


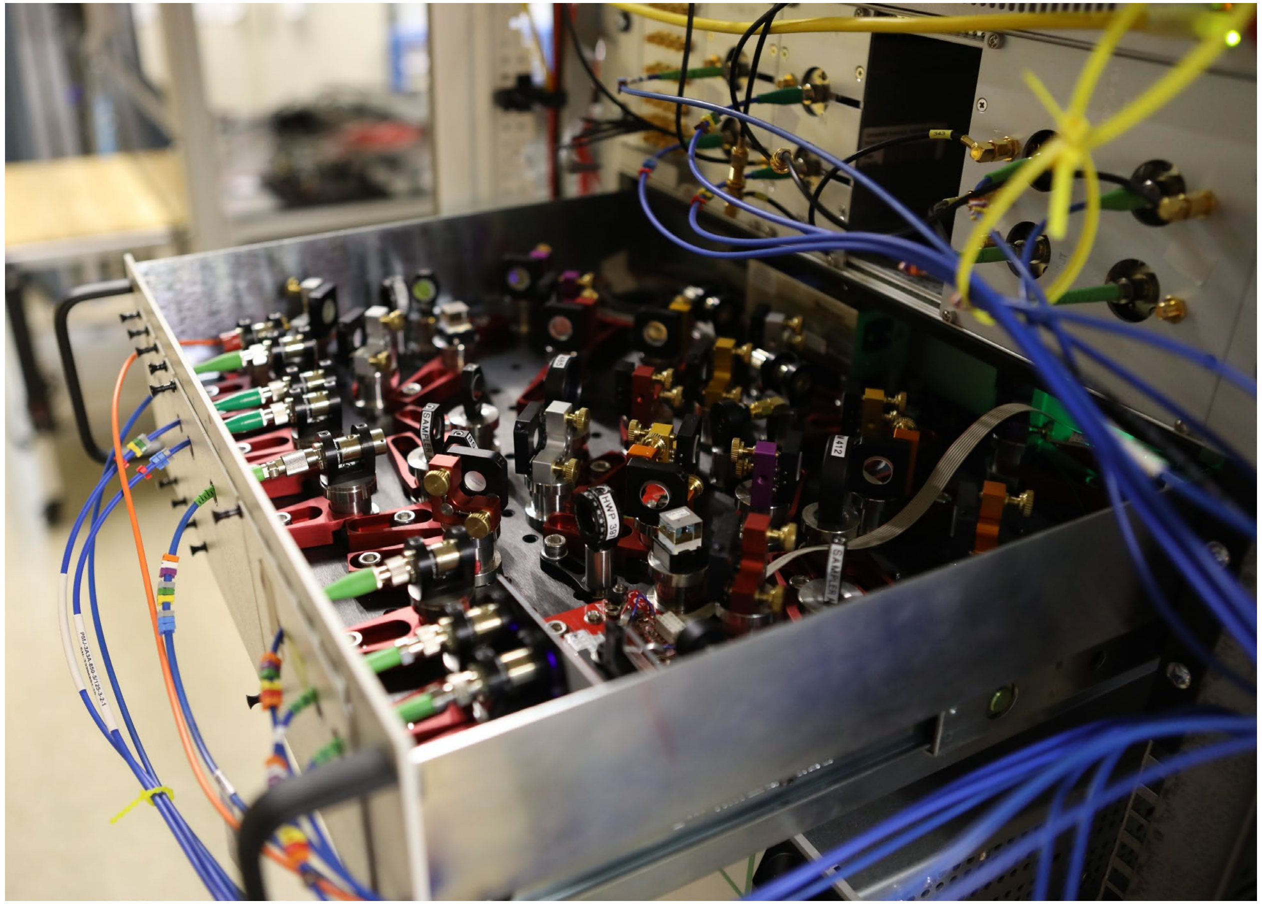
19 inch racks



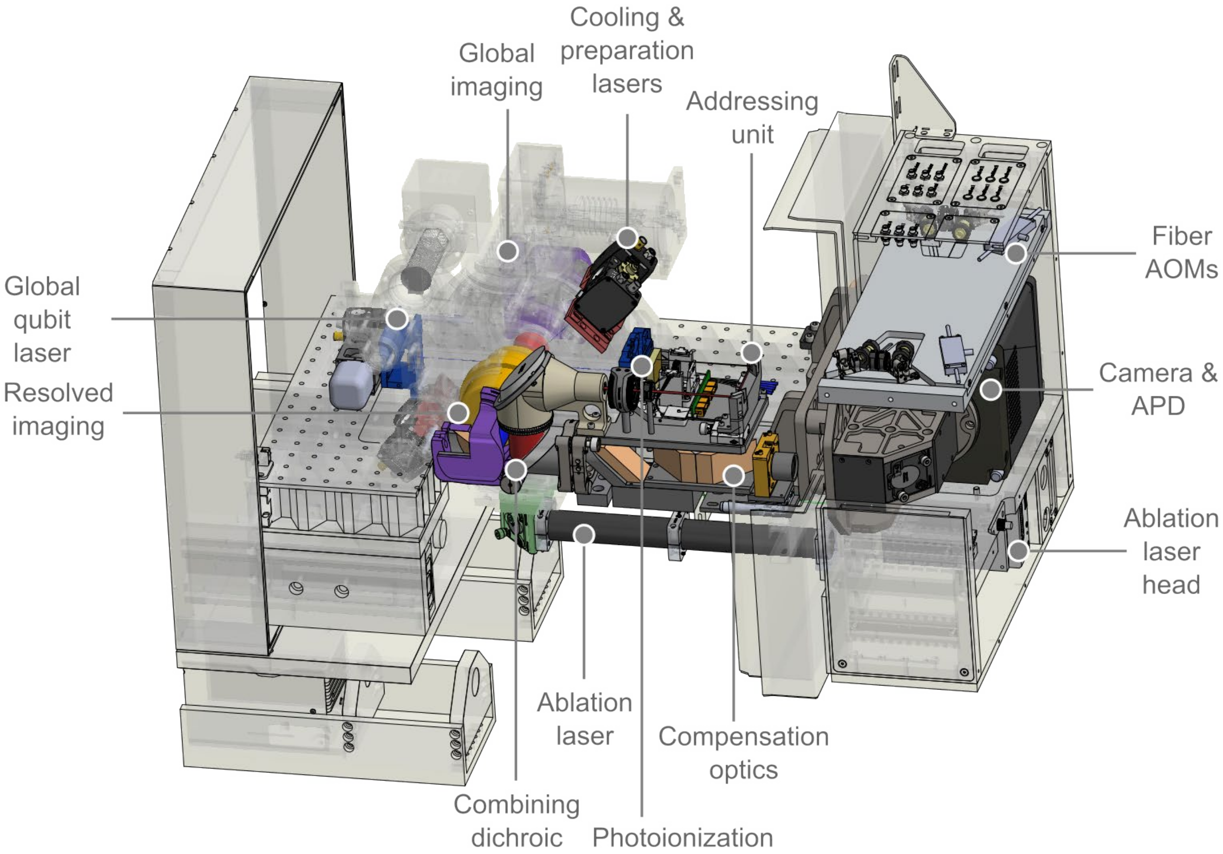
Compact optics



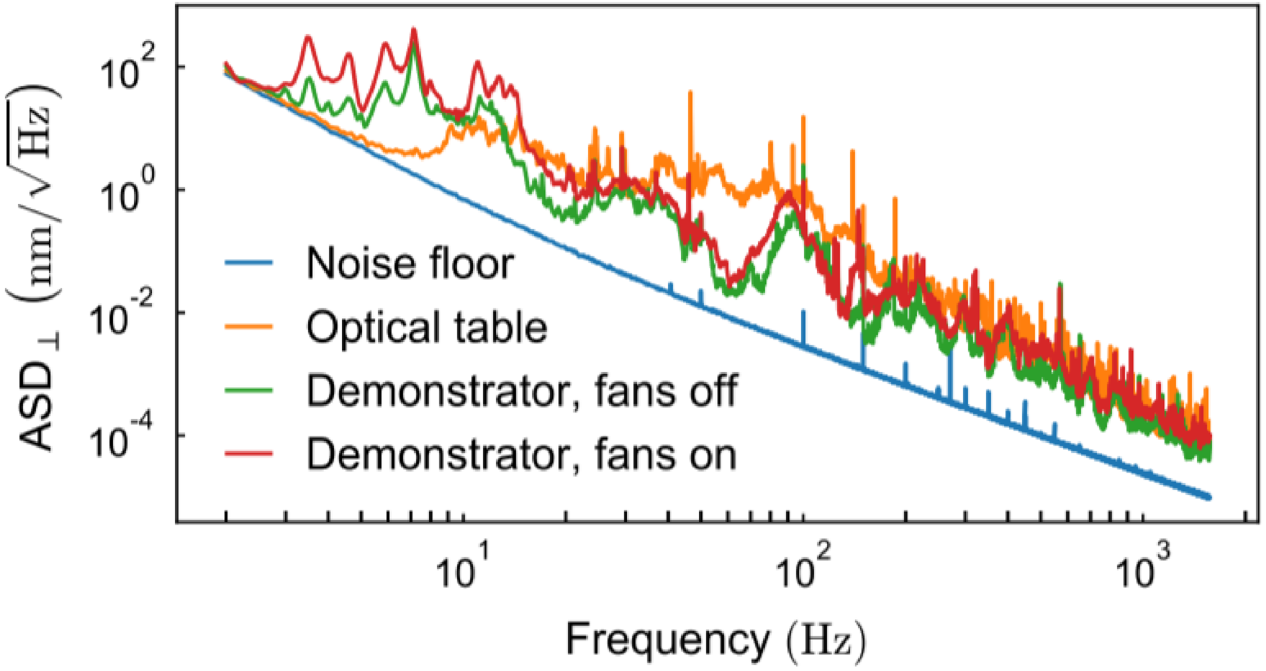




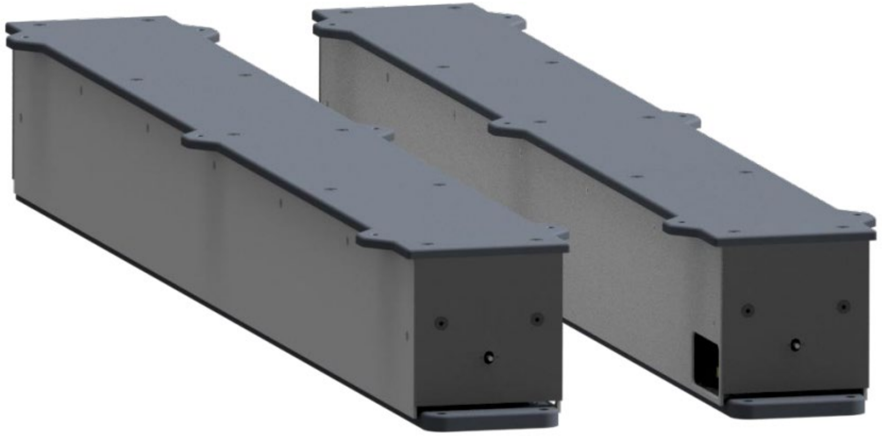
Trap drawer


Global imaging
Cooling & preparation lasers
Addressing unit
Fiber AOMs
Global qubit laser
Resolved imaging
Camera & APD
Ablation laser head
Ablation laser
Compensation optics
Combining dichroic
Photoionization

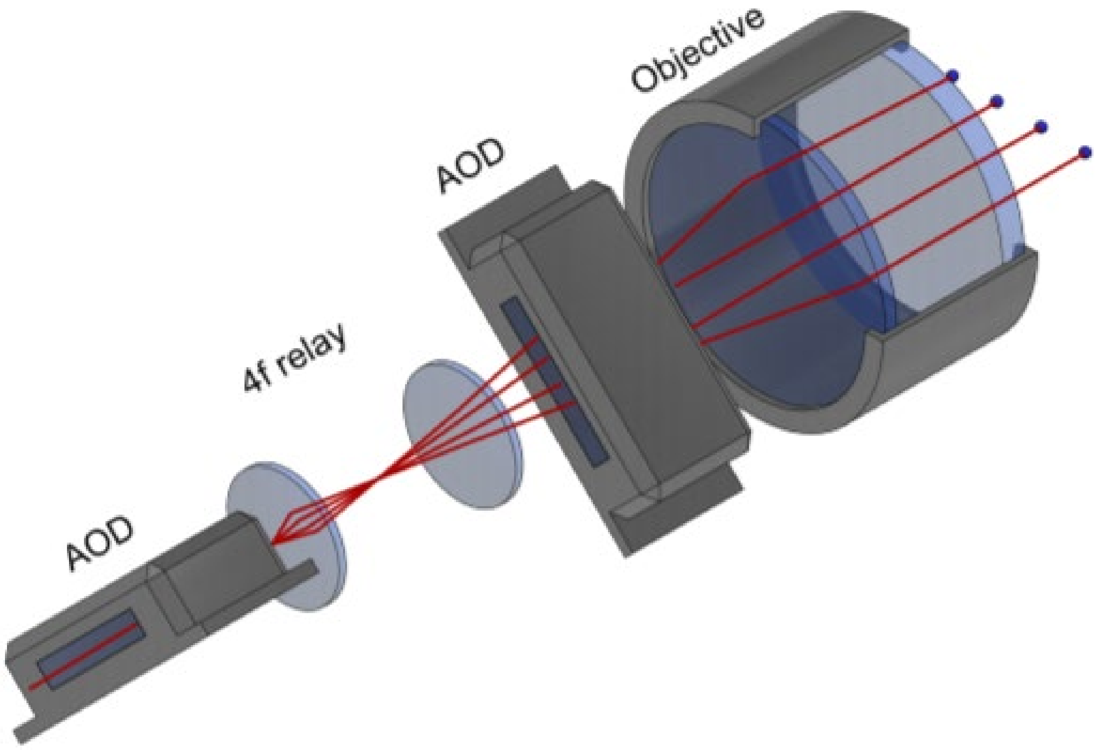
Vibration isolation

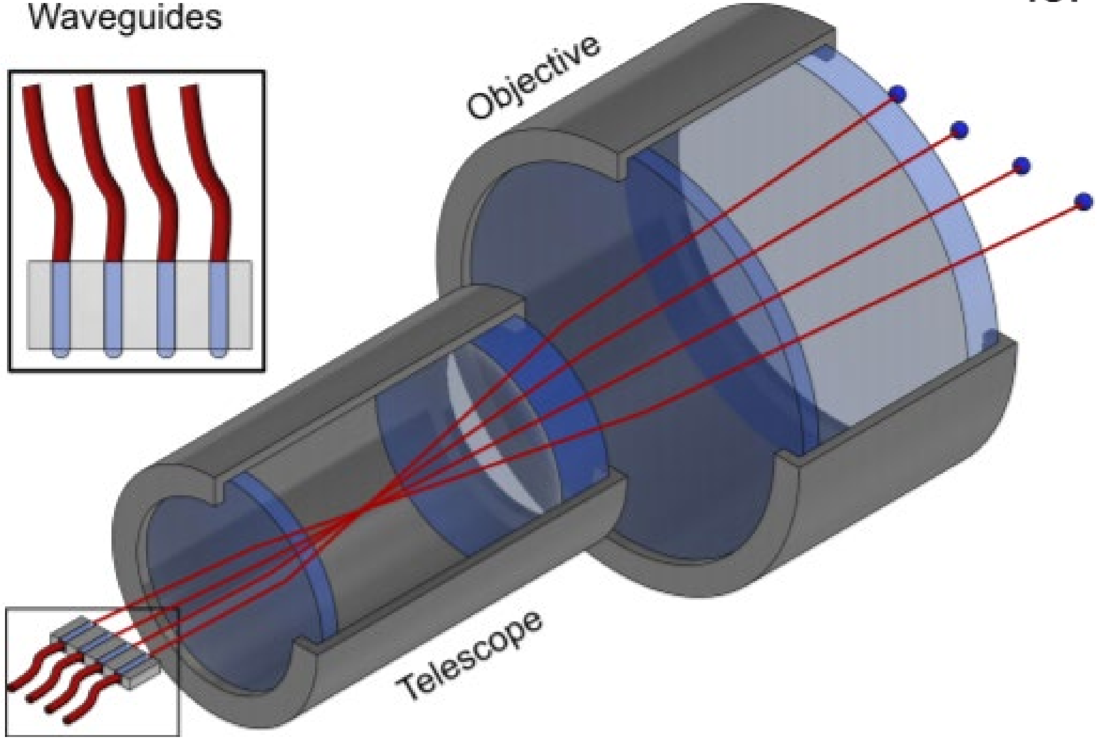


	Noise	Opt. table	Full w/o fans	Full w/ fans
$\text{RMS}_{\text{hor.}}$ (nm)	54	21	61	275
$\text{RMS}_{\text{vert.}}$ (nm)	50	33	139	335



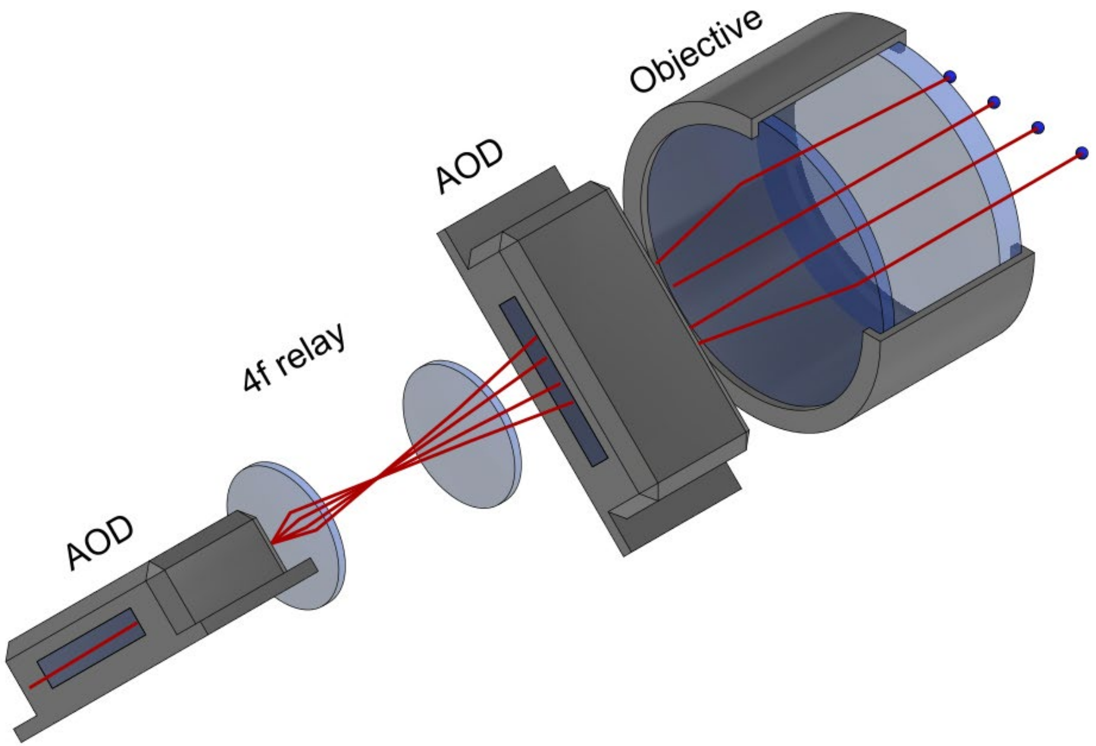
Single ion addressing



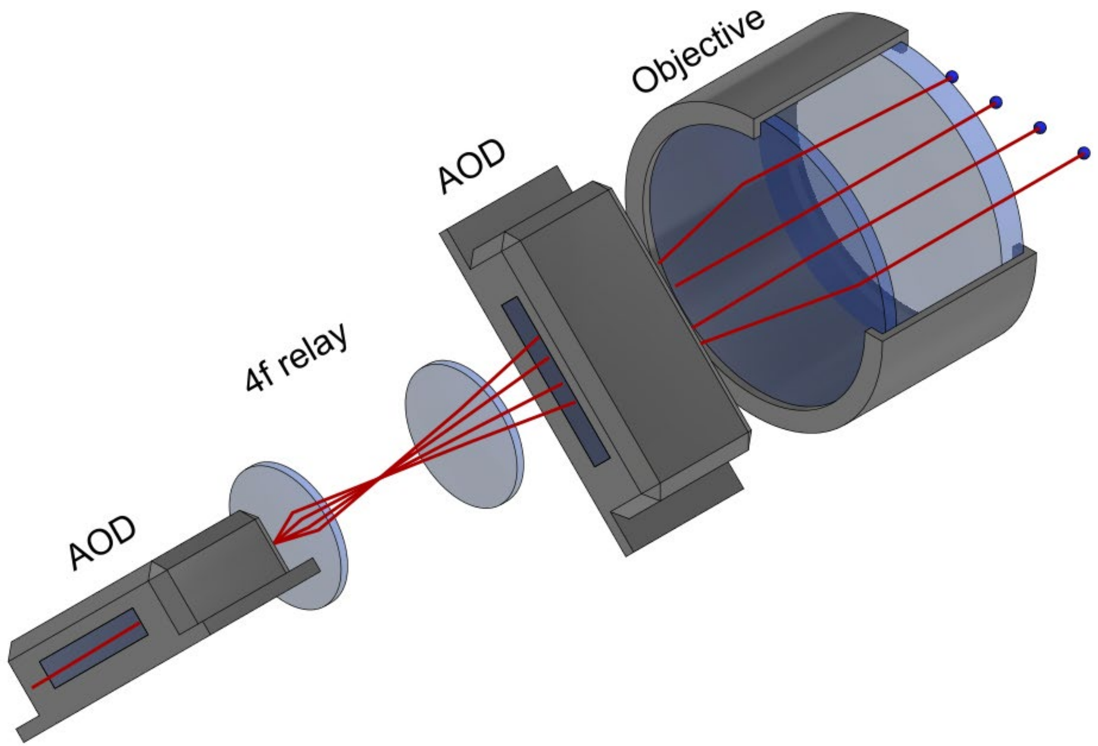


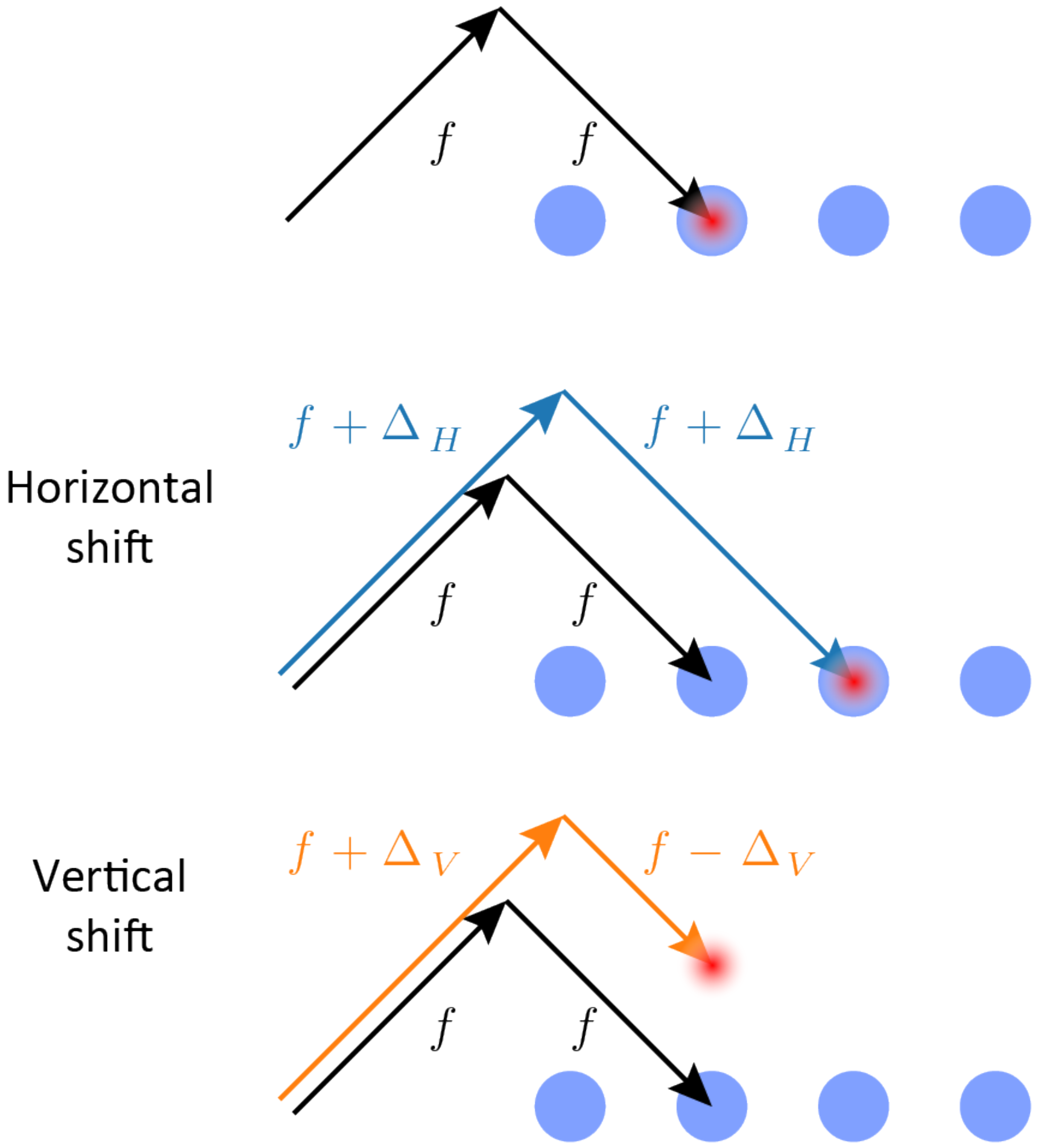
Fraunhofer IOF

Addressing unit

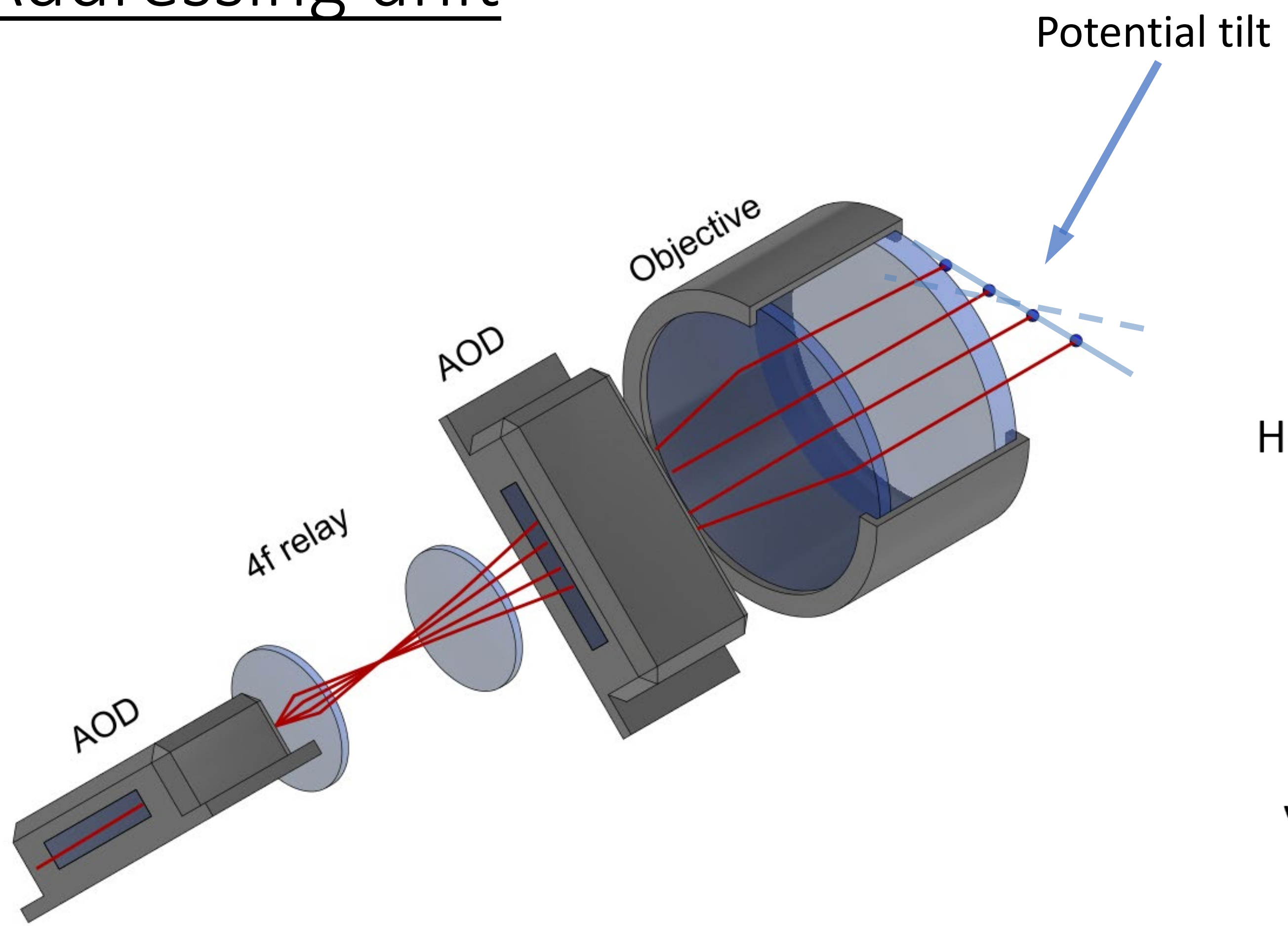


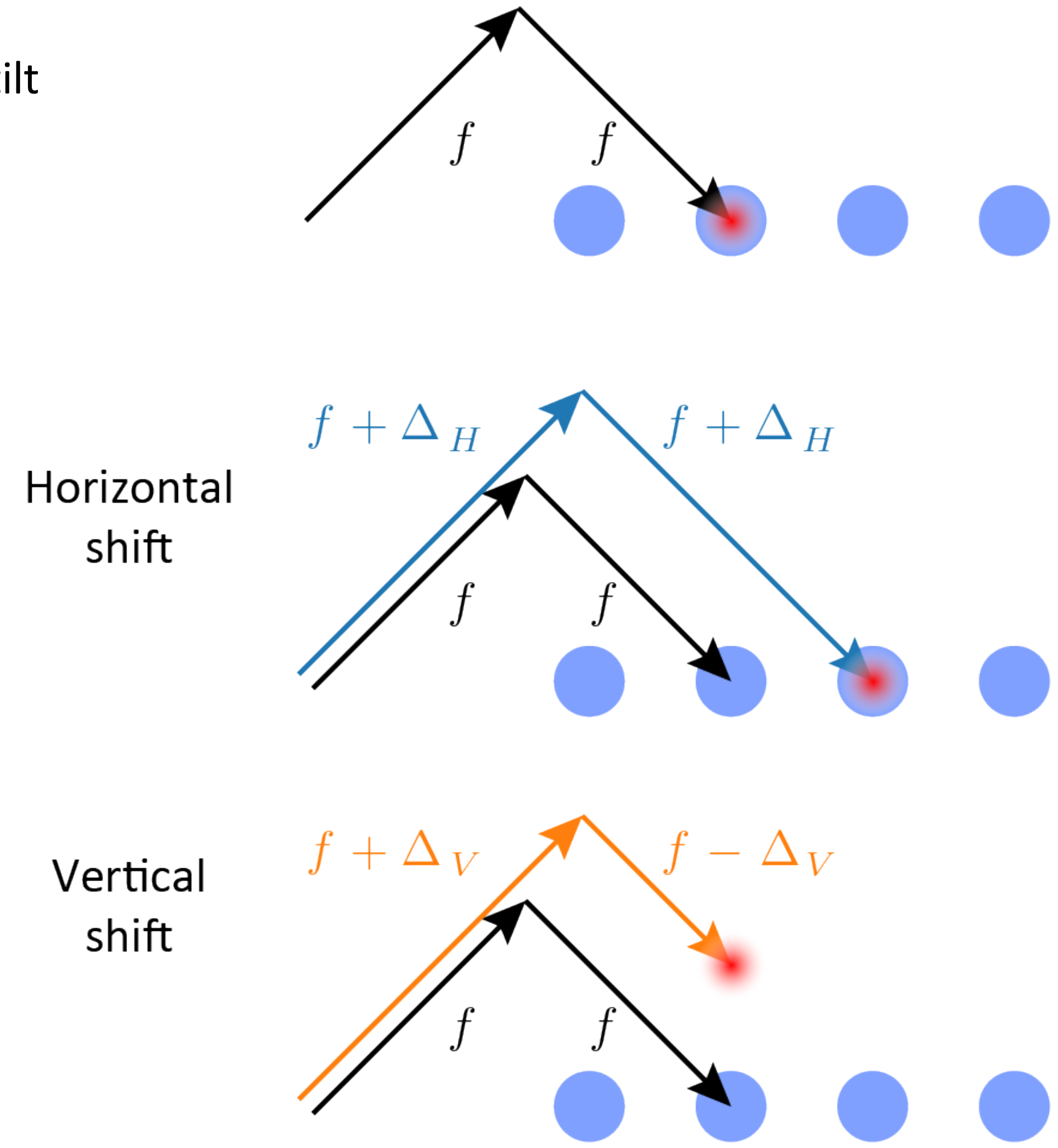
Addressing unit



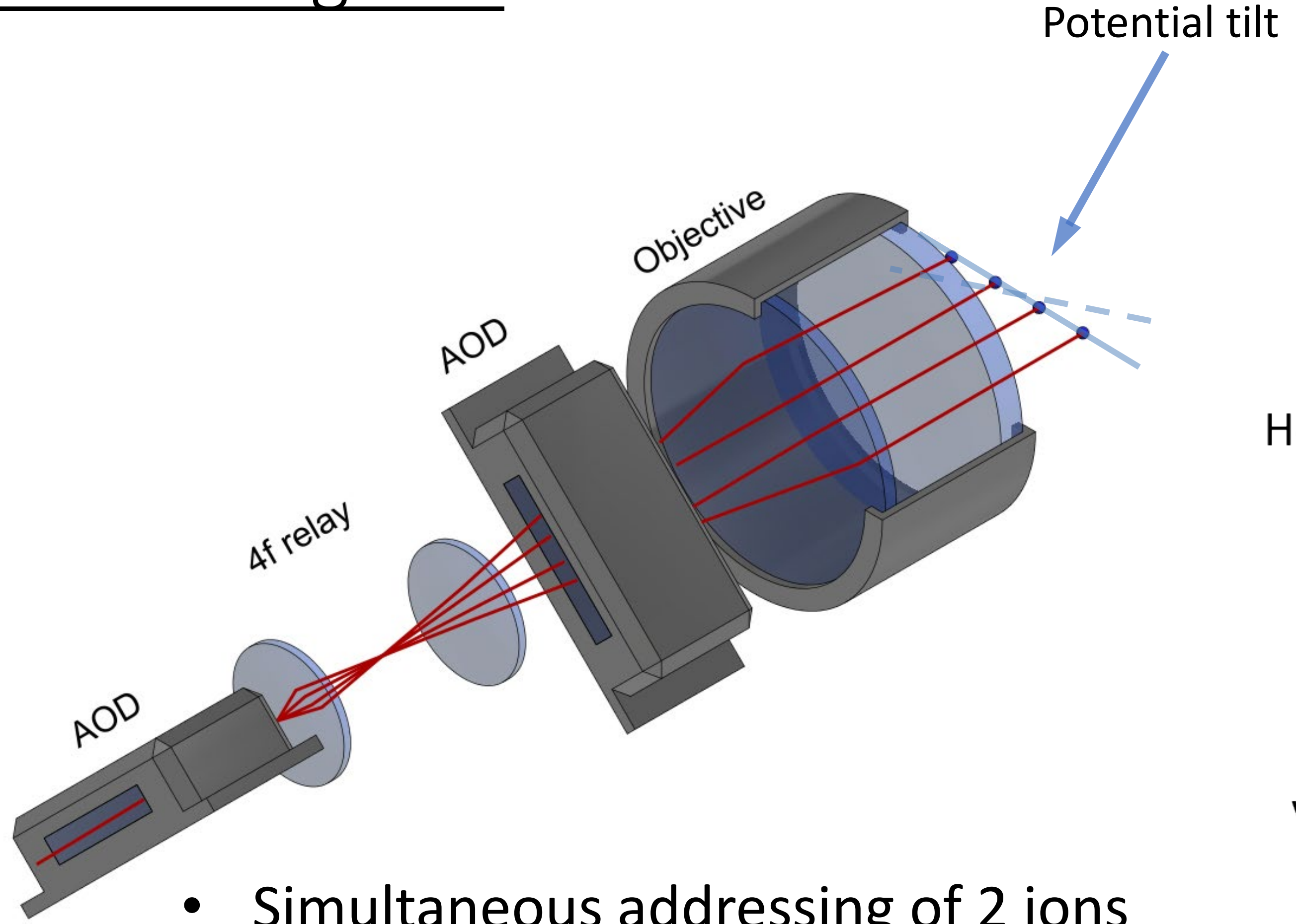


Addressing unit

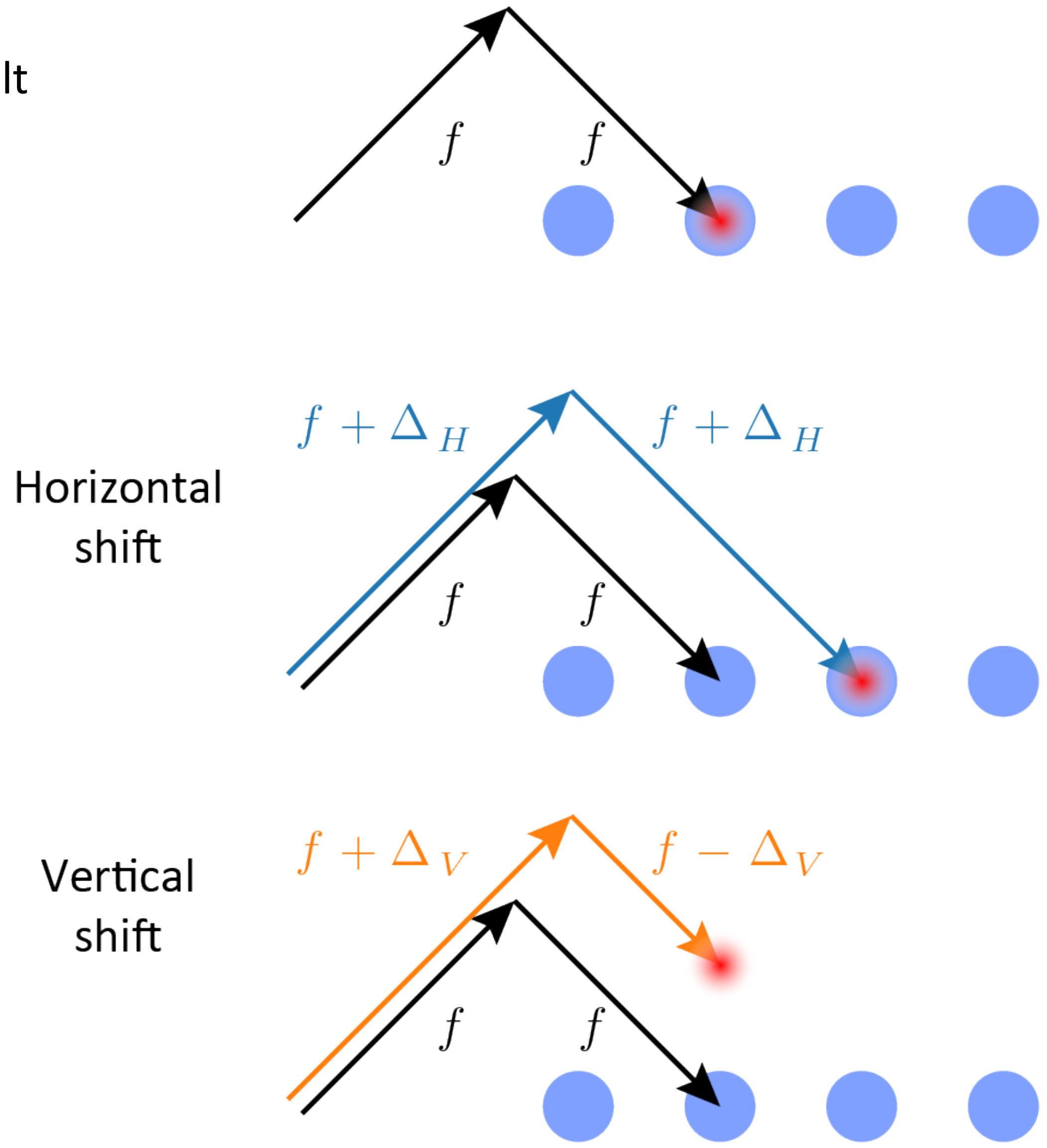




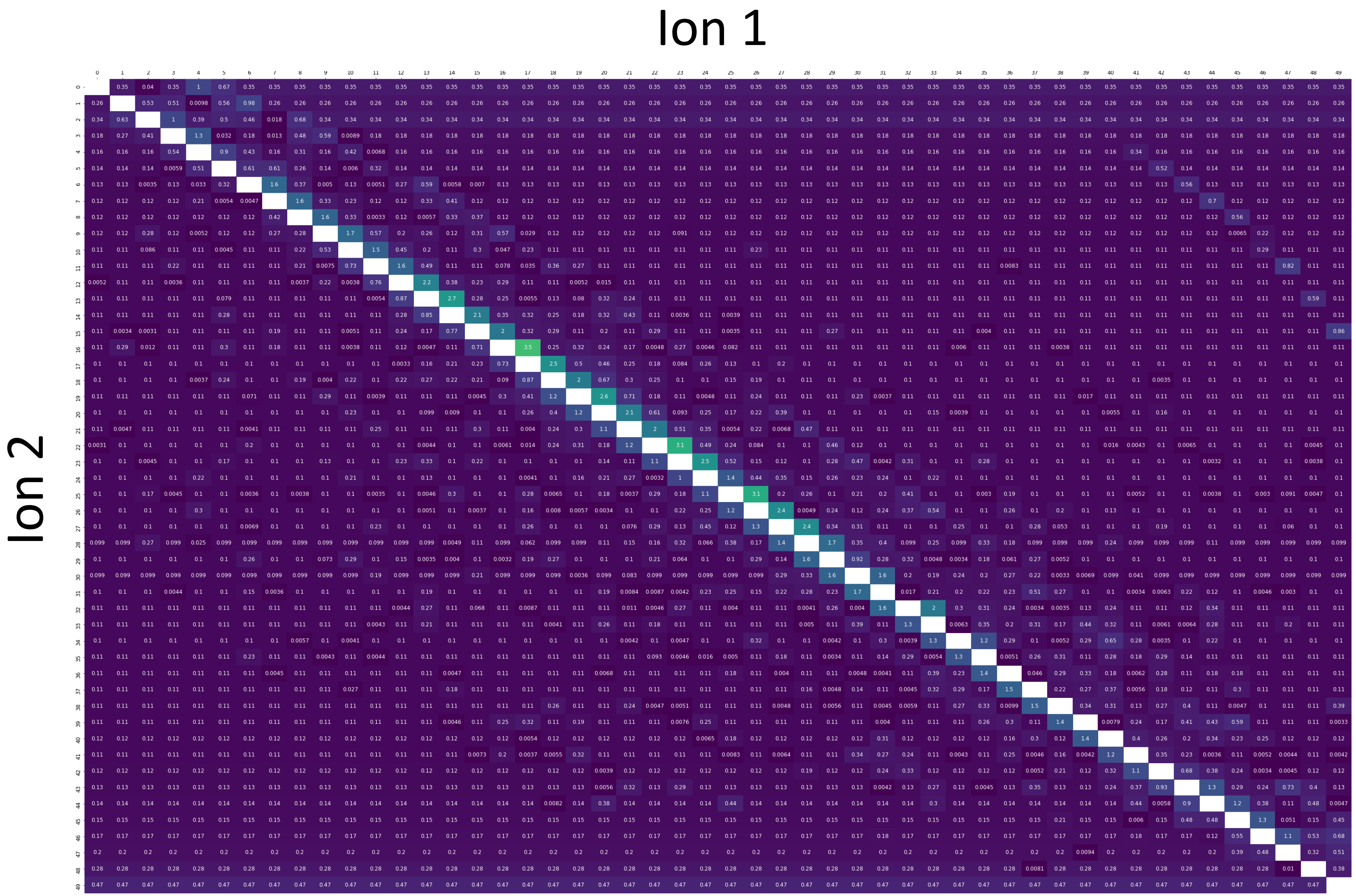
Addressing unit



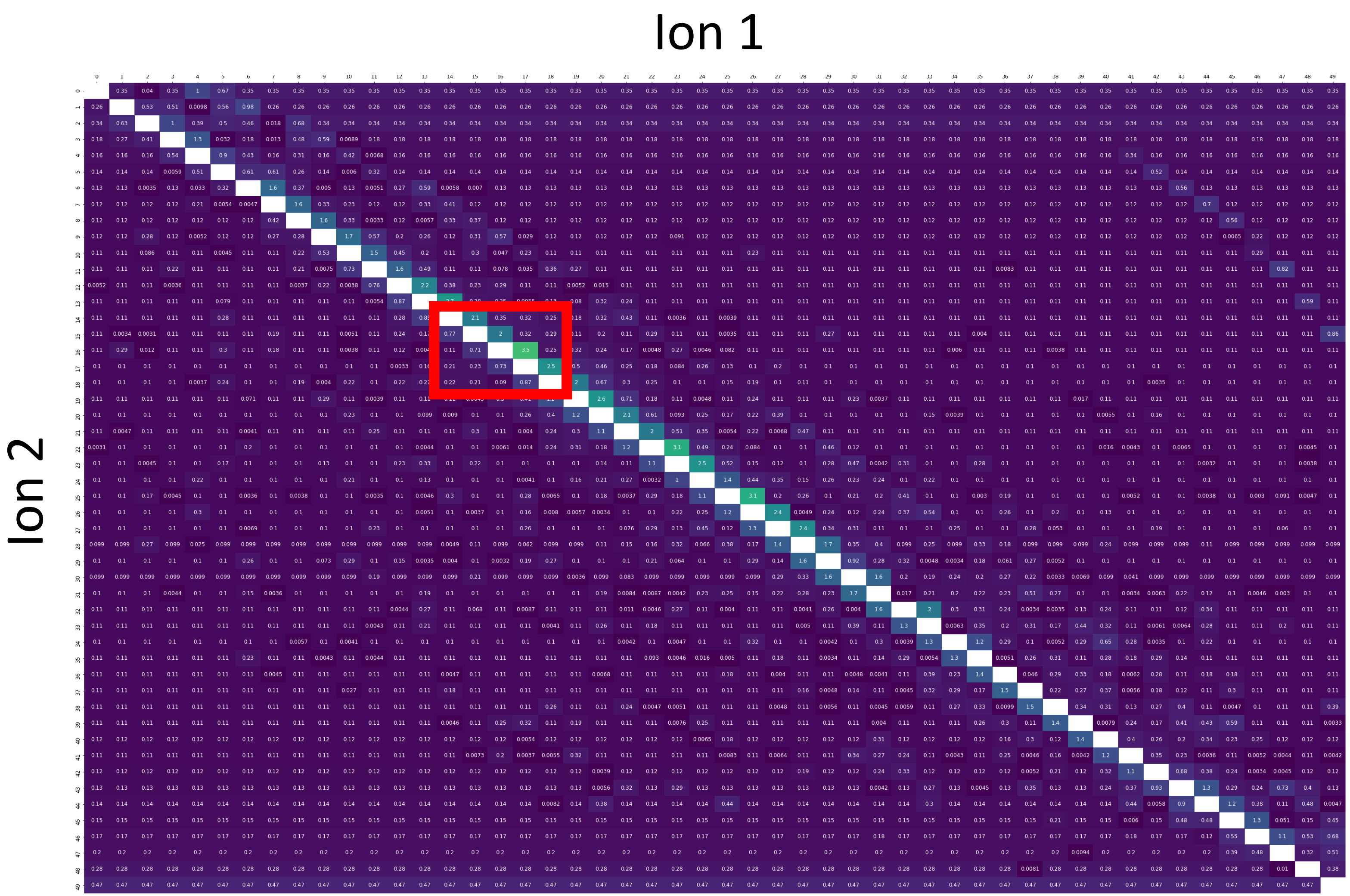
- Simultaneous addressing of 2 ions
- Individual phase/power adjustment

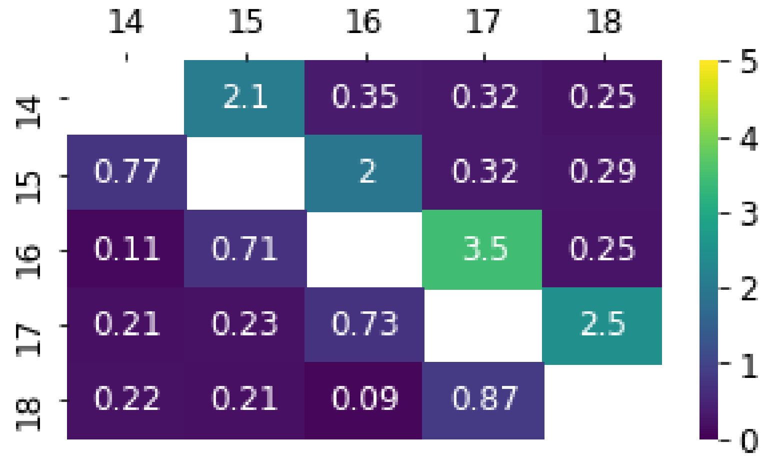


Addressing unit – cross-talk

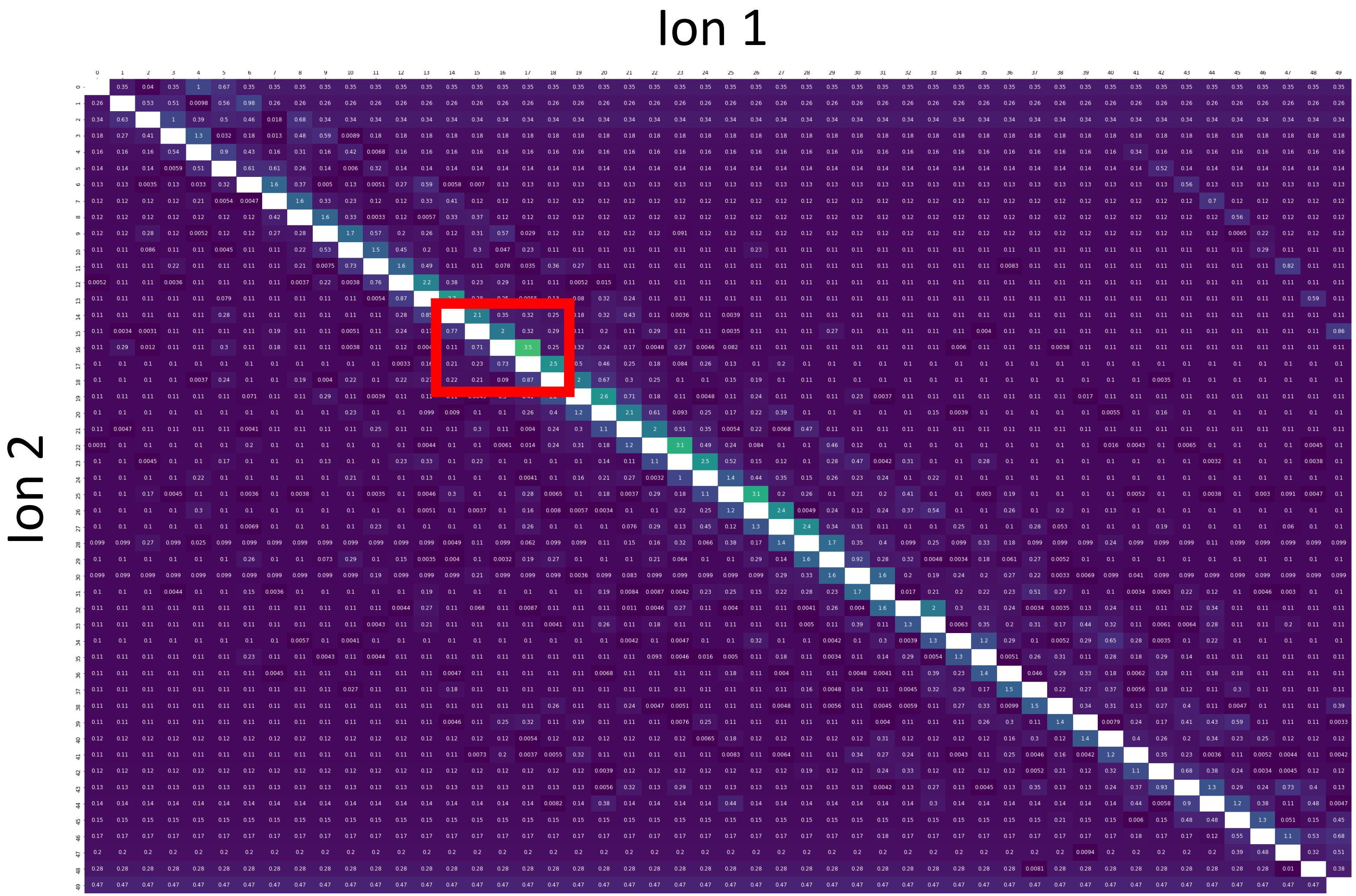


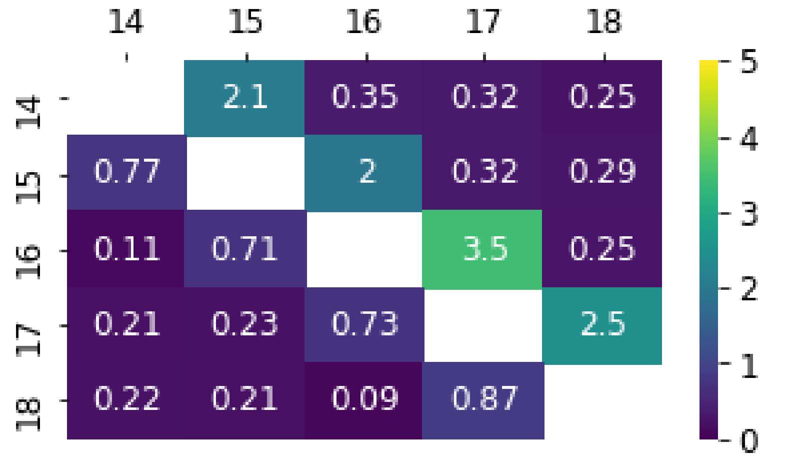
Addressing unit – cross-talk





Addressing unit – cross-talk





Max resonant cross-talk

3.5 %

Average ≈ 1.2 %

Qiskit compatible

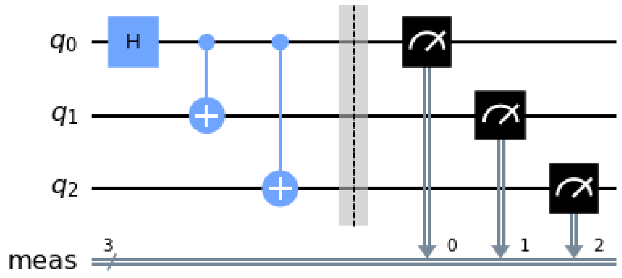
GHZ state - 3 qubits

[1]:
```python
from qiskit import QuantumCircuit

qc = QuantumCircuit(3)
qc.h(0)
qc.cx(0, 1)
qc.cx(0, 2)

qc.measure_all()
qc.draw('mpl')
```

[1]:



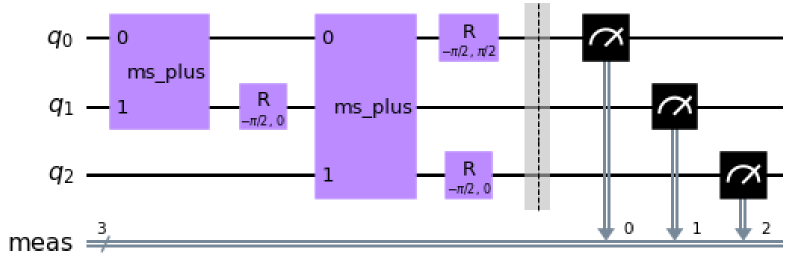
Init API

[2]:
```python
from qiskit_aqt_provider import AQTProvider, aqt_pass_manager
aqt = AQTProvider('MY_TOKEN')
backend_aqt = aqt.backends.aqtion_innsbruck
```

Transpile to ion trapping device

[3]:
```python
pass_manager = aqt_pass_manager()
aqt_qc = pass_manager.run(qc)
aqt_qc.draw('mpl')
```

[3]:

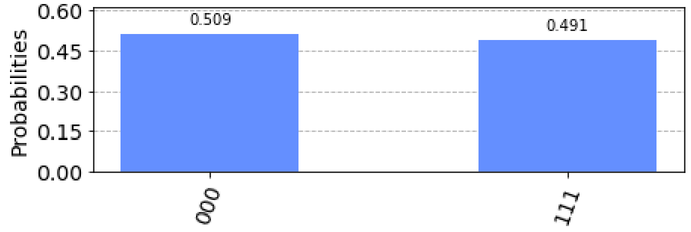


Measure

[4]:
```python
from qiskit.visualization import plot_histogram

job = backend_aqt.run(aqt_qc)
result = job.result()
plot_histogram(result.get_counts(), figsize=(7,2))
```

[4]:



Outline

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   - $^{40}Ca^+$
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   - Sideband cooling
   - Detection
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Outline

General

- Laser frequency & magnetic field

Single-qubit gates

- Addressing
- Amplitudes

Two-qubit gates

- Trap modes
- Amplitudes
- Phases

Overall budget

Outline

General

- Laser frequency & magnetic field

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Two-qubit gates

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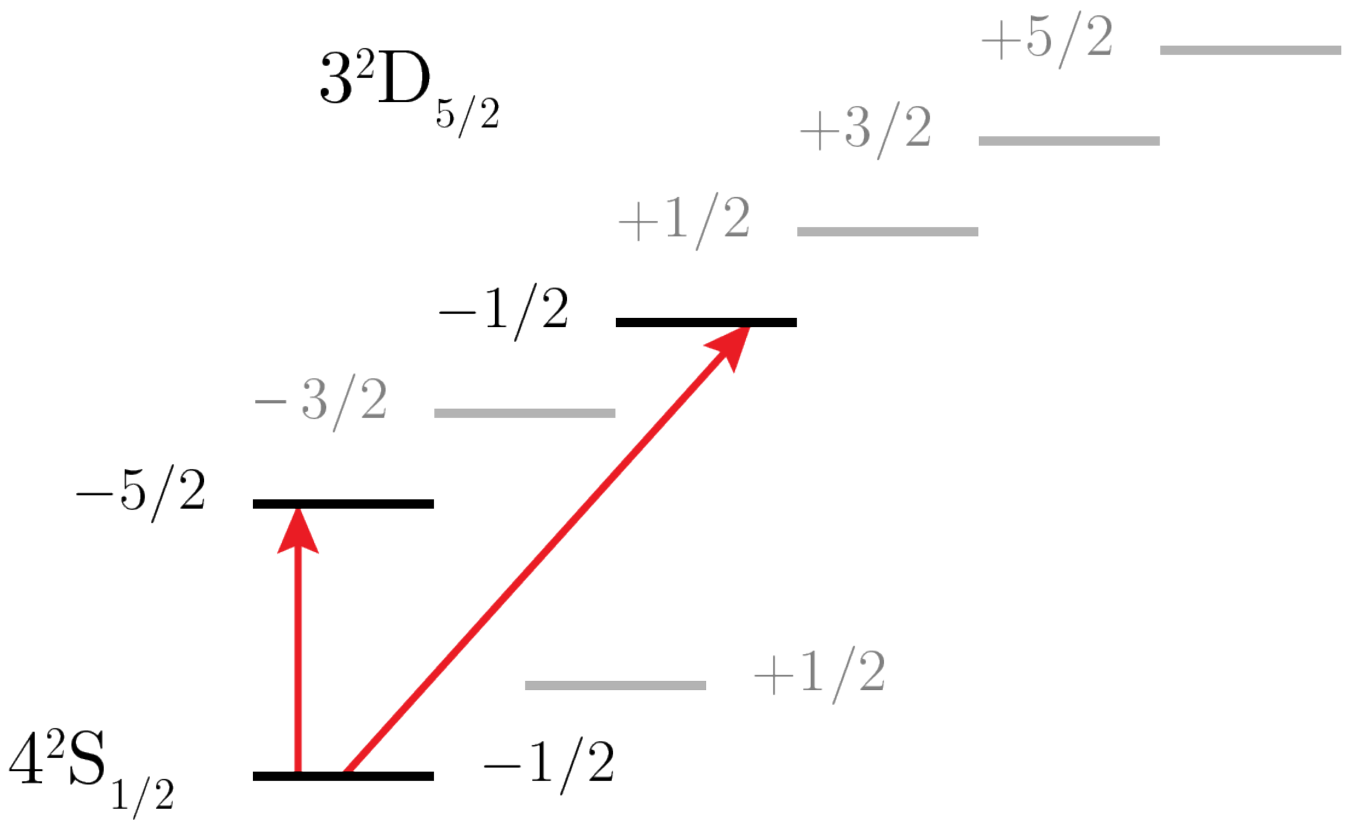
Overall budget

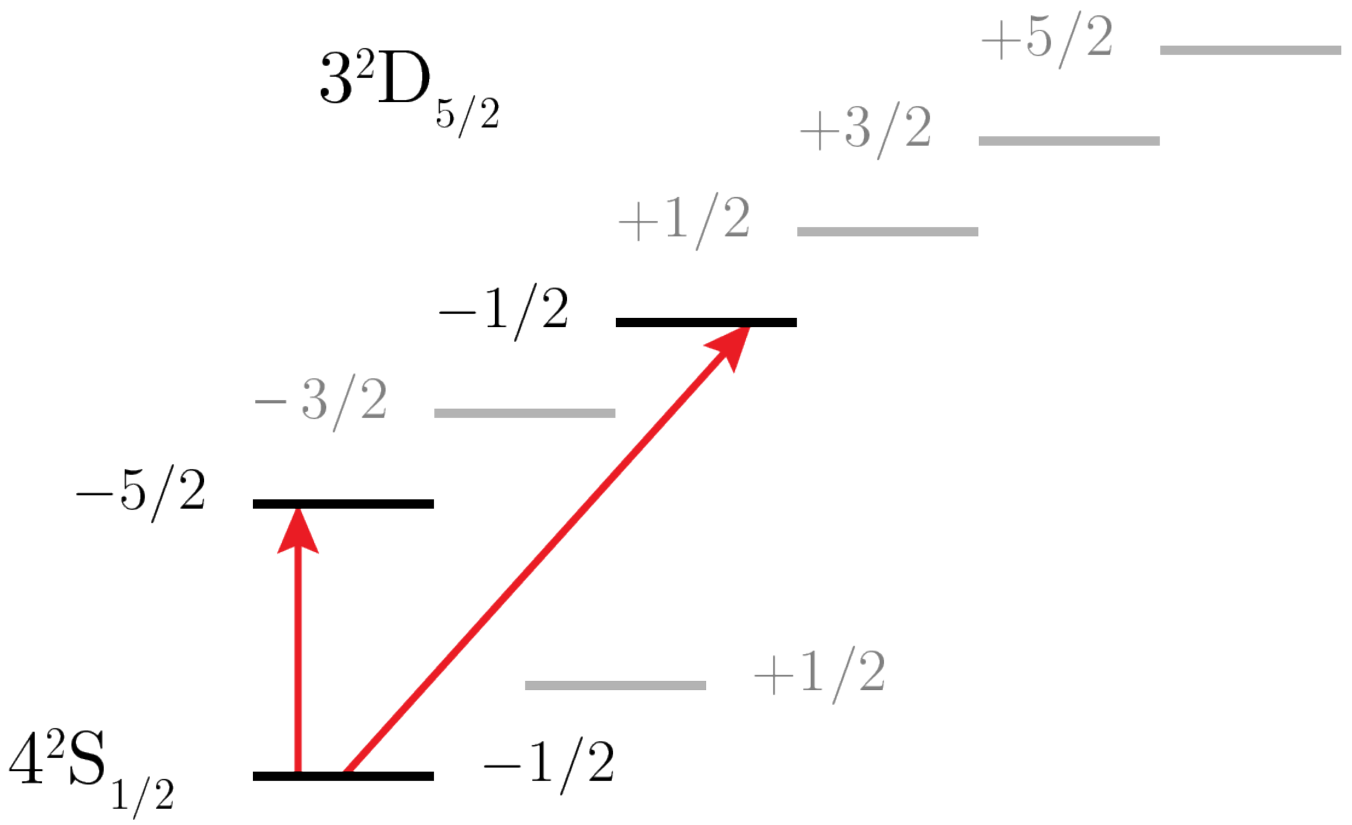
Laser frequency & magnetic field



Required for:

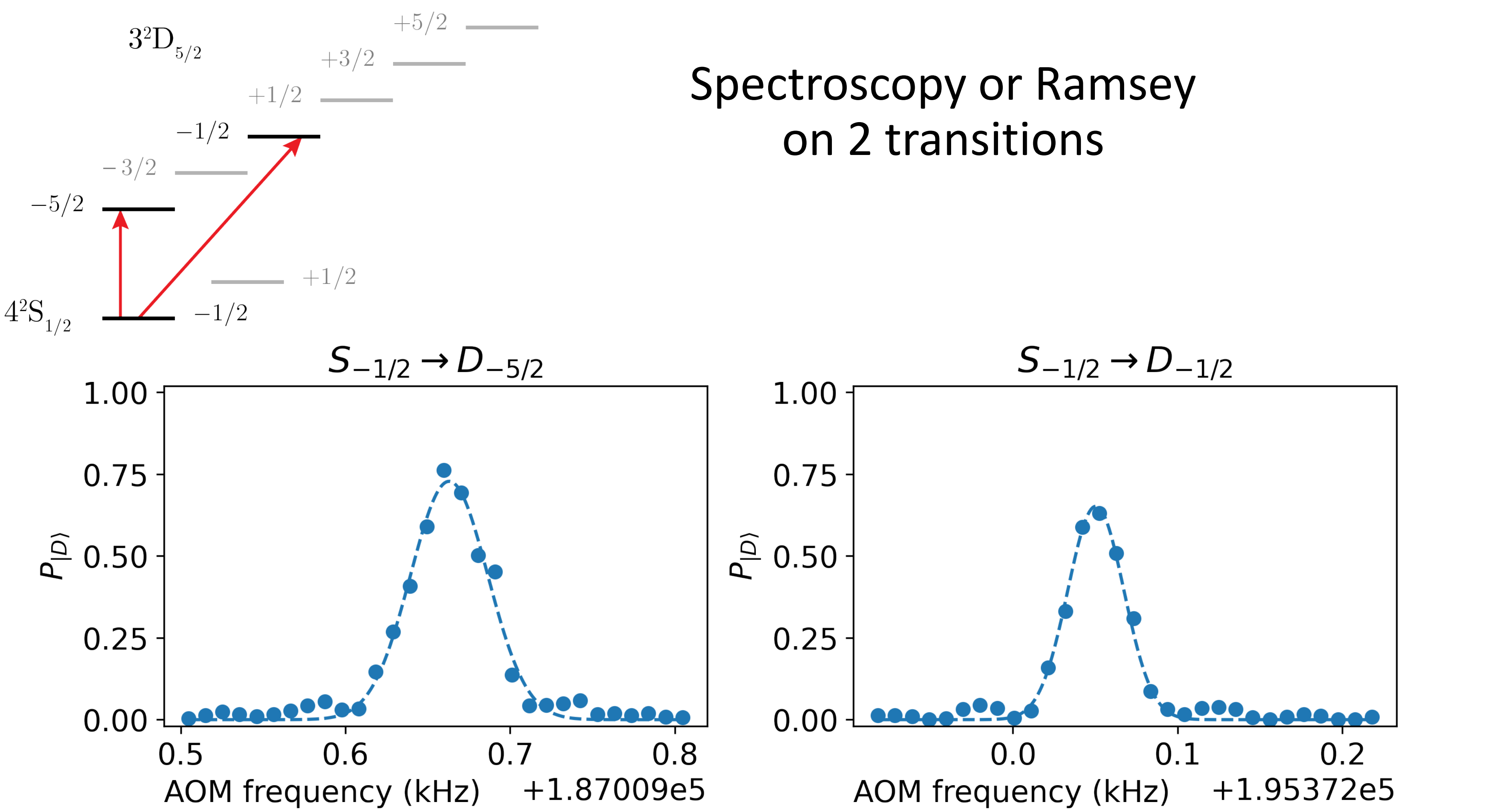
- Optical pumping
- Sideband cooling
- Single-qubit gates
- Two-qubit gates
- Shelving

Laser frequency & magnetic field – calibration

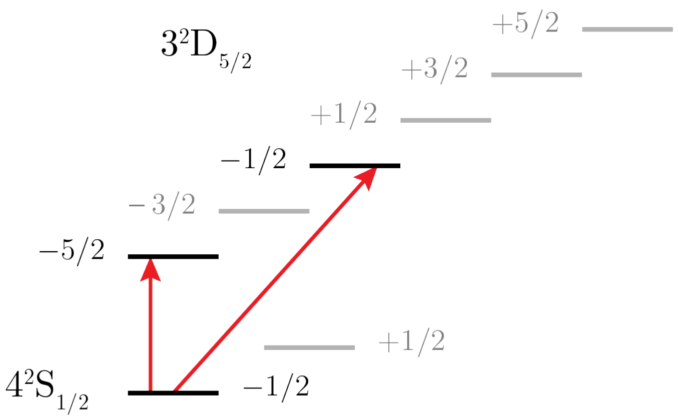


Laser frequency & magnetic field – calibration

Spectroscopy or Ramsey
on 2 transitions

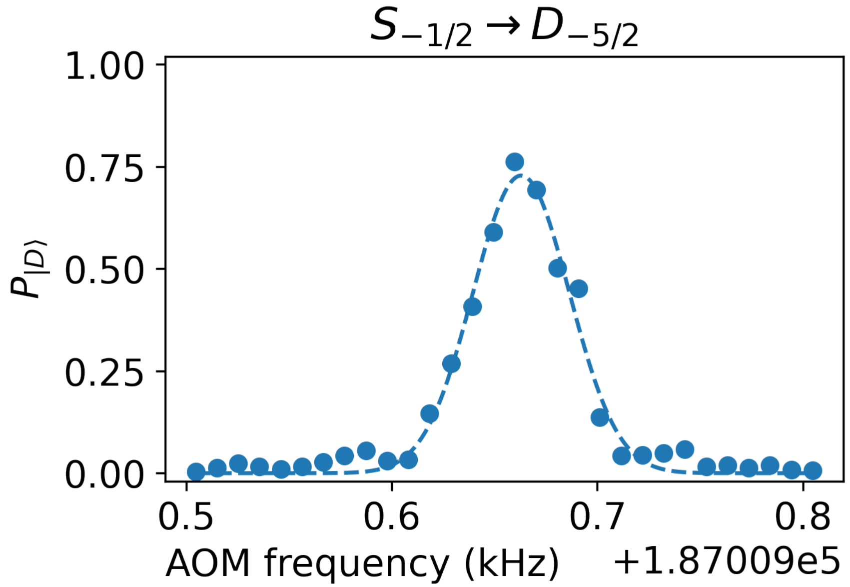


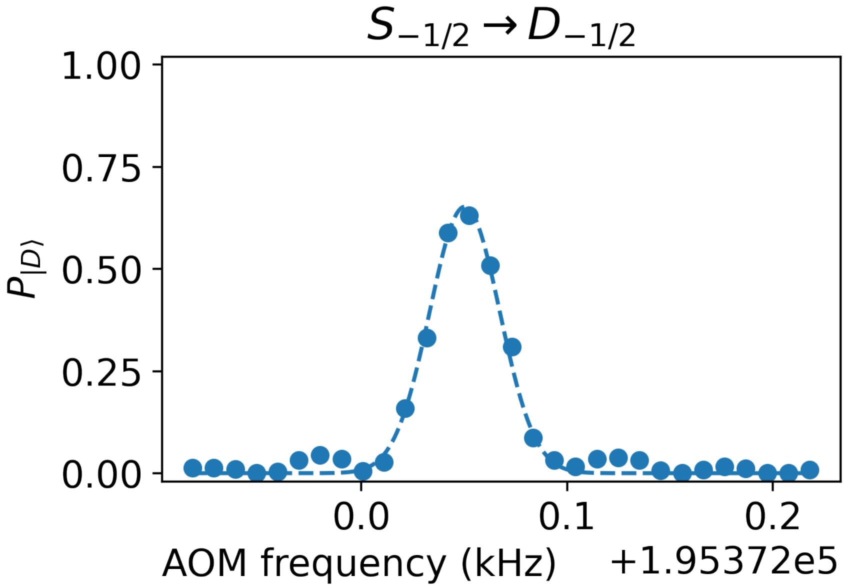
Laser frequency & magnetic field – calibration



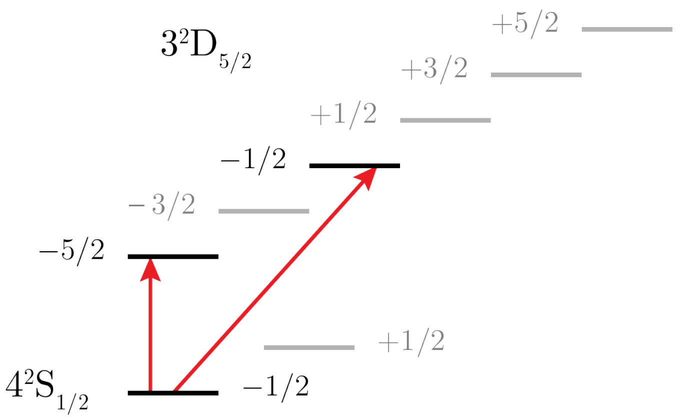
Spectroscopy or Ramsey on 2 transitions

Laser frequency & magnetic field

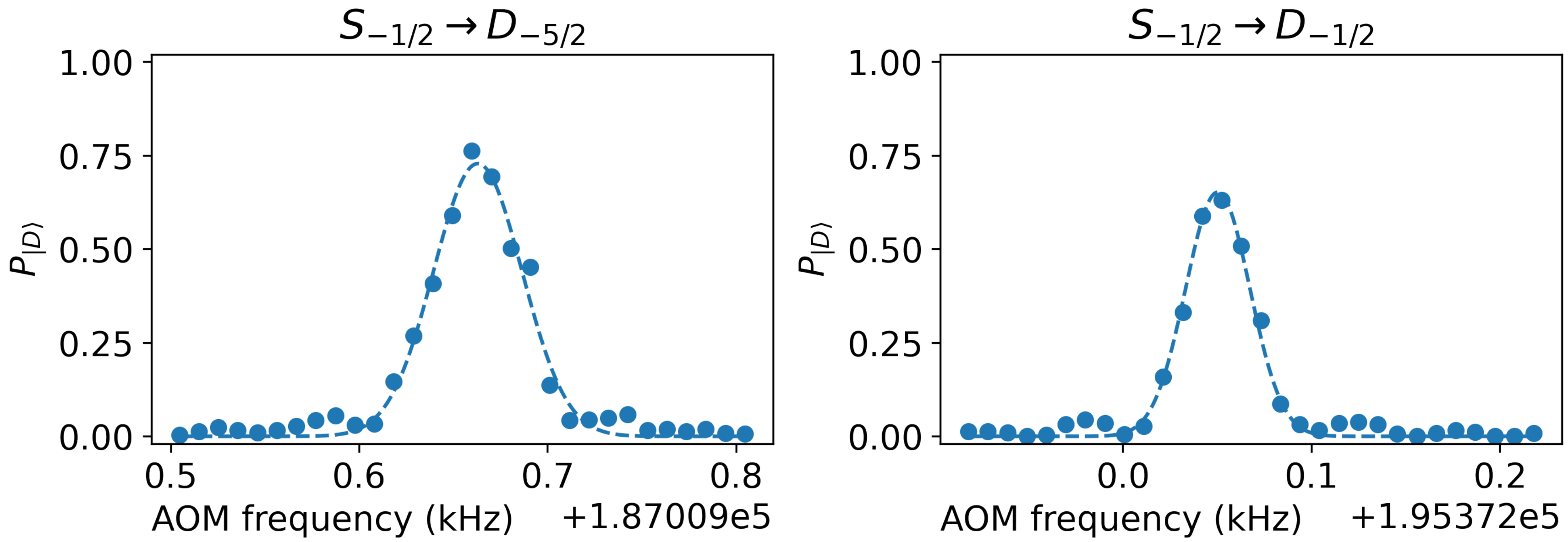




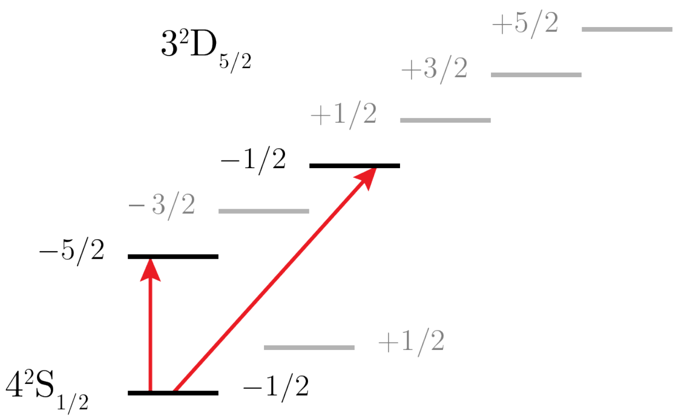
Laser frequency & magnetic field – calibration



Spectroscopy or Ramsey on 2 transitions → Laser frequency & magnetic field → All transitions



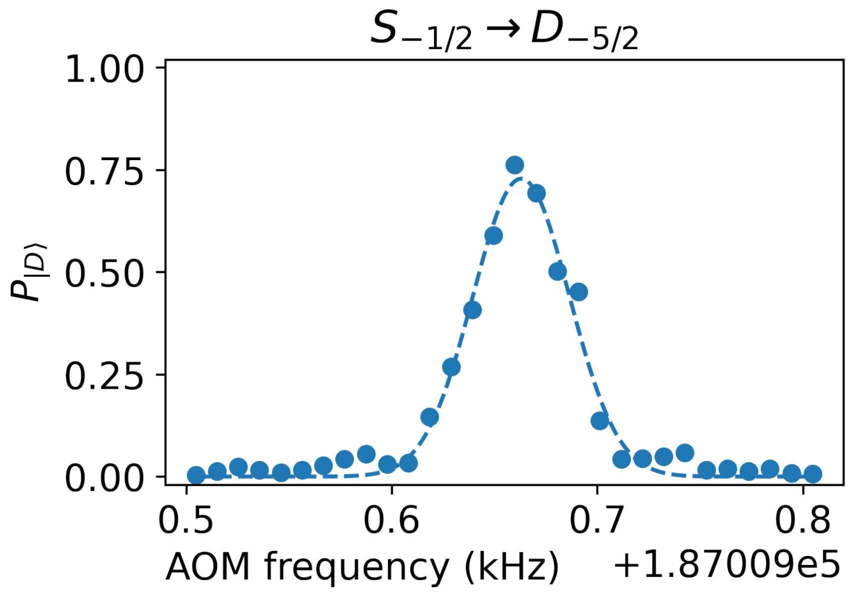
Laser frequency & magnetic field – calibration

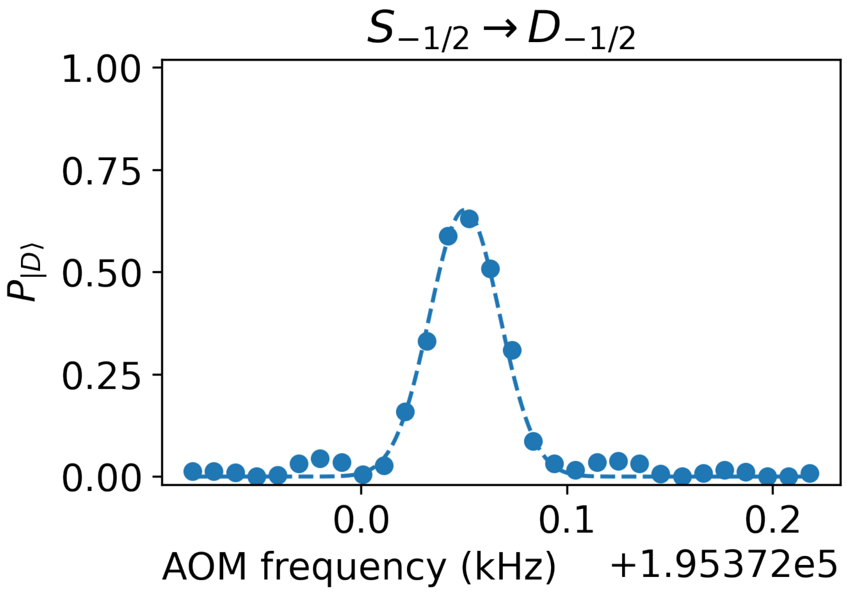


Spectroscopy or Ramsey on 2 transitions

Laser frequency & magnetic field

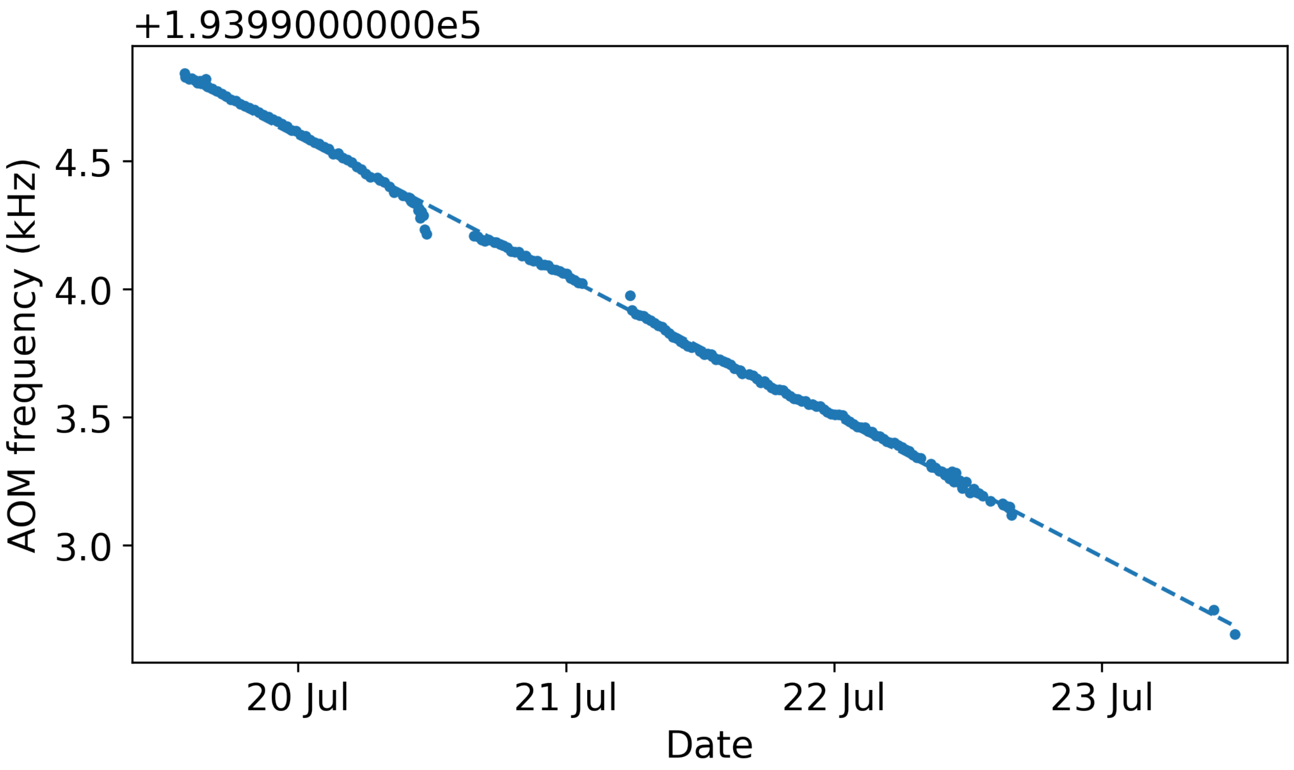
All transitions





<u>Every 20 mins</u>

Laser frequency & magnetic field – drift



- Extrapolates cavity drift
- Applies correction before each measurement

Outline

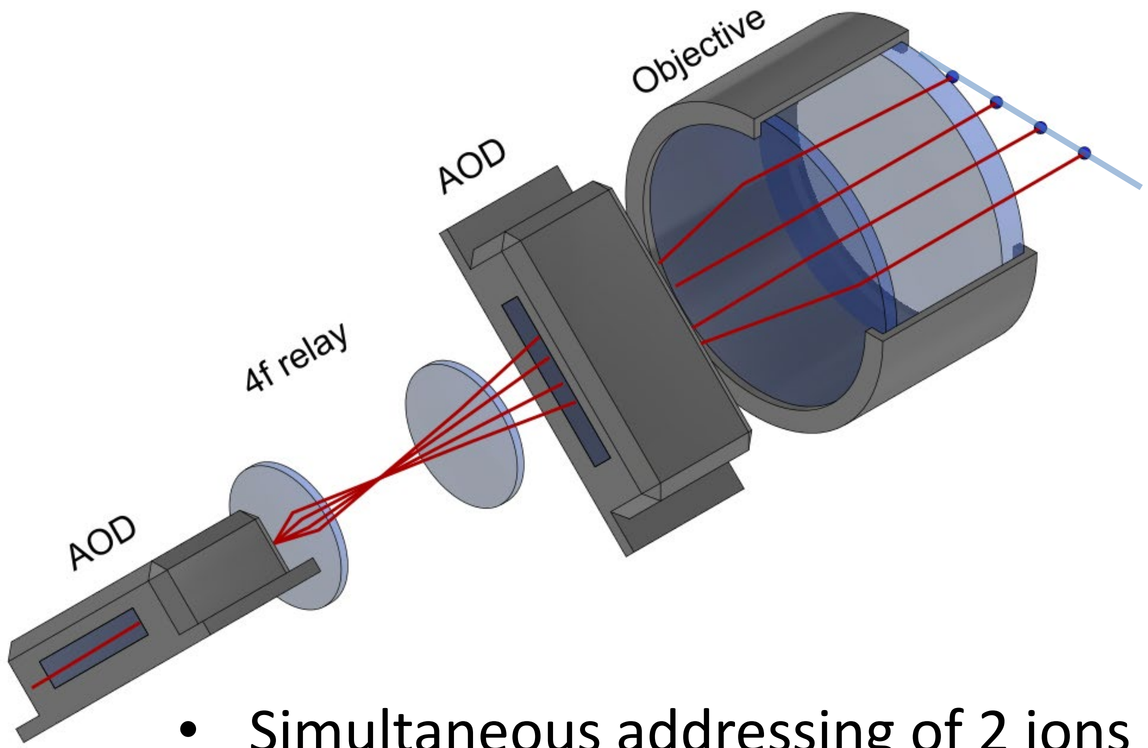
General
- Laser frequency & magnetic field

Single-qubit gates
- Addressing
- Amplitudes

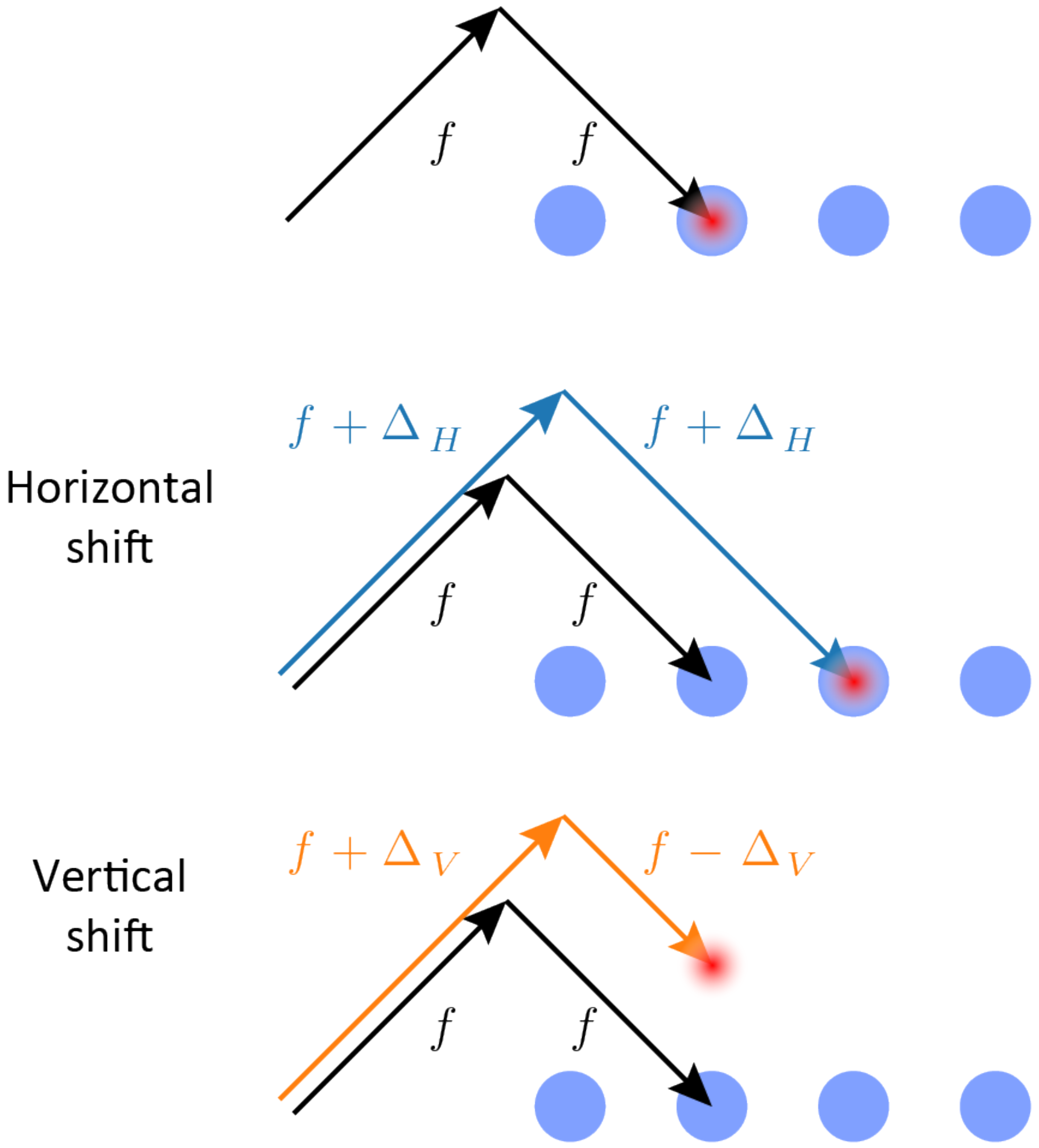
Two-qubit gates
- Trap modes
- Amplitudes
- Phases

Overall budget

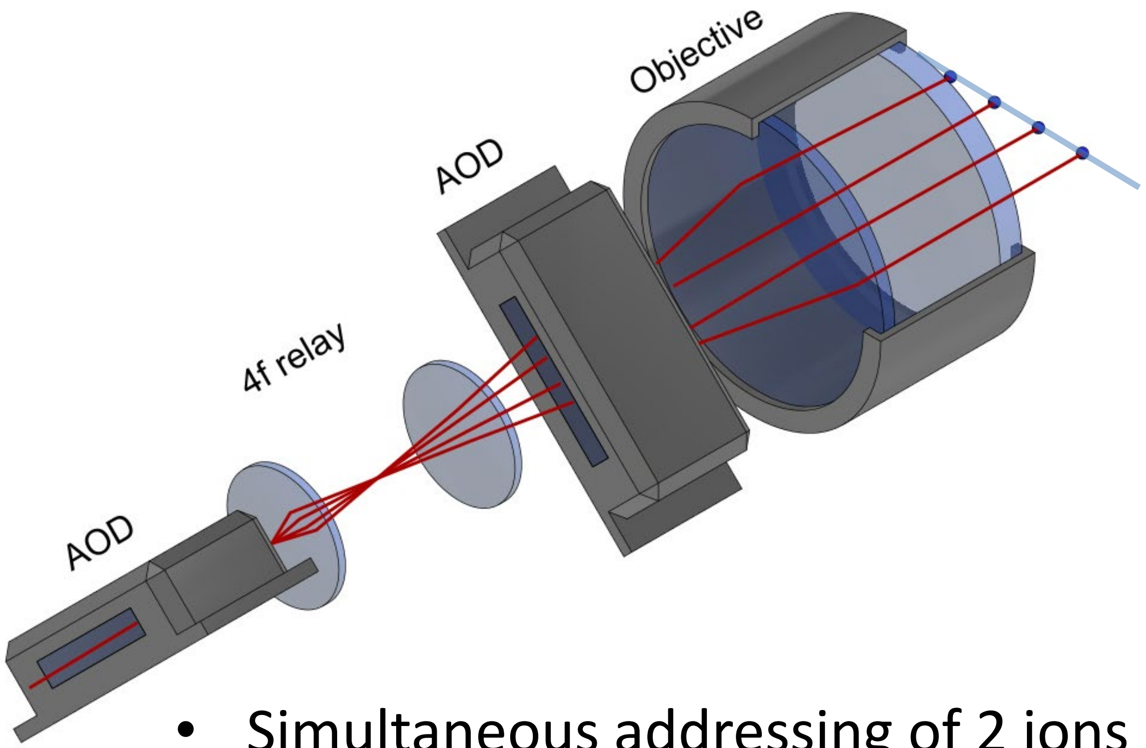
Addressing unit

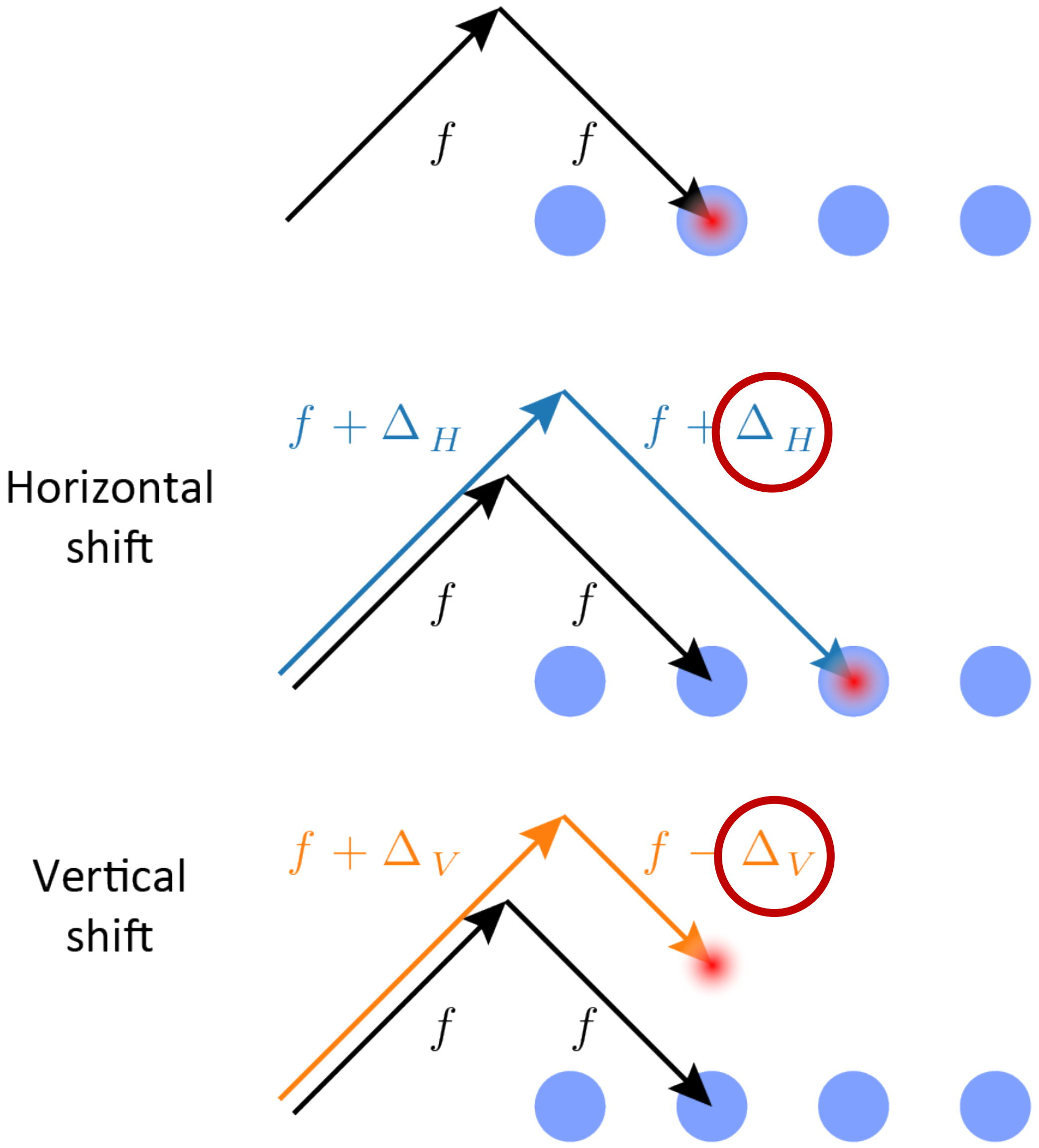


- Simultaneous addressing of 2 ions
- Individual phase/power adjustment



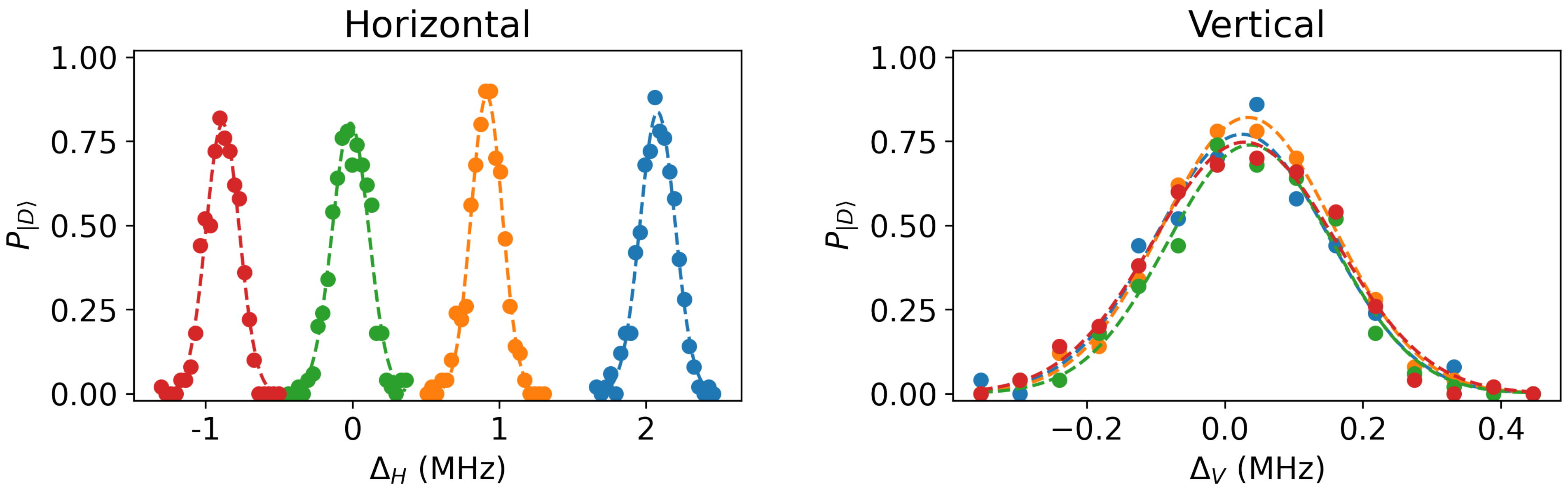
Addressing unit





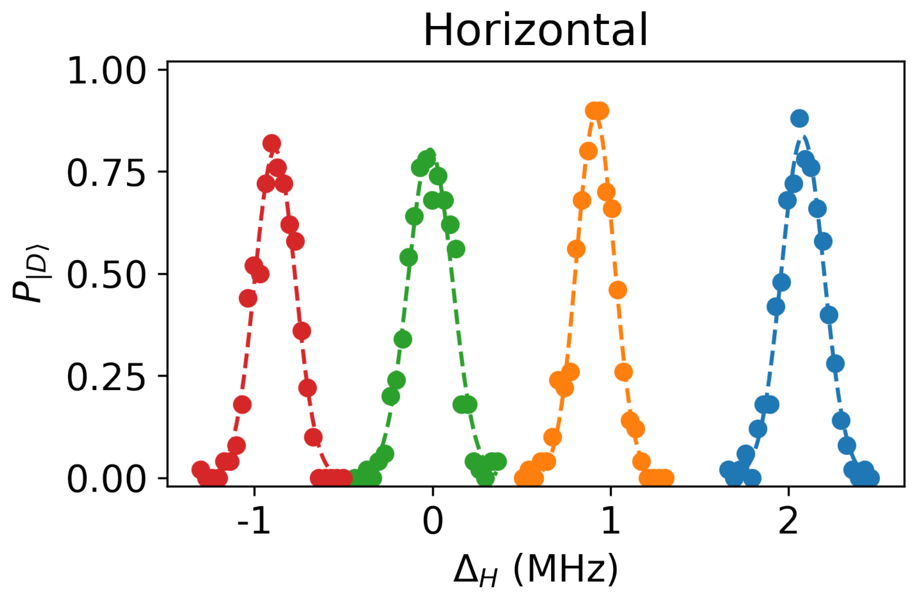
- Simultaneous addressing of 2 ions
- Individual phase/power adjustment

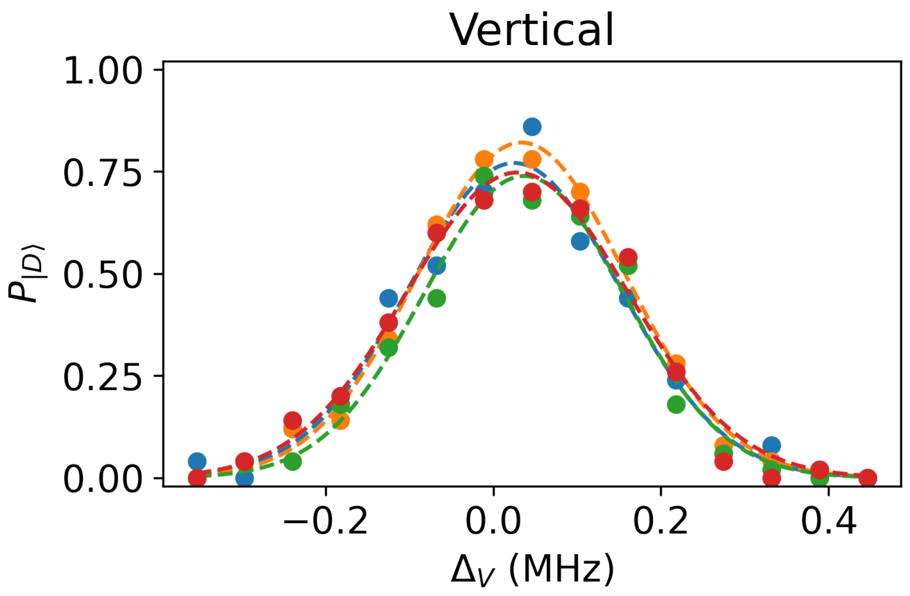
Addressing unit – calibration



Addressing unit – calibration

- Updates horizontal position for each ion individually

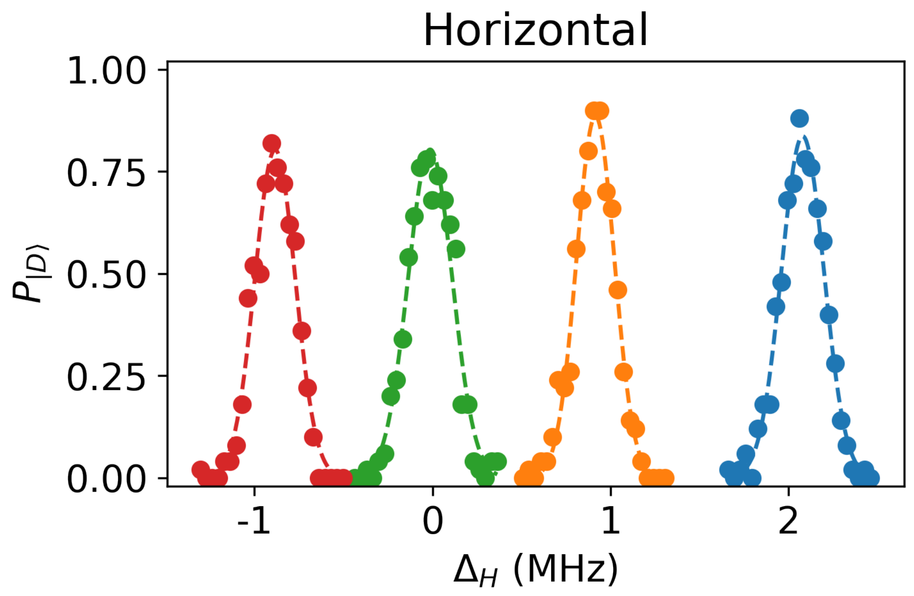


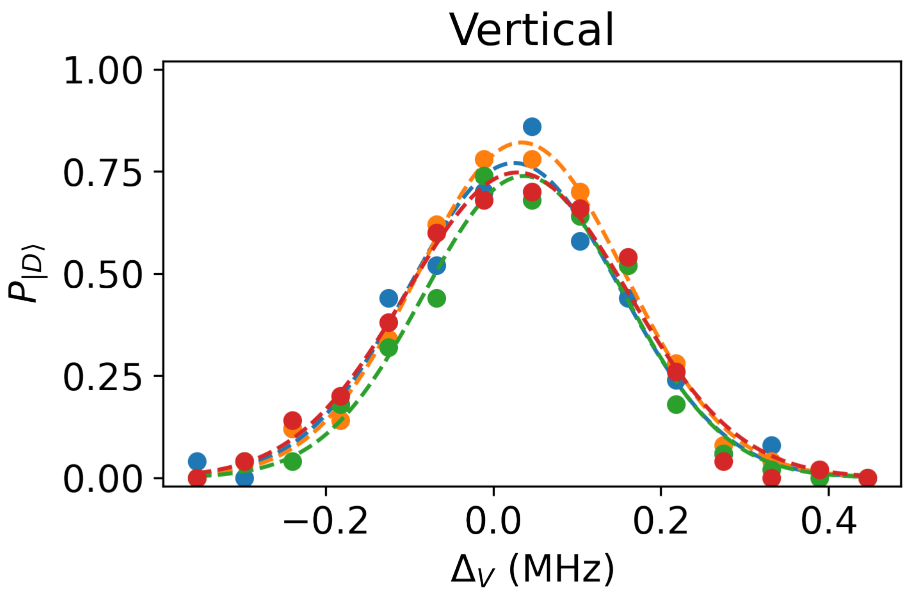


Addressing unit – calibration

- Updates horizontal position for each ion individually

- Updates vertical position for all ions based on averaged value
- Tracks tilt

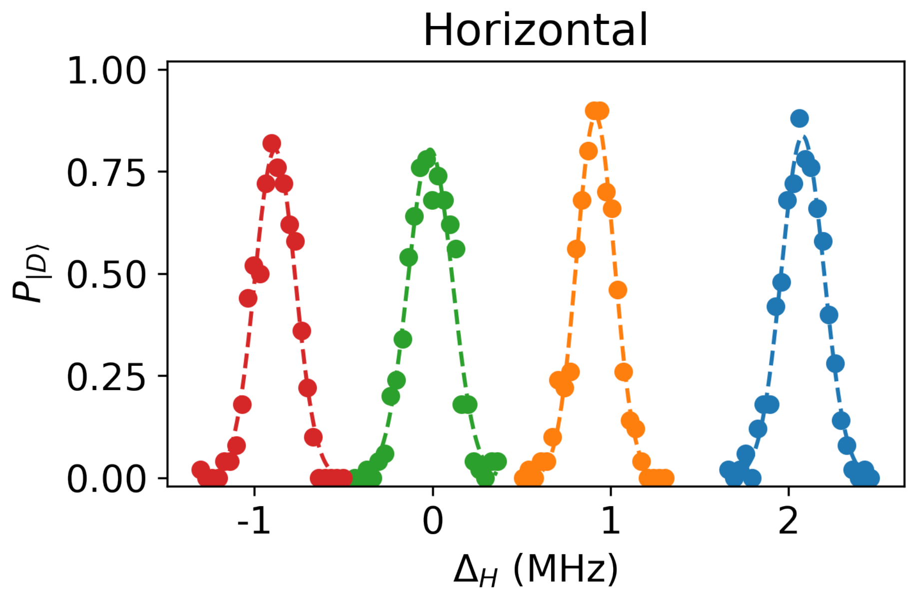


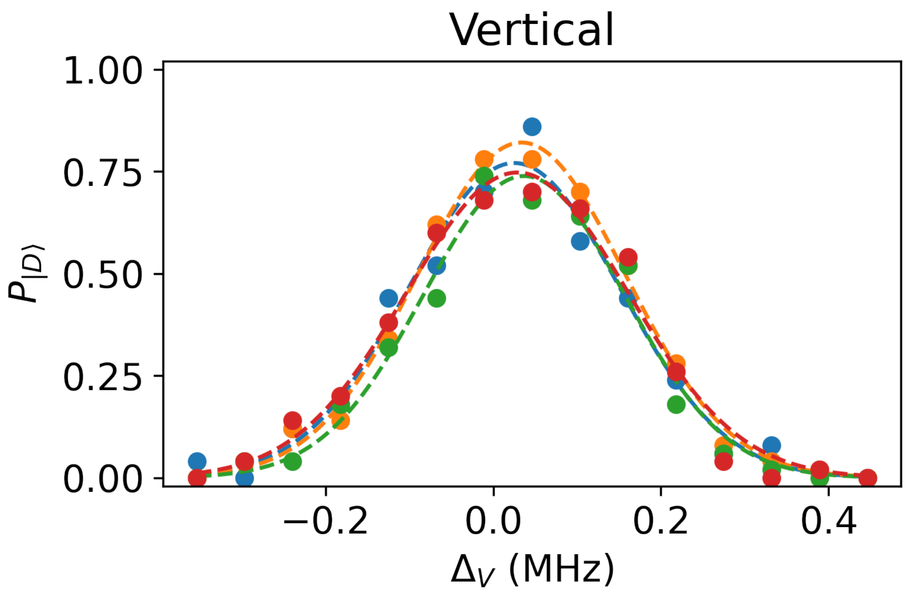


Addressing unit – calibration

- Updates horizontal position for each ion individually

- Updates vertical position for all ions based on averaged value
- Tracks tilt

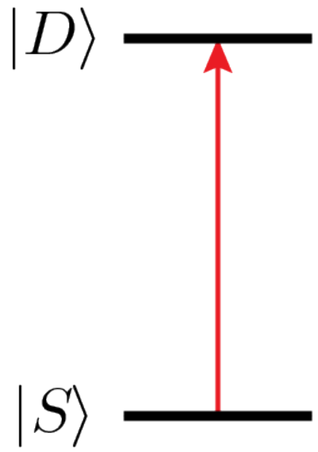




Every 30 mins

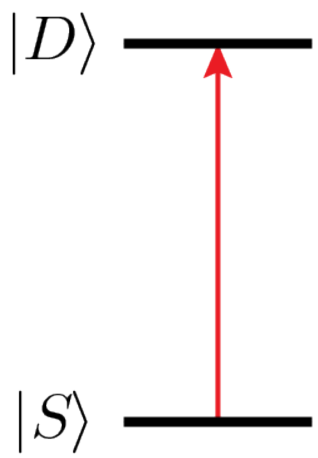
Single qubit gates

$$H = \hbar\Omega\sigma_+ e^{-i(\omega-\omega_{SD})t-\phi)} e^{i\eta(ae^{-i\nu t}+a^\dagger e^{i\nu t})} + h.c.$$



Single qubit gates

$$H = \hbar\Omega\sigma_+ e^{-i(\overbrace{\omega-\omega_{SD}}^{\text{Laser frequency \& magnetic field}})t-\phi)} e^{i\eta(ae^{-i\nu t}+a^\dagger e^{i\nu t})} + h.c.$$



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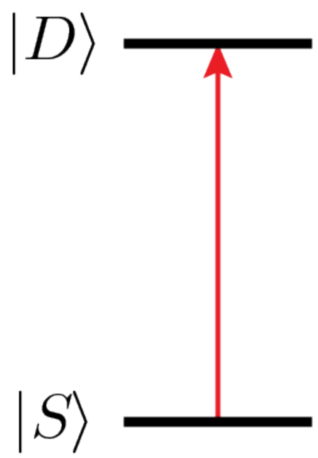

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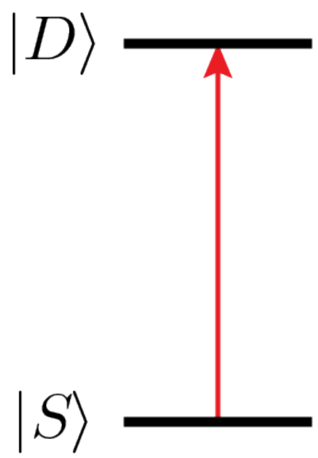
$$H = \underbrace{\hbar\Omega}_{\text{Laser amplitude}}\sigma_+ e^{-i\overbrace{(\omega-\omega_{SD})}^{\text{Laser frequency \& magnetic field}}t-\phi)} e^{i\eta\overbrace{(ae^{-i\nu t}+a^\dagger e^{i\nu t})}^{\text{Trap parameters}}} + h.c.$$



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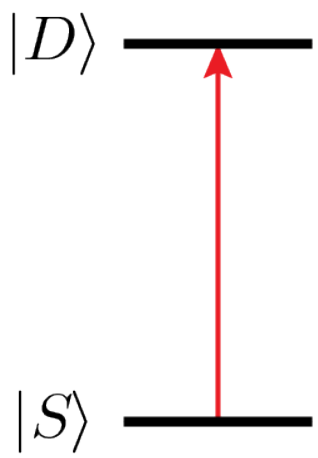

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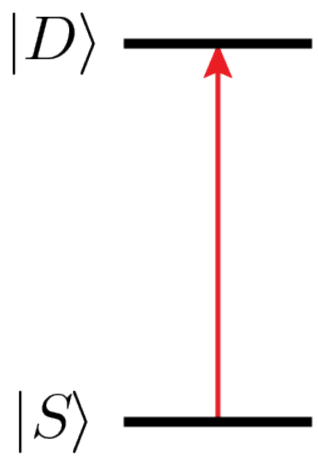
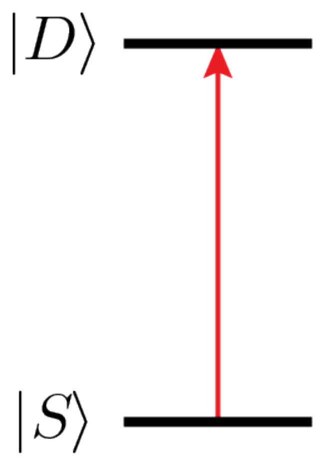


$$R_{xy}(\theta,\phi) = e^{-i\frac{\theta}{2}(\sigma_x\cos\phi+\sigma_y\sin\phi)}$$

Single qubit gates

$$H = \hbar \underbrace{\Omega}_{\text{Laser amplitude}} \sigma_+ e^{-i(\overbrace{\omega-\omega_{SD}}^{\text{Laser frequency \& magnetic field}})t-\underbrace{\phi}_{\text{RF pulse}})} e^{i\eta\overbrace{(ae^{-i\nu t}+a^\dagger e^{i\nu t})}^{\text{Trap parameters}}} + h.c.$$



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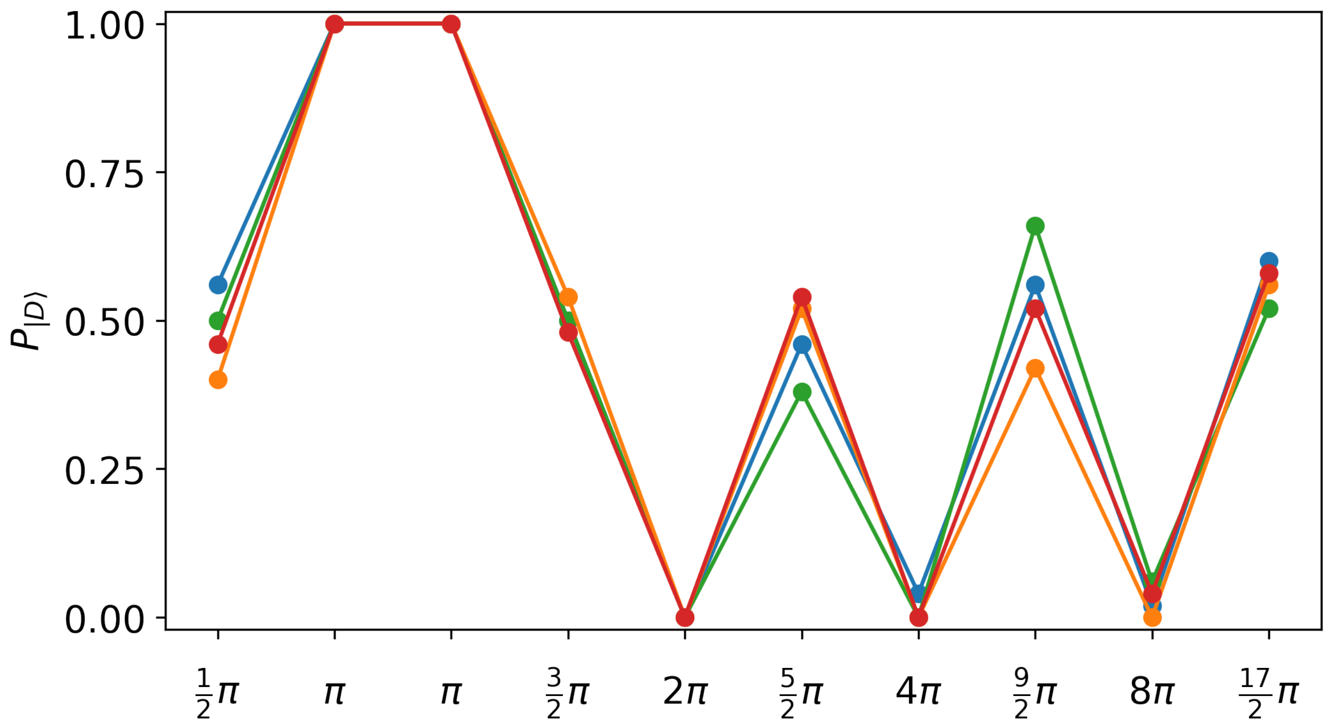
Single qubit gates – calibration

Robust phase estimation on each ion



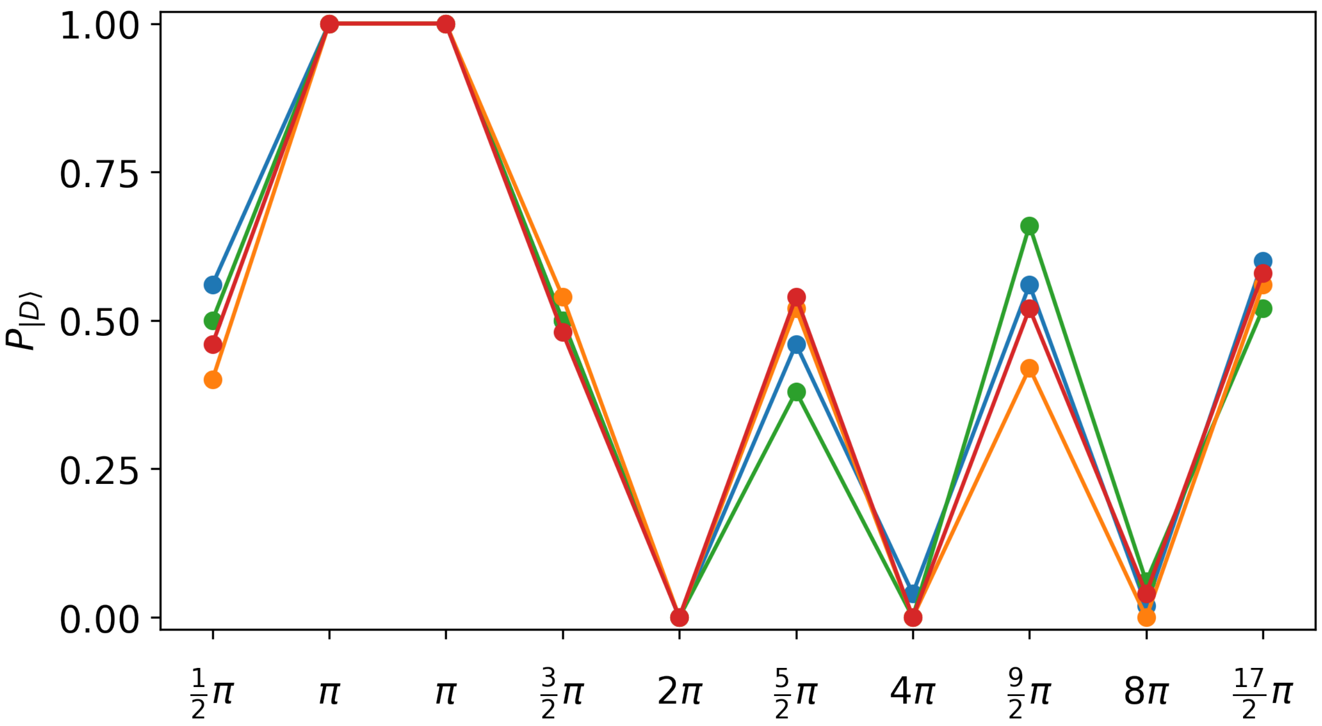
Single qubit gates – calibration

- Fixed pulse time
- All ions in one sequence
- Done 2 times to avoid cross-talk

1.
2.

- Adjusts addressing amplitudes

Robust phase estimation on each ion



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Same Rabi frequency for all ions

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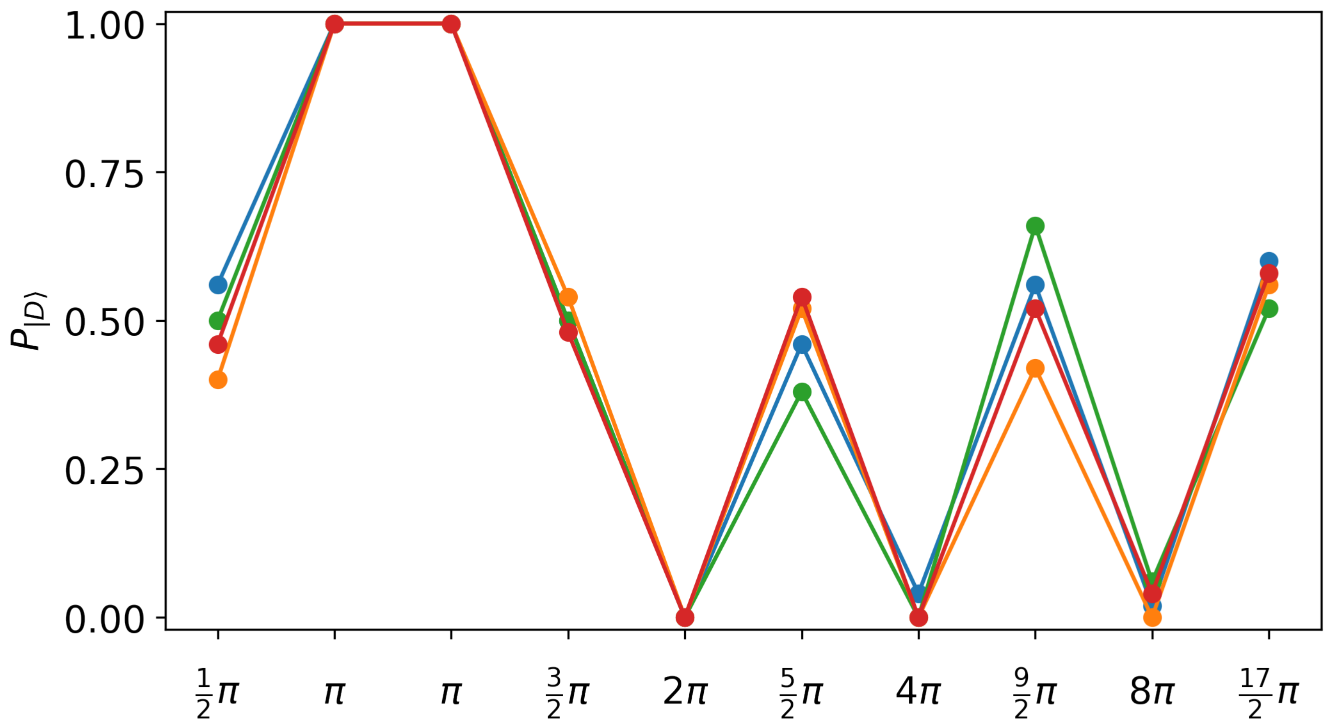

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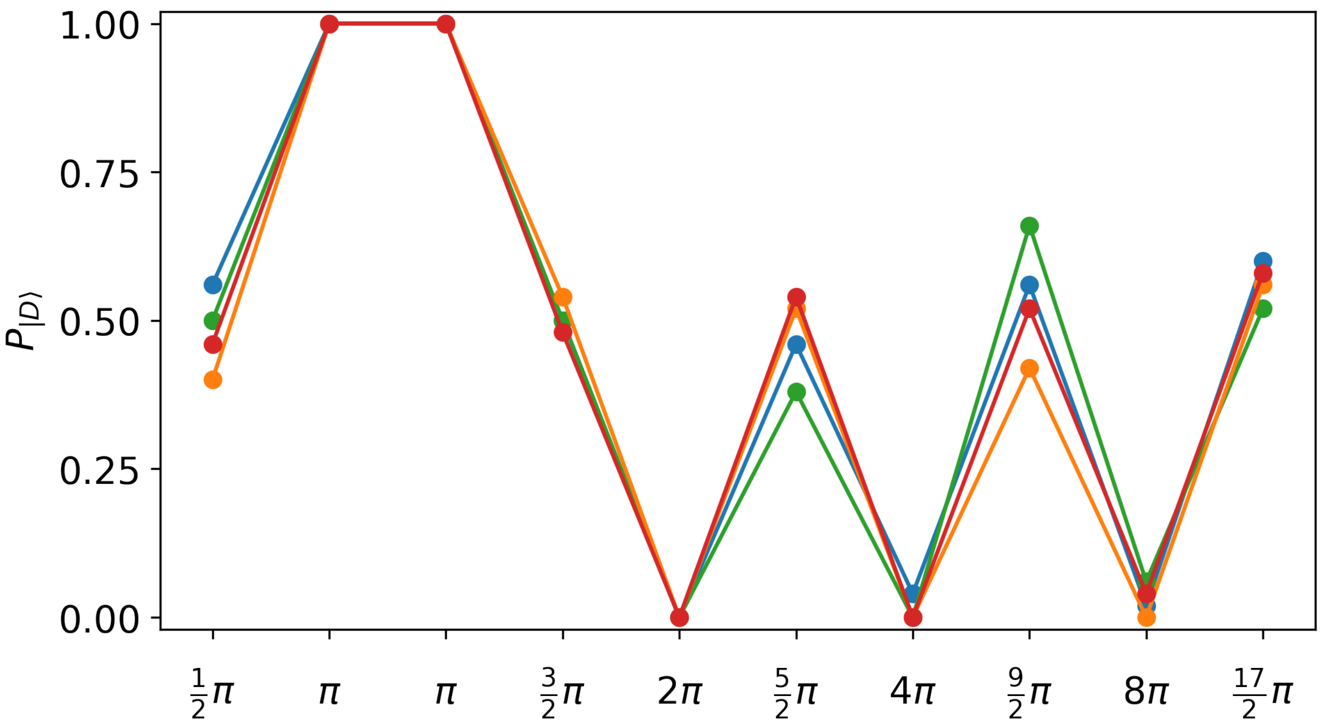


Every 30 mins

Outline

General
- Laser frequency & magnetic field

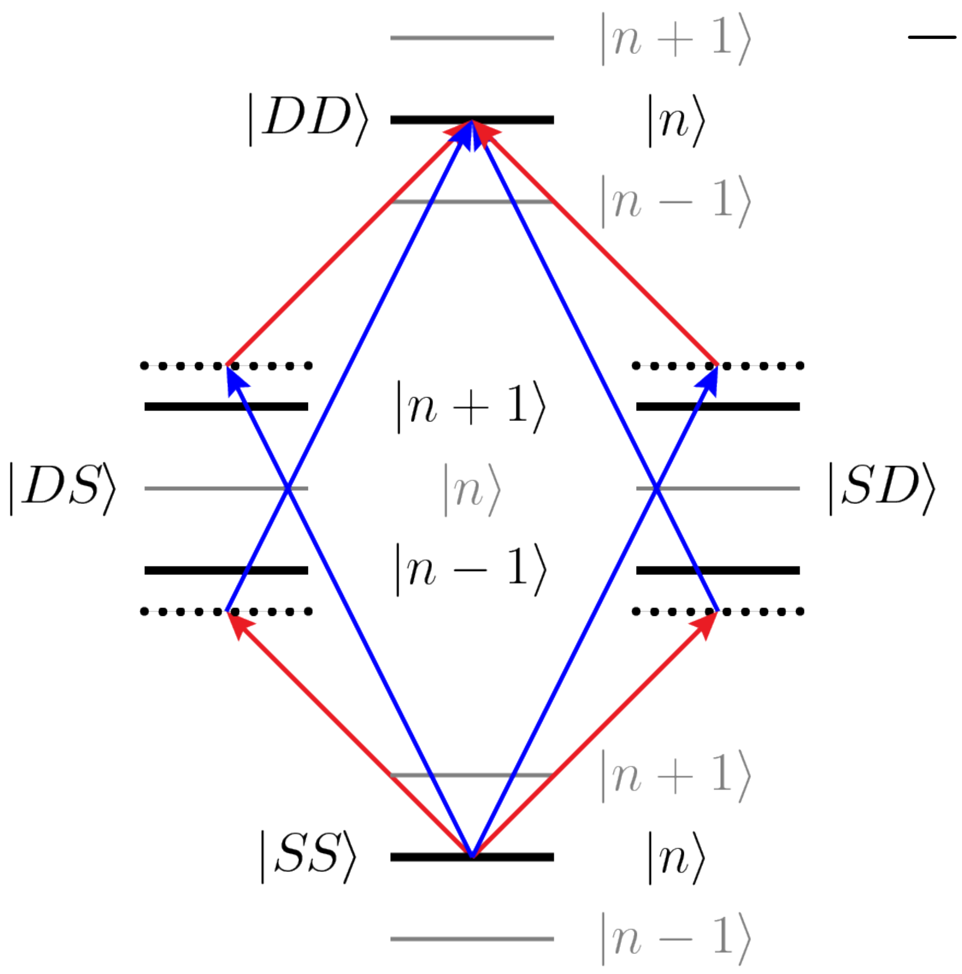
Single-qubit gates
- Addressing
- Amplitudes

Two-qubit gates
- Trap modes
- Amplitudes
- Phases

Overall budget

MS gate

$$H(t) =$$
$$-\hbar\eta\Omega(t)(a^\dagger e^{i(\nu-\delta)t} + a e^{-i(\nu-\delta)t})S_x + \epsilon(t)S_z$$



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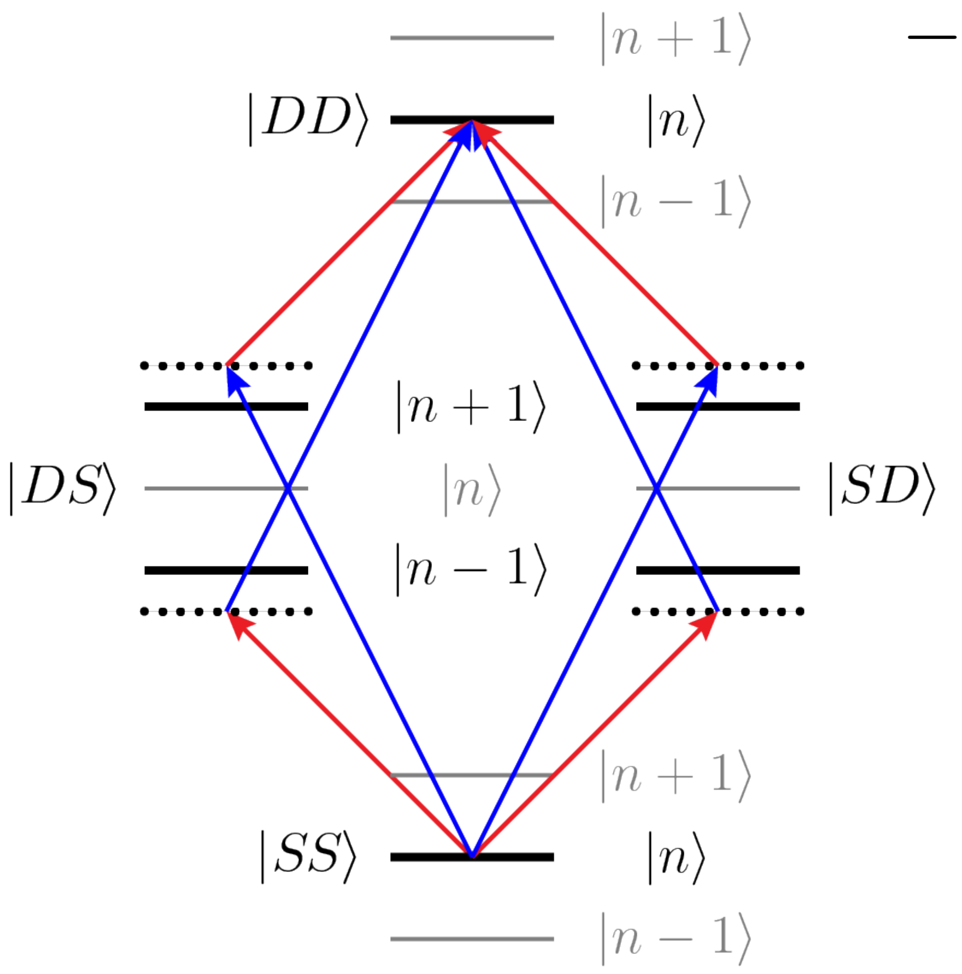
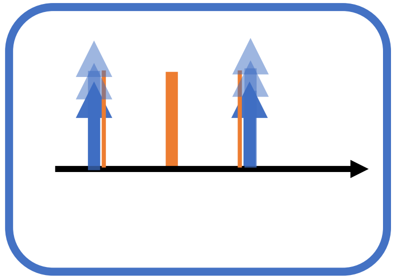
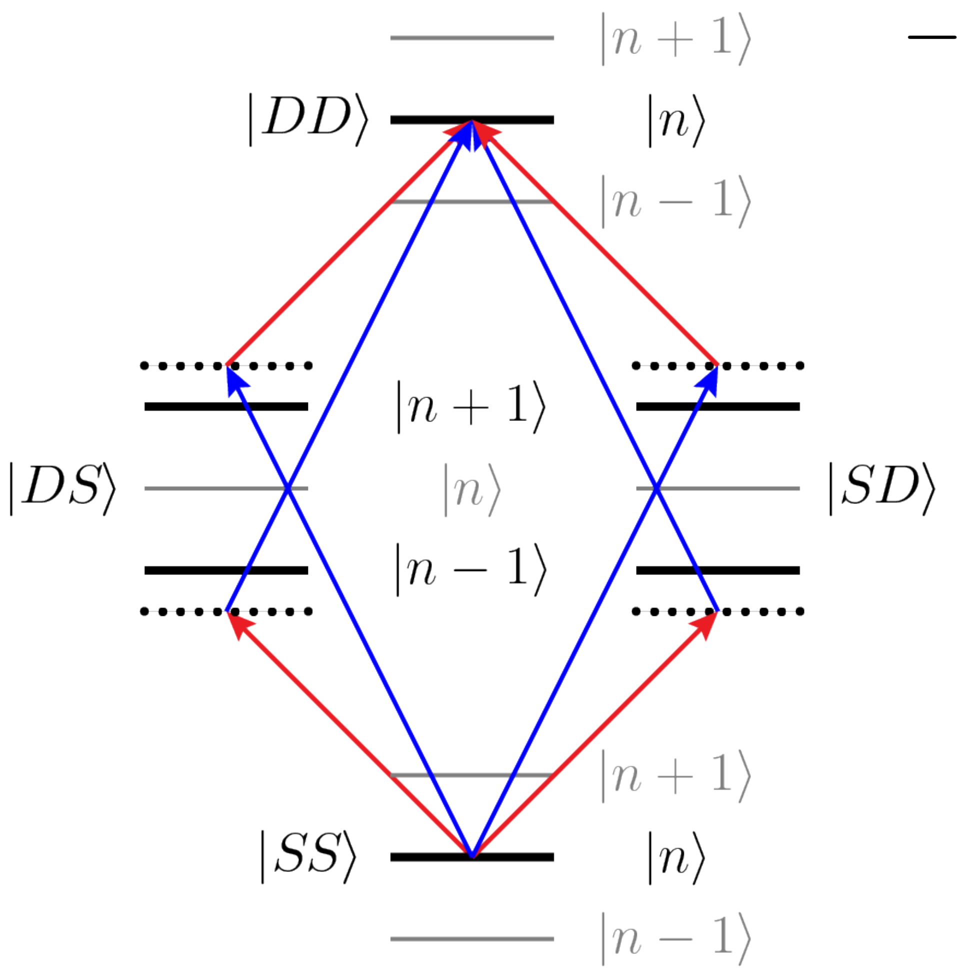


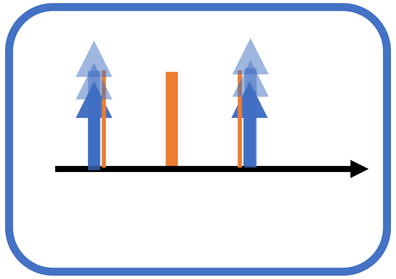


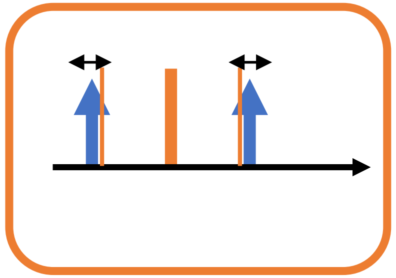
MS gate

$$H(t) = -\hbar\eta\underbrace{\Omega(t)}_{\text{Laser amplitude}}\left(a^\dagger e^{i\overbrace{(\nu-\delta)}t} + a e^{-i\overbrace{(\nu-\delta)}t}\right)S_x + \epsilon(t)S_z$$

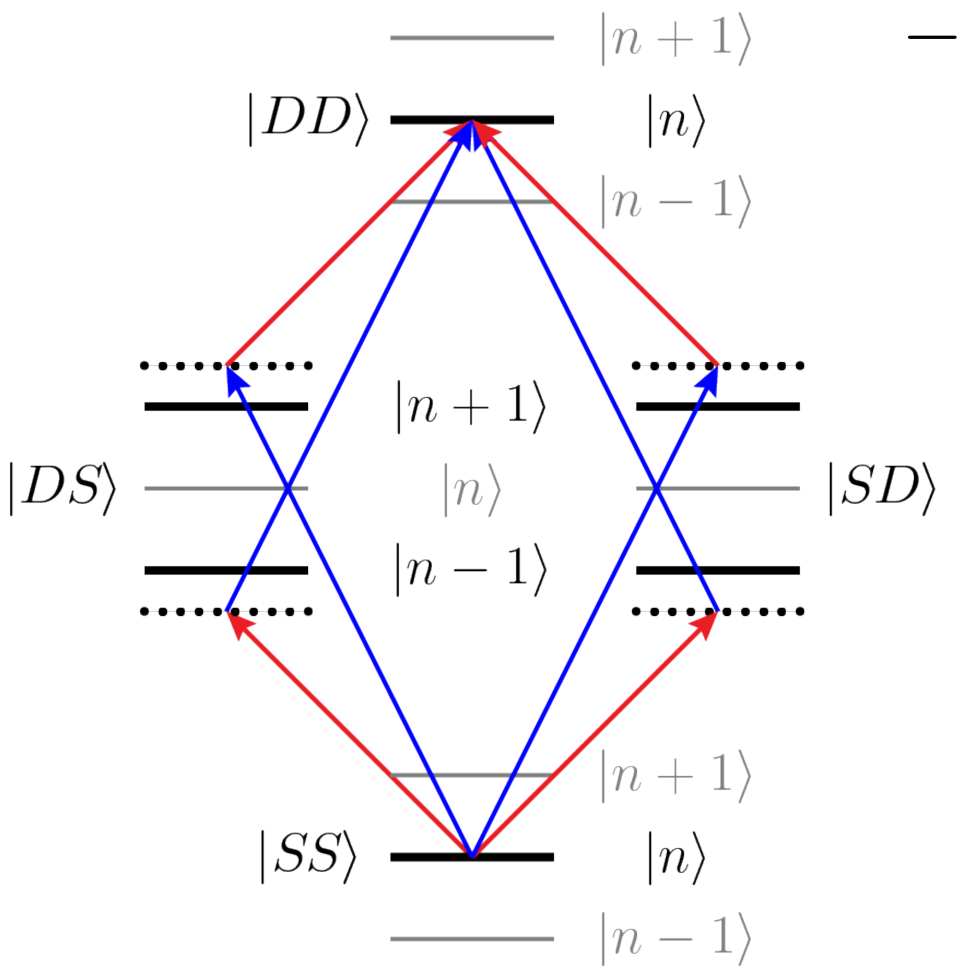
Laser & mode frequencies







MS gate

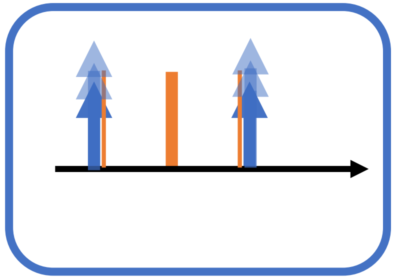


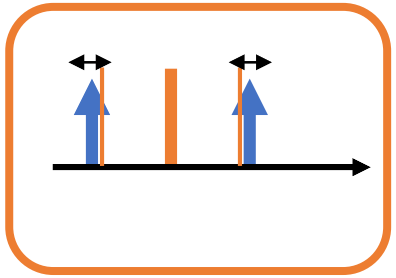
$$H(t) = -\hbar\eta\Omega(t)(a^\dagger e^{i(\nu-\delta)t} + a e^{-i(\nu-\delta)t})S_x + \epsilon(t)S_z$$

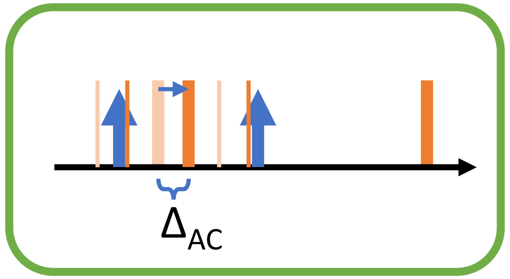
Laser amplitude

Laser & mode frequencies

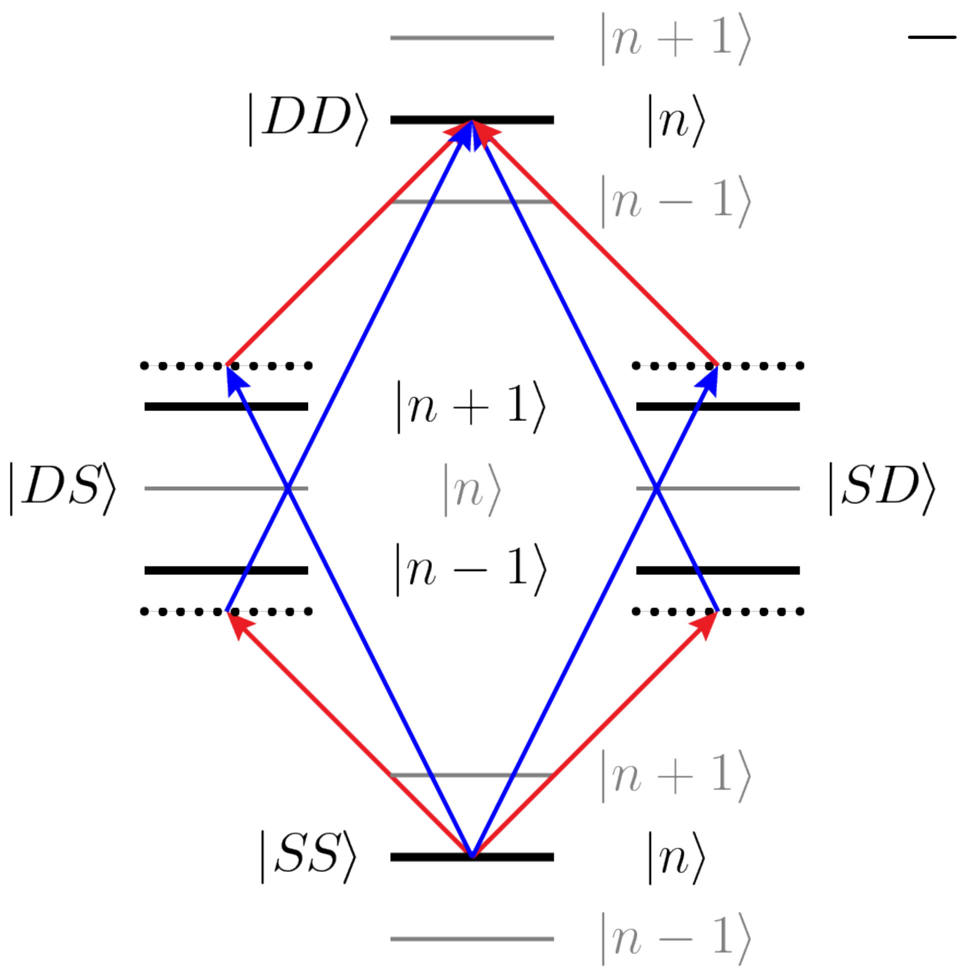
Stark shift







MS gate



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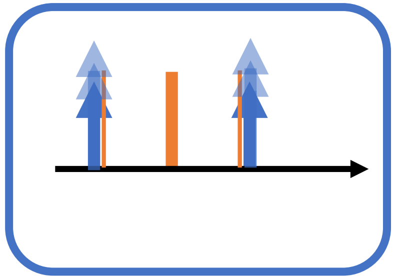
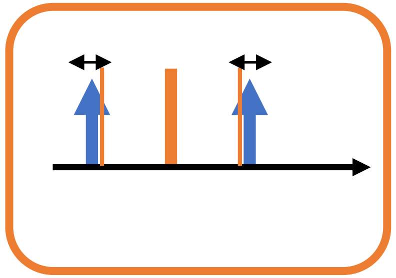
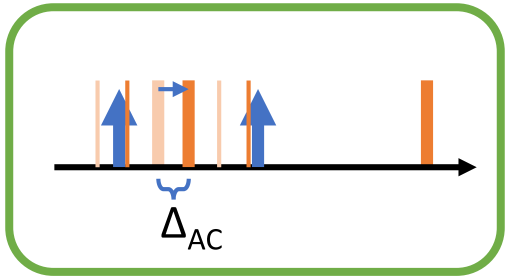
Laser & mode frequencies





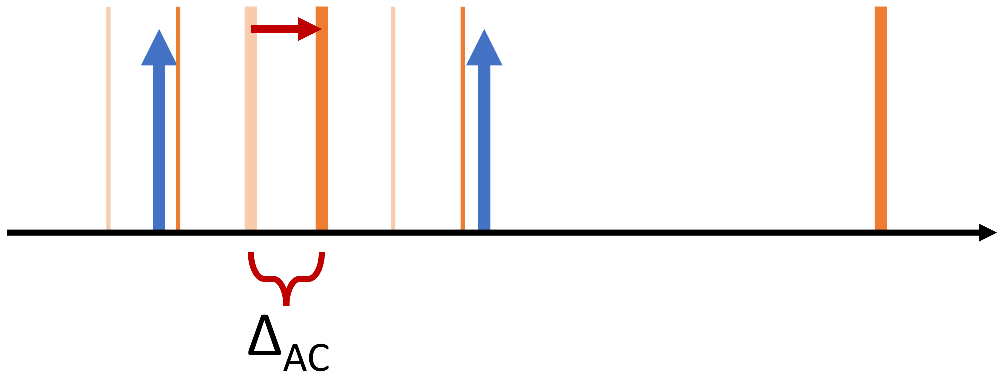


$$XX\left(\frac{\pi}{2}\right) \approx e^{-i\frac{\pi}{4}\sigma_x\otimes\sigma_x}$$

Fixed set of parameters for ion pair

MS gate – variants

Central line detuned



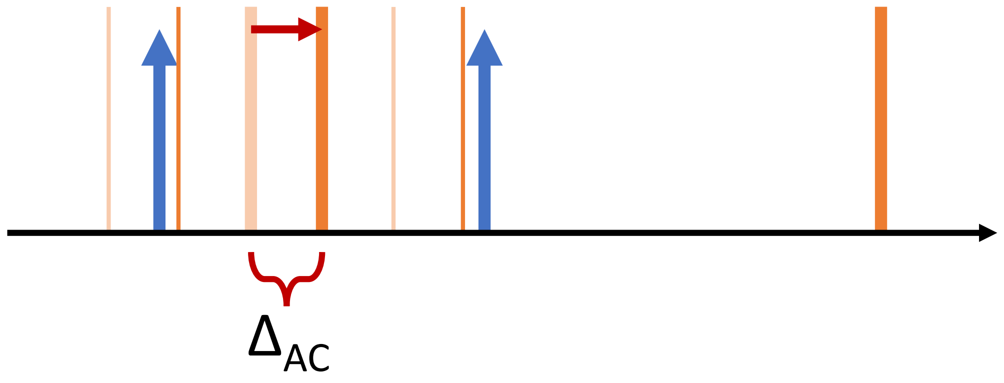
MS gate – variants

Central line detuned

- Central line detuning depends on intensity
- Induces phase shift (depends on intensity)

Result:

- Gates are intensity sensitive
- <u>Each ion pair needs individual calibration</u>



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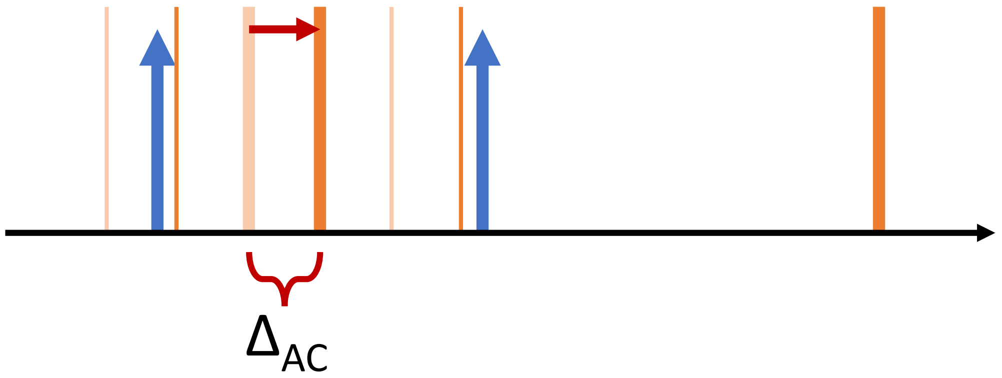
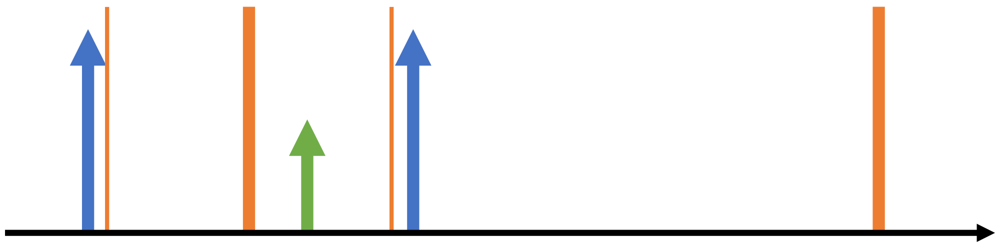


With 3rd tone



MS gate – variants

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- Central line detuning depends on intensity
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Result:

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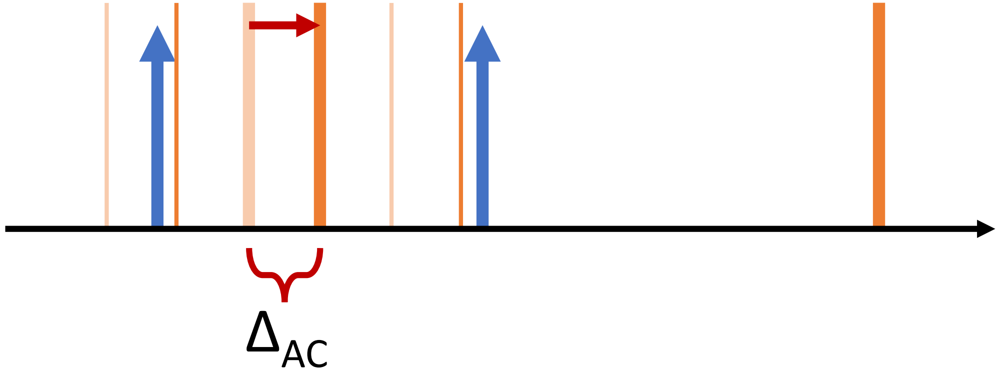
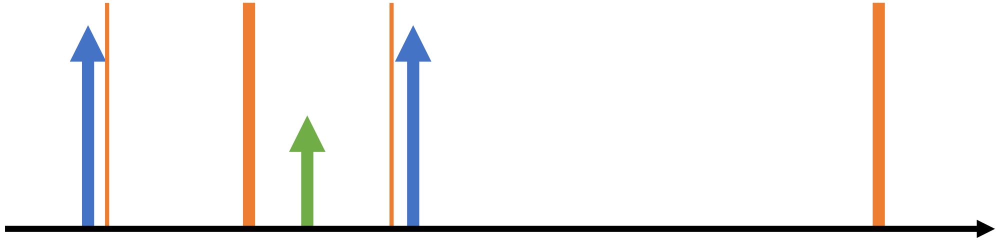


With 3rd tone

- 3rd tone params doesn’t depend on intensity
- No phase shifts

Result:

- Gates are less intensity sensitive
- <u>Single parameter set for all ion pairs</u>

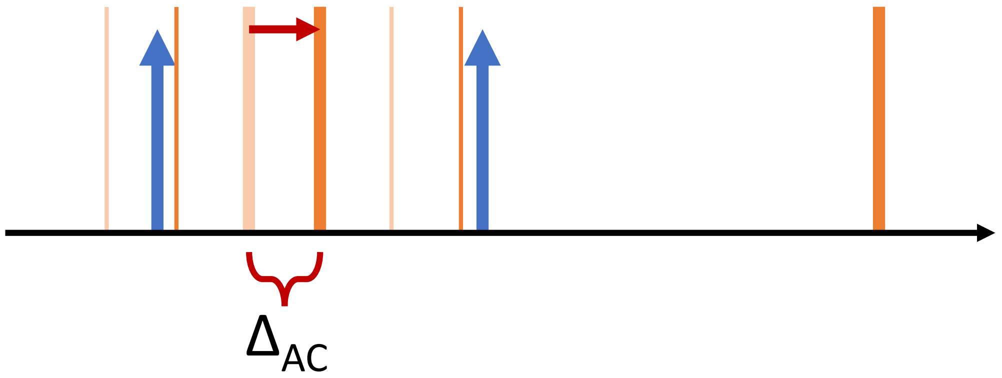


MS gate – variants

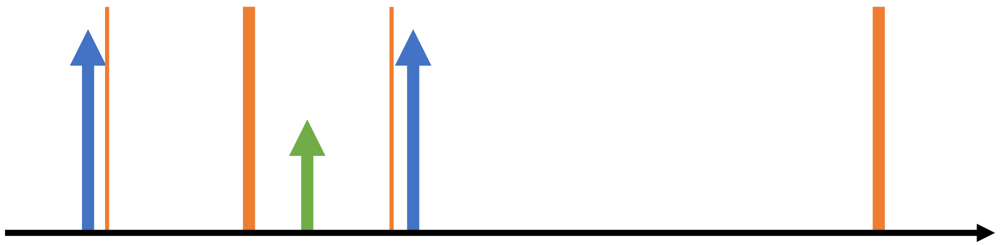
Central line detuned	With 3rd tone

For N ion pairs

4N parameters



2 parameters



MS gate with 3rd tone – power corrections

Spectator modes become important as chains grow longer

- Accumulation of geometric phase different along chain
- Imperfect spin-motional disentanglement

Long-term solution: Modulated gates

Medium chains: Analytic power correction

- Chose gate duration to close phase space for 1st and 2nd mode simultaneously
- Adjust powers to accumulate same phase

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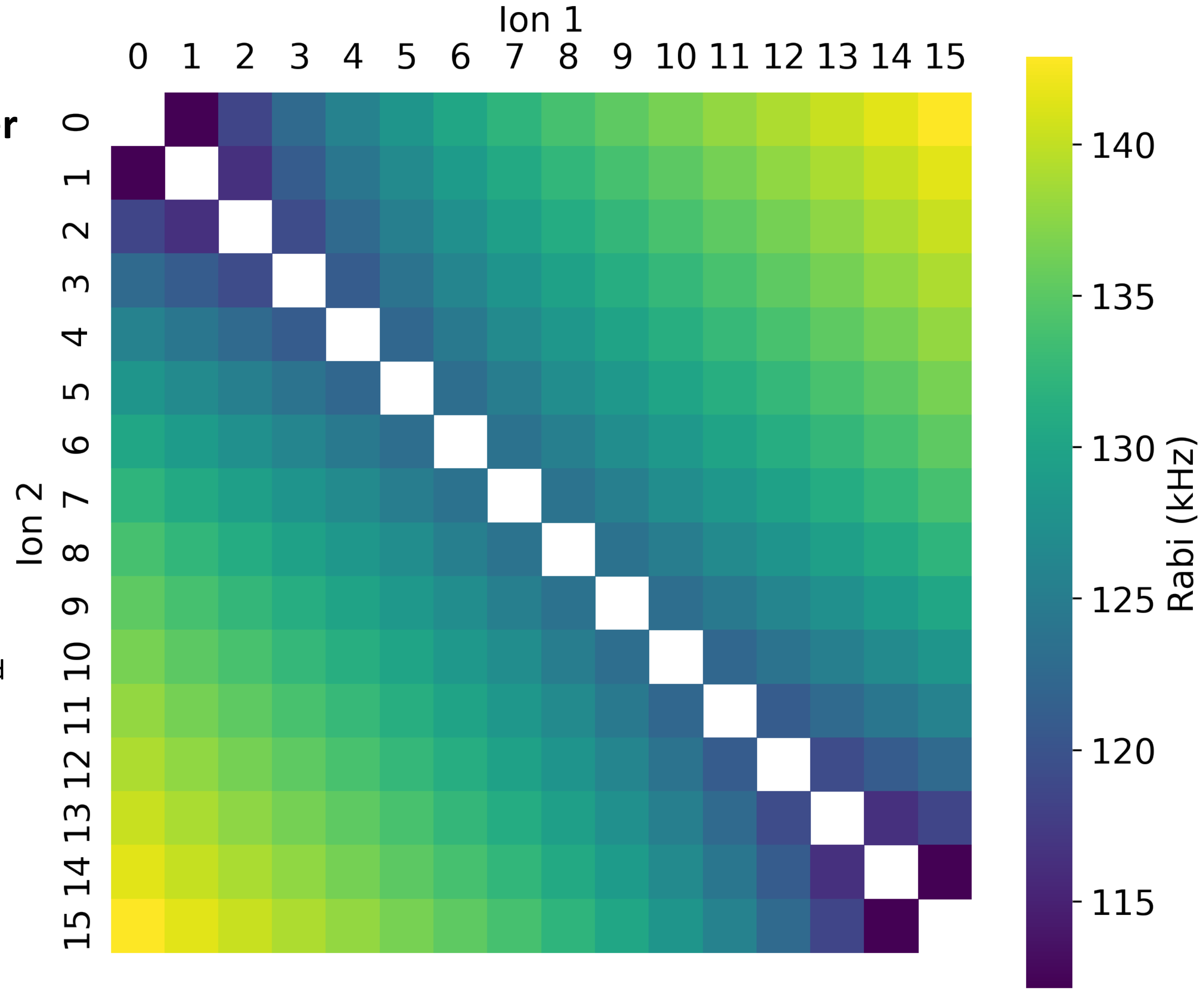
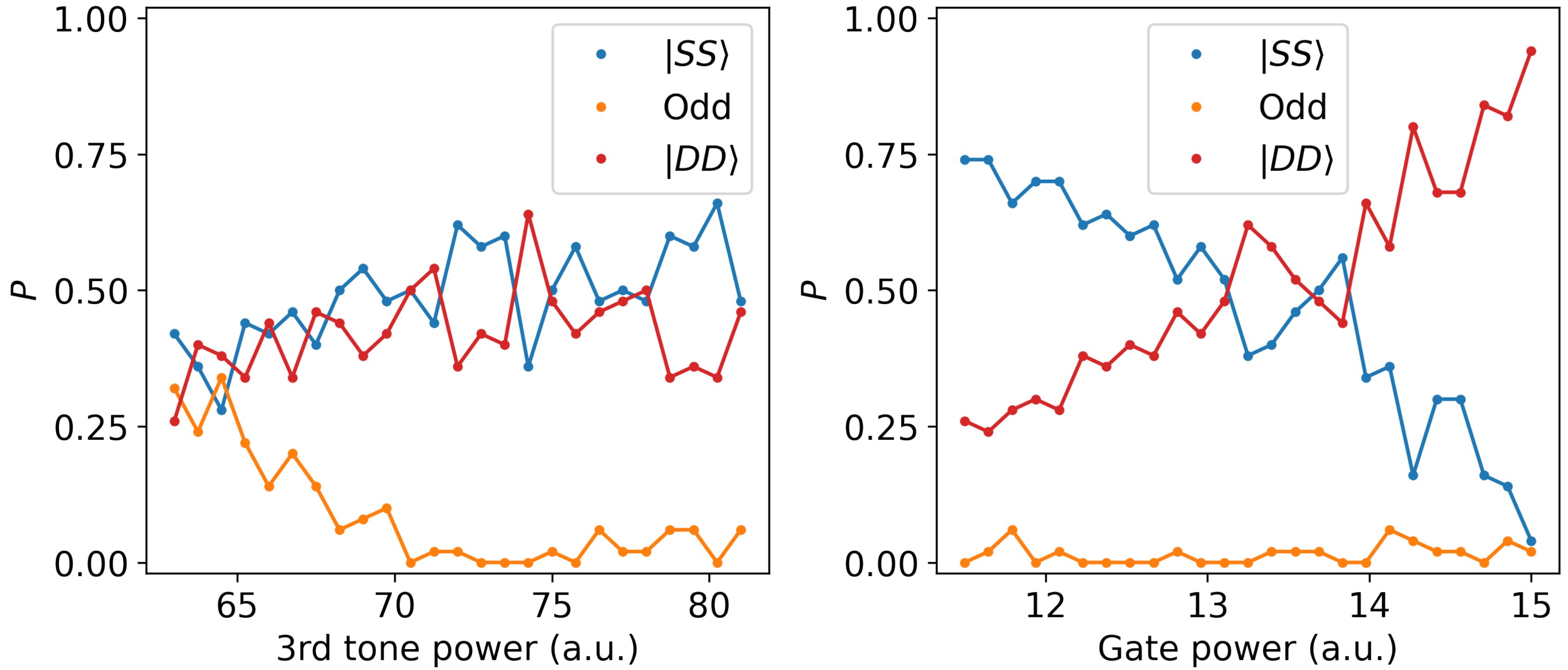


MS gate with 3rd tone – calibration

Option 1:

Calibrate gate on a single ion pair



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MS gate with 3rd tone – calibration

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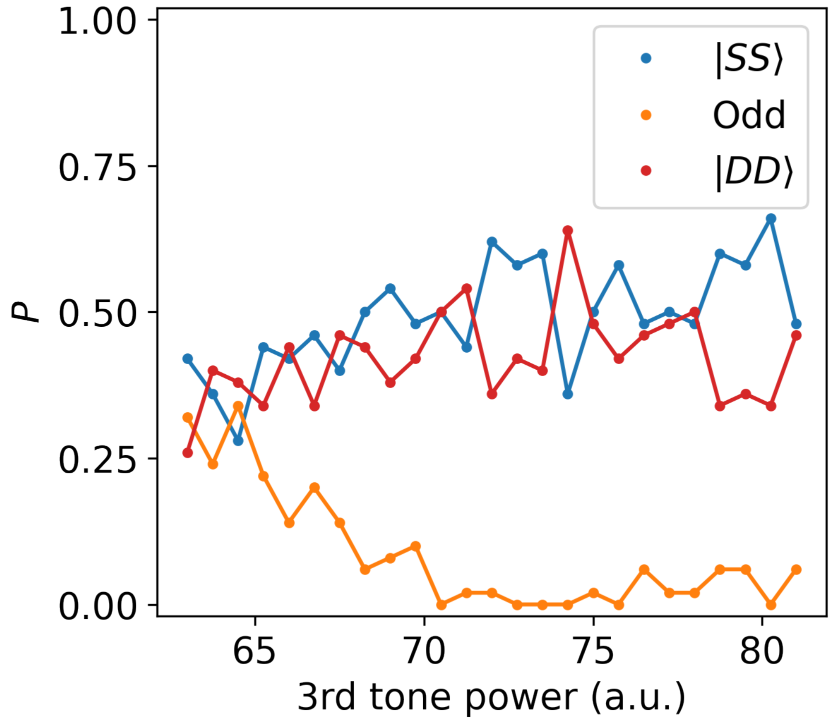
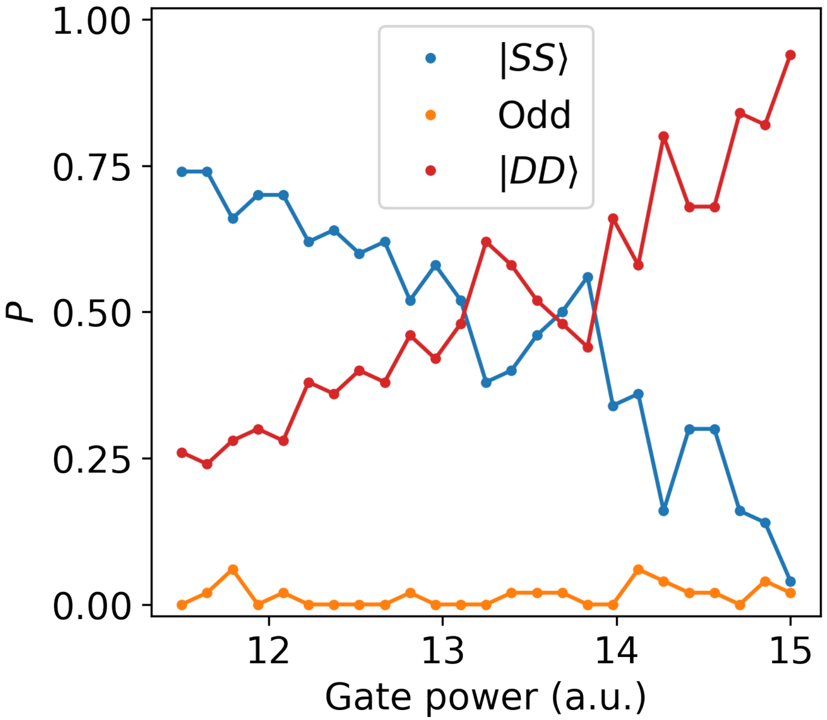




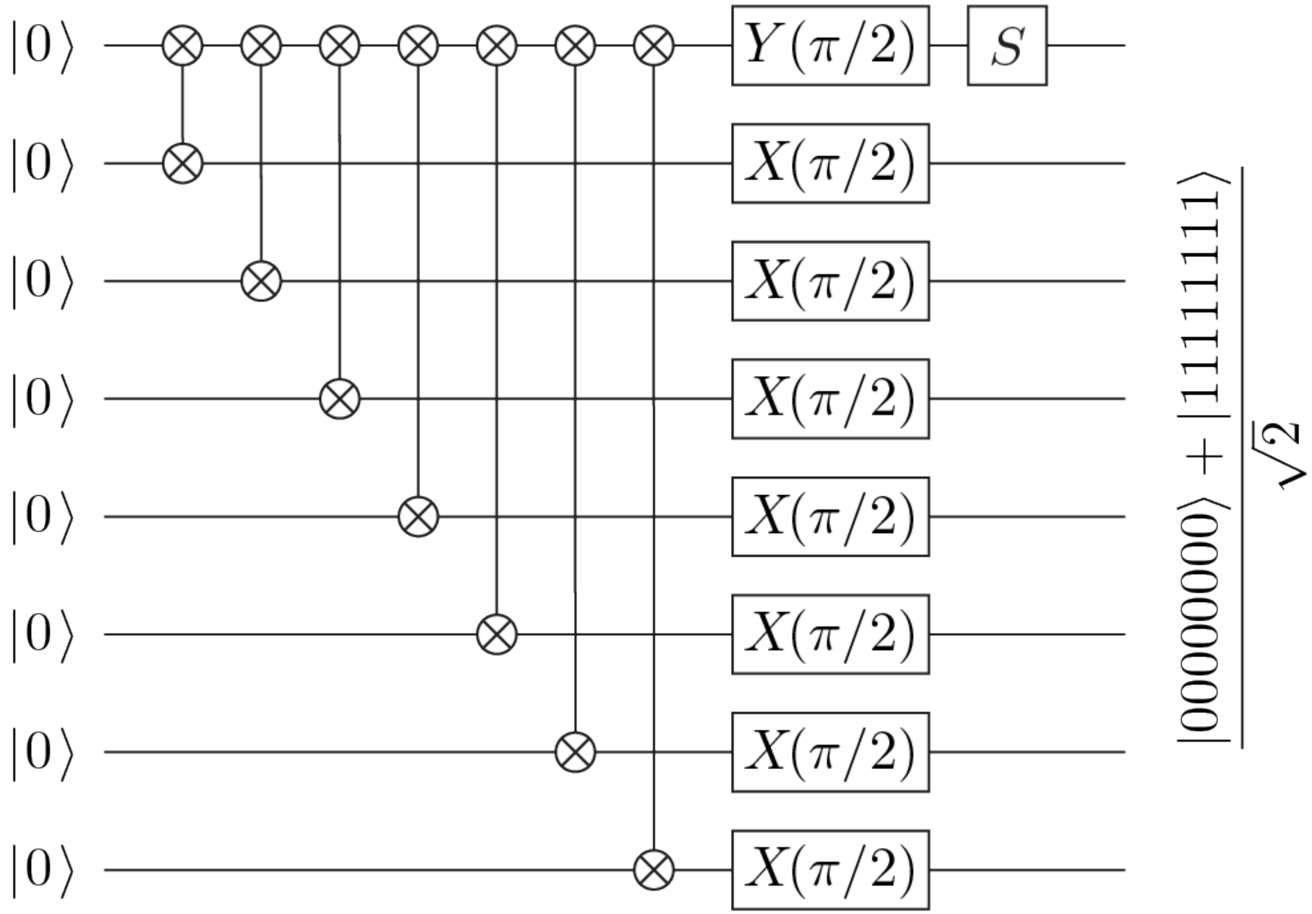
Every 30 mins

MS gate with 3rd tone – calibration

Option 2:

Calibrate gate via full register GHZ state

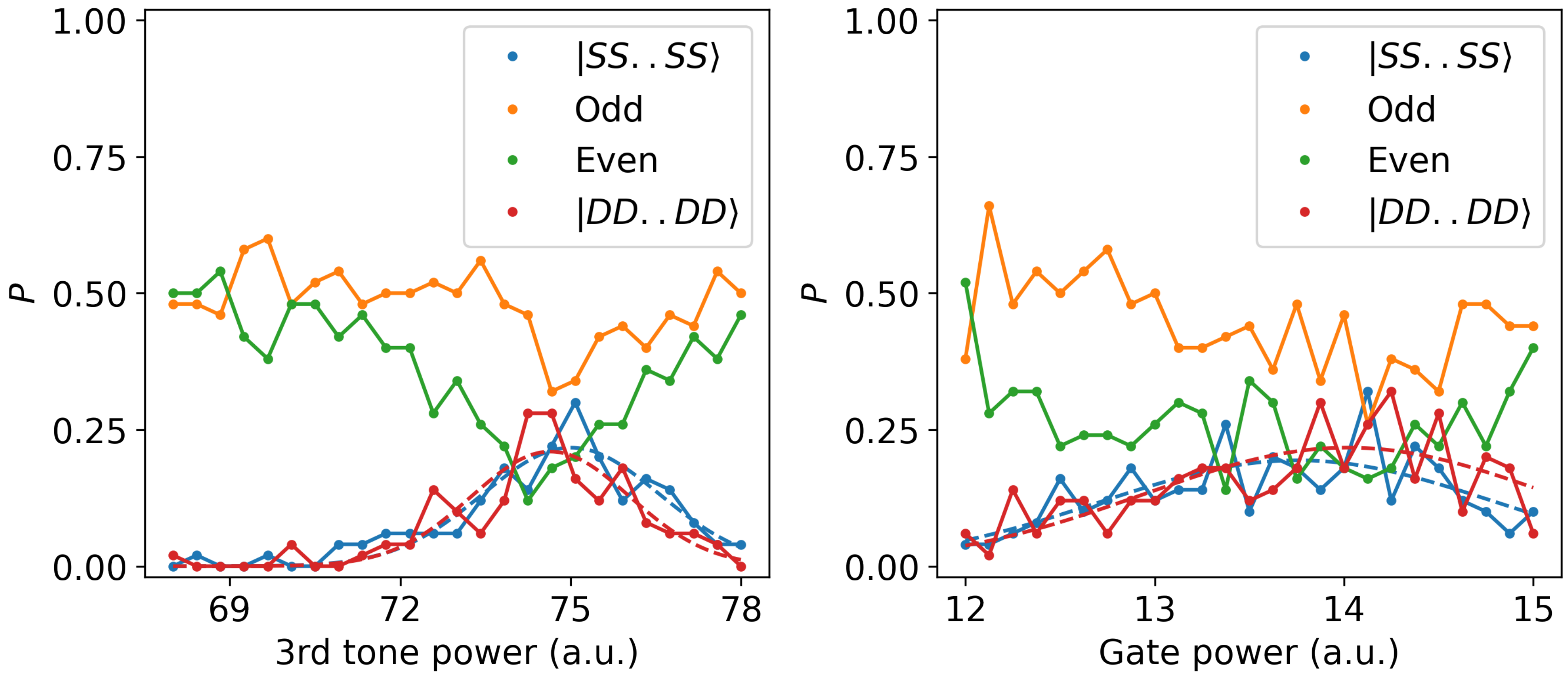
Involves n-1 gates for n-ion chain



MS gate with 3rd tone – calibration

Option 2:

Calibrate gate via full register 16 ions GHZ state



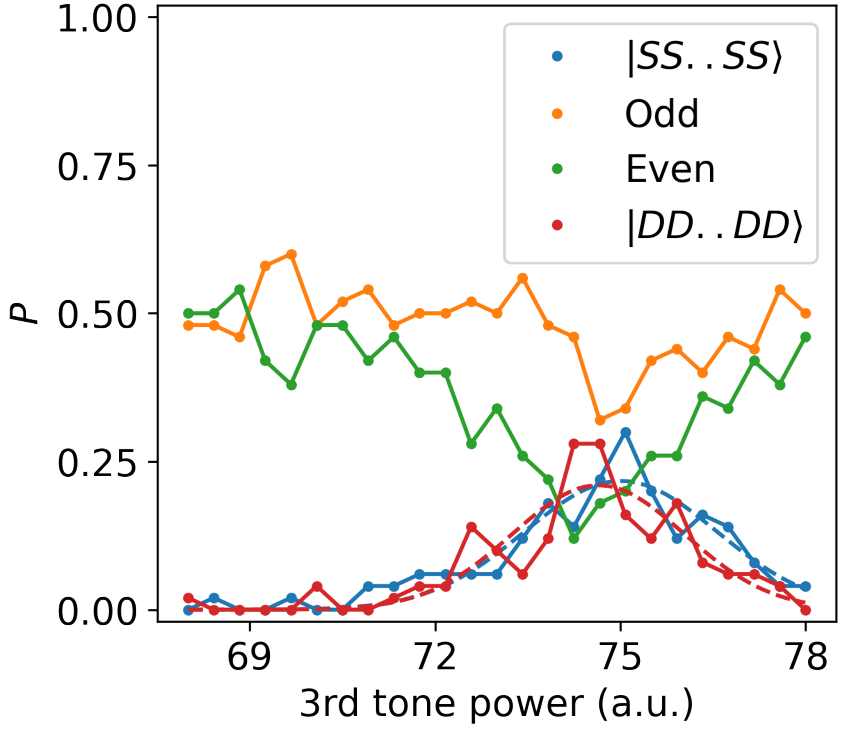
MS gate with 3rd tone – calibration

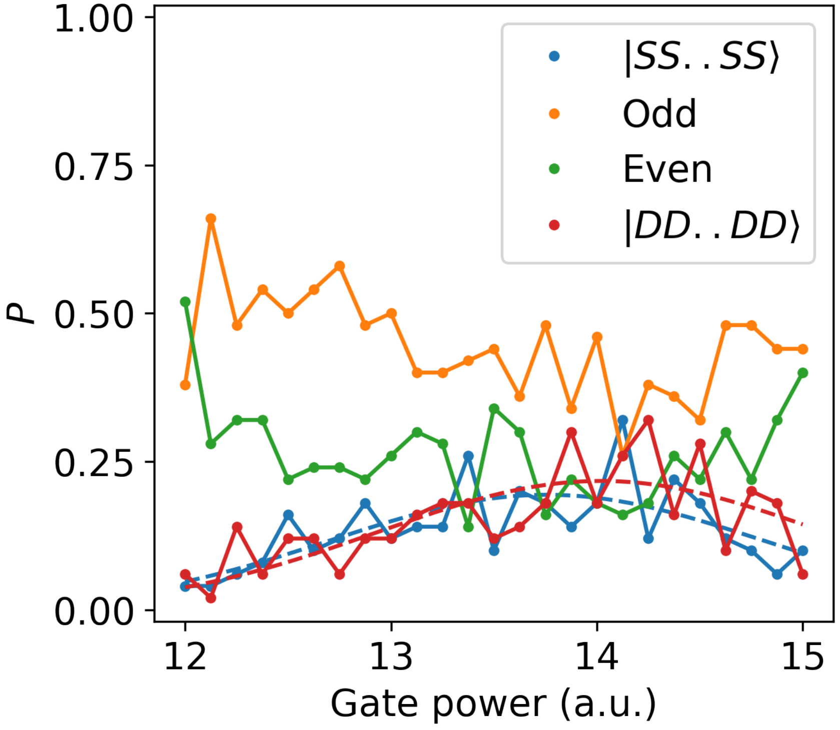
Option 2:

Calibrate gate via full register 16 ions GHZ state

Fit

$$|SS\dots SS\rangle + |DD\dots DD\rangle$$





MS gate with 3rd tone – calibration

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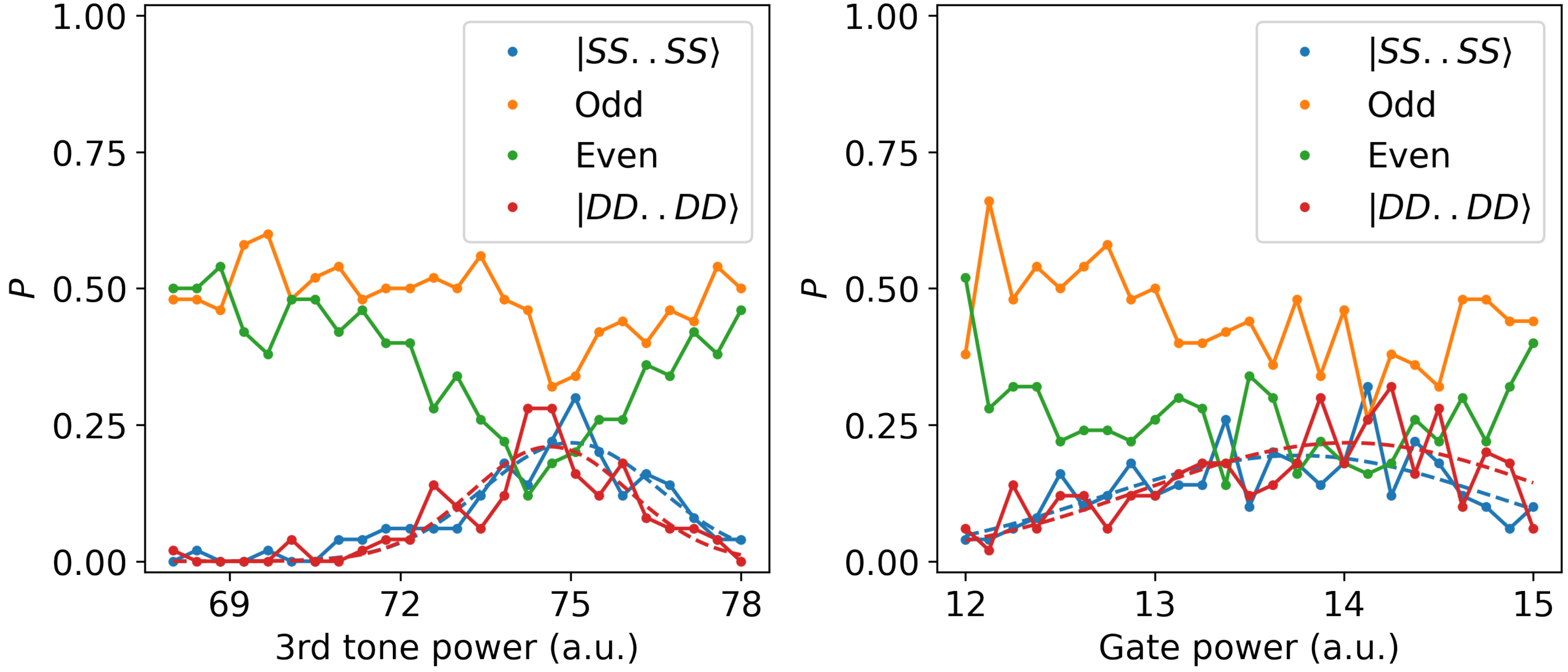
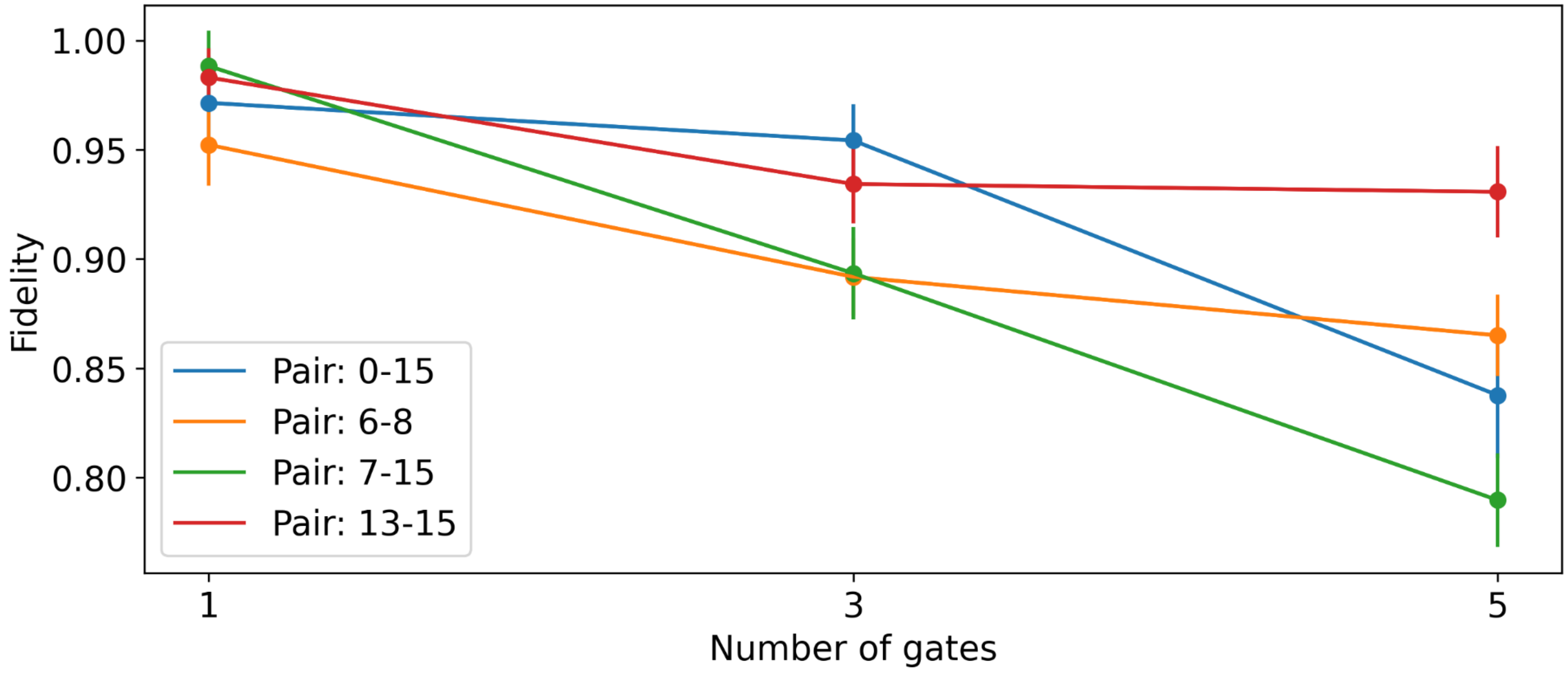


Every 30 mins

MS gate with 3rd tone – various pairs

Calibrate one set of parameters, check behaviour for different pairs



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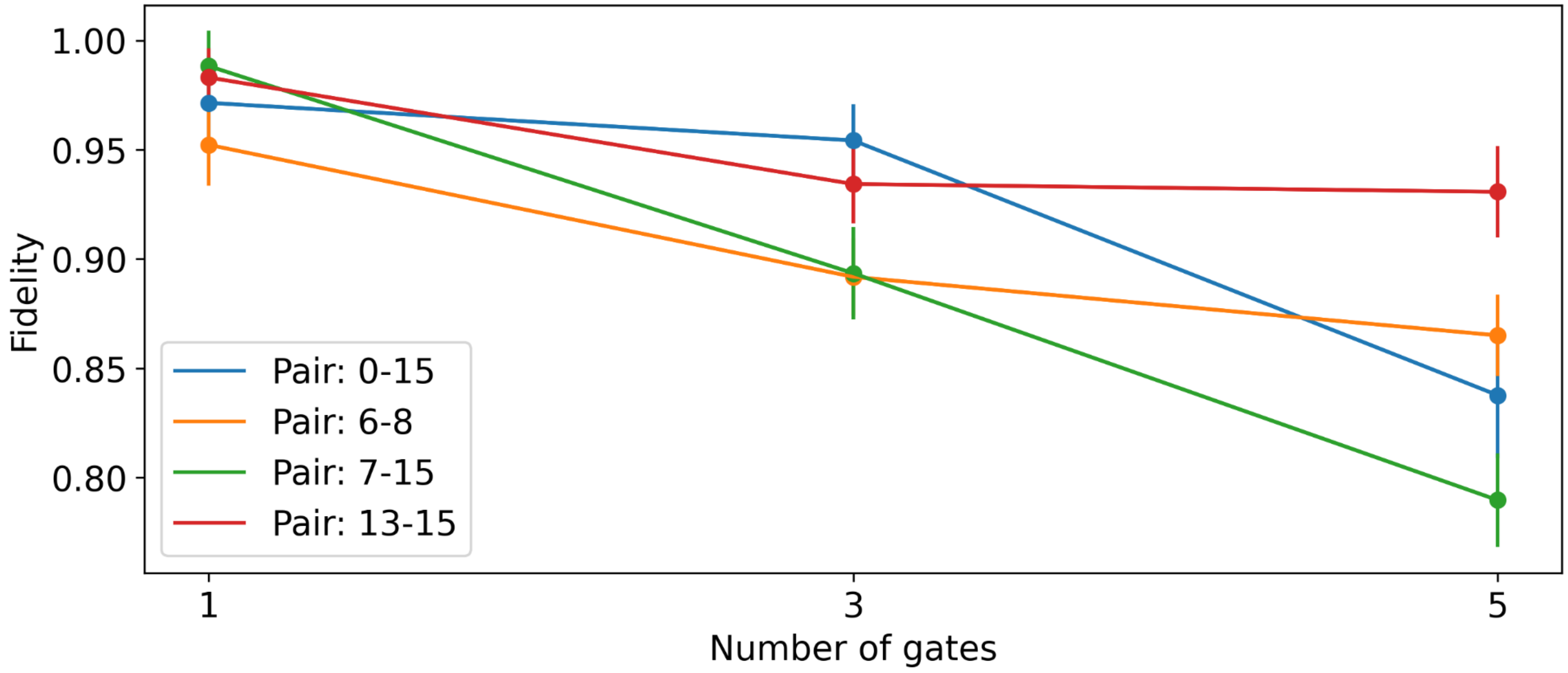

Fidelity decay is consistent, Stark shifts are compensated across chain

Trap modes – calibration

Radial trap modes drift due to RF power fluctuations

- Fast RF power stabilization
- Slow drifts compensation – feed back to RF power level set point

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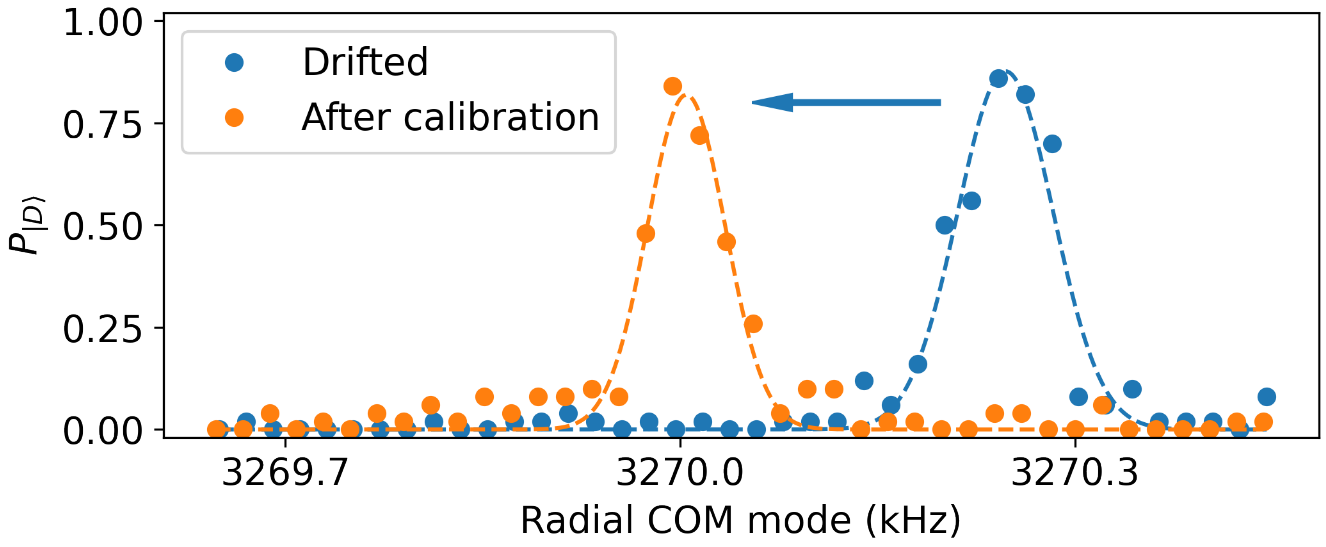

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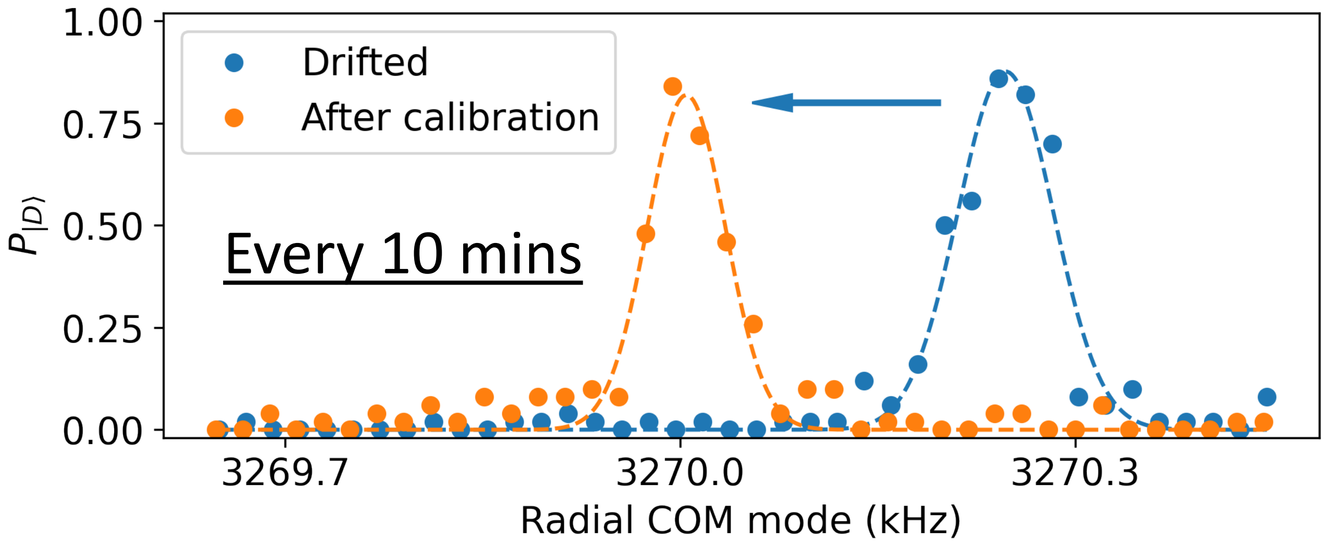

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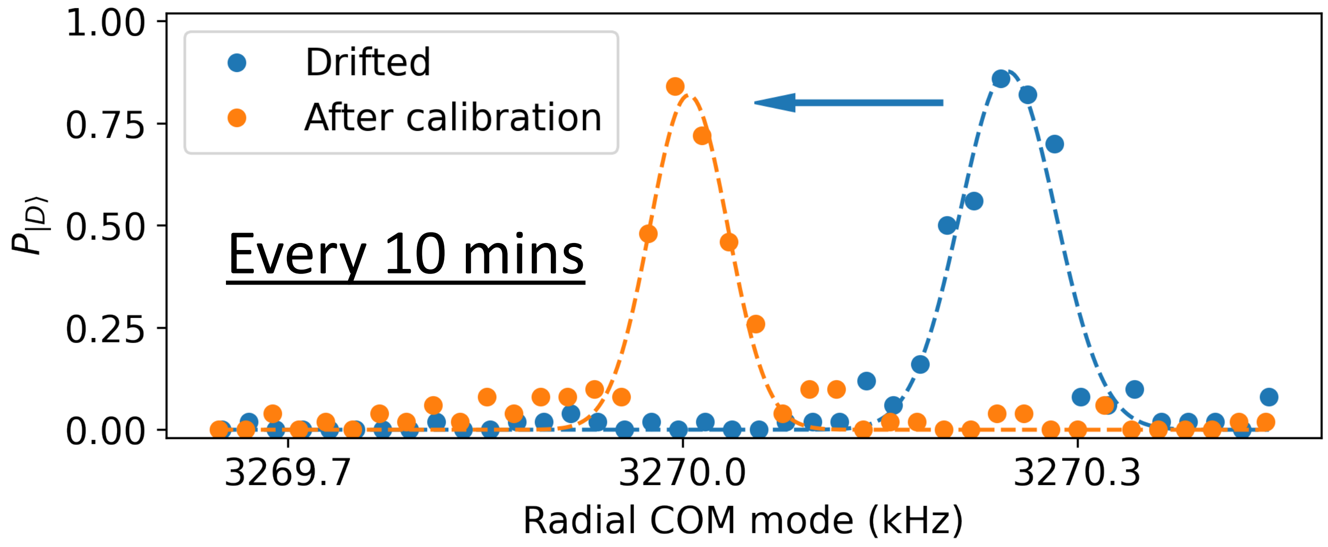

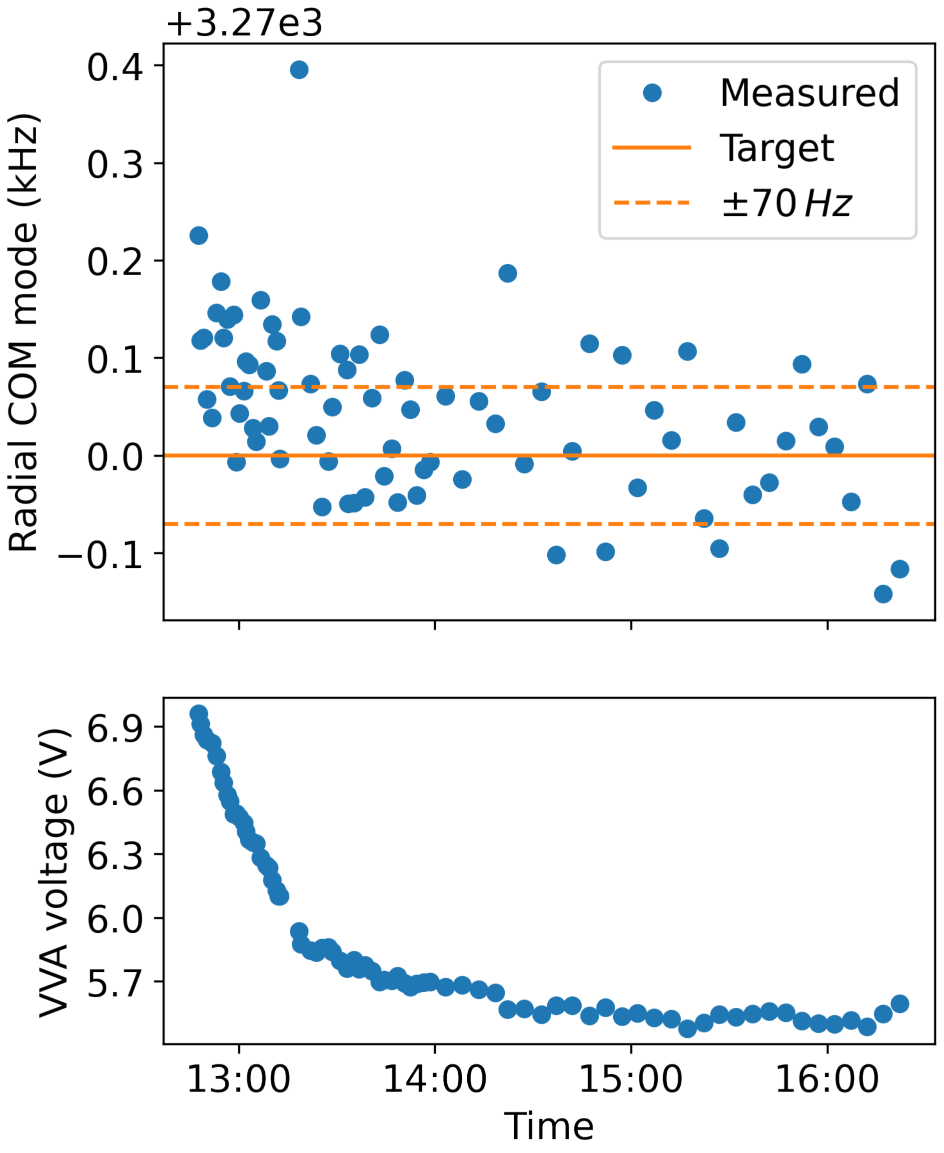

Outline

General

- Laser frequency & magnetic field

Single-qubit gates

- Addressing
- Amplitudes

Two-qubit gates

- Trap modes
- Amplitudes
- Phases

Overall budget

Duty cycle

	Repeat (mins)	Approx. time spent (s)
Frequency scan	20	13
COM mode scan	10	22
AOD scans	30	88
RPE	30	44
MS Scans	30	110

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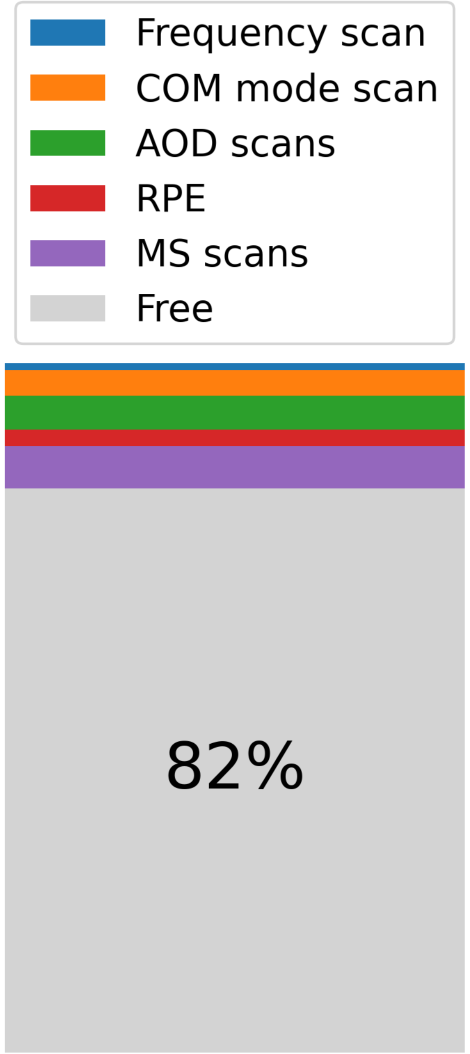


Outline

1. Trapping
2. State manipulation
    - $^{40}Ca^+$
    - Optical pumping
    - Sideband cooling
    - Detection
3. Qubit manipulation
    - Single qubit gate
    - MS gate
4. Pulse sequence
5. Scaling problems
6. AQTION platform
    - Compact optics
    - Trap drawer
    - Vibrations
    - Addressing
7. Automation
    - Keeping constant fidelity
8. Performance
    - Benchmarking
    - Quantum volume

Benchmarking – 16 ions

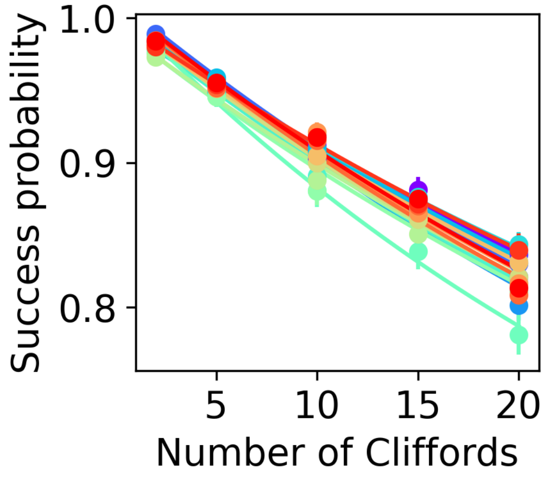
Single-qubit

F = 99.51 ± 0.05 %

Benchmarking – 16 ions

Single-qubit

F = 99.51 ± 0.05 %



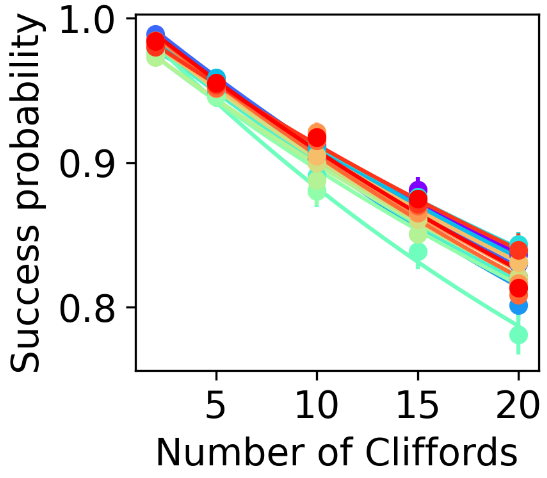
Benchmarking – 16 ions

Single-qubit

F = 99.51 ± 0.05 %

Two-qubit

F ≈ 97.6 %



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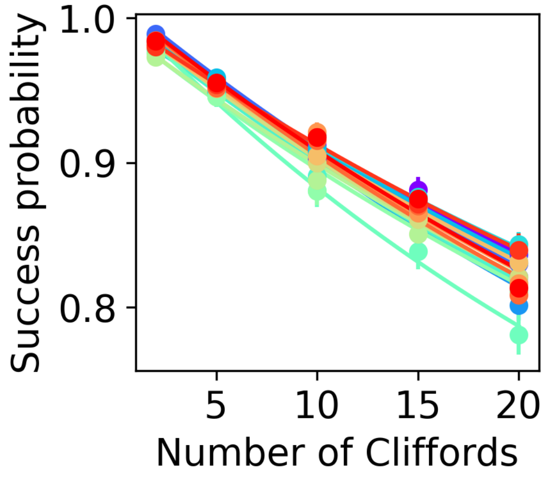

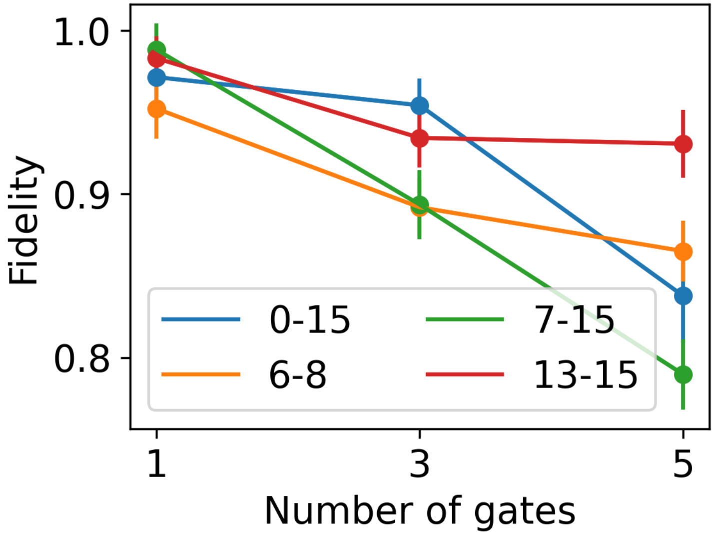

Benchmarking – 16 ions

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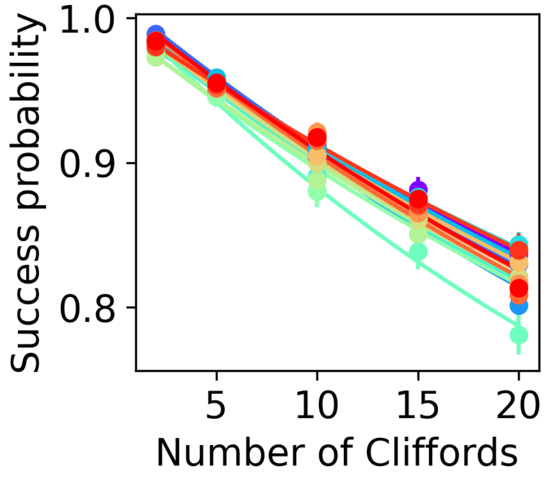
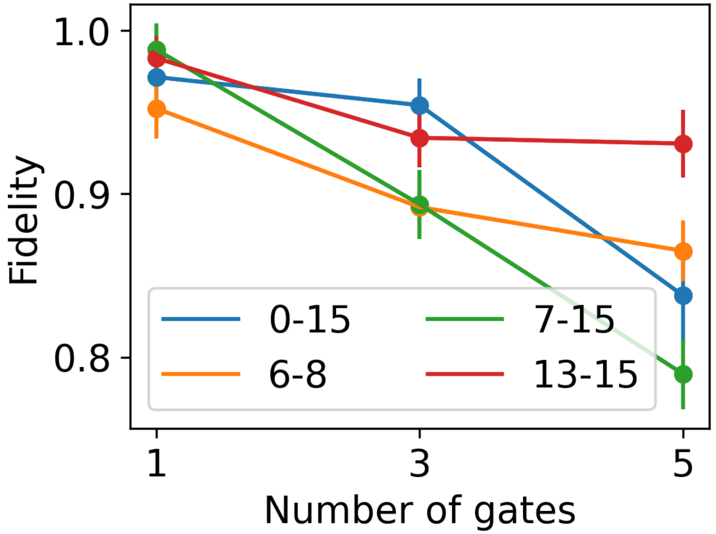


Two-qubit

F ≈ 97.6 %



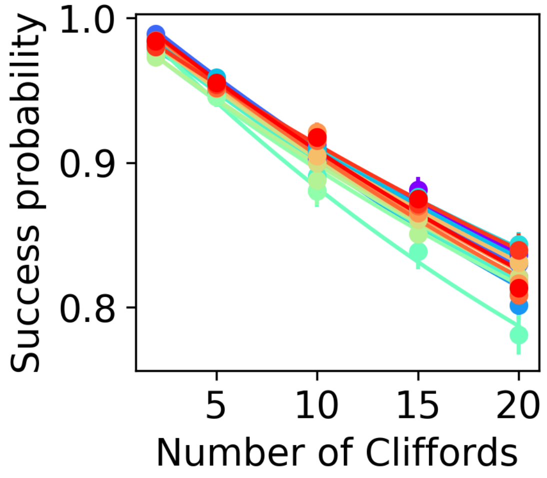
16-ions GHZ

F ≈ 64 %

Benchmarking – 16 ions

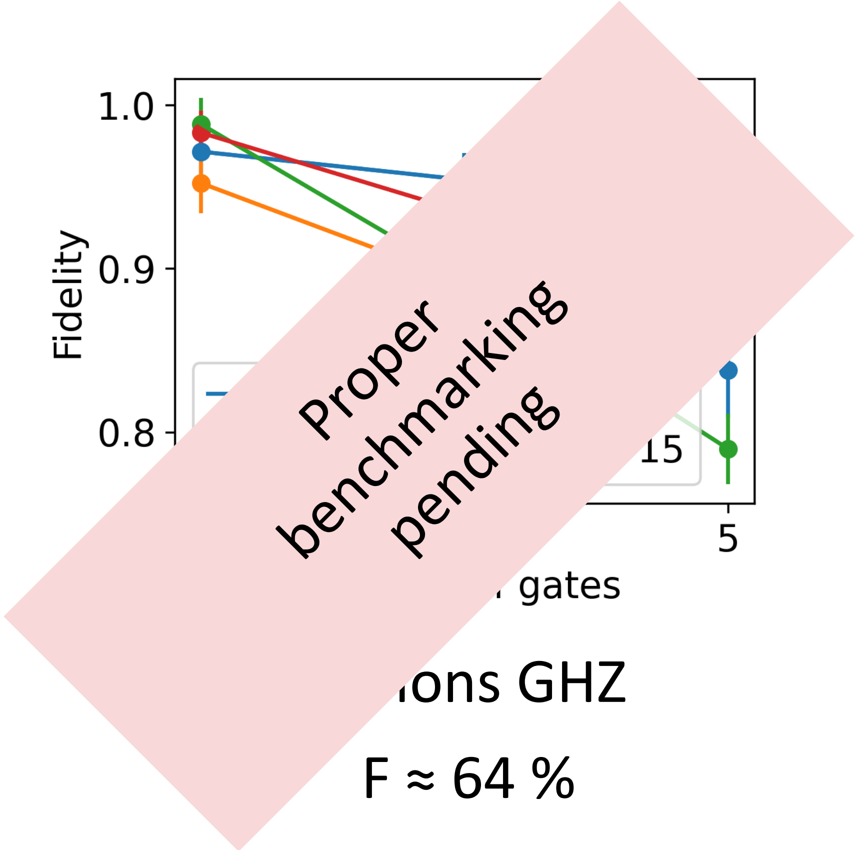
Single-qubit

F = 99.51 ± 0.05 %



Two-qubit

F ≈ 97.6 %



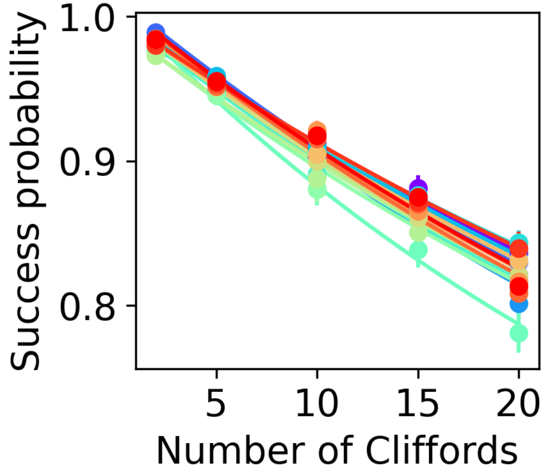
ions GHZ

F ≈ 64 %

Benchmarking – 16 ions

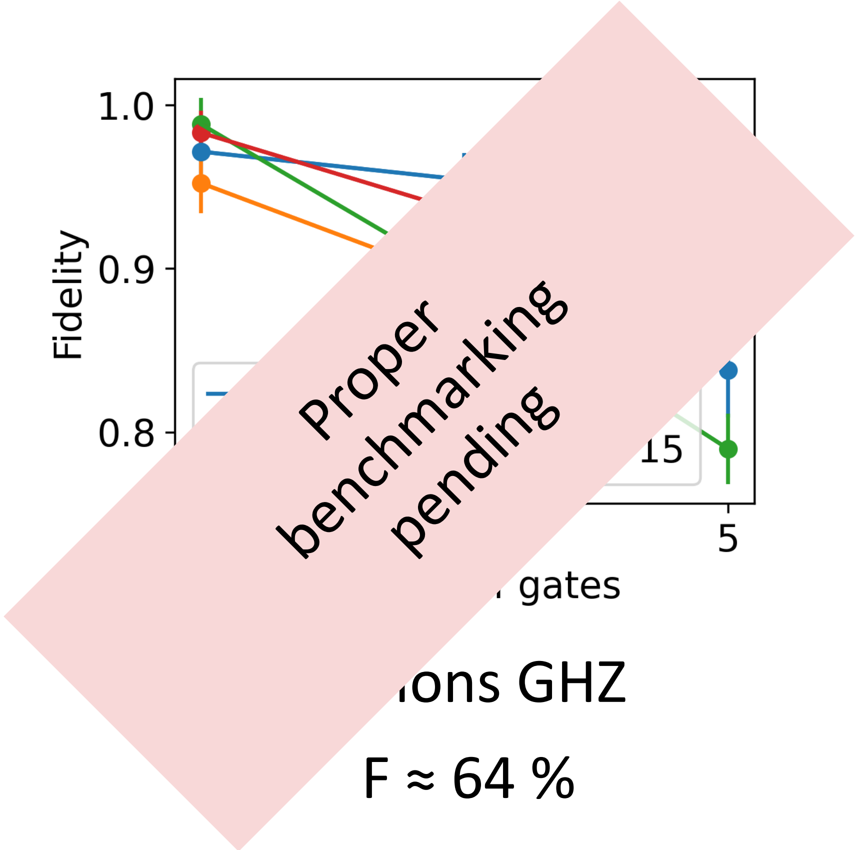
Single-qubit

F = 99.51 ± 0.05 %



Two-qubit

F ≈ 97.6 %

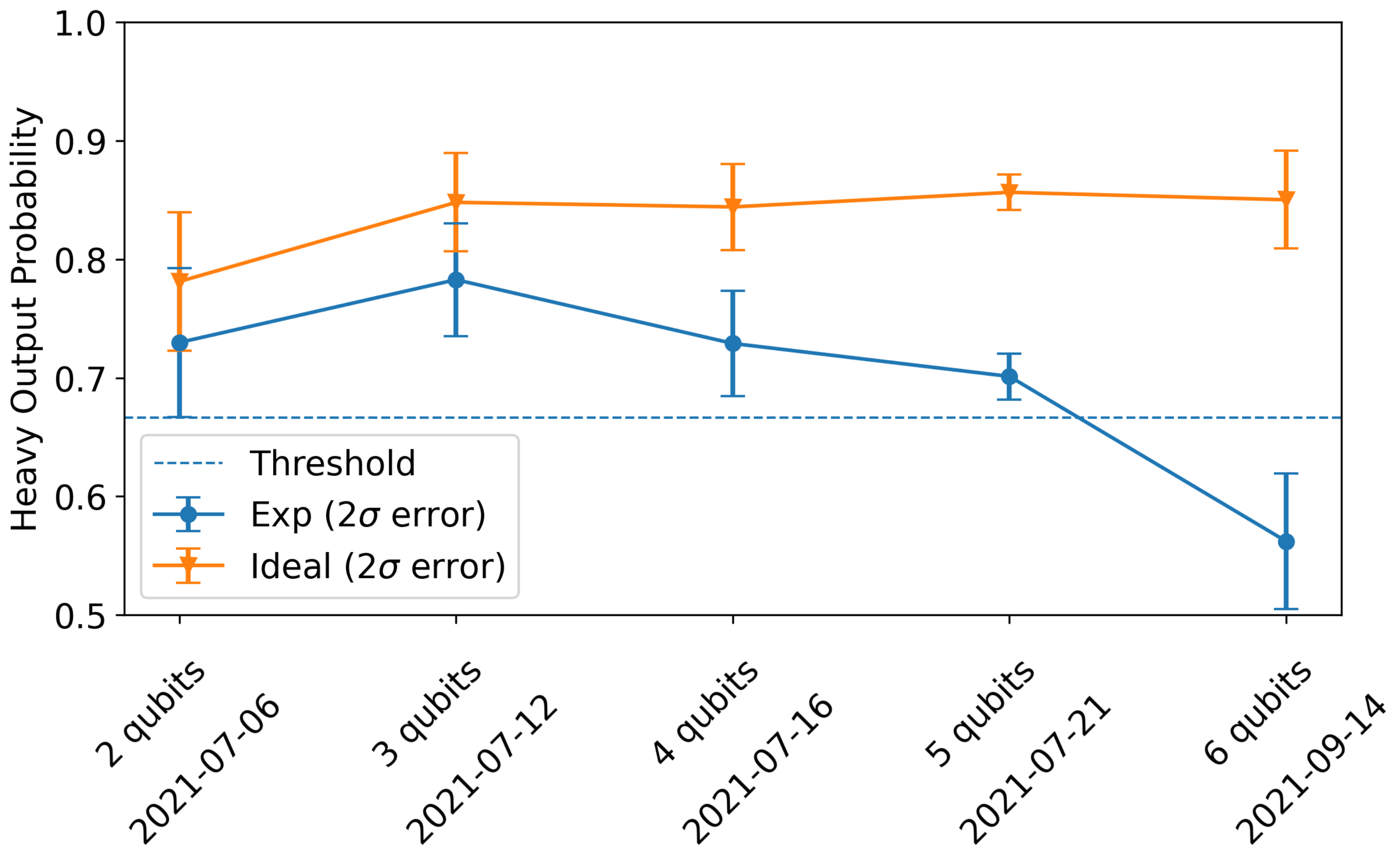


ions GHZ

F ≈ 64 %

	Fidelity (%)
State init	99.8
Readout	> 99.7
Single-qubit	99.5
Two-qubit	≈ 97.6

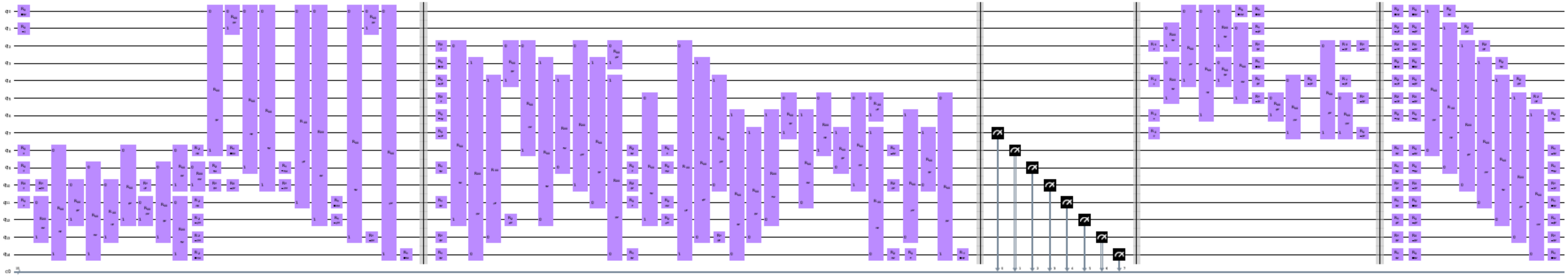
Quantum volume – 6 ions



Complexity illustration – Color code

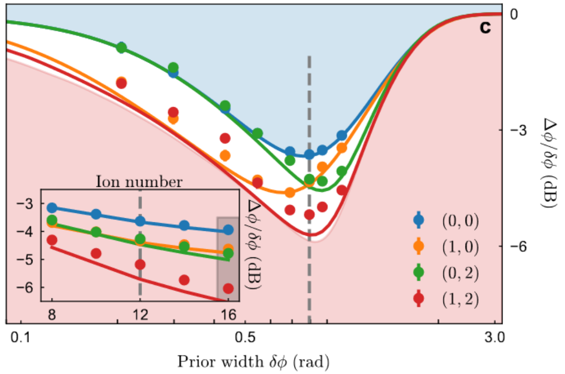
106 SQ gates

65 MS gates



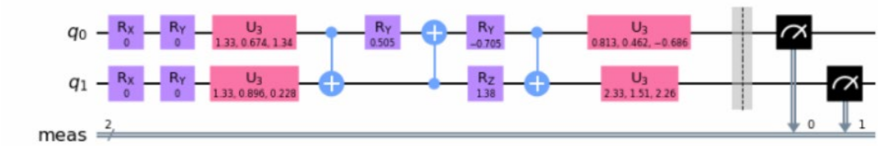
Manuscript is in preparation

AQTION – (Mostly) finished projects



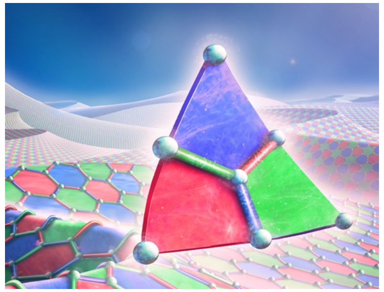
» Metrology

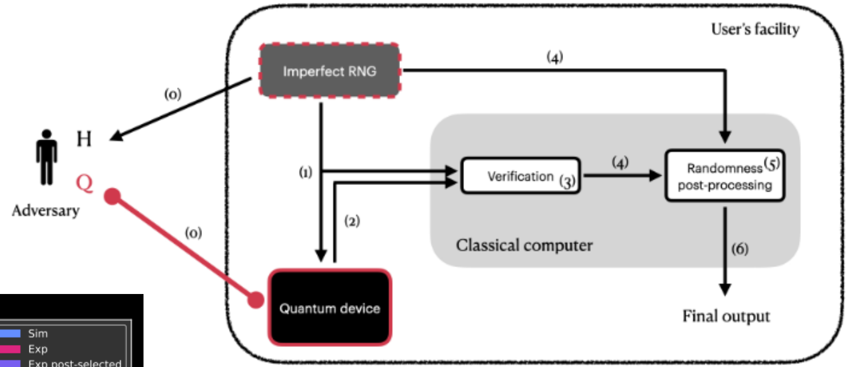
- Optimal metrology with programmable quantum sensors
- Multiparameter estimation with Holevo Cramér-Rao bound



» Quantum information

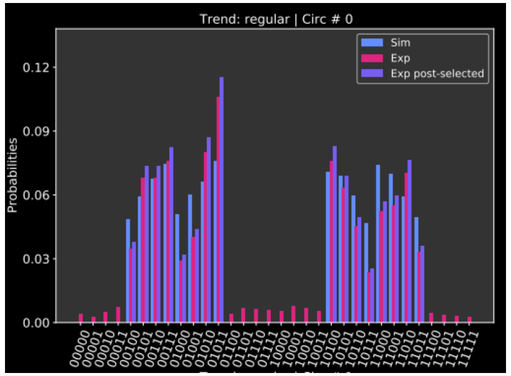
- Color code





» Industry collaborations

- Privacy and randomness amplification (CQC)
- Quantum-enhanced portfolio estimation (Multiverse Computing)



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Thank you for the attention!