POLITECNICO MILANO 1863 | DIPARTIMENTO DI ELETTRONICA INFORMAZIONE E BIOINGEGNERIA

Laboratory 3 – Quantum system characterization
058171 - Quantum Circuits and Devices

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1. Modeling nonideal quantum systems
2. Frequency calibration
3. T1 characterization
4. T2 characterization
5. Recap and conclusions

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Detuning

- In the previous laboratory, we considered an idealized two-level qubit with perfectly resonant driving field:

$$\frac{\hat{\mathcal{H}}}{\hbar} = \hat{H} = \frac{1}{2}\omega\hat{\sigma}_z + \Omega\cos(\omega t)\hat{\sigma}_x$$

- A first step towards nonideality is considering a near-resonance driving at frequency ω_d, accounting for detuning:

$$\frac{\hat{\mathcal{H}}}{\hbar} = \hat{H} = \frac{1}{2}\omega\hat{\sigma}_z + \Omega\cos(\omega_d t)\hat{\sigma}_x$$

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Energy relaxation and dephasing

- Energy relaxation and dephasing require the introduction of *Lindbladian dissipators*, describing the system tendency to evolve towards a mixed ensemble:

Energy relaxation: $$\mathcal{D}_1[\rho] = \Gamma_1\left(\hat{\sigma}_+\rho\hat{\sigma}_- - \frac{1}{2}\{\hat{\sigma}_-\hat{\sigma}_+, \rho\}\right)$$

Dephasing: $$\mathcal{D}_2[\rho] = \Gamma_2(\hat{\sigma}_z\rho\hat{\sigma}_z - \rho)$$

- Where Γ_1, Γ_2 are the corresponding energy relaxation and dephasing frequencies, and $\hat{\sigma}_\pm = \frac{1}{2}\left(\hat{\sigma}_x \pm \hat{\sigma}_y\right)$

- The dissipating system is then modeled by the *Lindblad master equation*:

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[\mathcal{H}, \rho] + \mathcal{D}[\rho]$$

Dissipative Solvers

- Dissipators can be included in `Solver` objects by specifying the `static_dissipators` key at construction:

```
diss1  = np.sqrt(Gamma_1) * 0.5 * (X + 1j * Y);
diss2  = np.sqrt(Gamma_2) * Z;
solver = Solver(      static_hamiltonian=hdrift,
                      hamiltonian_operators=[hdrive],
                      hamiltonian_channels=["d0"],
                      rotating_frame=hdrift,
                      channel_carrier_freqs={"d0":omegad/2/np.pi},
                      dt=dt,
                      static_dissipators=[diss1,diss2]);

backend = DynamicsBackend(solver=solver, solver_options={'max_step':200*dt});
```

- Time-step of `DynamicsBackend` should now be limited to avoid overlooking relaxation/dephasing events
  - The **`build_dissipative_backend`** helper is provided in **`qcd_lab_utils`**

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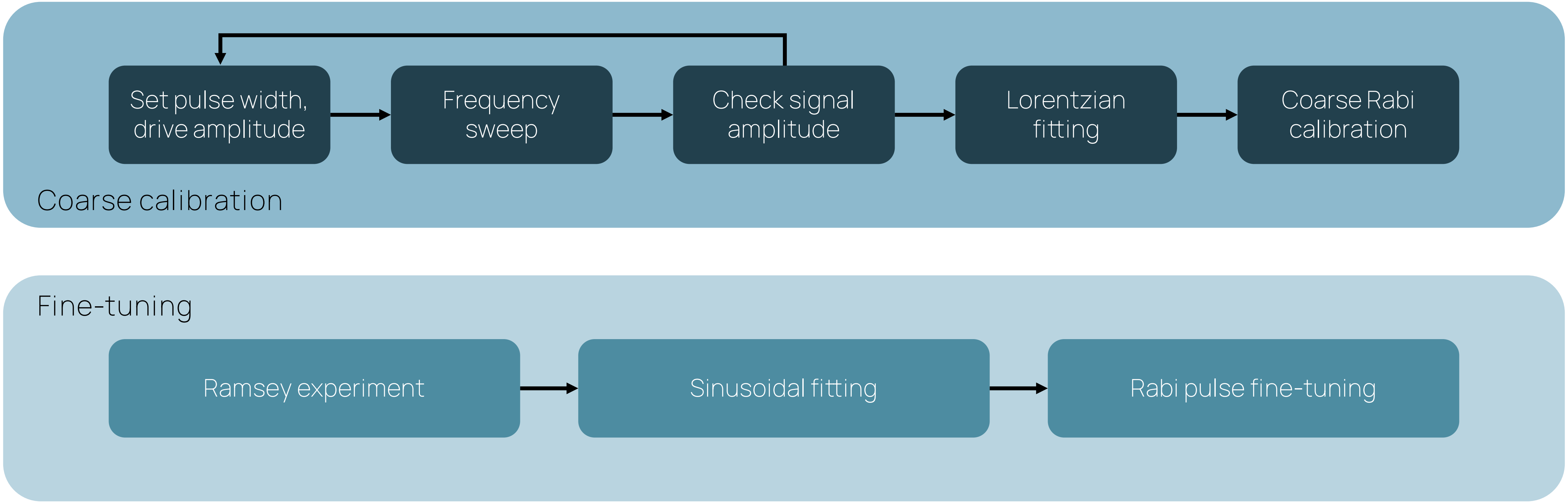
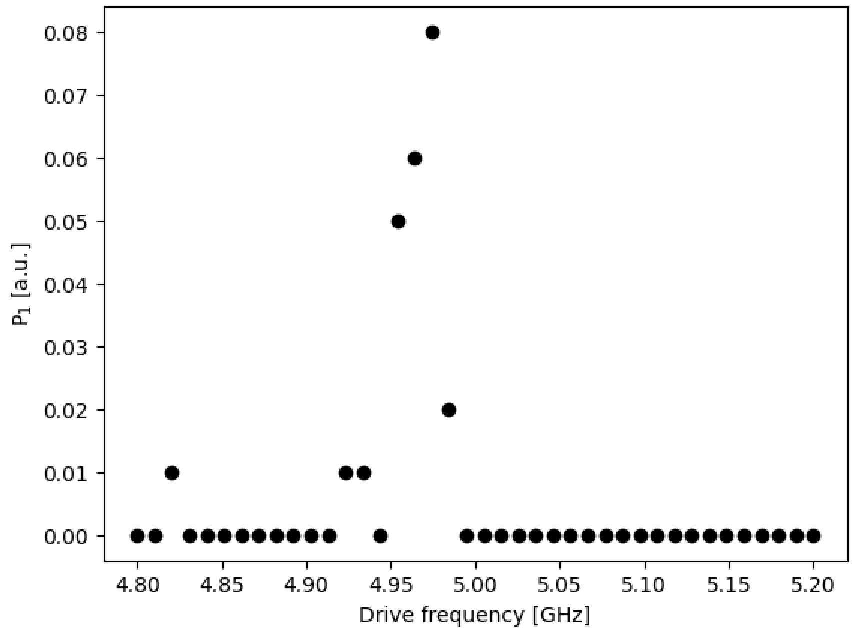
Frequency calibration



Coarse drive frequency calibration

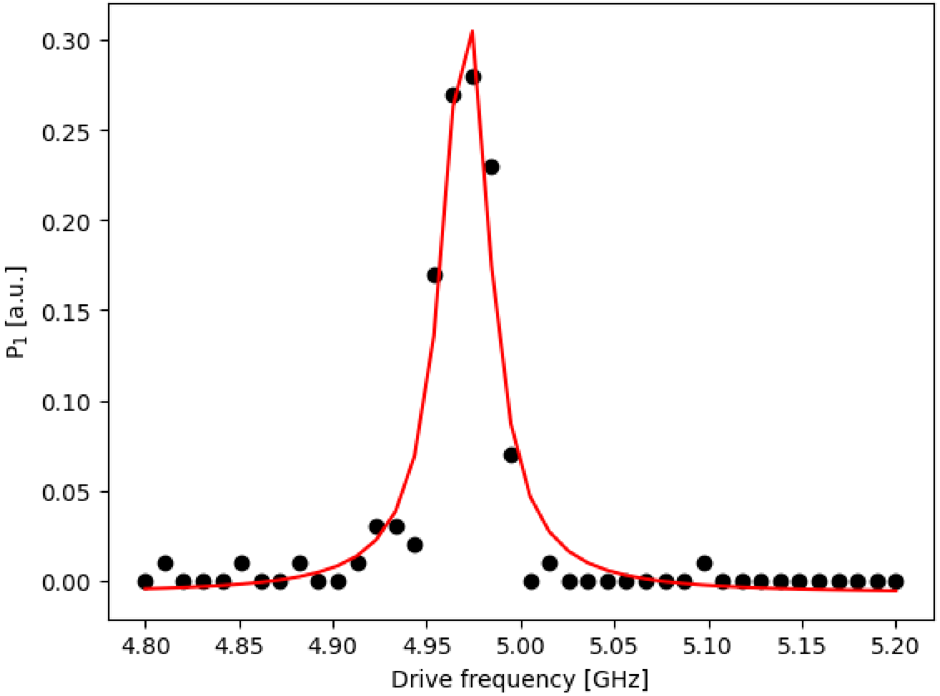
- To perform a frequency sweep, we can build a parametric Pulse Schedule including the set_frequency instruction:

```
duration = 128; pulse_amp = 0.175;
freq = Parameter('freq')
with pulse.build(default_alignment='sequential') as sweep_sched:
    pulse.set_frequency(freq,pulse.DriveChannel(0));
    pulse.play(pulse.Constant(duration,
                              pulse_amp,
                              name="Excitation Pulse"),
                              pulse.DriveChannel(0));
    pulse.acquire(1,0,pulse.MemorySlot(0));
```



- To improve the effectiveness of the estimate, we can increase the pulse amplitude until reaching a sufficient threshold for the P1 measurement

Drive frequency extrapolation

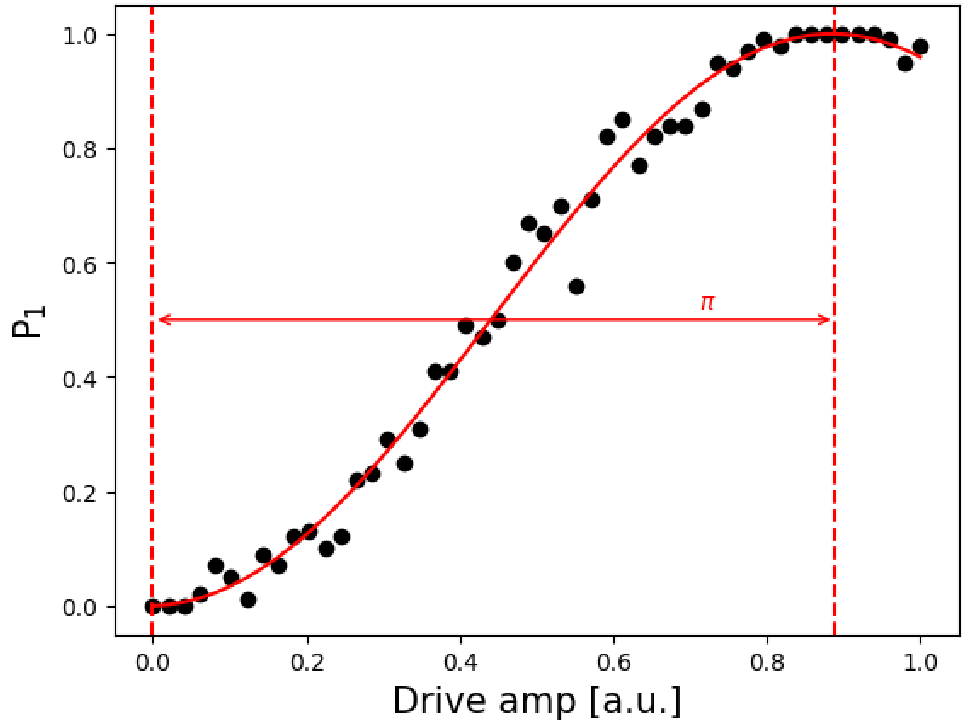


- Results are fitted with a Lorentzian curve:

$$\mathcal{L}(f) = \frac{A}{\pi} \frac{B}{(f - f_0)^2 + B^2} + C$$

- The `fit_function` helper is provided for curve fitting
- The precision estimate for this drive frequency is related to the step of the frequency sweep
- Example: sweep with 10 MHz step provides a ~10 MHz confidence on the drive frequency
- Detuning effects will thus have time constants in the order of (at minimum) 1/10 MHz = 100 ns
- See **`calibrate_coarse_frequency`** in **`qcd_lab_utils`**

Coarse Rabi calibration

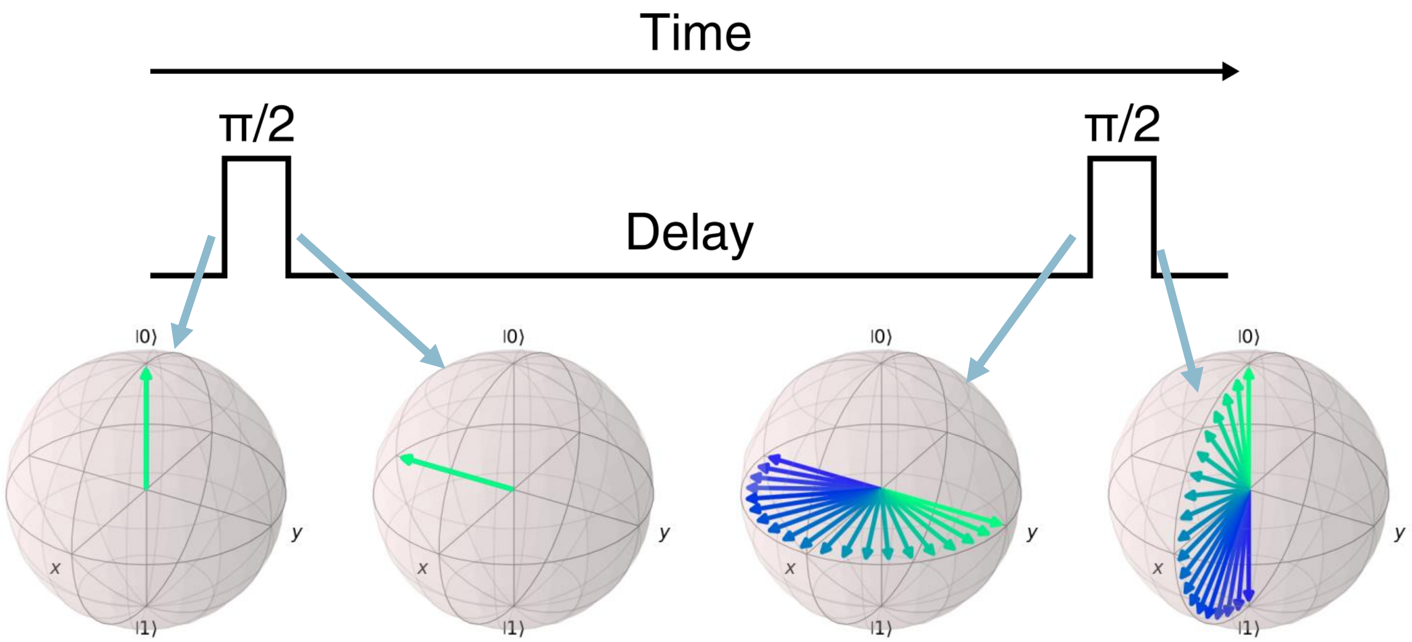


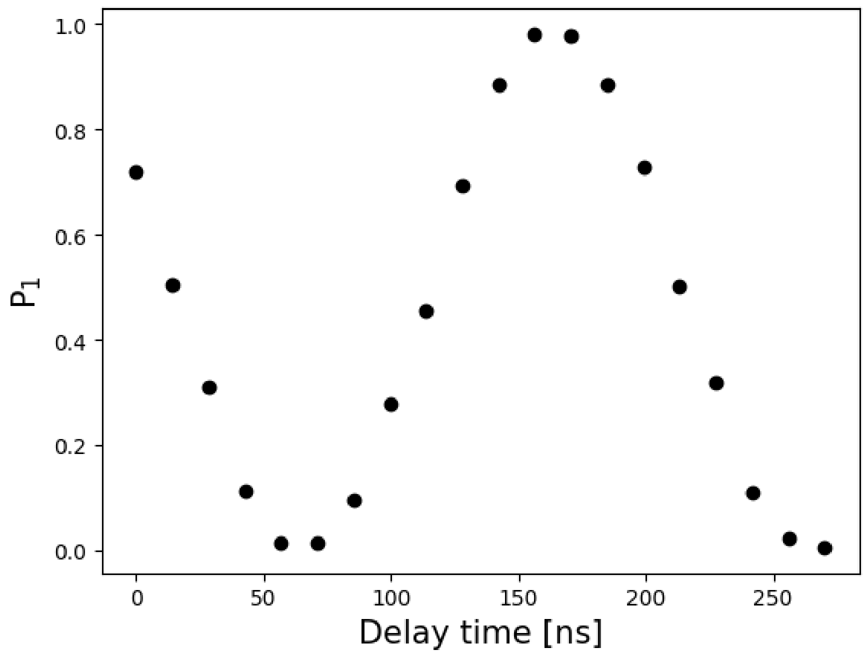
- Rabi calibration is performed as in Laboratory 2

- Pulse duration is selected to be well below the estimated detuning time constant $(D \cdot dt \ll 1/\Delta f)$

- See **`calibrate_rabi`** in **`qcd_lab_utils`**

Ramsey experiment





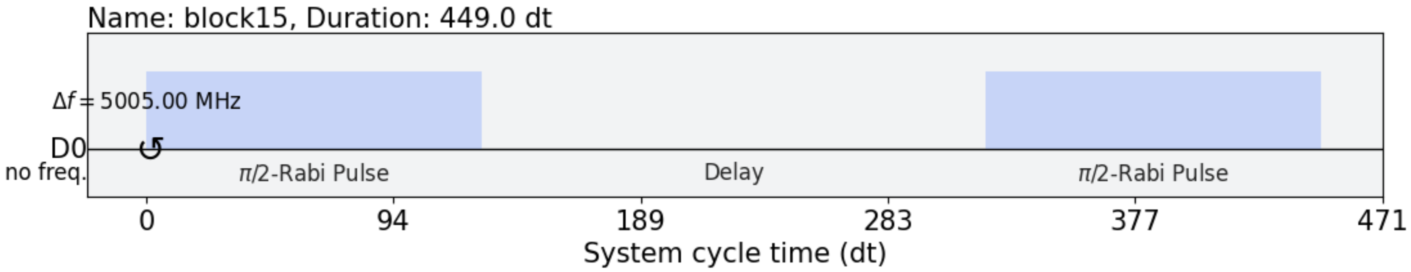
- Sequence of $\pi/2$ pulse → delay → $\pi/2$ pulse (ideal behavior: $|0\rangle \rightarrow |+\rangle \rightarrow |1\rangle$)
- In presence of detuning, the qubit exhibits precession during the delay phase, thus ending up in a different state
- Repeating the experiment with different delays enables fine-grained estimation of the drive-qubit detuning

Ramsey experiment setup

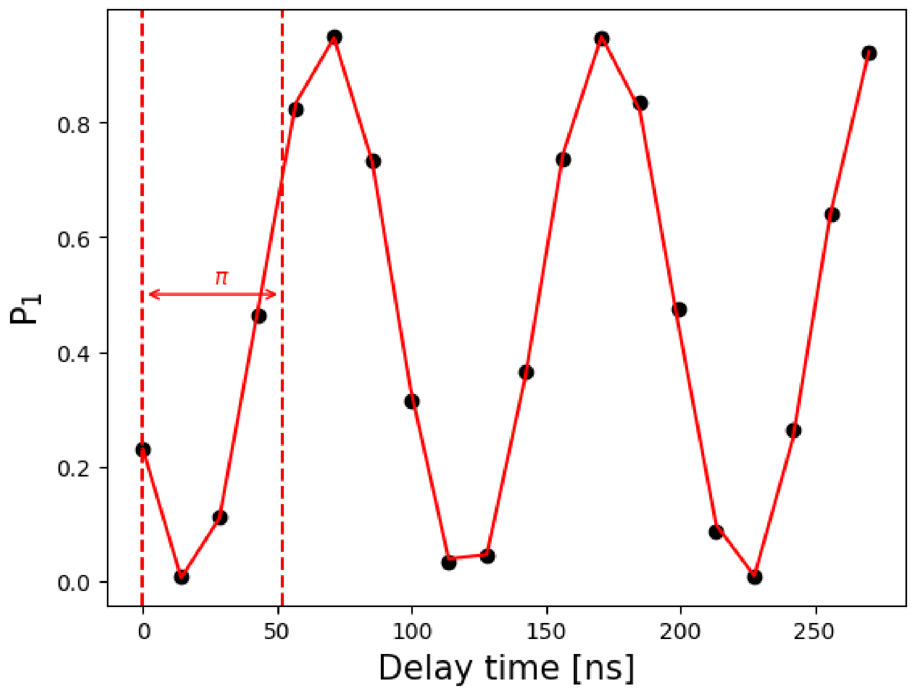
- If the coarse estimation is only slightly off-resonance, long delays may be required to observe Ramsey oscillations, potentially triggering relaxation effects

- As a wayaround, we add a *forced* detuning on top of the *natural* detuning to constrain delay times

```
detune = 10e6;
delay = Parameter('delay')
with pulse.build(default_alignment='sequential') as rams_sched:
    pulse.set_frequency(rough_f+detune,pulse.DriveChannel(0));
    pulse.call(x_pihalf);
    pulse.delay(delay,pulse.DriveChannel(0));
    pulse.call(x_pihalf);
    pulse.acquire(1,0,pulse.MemorySlot(0));
```



Fine-grained frequency estimation



- Results are fitted with a sinusoidal curve:

$$P_1(\tau) = A \cdot \sin\left(\frac{2\pi\tau}{T} - \phi\right) + B$$

- Inverse of delay period T corresponds to the drive-qubit detuning:

```
delay_period    = fit_params[2];
ramsey_f        = 1/delay_period;
qubit_f         = rough_f - (ramsey_f - detune);
```

- Ramsey experiment allows accuracy up to kHz, thus providing ~ms window to execute pulses before observing detuning effects

- Iterative procedures may be used to further refine the estimate

- See **`ramsey_experiment`** in **`qcd_lab_utils`**

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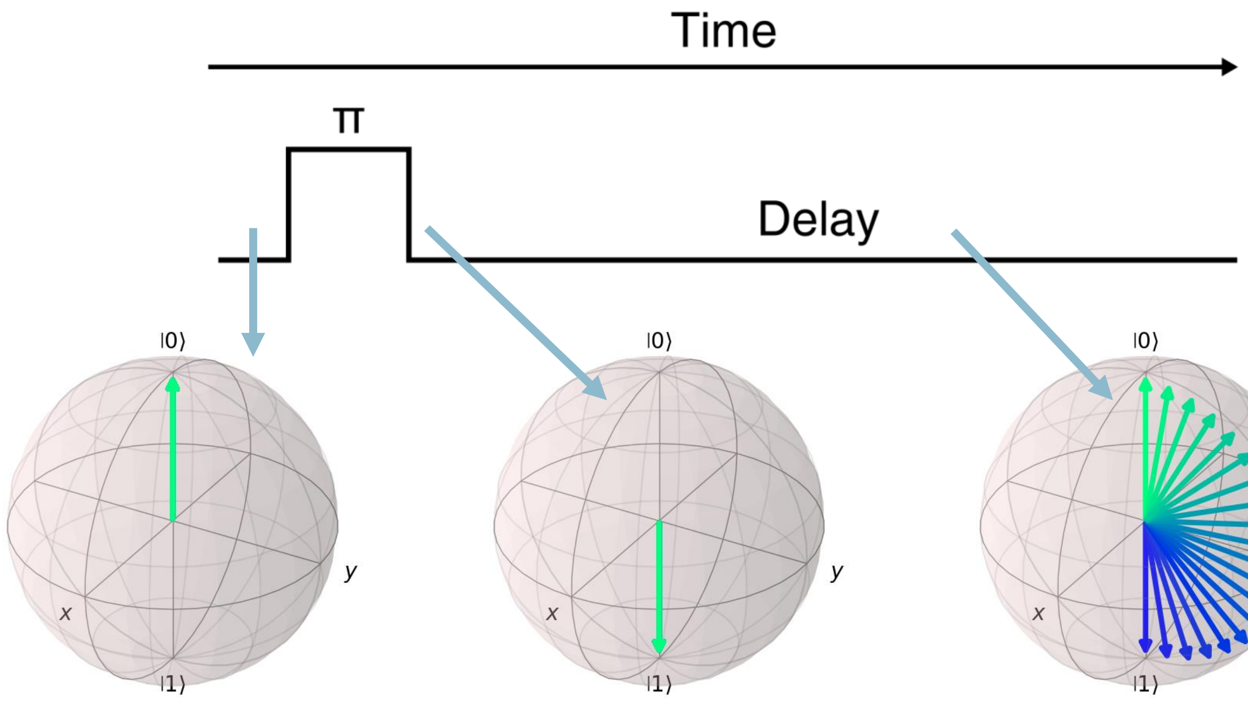
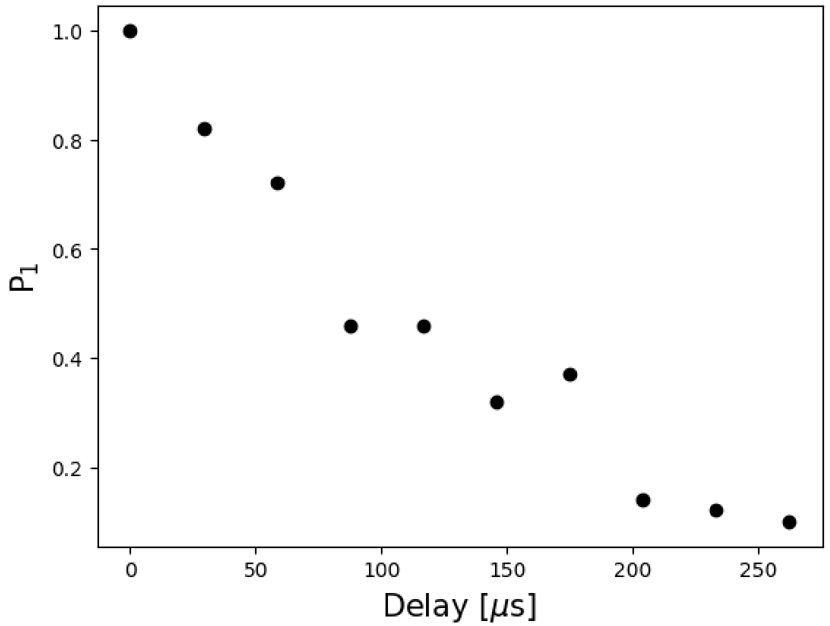
Energy relaxation

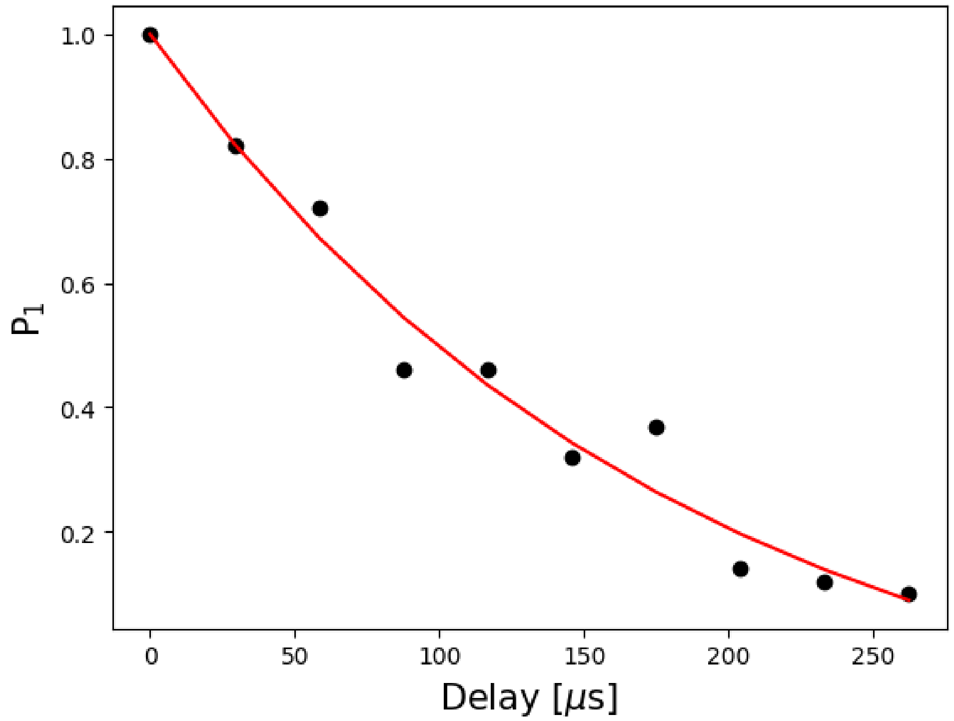




- Energy relaxation effects lead to state $|1\rangle$ progressively collapsing on $|0\rangle$ with increased probability over time
- Measured by the T1 metric, namely the time constant of spontaneous decay of the $|1\rangle$ state
- Inversion recovery: the qubit is first brought to the $|1\rangle$ state with a π-pulse, then measured after increasing delay

Inversion recovery experiment


```
delay = Parameter('delay')
with pulse.build(default_alignment='sequential'):
        pulse.set_frequency(qubit_f,pulse.DriveChannel(0));
        pulse.call(x_pi);
        pulse.delay(delay,pulse.DriveChannel(0));
        pulse.acquire(1,0,pulse.MemorySlot(0));
```



- Parametric Schedule with increasing delays
- Measured P1 probabilities are fitted with a decaying exponential:

$$P_1(\tau) = Ae^{-\frac{\tau}{T_1}} + C$$

- T1 coefficient extrapolated from fit
- Pulse schedules must be sufficiently shorter than T1 to avoid observing relaxation effects
- See **`inversion_recovery`** in **`qcd_lab_utils`**

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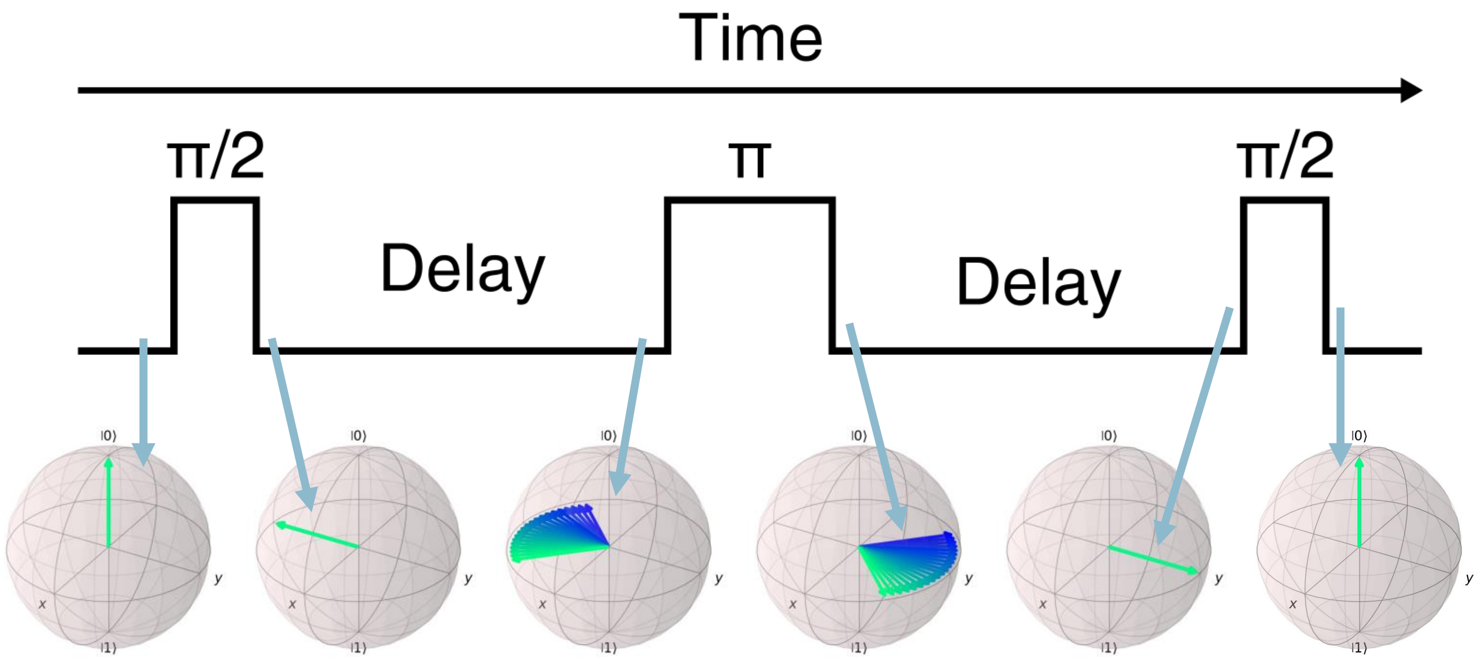
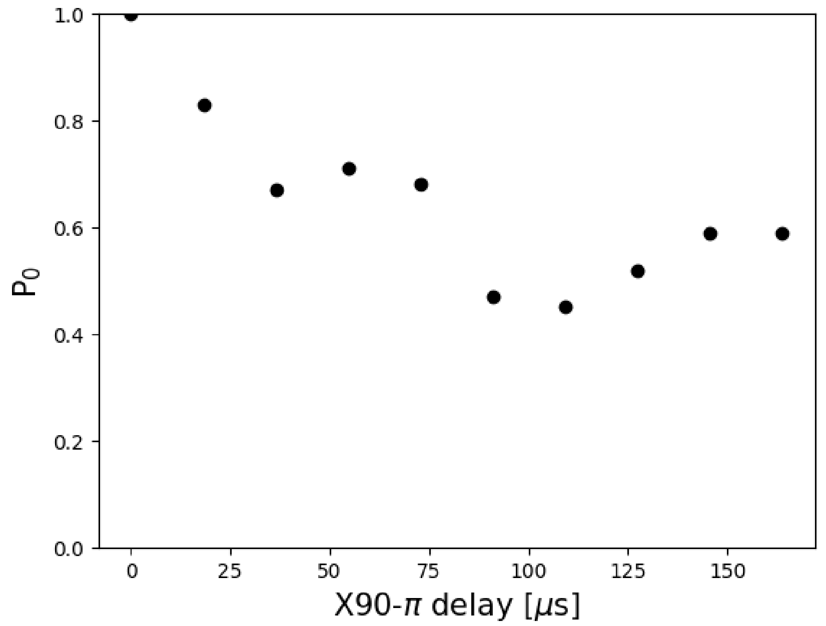
Hahn echoes





- Dephasing leads to a superposition with definite phase progressively relaxing towards a mixed ensemble
  - Example: $|+\rangle$ progressively relaxes towards an ensemble of $|+\rangle$ and $|-\rangle$

- Hahn echo experiment: qubit is brought to the *xy* plane, let dephase, inverted, let rephase, brought back to $|0\rangle$
  - Probability of measuring $|0\rangle$ progressively evolves towards 0.5 as state evolves towards mixed ensemble

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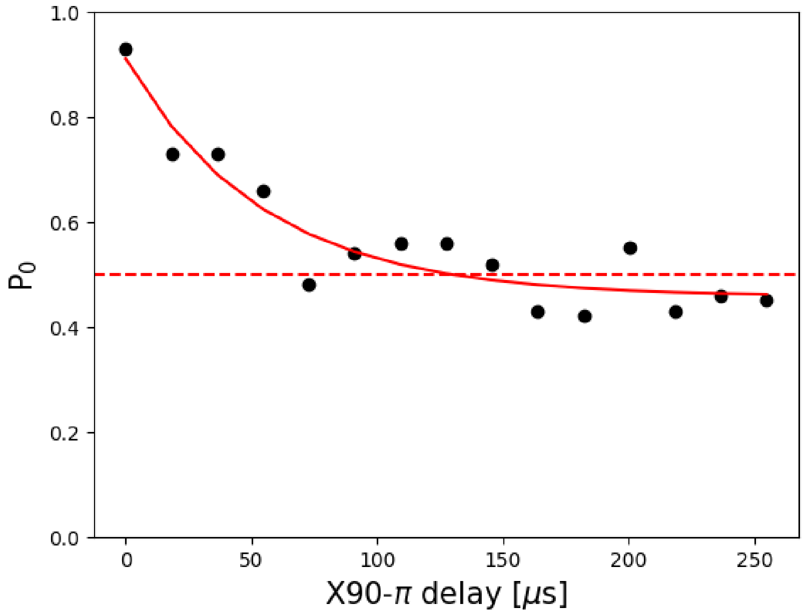
Hahn echoes experiment


```
delay = Parameter('delay')
with pulse.build(default_alignment='sequential') as t2_sched:
    pulse.set_frequency(qubit_f,pulse.DriveChannel(0));
    pulse.call(x_pihalf);

    pulse.delay(delay,pulse.DriveChannel(0));
    pulse.call(x_pi);
    pulse.delay(delay,pulse.DriveChannel(0));

    pulse.call(x_pihalf);
    pulse.acquire(1,0,pulse.MemorySlot(0));
```



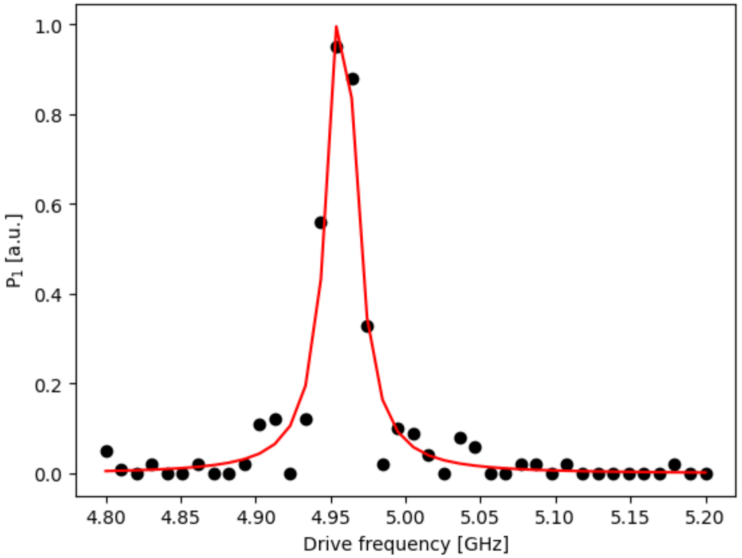
- Parametric Schedule with increasing delays
- Measured P0 probabilities are fitted with a decaying exponential:

$$P_1(\tau) = Ae^{-\frac{\tau}{T_2}} + C$$

- T2 coefficient extrapolated from fit
- Pulse schedules must be sufficiently shorter than T2 to avoid observing relaxation effects
- See **`hahn_echo_experiment`** in **`qcd_lab_utils`**

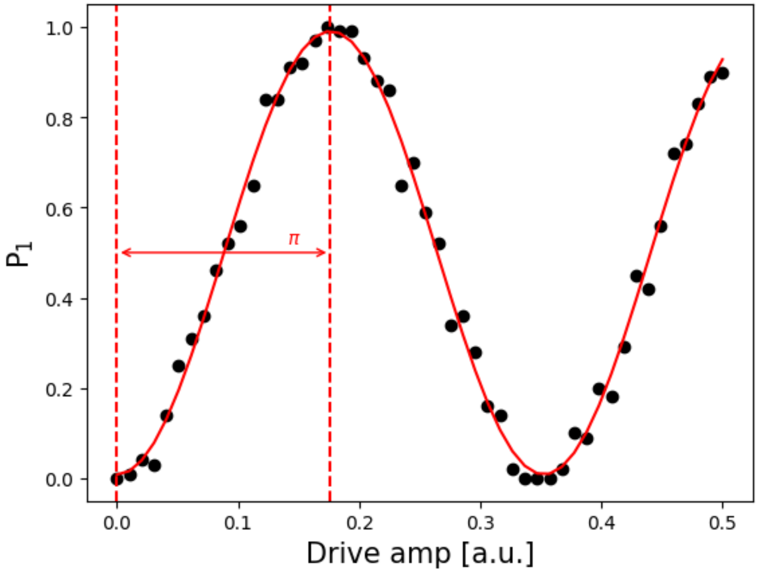
Hands-on time!
Exercise 1

Drive frequency tuning



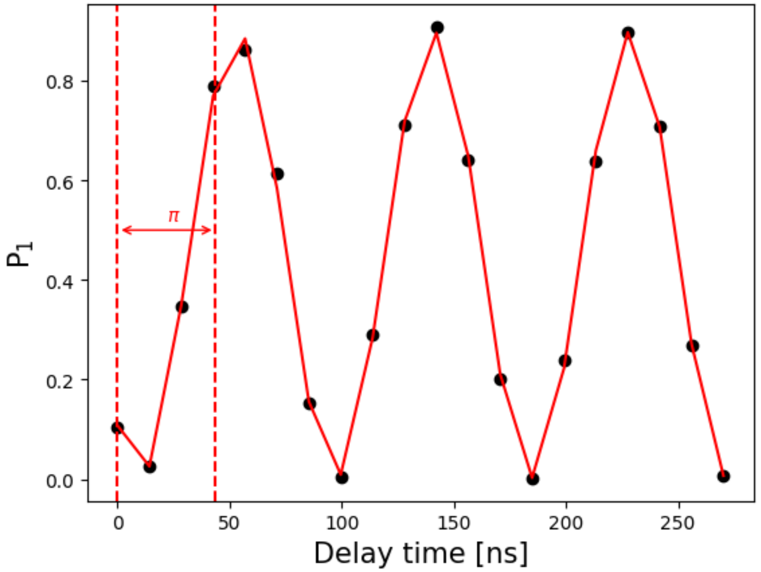
- Coarse frequency sweep

f_{est} = 4.9577 GHz



- Coarse Rabi calibration

π-amplitude: 0.176



- Ramsey experiment

f_{drive} = 4.956229 GHz

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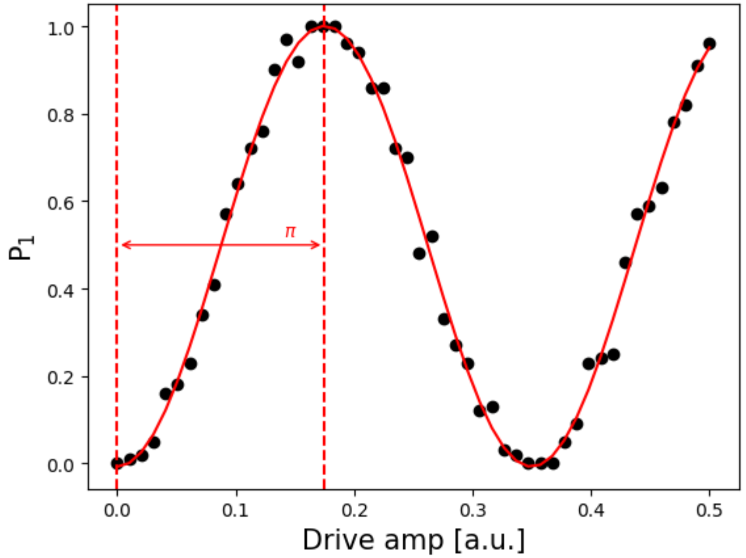
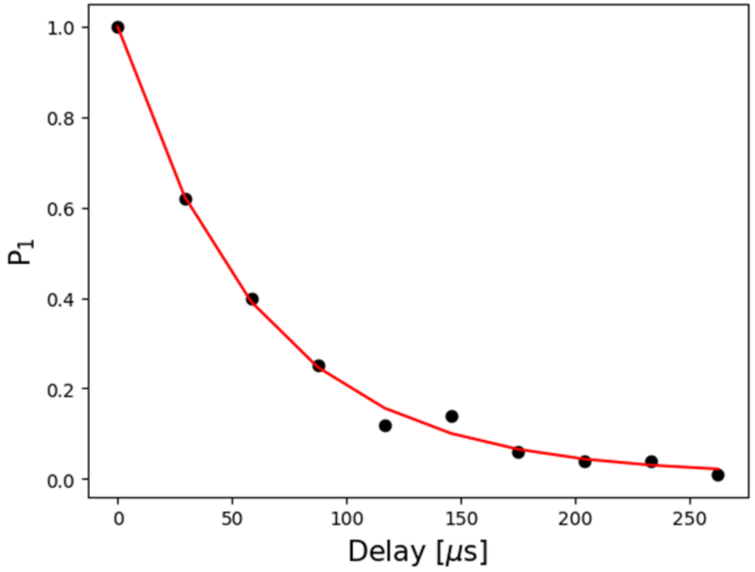
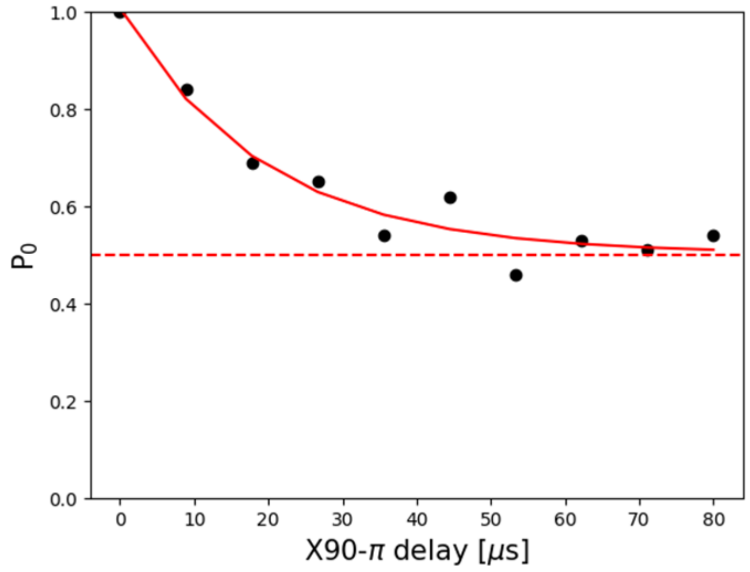
Drive frequency tuning







- Rabi fine-tuning

π-amplitude: 0.1749

- Inversion recovery experiment

T1 = 61.396 μs

- Hahn echoes experiment

T2 = 19.321 μs

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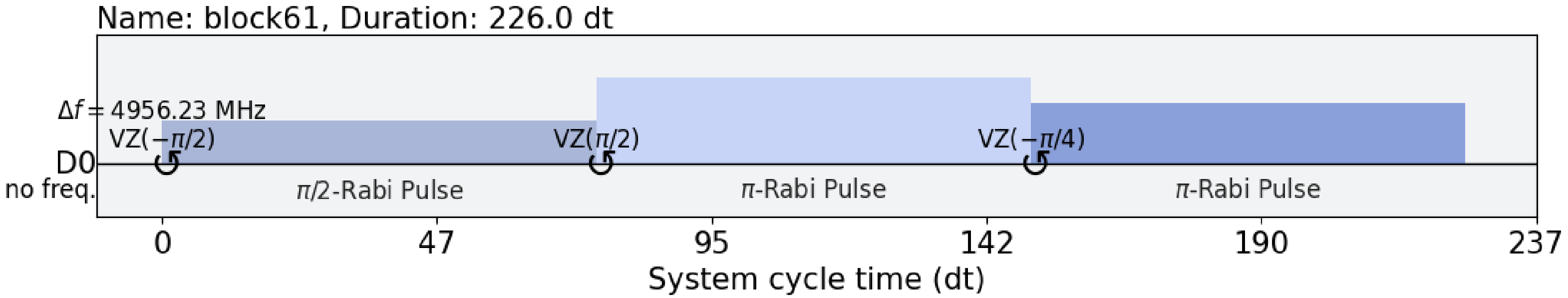
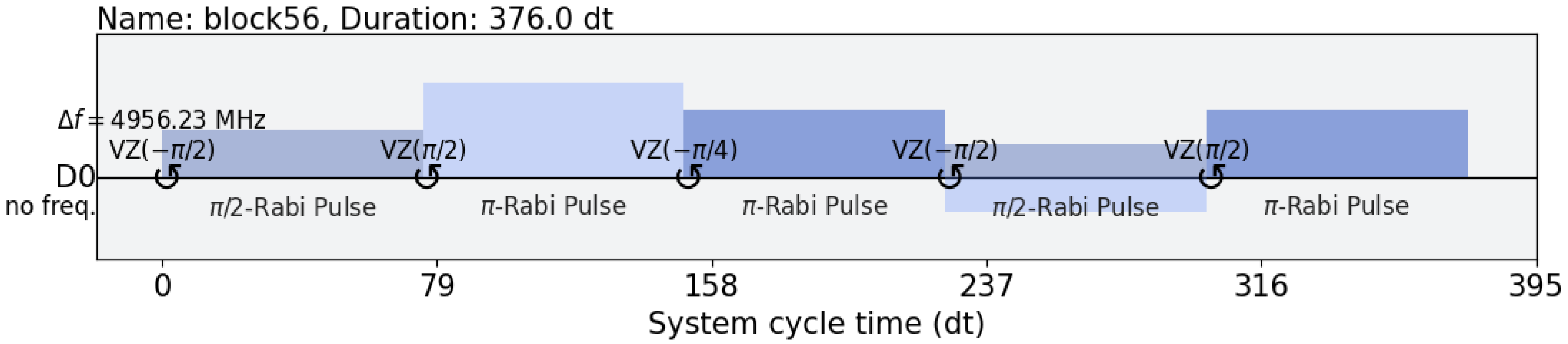
Pulse schedules for quantum tomography

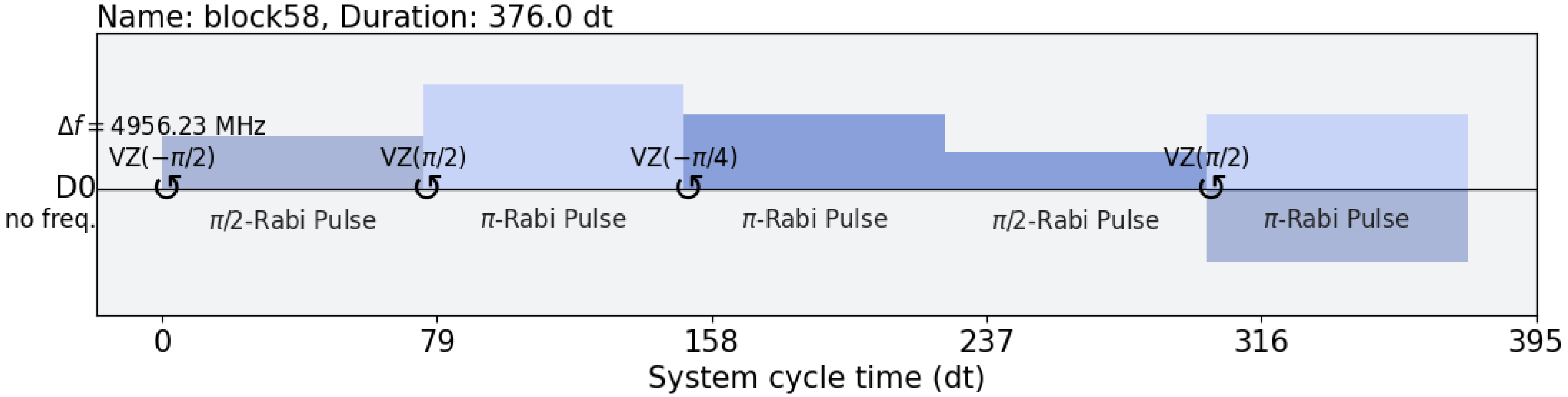
$\hat{X}\hat{T}\hat{H}$
(z-projection)



$\hat{H}\hat{X}\hat{T}\hat{H}$
(x-projection)

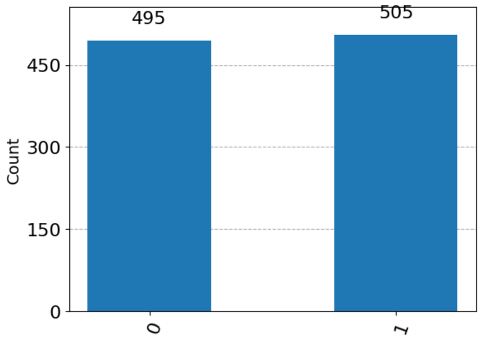


$\hat{H}\hat{S}^{\dagger}\hat{X}\hat{T}\hat{H}$
(y-projection)

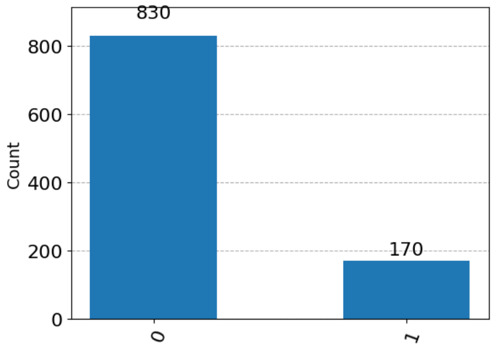


Quantum tomography experiments

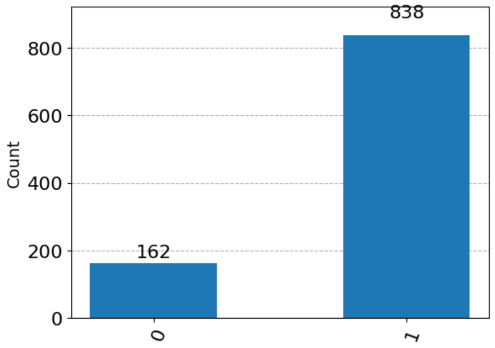
$\hat{X}\hat{T}\hat{H}$
(z-projection)



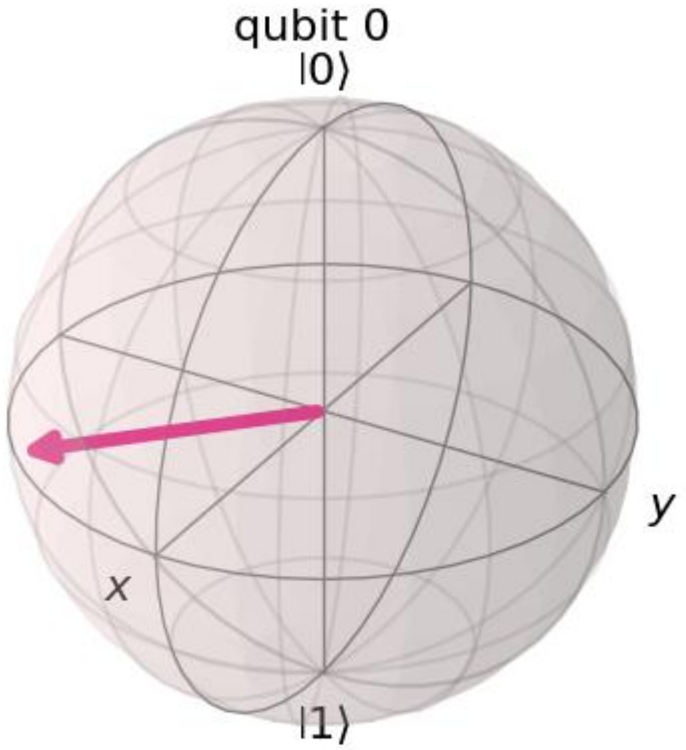
$\hat{H}\hat{X}\hat{T}\hat{H}$
(x-projection)



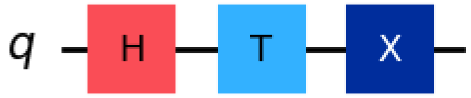
$\hat{H}\hat{S}^{\dagger}\hat{X}\hat{T}\hat{H}$
(y-projection)



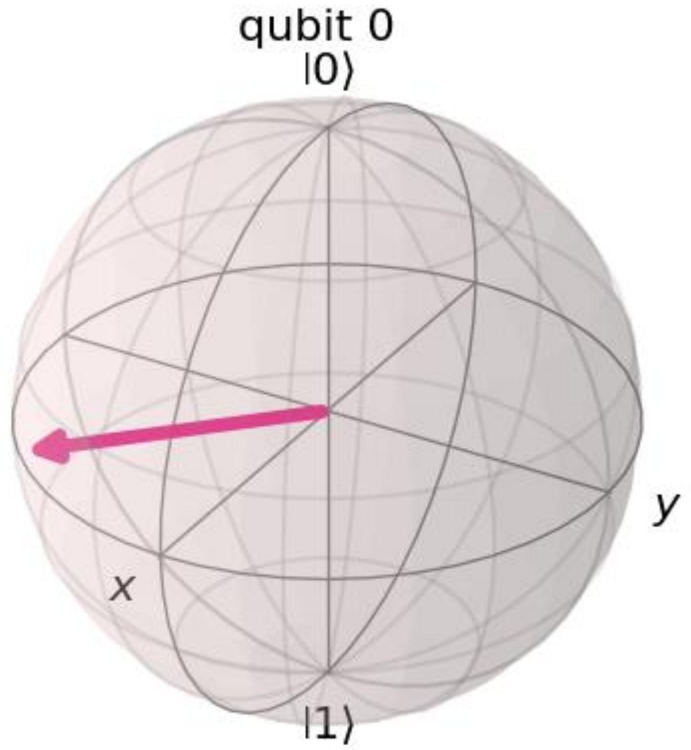
$\theta = 1.58$ rad, $\phi = 5.49$ rad

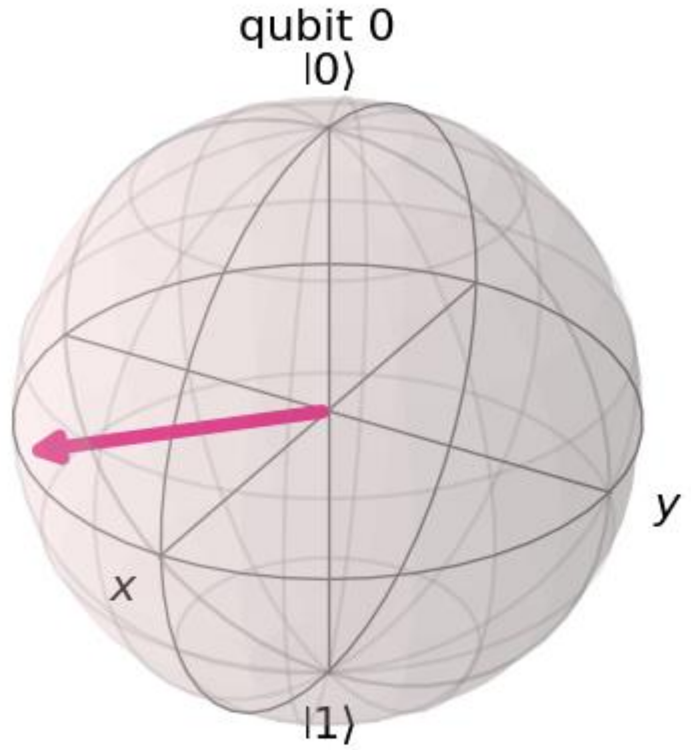


QuantumCircuit verification



θ = 1.58 rad, ϕ = 5.49 rad





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Recap

- Dissipating quantum system nonidealities can be modeled by Lindbladian dissipators
- Detuning can be contrasted by performing a coarse-fine drive frequency tuning
- Energy relaxation time constant (T1) can be characterized by inversion recovery experiments
- Dephasing time constant (T2) can be characterized by Hahn echoes experiment
- T1 and T2 provide upper bounds for the useful operating time of a quantum system