Operations in superconducting qubits: Single qubit gates - Brian Tarasinski

In this lecture, I want to show you how we control the state of a single superconducting transmon qubits, that is, doing so-called single-qubit gates.

The state of a single qubit can be visualized on the Bloch sphere, with the ground and excited state on the poles and the other points on the surface corresponding to quantum superpositions. Single-qubit gates are then rotations of the Bloch sphere, for instance here the X90 gate, which converts the ground and excited states into superpositions.

We use the physical effect called Rabi oscillation: We change the qubit state by applying an external oscillating electric field at the qubit frequency, corresponding to the energy difference between the ground and excited state. That frequency is usually in the microwave range, between 3 and 10 GHz.

To apply the electric field, we need a microwave line that ends next to the transmon. We can use the same line that is also used for measurements, about which you will hear more in the next videos. Or, on larger devices with many qubits, we often make a “dedicated drive line” for each qubit. With this, we can generate the electric field close to only one selected qubit.

Let’s see how the oscillating field affects the qubit state. When we apply it, it drives the qubit from the ground to the first excited state and back. On the Bloch sphere, this looks like a rotation with constant speed. The axis of rotation always lies in the x-y plane. We can control where exactly it lies by changing the phase of the applied field: A sine wave leads to a rotation around the x-axis, while a cosine with 90 degrees phase offset will induce a rotation around the y-axis.On the other hand, the speed of the rotation is proportional to the amplitude of the electric field.

In order to perform a desired gate, for instance a rotation by 90 degrees around the x-axis, we thus need to apply a short pulse with the correct phase, amplitude and length. The rotation angle is determined by the product of length and amplitude, that is, by the area under the pulse envelope.

This way, we can perform any rotation with the axis in the x-y plane. If we want to rotate around another axis, which does not lie in the x-y plane, we have to decompose it. It turns out that any single-qubit gate can be performed using no more than three microwave pulses in sequence.

Of course, we want to make the pulses as short and strong as possible, to be able to do quantum computations quickly. However, the shorter the pulse, the more frequency components it has besides the transition frequency f01. We can see this by looking at the spectral decomposition of the pulse.

Unfortunately, that means that if we make the pulses shorter and shorter, at some point, the spectrum is so broad that the pulse drives oscillations not only between the states 0 and 1, but also 1 and 2!

Then, the transmon does not work as a qubit anymore, since three transmon states are involved, and the nice Bloch sphere rotation picture breaks down. We must avoid this situation, and this limits us in making the pulses too short.

To push the limit of how short we can make the pulse, instead of a square pulse, we need a pulse which is well localized in time and also frequency. A much better choice is a pulse with a Gaussian shaped envelope. It has the same area, but affects the 1-2 transition much, much less.

Using a technique called "derivative removal by adiabatic gate", or DRAG, we can push the limit further: By superimposing a fine-tuned out-of-phase component with an envelope proportional to the derivative of the original pulse, the rotation angle is unchanged, but the transitions to the 2 state are actively suppressed. Using this technique, pulse lengths can be reduced to well below 5 ns without the second transmon state being a concern.

This concludes our quick look at how we control the state of individual transmon qubits using microwave pulses. In the next videos, Niels and Adriaan will show you how we measure the transmon state, and how we change the state of a transmon depending on the state of another transmon, to perform larger calculations.