Zurich Instruments

ROHDE&SCHWARZ

Double-Superheterodyne architecture for high-fidelity quantum computing control and readout

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RF 2022 TECHNOLOGY EVENT

29 MAART 2022

QuTech/TU Delft

Outline

- Readout of superconductive qubits
  - → Challenge and principles
  - → Approaches to frequency conversion: the Double super-heterodyne. Comparison with IQ modulation
  - → Matched filters and multi-qubit readout

- Control of superconductive qubits
  - → Double super-heterodyne upconversion
  - → Digital modulation and efficient pulse sequencing
  - → Randomized benchmarking: a practical example

- Conclusions

Superconducting qubit readout

Strongly-coupled cavity QED in the dispersive regime

Superconducting qubit readout

Qubit state changes

→ Readout resonator shifts

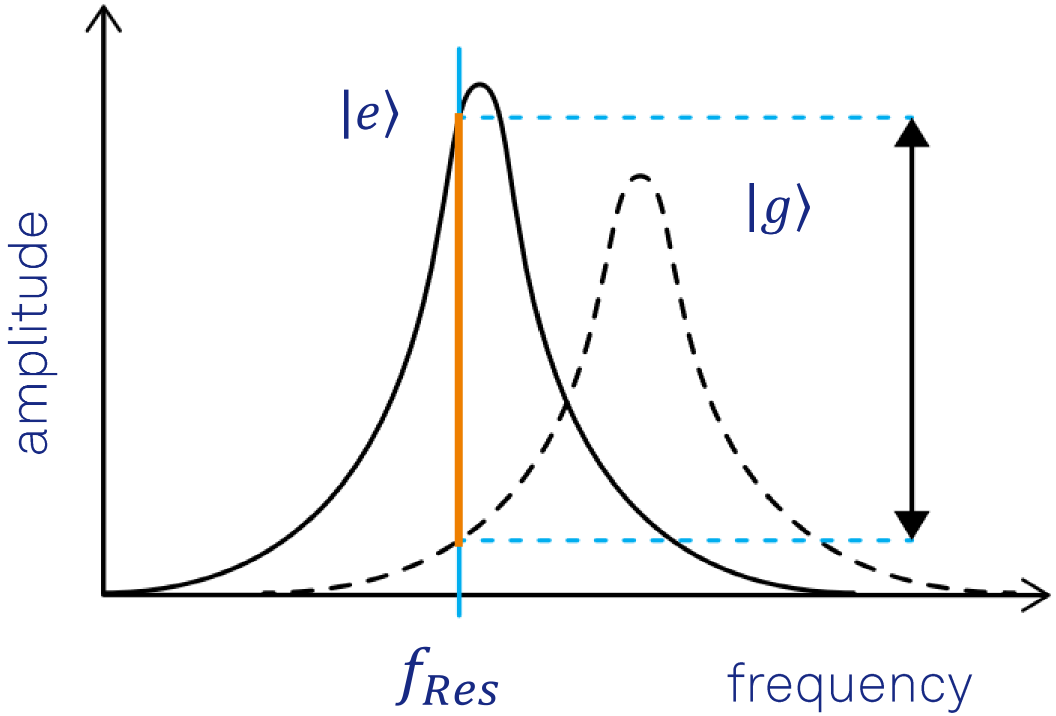
→ Resonator probe signal changes

Multiplexed readout

- Multiple resonators – one feedline
- Frequency-multiplexed probe

Main challenge

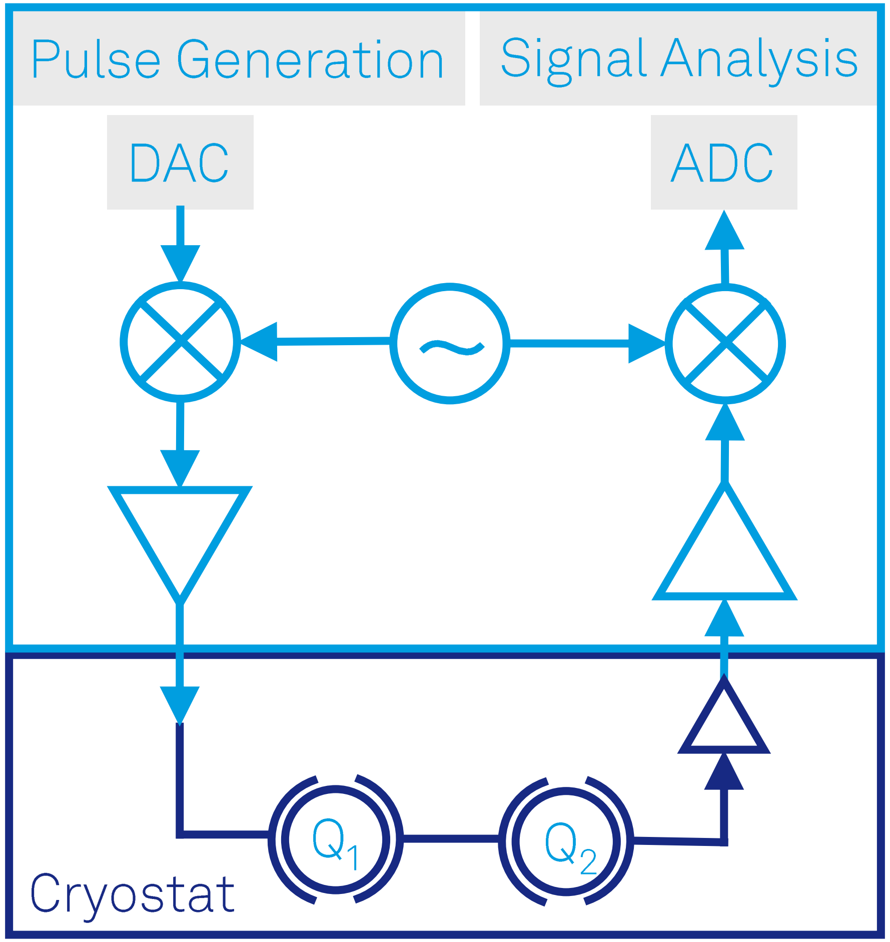
Optimize SNR for all qubits



A full room-temperature qubit readout system

Main tasks of the readout system

1. Generate readout signal for multiple qubits
2. Frequency conversion to/from microwave frequencies
3. Detection of readout of signal
4. Signal analysis to determine state of each qubit in real time



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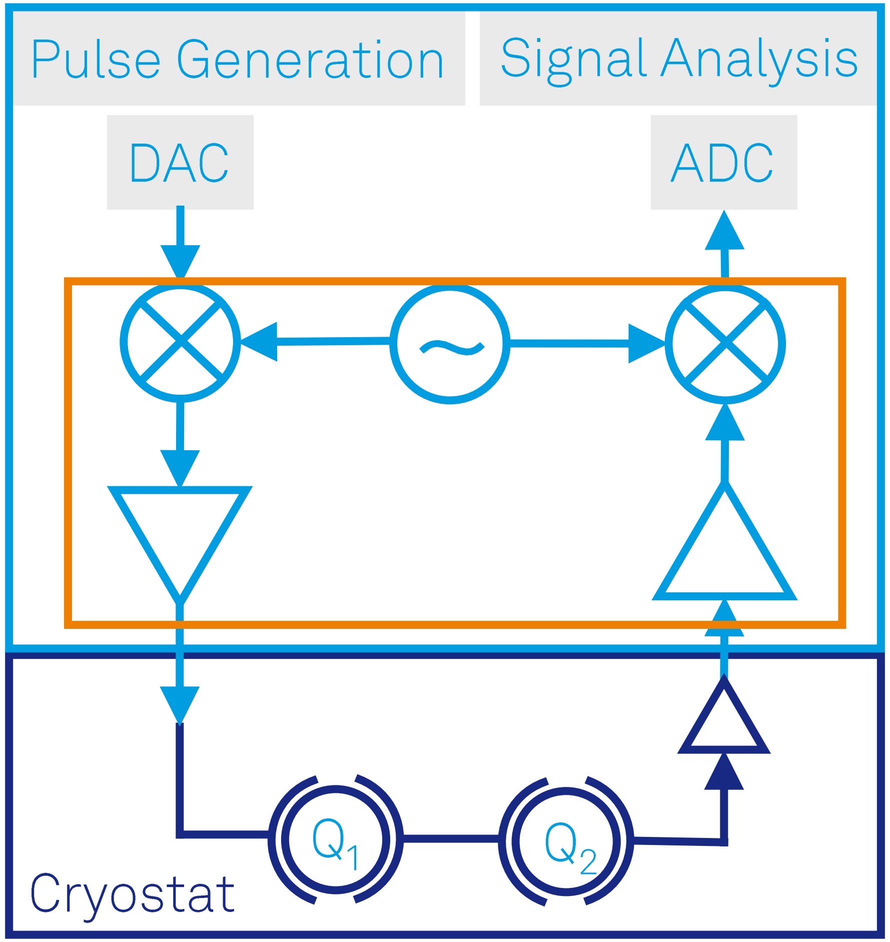
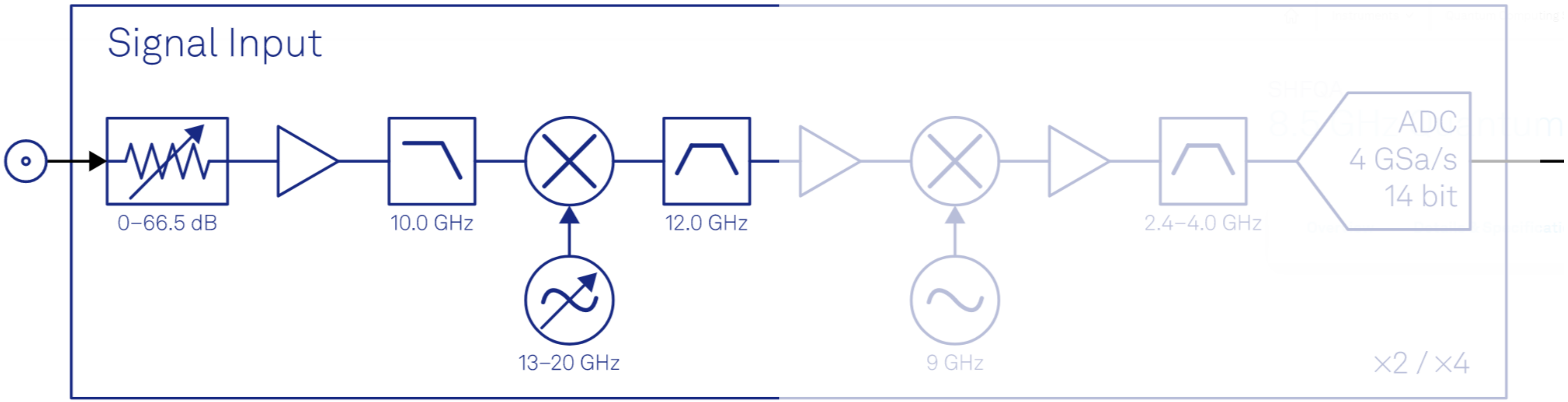
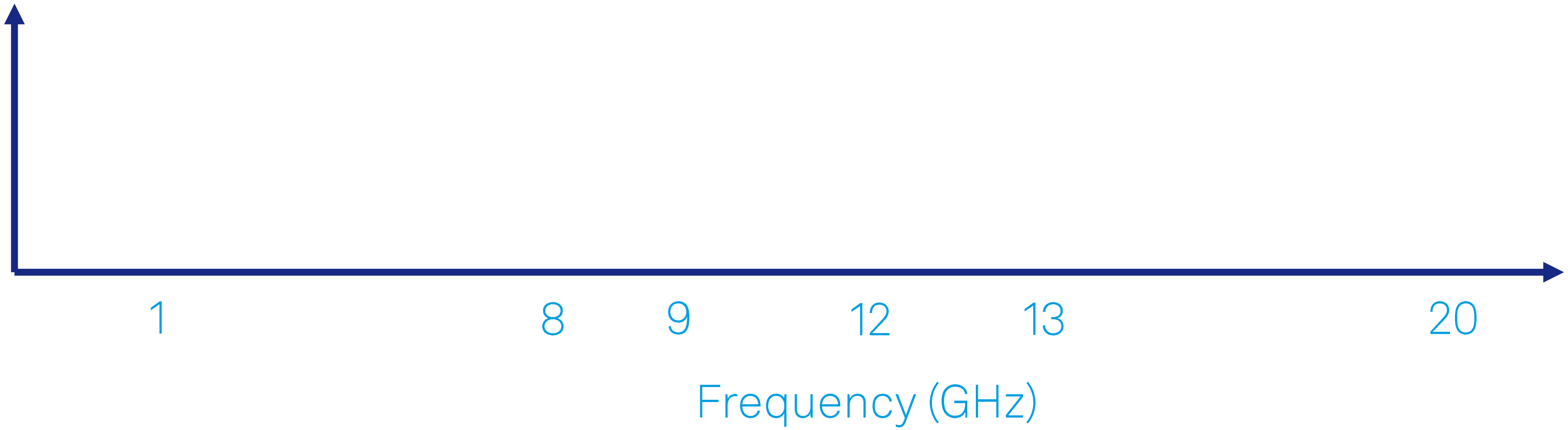


Double super-heterodyne frequency conversion

How does it work?





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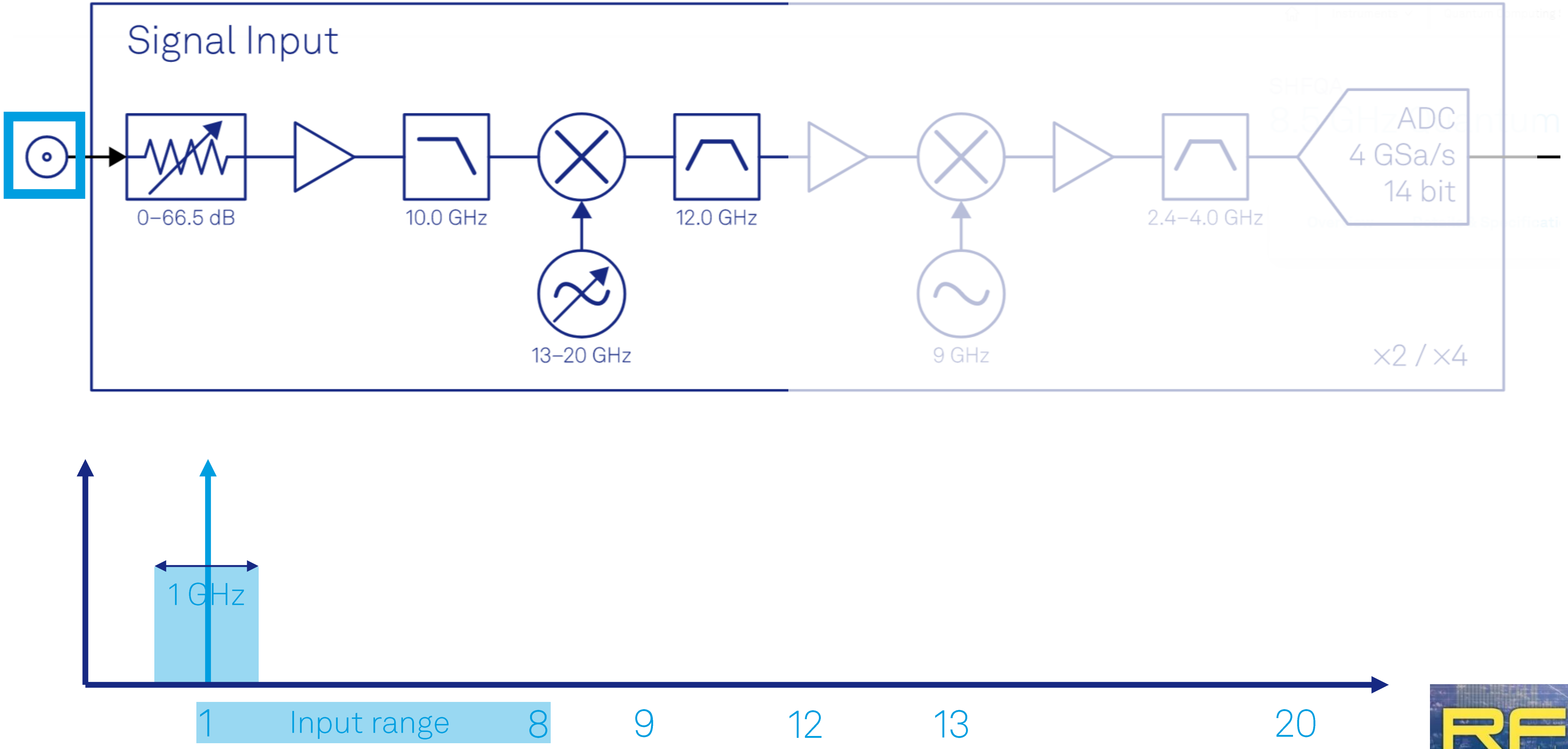

Frequency (GHz)

Double super-heterodyne frequency conversion

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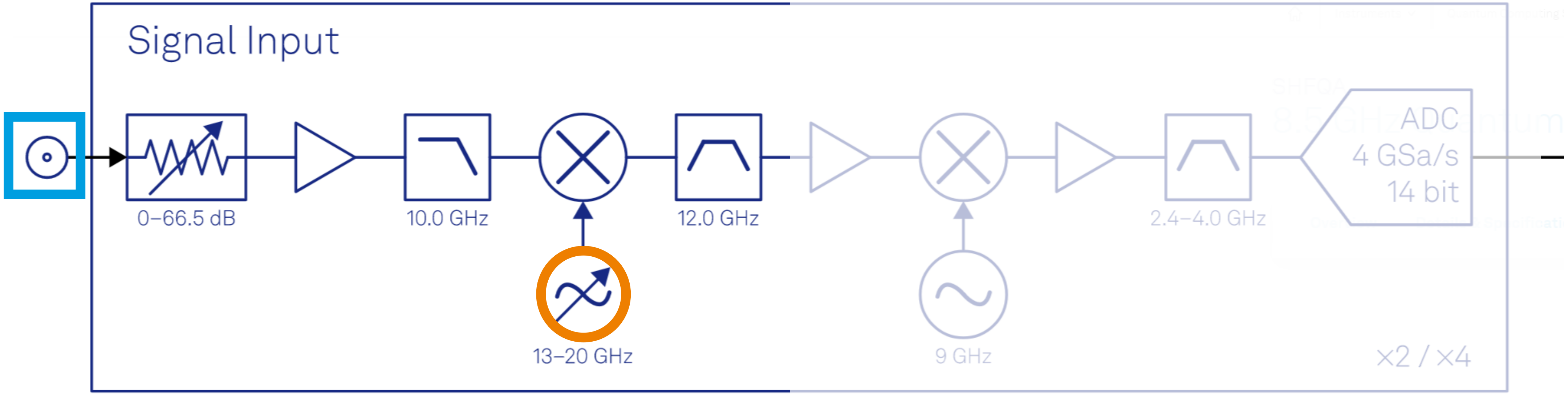

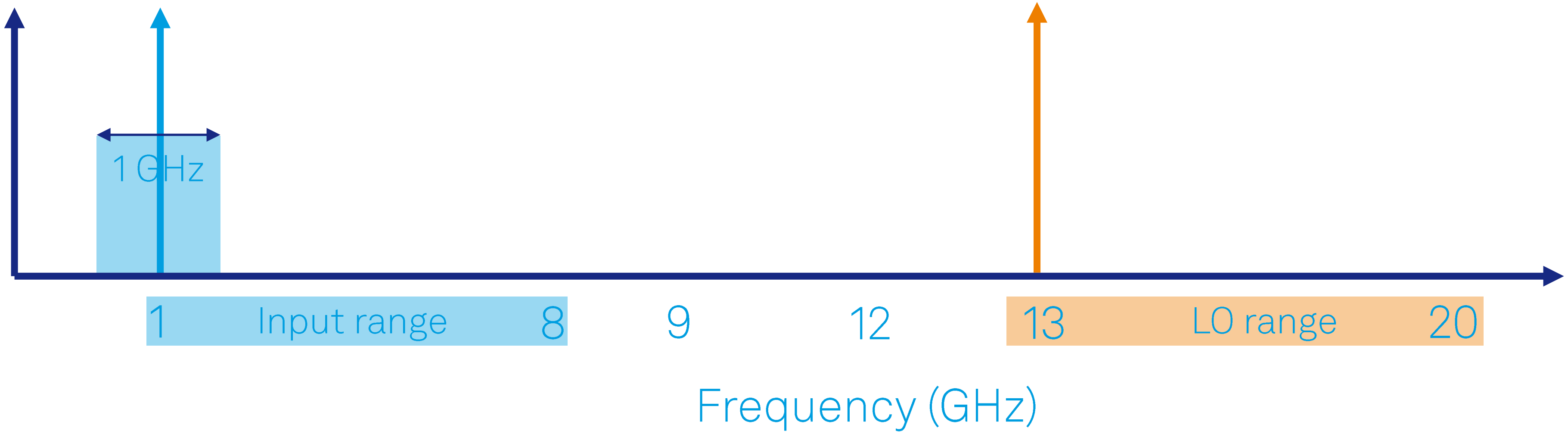

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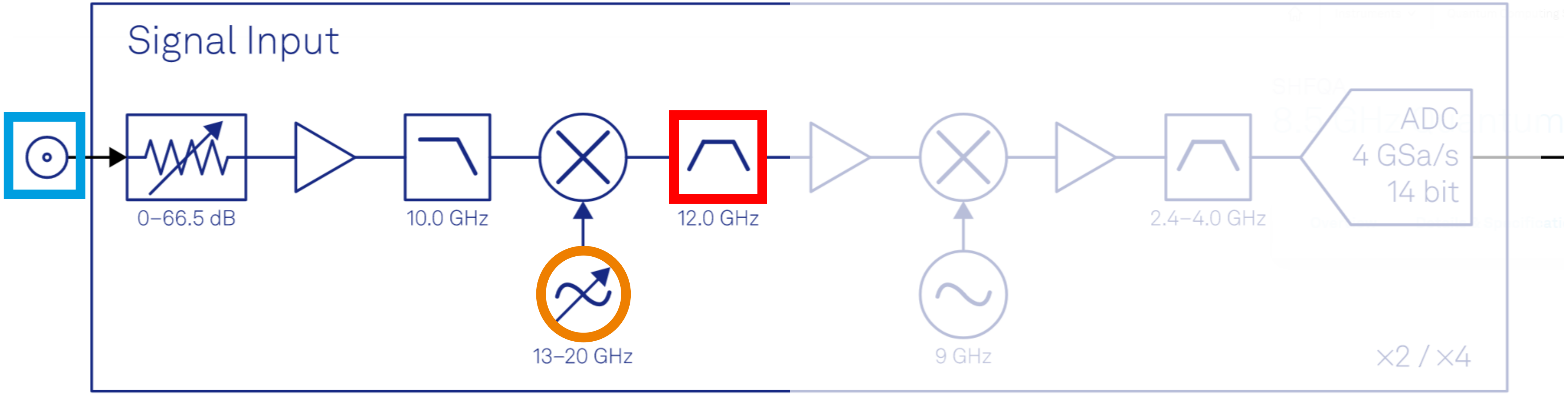

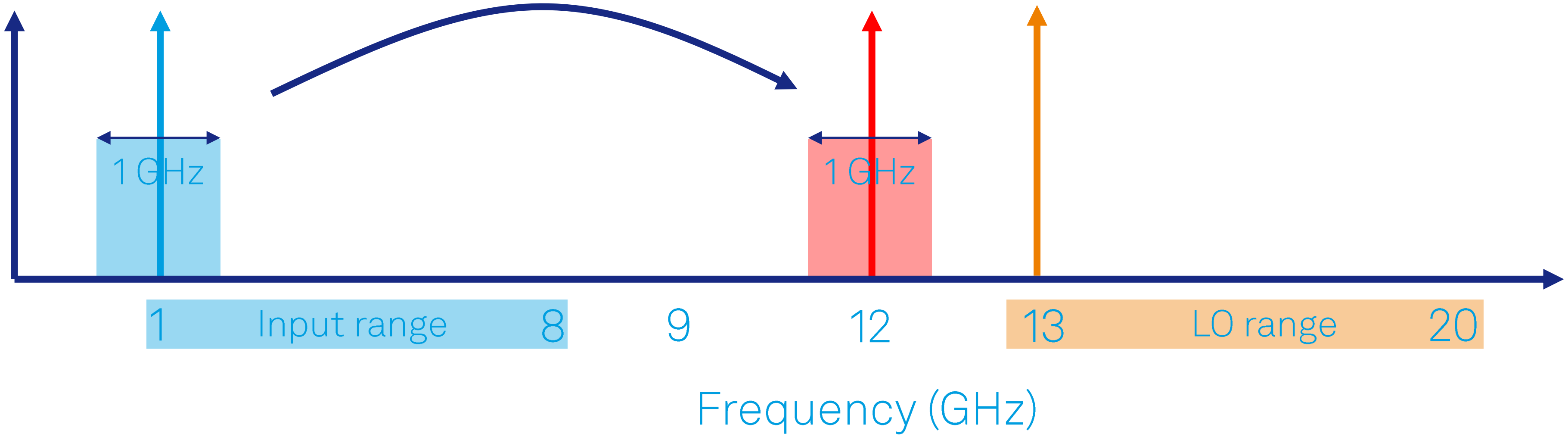

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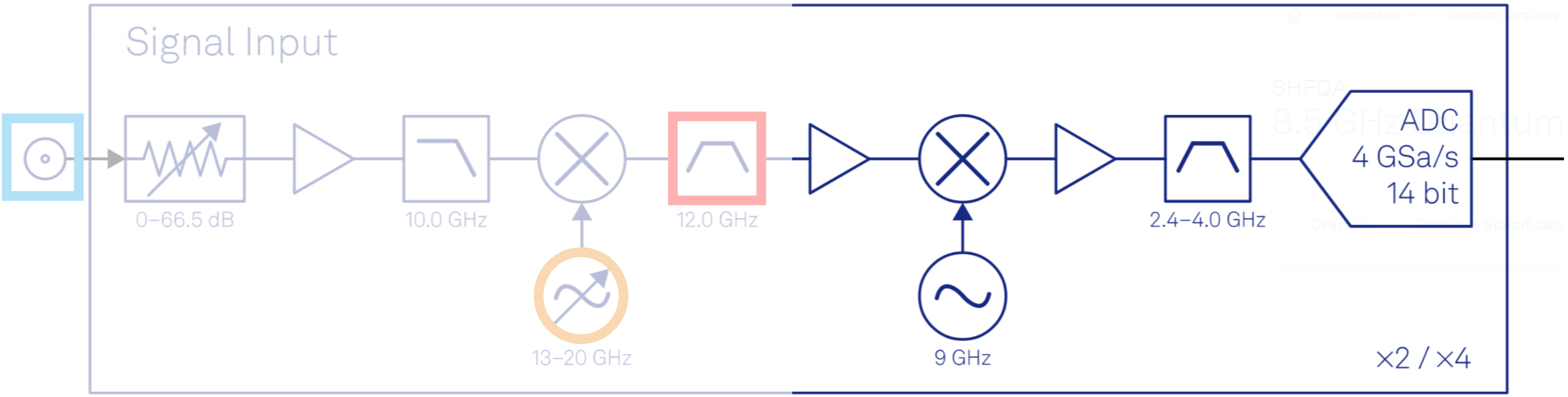

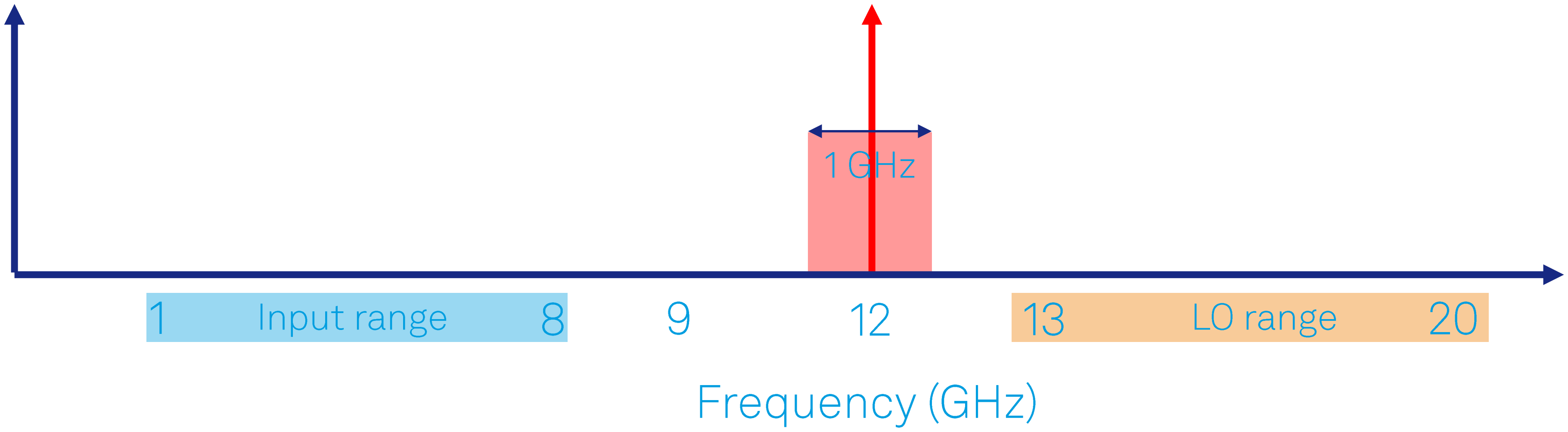

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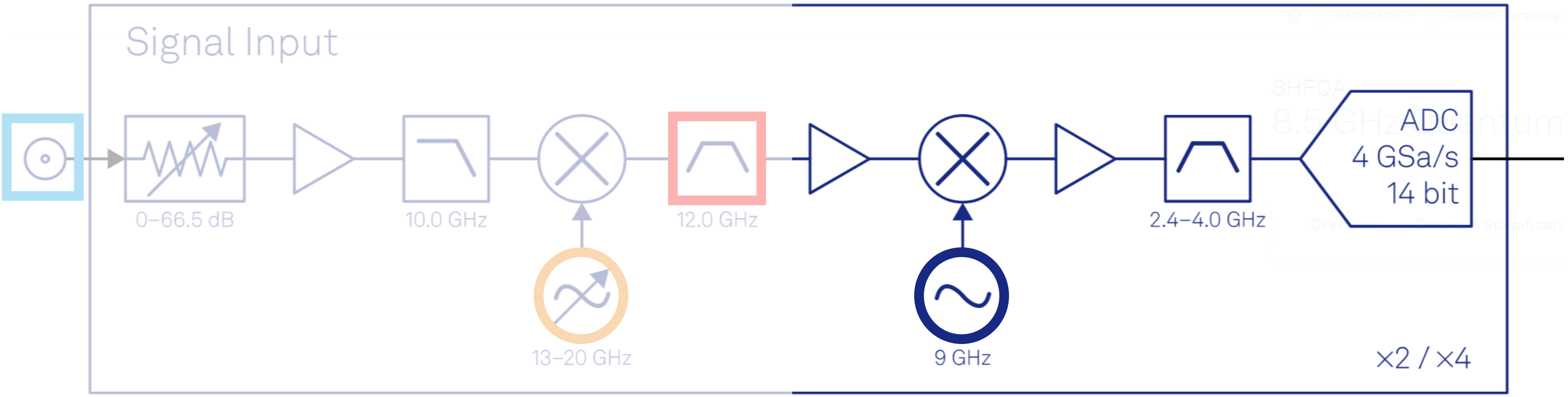

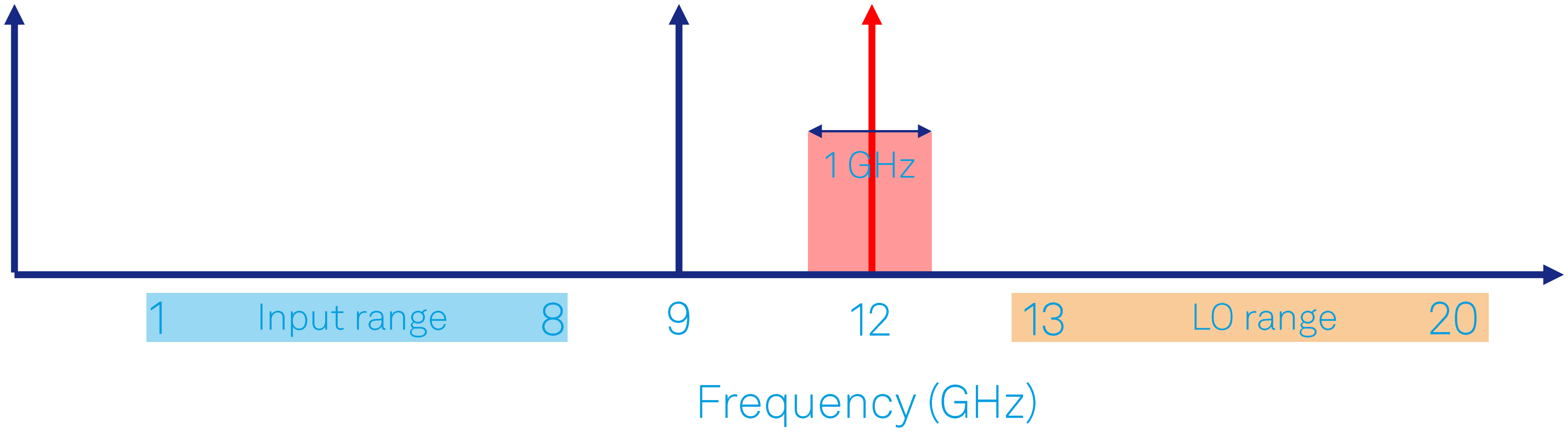

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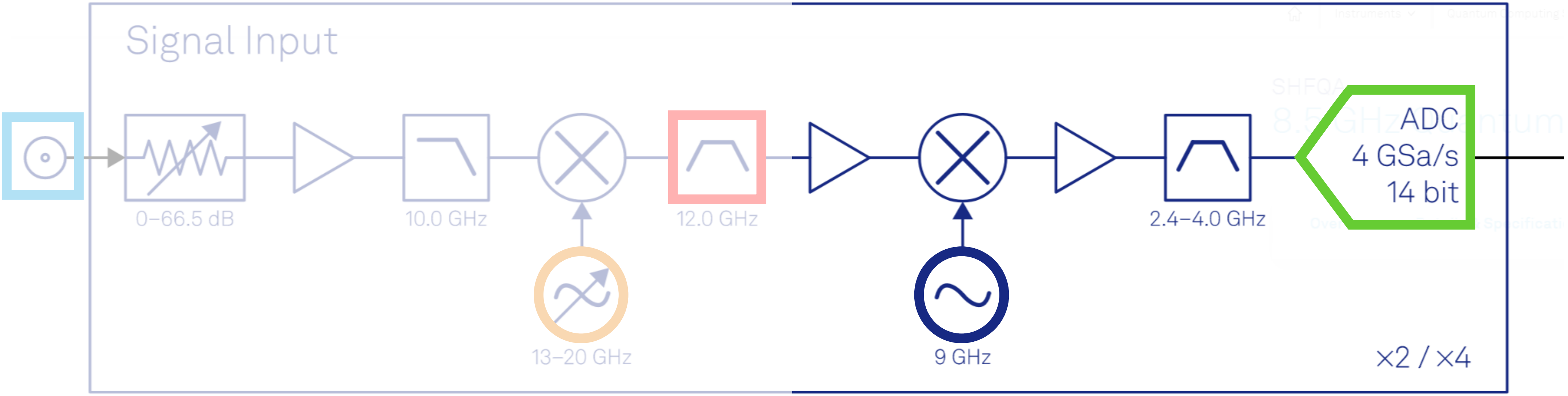

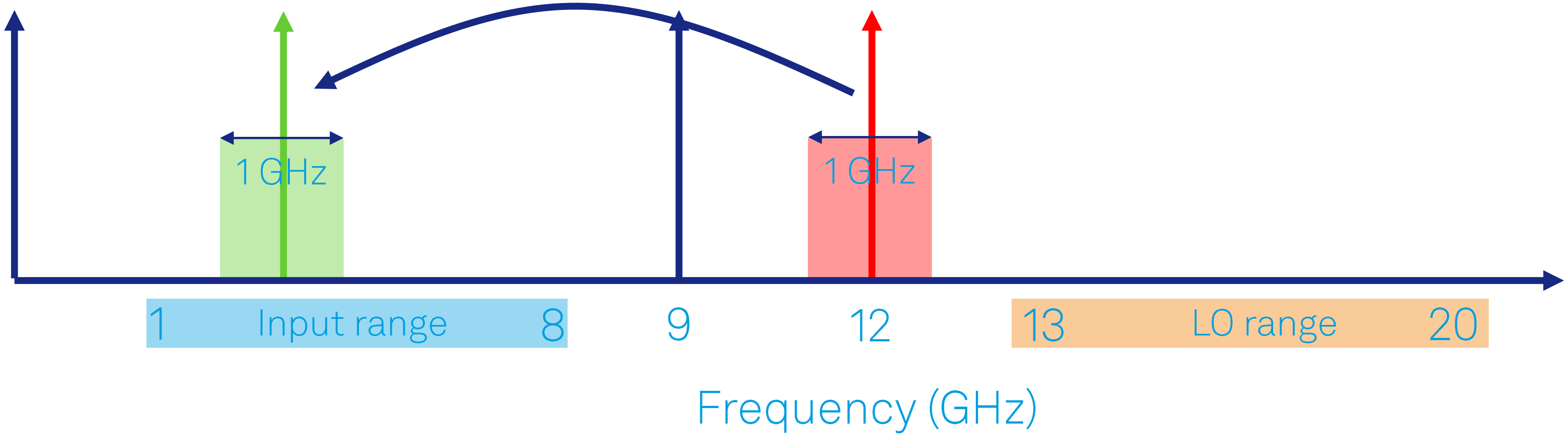

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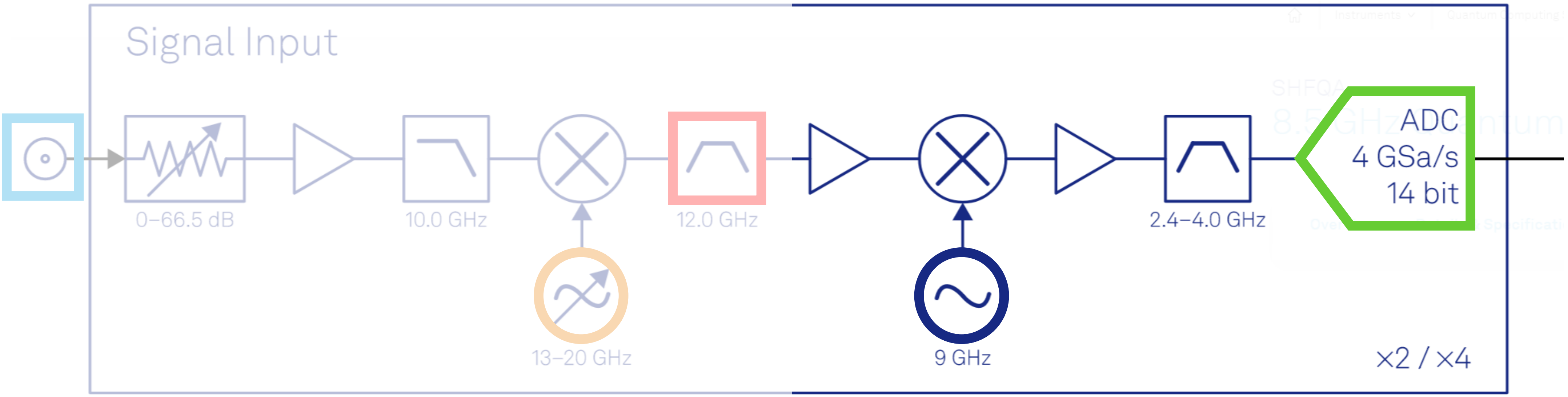

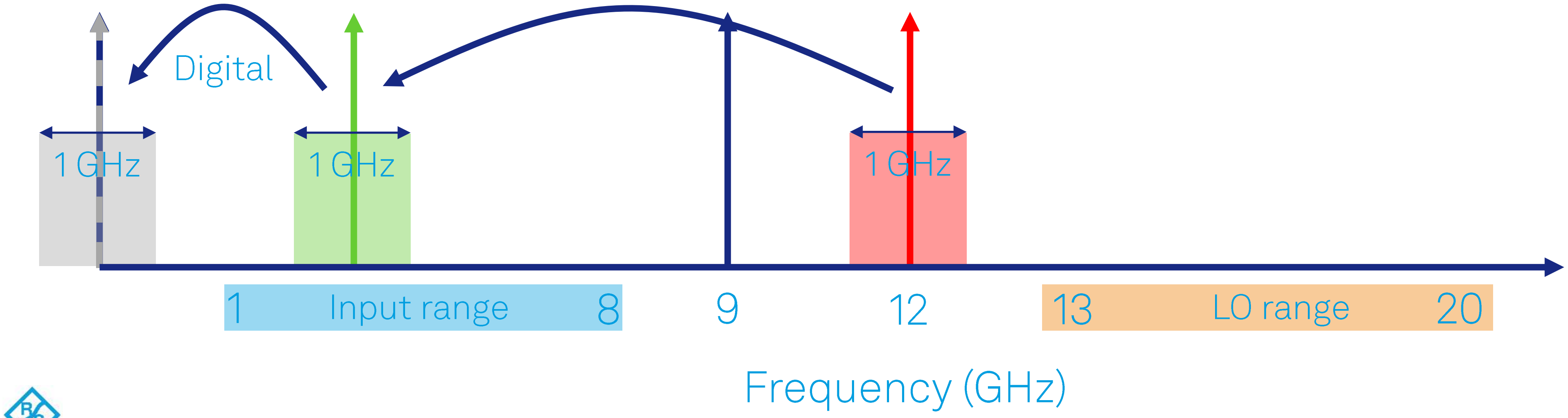

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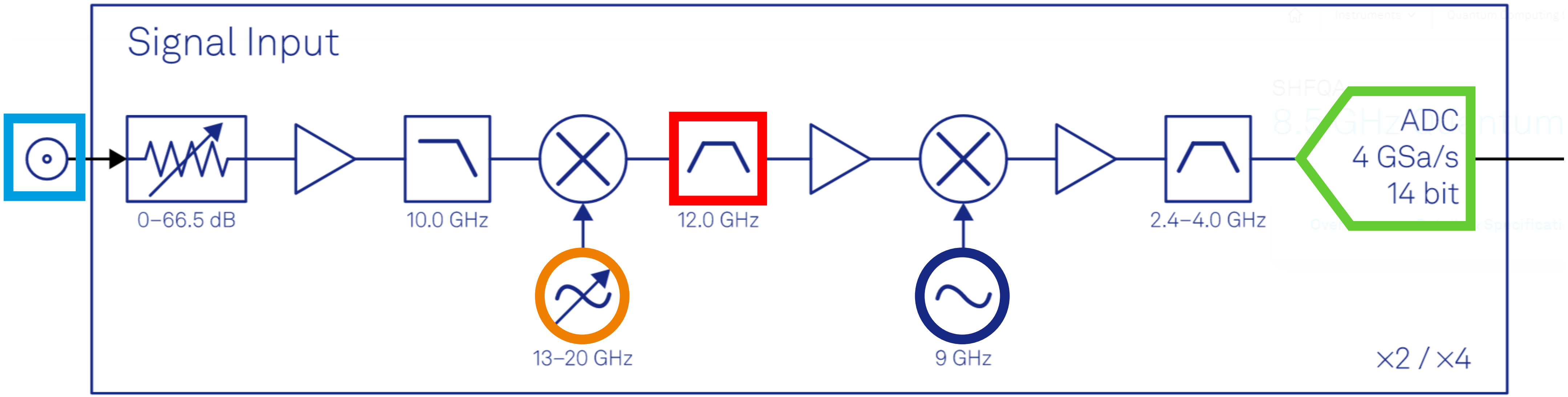
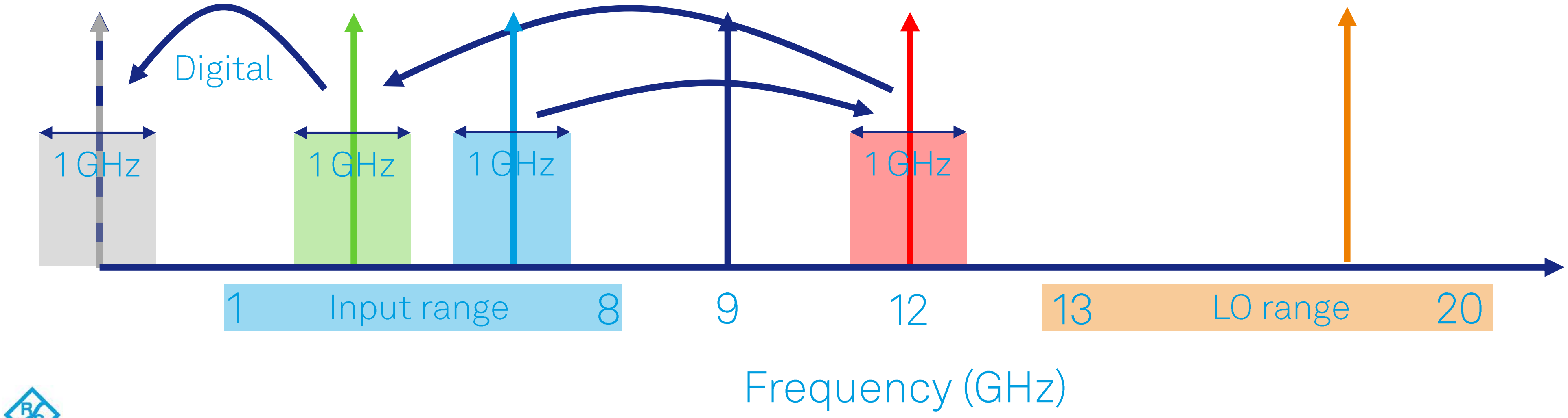




Double super-heterodyne frequency conversion

How does it work?

Minimal overlap of analog bands

- Spin qubits: < 2 GHz
- Superconducting qubits: 4 - 8 GHz

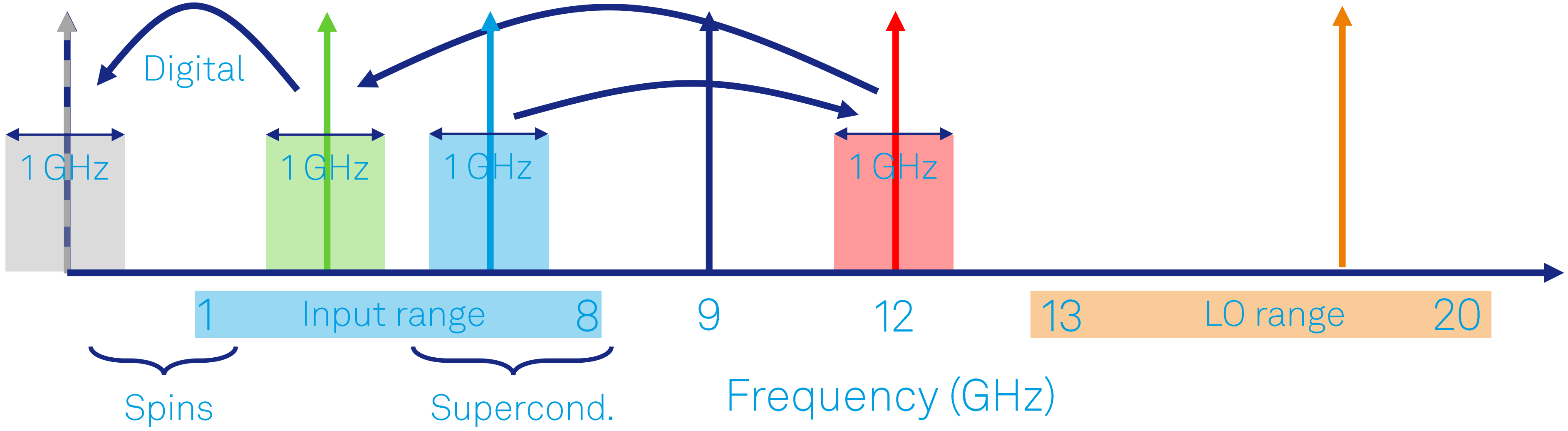
Digital IQ down-conversion

Provides full IQ signal information

Good user experience

Set only center frequency (1-8 GHz) and power range (~ -40 dBm to 10 dBm),

→ The hardware sets the rest



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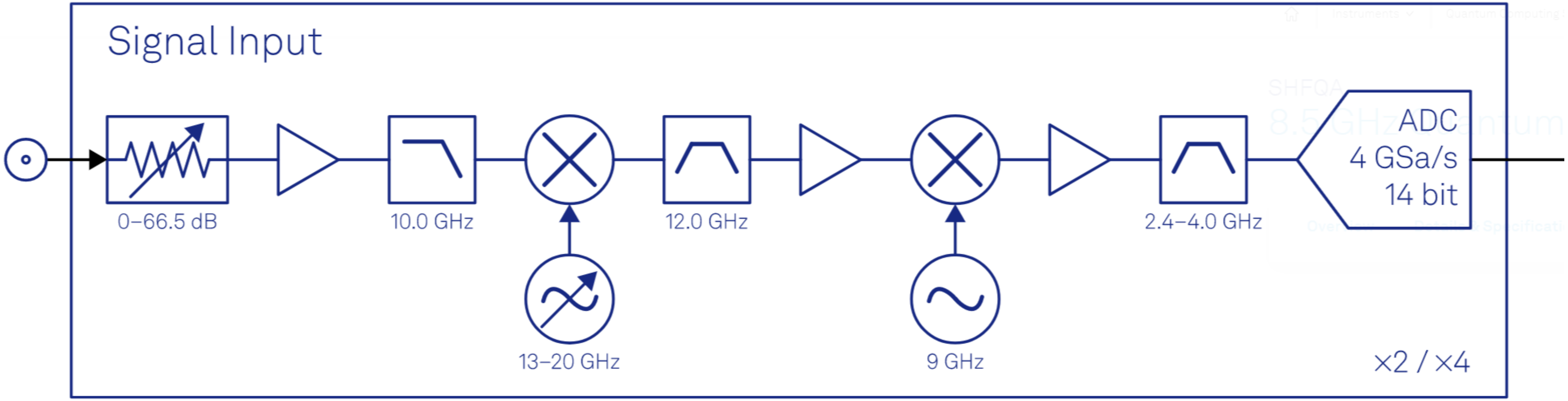
Double super-heterodyne frequency conversion

Optimal for fast, high-fidelity qubit readout



Compared to IQ-mixer scheme

- No mixer calibration needed
- 1 GHz wide spectrum with high SFDR
- Higher stability, e.g. temperature changes
- Only a single ADC needed

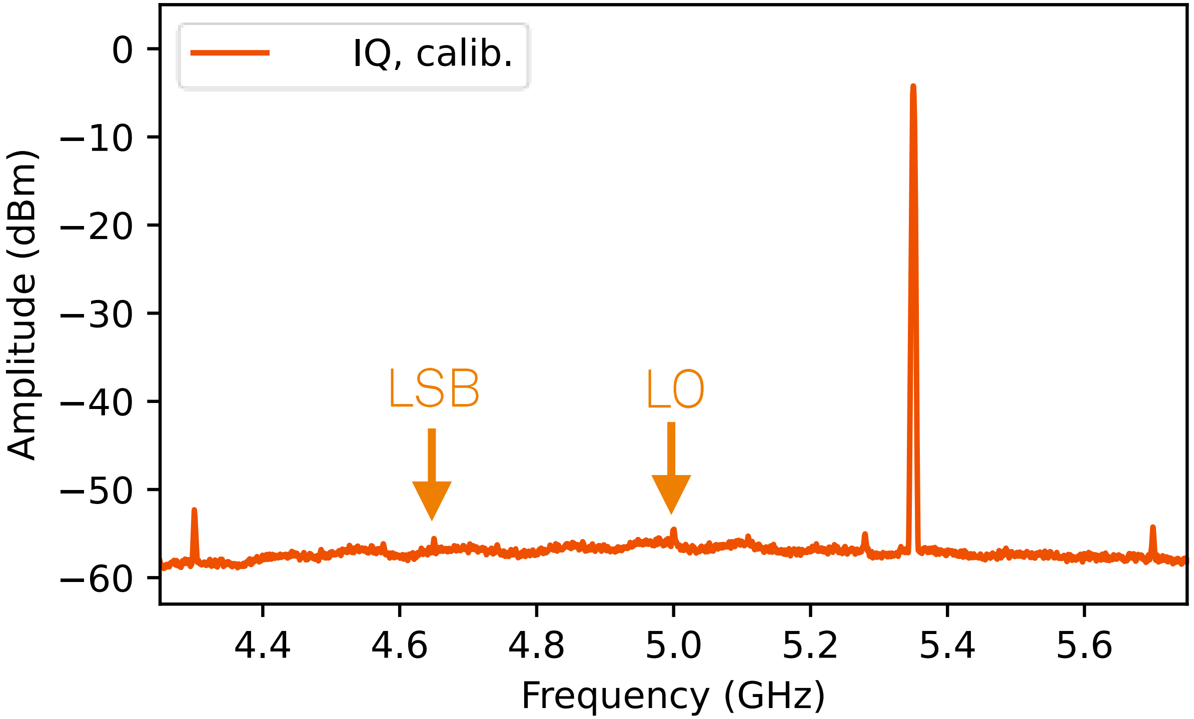
Double superheterodyne vs. IQ-mixer

Better bandwidth for fast pulses

Bandwidth performance

- IQ mixing limited to ~100 MHz bandwidth

→ Cannot be fixed with re-calibration



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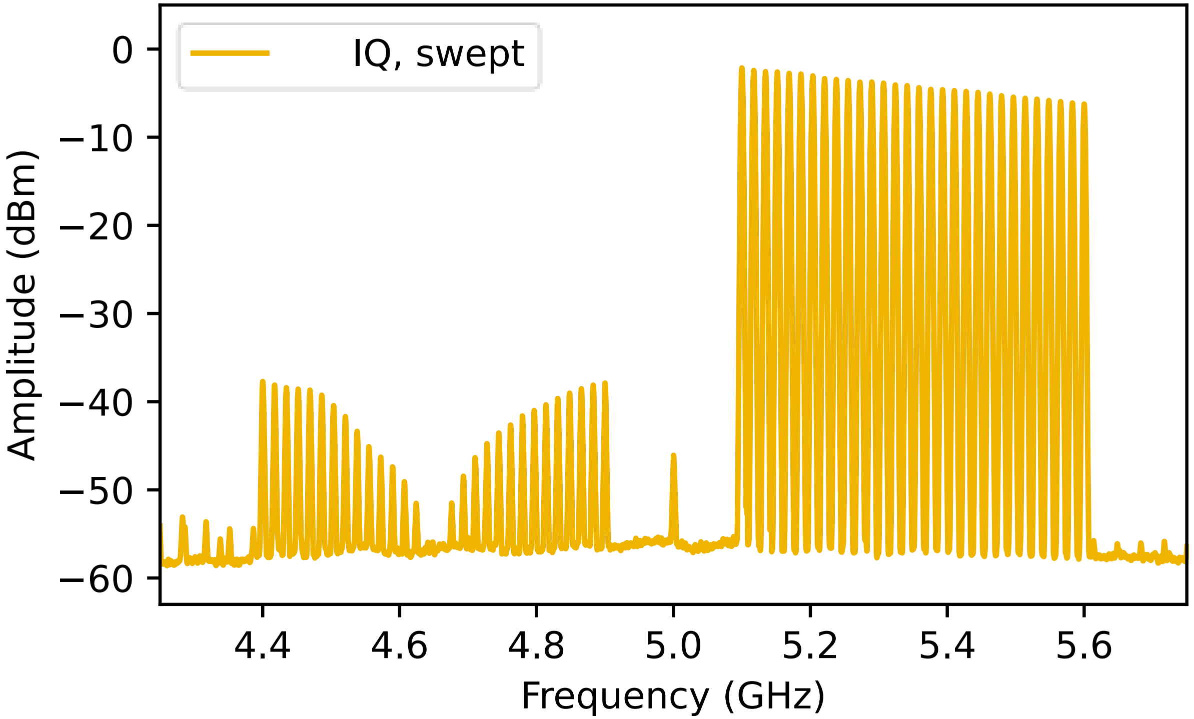

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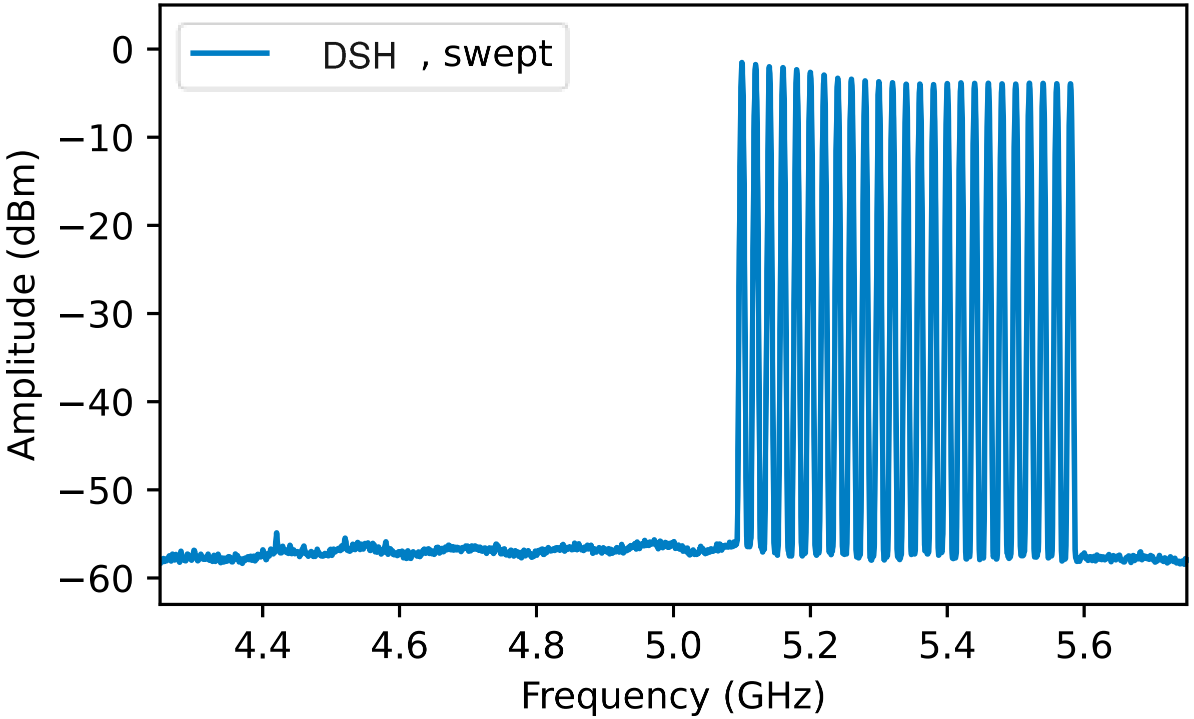
- DSH has 1 GHz bandwidth
- → No degradation at spectral edges



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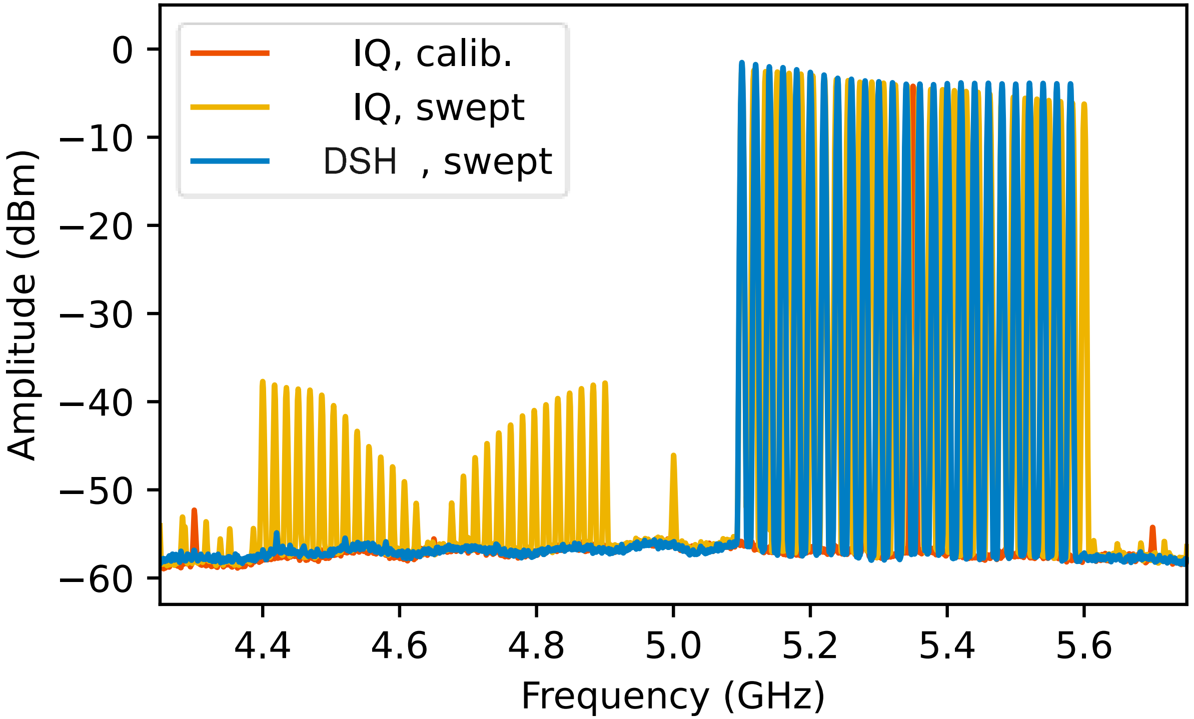

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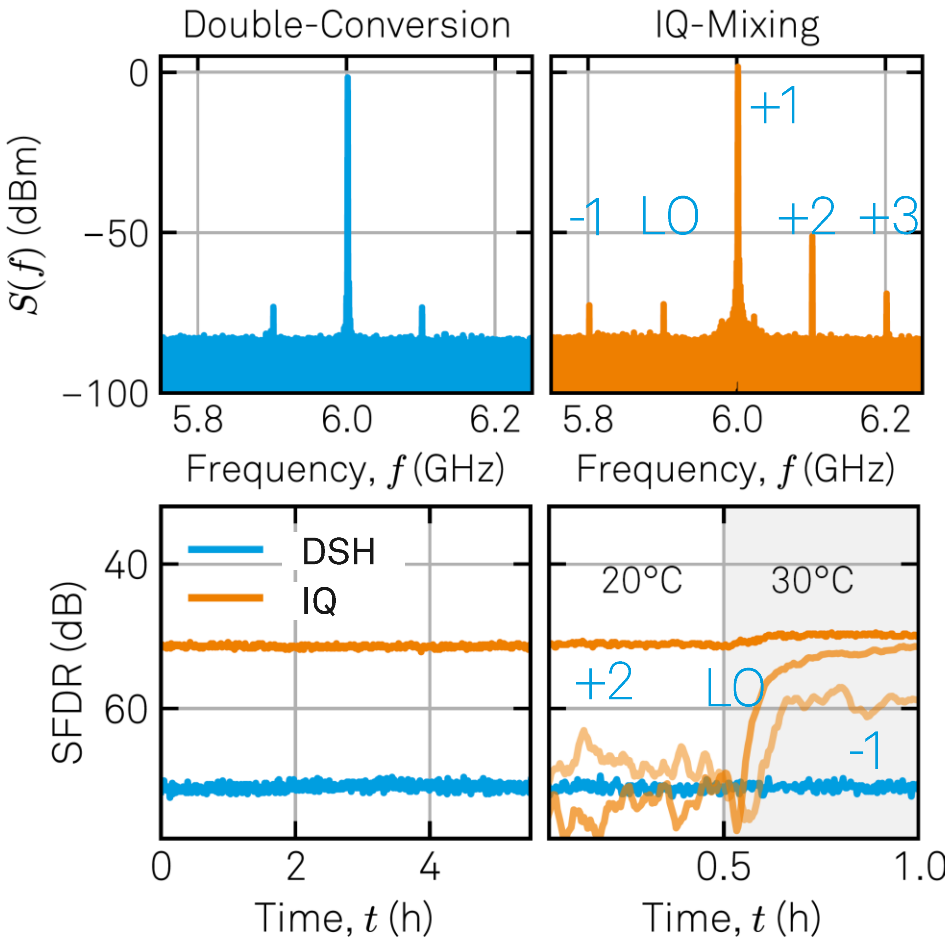
Double superheterodyne vs. IQ-mixer

Better analog performance and stability

Analog performance of frequency conversion

- Already better than freshly-calibrated IQ mixer on SFDR-optimized PCB
- No time-dependence observed



Temperature measurement

- Increase temperature by 10° C at 0.5 hours
- LO and ILR start to increase

→ larger than 2nd harmonic at 0.75 hours

Real-time analysis chain per channel

Optimize readout signal at minimal latency

Result integration

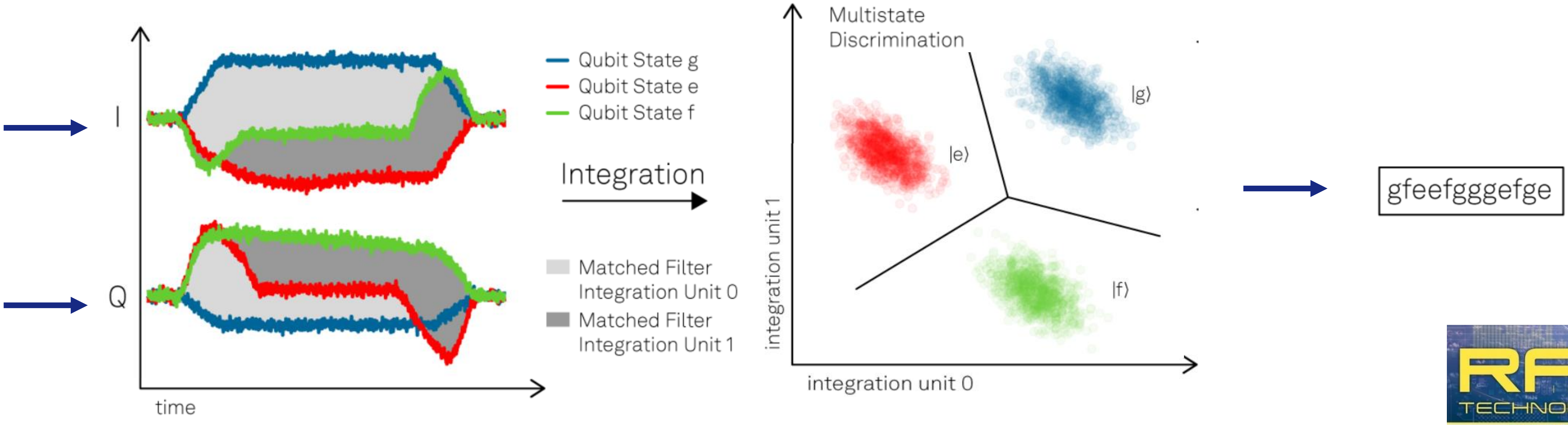
- Define complex integration weights
- Weighted integration performed in real time
- Matched filters for optimal state discriminations

Comprehensive multi-state discrimination

Enables real-time readout or active reset of higher levels (up to 4 total)

Real-time state distribution

Fast feedback and global error correction



Real life integration

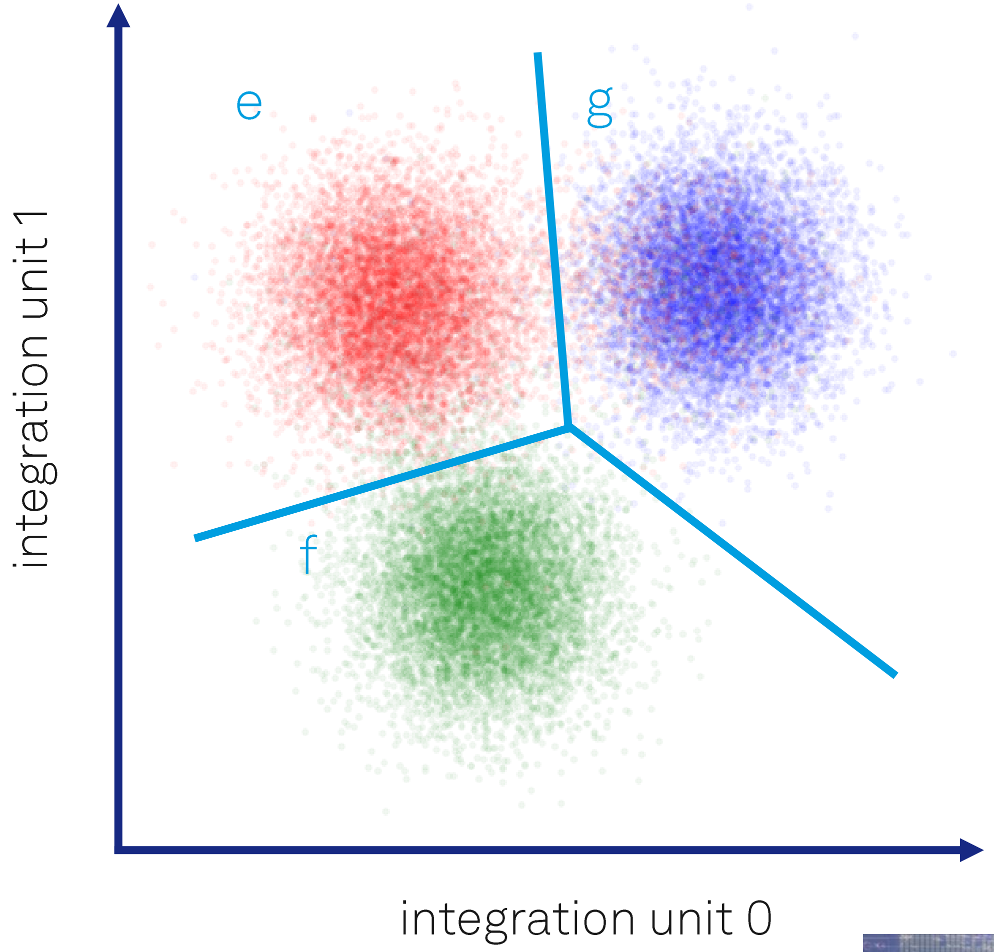
Qutrit readout at ETH Zürich

Measurement

1. 30000 measurements
2. Use 2 integration units with matched filters for optimal state discrimination

Results

- Colors indicate initialized state
- Avg. assignment ≈ 95%



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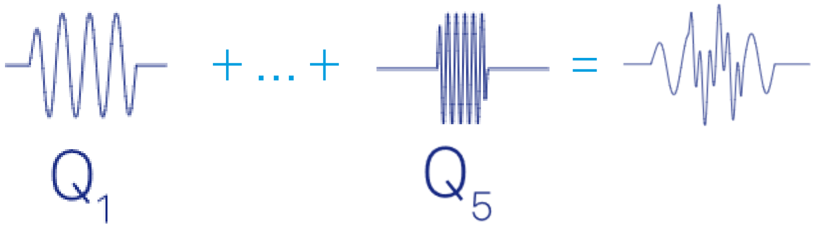
Quantum Analyzer Channel Features

Multiplexed qubit readout

Create composite readout pulse
in real-time using indiv. readout pulses ...



... and a single sequencer instruction in a simple program

```
waitDigTrigger(1);

repeat (1000) {
  repeat (10000) {
    playZero(4016);
    startQA(QA_GEN_0 | QA_GEN_1 | QA_GEN_2 | QA_GEN_3 | QA_GEN_4,
            QA_INT_0 | QA_INT_1 | QA_INT_2 | QA_INT_3 | QA_INT_4,
            true, 0, 0x0);

    setTrigger(1);wait(1);setTrigger(0);
  }
}
```

Starts experiment

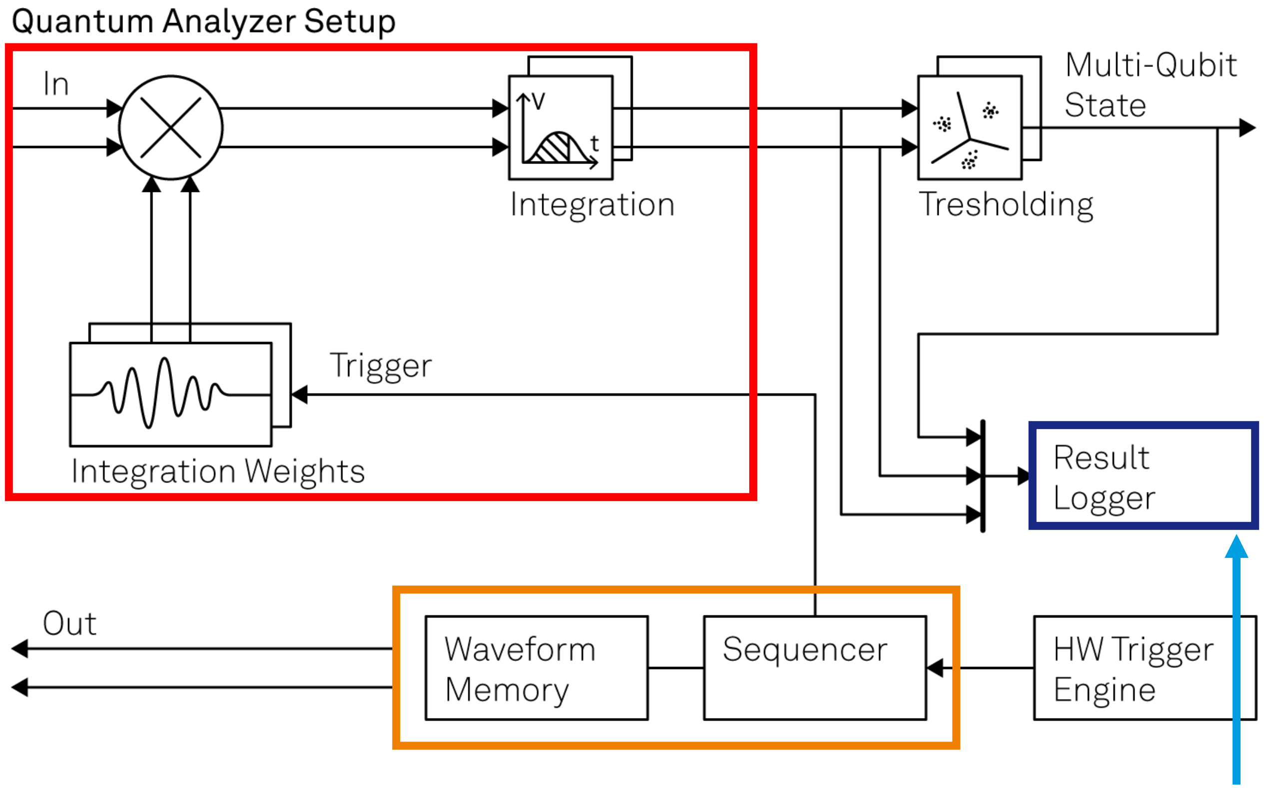
Number of points

Averages (to 20 ms)

Which readout pulses are played

Which qubits/pulses are analyzed

Triggers control channels



Collect and average results in real time

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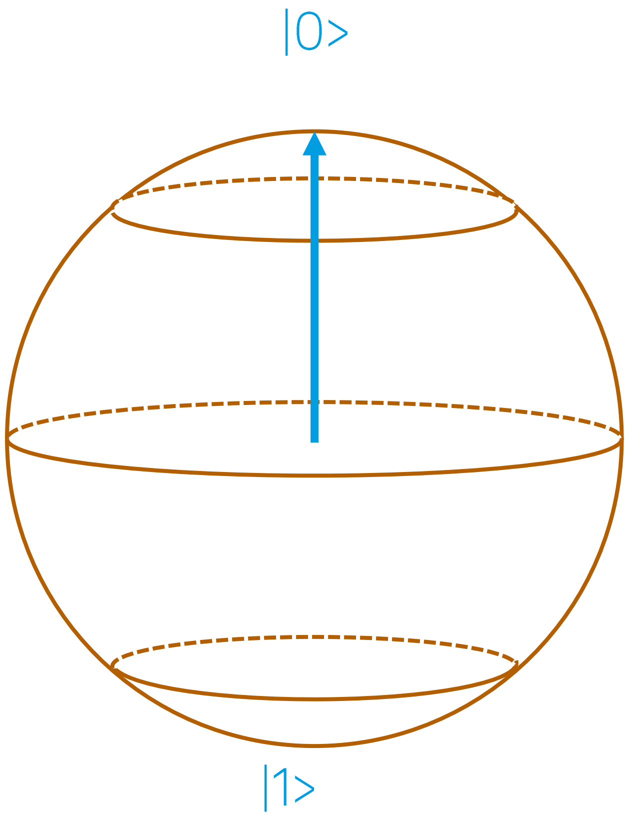
Qubit Control Essentials

Single-qubit gate operations



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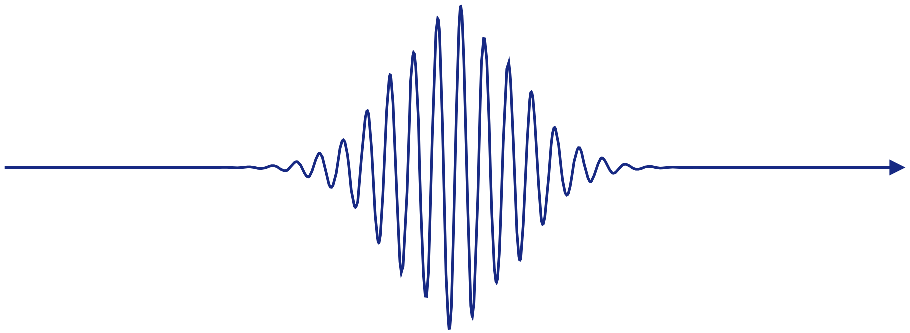

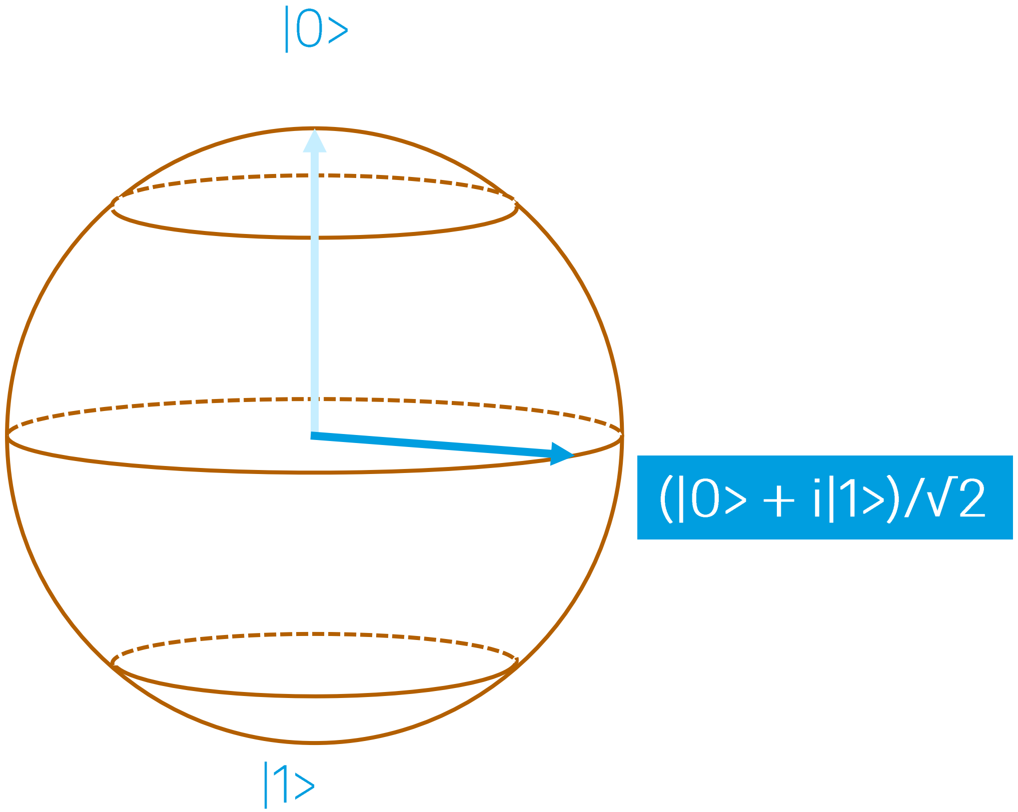

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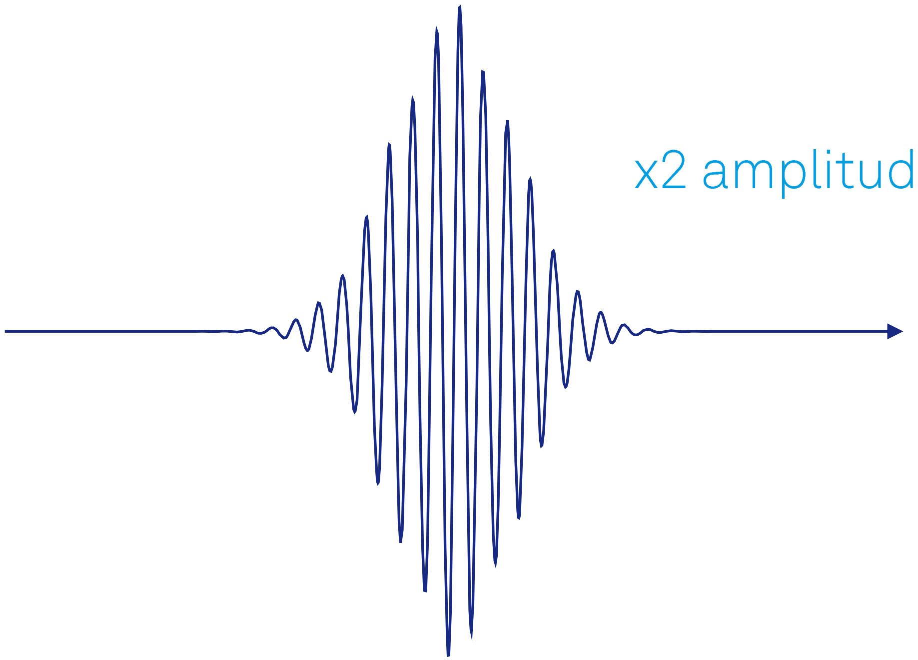
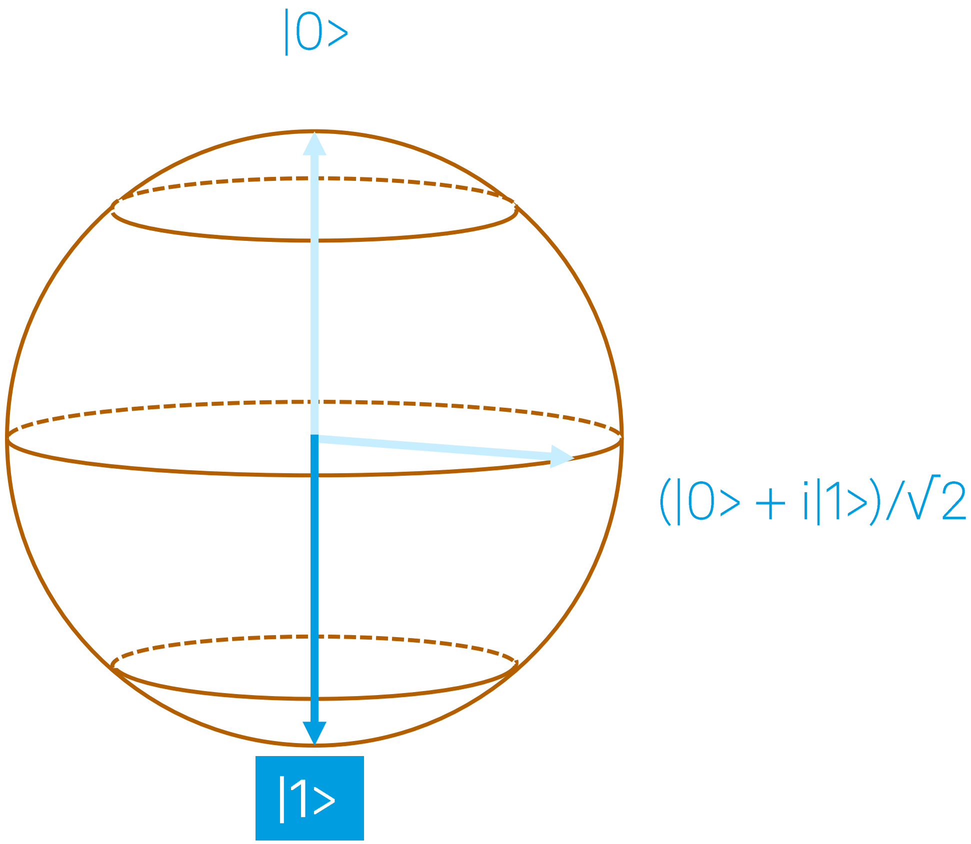


x2 amplitude



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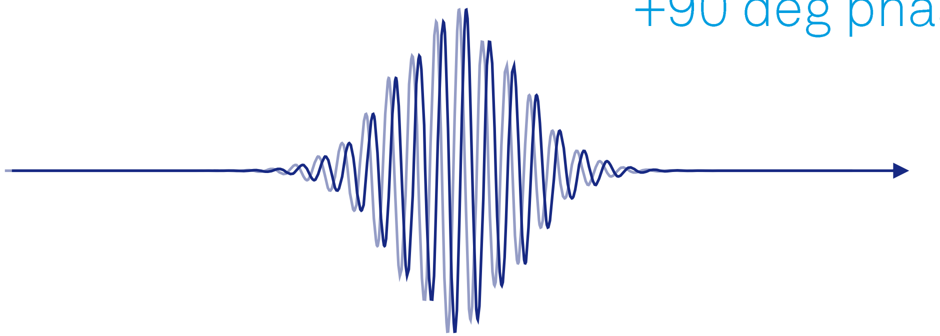
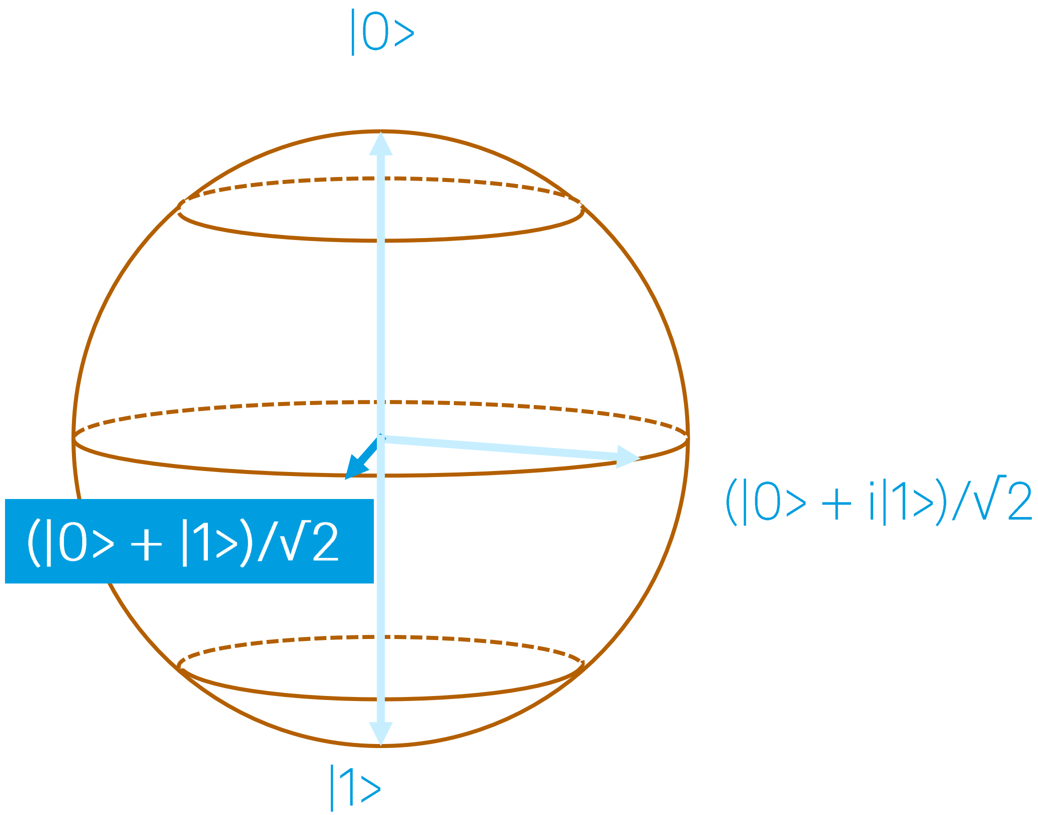


+90 deg phase



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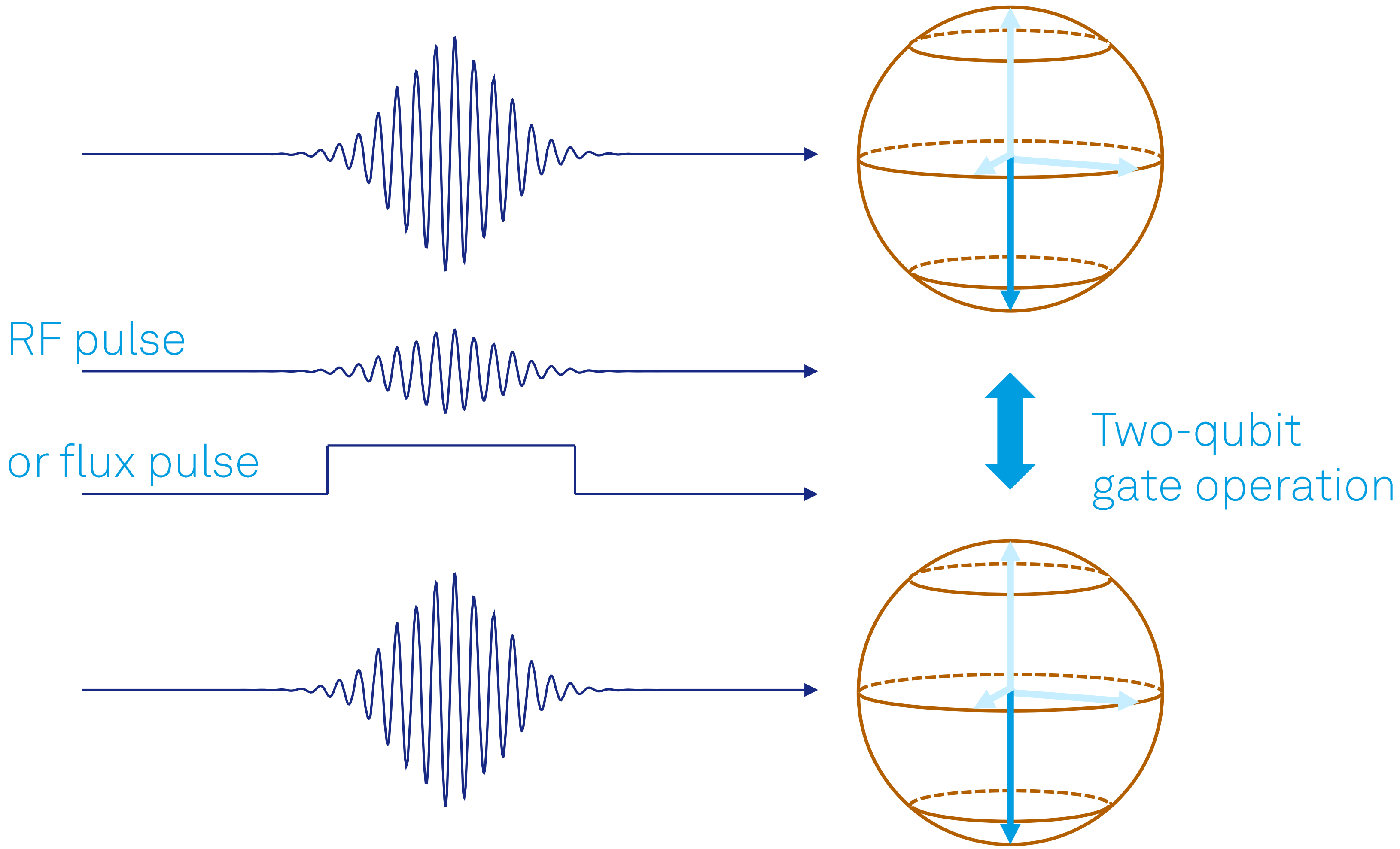
Two-qubit gate operations



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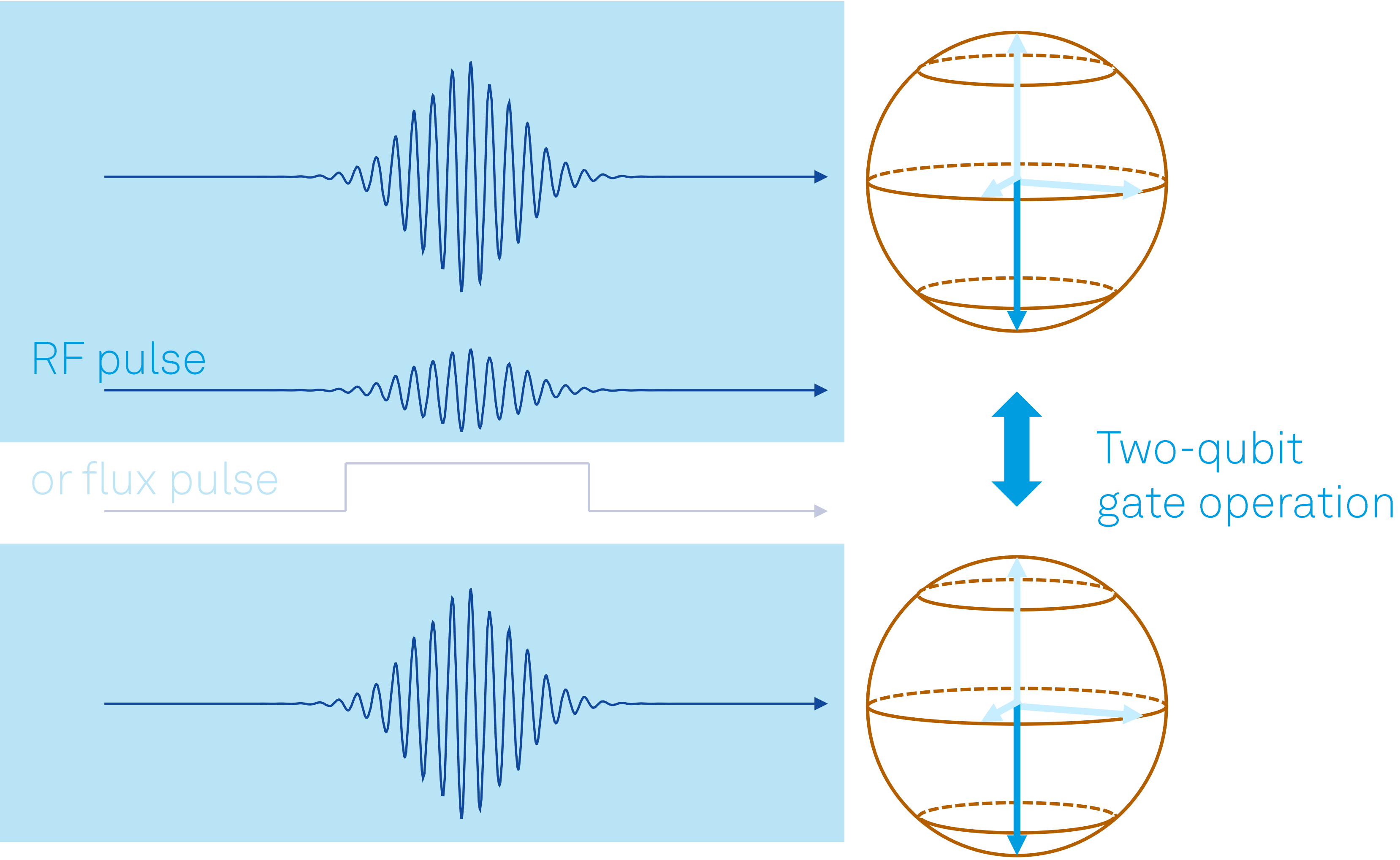


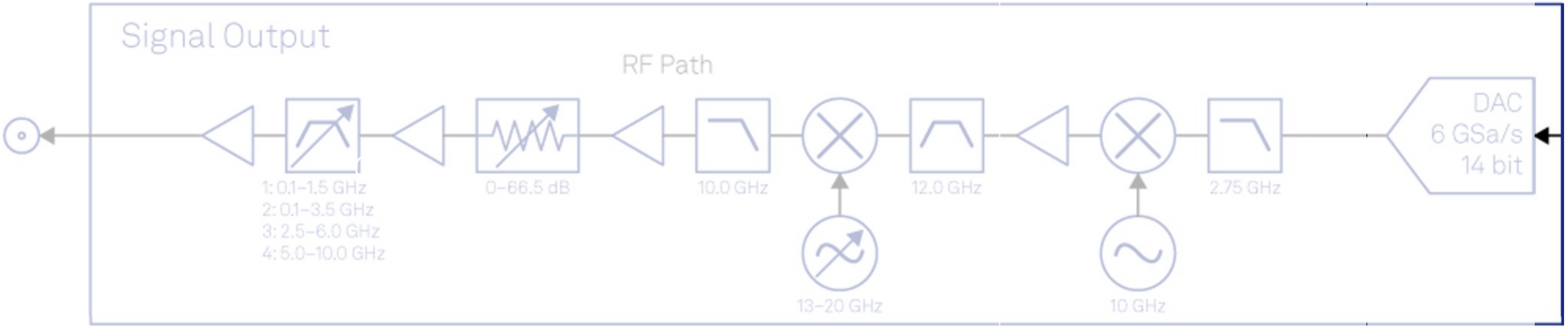
RF pulse

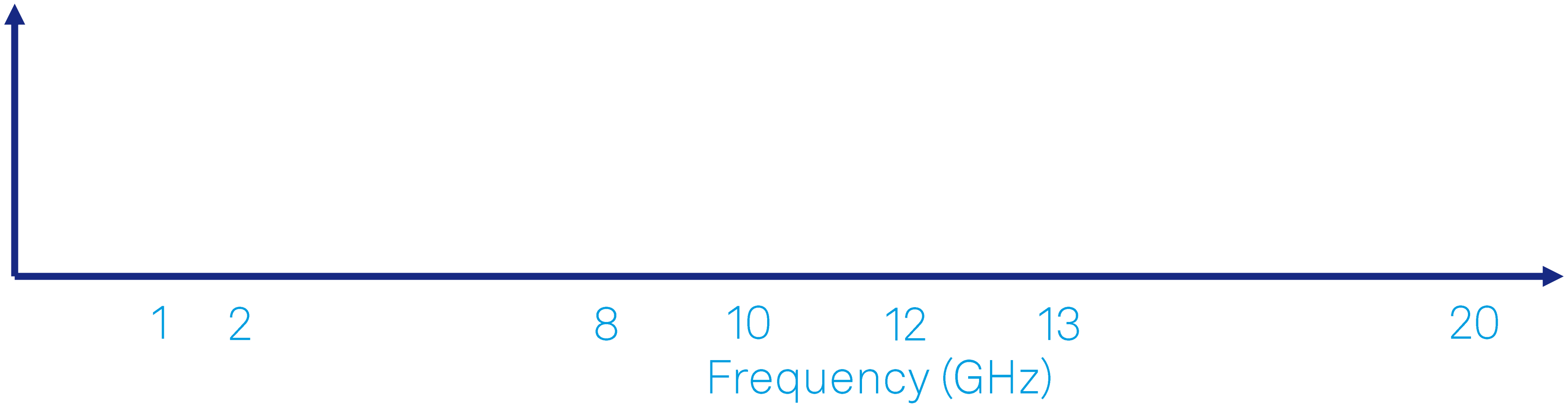
or flux pulse

Two-qubit
gate operation

Double superheterodyne frequency conversion

Optimal for fast, high-fidelity qubit control





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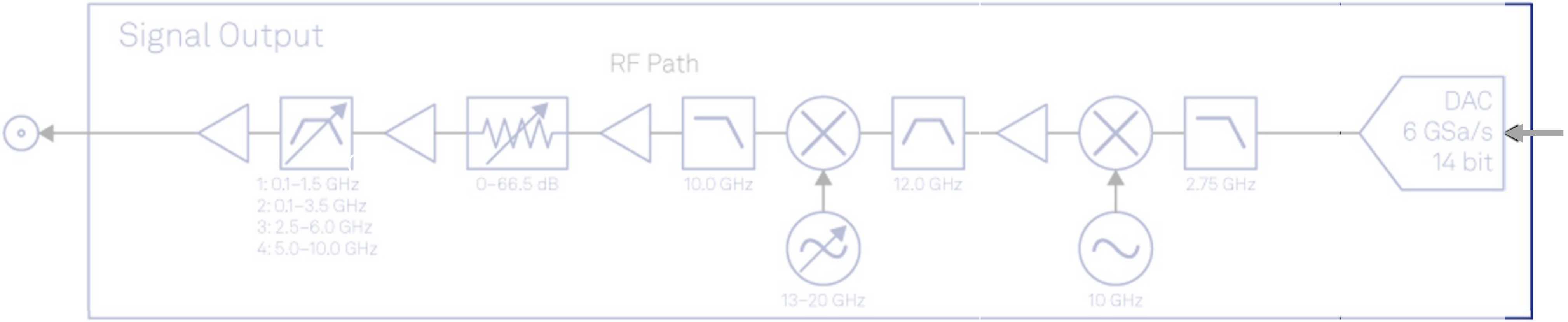

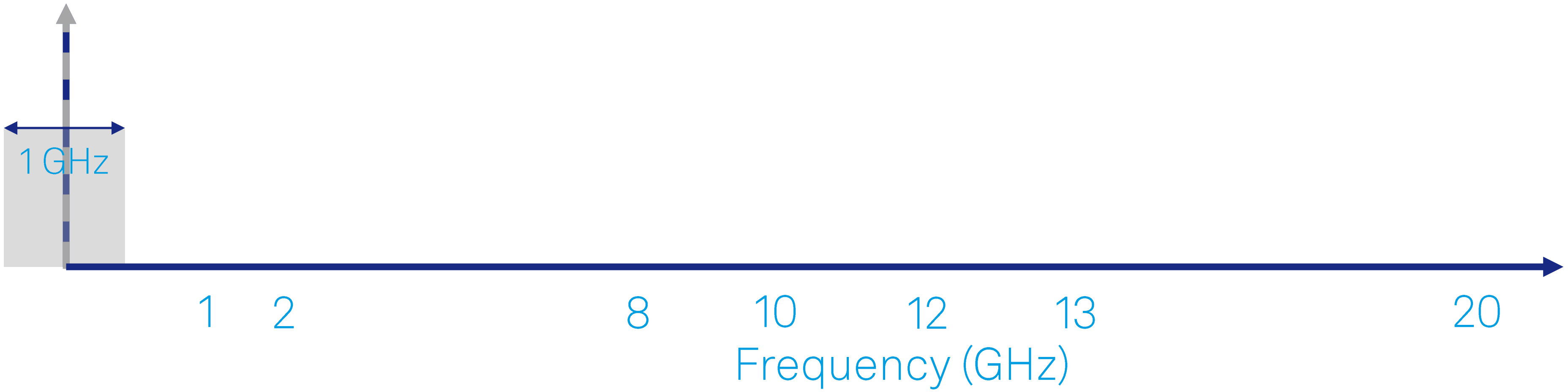

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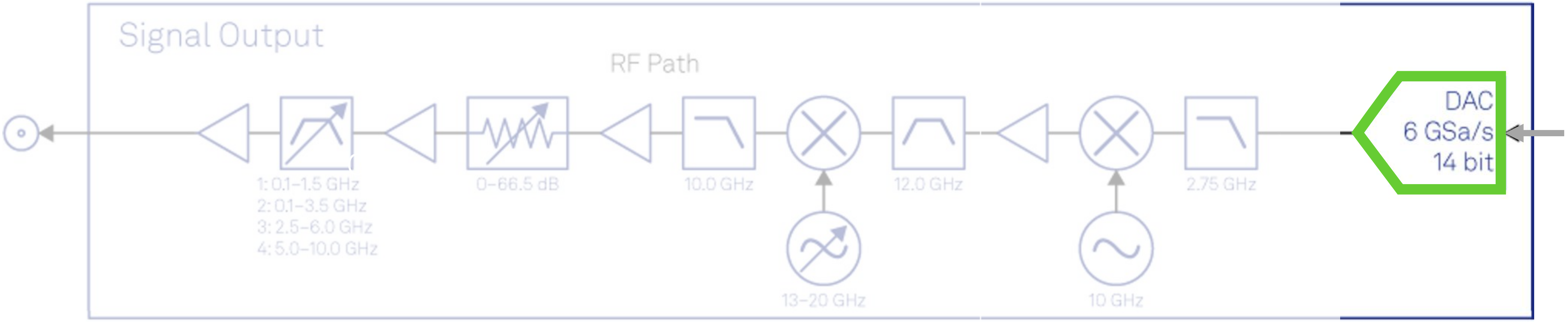

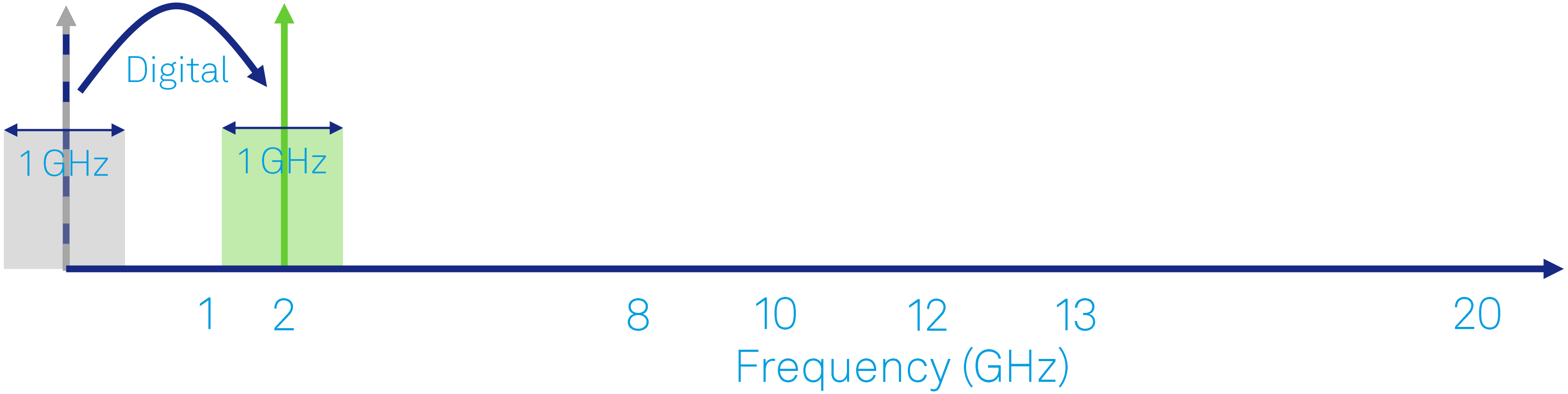

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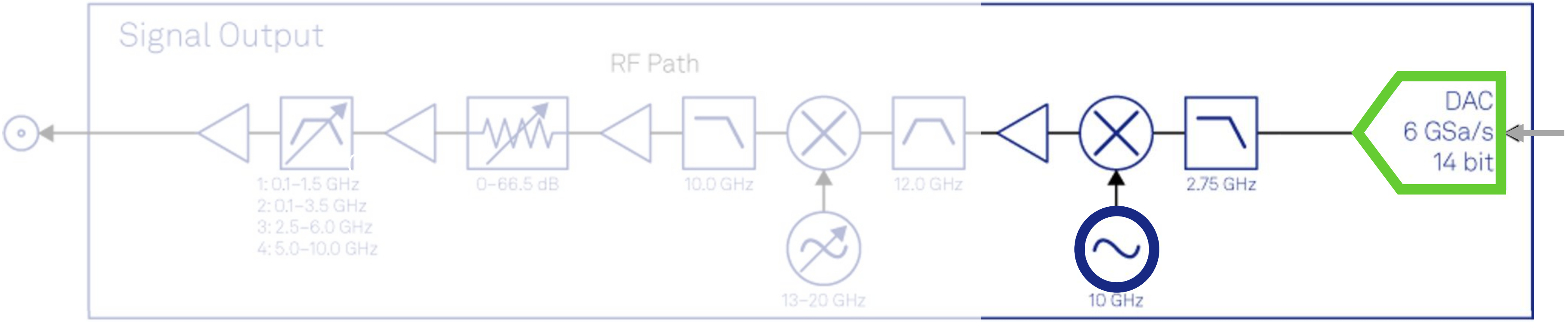

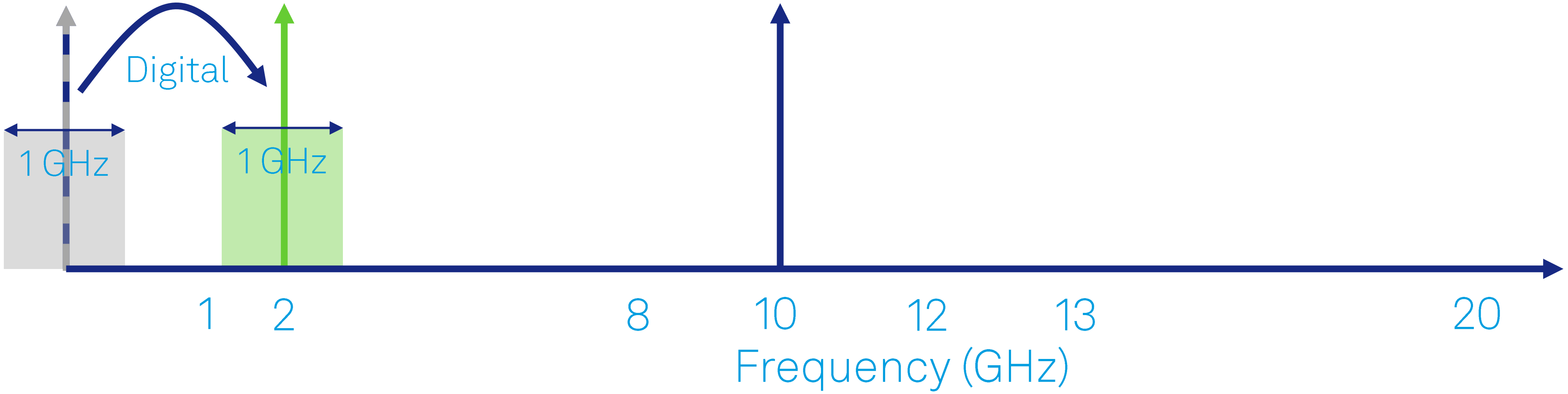

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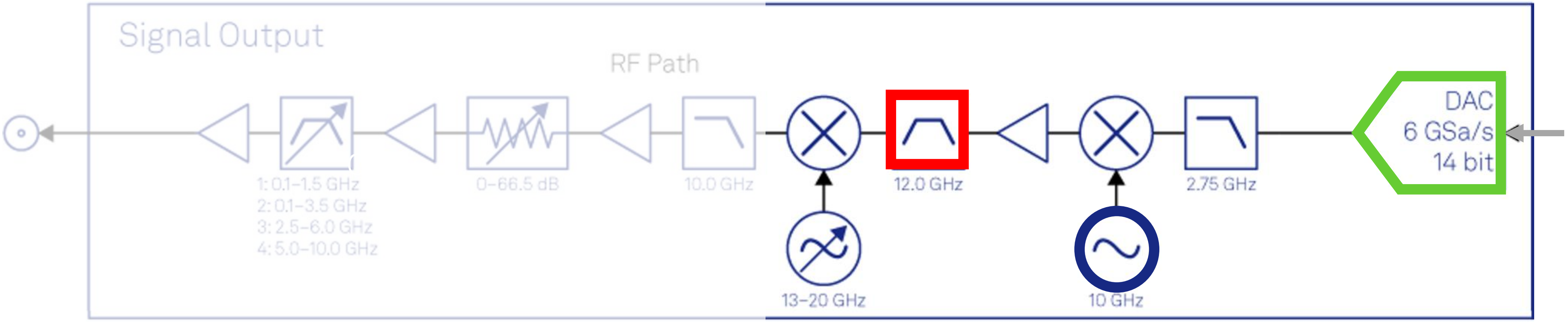

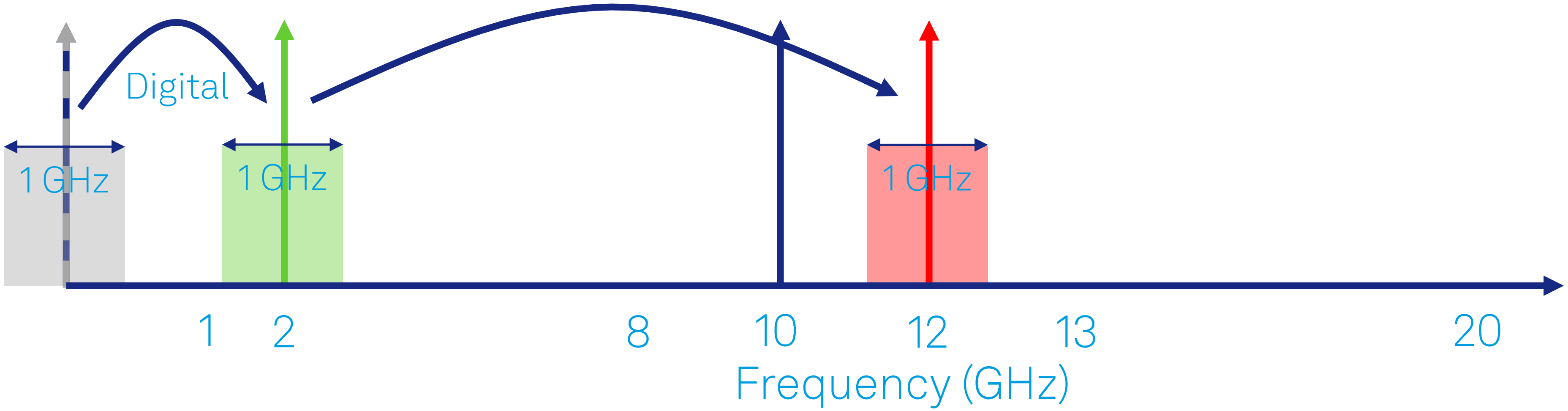

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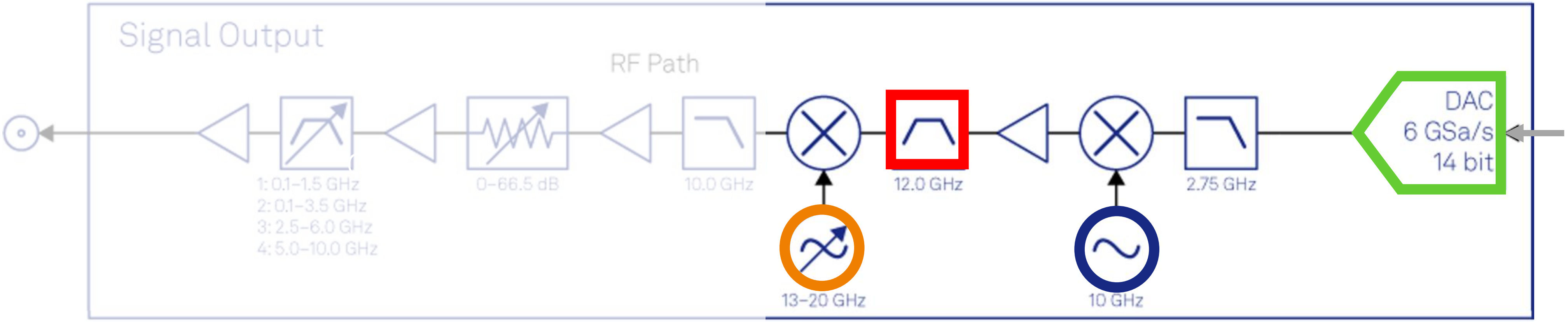

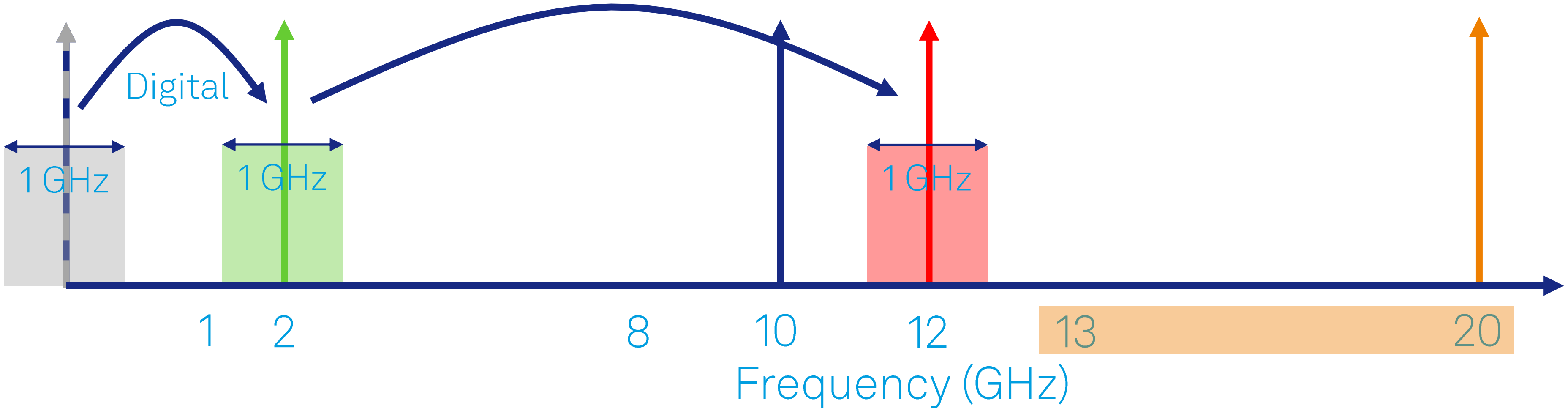

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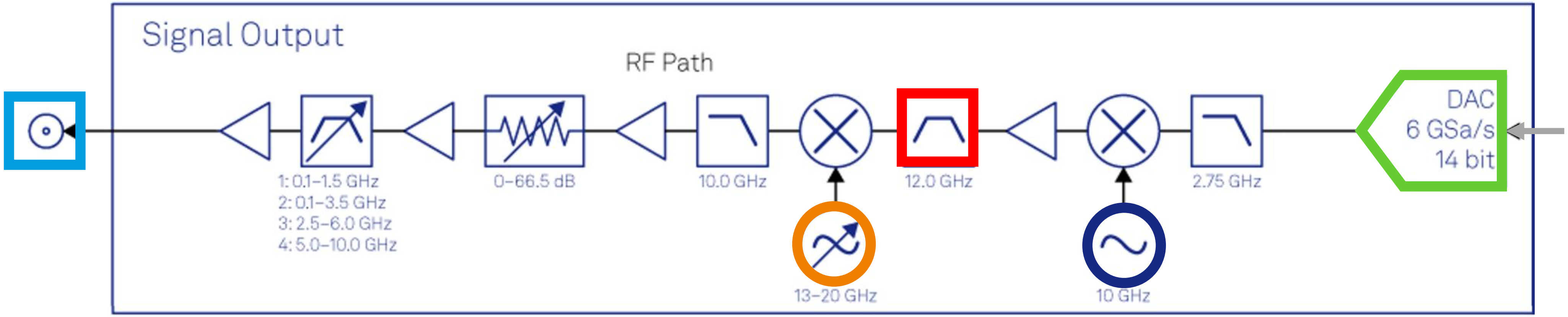

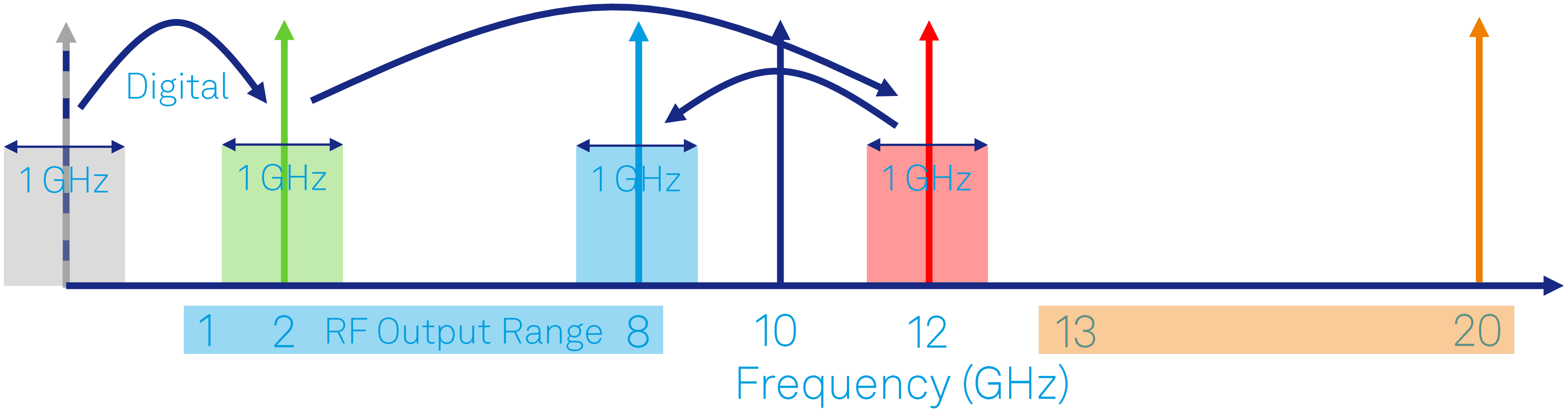

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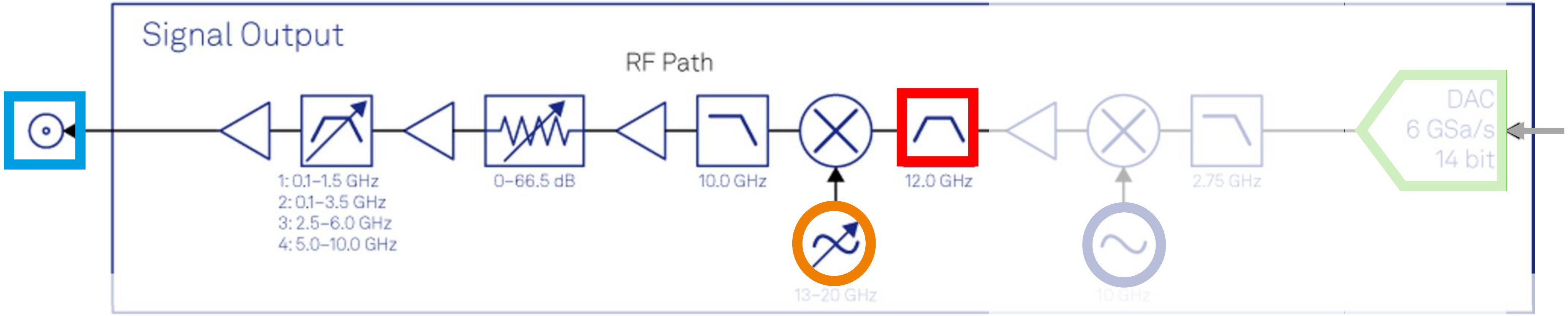
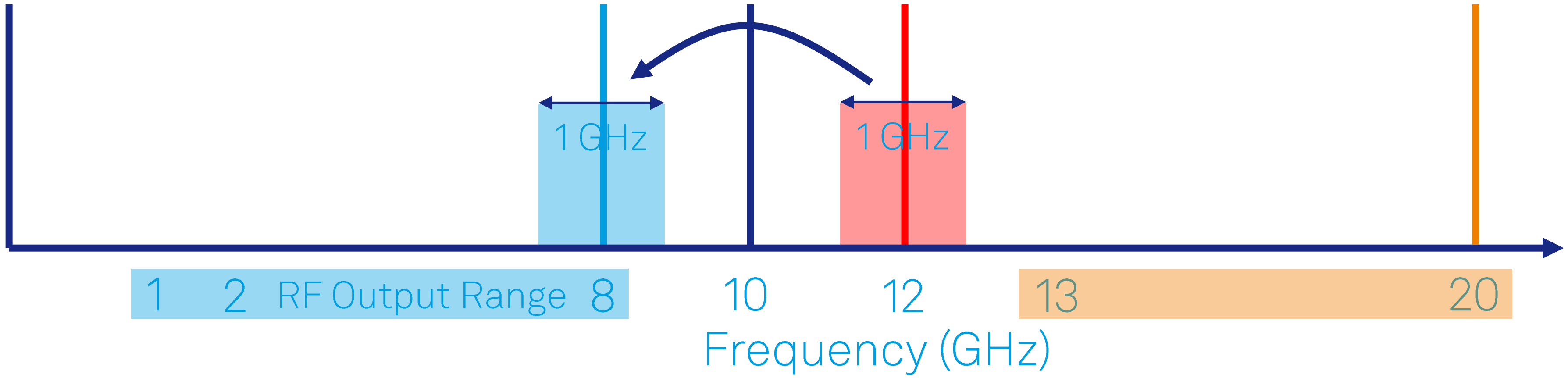




Double superheterodyne frequency conversion

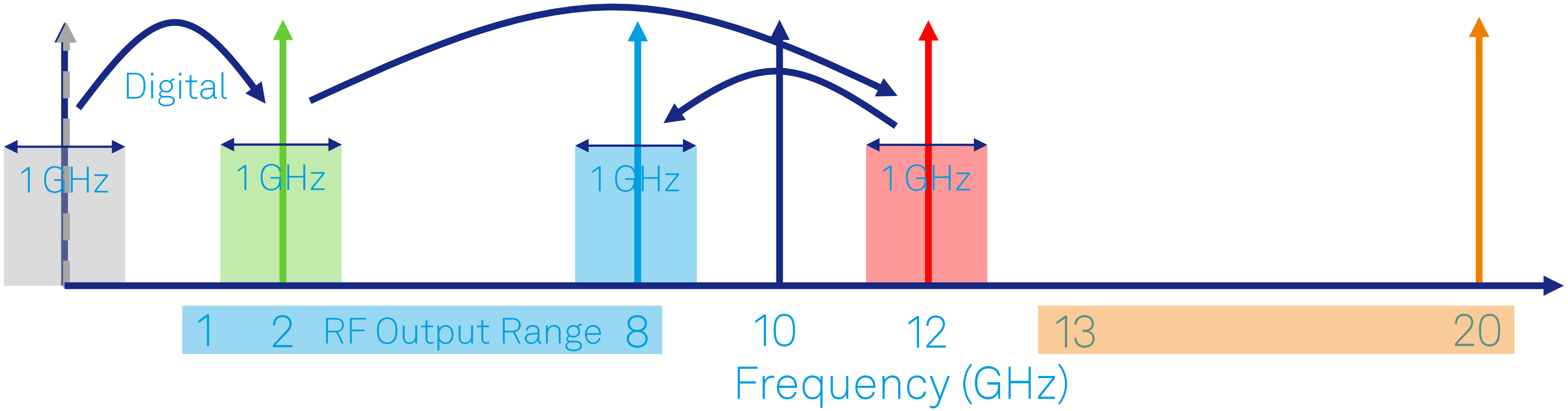
Who is it designed for?

Single qubit gates

- Superconducting qubits: 4 - 8 GHz
- Spin qubits that are <8 GHz

Two qubit gates

- Cross-resonance gates: 4-8 GHz
- Parametric two-qubit gates (<1 GHz)



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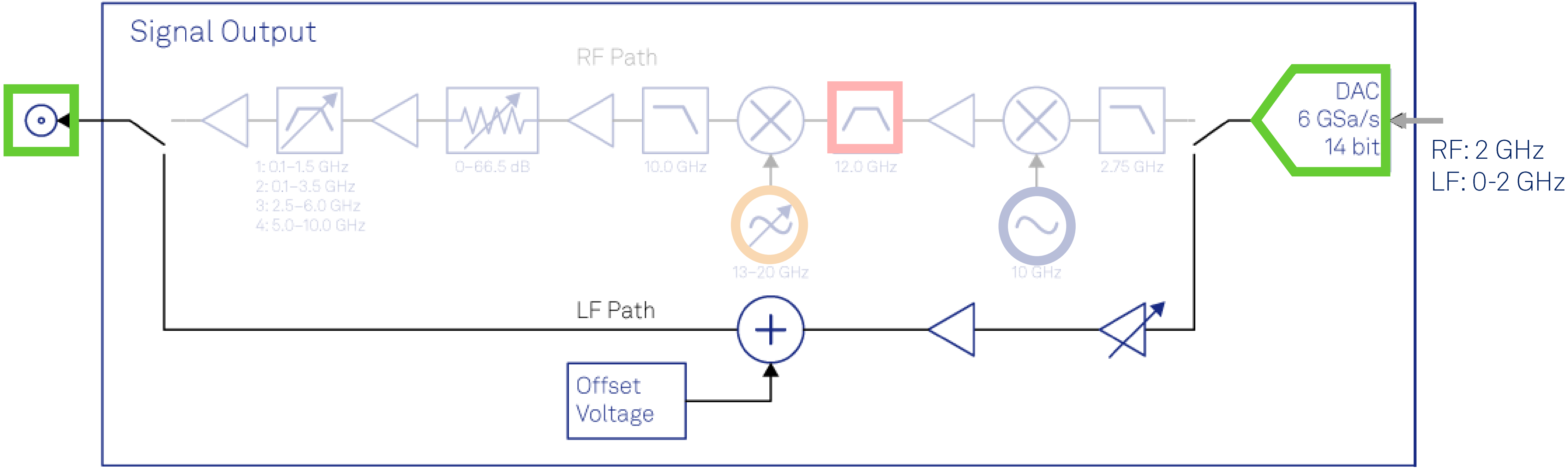
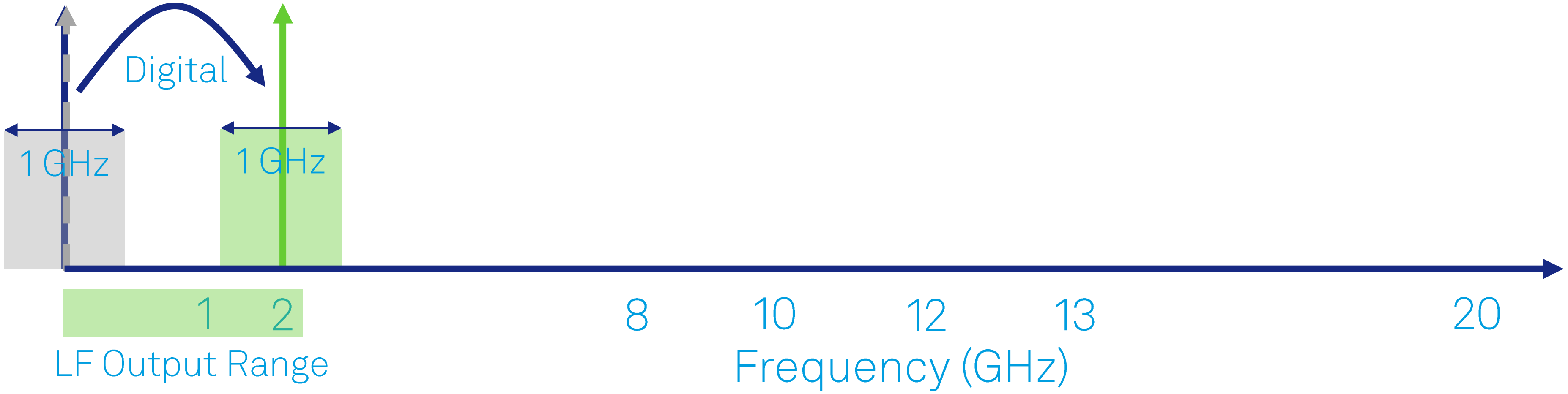
Complete range from DC to 8.5 GHz

Direct pathway for pulses below 2 GHz





Efficient Generation of Pulse Sequences

Efficient generation of pulse sequences

Pulse-level sequencing

Pulse: Frequency, phase, amplitude, waveform

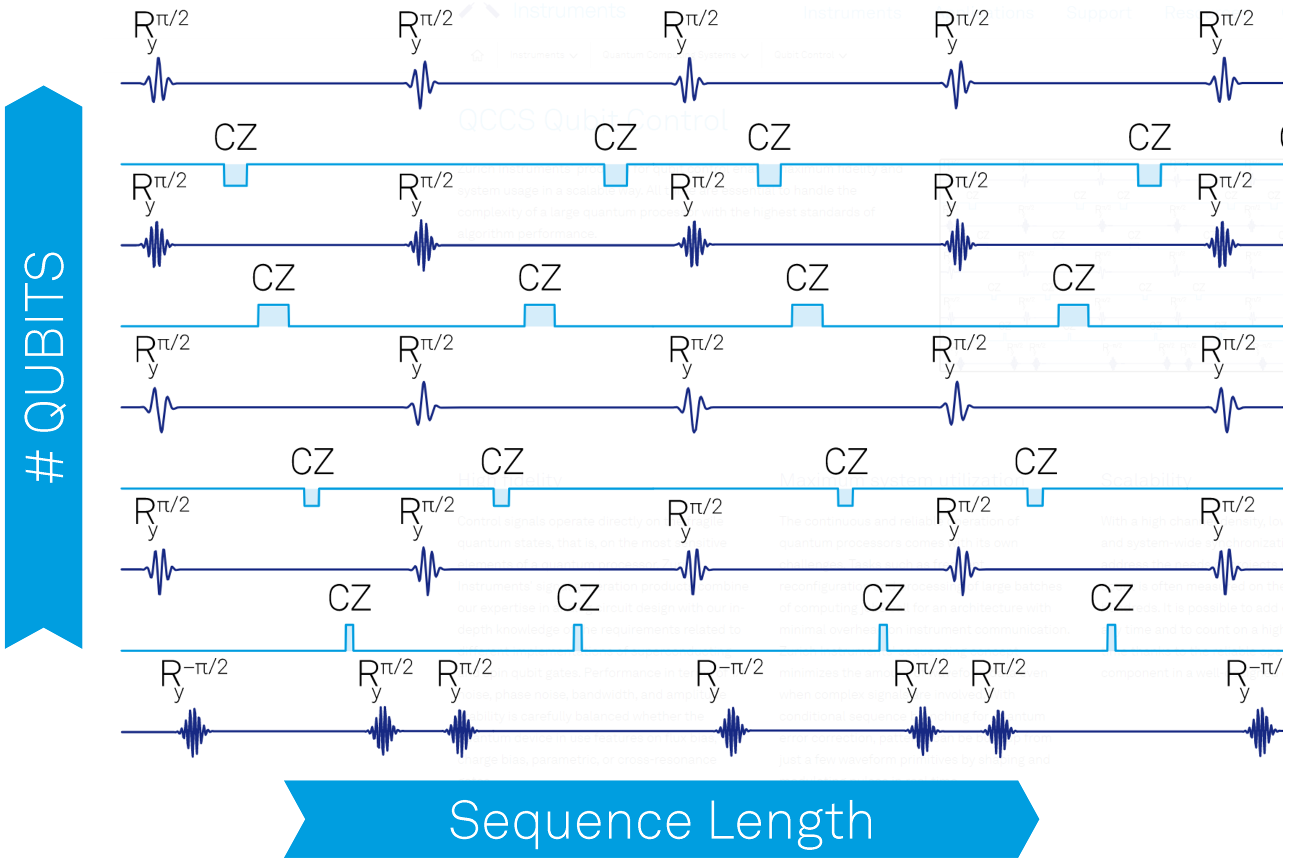
→ Transfer minimal information to system and execute in minimal time

Sequencer program

Defines flow of experimental sequence (loops, decision making pulse timings)

→ Improves communication overhead and waveform memory consumption

→ Inefficient for long, time-optimized sequences with branching and feedback



Efficient generation of pulse sequences

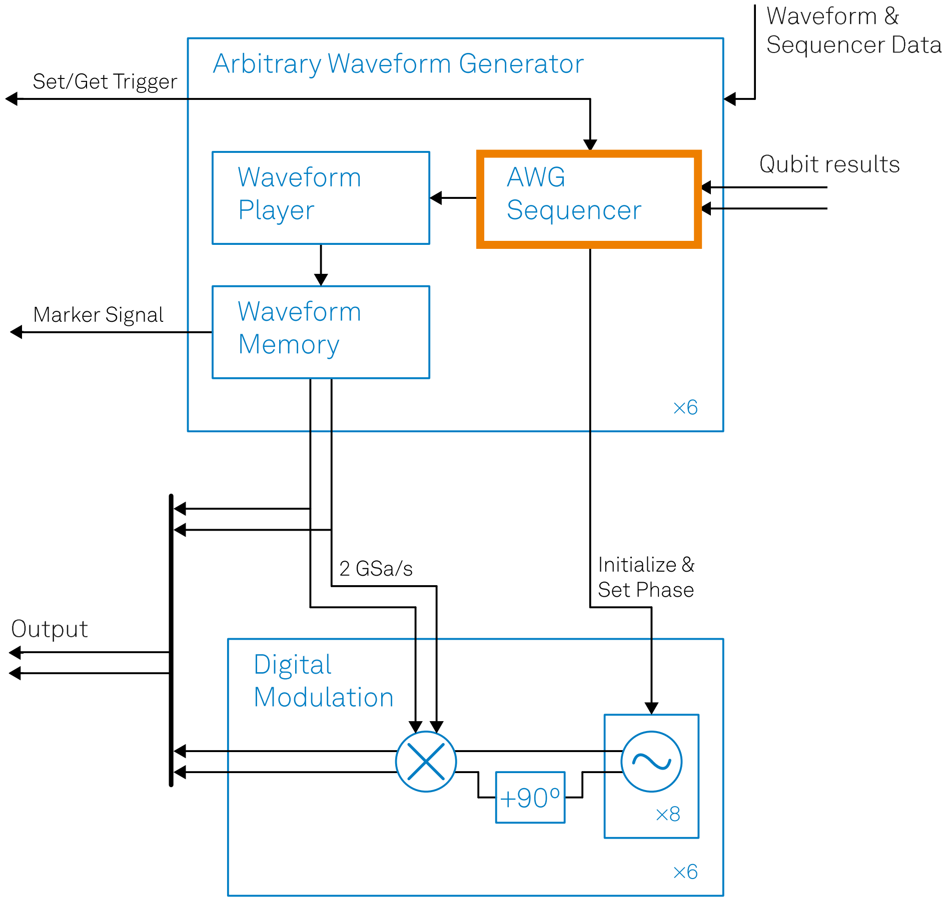
Pulse-level sequencing

Pulse: Frequency, phase, amplitude, waveform

→ Transfer minimal information to system and execute in minimal time

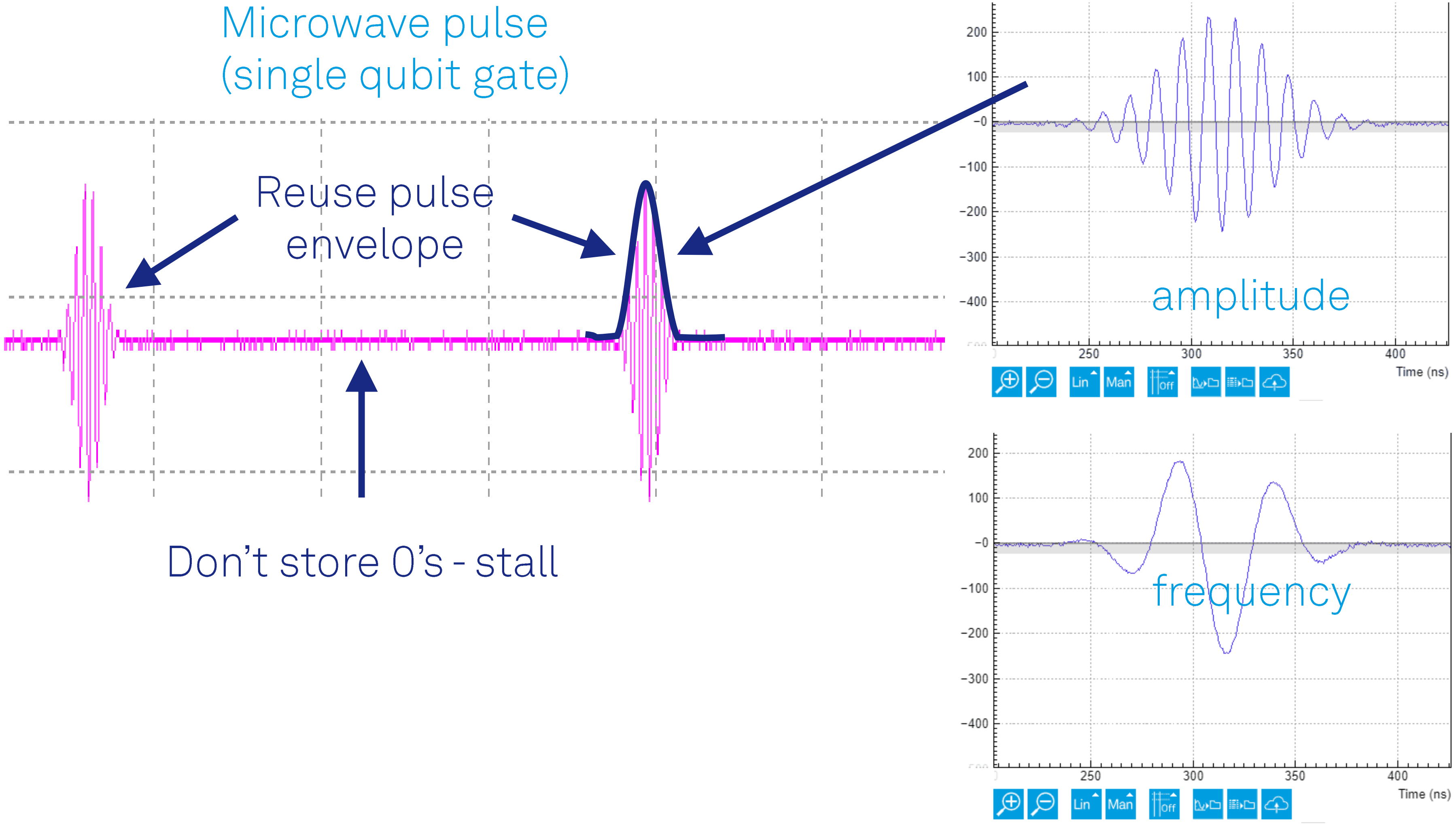
Sequencer program

Defines flow of experimental sequence (loops, decision making, pulse timings)



Efficient Generation of Pulse Sequences

Reduction of memory and upload time



Microwave pulse
(single qubit gate)

Reuse pulse
envelope

Don’t store 0’s - stall

amplitude

frequency

Efficient Generation of Pulse Sequences

Efficient pulse-level sequencing

Pulse-level sequencing

Pulse: Frequency, phase, amplitude, waveform

→ Transfer minimal information to system and execute in minimal time

Sequencer program

Defines flow of experimental sequence (loops, decision making pulse timings)

Command table

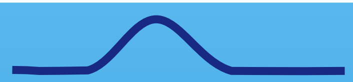
Contains parametric pulse description (frequency, phase, amplitudes, which waveform)

Waveform table

Contains all uploaded waveforms

```
repeat (AVG) {
  executeTableEntry(0);     //First pi/2 pulse
  playZero(WAIT_TIME);      //Evolution time
  executeTableEntry(1);     //Second pi/2 pulse
  playZero(READOUT_TIME);   //Readout
}
```

Index	Wave	Amplitude		Osc.	Phase	
		Value	Incr.		Value	Incr.
0	0	1.0	False	0	0	False
1	0	1.0	False	1	1°	True

Index	Wave
0	
1	...

Pushing Pulse-Level Sequencing to the Limit

Use case: randomized benchmarking

Objective

Optimize the performance of a single-qubit gate by playing many Clifford gates in a short time

Challenge

Requires randomized sequences and a recovery gate

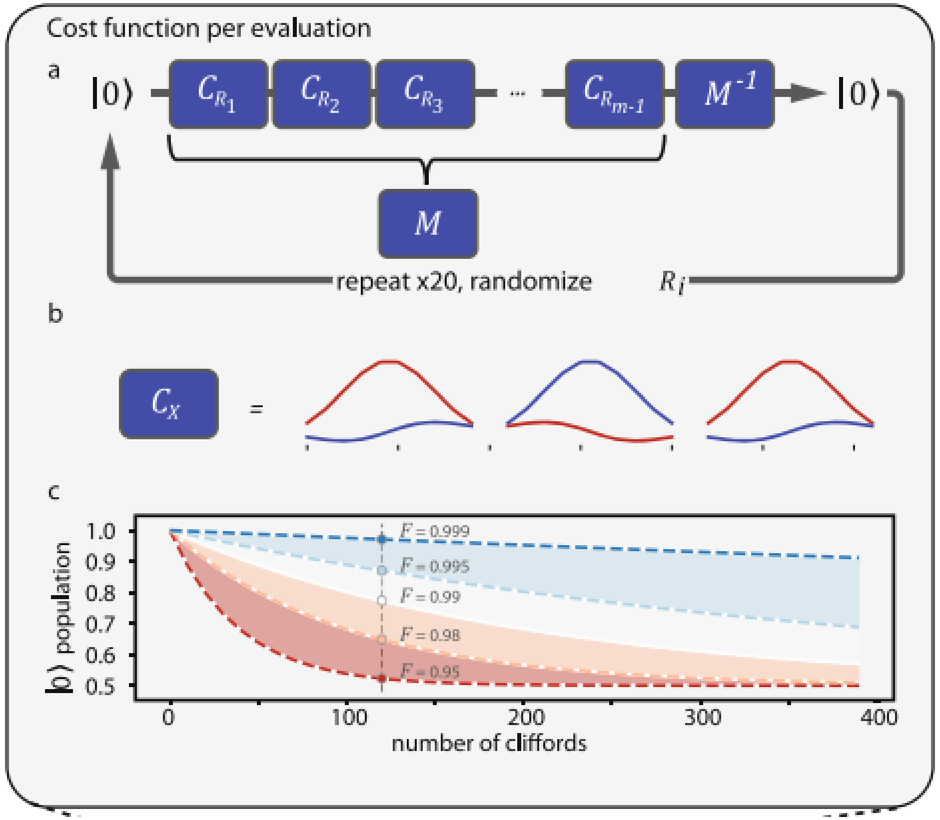
→ Each repetition is different

Quickly change parameters, e.g. frequency or shape

→ Inefficient to precalculate

Implementation strategy

Use pulse-level sequencing



M. Werninghaus *et al.*, NPJ Quantum Information 7 (2021)

Pushing Pulse-Level Sequencing to the Limit

Use case: randomized benchmarking

Implementation steps before experiment

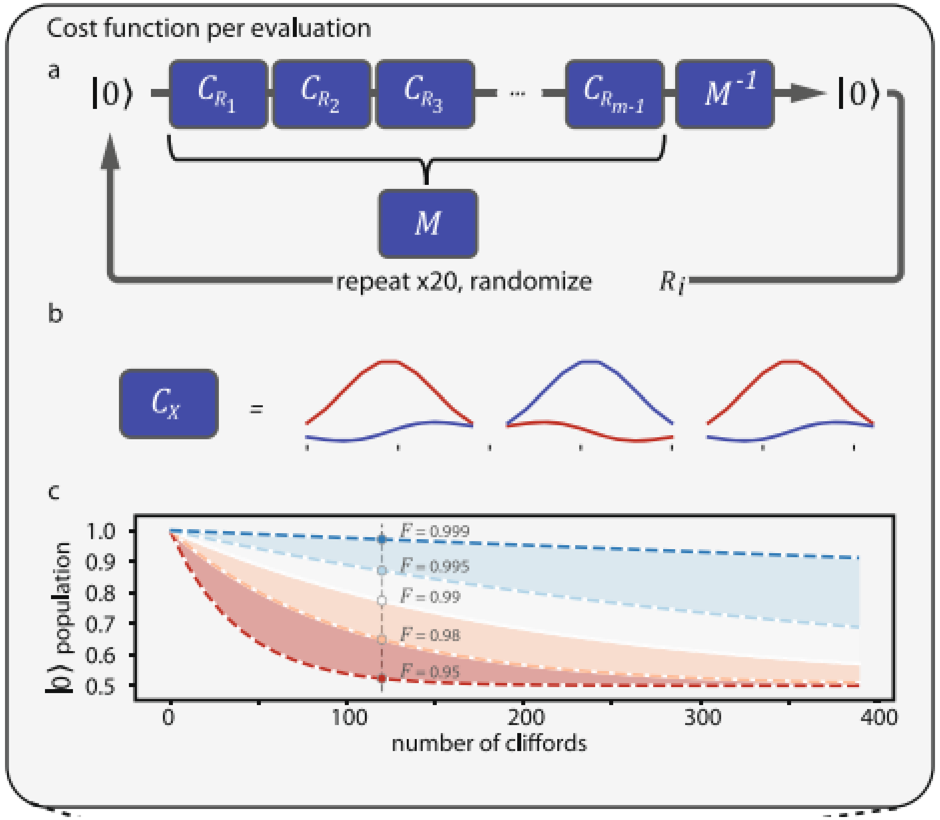
1. Upload single-qubit waveform shape
2. Upload command table containing only 24 Clifford gates
3. Upload sequence program using PRNG

For each random sequence

- Precalculate recovery gate for a seed
- Upload seed, recovery gate index (2 numbers)
- Send start trigger

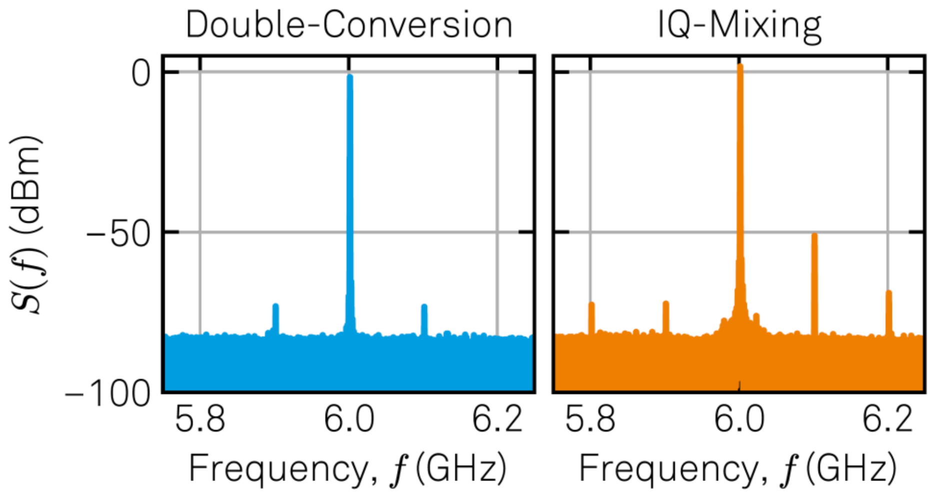
→ If needed, reupload: Pulse-shape, seed/recovery

→ Don’t reupload: Frequency, amplitudes (qscale)



Conclusions

- The Double super-heterodyne it’s a frequency conversion scheme that provides excellent performances, suitable for both readout and control of qubits



- Pulse level sequencing enable efficient workflow and enable realization of complex experiments

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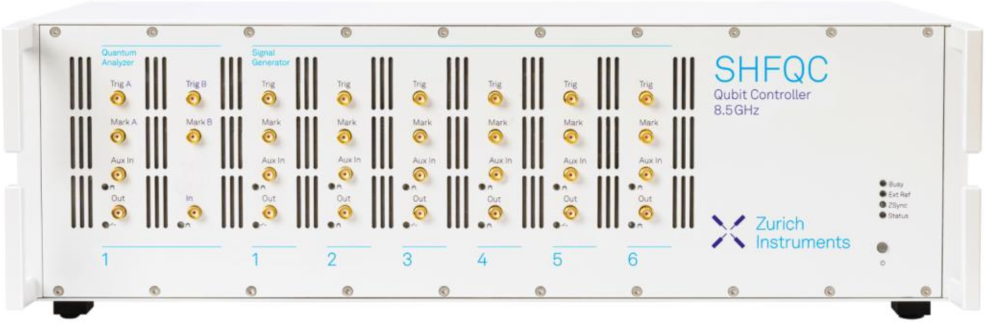

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