Zurich Instruments

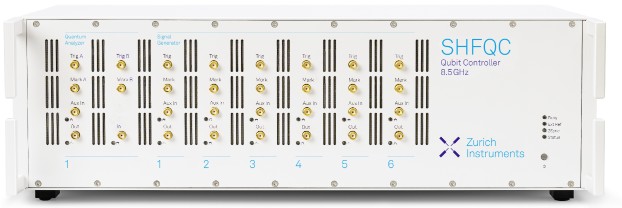
SHFQC
8.5 GHz Qubit Controller

Qubit control and readout of up to 6 qubits in a single instrument

Product Leaflet
Release date: 25.11.2021

Key Features

- 2, 4, or 6 signal generator channels, 1 quantum analyzer channel
- Operation at up to 8.5 GHz with 1 GHz analysis bandwidth and free of mixer calibration
- Low phase noise, low spurious tones and high output power for fast, high-fidelity gates
- Real-time signal processing chain with matched filters and multi-state discrimination
- Ultrafast instrument-internal feedback
- Controlled through LabOne, the LabOne QCCS Software, or APIs for Python



Introduction

The SHFQC Qubit Controller controls, reads out and provides fast feedback on up to 6 superconducting qubits. The signal generator channels for qubit control and quantum analyzer channel for readout are tightly linked through trigger and data distributions. The SHFQC comes in three possible configurations, in which either 2, 4, or 6 of the signal generator channels are enabled. Additional signal generator channels can be enabled in the field. As a result, the SHFQC is fully software-controlled and can be easily reconfigured.
The signal generator channels have powerful sequencers for real-time phase, frequency and timing control of waveforms, and branching based on inputs from other channels. The quantum analyzer channel and the SHFQC-16W option enable multiplexed and multi-state single-shot readout. Features such as a real-time oscilloscope, fast spectroscopy, and pulse-level sequencing improve system tune-up and measurement speeds.
As part of the Zurich Instruments Quantum Computing Control System (QCCS), the SHFQC benefits from intuitive operation through the LabOne QCCS Software and seamlessly interfaces with other QCCS instruments.

Applications

Quantum computing applications

- Coherent control of qubits through single and multi-qubit gates
- Frequency-multiplexed readout
- Dispersive single-shot readout
- Fast qubit and resonator spectroscopy, and setup characterization
- Real-time, low-latency feedback for system-wide operations and error correction protocols
- Systems from 1 or 2 qubits to more than 100 qubits

Supported qubit types

- Superconducting qubits
- Spin qubit/superconducting resonator hybrids
- Qubits, qutrits und ququads

Other applications

- Amplifier noise characterization
- Microwave setup calibration

Highlights

High-fidelity qubit manipulation and readout

Operating over a range that extends up to 8.5 GHz, the SHFQC's double superheterodyne up- and down-conversion scheme relies on filtering rather than on interference, so that it performs over a wider frequency band and with better linearity than standard IQ-mixer-based conversion approaches. In combination with synthesizers offering low phase noise and low timing jitter across the whole output frequency range, the SHFQC generates spurious-free and stable signals ideal for high-fidelity qubit control and readout - all available without spending time on mixer calibration.

The combination of superheterodyne frequency conversion with a linear amplification chain allows users to drive all single- and multi-qubit gates within short time intervals and free of distortion. Furthermore, the SHFQC's large spurious free dynamic range also allows for more flexibility when designing the readout frequencies as sub-optimally located spurs - normally leading to confusing or smaller readout signals - do not need to be avoided. In summary, the integrated frequency conversion offered by the SHFQC ensures that qubit control and readout operations realize the full potential of a quantum processor in terms of fidelity.

Efficient workflow and resource handling

The SHFQC's signal generator and quantum analyzer channels require minimal waveform and instruction memory even for complex gate sequences thanks to an efficient pulse-level sequencing approach. This approach ensures that complex tune-up and calibration routines are completed with a minimum of instrument communication overhead - even for large systems.

For example, loops and conditional branching support the implementation of active reset, while real-time phase and frequency control enable virtual Z gates. With up to 100 kSa waveform memory per channel, up to 16k sequence instructions, and a sampling rate of 2 GSa/s, the SHFQC provides customizable multi-channel arbitrary waveform generator (AWG) signals for qubit control and readout.

Fast readout with high fidelity

The SHFQC performs pulsed measurements to determine the transmission amplitude and phase of a readout resonator. Two methods help maximize the signal-to-noise ratio (SNR): pulse shaping and matched filtering. Pulse shaping with an arbitrary readout pulse generator minimizes ring-up and ring-down times. Matching the SHFQC's digital filters to the transient response of the readout resonator using a 2-μs-long weight function for each filter significantly improves the SNR compared to a simple, unweighted integration. In addition, the real-time analysis chain can discriminate up to 4 states per qubit.

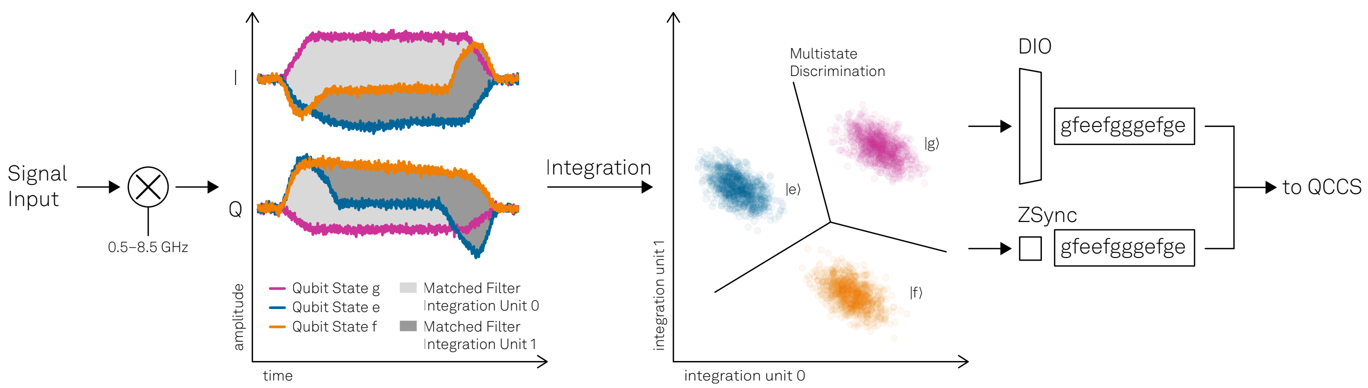
Scalable system approach

By design, the SHFQC supports control and readout of up to 6 fixed-frequency qubits, qutrits or 5 ququads. To optimally support other qubit types, or to extend the number of qubits, the SHFQC can be efficiently interfaced with other instruments too. For example, the low-latency 32-bit DIO VHDCI interface enables feed-forward of the multi-qubit state to a few HDAWGs for fast active qubit reset or optimal flux-pulse control.

For systems with larger qubit counts, several SHFQCs, SHFSGs, SHFQAs and HDAWGs can be combined to form a scalable QCCS. The Zurich Instruments ZSync interface links up to 18 instruments through the PQSC, namely the instrument acting as the central controller. This enables coordinated readout and control of up to 128 qubits using SHFSGs and SHFQAs, or up to 108 qubits including ultra-fast feedback using only SHFQCs.

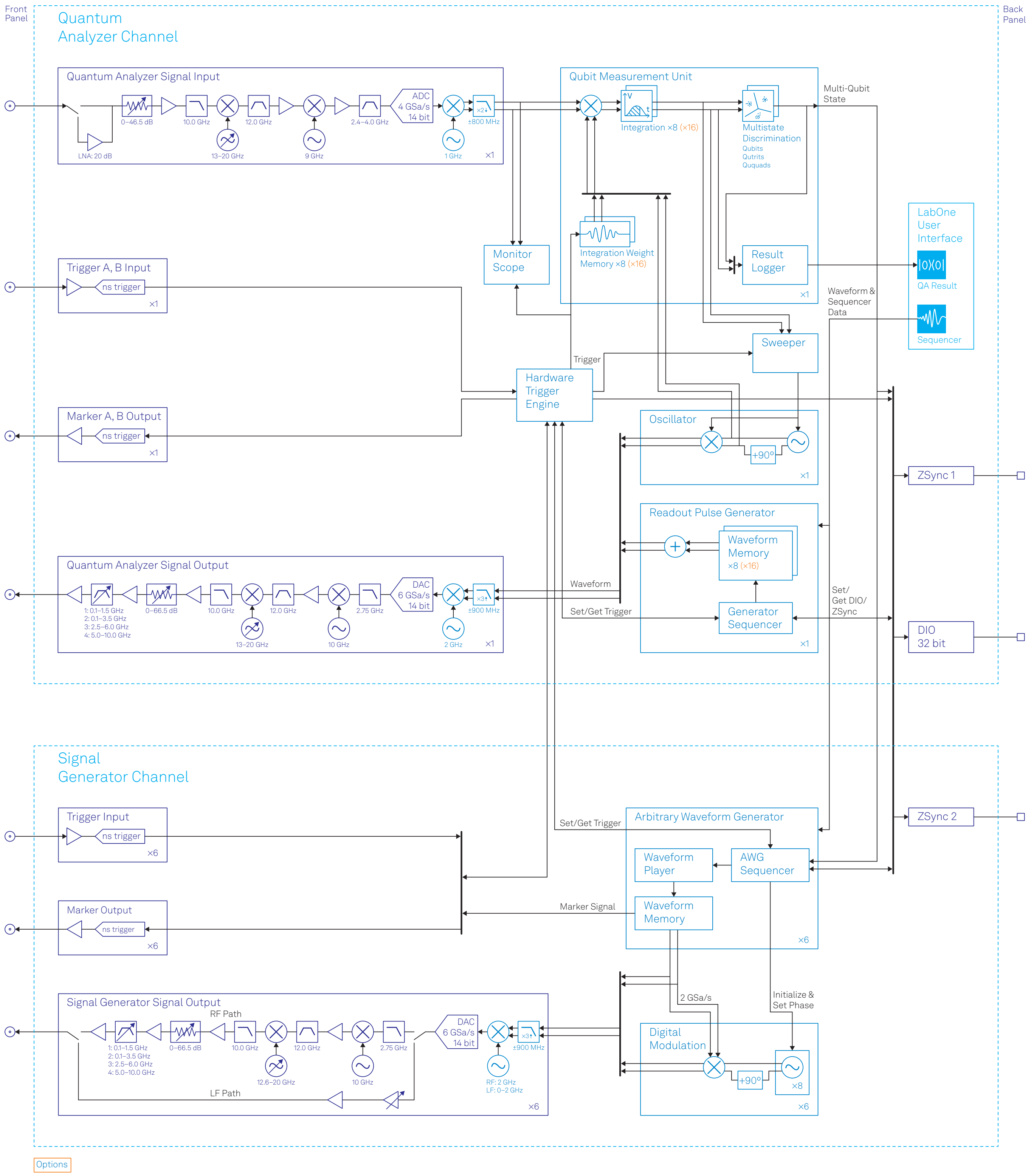
Quantum system control software

Using the LabOne QCCS Software or our Python APIs, the SHFQC - as part of our QCCS - can be seamlessly integrated into new or existing setups as well as into established measurement frameworks. The one-system-control approach, combined with an extended example library, advanced data structuring and the processing functionality offered by the LabOne Data Server, ensures that the user portion of the stack remains simple and intuitive to operate and maintain.



Quantum analyzer channel analysis chain for a qutrit readout. After analog and digital down-conversion, the reference traces from the readout resonators are integrated using matched filters. Multi-state discrimination assigns the qubit states |g⟩, |e⟩, or |f⟩ to the results and then communicates them to the signal generator channels or other instruments of the QCCS. The signals for multiplexed qutrit readout as well as the control pulses can be created with the SHFQC.

Functional Diagram



Specifications

General

Signal Generator (SG)	2, 4, or 6 (signal outputs)
Quantum Analyzer (QA)	1 (signal input and output)
Dimensions	449 × 460 × 145 mm 17.6 × 18.1 × 5.7 inch
Weight	15 kg (33 lb)
Power supply	AC: 100 – 240 V, 50/60 Hz
External reference	10 MHz or 100 MHz
Connectors	SMA, 32-bit DIO, ZSync LAN, USB 3.0

Signal outputs

Configuration	1 per SG channel 1 for QA channel
Frequency range	DC - 8.5 GHz (SG) 0.5 GHz - 8.5 GHz (QA)
Signal bandwidth	> 1.0 GHz
Output ranges	-30 dBm to +10 dBm
Output impedance	50 Ω
D/A conversion	14-bit, 6 GSa/s
Output level accuracy	±(1 dBm of setting)
Output voltage noise	14.1 nV/$\sqrt{\text{Hz}}$ (@ 6 GHz)
Output voltage noise density (10 dBm, offset > 200 kHz)	-135 dBm/Hz @ 1 GHz -140 dBm/Hz @ 4 GHz -144 dBm/Hz @ 8 GHz

Signal inputs

Configuration	1 for QA channel
Frequency range	0.5 GHz - 8.5 GHz
Signal bandwidth	> 1.0 GHz
Input impedance	50 Ω
Input voltage noise	1.1 nV/$\sqrt{\text{Hz}}$ (@ 3 GHz)
Input ranges (dBm)	-50 to 10 dBm (calibrated)
D/A conversion	14-bit, 4 GSa/s

Markers and triggers

Marker outputs	2 for QA channel, 1 per SG channel
Output voltages	0 V (low), 3.3 V (high)
Output impedance	50 Ω
Trigger inputs	2 for QA channel, 1 per SG channel
Input impedance	50 Ω / 1 kΩ

Synthesizers

Synthesizers	1 for QA channel 3 shared by SG channels
Phase noise (@ 6 GHz)	-90 dBc/Hz @ 1 kHz -98 dBc/Hz @ 10 kHz -100 dBc/Hz @ 100 kHz
Spurious-free dynamic range (ex. harmonics, 0 dBm)	74 dBc @ 1 GHz 66 dBc @ 4 GHz 60 dBc @ 6 GHz 65 dBc @ 8 GHz
Output worst harmonic component (10 dBm)	-40 dBc @ 1 GHz -40 dBc @ 4 GHz -38 dBc @ 6 GHz -36 dBc @ 8 GHz

Waveform generation

AWG cores	1 per channel
Instruction memory (SG)	32k instructions per core
Instruction memory (QA)	16k instructions
AWG sampling rate	2 GSa/s
Sequencing capability	Advanced sequencing, command table, advanced trigger control, staggered readout
Oscillators	1 per QA channel 8 per SG channel
Waveform resolution	14-bit analog
Wave memory (SG)	98 kSa per channel
Wave memory (QA)	8 × 4 kSa 16 × 4 kSa (w. SHFQC-16W)
Min. waveform length	32 Sa (only for SG channel)

Qubit measurement unit

Integration weights (Matched filters)	8 × 4 kSa 16 × 4 kSa (w. SHFQC-16W)
Multi-state discrimination	Up to 4 discriminators (qubits, qutrits, ququads)
Data logger	Memory: 2^{20} samples Averages: Max. 2^{17}
Monitor scope	Memory: 2^{17} Sa Averages: Max. 2^{16}

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