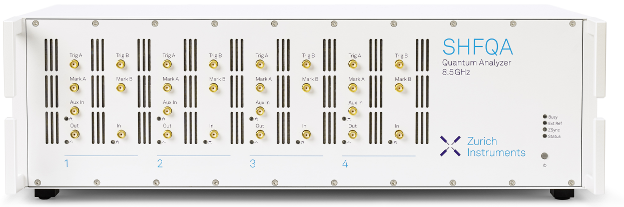
SHFQA
8.5 GHz Quantum Analyzer

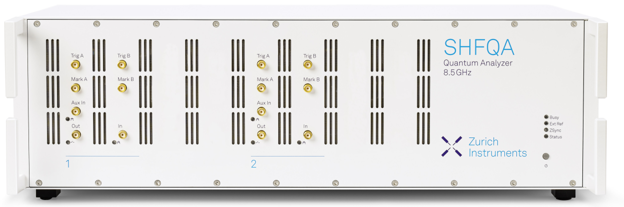
Zurich Instruments

Real-time measurement of up to 64 qubits with readout frequencies up to 8.5 GHz

Key Features

- 2 or 4 readout channels
- Fast resonator spectroscopy
- Readout of up to 64 qubits, 32 qutrits or 20 ququads
- Operation at up to 8.5 GHz with 1 GHz analysis bandwidth and free from mixer calibration
- Real-time signal processing chain with matched filters and multi-state discrimination
- 14-bit input at 4 GSa/s
- 14-bit output at 6 GSa/s
- Controlled through LabOne®, the LabOne QCCS control software, or APIs for Python, C, MATLAB®, LabView™ and .NET





Introduction

The Zurich Instruments SHFQA Quantum Analyzer integrates in a single instrument a full real-time readout setup for up to 64 superconducting and spin qubits. The SHFQA operates in a frequency range from 0.5 to 8.5 GHz with a clean analysis bandwidth of 1 GHz and without the need for mixer calibration. Each of its 2 or 4 readout channels can analyze up to 16 qubits, 8 qutrits or 5 ququads. For the 2-channel instrument, this performance requires the SHFQA-16W option.
The SHFQA enables multi-state discrimination with an optimal signal-to-noise ratio and minimal latency thanks to its advanced sequencer and the low-latency signal processing chain with matched filters and result correlation. The data can be transmitted in real time to other instruments for active qubit reset or global error correction protocols. Controlled through the LabOne software suite, which comprises the user interface, several APIs and the LabOne QCCS control software, the SHFQA supports quantum computing projects with sizes ranging from a few to several hundreds of qubits.

Applications

The SHFQA Quantum Analyzer is ready for use in the most demanding quantum computing applications, and it proves invaluable for daily tasks such as characterizing a quantum processor.

Quantum computing applications

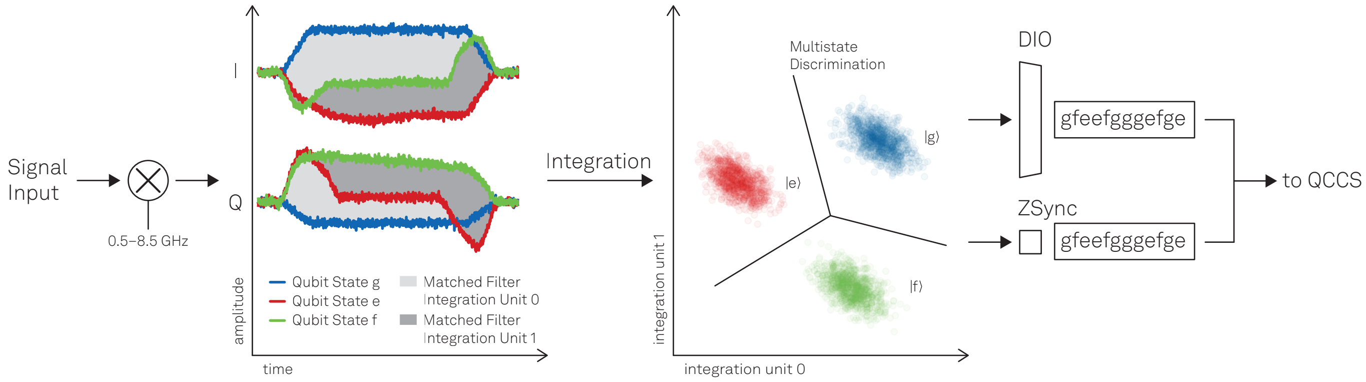
- Frequency-multiplexed readout
- Multi-state discrimination
- Single-shot dispersive readout
- Resonator spectroscopy and characterization
- Real-time, low-latency and global feedback for error correction

Supported qubit types

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

Other applications

- Amplifier noise characterization
- Data acquisition and FFT spectrum analysis



SHFQA analysis chain for a qutrit readout. After analog and digital down-conversion, the matched filters are used to achieve the maximum separation of qubit states g, e and f, then it will be discriminated and the digital bits are ready for feedback experiments.

Highlights

Fast resonator spectroscopy

Characterizing readout resonators of large qubit chips can be time consuming, especially for high Q resonators. With the SHFQA feature FPGA-based frequency sweep, the resonator spectroscopy can be performed with an integration-time limited speed.

Fast readout with high fidelity

The SHFQA performs pulsed measurements to determine the transmission amplitude and phase of the device under test. There are two methods to maximize the signal-to-noise ratio (SNR): pulse shaping and matched filtering. Pulse shaping with an arbitrary waveform generator minimizes the ring-up and ring-down time even for a device with a slow response.
The step response of the SHFQA's digital filters can be matched to the transient response of the device by programming a 2-μs-long weight function for each filter. Compared to a simple, unweighted integration, applying a properly matched filter significantly improves the SNR. In addition, the real-time analysis chain makes it possible to discriminate up to 4 states per qubit and to correlate the qubit results.

Clean and calibration-free frequency conversion at up to 8.5 GHz

When reading out multiple qubits through resonators coupled to the same readout line, even small spurs can lead to a confusing or smaller readout signal if they are sub-optimally located. As the SHFQA's double super-heterodyne up- and down-conversion scheme up to 8.5 GHz relies on filtering rather than on interference, it performs over a wider frequency band and with better linearity than standard IQ-mixer-based conversion. As a result, even a single tone can be generated with fewer spurs and straight out of the box. Importantly, the performance is stable and does not require tedious mixer calibrations. This approach, combined with an analysis bandwidth of 1 GHz, affords more flexibility when designing the resonator frequencies for frequency-multiplexed qubit readout; it also simplifies greatly the system's tune-up and maintenance.

Scalable quantum setup

Measuring 16 qubits or 8 qutrits on a single microwave line means optimizing the cryogenic amplification chain. The freely configurable integration weights reduce qubit crosstalk and, consequently, relax tolerances in device fabrication. The memory blocks (up to 16) in the arbitrary waveform generator enable the readout and trigger readout of the qubits, qutrits or ququads in a time-staggered manner. The possibility to choose 2 or 4 readout channels, and to extend the number of integration weights from 8 to 16 for the 2-channel version, means that users can tailor the instrument to their system requirements.

For maximum integration, the SHFQA 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. For systems with larger qubit counts, several SHFQAs, HDAWGs, HDIQs and a PQSC can be combined to form a scalable Quantum Computing Control System (QCCS). The Zurich Instruments ZSync interface links the SHFQA to all other instruments in the QCCS through the central PQSC, which is especially important for global error correction protocols.

Quantum system control software

As part of our Quantum Computing Control System, the SHFQA can be fully integrated into new or existing setups using the LabOne QCCS control software. As a standalone unit, it can be controlled with LabOne and its APIs for Python, C, MATLAB®, LabVIEW™ and .NET. An extended example library facilitates integration into established measurement frameworks. Thanks to the data structuring and processing functionality offered by the LabOne Data Server, the user portion of the software stack remains simple and easy to maintain.

Frequently Asked Questions

Functionality

How many qubits, qutrits and ququads can I read out with one readout channel of the SHFQA? The 4-channel version and fully featured (i.e., including the SHFQA-16W-option) 2-channel version of the SHFQA allow you to optimally detect 16 qubits, 8 qutrits or 5 ququad states per readout channel. The base version of the 2-channel SHFQA allows you to detect 8 qubits, 4 qutrits or 2 ququads.

For what qubit types and readout methods is the SHFQA suitable? The SHFQA is best suited for readout schemes that modify a probe signal in the microwave regime: for example, the schemes commonly used for reading out superconducting circuits or hybrid superconducting/spin-qubit systems.
The SHFQA is not suitable for readout schemes that are based on photon counting, because it does not include counter functionality, or for schemes requiring operation below 0.5 GHz.

What are the additional tools that will help me with my experiments? With every release of our LabOne software, we provide new tools and features. For example, fast resonator spectroscopy helps you measure and characterize your readout line in the shortest time. We also offer a library of Python notebooks and tutorials to help you set up and control your SHFQA as quickly as possible.

Hardware

Do I need additional amplifiers or mixers external to the cryostat to be able to read out a set of superconducting qubits with the SHFQA? No, you don't. Both RF input and output of the SHFQA are designed to be directly connected to the qubit readout line of the cryostat as long as the readout frequencies are within the measurement band of 0.5–8.5 GHz and the signal has been pre-amplified at the cold stage, e.g., by a HEMT amplifier.

When I use a parametric amplifier such as a TWPA or JPA, a strong pump tone co-propagates on the signal line: will this cause problems? A strong pump tone may cause the pre-amplifiers before the first mixer stage to become non-linear, leading to a potentially reduced SNR or more spurs in the readout spectrum. You have two options to overcome this effect:

- Do not use the pre-amplifiers. In this case, the filter after the first mixer stage might be able to filter out the pump tone signal. Of course, you need to make sure that the signal level is still in a suitable range for the SHFQA to be detected.
- Add a pump tone cancellation circuit between the SHFQA and the cryostat.

Software

With what software can I control the SHFQA, and where can I obtain it? The SHFQA comes with the LabOne software and its APIs for Python, C, MATLAB®, LabVIEW™ and .NET. The examples of Python APIs included with the software are guided by the qubit readout application and enable fast integration into other measurement frameworks. The LabOne software and APIs are produced by Zurich Instruments and upgraded on a regular basis, providing you with new instrument features and functionalities.

System integration

How can I connect the SHFQA to other instruments that are part of the QCCS? The SHFQA was conceived to be interfaced with the PQSC through the Zurich Instruments ZSync link that provides both system-wide clock synchronization and data distribution. Furthermore, it also provides a 32-bit DIO VHDCI interface that can be used to directly connect the SHFQA to other instruments of the QCCS for fast feedback, such as the HDAWG, or to third-party instruments.

Do I need the PQSC to operate the SHFQA? No, you don't. The SHFQA can be controlled, and its measurement data obtained, with a conventional computer. The measurement data for real-time processing can be transmitted as a basic parallel TTL signal through the 32-bit DIO VHDCI. However, for optimal synchronization with other instruments of the QCCS, we strongly recommend that you use a PQSC.

Do I need an HDAWG and/or HDIQ to operate the SHFQA? No, because the SHFQA can be used as a standalone system: it offers everything that is needed to replace 4 full room-temperature multi-qubit readout systems, including frequency conversion up to 8.5 GHz. It can be triggered through an internal trigger source or any conventional TTL-signal generator.

Can I replace one or more UHFQAs with an SHFQA? Yes, each readout channel of the SHFQA is a drop-in replacement of one UHFQA.

Can I mix UHFQAs and SHFQAs in a single setup? Yes, but we strongly recommend to use only one type of instrument in a given setup.

Specifications

General

Readout channels	2 or 4
Dimensions	449 × 460 × 145 mm^3 17.6 × 18.1 × 5.7 $inch^3$ (19” rack)
Weight	15 kg (33 lb)
Power supply	AC: 100 – 240 V, 50/60 Hz
Connectors	SMA, 32-bit DIO, 2 ZSync, LAN, USB 3.0

Signal inputs (2 or 4)

Frequency range	0.5 – 8.5 GHz
Signal bandwidth	1.0 GHz
Input voltage noise	< 2.2 nV/$\sqrt{Hz}$ (@ -50 dBm)
Input ranges (dBm)	-50 to 10 dBm (calibrated)
A/D conversion	14-bit, 4 GSa/s

Signal outputs (2 or 4)

Frequency range	0.5 – 8.5 GHz
Signal bandwidth	1.0 GHz
Output voltage noise	14.1 nV/$\sqrt{Hz}$ (@ 6 GHz)
Output ranges (dBm)	-30 to 10 dBm (calibrated)
D/A conversion	14-bit, 6 GSa/s

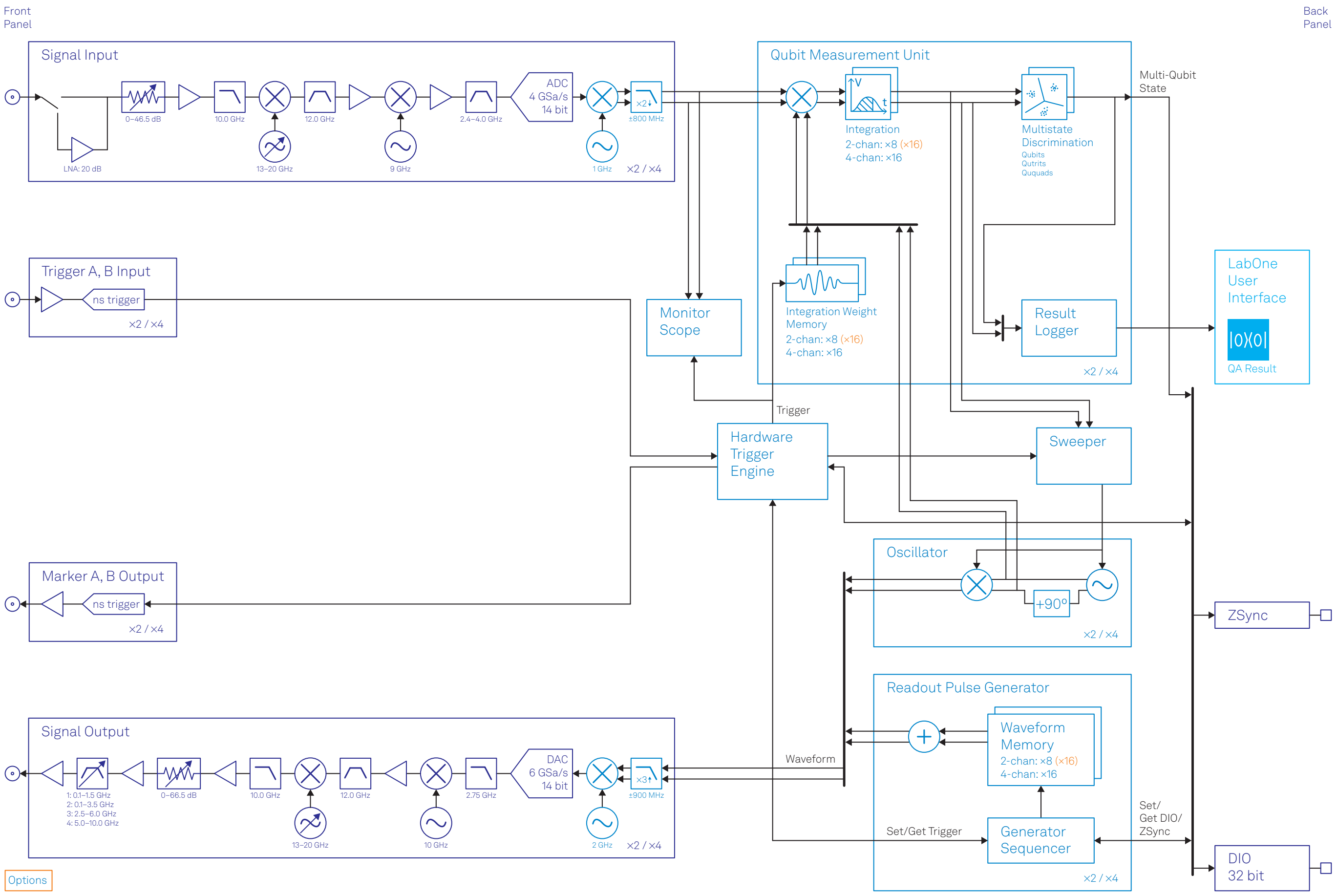
Qubit measurement unit (2 or 4)

Integration weights[1] (Matched filters)	16 complex filters/channel 4 kSa/filter/quadrature
Multi-state discrimination	Up to 4 discriminators 16 qubits, 8 qutrits, 5 ququads
Data logger	Memory: 2^{19} samples max. 2^{16} averages
Monitor scope	Memory: 2^{18} Sa for 1 channel 2^{17} Sa for 2 channels 2^{16} Sa for 3 and 4 channels max. 2^{16} averages

Readout pulse generator (2 or 4)

Sequencing capability	Advanced sequencing (loop, branching) Command table Advanced trigger control
Waveform memory[1]	16 × 4 kSa/quadrature or 8 × 8 kSa/quadrature or 1 × 64 kSa/quadrature
Marker outputs	2/channel
Trigger inputs	2/channel

[1] Specified numbers include the SHFQA-16W option.



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